OpenMinds

NextGen CCUS - Calpine Final Presentation

February 2025

CALPINE®

DRAFT

NextGen CCUS Team

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And with the support of our accomplished sponsors!

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Executive Summary

A cost-effective pathway for Calpine to deploy carbon capture

/ FINAL

Context and problem statement

- **Natural gas dominates power generation**, accounting for approximately 46% of U.S. electricity in 2024, and its demand continues to rise. However, natural gas is a significant source of emissions, necessitating its cleanup.
- Currently, carbon capture on natural gas is more expensive compared to other carbon capture applications due to the low CO2 concentration (3-4%) in the flue gas stream
- To make carbon capture on natural gas economically viable, several key levers need to be addressed, including reducing costs, implementing government incentives, and identifying customers willing to pay a premium for green energy.

View on cost reduction levers

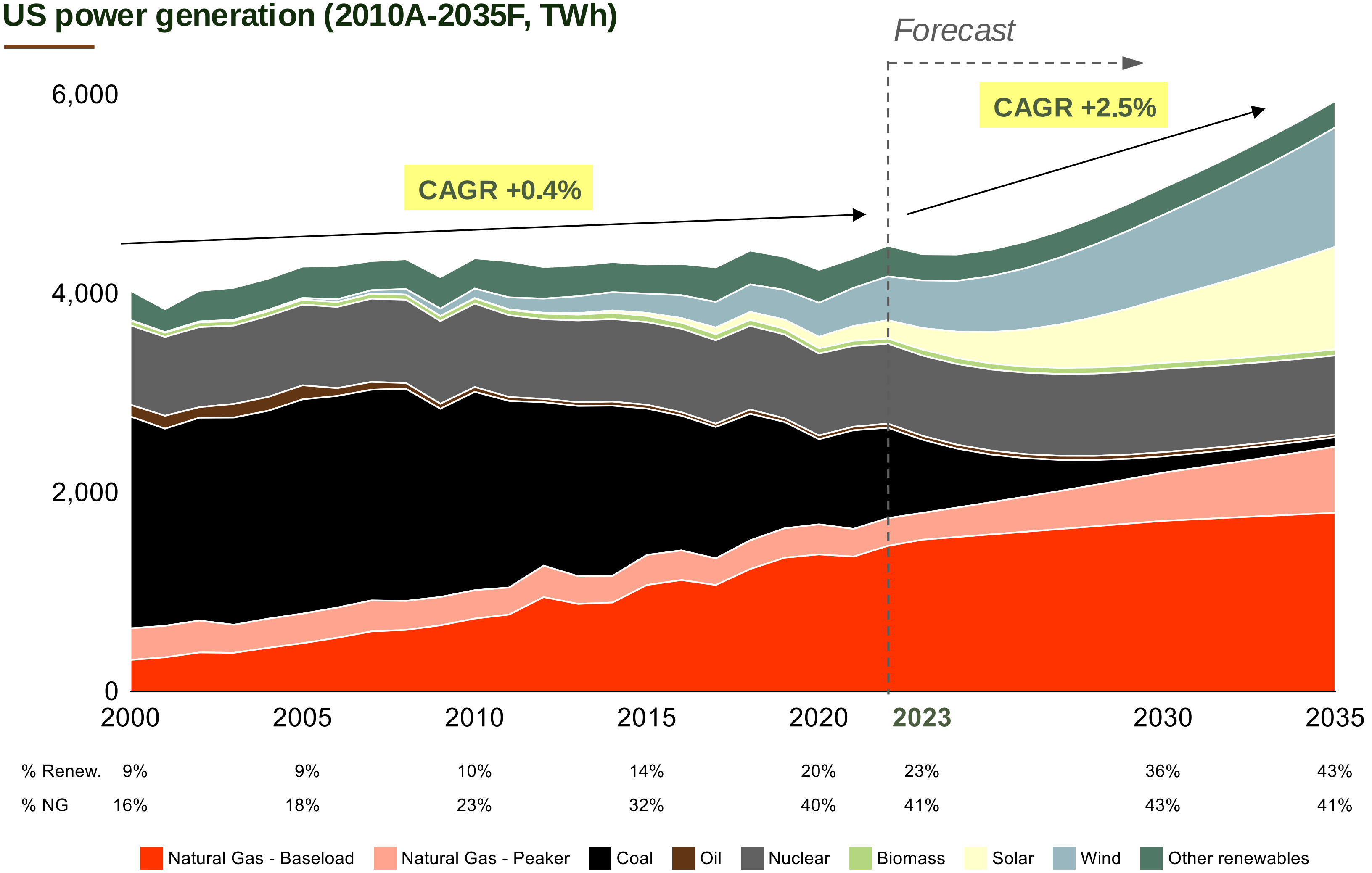
- **Energy-efficient amines and capture technologies** like MUF-1 MOF, Amine Intensification process (AIP), and HPC-based capture can significantly reduce energy consumption and cost of capture
- Modular absorber columns, utilizing ceramic packing and a modular design, can reduce CAPEX by up to 15% while simultaneously enhancing scalability.
- Existing 45Q incentive ($85/ton CO_2) is insufficient to cover all-in costs, and its longevity beyond 2032 remains uncertain.

Final recommendation

- **Main ways to reduce cost that is very tangible for Calpine**
  - Deploy and be on a close lookout for these advanced capture technologies
    - Low Partial pressure CO_2 capture, ICE-31, Entropy23 solvent, Chilled ammonia, HPC-based capture, AIP, MUF-1 MOF
  - Reducing CapEx through absorption column
    - Source column directly from specialty supplier (markup and construction cost of EPCs are too much)
    - Implement modular columns with plastic packing
  - Integrated approach- Combining optimized amines and absorber design lowers LCOC by up to 25%

Natural Gas is Here to Stay and Needs to be Cleaned Up

US power generation (2010A-2035F, TWh)



	2000	2005	2010	2015	2020	2023	2030	2035
% Renew.	9%	9%	10%	14%	20%	23%	36%	43%
% NG	16%	18%	23%	32%	40%	41%	43%	41%

Source: OpenMinds 2024 'P50' Outlook; EIA 2024 outlook

Not reflective of recent uptick in coal retirement delays

Commentary

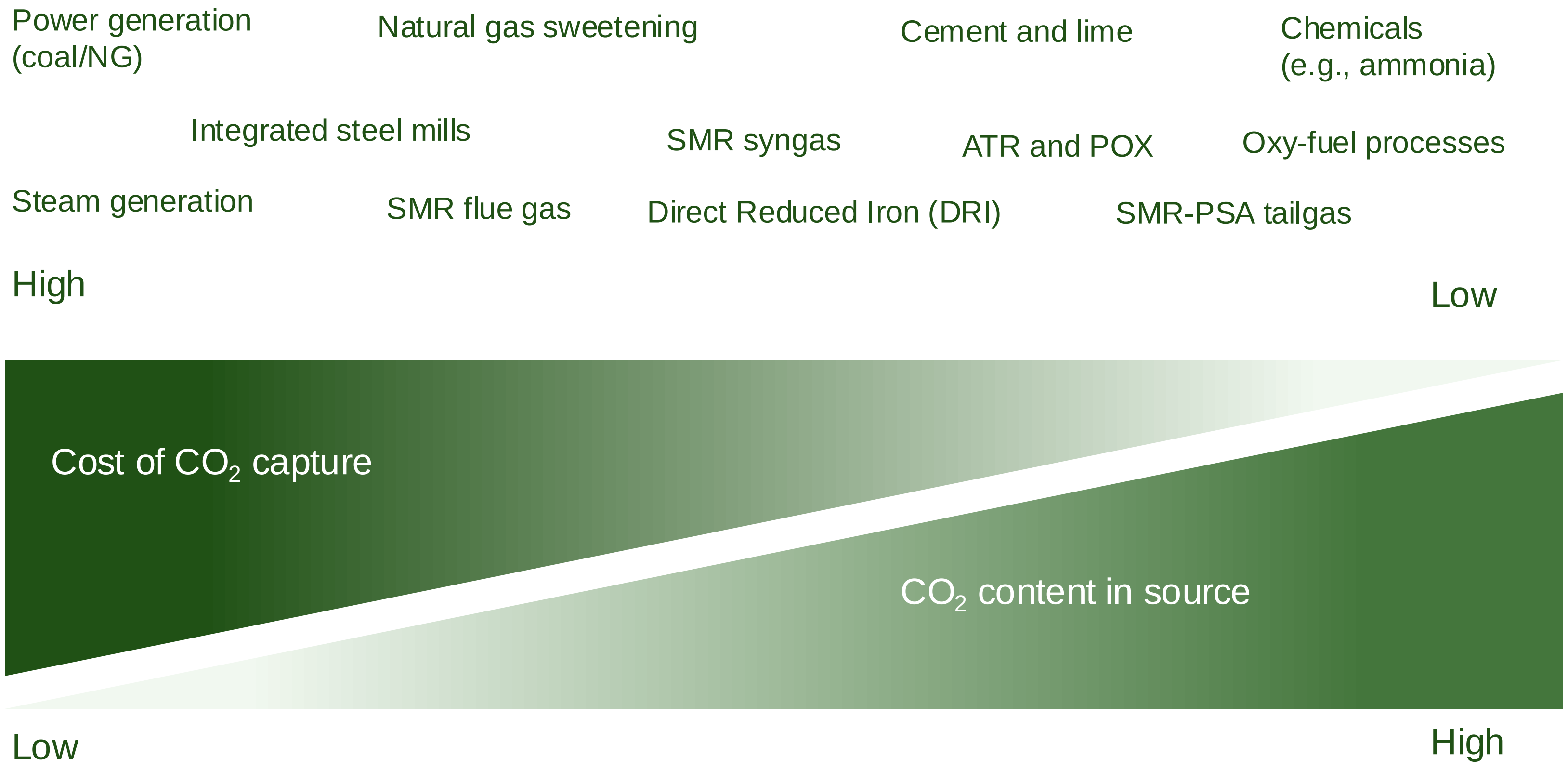
- Natural gas, a reliable and affordable power source, faces urgent action due to its carbon footprint.
- With growing regulatory pressure and investor scrutiny, cleaning up natural gas is crucial for its long-term viability. CCUS and efficiency improvements are prioritized to align natural gas with global decarbonization goals.
- The focus now is on how clean gas can become, and those who act now will lead the transition.
- **"Global electricity demand will grow by an average of 3.4% annually through 2026**, driven by economic growth and increased electrification, particularly in sectors like electric vehicles and data centers"

IEA, 2024

- "Natural gas-fired power plants generated approximately 1,767 billion kilowatt-hours (kWh) of electricity, accounting for around 42% of the nation's electricity mix. This represents a 4% increase from 2023"

EIA, 2024

Capturing CO_2 from natural gas plant is expensive due to low concentration of CO_2 in flue gas



Power generation (coal/NG)

Natural gas sweetening

Cement and lime

Chemicals (e.g., ammonia)

Integrated steel mills

SMR syngas

ATR and POX

Oxy-fuel processes

Steam generation

SMR flue gas

Direct Reduced Iron (DRI)

SMR-PSA tailgas

Commentary

- Increasing CO_2 concentration in flue gas streams reducing capture costs exponentially
- CO_2 concentrations in flue gas below 8-10% are generally uneconomic (depending on technology and incentives)
- Natural gas power plants generally have CO_2 concentrations in flue gas of 3-5%

Source: Adapted from BakerHughes report 2023; NETL

Levers to make CCS on Natural Gas Power Plants Economical

Cost

- **Technological Innovation**
  - – Advanced Amine Solvents
  - – Absorber Column
  - – Cryogenic & Membrane-based Capture
  - – Waste Heat Integration
- **Process Optimization**
- **Economies of Scale & Standardization**
  - – Modular CCS Skids
  - – Larger Capture Units

Focus of this presentation

Government Incentives

- **Tax Credits & Direct Incentives**
  - – 45Q Tax Credit
  - – Investment & Production Tax Credits (IRA)
  - – DOE Grants & Loans
- **Carbon Pricing & Market Mechanisms**
  - – EPA Emissions Regulations
  - – California LCFS (Low Carbon Fuel Standard)
  - – State Renewable Portfolio Standards (RPS)
- **Regulatory & Procurement Levers**
  - – Federal & State Procurement
  - – Clean Dispatchable Power Mandates

Market-Driven Revenue

- **Hyperscalers and Data centers**
  - – Big Tech (Google, Microsoft, Amazon) are premium buyers of low-carbon electricity
- **Utility Green Tariffs & Clean Firm Power Contracts**
  - – Regulated utilities
  - – Corporate PPA buyers
- **Carbon Removal &Offsets**
  - – Voluntary Carbon Markets
  - – Green Hydrogen Production

Key Cost Reduction drivers

①

Novel capture solutions

Energy efficient amines

Novel, non-amine capture technologies

OPEX-focused

②

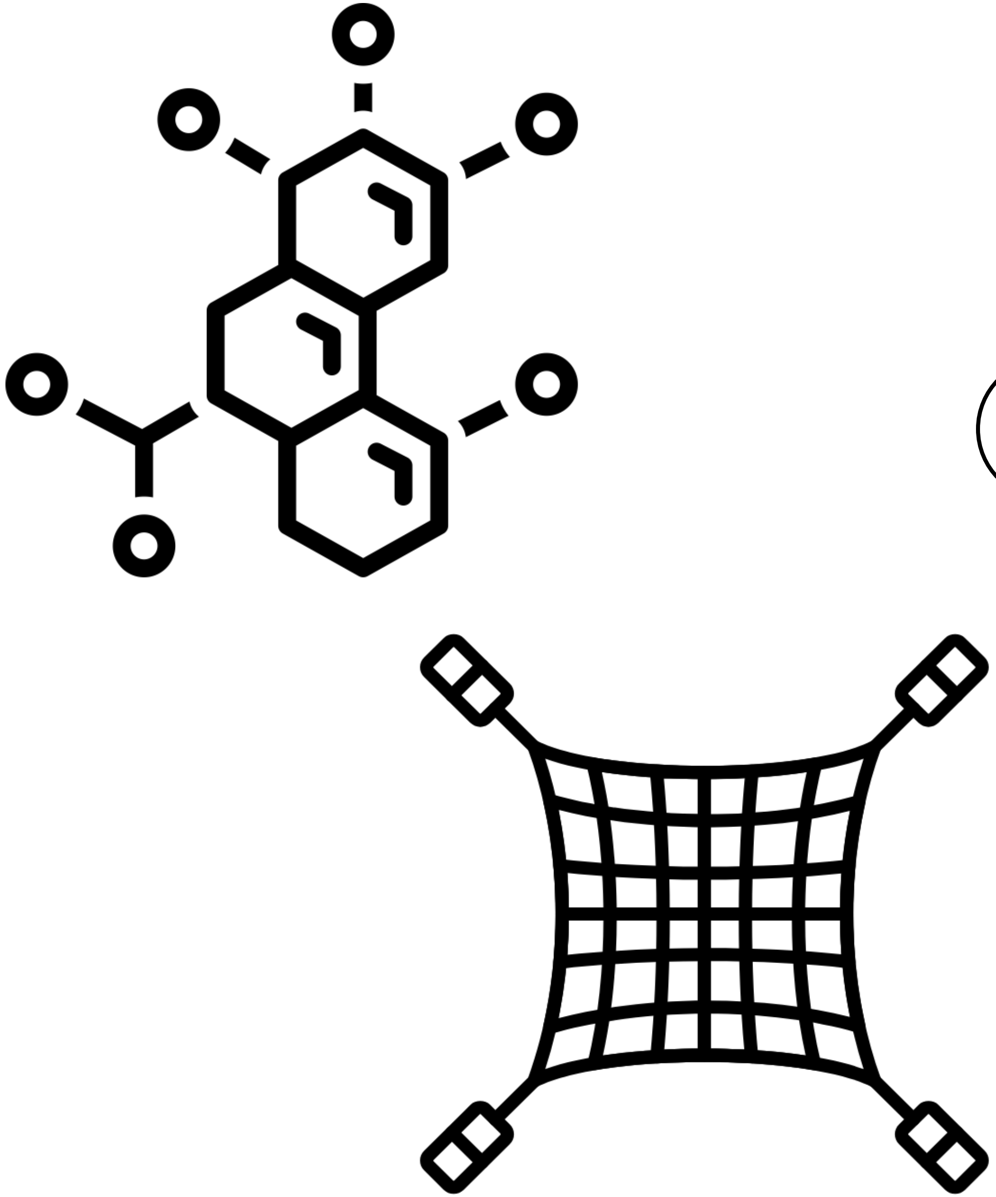
Absorber column

Plastic packing materials

Modular absorber column design

Smart Operations

CAPEX-focused



①

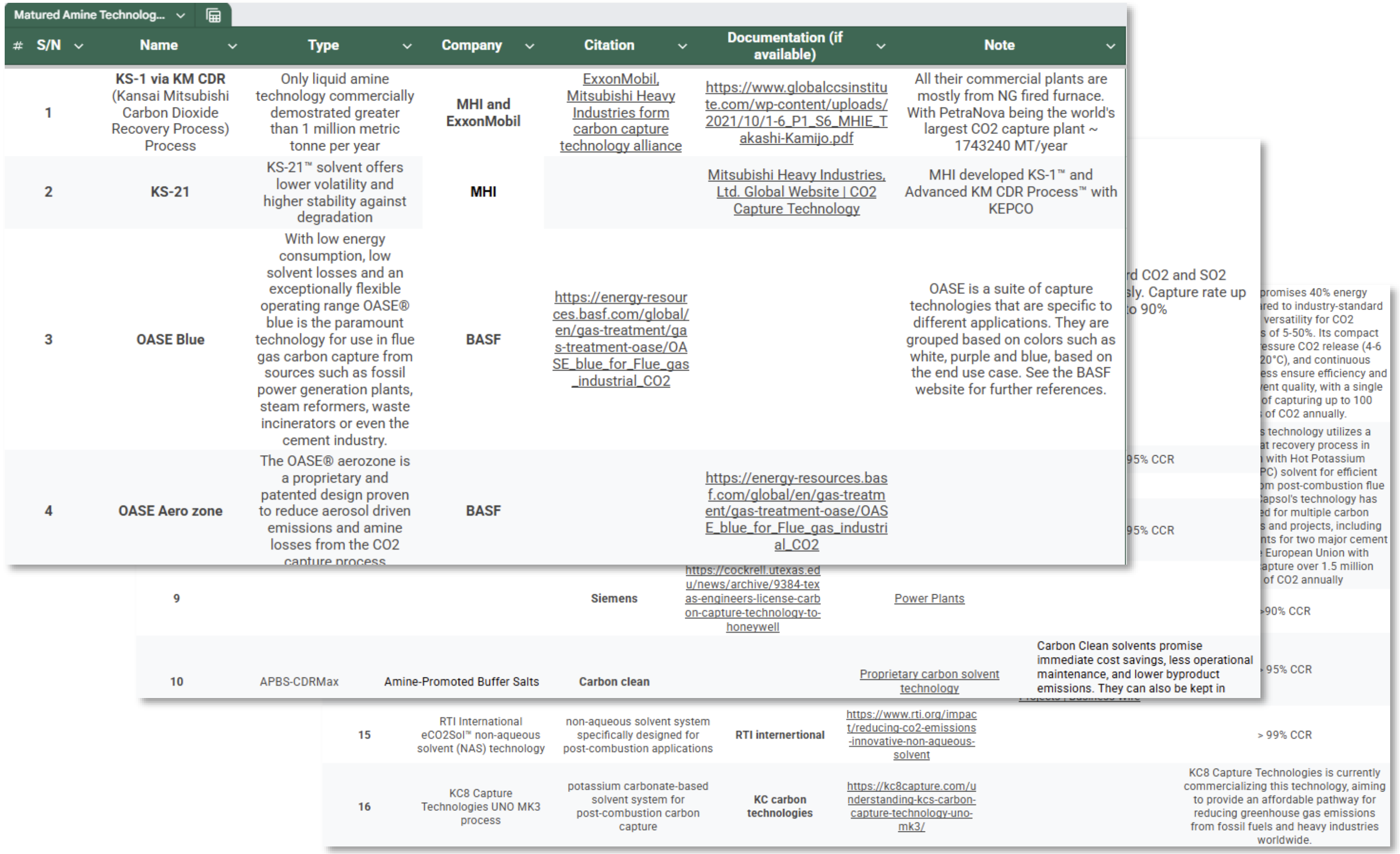
Amines and novel capture technologies

OPEX-focused

Novel capture solvents

1

Evaluation of 41 distinct amines and capture technologies reveals that approximately 7 of them meet our evaluation criteria and assessment standards.



Matured Amine Technolog...

# S/N	Name	Type	Company	Citation	Documentation (if available)	Note
1	**KS-1 via KM CDR** (Kansai Mitsubishi Carbon Dioxide Recovery Process) Process	Only liquid amine technology commercially demostrated greater than 1 million metric tonne per year	**MHI and ExxonMobil**	ExxonMobil, Mitsubishi Heavy Industries form carbon capture technology alliance	https://www.globalccsinstitute.com/wp-content/uploads/2021/10/1-6_P1_S6_MHIE_Takashi-Kamijo.pdf	All their commercial plants are mostly from NG fired furnace. With PetraNova being the world's largest CO2 capture plant ~ 1743240 MT/year
2	**KS-21**	KS-21™ solvent offers lower volatility and higher stability against degradation	**MHI**		Mitsubishi Heavy Industries, Ltd. Global Website | CO2 Capture Technology	MHI developed KS-1™ and Advanced KM CDR Process™ with KEPCO
3	**OASE Blue**	With low energy consumption, low solvent losses and an exceptionally flexible operating range OASE® blue is the paramount technology for use in flue gas carbon capture from sources such as fossil power generation plants, steam reformers, waste incinerators or even the cement industry.	**BASF**	https://energy-resources.basf.com/global/en/gas-treatment/gas-treatment-oase/OASE_blue_for_Flue_gas_industrial_CO2		OASE is a suite of capture technologies that are specific to different applications. They are grouped based on colors such as white, purple and blue, based on the end use case. See the BASF website for further references.
4	**OASE Aero zone**	The OASE® aerozone is a proprietary and patented design proven to reduce aerosol driven emissions and amine losses from the CO2 capture process	**BASF**		https://energy-resources.basf.com/global/en/gas-treatment/gas-treatment-oase/OASE_blue_for_Flue_gas_industrial_CO2	

9			**Siemens**	https://cockrell.utexas.edu/news/archive/9384-texas-engineers-license-carbon-capture-technology-to-honeywell	Power Plants		>90% CCR
10	APBS-CDRMax	Amine-Promoted Buffer Salts	**Carbon clean**		Proprietary carbon solvent technology	Carbon Clean solvents promise immediate cost savings, less operational maintenance, and lower byproduct emissions. They can also be kept in	95% CCR

15	RTI International eCO2Sol™ non-aqueous solvent (NAS) technology	non-aqueous solvent system specifically designed for post-combustion applications	**RTI internertional**	https://www.rti.org/impact/reducing-co2-emissions-innovative-non-aqueous-solvent		> 99% CCR
16	KC8 Capture Technologies UNO MK3 process	potassium carbonate-based solvent system for post-combustion carbon capture	**KC carbon technologies**	https://kc8capture.com/understanding-kcs-carbon-capture-technology-uno-mk3/		KC8 Capture Technologies is currently commercializing this technology, aiming to provide an affordable pathway for reducing greenhouse gas emissions from fossil fuels and heavy industries worldwide.

Recommended solvents

- **ICE-31**
- **HNC-6**
- **Entropy23 solvent**
- **Amine capture**

Recommended technologies

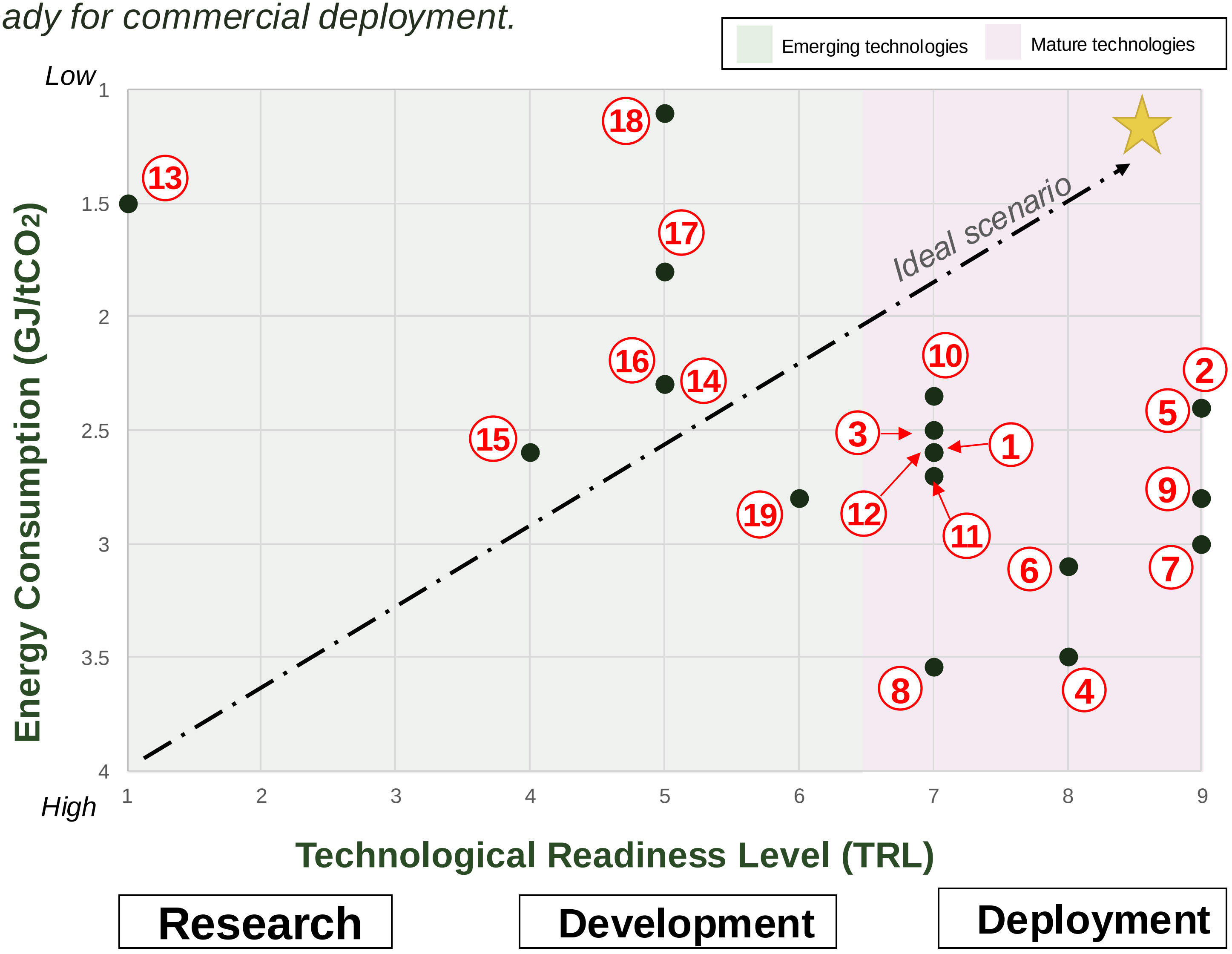
- **Low Partial Pressure**
- **Chilled Ammonia**
- **HPC-based capture**
- **AIP**

The amine mastersheet, evaluation matrix and python files can be found here

1

Capture Solvent Comparison

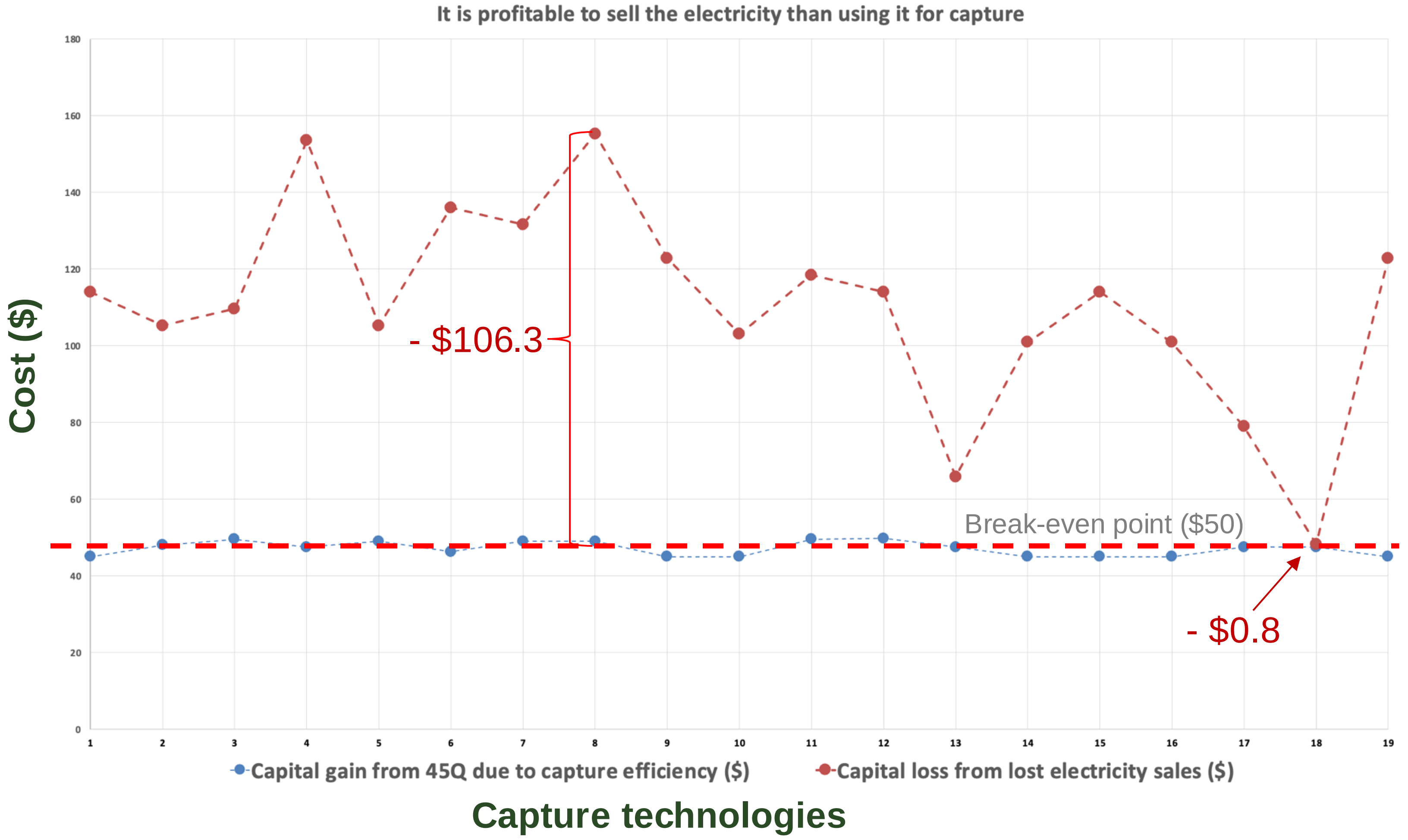
Current capture technologies consume a significant amount of energy. Emerging technologies, however, are not yet ready for commercial deployment.



1	CarbonOro	Bi-phasic Amine Solvent
2	Sinopec NRICI	Low Partial Pressure CO2 Capture
3	ION Clean Energy	ICE-31
4	Saipem	Bluenzyme
5	Entropy	Entropy23 solvent
6	Carbon Clean	APBS-CDRMax
7	Shell & Technip	CANSOLV
8	Gassnova	CESAR-1
9	China (CERI)	Advanced Amine (HNC-5)
10	China Energy	Amine Capture
11	Axens	DMX Process
12	Baker Hughes	Chilled Ammonia
13	Capsol Technologies	HPC-based capture
14	Baker Hughes	Mixed- Salt Process (MSP)
15	China (CERI)	Potassium Sulfate slurry
16	China (CERI)	Advanced Amine (HNC-6)
17	InnoTech Alberta	Amine Intensification Process (AIP)
18	Captivate Technology	MUF-1 MOF
19	CO2CRC Ltd	HyCaps

Opportunity Cost (Capture Efficiency vs Energy Loss)

You lose more money by not selling your electricity and instead using it for carbon capture. Even with the best technology + 45Q tax credit, you can't breakeven– a huge disincentive



1 Bi-phasic Amine Solvent 2 Low Partial Pressure CO2 Capture. 3 ICE-31 4 Bluenzyme 5 Entropy23 solvent 6 APBS-CDRMax 7 CANSOLV 8 CESAR-1 9 Advanced Amine (HNC-5) 10 Amine Capture

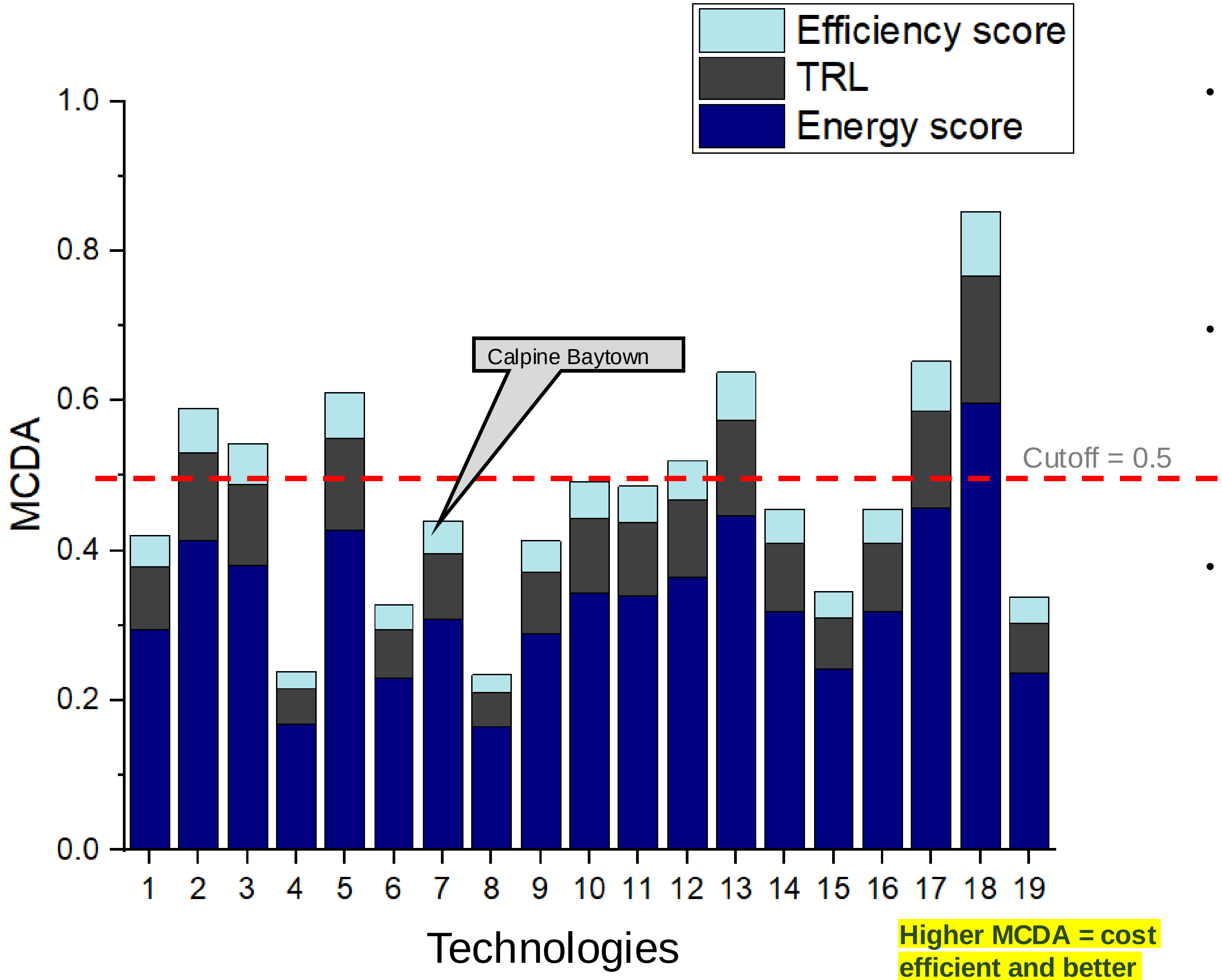
11 DMX Process 12 Chilled Ammonia13 HPC-based capture. 14 Mixed- Salt Process (MSP) 15 Potassium Sulfate slurry 16 Advanced Amine (HNC-6). 17 Amine Intensification Process (AIP) 18 MUF-1 MOF 19 HyCaps

Commentary

- If you decide to sell your electricity; electricity price at Baytown Texas = 15.79 ¢/kWh or **43.86 $/GJ**
- But instead, if you decide to use that electricity to capture CO_2, your cost of capture is shown in red dots
- Alternatively, you can decide to use that electricity to capture CO_2 and get 45Q tax credit for it. The revenue potential is shown in blue dots.
- We assumed that of the $85 tax credit from **45Q**, you would get $50 for capture. That means 45Q cannot offset your capture cost and the loss is even greater if you factor in the opportunity cost of not selling the electricity
- While Capture efficiency is not very important from a cost standpoint, it is very important from an environmental standpoint. **CO_2 not captured is CO_2 lost to the environment**

1

Capture Multi-Criteria Decision Analysis (MCDA)



Higher MCDA = cost efficient and better capture technologies

Score = (W_1 x Energy Score) + (W_2 x TRL Score) + (W_3 x Efficiency Score)

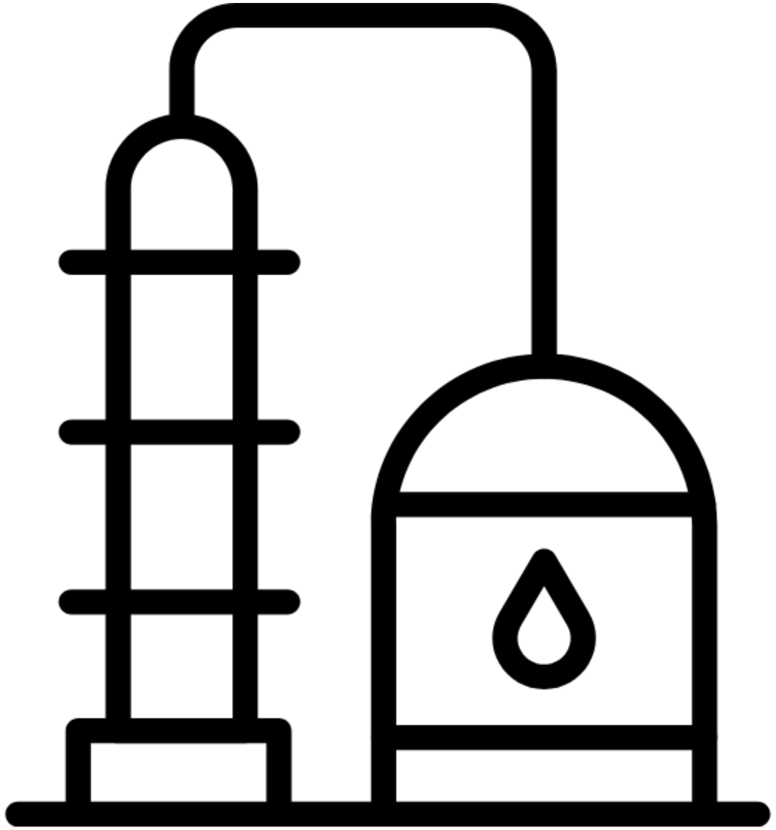
Where ; $W_1 = 0.7$, $W_2 = 0.2$, $W_3 = 0.1$

Commentary

- There's currently no global method of comparing various capture technologies. So, we adopted the MCDA approach by normalizing each parameter (Energy, TRL and capture efficiency). Then, we applied our user-defined weighted formula and ranked the technologies from best (high MCDA) to worst (low MCDA).
- Energy consumption (70%) plays a crucial role in determining the cost of capture. Technological readiness level (TRL) (20%) is another important factor. A higher TRL indicates that the technology is closer to deployment. Capture efficiency (10%) is the least important factor, as most technologies capture over 90%.
- Initially, we considered the environmental impact of capture technologies as a parameter, but we eliminated it due to the lack of high-fidelity data.

Technologies with MCDA > 0.5

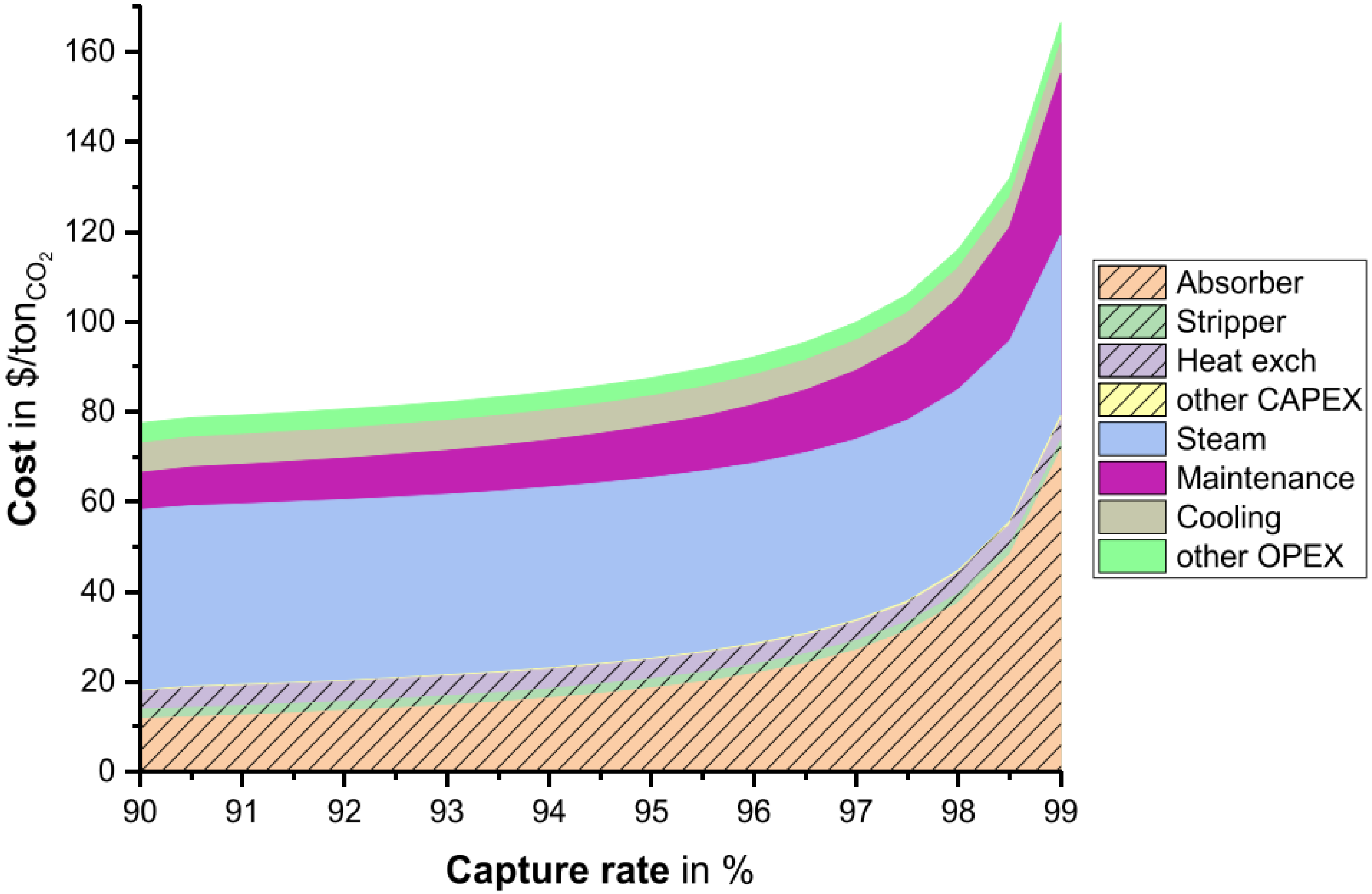
2	Sinopec NRICI	Low Partial Pressure CO2 Capture
3	ION Clean Energy	ICE-31
5	Entropy	Entropy23 solvent
12	Baker Hughes	Chilled Ammonia
13	Capsol Technologies	HPC-based capture
17	InnoTech Alberta	Amine Intensification Process (AIP)
18	Captivate Technology	MUF-1 MOF



② Absorber Column

CAPEX-focused

② Absorber Column is a Significant Contributor to CAPEX



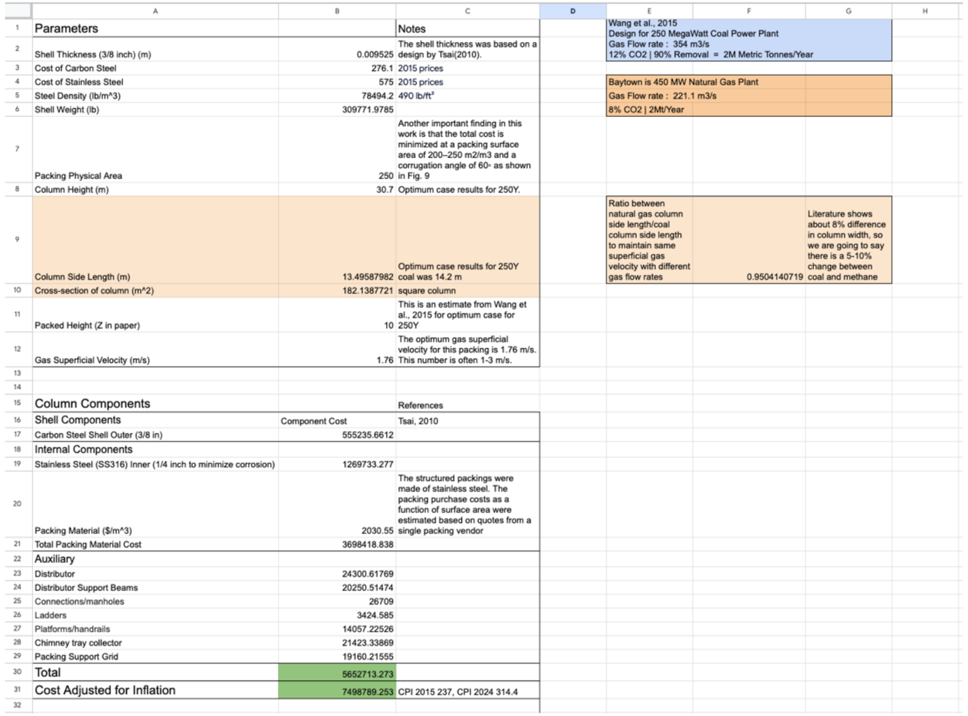
- Above 90% capture rate, the main contribution to the increase in capture cost is the size of the absorber column, with a minor increase in steam costs. (CAPEX)
- The cost of steam (OPEX) is the largest contributor to the cost of capture.

Data from - Brandl, P., Bui, M., Hallett, J. P. & Mac Dowell, N. (2021).

2

Absorber Column Costing Tool

The absorber column is a significant component of building a carbon capture plant. Controlling your column design can substantially reduce this cost, rather than relying solely on EPCs.

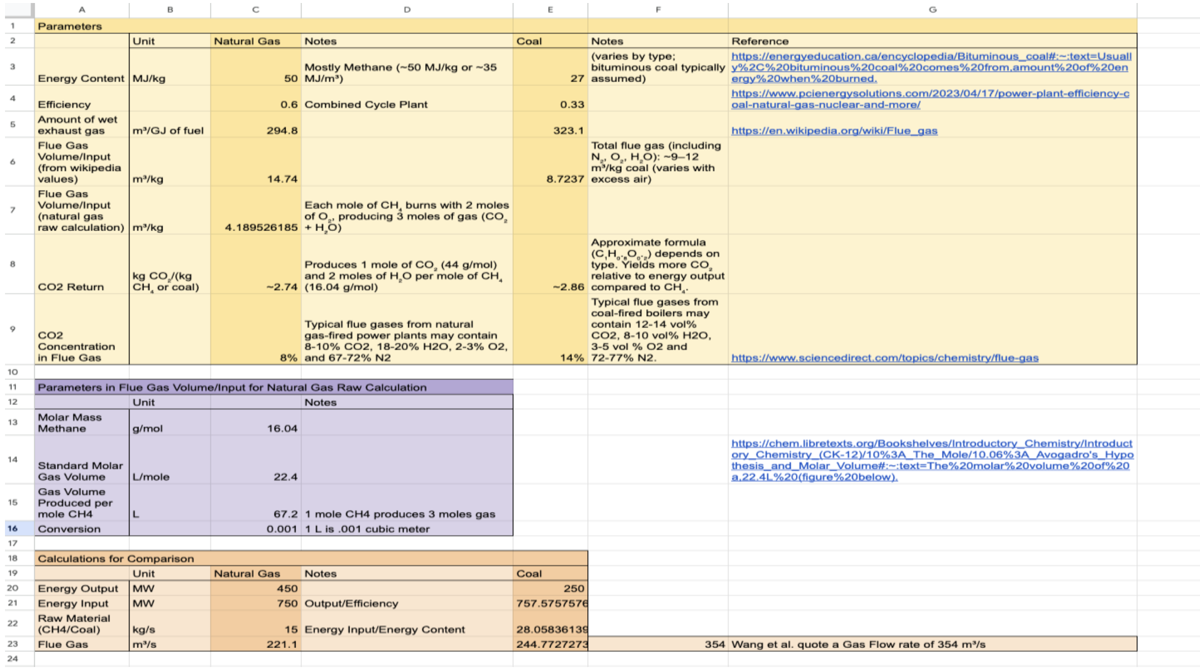


Parameters		Notes
Shell Thickness (3/8 inch) (m)	0.009525	The shell thickness was based on a design by Tsai(2010).
Cost of Carbon Steel	276.1	2015 prices
Cost of Stainless Steel	575	2015 prices
Steel Density (lb/m^3)	78494.2	490 lb/ft³
Shell Weight (lb)	309771.9785	
Packing Physical Area	250	Another important finding in this work is that the total cost is minimized at a packing surface area of 200–250 m2/m3 and a corrugation angle of 60◦ as shown in Fig. 9
Column Height (m)	30.7	Optimum case results for 250Y.
Column Side Length (m)	13.49587982	Optimum case results for 250Y coal was 14.2 m
Cross-section of column (m^2)	182.1387721	square column
Packed Height (Z in paper)	10	This is an estimate from Wang et al., 2015 for optimum case for 250Y
Gas Superficial Velocity (m/s)	1.76	The optimum gas superficial velocity for this packing is 1.76 m/s. This number is often 1-3 m/s.
Column Components		References
Shell Components	Component Cost	Tsai, 2010
Carbon Steel Shell Outer (3/8 in)	555235.6612	
Internal Components		
Stainless Steel (SS316) Inner (1/4 inch to minimize corrosion)	1269733.277	
Packing Material ($/m^3)	2030.55	The structured packings were made of stainless steel. The packing purchase costs as a function of surface area were estimated based on quotes from a single packing vendor
Total Packing Material Cost	3698418.838	
Auxiliary		
Distributor	24300.61769	
Distributor Support Beams	20250.51474	
Connections/manholes	26709	
Ladders	3424.585	
Platforms/handrails	14057.22526	
Chimney tray collector	21423.33869	
Packing Support Grid	19160.21555	
Total	5652713.273	
Cost Adjusted for Inflation	7498789.253	CPI 2015 237, CPI 2024 314.4

Wang et al., 2015
Design for 250 MegaWatt Coal Power Plant
Gas Flow rate : 354 m3/s
12% CO2 | 90% Removal = 2M Metric Tonnes/Year

Baytown is 450 MW Natural Gas Plant
Gas Flow rate : 221.1 m3/s
8% CO2 | 2Mt/Year

Ratio between natural gas column side length/coal column side length to maintain same superficial gas velocity with different gas flow rates	0.9504140719	Literature shows about 8% difference in column width, so we are going to say there is a 5-10% change between coal and methane



Parameters

	Unit	Natural Gas	Notes	Coal	Notes	Reference
Energy Content	MJ/kg	50	Mostly Methane (~50 MJ/kg or ~35 MJ/m³)	27	(varies by type; bituminous coal typically assumed)	https://energyeducation.ca/encyclopedia/Bituminous_coal#:~:text=Usually%2C%20bituminous%20coal%20comes%20from,amount%20of%20energy%20when%20burned.
Efficiency		0.6	Combined Cycle Plant	0.33		https://www.pcienergysolutions.com/2023/04/17/power-plant-efficiency-coal-natural-gas-nuclear-and-more/
Amount of wet exhaust gas	m³/GJ of fuel	294.8		323.1		https://en.wikipedia.org/wiki/Flue_gas
Flue Gas Volume/Input (from wikipedia values)	m³/kg	14.74		8.7237	Total flue gas (including N_2, O_2, H_2O): ~9–12 m³/kg coal (varies with excess air)	
Flue Gas Volume/Input (natural gas raw calculation)	m³/kg	4.189526185	Each mole of CH_4 burns with 2 moles of O_2, producing 3 moles of gas (CO_2 + H_2O)			
CO2 Return	kg CO_2/(kg CH_4 or coal)	~2.74	Produces 1 mole of CO_2 (44 g/mol) and 2 moles of H_2O per mole of CH_4 (16.04 g/mol)	~2.86	Approximate formula ($C_1H_{0.8}O_{0.2}$) depends on type. Yields more CO_2 relative to energy output compared to CH_4.	
CO2 Concentration in Flue Gas		8%	Typical flue gases from natural gas-fired power plants may contain 8-10% CO2, 18-20% H2O, 2-3% O2, and 67-72% N2	14%	Typical flue gases from coal-fired boilers may contain 12-14 vol% CO2, 8-10 vol% H2O, 3-5 vol % O2 and 72-77% N2.	https://www.sciencedirect.com/topics/chemistry/flue-gas

Parameters in Flue Gas Volume/Input for Natural Gas Raw Calculation

	Unit		Notes			
Molar Mass Methane	g/mol	16.04				
Standard Molar Gas Volume	L/mole	22.4				https://chem.libretexts.org/Bookshelves/Introductory_Chemistry/Introductory_Chemistry_(CK-12)/10%3A_The_Mole/10.06%3A_Avogadro's_Hypothesis_and_Molar_Volume#:~:text=The%20molar%20volume%20of%20a,22.4L%20(figure%20below).
Gas Volume Produced per mole CH4	L	67.2	1 mole CH4 produces 3 moles gas			
Conversion		0.001	1 L is .001 cubic meter			

Calculations for Comparison

	Unit	Natural Gas	Notes	Coal		
Energy Output	MW	450		250		
Energy Input	MW	750	Output/Efficiency	757.5757576		
Raw Material (CH4/Coal)	kg/s	15	Energy Input/Energy Content	28.05836139		
Flue Gas	m³/s	221.1		244.7727273	354	Wang et al. quote a Gas Flow rate of 354 m³/s

We’ve developed a user-friendly plug-and-play tool to assess the actual cost of your absorber column. It lets you compare options and understand the appropriate price range. It also streamlines the decision-making process for selecting the EPC firm for your CCS plant. The tool can be found here.

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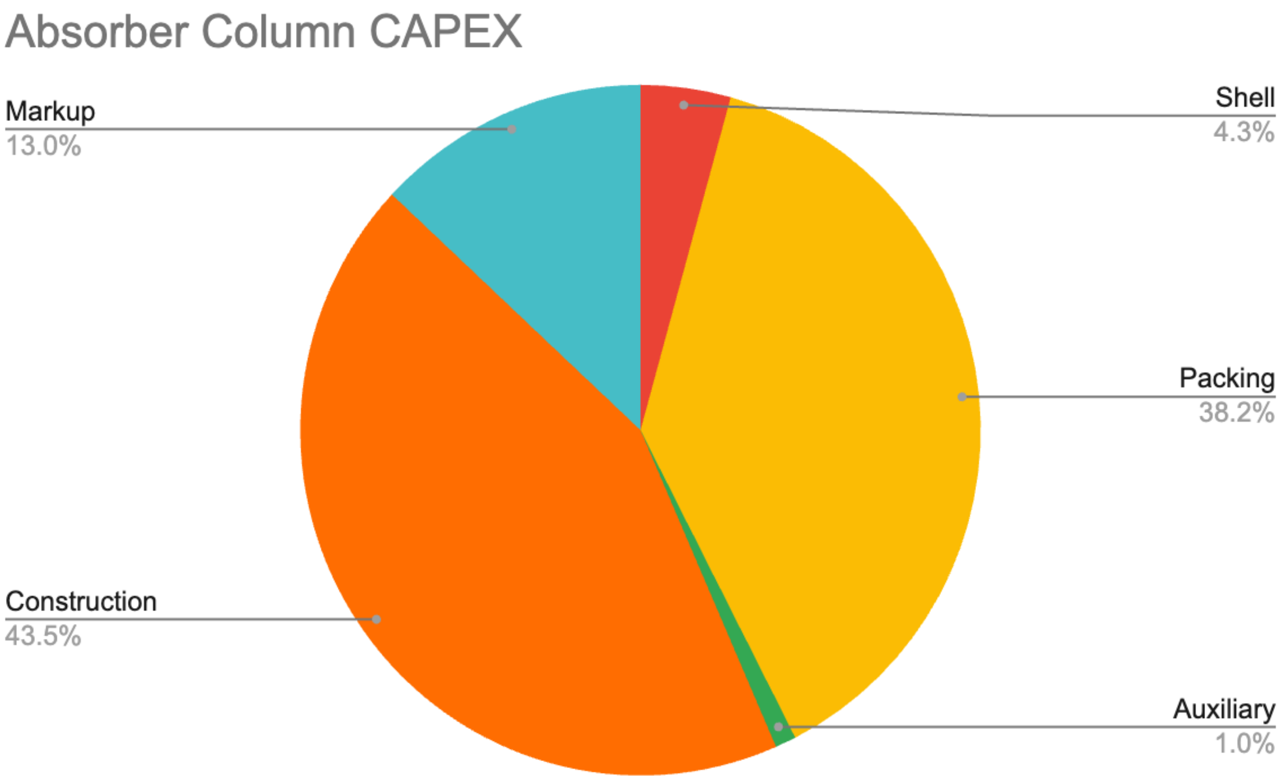
Packing Design Drives Cost



450 MW Plant

2Mt/year Capture

Calpine
Baytown

8% CO_2 Flue Gas

95% Capture Rate

• Shell	• $737,000
• Packing	• $6,600,000
• Auxiliary	• $170,000
• Construction	• $7,500,000
• Markup	• $2,200,000
• **Total**	• **$17,000,000**

- Markup is often 10-20% of material cost and up to the EPCs
- Construction is dependent on location, EPCs, and material cost
- Shell cost is pretty fixed, can be adjusted slightly by using modular designs
- **Packing material and design is the biggest variable we can control**

2

Opportunities for cost reduction

Packing Materials

- Optimize Amongst Existing Packing Materials
  - There's a variety of random and structured packing materials, from \$100/m^3 to \$3000/m^3, sold by a myriad of companies such as GEA Group, Sulzer, Linde Engineering, Mitsubishi Heavy Industries (MHI), and Munters
- Explore Novel Materials
  - Polymers show high potential with ongoing R&D, packing height could decrease by 33% (textured polymer structured packing)

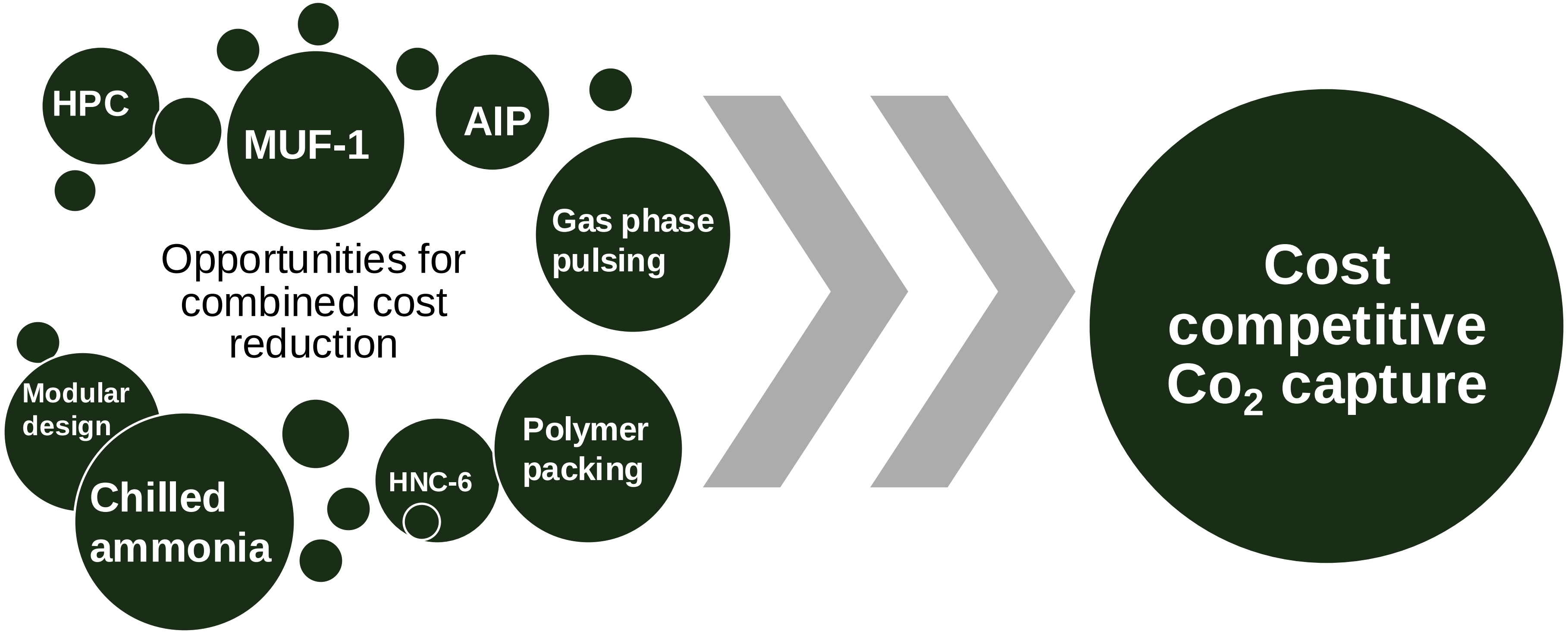
Modular Design

- Install small rectangular units
  - Allows smart scale-up of the modular system

Smart Operations

- Optimize Operational Parameters for Your Facility
  - Run at ideal gas velocities, which depends on packing material and area as well as solvent type
- Explore using gas phase pulsing to increase CO_2 absorption
- Proper CFD monitoring of pressure drop during operation ensures the system remains efficient.

Final Recommendation (novel capture + absorber column)



HPC

MUF-1

AIP

Gas phase pulsing

Opportunities for combined cost reduction

Modular design

Chilled ammonia

HNC-6

Polymer packing

Cost competitive CO_2 capture

novel capture

+

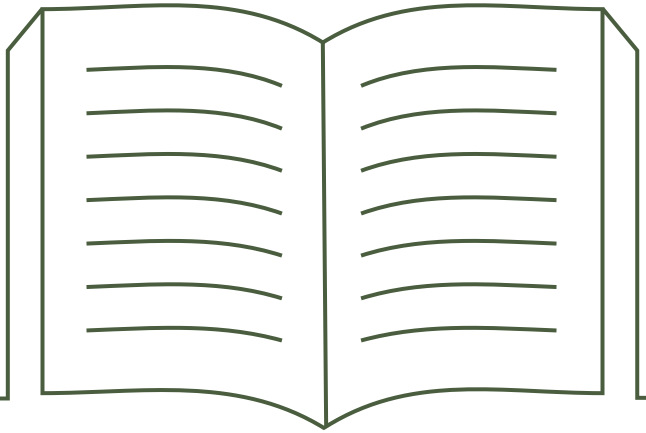
absorber column

practical decarbonization of natural gas power plants

Implication for the OpenMinds community

- Carbon Capture and Utilization (CCUS) technology is pivotal in producing cleaner and more readily dispatchable energy. We firmly believe that natural gas power plants will play a significant role in meeting our energy demands and decarbonizing our existing (over 2000) and future fleet of natural gas power plants. This is not only important but also the right thing to do.
- Currently, carbon capture from natural gas is not economically viable, but it can become so if we allocate our resources towards technological advancements in absorber column and capture technologies. To achieve this, we propose the following:
  - Establish a dedicated technical convention focused to reducing capture costs with a clear end date set for a 5-year timeline. The first 3 years should be dedicated exclusively on reducing the cost of carbon capture capture, while the last 2 years should focus on transportation and storage.
  - Alternatively, consider initiating a Manhattan-like project (5 years) to significantly reduce capture costs. This project could be funded by participating companies that would receive the benefits of reduced costs.
  - Incubate or support companies that aim to vertically integrate the carbon capture value chain and adopt a “made in America” approach. This strategy can help reduce the construction and operational costs of building and running a CCS plant.
  - Collaborate on joint research projects across companies and universities in carbon capture technologies, particularly in the areas of amines and adsorption. This collaborative approach can lead to breakthroughs and advancements in carbon capture for natural gas plants.

Appendix



Comparison of Capture Technologies

		Absorption	Membrane	Cryogenic	Adsorption
Capture Performance	CO2 capture efficiency	90-95%	60-80%	low- temperature dependent	90-95%
	Suitable for low CO2 conc.	✓	✗	✗	✓
	Energy requirement	high	moderate	very high	moderate - low
Cost Economics	Cost per ton of CO2 captured	\$50 - \$150/ton	\$60 - \$120/ton	\$150 - \$300/ton	\$50 - \$100/ton
	Cost trajectory	stable	decreasing	high	decreasing
Environmental Impact (Sust.)	Lifecycle emissions	moderate	low	high	low
	Estimated water, land, & waste use	Very high	minimal	Moderate -high	Minimal-moderate
Technology readiness	TRL	9	6-7	1-3	1-4
	Commercial track record	established	limited	minimal	experimental
	Breakthrough potential	incremental	high	low	high

1

Opportunity Cost (Capture Efficiency Vs Energy Consumption)

Symbol	Company	TRL	Energy Consumption (GJ/tCO2)	Capture Efficiency (%)	Capital gain from 45Q due to efficiency ($)	Capital loss from lost electricity sales ($)
18	Captivate Technology	5	1.1	95	47.5	48.246
17	InnoTech Alberta	5	1.8	95	47.5	78.948
13	Capsol Technologies	1	1.5	95	47.5	65.79
5	Entropy	9	2.4	98	49	105.264
2	Sinopec NRICI	9	2.4	96	48	105.264
3	ION Clean Energy	7	2.5	99	49.5	109.65
12	Baker Hughes	7	2.6	99.5	49.75	114.036
10	China Energy	7	2.35	90	45	103.071
11	Axens	7	2.7	99	49.5	118.422
14	Baker Hughes	5	2.3	90	45	100.878
16	CERI	5	2.3	90	45	100.878
7	Shell & Technip	9	3	98	49	131.58
1	CarbonOrO	7	2.6	90	45	114.036
9	CERI	9	2.8	90	45	122.808
15	CERI	4	2.6	90	45	114.036
19	CO2CRC Ltd	6	2.8	90	45	122.808
6	Carbon Clean	8	3.1	92.5	46.25	135.966
4	Saipem	8	3.5	95	47.5	153.51
8	Gassnova	7	3.54	98	49	155.2644

Capture Multi Criteria Decision Analysis (MCDA)

Normalization					Contribution to MCDA		
TRL	Energy Consumption	Capture Efficiency	MCDA	Symbol	Energy Score	TRL	Efficiency Score
0.5	1	0.526315789	0.85263158	18	0.59684211	0.17052632	0.08526316
0.5	0.713114754	0.526315789	0.65181191	17	0.45626833	0.13036238	0.06518119
0	0.836065574	0.526315789	0.63787748	13	0.44651424	0.1275755	0.06378775
1	0.467213115	0.842105263	0.61125971	5	0.42788179	0.12225194	0.06112597
1	0.467213115	0.631578947	0.59020708	2	0.41314495	0.11804142	0.05902071
0.75	0.426229508	0.947368421	0.5430975	3	0.38016825	0.1086195	0.05430975
0.75	0.385245902	1	0.51967213	12	0.36377049	0.10393443	0.05196721
0.75	0.487704918	0	0.49139344	10	0.34397541	0.09827869	0.04913934
0.75	0.344262295	0.947368421	0.48572045	11	0.34000431	0.09714409	0.04857204
0.5	0.508196721	0	0.4557377	14	0.31901639	0.09114754	0.04557377
0.5	0.508196721	0	0.4557377	16	0.31901639	0.09114754	0.04557377
1	0.221311475	0.842105263	0.43912856	7	0.30738999	0.08782571	0.04391286
0.75	0.385245902	0	0.41967213	1	0.29377049	0.08393443	0.04196721
1	0.303278689	0	0.41229508	9	0.28860656	0.08245902	0.04122951
0.375	0.385245902	0	0.34467213	15	0.24127049	0.06893443	0.03446721
0.625	0.303278689	0	0.33729508	19	0.23610656	0.06745902	0.03372951
0.875	0.180327869	0.263157895	0.3275453	6	0.22928171	0.06550906	0.03275453
0.875	0.016393443	0.526315789	0.23910699	4	0.16737489	0.0478214	0.0239107
0.75	0	0.842105263	0.23421053	8	0.16394737	0.04684211	0.02342105

1

Steps in MCDA calculation

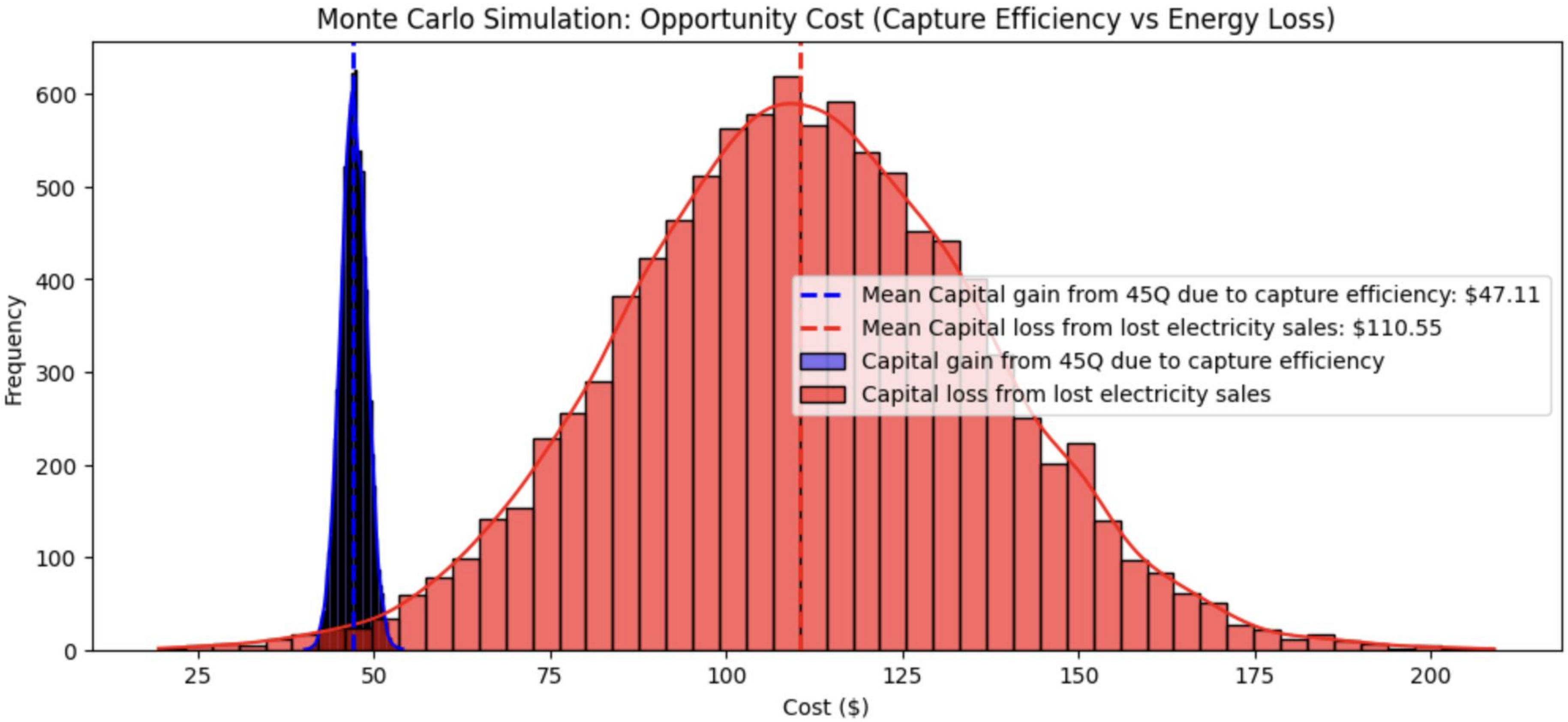
For each technologies, we have their 1) capture efficiency (%), 2) Energy consumption (GJ/tCO$_2$) and 3) Technological Readiness Level (TRL) from 1-9.Our goal is to rank the technologies on these 3 parameters. As you can see, these values have different units, so to compare apples to apples, first, we normalize the data.

1) Select evaluation criteria. Energy (most important), TRL, and capture efficiency (least important)
2) Assigning weights – Energy = 70%, TRL= 20% and Capture Efficiency = 10%... We justified these weights in slide 12 (opportunity cost slide) and based on our extensive research.
3) Normalize the data; Normalized value = ((value – min value) / (max value – min value) ; higher is better

   and Normalized value = 1 – ((value – min value) / (max value – min value))

4) Final MCDA score (0-1) = ∑ (Normalized Criterion Value X Weight), where higher MCDA = better technology

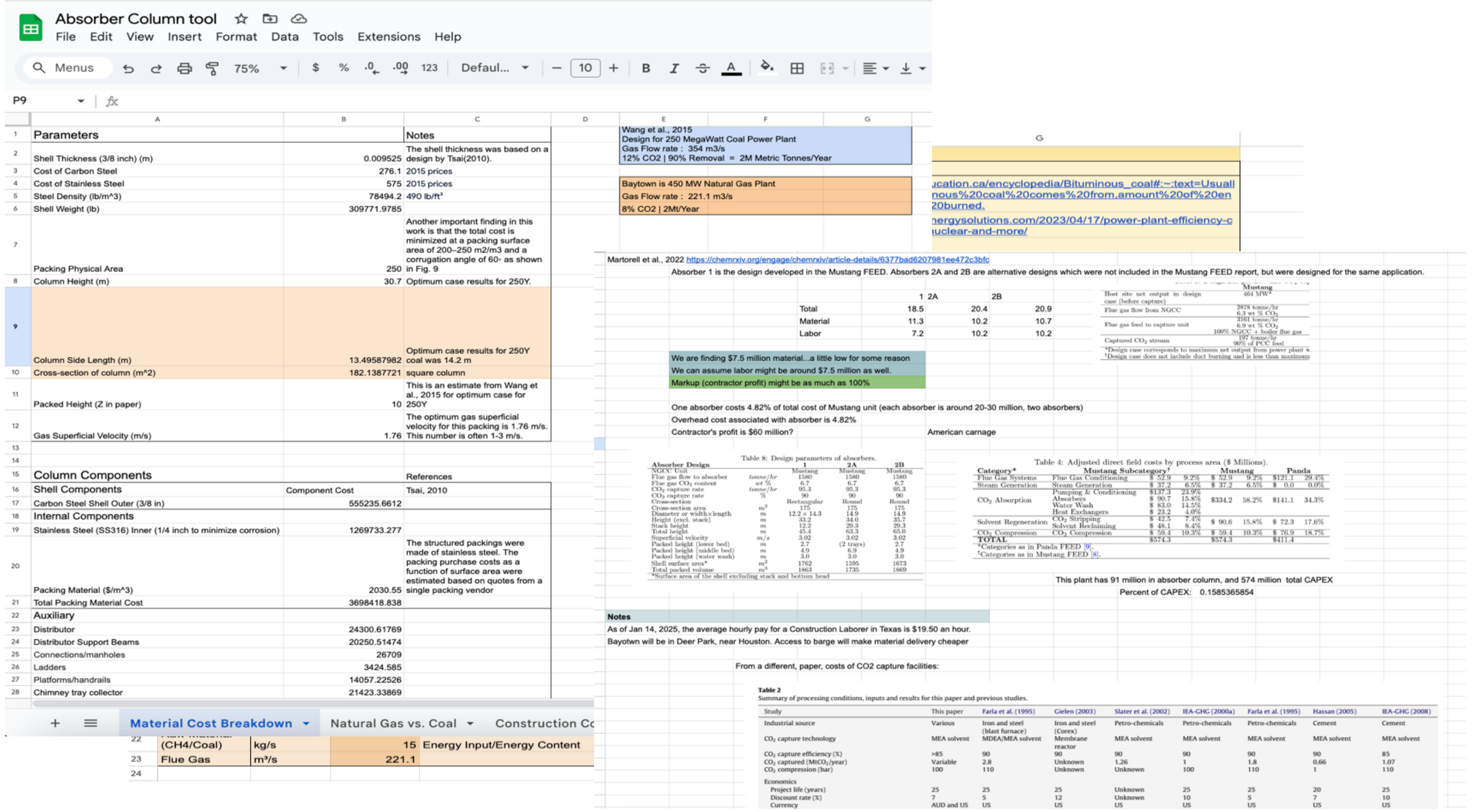
Monte Carlo simulation of opportunity cost (10,000 runs)



Given the limited data available for our analysis, we decided to expand our dataset statistically. This expansion allows us to explore the range of possible values and probability density, which aids in risk assessment. The blue curve is the distribution of capital gain from 45Q due to capture efficiency, while the red curve depicts the distribution of capital loss resulting from lost electricity sales. As evident from the graph, the mean capital loss in the expanded dataset remains substantially higher compared to the capital gain from 45Q. Additionally, the narrow blue curve indicates low variability and consistent 45Q revenue potential and the broader red curve shows greater variability, likely due to fluctuating electricity prices. Nevertheless, lost electricity sales are the dominant cost decision-making and this suggest that reducing parasitic load of CCS systems would yield greater financial benefits than relying solely on 45Q incentives. **NB- This expanded dataset was not used in any of our decision-making calculations.**

Absorber Column Costing Tool

The absorber column is a significant component of building a carbon capture plant. Controlling your column design can substantially reduce this cost, rather than relying solely on EPCs.



	A	B	C
1	Parameters		Notes
2	Shell Thickness (3/8 inch) (m)	0.009525	The shell thickness was based on a design by Tsai(2010).
3	Cost of Carbon Steel	276.1	2015 prices
4	Cost of Stainless Steel	575	2015 prices
5	Steel Density (lb/m^3)	78494.2	490 lb/ft³
6	Shell Weight (lb)	309771.9785	
7	Packing Physical Area	250	Another important finding in this work is that the total cost is minimized at a packing surface area of 200–250 m2/m3 and a corrugation angle of 60◦ as shown in Fig. 9
8	Column Height (m)	30.7	Optimum case results for 250Y.
9	Column Side Length (m)	13.49587982	Optimum case results for 250Y coal was 14.2 m
10	Cross-section of column (m^2)	182.1387721	square column
11	Packed Height (Z in paper)	10	This is an estimate from Wang et al., 2015 for optimum case for 250Y
12	Gas Superficial Velocity (m/s)	1.76	The optimum gas superficial velocity for this packing is 1.76 m/s. This number is often 1-3 m/s.
13			
14			
15	Column Components		References
16	Shell Components	Component Cost	Tsai, 2010
17	Carbon Steel Shell Outer (3/8 in)	555235.6612	
18	Internal Components		
19	Stainless Steel (SS316) Inner (1/4 inch to minimize corrosion)	1269733.277	
20	Packing Material ($/m^3)	2030.55	The structured packings were made of stainless steel. The packing purchase costs as a function of surface area were estimated based on quotes from a single packing vendor
21	Total Packing Material Cost	3698418.838	
22	Auxiliary		
23	Distributor	24300.61769	
24	Distributor Support Beams	20250.51474	
25	Connections/manholes	26709	
26	Ladders	3424.585	
27	Platforms/handrails	14057.22526	
28	Chimney tray collector	21423.33869	

22	(CH4/Coal)	kg/s	15	Energy Input/Energy Content
23	Flue Gas	m³/s	221.1	
24				

Wang et al., 2015
Design for 250 MegaWatt Coal Power Plant
Gas Flow rate : 354 m3/s
12% CO2 | 90% Removal = 2M Metric Tonnes/Year

Baytown is 450 MW Natural Gas Plant
Gas Flow rate : 221.1 m3/s
8% CO2 | 2Mt/Year

ucation.ca/encyclopedia/Bituminous_coal#:~:text=Usuall nous%20coal%20comes%20from,amount%20of%20en 20burned.
nergysolutions.com/2023/04/17/power-plant-efficiency-c uclear-and-more/

Martorell et al., 2022 https://chemrxiv.org/engage/chemrxiv/article-details/6377bad6207981ee472c3bfc

Absorber 1 is the design developed in the Mustang FEED. Absorbers 2A and 2B are alternative designs which were not included in the Mustang FEED report, but were designed for the same application.

	1	2A	2B
Total	18.5	20.4	20.9
Material	11.3	10.2	10.7
Labor	7.2	10.2	10.2

We are finding $7.5 million material...a little low for some reason
We can assume labor might be around $7.5 million as well.
Markup (contractor profit) might be as much as 100%

One absorber costs 4.82% of total cost of Mustang unit (each absorber is around 20-30 million, two absorbers)
Overhead cost associated with absorber is 4.82%
Contractor's profit is $60 million?
American carnage

Table 8: Design parameters of absorbers.

Table 4: Adjusted direct field costs by process area ($ Millions).

This plant has 91 million in absorber column, and 574 million total CAPEX
Percent of CAPEX: 0.1585365854

Notes
As of Jan 14, 2025, the average hourly pay for a Construction Laborer in Texas is $19.50 an hour.
Bayotwn will be in Deer Park, near Houston. Access to barge will make material delivery cheaper

From a different, paper, costs of CO2 capture facilities:

Table 2
Summary of processing conditions, inputs and results for this paper and previous studies.

Recommendations

Packing materials: Polymers show high potential and can decrease packing height by 33%

Modular absorber column design

Smart operations: Look into using gas phase pulsing to increase CO_2 absorption

We've developed a user-friendly plug-and-play tool to assess the actual cost of your absorber column. It lets you compare options and understand the appropriate price range. It also streamlines the decision-making process for selecting the EPC firm for your CCS plant. The tool can be found here.

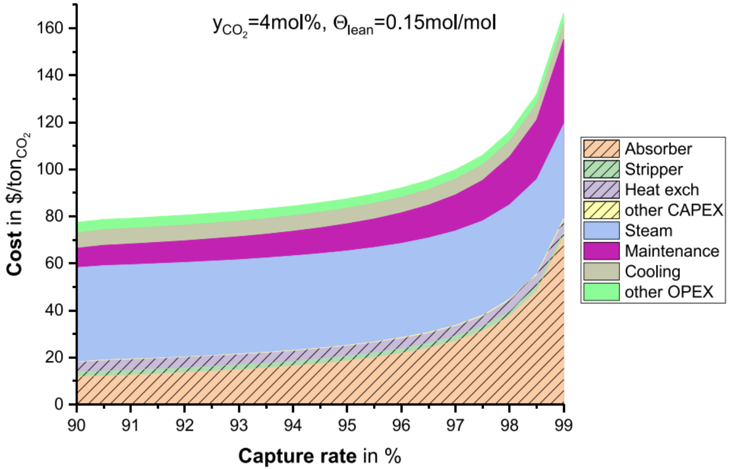
2

Absorber column breakdown

Cost Breakdown

Role of Absorber Column in total CAPEX

- At 98% capture rate or higher, the main contributor to capture cost is the absorber column (CAPEX).



Absorber Column CAPEX

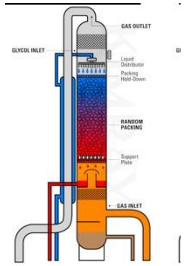
Brandl, P., Bui, M., Hallett, J. P. & Mac Dowell, N. (2021).
Beyond 90% capture: Possible, but at what cost? International Journal of Greenhouse Gas Control, 105, 103239.

Avenues for Cost Savings

Packing Materials

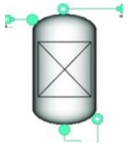
- Optimize Amongst Existing Packing Materials
  - There's a variety of random and structured packing materials, sold by a myriad of companies
- Look Into Novel Materials
  - Polymers show high potential with ongoing R&D
- Look Into Overseas Providers
  - Chinese producers sell lower cost ceramic packing

Smart Operations



- Optimize Operational Parameters for Your Facility
  - Run at ideal gas velocities, which depends on packing material and area as well as solvent type
- Look into using gas phase pulsing to increase CO2 absorption
- Proper monitoring of pressure drop during operation ensures the system remains efficient and within safe operating limits.

Modular Design



- Install small rectangular units
  - Allows smart scale-up of the modular system

②

Packing cost breakdown

• Shell	• $737,000
• Packing	• $6,600,000
• Auxiliary	• $170,000
• Construction	• $7,500,000
• Markup	• $2,200,000
• **Total**	• **$17,000,000**

Total = Packing + Markup + Construction;

T = P + M + C ; P = Packing, M= Markup, C= Construction

M = P + A + S; A = Auxiliary, S = Shell

Markup = 0.15 x M

M = P + 170,000 + 737,000;

Markup = 0.15 x (P + 907,000)

Markup = 0.15P + 0.15 x 907,000

Markup = 0.15P + 136,050

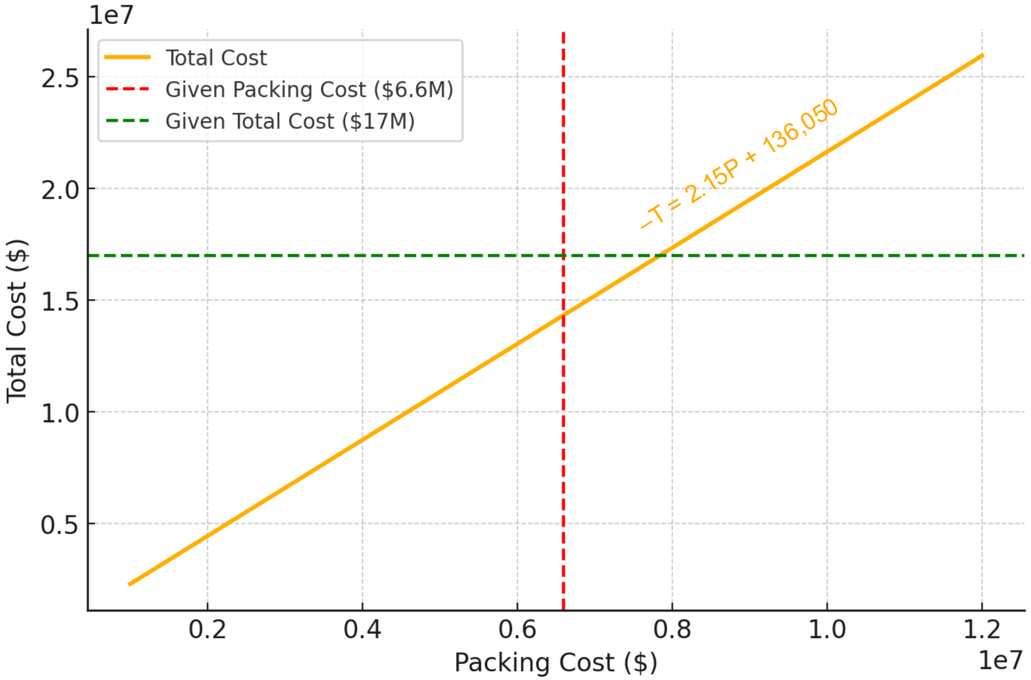
If C= P.. Recall that;

Total (T) = P + Markup + C

T = P + (0.15P + 136,050) + P

T = P + 0.15P + 136,000 + P

T = 2.15P + 136,050; T as a function of P, takes the form y = mx + b



②

Packing breakdown

Shell	$737,000
Packing	$6,600,000
Auxiliary	$170,000
Construction	$7,500,000
Markup	$2,200,000
Total	**$17,000,000**

$T = 2.15P + 136{,}050$;

T as a function of P… $y = mx + b$

P=$/m^3 * volume_packing

Random = $100/m^3 * 30 - bigger in size… this material has to be subpar (ceramic or plastic, metal)

Structured = $5000/m^3 * 15 – smaller in size (metal or plastic)

$P = 1/C$

absolute minimum P_{min} = smallest possible packing cost

Recall that the lowest bound of P is practically determined by the minimum packing required to capture 2 million metric ton of $CO_{2..}$ To find the minimum feasible cost, we need the engineering constraints that determine the least amount of packing required. And we do not have that data (extremely difficult to find)