Capturing Carbon Dioxide

Presentation to the Bioenergy Association of New Zealand

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Agenda

- Takeaways
- Introduction to Captivate Technology - a serendipitous discovery
- Vacuum Pressure Swing Adsorption
- The VPSA advantage
- Biogas upgrading applications; pre-combustion
- Bioenergy in horticulture; post-combustion
- The business case for carbon dioxide capture

Takeaways

- Carbon Capture technology is reducing capture costs, both OPEX and CAPEX
- Carbon Capture market for smaller sources (< 100,000 TPA) is expanding at pace
- Carbon Capture is becoming economic from lower % sources of CO_2
- Technology solutions will grow the carbon capture market
- Carbon capture is attracting major investment from industry, governments and investors.

  Market for carbon capture is forecast in the hundreds of billions per annum by the 2030s

  Reducing and removing CO_2 from our biosphere is happening.

Introduction Captivate Technology

Prof Shane Telfer, Founder & CEO

- Deep expertise in the field of Metal-organic framework (MOF) chemistry,
- 130 peer-reviewed publications; generated >NZ$8M in research funding,
- Fulbright Fellow at UC Berkeley,
- Massey University's Individual Research medallist (the university's highest accolade),
- Principal Investigator for the MacDiarmid Institute for Advanced Materials and Nanotechnology.

Dr Subo Lee, R&D Scientist

- PhD in Chemistry at Massey University,
- Ten publications in the peer-reviewed literature,
- Designed and constructed mobile PSA rig and deployed it on industrial sites.

Nigel Campbell, Business Development Manager

- Energy industry background, (NZ, Europe, N America). Gas development, emissions reduction, RNG project development
- Carbon Capture Engineering
- Carbon Storage and use
- Carbon markets, policy, pricing, offsets and credits, voluntary and compliance, clean fuel regulations

Game-changing discovery: MUF-16 adsorbent

- Metal-organic frameworks (MOFs) are porous, sponge-like crystals. They separate gases by selective adsorption.
- MUF-16 is Captivate's MOF material for capturing CO_2. Reported by Professor Telfer's team in the high-impact journal Nature Communications (MUF = Massey University Framework).
- MUF-16 has been manufactured at scale by four international partners
- Patented.

- MUF-16 combines the following advantages:

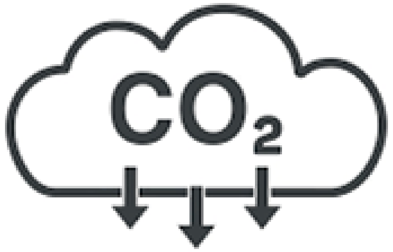
→ highly selective for CO_2 over N_2 and CH_4	▸ low CAPEX
→ tolerant to steam & contaminants, long-lived	▸ low CAPEX
→ inexpensive to synthesize and scalable	▸ low CAPEX
→ regenerated in a low energy process	▸ low OPEX
→ easily shaped into beads/pellets	▸ easy handling/use

Vacuum Pressure Swing Adsorption breakthrough technology

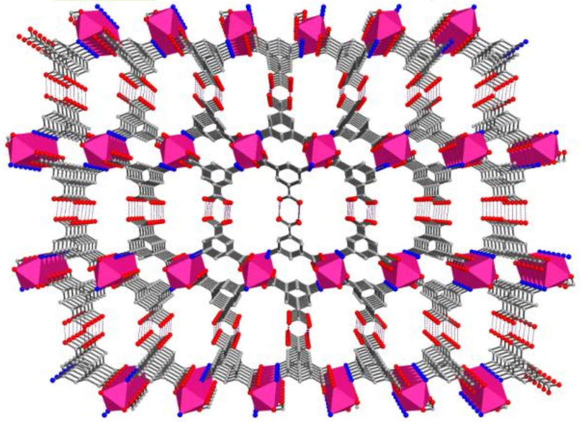
The serendipitous discovery is a recyclable superior sponge-like adsorbent material for the capture of CO_2. It is easy to manufacture and low cost. It is utilised in a Vacuum Pressure Swing Adsorption (VPSA) process which is used globally today for gas separation and manufacturing.

Adsorption can happen at ambient temperature and pressure with MUF-16 which, lowers energy requirements and costs, and expands the market and applicability of carbon capture, beyond mega-projects to smaller scale carbon capture.

The combination of new adsorbents like MUF-16 and VPSA is a gamechanger for carbon capture.

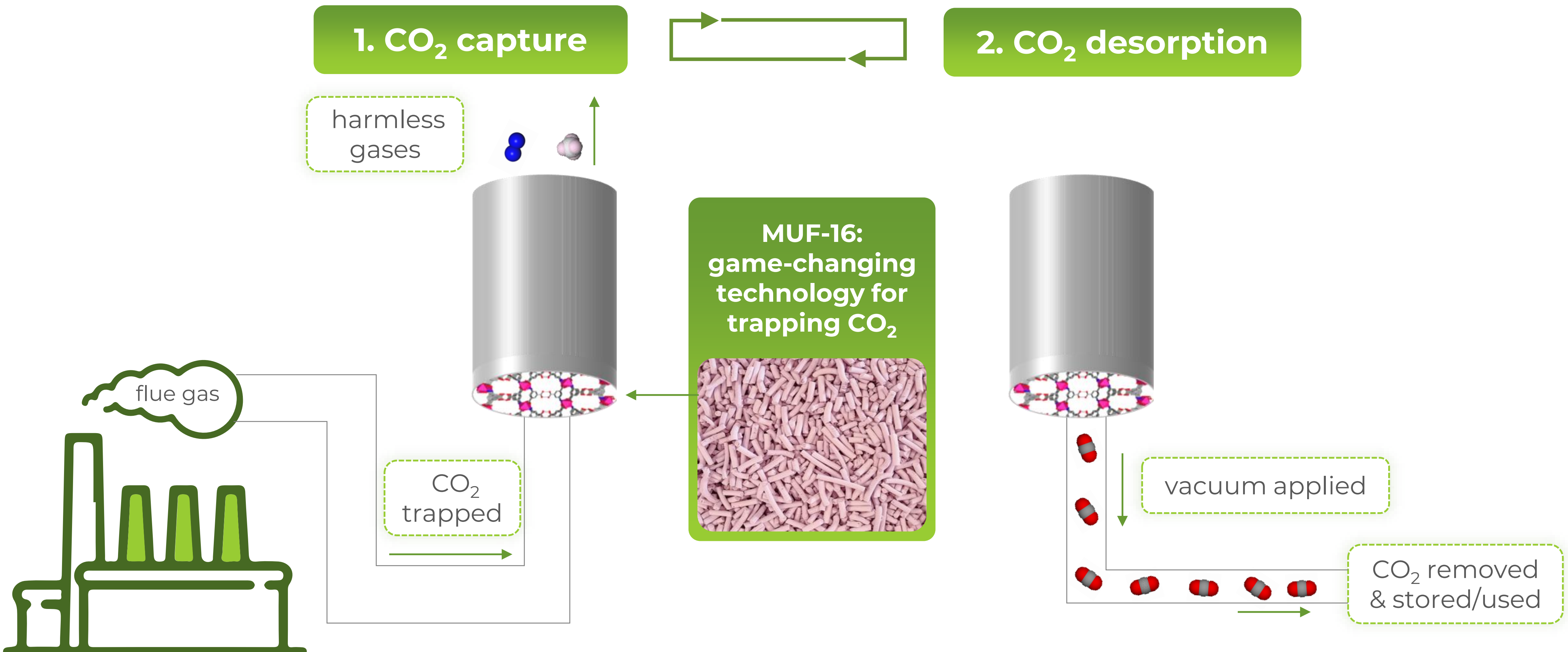


Gigaton scale



Superior absorbent

Capturing CO_2 using MUF-16 in a VPSA process



Technology derisked by using conventional Vacuum Pressure Swing Adsorption (VPSA)

Vacuum Pressure Swing Adsorption

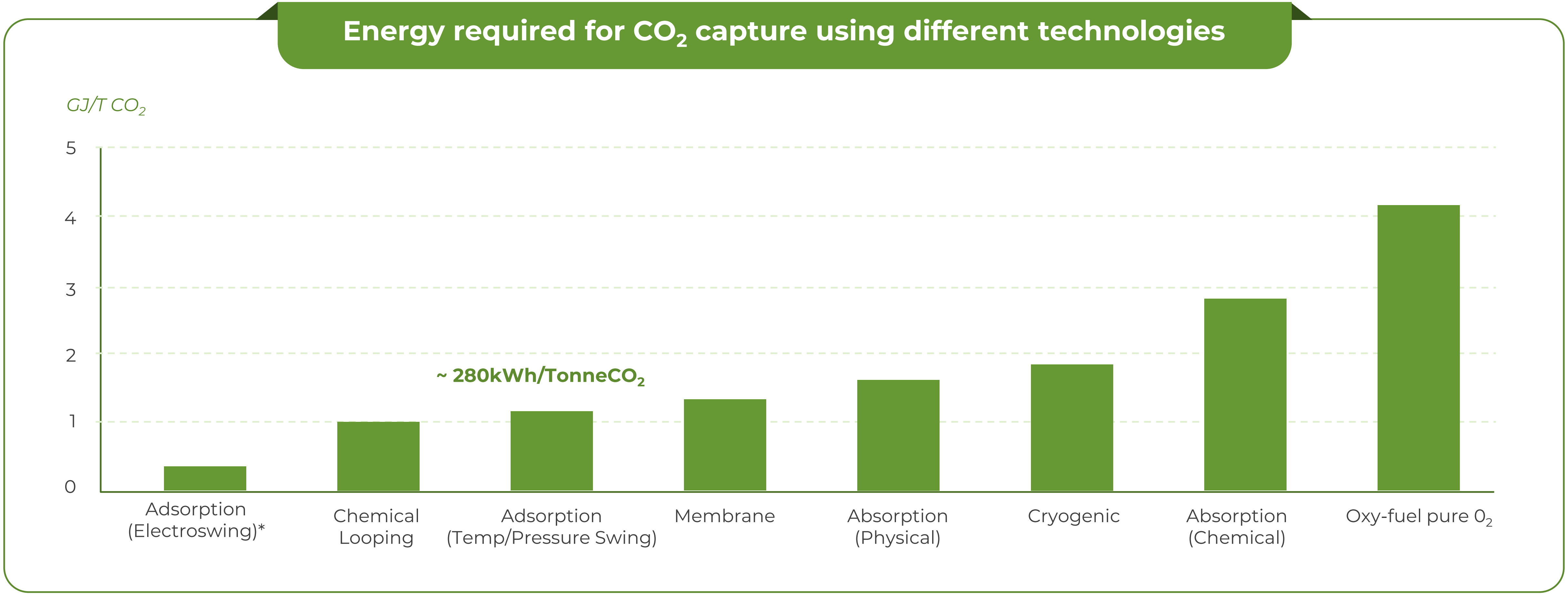
- **PSA is commonly in industry used to separate gases**
- **Used in manufacture of Oxygen and Hydrogen**
- **Operates at ambient temperature**
- **Uses porous adsorbents such as zeolites and activated carbon. Compression required.**
- **VPSA + and adsorbent like MUF-16 = ultra low energy solution for carbon capture**

A detailed comparison with zeolites

- Zeolites come in several different forms: zeolite 13X and zeolite 5A are the most common for CO_2 capture.
- They are porous solid-state materials; have been researched for decades and are manufactured on large scales
- Zeolites are used industrially, and MUF-16 can be a drop-in replacement, for example:
  - The Air Products 'Port Arthur CO_2' project uses PSA units retrofitted to a steam methane reformer (H_2 generation) captures 56,000 Nm^3/h CO_2 with >90% purity from the syngas stream,
  - Caterpillar uses zeolite 13X to capture CO_2 from engine emissions
- However, zeolites have many disadvantages compared to MUF-16, including:
  - they are susceptible to water vapour in the flue gas (even trace levels),
  - the incoming flue gas stream must be pressurised to high levels before meeting the adsorbent (expensive),
  - deep vacuum levels are required to remove CO_2 which means that expensive pumps are needed (or else a low working capacity results),
  - their Q_{st} for CO_2 binding is high so a lot of heat is released/consumed when adsorbing/desorbing.
- Zeolites are cheaper than MUF-16. But this cost is only a fraction of the capex of a carbon-capture unit and performance and longevity factors weigh strongly in MUF-16's favour.

PSA and especially VPSA will provide ultra low energy capture

Energy requirements can vary significantly between capture technologies



NOTES: Electro Swing Adsorption costs reflect industry estimates and have yet not been achieved at commercial scale.
SOURCE: Hong W.Y., (2022) A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO+ emissions future, Carbon Capture Science & Technology
https://www.energy-transitions.org/publications/carbon-capture-use-storage-vital-but-limited/

CO_2 capture in Bioenergy
Two immediate value add opportunities

1. **Upgrading Biogas to Biomethane/RNG; pre-combustion capture**

Biogas (upto 40% CO_2) historically combusted for elec. gen; price linked to power market

Biomethane price is linked to renewable fuels market

As Biomethane values increase, upgrading technology and solutions is retrofitted to sites

Extra value of biomethane must offset levelized cost if upgrading

2a. Combustion of Bioenergy (waste) and utilisation of CO_2 for horticulture; post-combustion capture

2b. Combustion of Bioenergy and utilisation (eFuels) or storage (e.g. concrete)

Co-location opportunities are emerging to enhance value proposition

1. Biogas Upgrading – options and a gamechanger

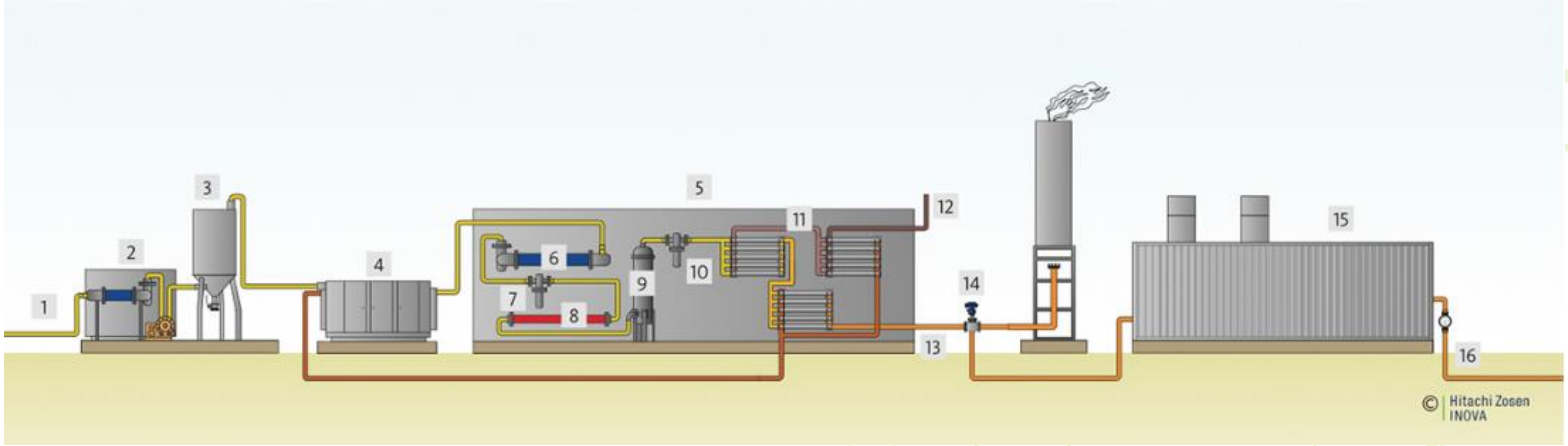
Current market options

1. Water Wash
2. Membrane
3. Amine scrubbing
4. Pressure Swing Adsorption (PSA) – conventional adsorbents

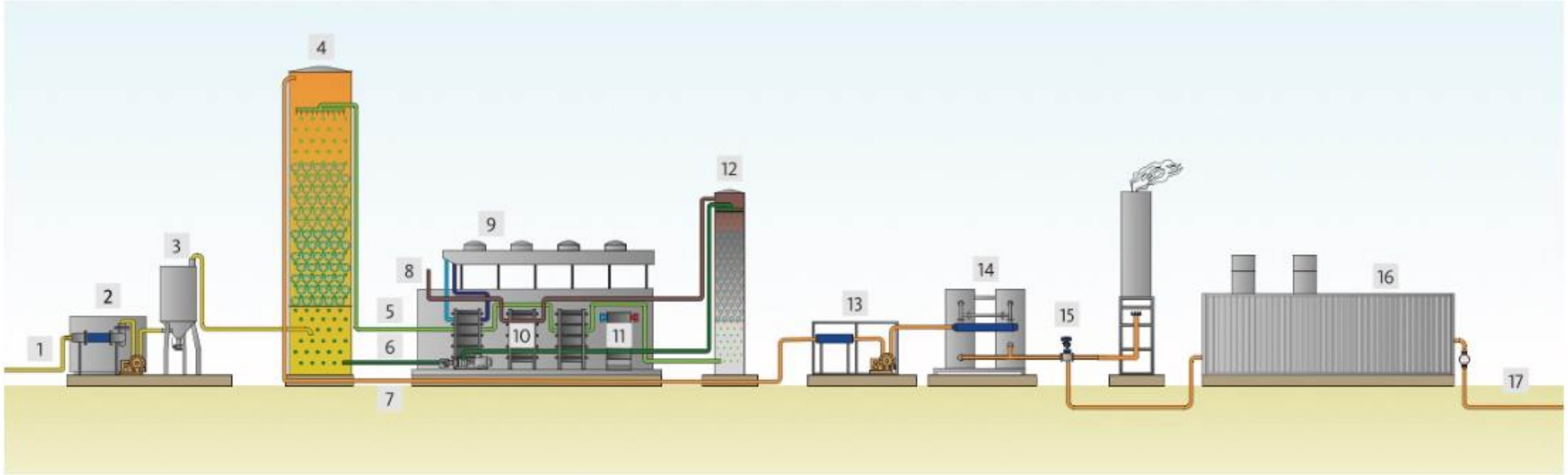
Market share has been shared between all methods – off the shelf solutions can be purchased for retrofit.

New adsorbents such as those discovered by Captivate are now **changing** the game. Their superior adsorption character *reduces energy consumption (ambient pressure and temperature) and reduces OPEX and CAPEX, giving the advantage to VPSA.*

Multiple Biogas upgrading options commercially available



membrane



Amine scrubbing

Amine scrubbing biogas upgrading units are commercially available

Biogas upgrading – Pressure Swing Adsorption (PSA)

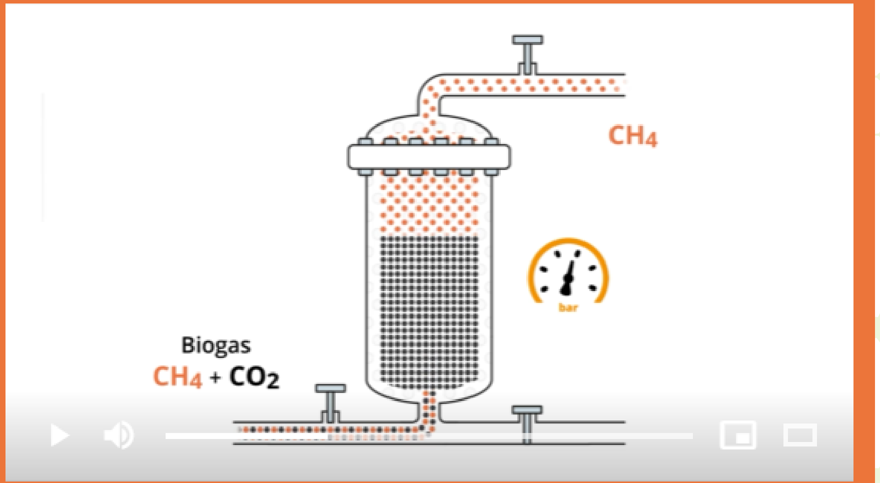
Biogas upgrading – Pressure Swing Adsorption (PSA)

HOW ETW SMARTCYCLE TECHNOLOGY WORKS

ETW uses the pressure swing adsorption process to separate gas mixtures. As such, CO2 or other disruptive elements are separated out in the treatment system.

The system has several columns that are filled with adsorbents. Each column goes through a cyclical sequence of pressure levels and generates highly pure and dry biomethane. The column cycles are timed in such a way that a continuous flow of gas is guaranteed.

After each adsorption phase, the adsorbent is regenerated and the CO2-rich off-gas is separated. Based on this principle, product gas purities of up to 99% methane content can be achieved.



2. Bioenergy carbon capture for horticulture

Bioenergy and fossil fuels have long been combusted to provide heat for greenhouses.

Provide CO_2 to supplement growth during the day and heat and supplemental heat .

CO_2 dosing from purchased liquid CO_2 is also common. CO_2 and fossil gas prices have increased in recent years - new opportunities for CO_2.

Several examples have emerged in recent years where captured post-combustion CO_2 has been used to supplement greenhouse growth.

New adsorbents such as those discovered by Captivate are now changing the game. Their superior adsorption character *reduces energy consumption and cost in the capture process. Captivate's capture process is suitable for all fuels and can store and supply* CO_2 *when needed.*

Biogas carbon capture for horticulture

Capturing Carbon: From what?

There are 3 categories of carbon source

Purity of CO_2 in source determines technology requirements and capture chemistry

Maturity   Immature

CO₂ concentration: High → Low

Source of emissions	Chemistry needed	Mechanism	Description	Maturity	Example technology providers[1]
01 **High purity point sources (50-90% flue gas)** Emissions from ethanol, ammonia, natural gas processing	✗	**Dehydration equipment**	Need dehydration & compression equipment which is low cost	Maturity	No specialized equipment or chemistry required
02 **Low purity point sources (5-15% flue gas)** CO_2 emissions from large point sources such as power stations and cement factories- required for Hard to Abate Industries	✓	**Solvent**	High performance chemical that selectively dissolves CO_2effluent stream	Maturity	Massachusetts Institute of Technology, DOOSAN, FLUOR, AKER CARBON CAPTURE, MITSUBISHI HEAVY INDUSTRIES, LTD., CO_2 SOLUTIONS BY SAIPEM, Shell, eni, Linde
		Sorbents	Typically solid materials that "adsorb CO_2 from effluent stream		
		Membranes	"Filter-like" technology that separates gasses from industrial streams		
		Novel concepts	Broad range of approaches targeting a step-change process enhancement		
03 **Direct air capture** CO_2 captured from ambient air at low concentrations - required for 'Negative Emissions	✓	**HT aqueous solution**	Basic aqueous solution, absorbs CO_2 and is then regenerated	Immature	Global Thermostat, Carbon Engineering, mosaic, climeworks
		LT solid sorbent (TSA)	Solid chemical that adsorbs CO_2 and is regenerated by heating	Immature	
		LT liquid solvent (MSA)	Liquid absorption of CO_2 with regeneration by microwaves	Immature	

Source: *Global CCS Institute*

VPSA technology is applicable across sectors

Captivate has demonstrated its technology on site in NZ on:

geothermal emissions

Power station Natural gas boiler emissions

Next tests in NZ are:

Gas turbine emissions

Bioenergy post–combustion emissions

Cement plant emissions

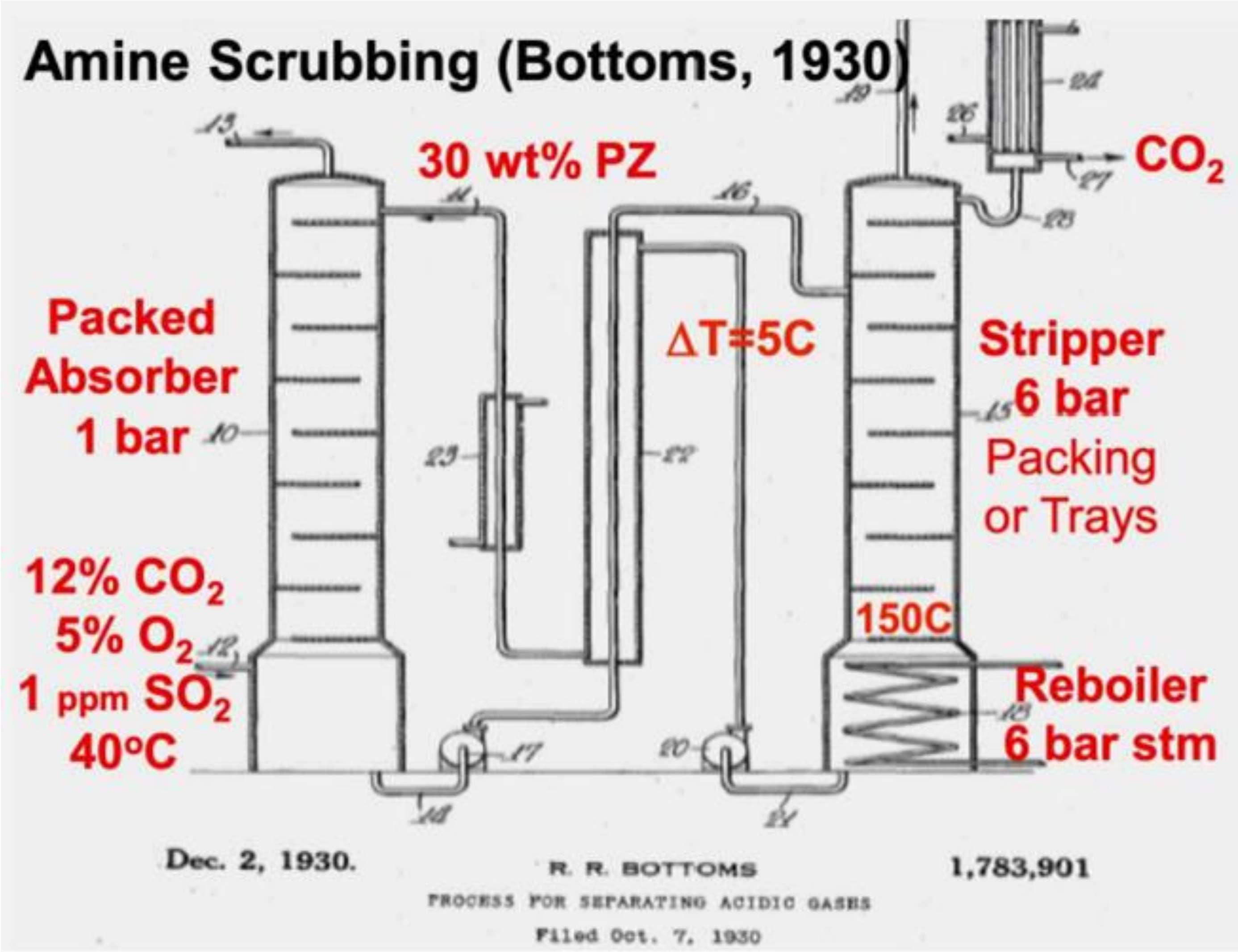
Key sectors

- Biogas
- Bioenergy
- Power
- Steelmaking
- Cement
- Geothermal
- H_2 production
- Fuel cells
- Pulp & paper
- Built environment
- Transportation

modular & scalable

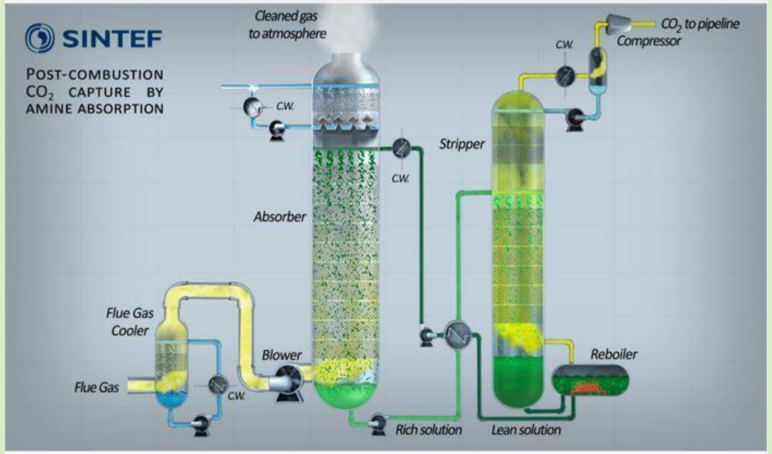
Global cross sector experience is relevant for NZ bioenergy sites

Amine scrubbing has been around for 100 years - it is ripe for disruption



Limitations of amines for CO_2 capture

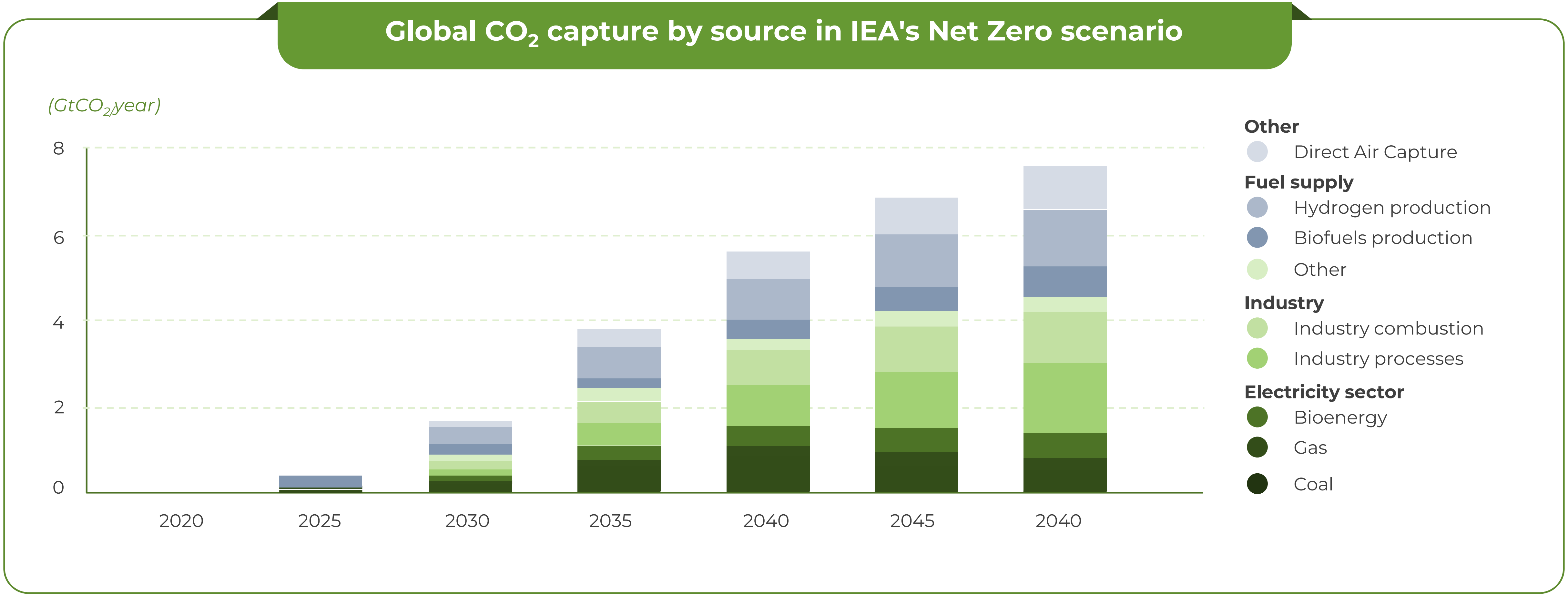
- CO_2 capture is needed for fossil fuel combustion, cement manufacturing, steelmaking, geothermal, biogas and other industries.
- Conventional technology for trapping CO_2 involves chemical reactions with amine solutions.
- The major players are Mitsubishi Heavy Industries, Shell, Fluor and Aker Carbon Capture.
- However, there are significant problems with amine-based carbon capture units, including:



Energy penalty	High energy penalty for regeneration/recycling due to their high heat capacity.
Toxicity	Amine degradation products are potentially toxic and carcinogenic.
Volatility	Amines evaporate into the gas flow and then the atmosphere (~1.5kg of amine lost per tonne of CO_2).
Degradability	Amines form side-products by reacting with contaminants such as SO_2 in the flue gas.
Bulkiness	Amine systems are only applicable to large-scale, fixed installations.
Handling issues	Amines are liquid chemicals that required specialized handling and storage.

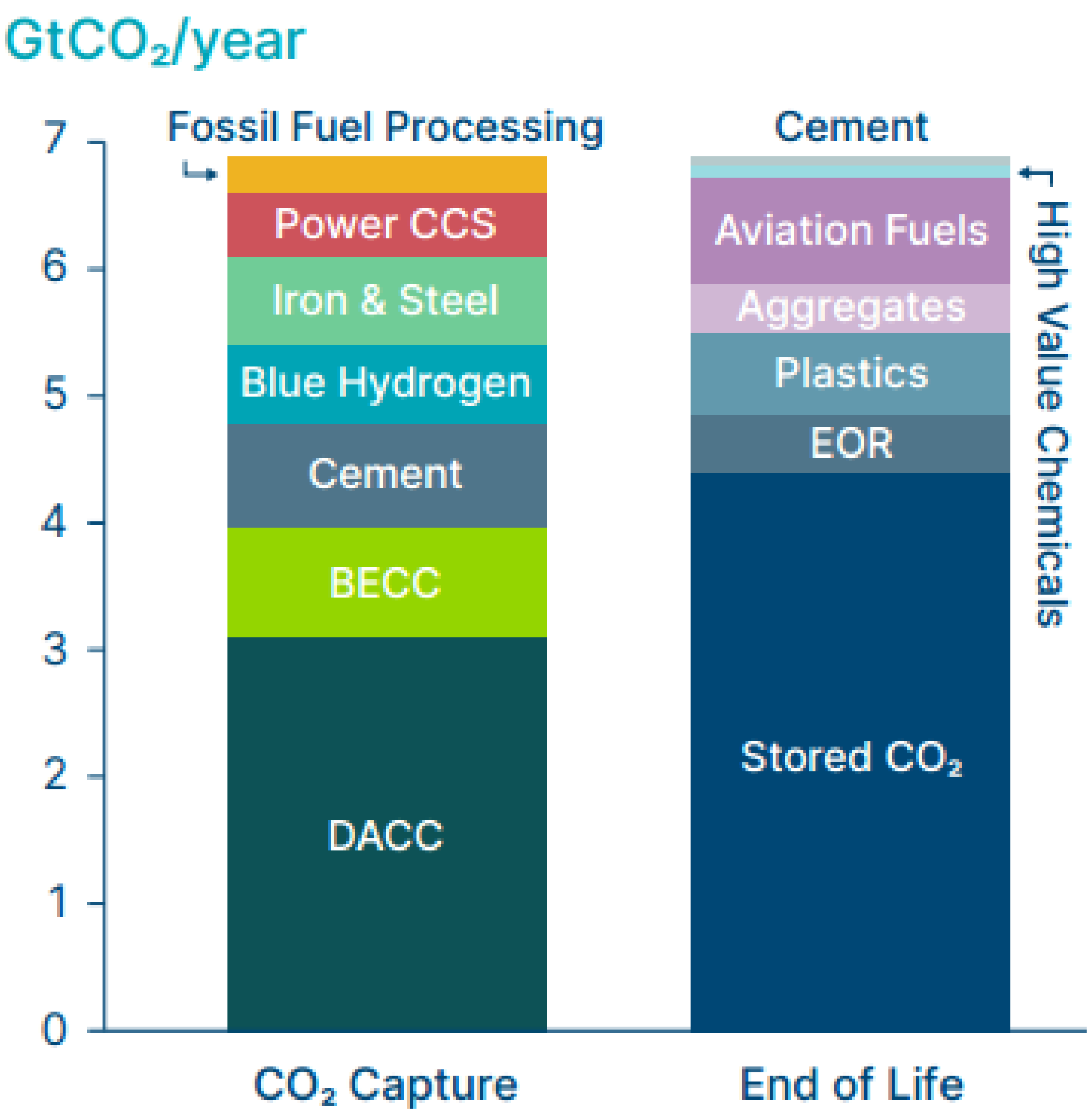
The downsides of amines mean that new technologies are in demand for point source carbon capture.

Capturing Carbon: Bioenergy is a growing wedge



SOURCE: IEA (2021) Net Zero by 2050, A Roadmap for the global energy sector

CCUS volumes in 2050



Source: CCUS in the Energy Transition (Energy Transitions Commission, 2022).

Commentary and market analysis

- Most industries just emit CO_2 at present. Only a few % is actually captured – typically by using amines in a large-scale operation.

- The world needs 20x more capture by 2030 and 100x by 2050 (IEA & McKinsey).

- "25,000 global industrial CO_2 emitters across 11 industrial sectors could be decarbonized through CCUS" – McKinsey.

- Amines are ripe for displacement given all of their drawbacks.

- Most emitters fall in the 'small' scale with less than 1 Mtpa of emissions and 25,000 emitters (Rystad Energy estimate).

- Smaller, distributed units allow early revenue and to benefit from the 'experience curve' where we expect to have a 10% drop in capex costs every time capacity doubles. The deployment of solid-sorbent technologies is accelerating rapidly

Captivate offers an energy-efficient low cost capture process, which can be deployed at any scale.

The Opportunity For Low Cost Carbon Capture Is Upon Us

Electrification using renewables continues to grow rapidly

CO_2 emissions decline but continue to be emitted from hard to abate sources such as pre-combustion biogas upgrading

CO_2 is being captured at scale now

CO_2 captured volumes will rapidly rise globally

CO_2 capture costs will decrease significantly

CO_2 capture scope can be expanded to harder (more expensive) to capture opportunities

New technology such as that offered by Captivate Technology will transform the CO_2 market and rapidly reduce emissions

CO_2 as a commodity moves locally and globally as a gas or liquid from sources to sinks

The growth of CO_2 as a commodity expedites a reduction in fossil fuel production

The bioenergy market is set for rapid growth

Takeaways

- Carbon Capture technology is reducing capture costs, both OPEX and CAPEX
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