CCUS Economics: Capture Costs, EOR Demand & Regional Supply and Demand Curves

Stanford Center for Carbon Storage Affiliates Meeting

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B2 E2 BROWN BROTHERS ENERGY & ENVIRONMENT

Sections of Today's Discussion

1. Basic feasibility equation for CCUS today: With new 45Q tax credits projects are feasible if capture cost is in the $50-60/MT range, assuming (i) projects can sell CO2 to EOR producers and (ii) that pipeline transport issues are solved.
2. During 2019, several projects examining cost of capture have helped us get a better handle on costs and on the individual emitters most likely to have feasible projects. That lets us create location-specific CO2 supply curves
3. The potential volumes and prices for sales to CO2-EOR are a black box, but at least ARI data lets us create location-specific CO2 demand curves.
4. We can link those supply and demand curves with pipeline modeling systems such as LANL's SimCCS to find regional market equilibriums of supply and demand.

Part I: Basic Feasibility Test

85 Broad Street, NY, NY

Feasibility: Capture Cost has to be Less Than Revenues, Credits & Transport Costs

Cost of Capture
- Equipment x Financing % Rate
- O&M
- Energy penalties

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+ $35/MT Section 45 Q Tax Credit* + EOR Sales Revenues minus Transport Cost to EOR field

OR

+ $50/MT Section $45 Q Tax Credit* minus Storage Charges by Saline Operator minus Transport Cost to Saline Reservoir

*For simplicity we are showing the maximum amount, before adjustments for inflation. In the analyses we account for the fact that the credits can only be earned for 12 years. We are showing solely for analytical purposes that the credits are received by the injectors. Clearly, the tax credit may not be worth its full nominal amount if it is monetized through an inefficient financial transaction, a factor we are not able to systematically quantify at present.

Why Cost, Drivers and Selection Matter: Current CO_2 Cost Feasibility Cutoff @ ~$50s/MT

Cost /Revenue Item	$/MT	Key Factors
Sales of CO_2 to EOR producer	~$20-30/MT	Price of oil, because CO_2 contract sales prices typically linked to oil. Could be higher in most productive EOR fields—if they lack access to geologic CO_2.
Less Cost of Transport to EOR field	($5-10)/MT	Depends whether can use existing trunk line or whether need new build trunk. Also very sensitive to length of any spur/connector lines.
Value of §45Q Tax Credit (non-cash)	$35/MT	Rises year-by-year per statute reaching $35/MT by 2026. Rises with inflation thereafter (similar to renewable Production Tax Credit).
	~$45-60/MT maximum for feasibility	Range likely includes best SMR/H2, Cement, and Coal Power Projects, perhaps FFCUs

Saline Disposal Makes Feasibility Harder (except Special Cases*)

Cost /Revenue Item	$/MT	Key Factors
Fees paid to Operator of Saline Storage Site	($5-15)/MT	Source:
Less Cost of Transport to EOR field	($5-10)/MT	Depends whether can use existing trunk line or whether need new build trunk. Also very sensitive to length of any spur/connector lines.
Value of §45Q Tax Credit (non-cash)	$50/MT	Rises year-by-year per statute reaching $50/MT by 2026. Rises with inflation thereafter (similar to renewable Production Tax Credit).
	~$25-40/MT maximum for feasibility	Unlikely to include any projects build new separation equipment funded solely by 45Q and EOR sales. Ethanol and special cases.

*Special case example: Wabash gasifier/ ammonia plant already has to build Rectisol in due course, so saline storage is almost free money.

Part II: Capture Project Costs, Drivers, and Selection

Cheap carbon capture equipment.

Expensive carbon capture equipment.

NPC/RDI Research

- I led a group during the NPC process that will publish a Topic Paper on regional supply and demand curves for CO2. Carbon Capture Coalition's Regional Deployment Initiative is continuing and extending the work.
- Went through multiple carbon capture project engineering studies for each of the most promising industries. Tore them apart to distinguish real "capture cost" differences vs. mere noise in the assumptions.
- Bottom line(s):
  - Studies were relatively consistent in terms of the basic cost of capture equipment, compression, and balance of plant given size of project (MTPA) and CO2 molar concentration.
  - The headline "capture cost" (or avoided cost) numbers vary wildly because studies made wildly different assumptions <u>about contractor process and project contingencies, estimates of remodeling/brownfield risks, extra non-capture equipment needed, owner costs and contingencies, financing rates, host plant capacity factors, project physical configurations</u>, etc.
  - There were also plenty of straight up errors or strange assumptions made.
- Studies that showed capture numbers in the $80-$150/MT had either gone to the expensive side of every assumption, made major mistakes, or both.

Cost, Drivers & Selection

- Costs:
  1. Function of original equipment cost (per ton captured) X financing rates,
  2. Operating & maintenance costs,
  3. and the fuel/electricity needed to run the capture equipment.
- Drivers:
  1. Lower equipment costs if capture plants are big,
  2. Lower equipment costs if emissions are concentrated,
  3. and lower operating costs where electricity and gas prices are low.
- Project selection/identification:
  1. Even if costs and drivers are similar need to look for emitters that operate most hours of the year,
  2. efficient emitter plants that are competitive in their particular industries,
  3. and the best streams of emissions inside complex plants.

Costs

- Biggest factor each year is **financing**: the original equipment cost ($ millions), multiplied times the annual financing rate (%).
- Remaining costs, typically in the area of ~$15-20/MT.
  - Typically about 3-6% of original equipment cost each year for overhead, taxes, and labor.
  - Balance for electric power and fuel. The fuel typically used to “regenerate” the materials (liquid or solid) that capture the CO2.
- The values of individual coefficients and prices vary widely among governments and consultants, but the calculation methodology is simple.

Simplified Example: Cement @ $43.25/MT CO2 Captured

- Financing:
  - $200 million plant x 10% per year financing rate = $20 million per year
  - Captures 1 million MT per year
  - So financing cost is <u>$20/MT</u> captured
- Running Costs:
  - $200 million plant x 5% O&M costs per year = $10 million per year.
  - Captures 1 million MT per year.
  - So <u>$10/MT</u> captured
- Fuel and electricity:
  - 2.5 MMBtu/MT x $3.50/MMBTU = <u>$8.75/MT</u> captured
  - 0.15 MWh/MT x $50/MWh = <u>$4.50/MT</u>

Putting Studies on Comparable Basis: Cement

Author	NETL/Booz	IEA/ Mott MacDonald	CEMCAP
Year	2014	2008	2019
TPY Product	~ 1 million MT/yr cement	~ 1 million MT/yr cement	Approx 685 MT/yr Cement @ 85%
Estimated actual captured tonnage	~1 million MT/yr CO2	~1 million MT/yr CO2	0.791 million MT/yr CO2
Cap Cost MT/yr	$ 189.42	$ 132.61	$ 125.55
O&M as % CapCost	8.9%	10.3%	10.1%
O&M per MT ex fuel, w/ tax ins	$ 12.98	$ 13.71	$ 12.71
Fuel MMBtu/MT for regen	4.09	3.16	3.8016
Elec. MMBtu/MT for capture	0.16	0.19	0.15
Est Cost 13% CRF, $3.5 gas, $50 elec	$ 63.78	$ 51.48	$ 49.84
Per Source Study unadjusted	$100.44/MT "first year break-even"	$88 /MT cost of capture and $158/MT avoided cost	$90/MT avoided cost
MDEA Unit $/MTPA	$68.40	$46.75	~$45-50 (not broken out)

NETL study had mistaken ~$10/MT for spare parts each year.
70% of IEA capex was irrelevant, and they double counted interest during construction.
CEMCAP used 18% contingencies just on MEA unit; NETL used 22% contingencies on whole project.

Generic CO_2 Capture Cost Ranges for Various Industries

Cost *generally* rises as concentration falls. But other factors such as gas pressure and site difficulties also come into play.

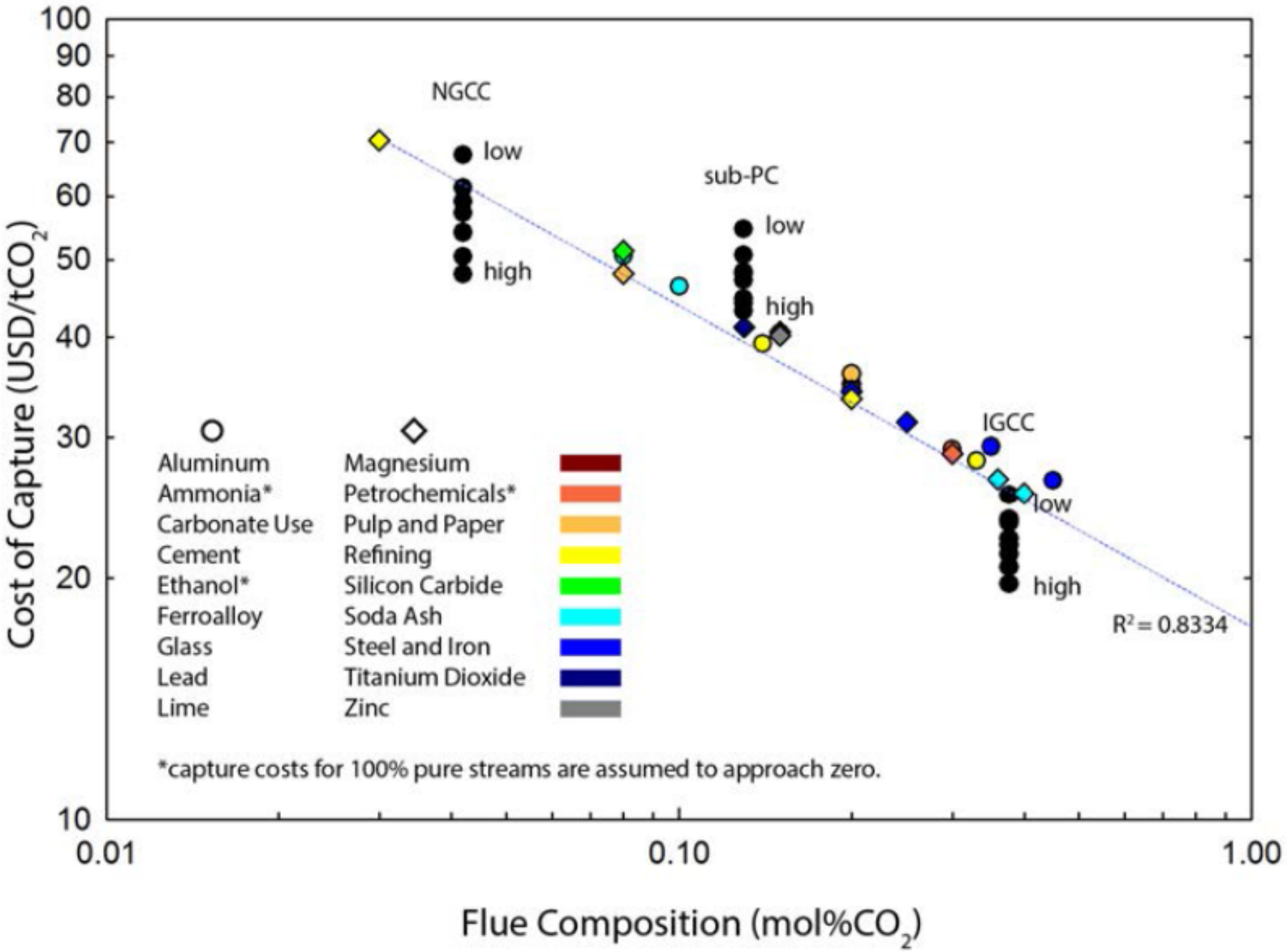
Industry	CO2 % in Gas Stream	Construction Cost per MTPA (from multiple industry studies reviewed): Capturable Emissions MTPA @ 85% NCF	$ Construction Cap. Cost for Project	Construction Capital Cost $/MTPA	Capital Recovery/MT Captured @ 9.6%[1] CRF	(~5-8% x Cap Cost) O&M	$3.50 /MMBtu Fuel	$50.00 / MWh Power	Total @ 9.6%[1] CRF	Total @ 13%[1] CRF
Gas Processing	100%	600,000	$23,523,777	$39.2	$3.8	$2.4	$0.0	$4.8	$11.0	$13.8
Ethanol	100%	500,000	$24,468,162	$48.9	$4.7	$3.4	$0.0	$5.8	$13.9	$17.5
Ammonia[2]	100%	400,000	$27,238,098	$68.1	$6.5	$3.4	$0.0	$5.0	$14.9	$19.7
Hydrogen	15-20% @ 20 Atm.	350,000	$58,781,549	$167.9	$16.1	$8.4	$8.9	$9.0	$42.4	$54.2
FCCU(Cat Cracker)[3]	12-15%	1,000,000	$224,567,075	$224.6	$21.6	$9.9	$8.9	$7.2	$47.6	$63.0
Cement	21%	1,000,000	$187,382,810	$187.4	$18.0	$13.1	$8.9	$8.2	$48.3	$62.1
Blast Furnace Gas[3]	26%	3,000,000	$841,816,517	$280.6	$26.9	$14.0	$8.9	$8.2	$58.1	$77.8
Pulverized Coal	13%	1,600,000	$478,097,307	$298.8	$28.7	$12.4	$8.9	$8.2	$58.3	$78.7
NGCC (gas power)	4%	1,000,000	$356,073,692	$356.1	$34.2	$17.8	$8.2	$0.0	$60.2	$85.1

(1) 9.6% is reasonable for projects with strong sponsors or balance sheets, or for utilities (NETL uses ~ this rate). 13% would be more appropriate for industrial companies.
(2) Only applies when there is an existing capture unit & not all captured CO2 is used to make final products such as urea.
(3) Few well-documented public studies isolating the high value Fluidized Catalytic Cracking Units in oil refineries or "stoves" burning Blast Furnace Gases in integrated steel mills.

Cost Drivers

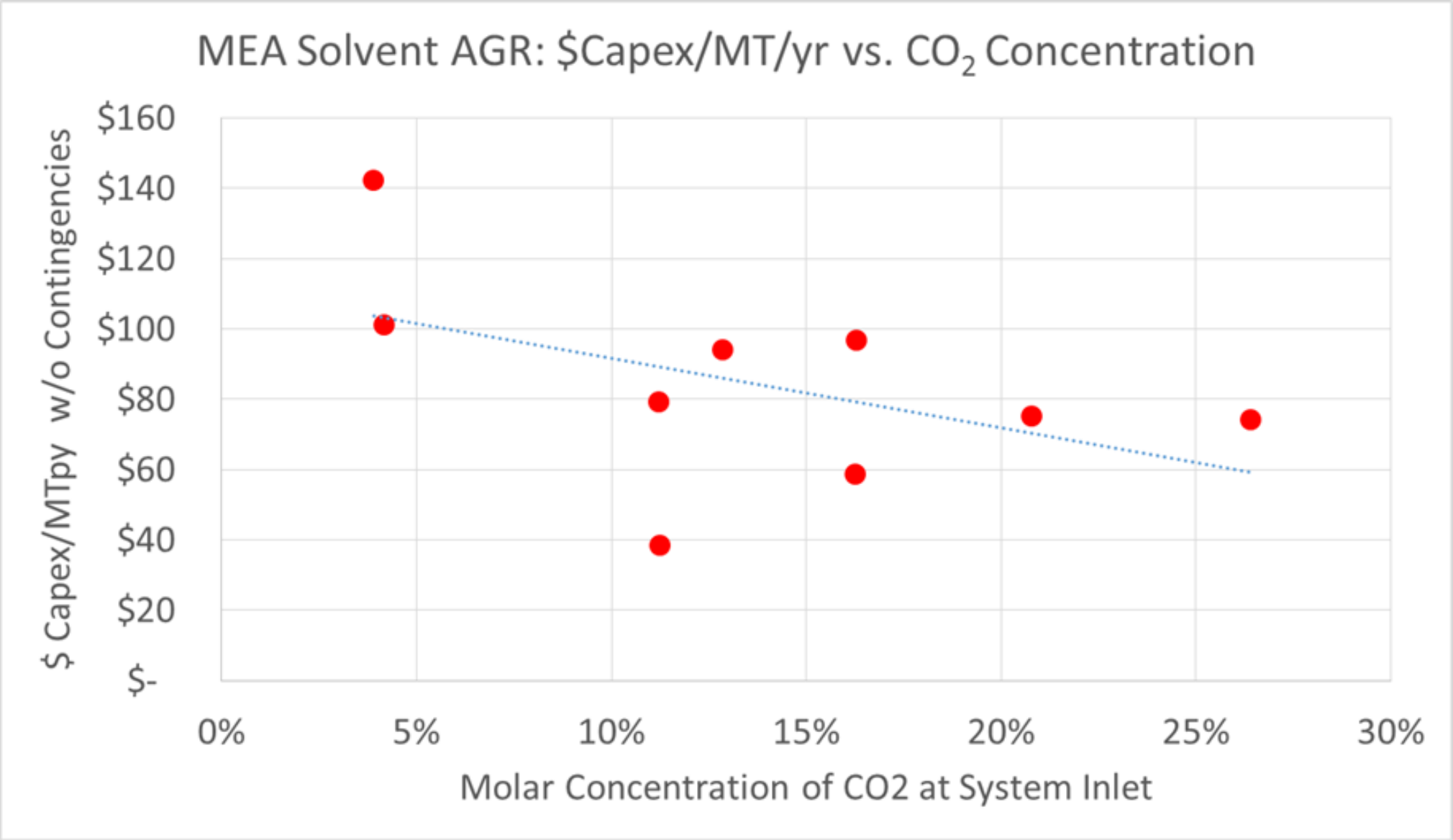
- Physical factors:
  - Concentration of CO_2 in exhaust gases: higher = cheaper
  - Pressure of gas treated: higher = cheaper
  - Scale: bigger = cheaper
- Commodity prices:
  - Gas cost: low = better. Buy gas to make steam for capture process
  - Electricity cost: low = better. Buy electricity to run capture and compression equipment

Theory: CO_2 Concen-tration vs. Cost



(Psarras, Comello, Bains, et al. "Carbon Capture and Utilization in the Industrial Sector." August 17, 2017.)

Practice: Project Engineering Sample Confirms Theory



GCCSI and NETL Show Capture Cost RISING with Rising CO2 Concentration: Why?

Industry	Capture Plant Size MMTPA	Flue Gas Concen-tration mol/mol	Steyer-Taylor Estimate of Capture Cost/MT*	Navigant Capture Median ($/€ @ 1.12)	Comello, Reichelstein, Wilcox et al Capture (added $10 for compression)	GCCSI Avoided FOAK (USA-Germany)	Booz Allen NETL Capture for NETL **
Pulverized Coal Plant	1.5	13%	$58		$47-53	$74-121	$56
Steel blast furnace gas	2.0	26%	$58	$60	$41-$44	$77-113	$99
Cement	1.0	21%	$48	$44	$38-$49	$124-188	$96-100
Hydrogen SMR	1.0	16% @ 20 ATM	$43	$32	~$38 [earlier paper]		$112-118

Everybody is pretty close on coal.

Huge divergence on BFG, Cement, SMR

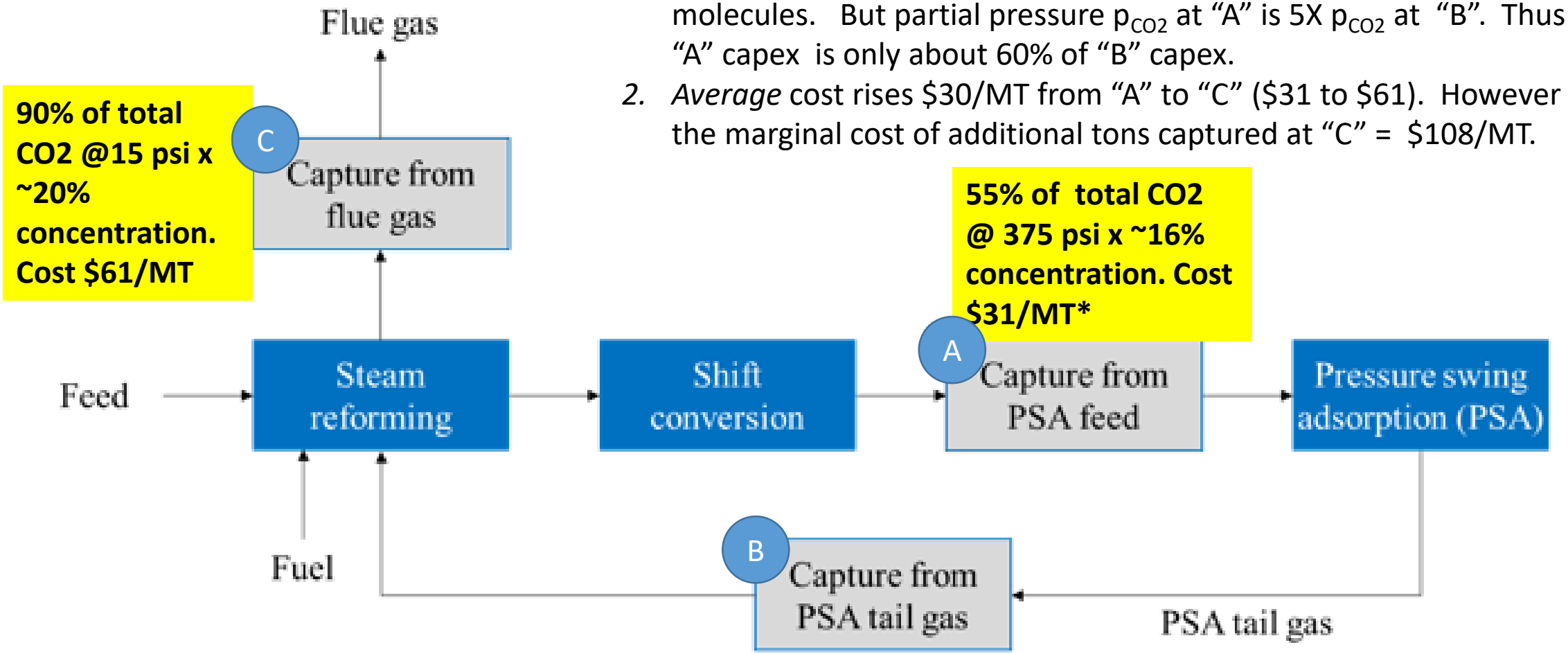
*used 9.6% capital recovery factor for 12 year project life.
** H2 p. 88, Steel p. 101, Cement p. 112. The coal number was 2013 case 11A vs 11B w/ extra $210.5 M/yr cost and 3.72 MMTPA captured

Selection and Configuration: Capturing CO_2 Efficiently

- Inside multi-emitter industrial complexes: focus on sub-systems with lowest-cost CO_2 capture
- Capture at the cost-minimizing spot in process (e.g., at a high pressure vs. low pressure stream point)—H_2 example.
- Customize capacity of equipment: don't add extra capture equipment that won't run very often
- Supply parasitic steam and electric loads cheaply
- Turnkey EPC if possible

Selection: SMR Capture at Right Spot & Watching Marginal Cost

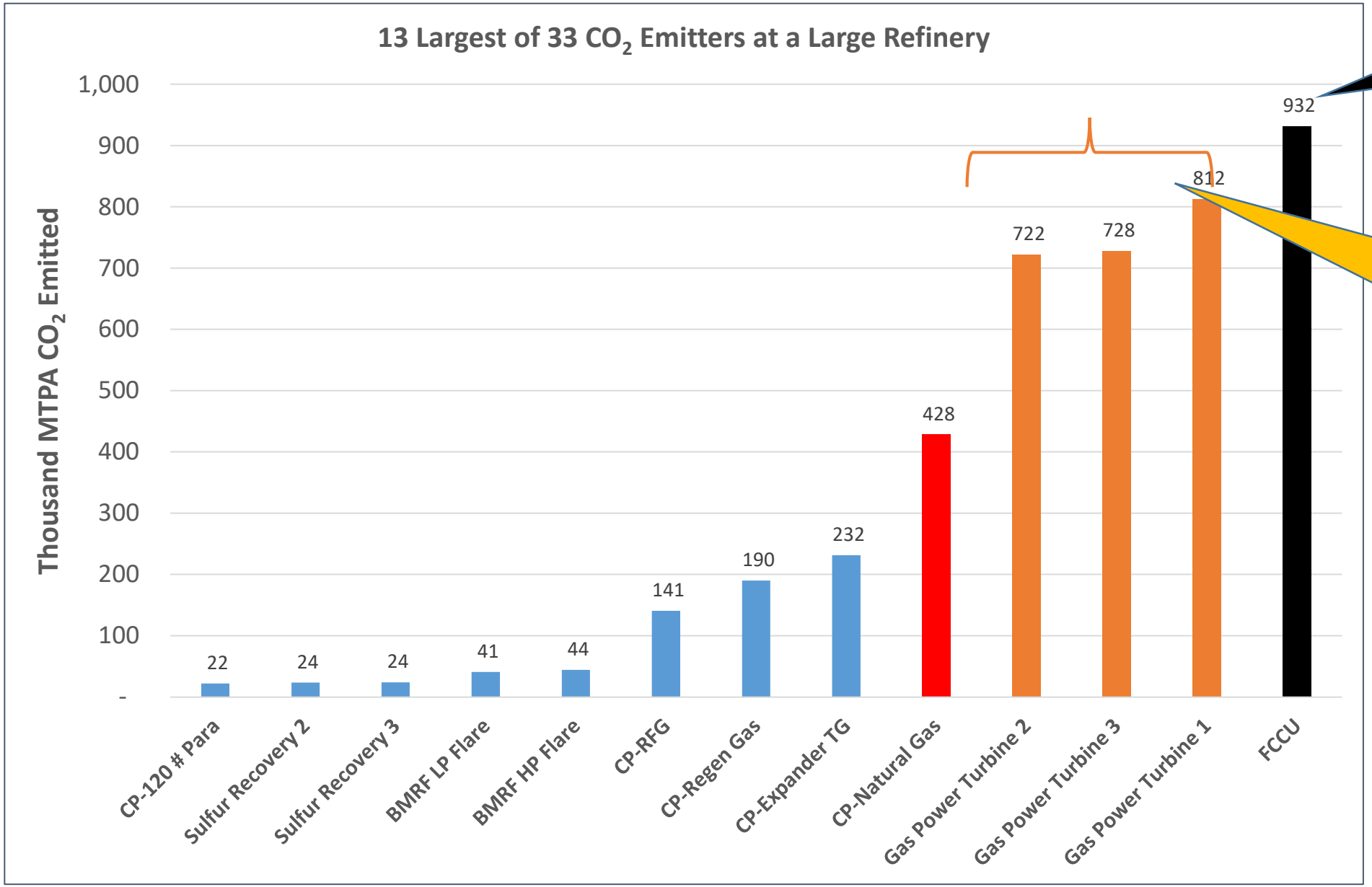
1. Both Point "A" & Point "B" capture same number of CO2 molecules. But partial pressure p_{CO2} at "A" is 5X p_{CO2} at "B". Thus "A" capex is only about 60% of "B" capex.
2. *Average* cost rises $30/MT from "A" to "C" ($31 to $61). However the marginal cost of additional tons captured at "C" = $108/MT.



*These are IEA figures converted to USD, and with energy costs at US levels. My study used "point A" configuration but more conservative capital costs, contingencies, etc. Using the IEA figures because they were only study I have seen that clearly examined all three capture points.

55% of total CO2@ 20 psi x ~50% concentration. Cost $48/MT

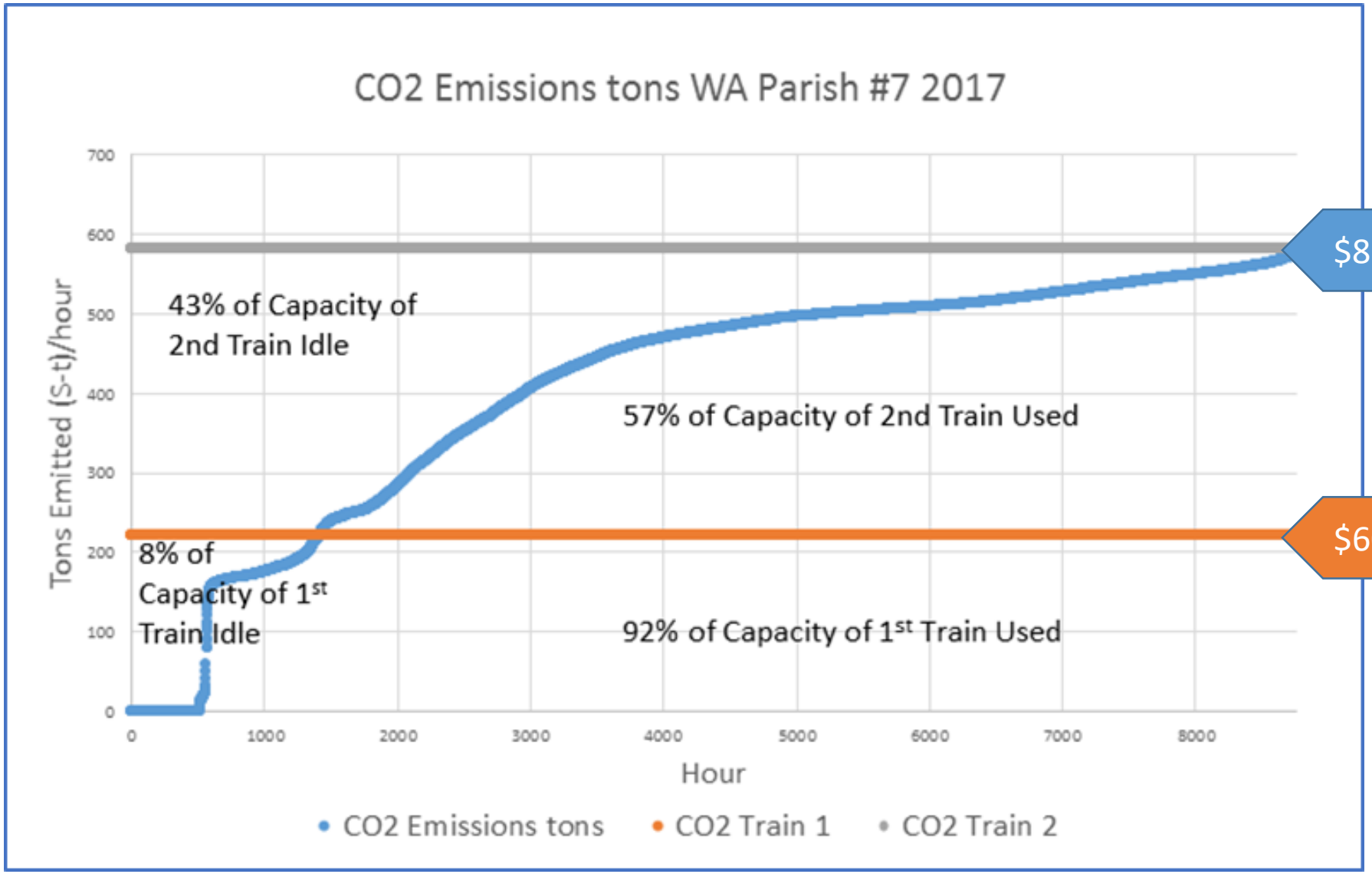
Selection: Cherry-picking Bigger and/or Higher Concentration Units



FCCU is biggest and has highest CO_2 concentration

Three gas turbines could feed into a single ~2 million MTPA capture unit. Low concentration but large size and high NCF.

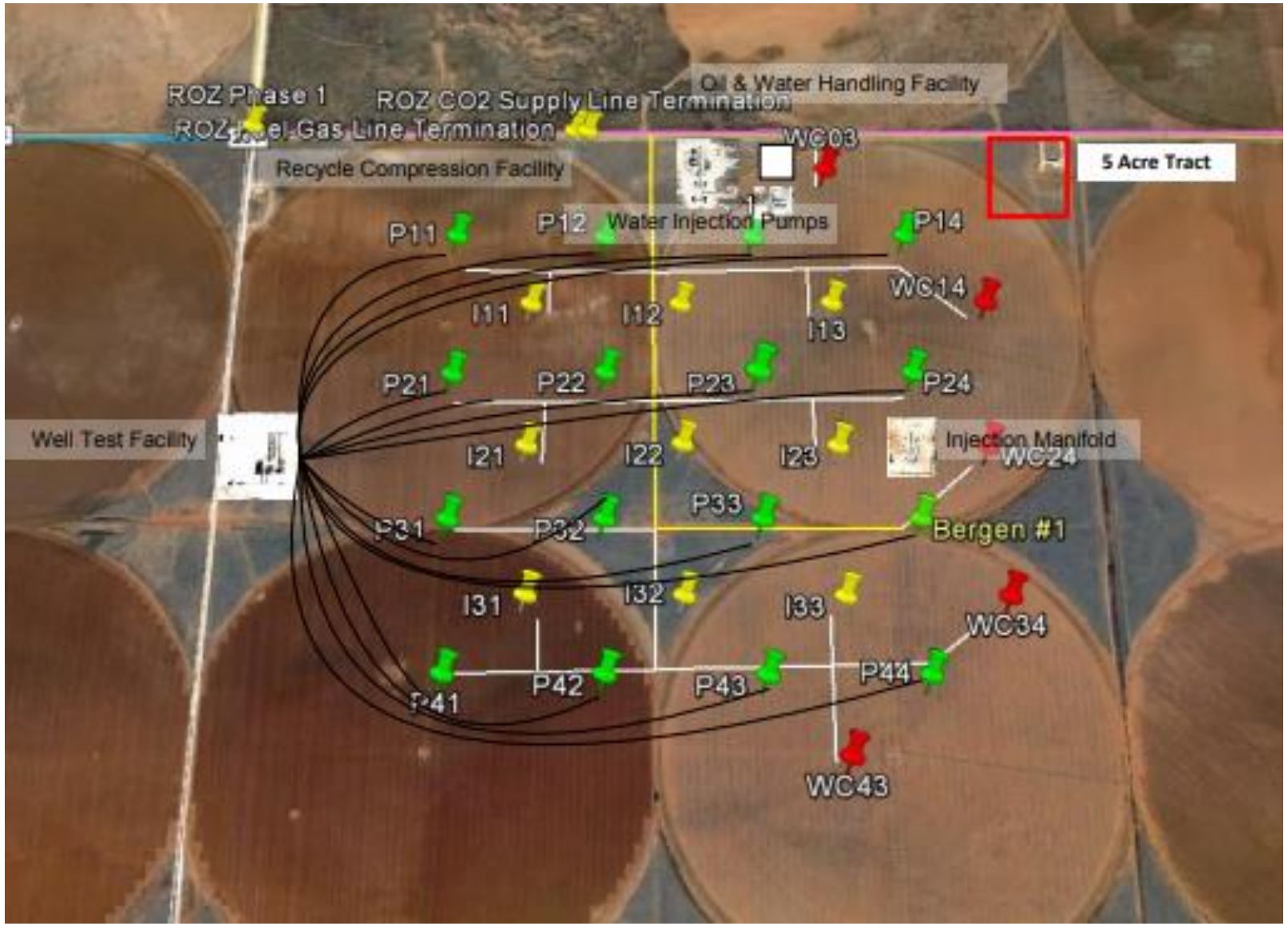
Selection Example: Sizing Capture Equipment so it Will Be Used Most Hours of the Year



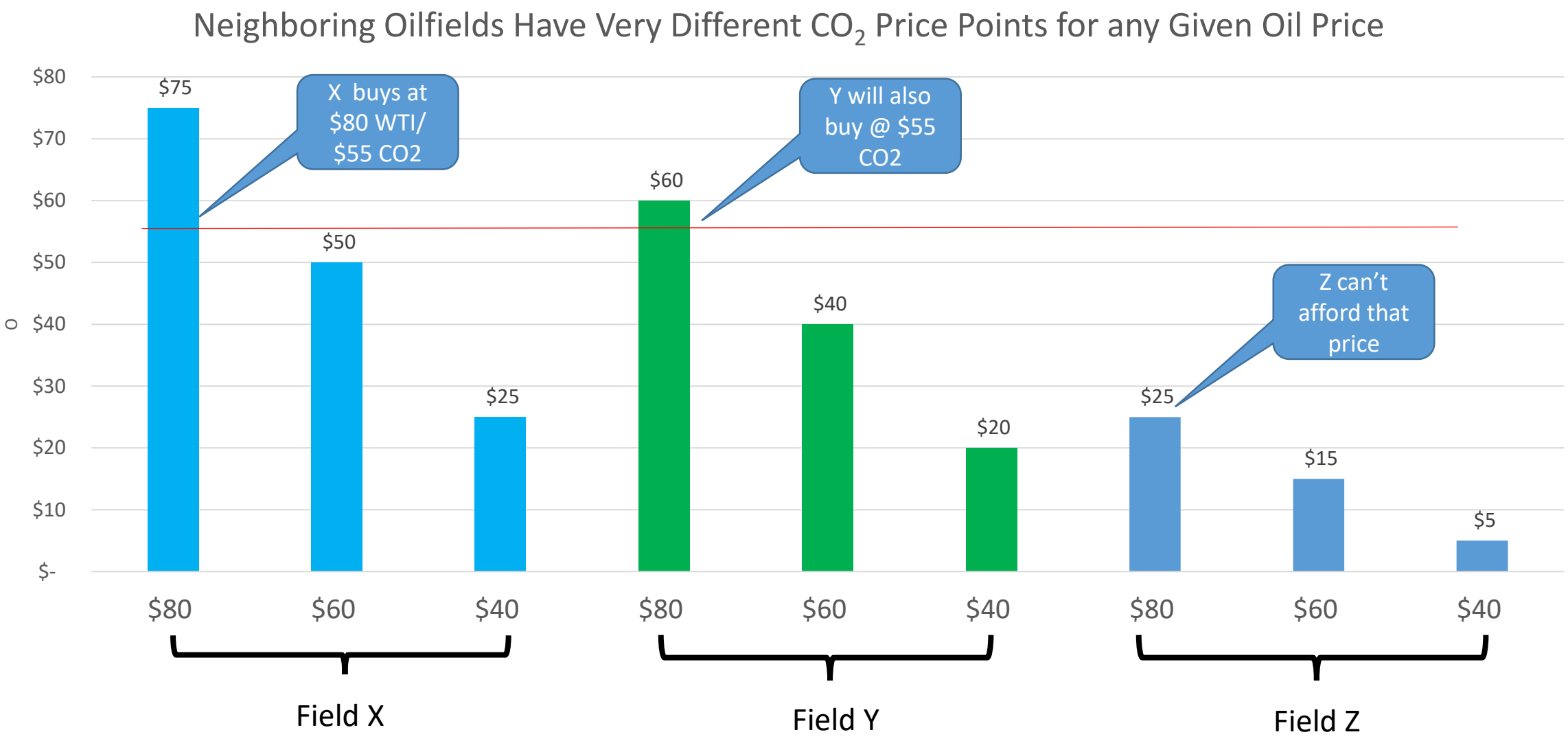
Selection: Digging Through Top US Emitting Facilities

C	D	E	G	I	N	O	Q	T	U	AB	AC	AD
Reason Selected	Industry Code Jeff	Facility Id	Facility Name	State	Latitude	Longitude	Industry Type (subparts)	Captured Emissions--Jeff's Changes see COMMENTS	Total reported direct emissions	Total Expected Cost	Total Sensitivity	Cumulative MT in region (mm)
3x720MW, could hook up differen	PC	1000581	WESTAR ENERGY, INC	KS	39.2825	-96.1153	C,D	3,200,000	11,494,053	$ 54.5	$ 71.4	82.33
new runs at high ncf & big. UNIT 2	PC	1001026	Nebraska City Statior	NE	40.6215	-95.7765	C,D	3,200,000	8,543,454	$ 54.5	$ 71.4	85.53
cement	Cement	1007552	ASH GROVE CEMENT (	NE	41.005565	-96.1549	C,H	629,042	711,186	$ 54.6	$ 70.0	86.16
IGCC	PC	1001541	Edwardsport IGCC	IN	38.8067	-87.2472	C,D	3,043,300	3,431,750	$ 54.7	$ 71.7	89.20
H2 >100k useful	H2	1001920	Phillips 66 Ponca Cit	OK	36.68807	-97.0879	C,MM-REF,F	116,035	1,995,829	$ 55.0	$ 71.3	89.32
cement	Cement	1002421	ASH GROVE CEMENT (	TX	32.51993	-97.0068	C,H	607,184	674,956	$ 55.1	$ 70.7	89.92
Two 3x1, 70% NCF ERCOT, 71`00HR	NGCC	1006085	FORNEY POWER PLAN	TX	32.7563	-96.4916	D	1,600,000	3,654,771	$ 55.4	$ 76.2	91.52
ERCOT, 7900hrs, 7100HR, 83% NCF	NGCC	1001310	Lamar Power (Paris)	TX	33.6314	-95.589	D	1,600,000	2,322,417	$ 55.4	$ 76.2	93.12
2 units CC2 2017 built, 6800HR	NGCC	1013006	Wolf Hollow II	TX	32.33793	-97.7367	C,D	1,600,000	1,367,688	$ 55.4	$ 76.2	94.72
Steel	BFG	1000156	Mittal Steel USA - Ind	IN	41.68	-87.4264	C,Q,S	4,372,598	6,972,176	$ 55.5	$ 72.3	99.10
#3 37yo, 9800hr, ran 7600hrs, 79%	PC	1000716	Thomas Hill Energy C	MO	39.5531	-92.6392	C,D	2,400,000	7,998,057	$ 55.6	$ 73.0	101.50
med size cement	Cement	1005352	LEHIGH CEMENT CO L	IA	43.1788	-93.2136	C,H	543,429	616,524	$ 56.6	$ 72.8	102.04
FCC .6MM Mty	FCC	1000343	Lemont Refinery	IL	41.6439	-88.0467	C,MM-REF,F	522,113	1,760,804	$ 56.7	$ 75.0	102.56
small FCC	FCC	1006985.2	Flint Hills Resources	MN	44.7684	-93.0406	C,P,Y	520,261		$ 56.8	$ 75.1	103.08
large blast	BFG	1003962	ARCELORMITTAL BURI	IN	41.627864	-87.1438	C,Q	2,885,381	10,134,131	$ 57.1	$ 74.7	105.97

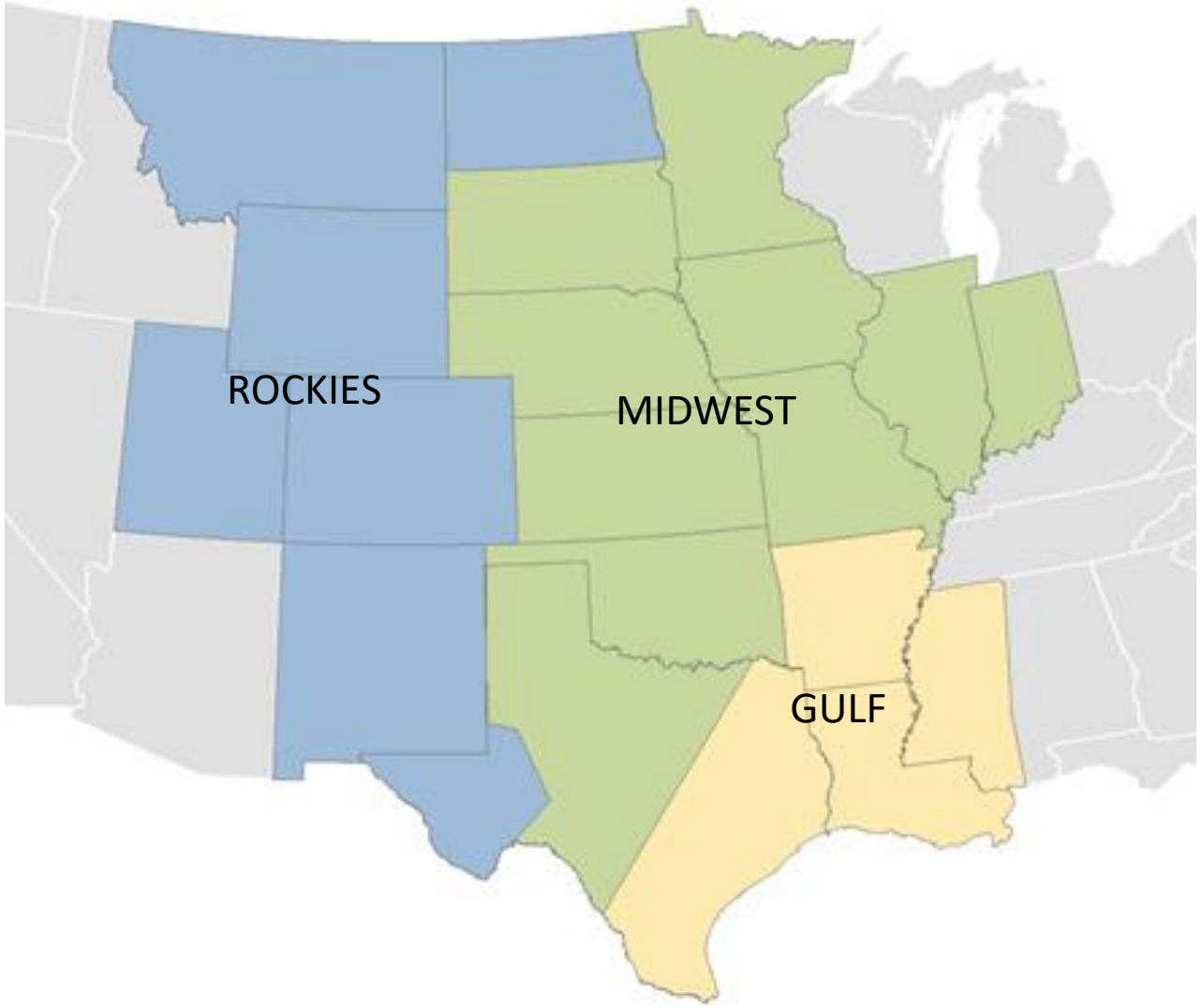
Part III: Sales to CO2-EOR Market

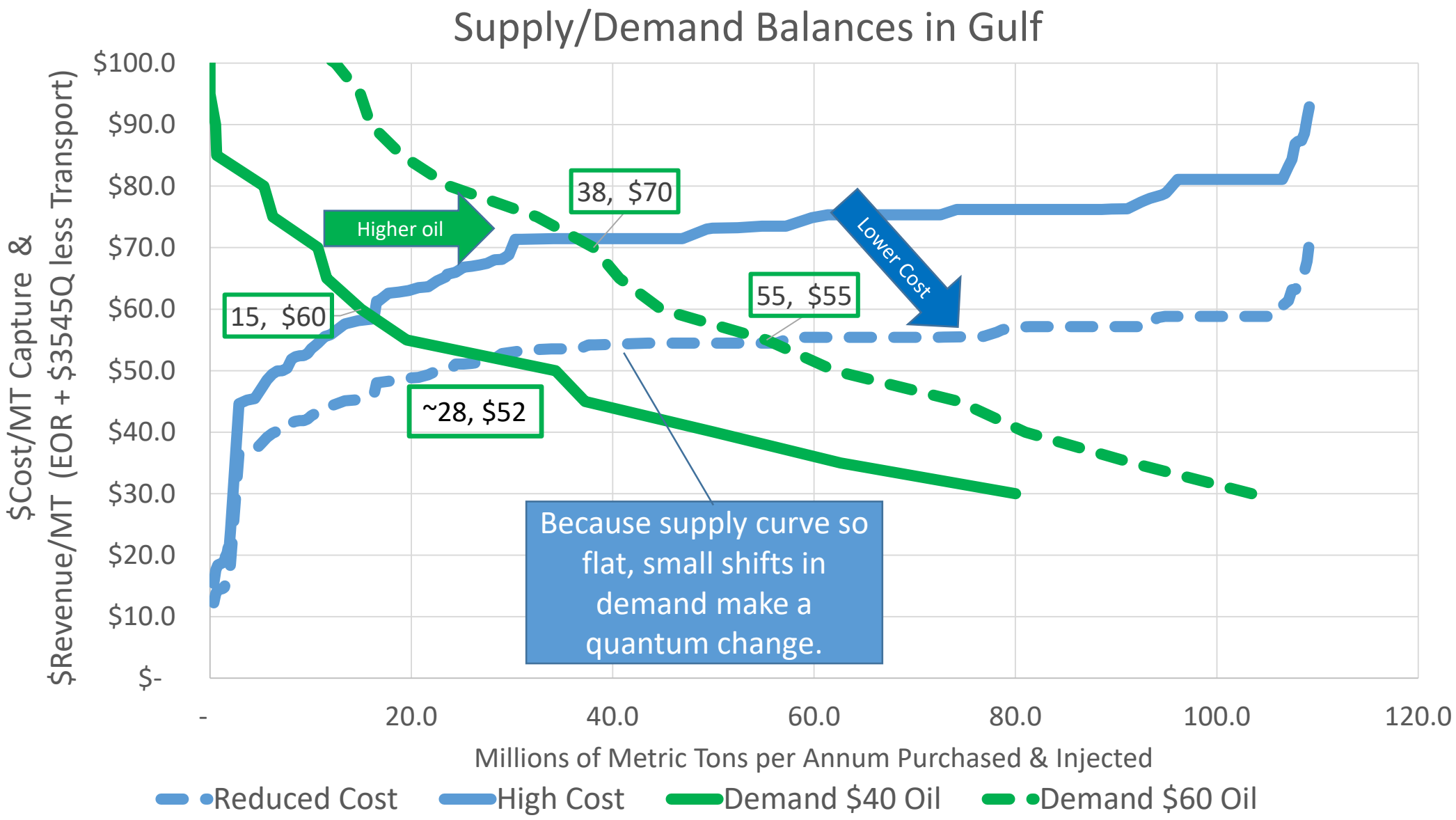


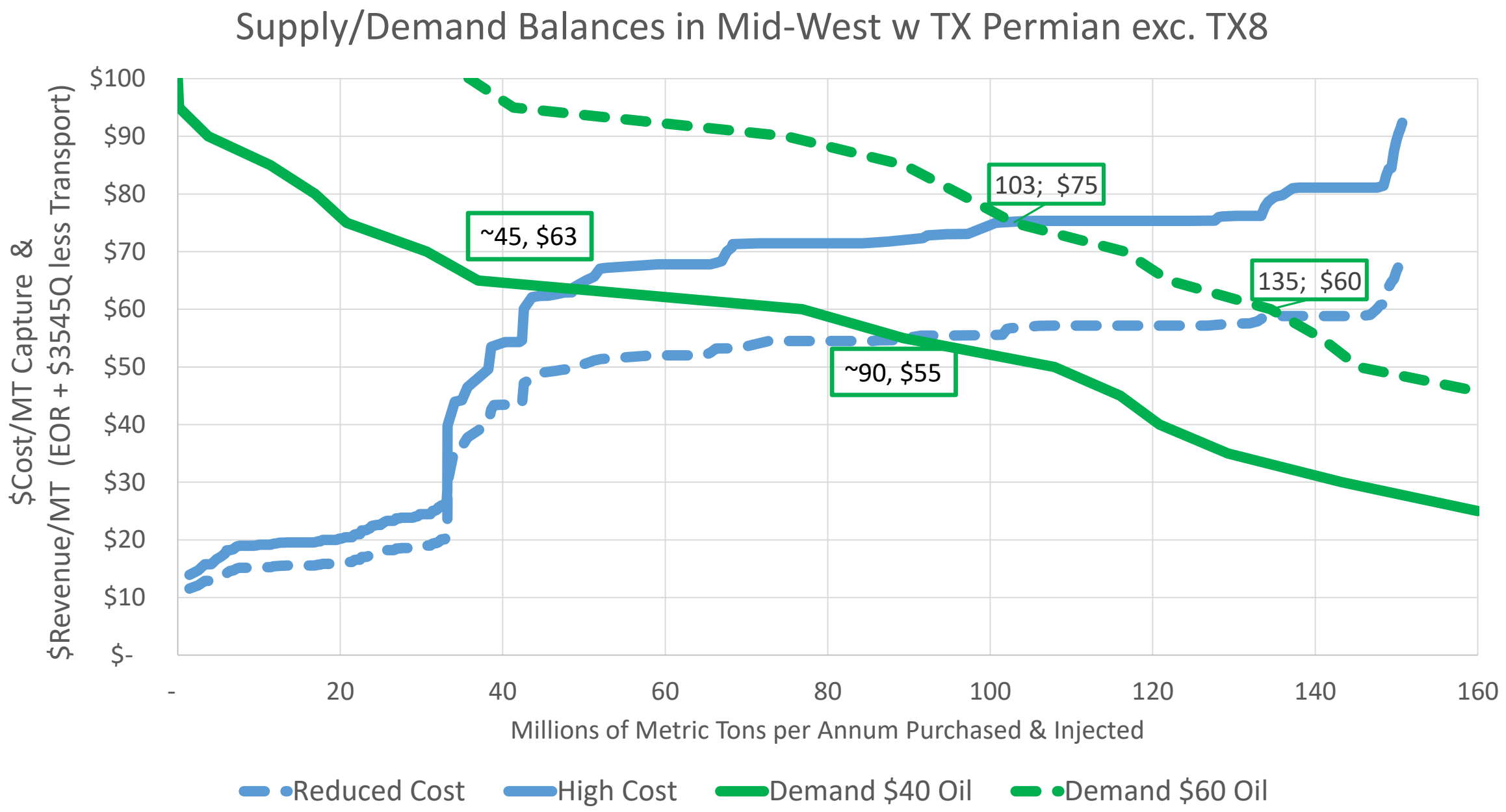
CO2-EOR Break-evens by Field with Varying Oil Prices

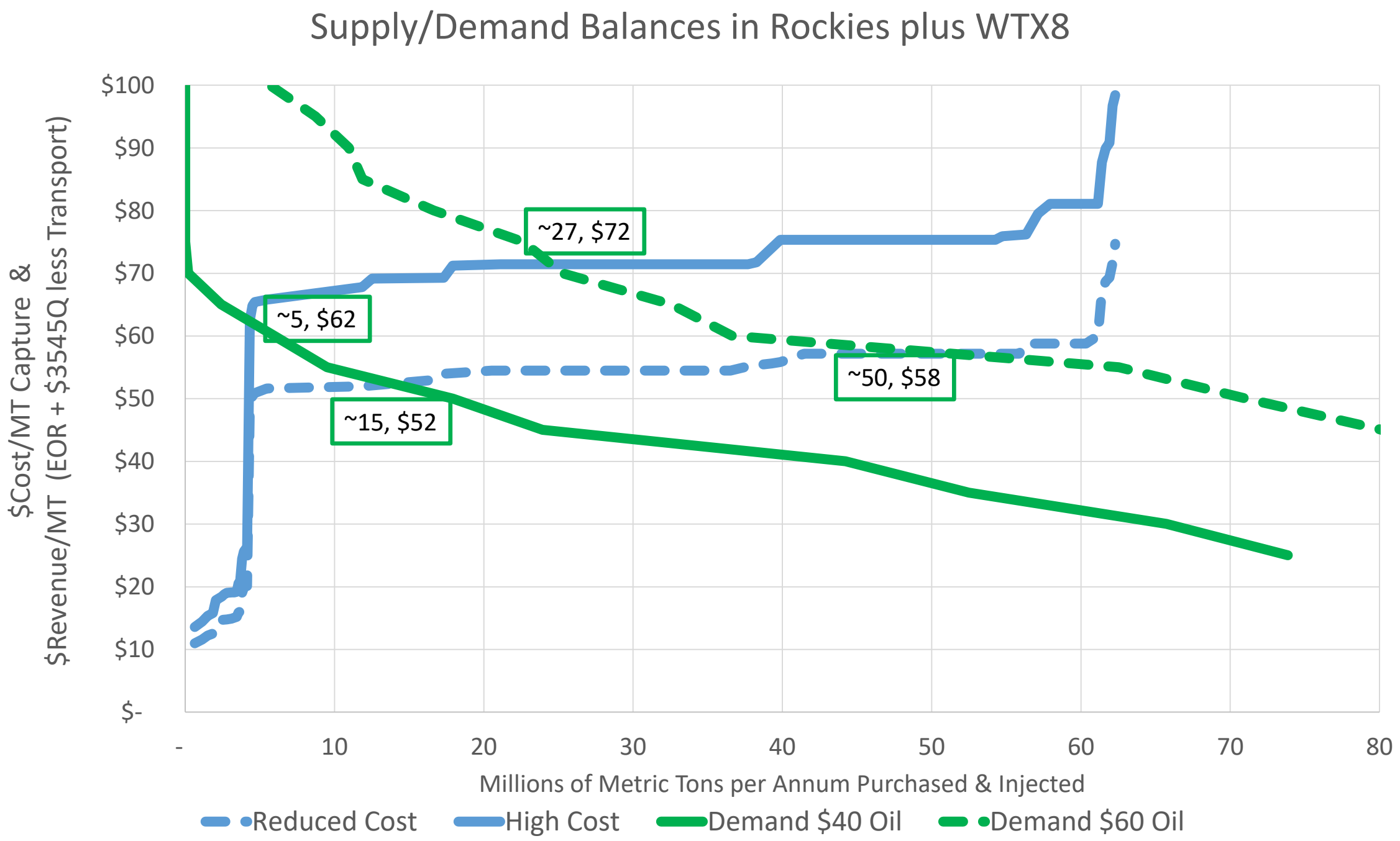


Part IV: Regional Supply & Demand




Supply/Demand Balances in Gulf
$Cost/MT Capture &
$Revenue/MT (EOR + $3545Q less Transport)
$100.0
$90.0
$80.0
$70.0
$60.0
$50.0
$40.0
$30.0
$20.0
$10.0
$-
-
20.0
40.0
60.0
80.0
100.0
120.0
Millions of Metric Tons per Annum Purchased & Injected
Higher oil
Lower Cost
38, $70
15, $60
55, $55
~28, $52
Because supply curve so flat, small shifts in demand make a quantum change.
Reduced Cost
High Cost
Demand $40 Oil
Demand $60 Oil

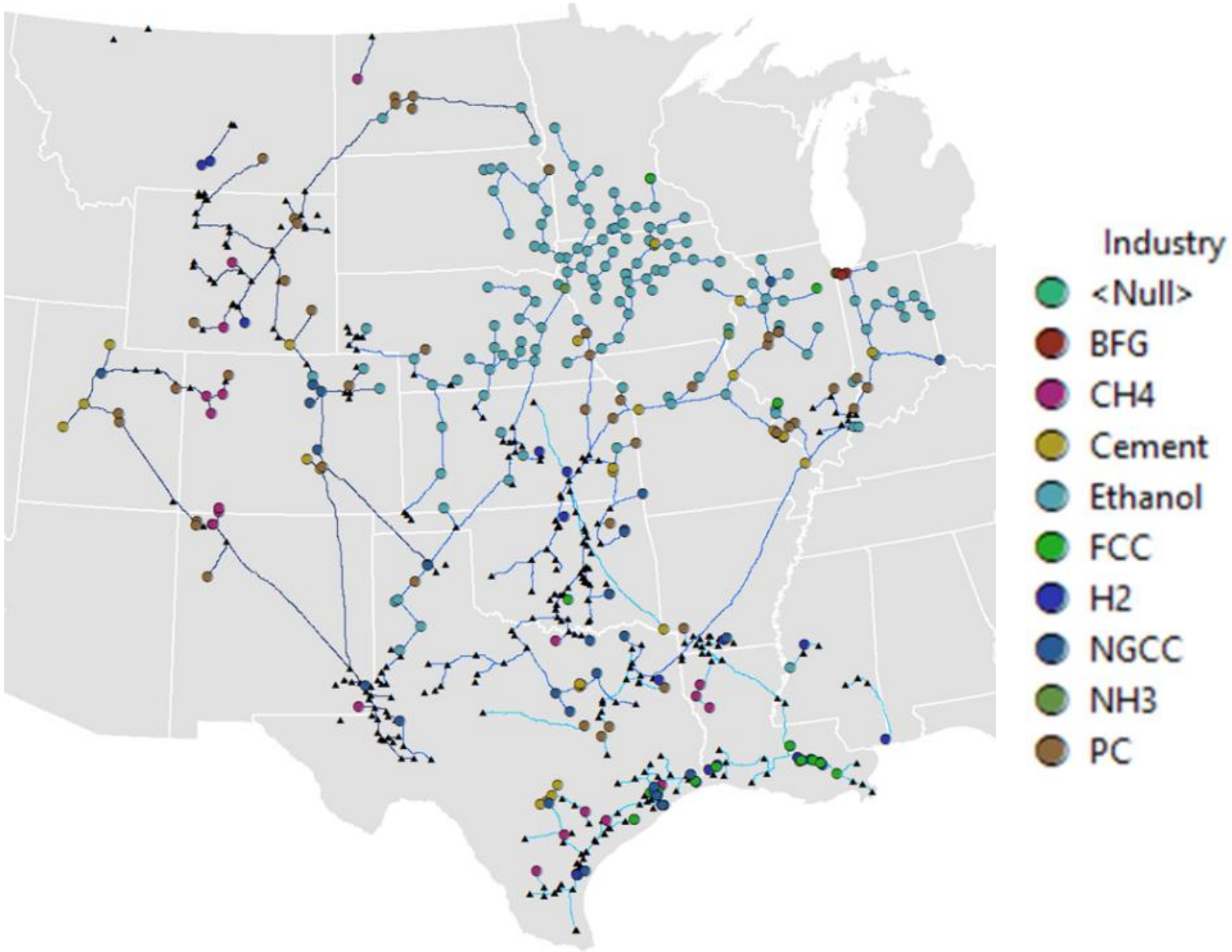

Supply/Demand Balances in Mid-West w TX Permian exc. TX8
$Cost/MT Capture &
$Revenue/MT (EOR + $3545Q less Transport)
$100
$90
$80
$70
$60
$50
$40
$30
$20
$10
$-
-
20
40
60
80
100
120
140
160
Millions of Metric Tons per Annum Purchased & Injected
~45, $63
103; $75
135; $60
~90, $55
Reduced Cost
High Cost
Demand $40 Oil
Demand $60 Oil


Supply/Demand Balances in Rockies plus WTX8
$Cost/MT Capture &
$Revenue/MT (EOR + $3545Q less Transport)
$100
$90
$80
$70
$60
$50
$40
$30
$20
$10
$-
-
10
20
30
40
50
60
70
80
Millions of Metric Tons per Annum Purchased & Injected
~27, $72
~5, $62
~50, $58
~15, $52
Reduced Cost
High Cost
Demand $40 Oil
Demand $60 Oil

Annual CO2 Volumes (in MMTPA) Captured in 3 Regions x Four Cases

	Commodity price risk not addressed: Low/unstable oil		Commodity price risk is addressed: High/stable oil	
"First-mover" risk not addressed: High capture cost.	#1 Worst/Worst		#2 Oil Mitigated	
	Gulf	15	Gulf	38
	Midwest	45	Midwest	103
	Rockies	5	Rockies	27
	All three	65	All three	168
"First- mover" risk is addressed: Lower capture cost	#3 1st Mover Mitigated		#4 Best Case	
	Gulf	28	Gulf	55
	Midwest	45	Midwest	135
	Rockies	15	Rockies	50
	All three	88	All three	240

Three-Region Pipeline Optimization for “Best Cases”



Key Policy Issues

- Taking the fear factor out of “first-mover through fifth-mover projects”. Much more active commercial deployment support at DOE is mandatory in my view.
- Mitigating commodity price risk and its consequences for capital structure and cost of funds.
  - Federal Contract for Differences program similar to UK
  - In power sector, Clean Energy Standards procurement with solid long term capacity payments
- Mitigating the timing/logistical risk of assembling large groups of shippers—all at the same time—to contract for CO2 pipeline capacity.

What data & analysis are needed to inform policymakers and stakeholders in order to spur more CO2 EOR activity in the US?