27 FEB 2025

ADVANCEMENTS IN CCS TECHNOLOGIES AND COSTS

GLOBAL CCS
INSTITUTE

AGENDA

Introductions

Technology Advancements and TRL table

Capture

Pipelines and Compression

Shipping

Q&A

GLOBAL CCS
INSTITUTE

THE GLOBAL CCS INSTITUTE

Accelerating the deployment of CCS for a net-zero emissions future.

WHO WE ARE

International CCS think tank with offices around the world.

Over 200 members across governments, global corporations, private companies, research bodies and NGOs, all committed to a net-zero future.

WHAT WE DO

Fact-based influential advocacy, catalytic thought leadership, authoritative knowledge sharing.

INTRODUCTIONS

David Kearns – Principal Carbon Capture Technologies

- Technical expert in CO_2 capture technologies, with experience across energy, industrial, and research sectors.
- Chemical Engineer with experience in consulting, engineering design, research, and plant operations.

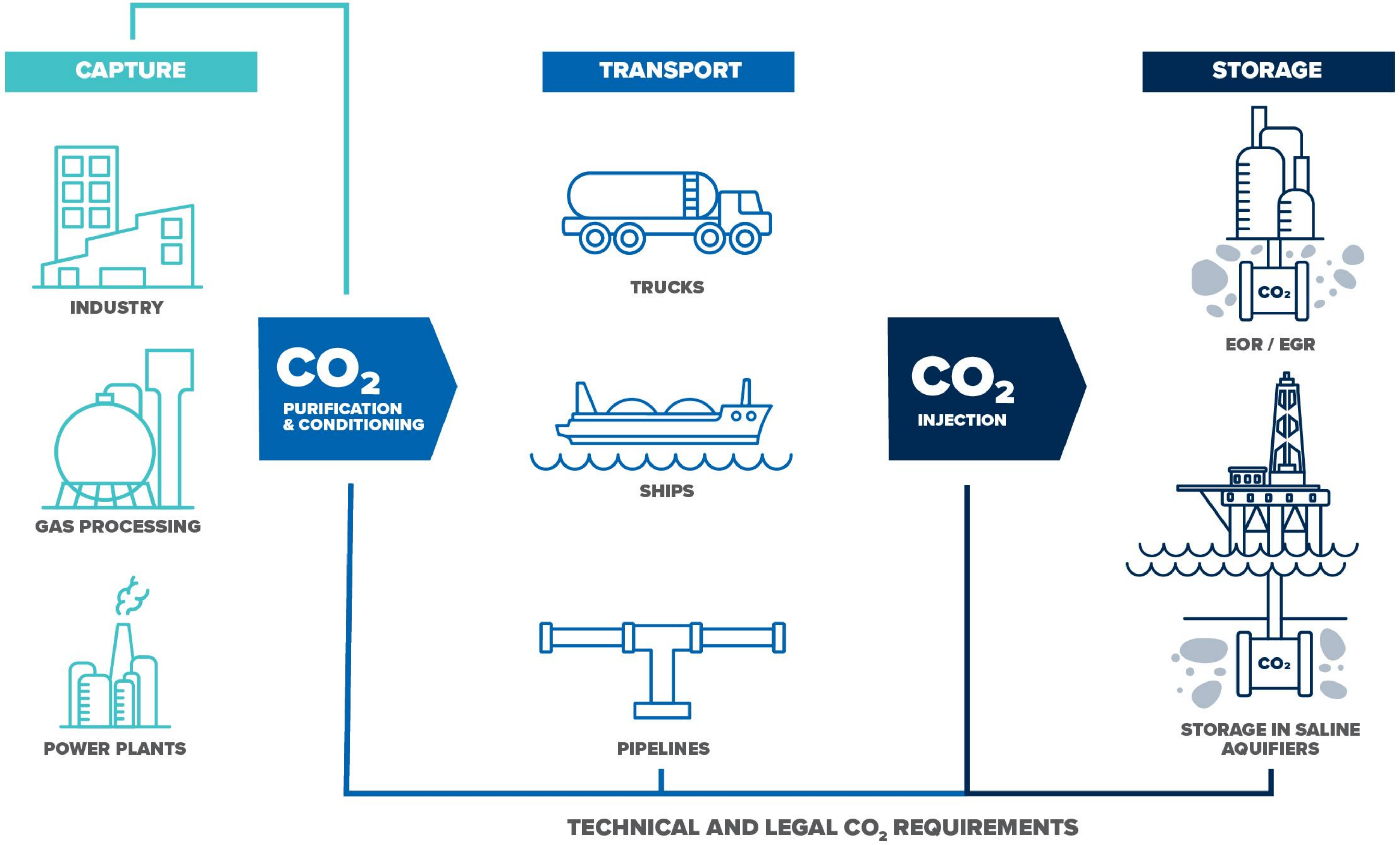
Shahrzad S. M. Shahi – Carbon Capture Technology Lead

- Expertise in process-related analytical modelling, concept development and feasibility studies.
- Chartered Chemical Engineer with a background in O&G and Renewable Hydrogen.

Hugh Barlow – Carbon Capture Technology Lead

- Coordinator of the Technology Compendium.
- Chemical Engineer with a background in ASU, CO_2 Capture, and LNG Liquefaction.

CCS AT A GLANCE



GLOBAL CCS INSTITUTE

TECHNOLOGY COMPENDIUM

The Technology Compendium is a platform for CCS technology providers and owners to share information about their technology to an audience of designers, developers, and advocates.

Next edition – Mid-year 2025; submissions opened in Feb 2025 and will close on 31 Mar 2025.

TECHNICAL REPORT

STATE OF THE ART:
CCS TECHNOLOGIES 2022

GLOBAL CCS
INSTITUTE

NOUMAN MIRZA, Ph.D
Consultant - CCS Technologies

DAVID KEARNS, Ph.D
Principal Consultant - CCS Technologies

TECHNICAL REPORT

STATE OF THE ART:
CCS TECHNOLOGIES 2023

GLOBAL CCS
INSTITUTE

HUGH BARLOW
Consultant CCS Technology

SHAHRZAD S M SHAHI
Consultant CCS Technology

MATTHEW LOUGHREY
Principal Consultant CCS Technology

TECHNICAL REPORT

STATE OF THE ART:
CCS TECHNOLOGIES 2024

GLOBAL CCS
INSTITUTE

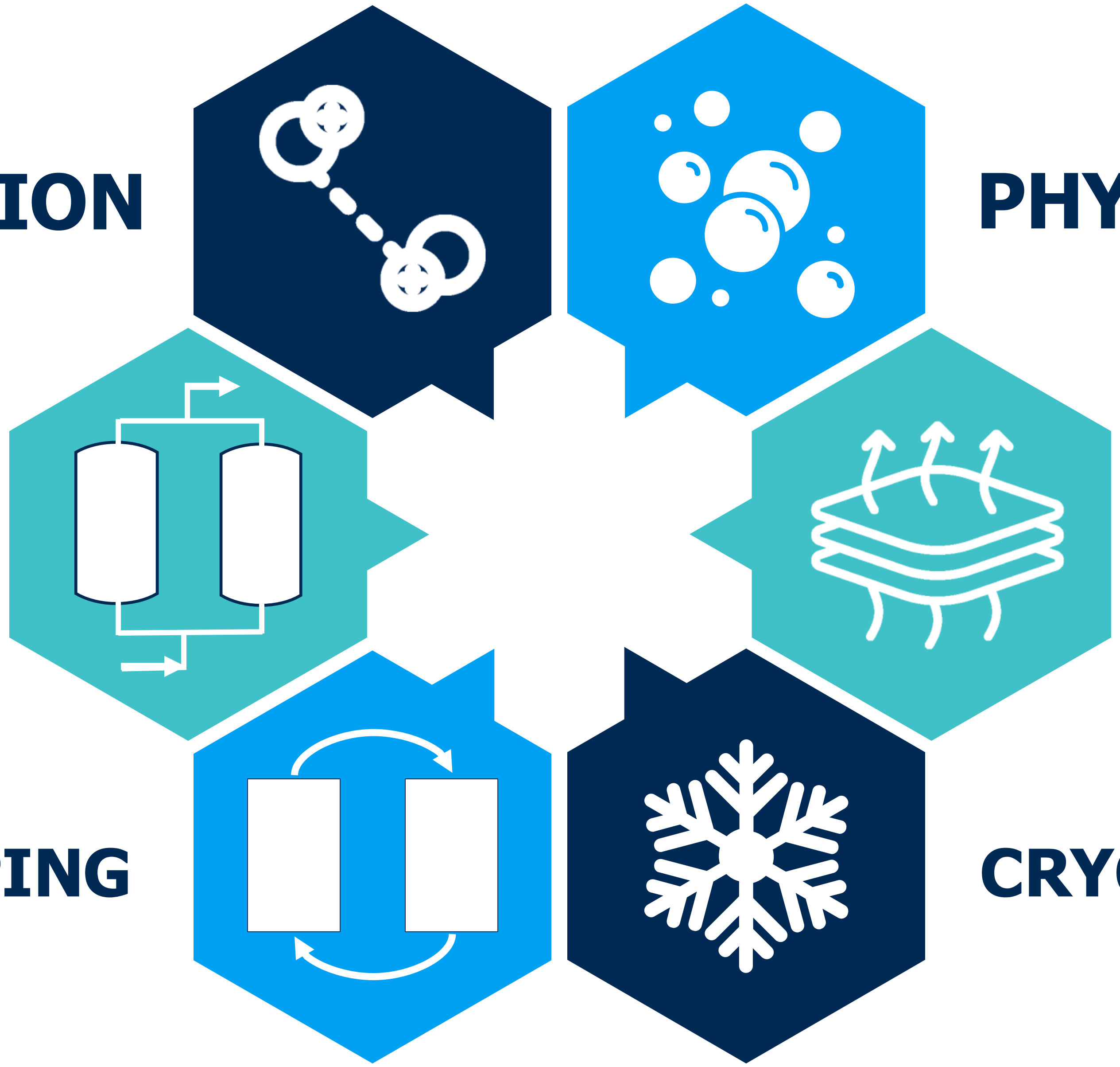
HUGH BARLOW
Carbon Capture Technology Lead

SHAHRZAD S M SHAHI
Carbon Capture Technology Lead

CO_2 CAPTURE TECHNOLOGIES AND COSTS

GLOBAL CCS
INSTITUTE

TECHNOLOGY PATHWAYS



CHEMICAL ABSORPTION

PHYSICAL ABSORPTION

ADSORPTION

MEMBRANES

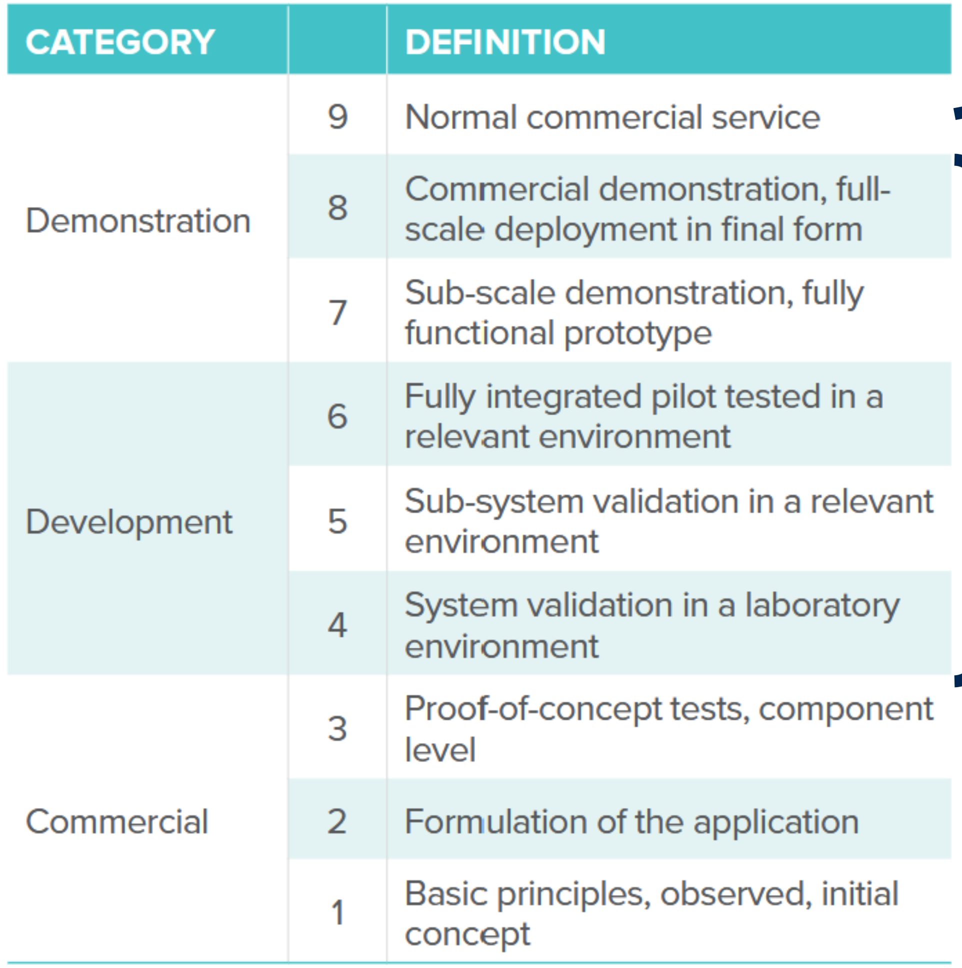
SOLID LOOPING

CRYOGENIC

Alongside inherent capture processes – Ethanol, Allam-Fetvedt Cycle, Novel Calciners

GLOBAL CCS INSTITUTE

TECHNOLOGY READINESS



CATEGORY		DEFINITION
Demonstration	9	Normal commercial service
	8	Commercial demonstration, full-scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Commercial	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles, observed, initial concept

Several technologies across the pathways at TRL 9 including **amine solvents, hot potassium carbonate, physical solvents, pressure swing absorbers, membranes,** and **cryogenic systems**.

Emerging technologies in various phases of deployment, from lab testing to commercial demonstration.

Aim: To improve on current capture systems.

This report includes our latest TRL assessments, factoring in updates from the 2024 Technology Compendium.

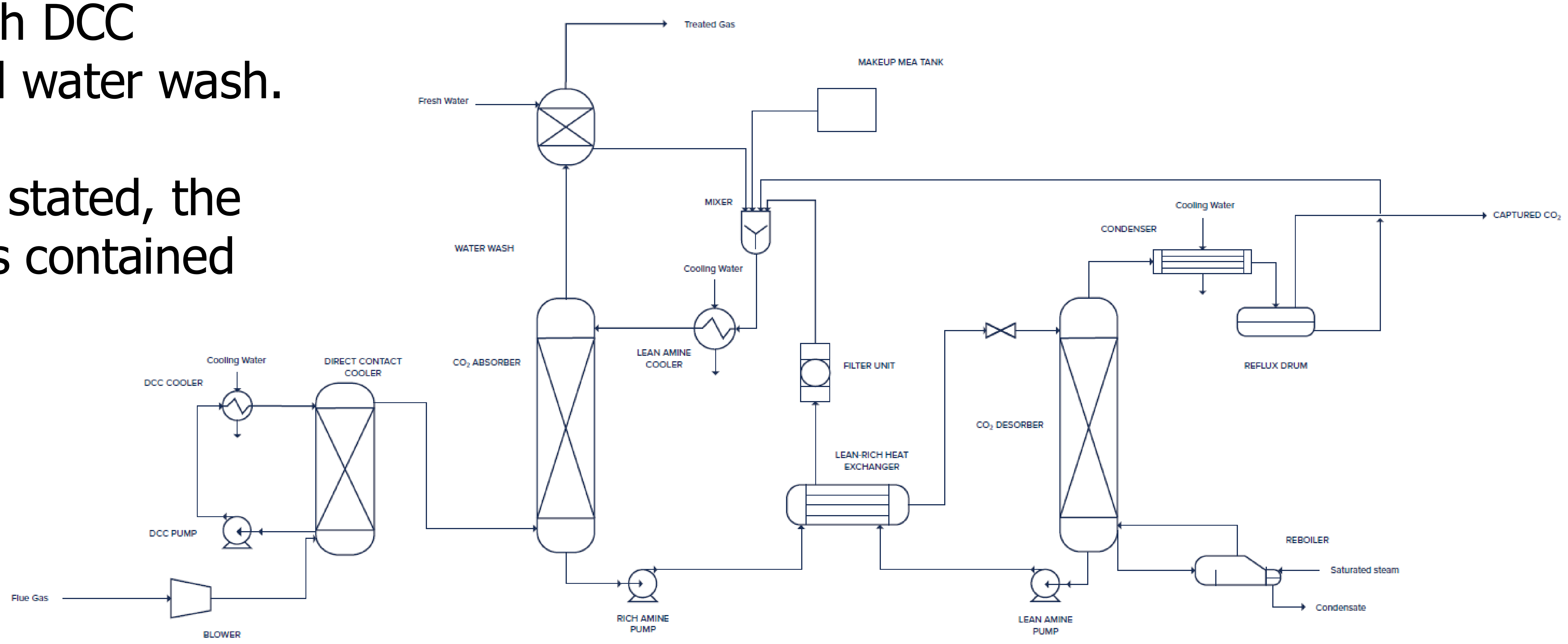
Table 1 - TRL Assessment of CO_2 capture technologies commercially available or under development. TRL 2020 Assessment from Technology Readiness and Costs Report (Global CCS Institute, 2021)

CATEGORY	TECHNOLOGY	2020 TRL ASSESSMENT	2024 TRL ASSESSMENT	DETAILS
	Amine based Solvents	9	9	Widely used in fertiliser, soda ash, natural gas processing plants, e.g. Sleipner, Snøhvit, and used in Boundary Dam
	Hot Potassium Carbonate (HPC)	9	9	Fertiliser plants, e.g. Enid Fertilizer
	Sterically hindered amine	6-9	6-9	Demonstration to commercial plants,

TYPICAL MEA CAPTURE PLANT

Standard absorber-desorber arrangement, with DCC pretreatment and water wash.

Unless otherwise stated, the modelled flue gas contained 13.7 mol% CO_2.



CAPTURE PLANT ASSUMPTIONS

Further Assumptions and Parameters	
Where not mentioned, capture fraction is 90% across the absorber.	Capacity Factor: 90% Operating Life: 30 years Discount Rate: 10%
Inlet flue gas is at a temperature of 55°C and a pressure of 5 kPag.	Cooling Water: \$0.0317/m^3 Electricity: \$77/MWh Low Pressure Steam: \$19.4/tonne
Minimum temperature approaches of 10°C are controlled on all heat exchangers.	Costing Calculations based on the United States NETL Quality Guidelines for Energy System Studies: Cost Estimations Methodology for NETL Assessments of Power Plant Performance

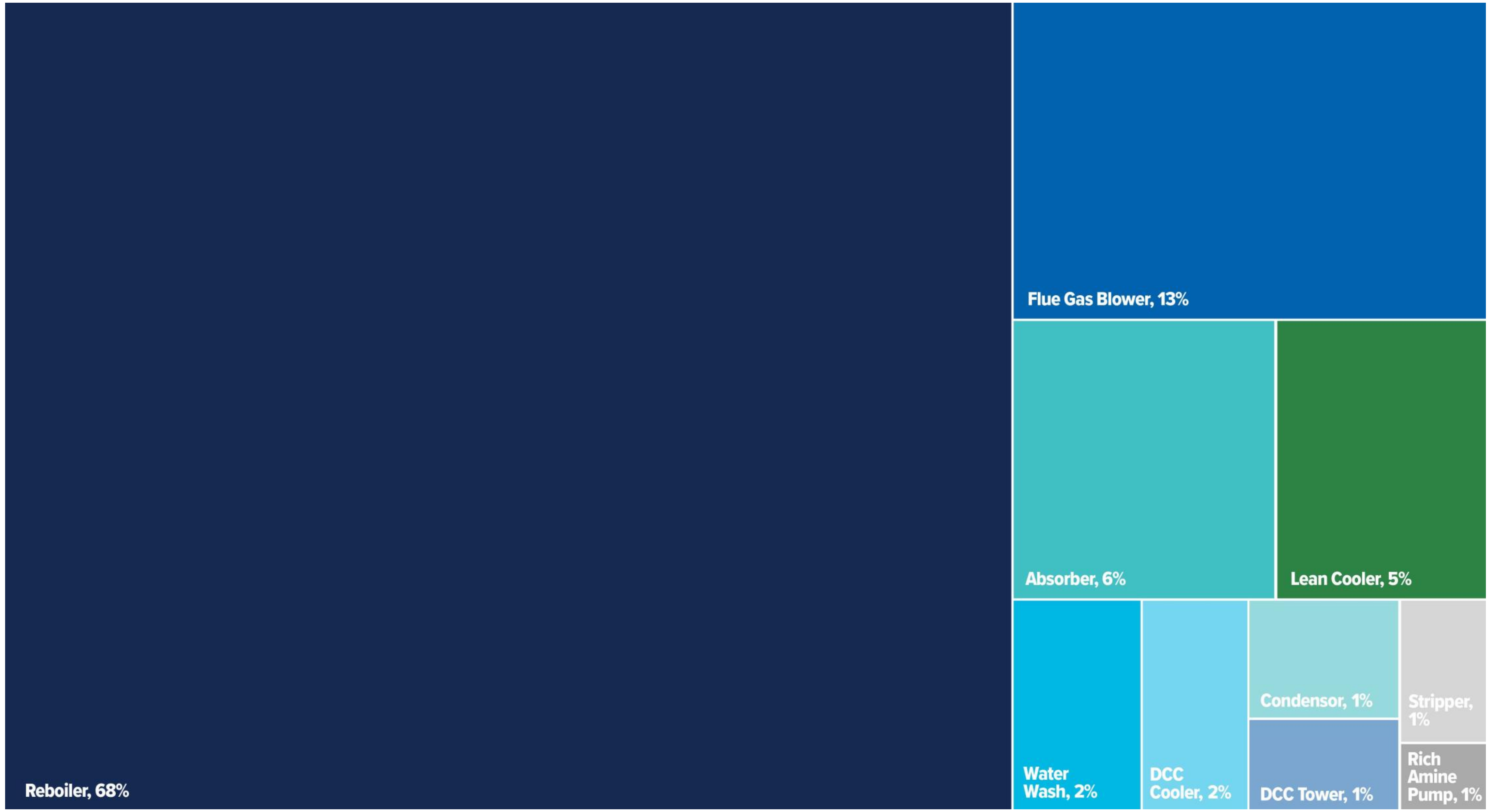
COST BREAKDOWN – MEA

The reboiler dominates in the modelled MEA capture system.

Other key operating cost units such as the blower and coolers also contribute significantly.

These costs are **estimates.**

- Highly sensitive to assumptions and design.
- Often a trade-off between Capex and Opex.



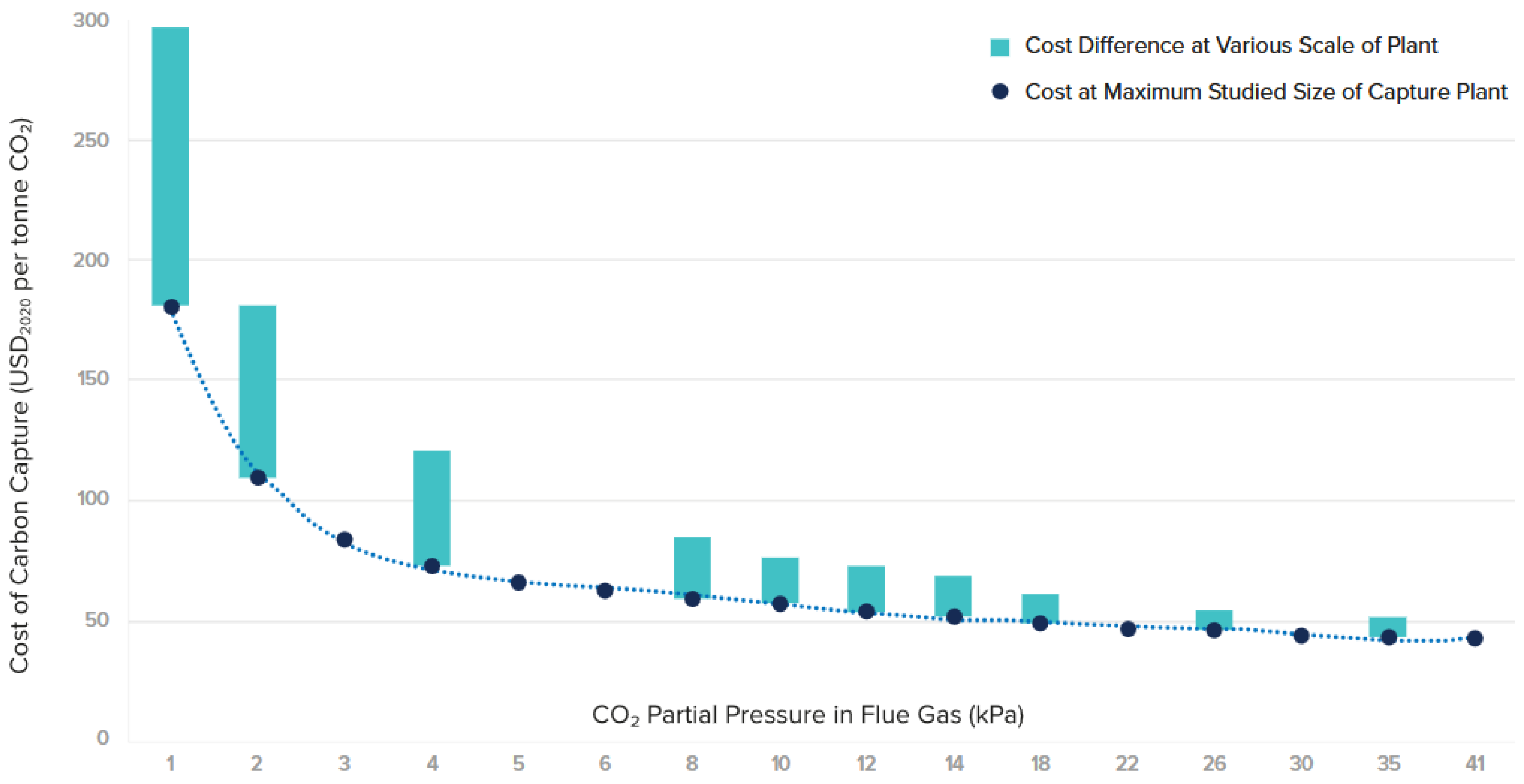
Total Annual Costs per unit, inclusive of both capital and variable operating costs. 90% Capture – Estimated $77.26 US/tonne CO_2

DRIVERS OF COST

- CO_2 Partial Pressure
- Technology Selection
- Energy Costs
- Location
- Capture Fraction
- Plant Scale
- Flue Gas Treatment
- Retrofit v New Build

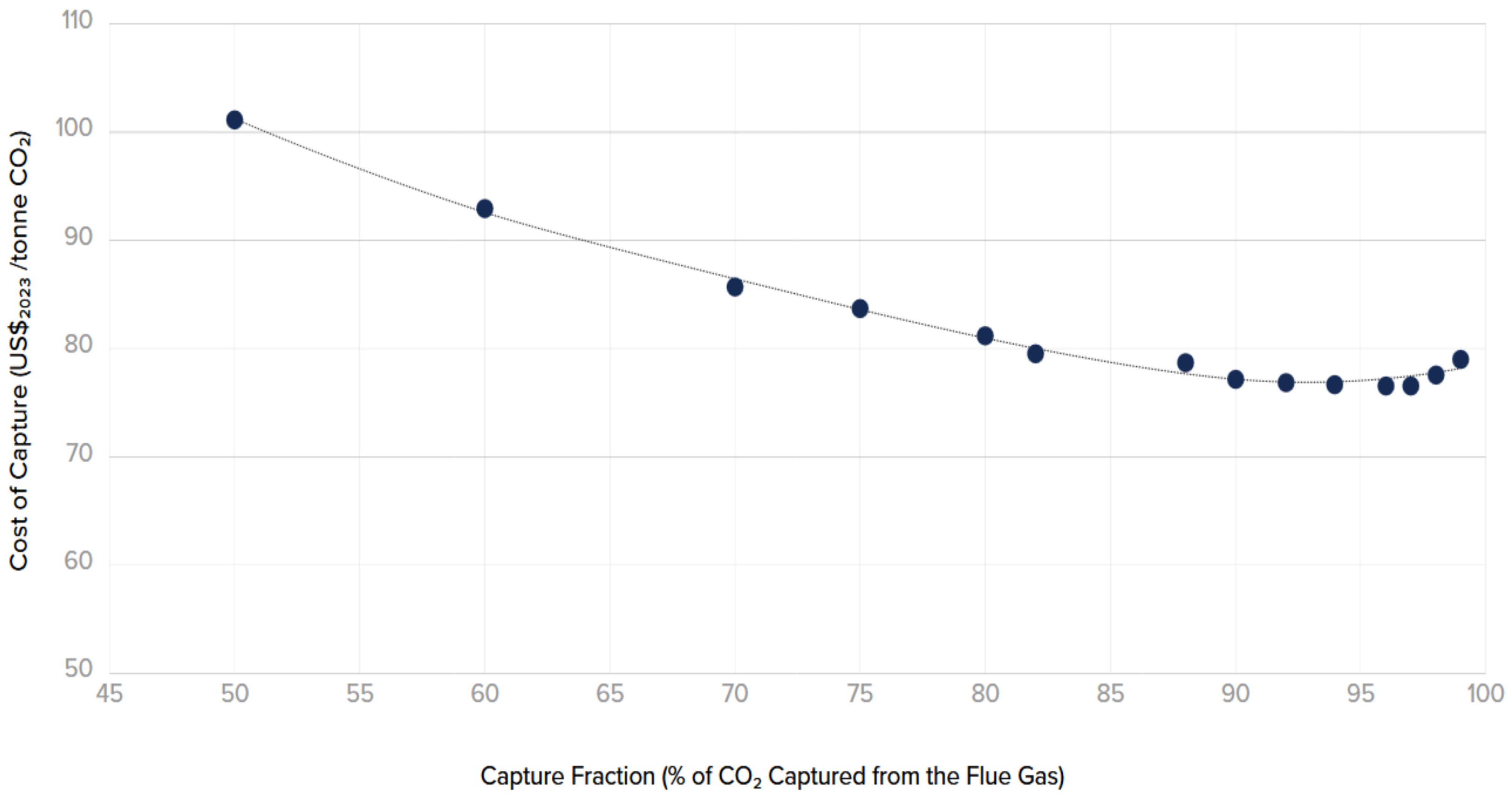
PARTIAL PRESSURE AND CAPTURE FRACTION

Partial pressure determines size of the process equipment, the energy requirements, and applicable capture technologies.



A capture fraction of 90% is a benchmark, not a technical limitation.

Capture fraction can rise to near 100% - Marginal costs tend to rise above 97%.

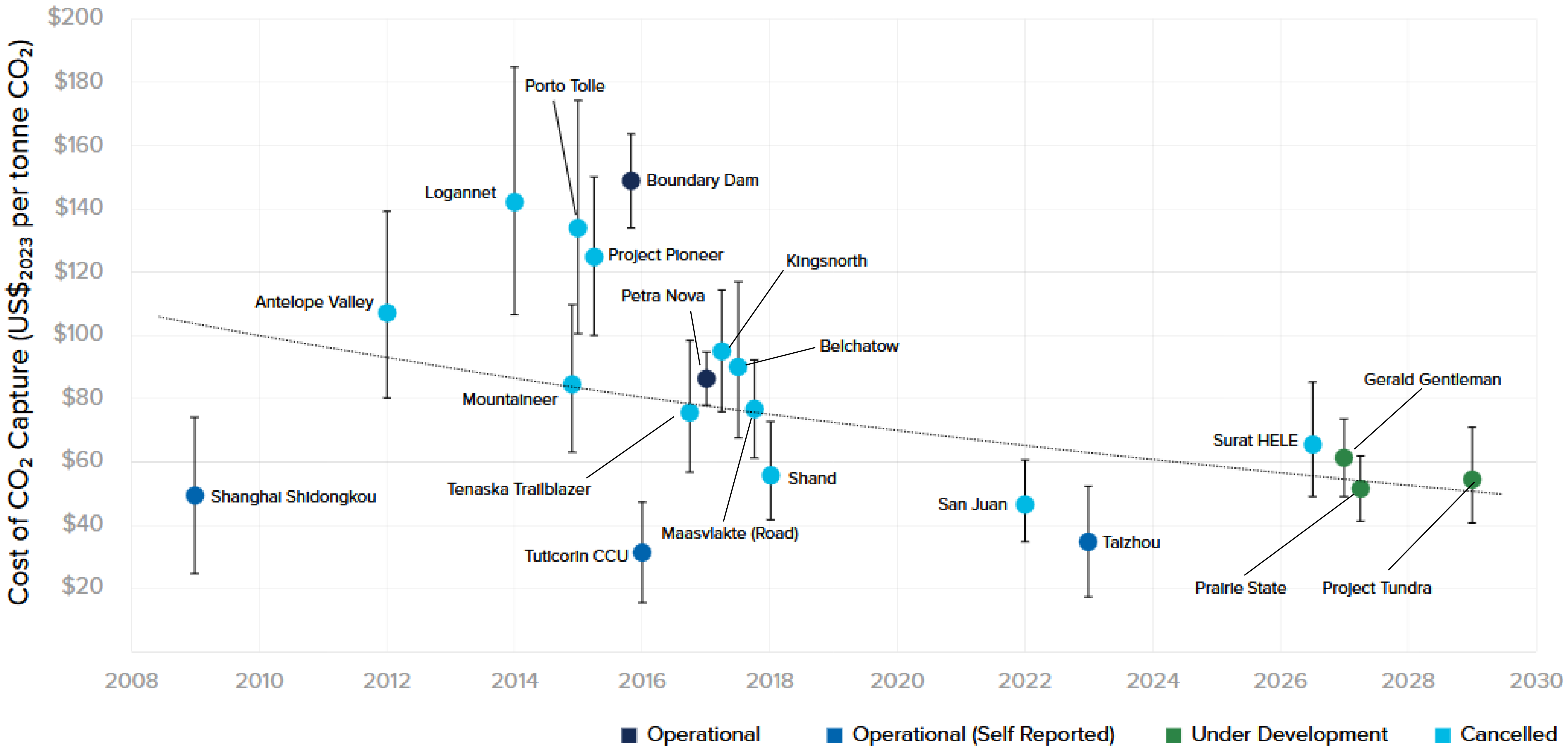


STRATEGIES FOR COST REDUCTION

- **Economies of Scale**
- **Technology Innovation**
  - *Novel Solvents*
  - *Novel Capture Pathways*
  - *Process Optimisation*
  - *Upstream Process Adjustments*
- **Modularisation**
- **Heat Integration**
- **Learning by Doing**
- **Subsidised Finance**

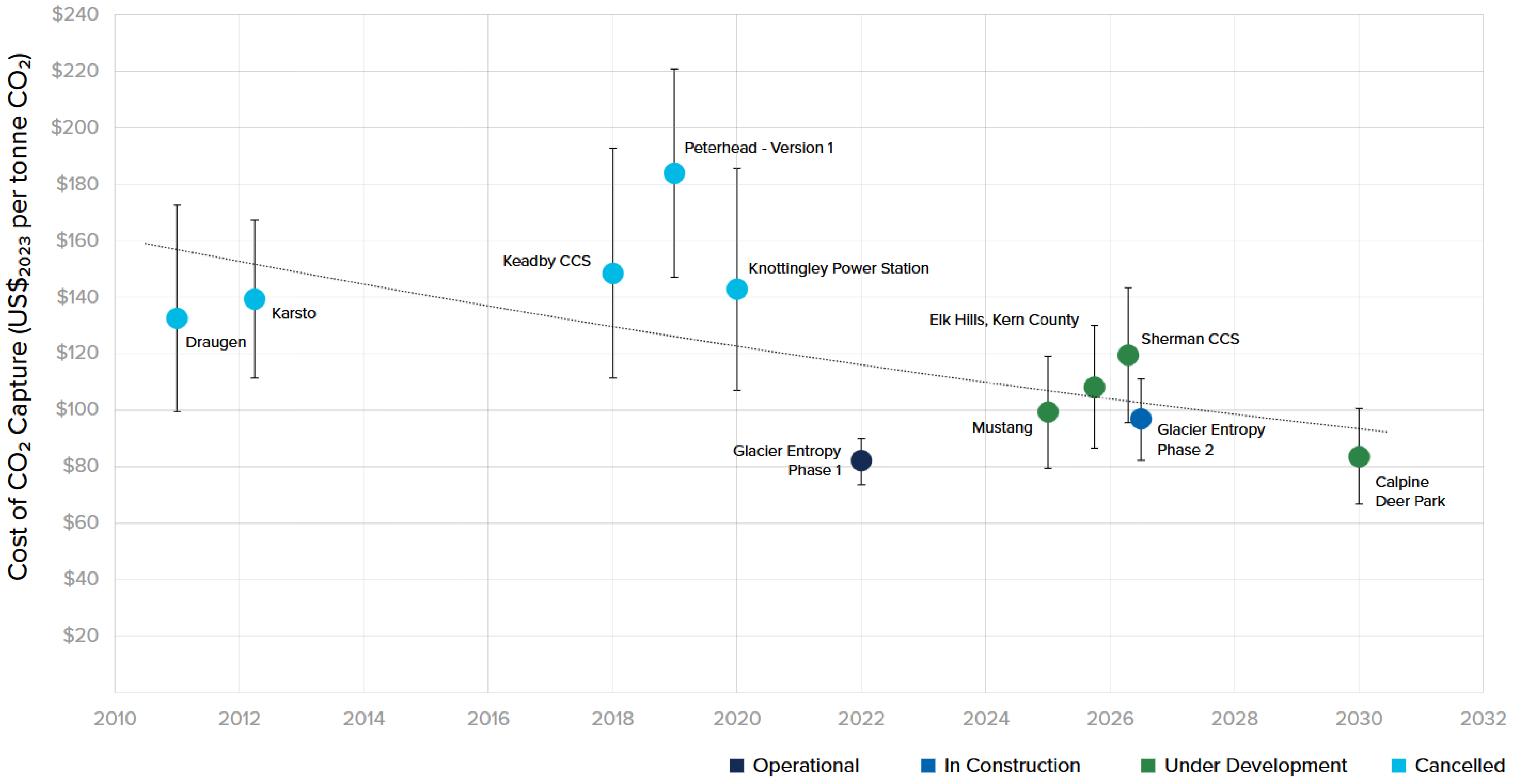
GLOBAL CCS INSTITUTE

TRENDS IN COSTS – COAL



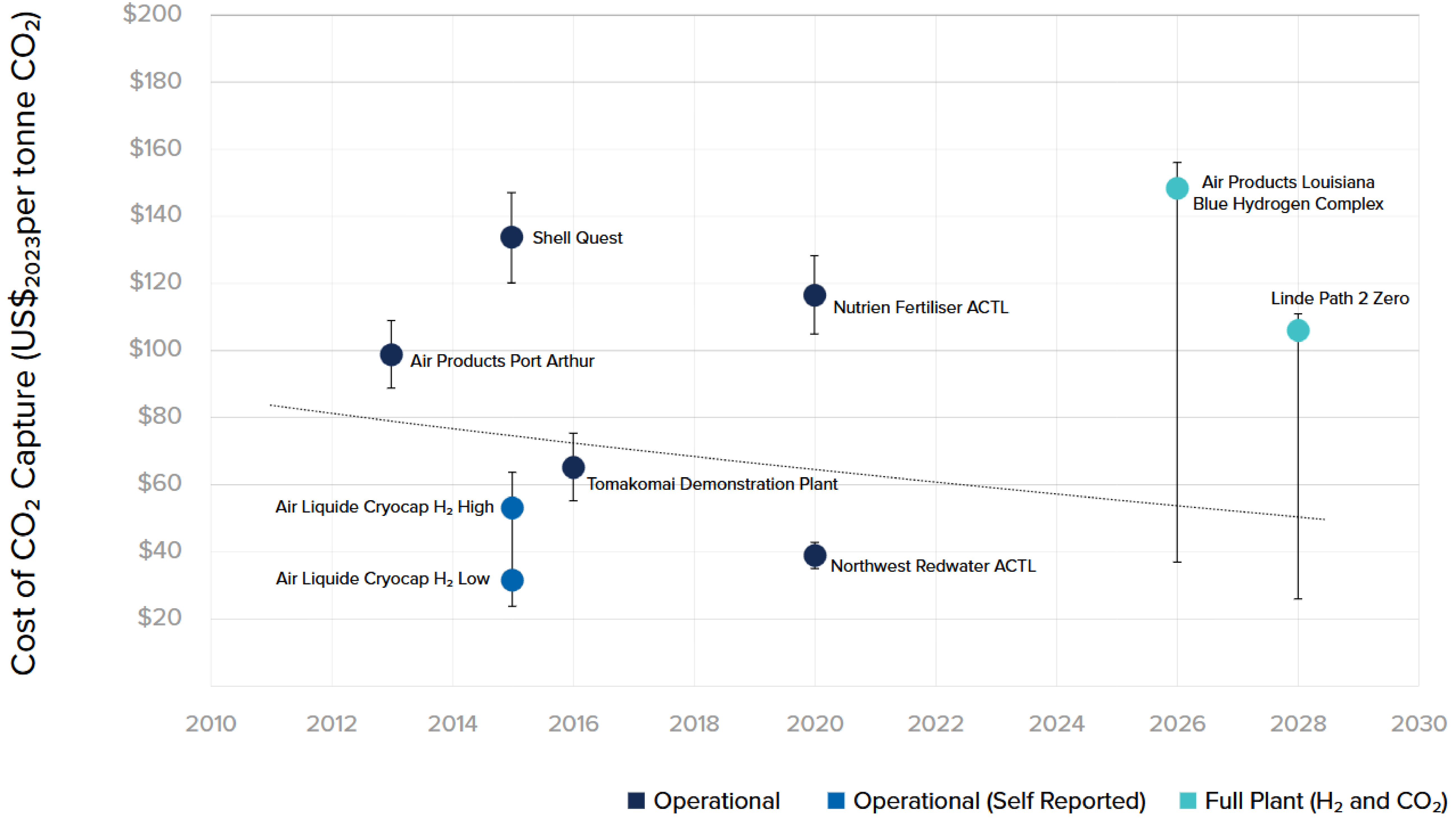
GLOBAL CCS INSTITUTE

TRENDS IN COSTS – NATURAL GAS



GLOBAL CCS INSTITUTE

TRENDS IN COSTS – HYDROGEN

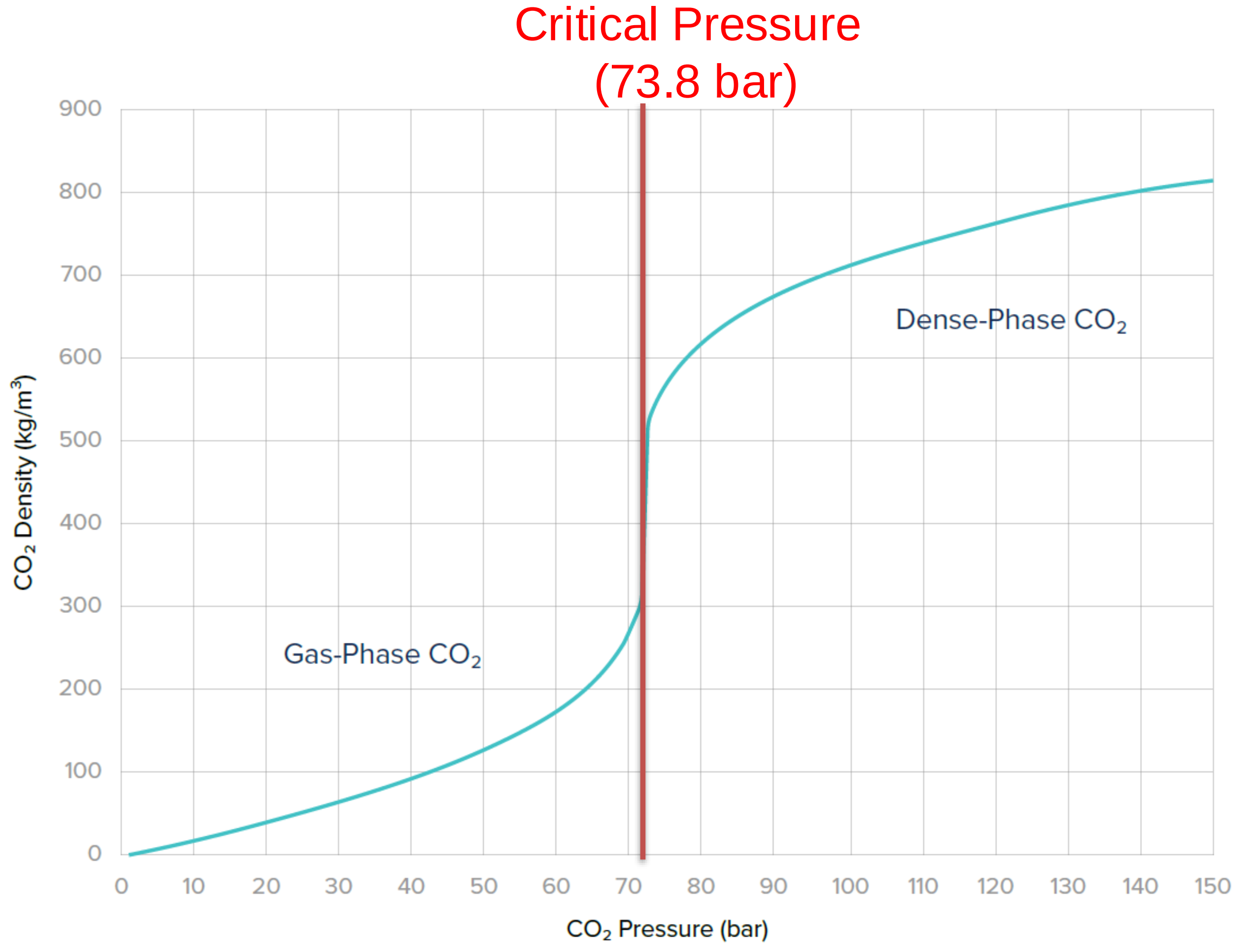


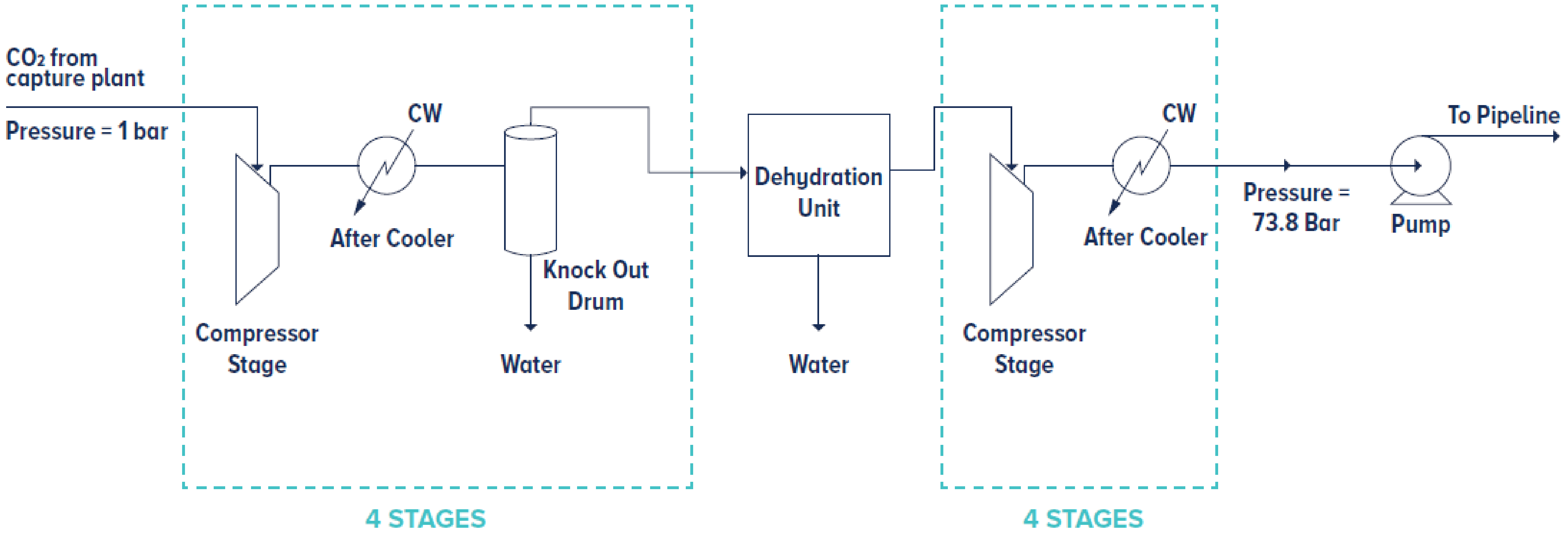
GLOBAL CCS INSTITUTE

CO_2 COMPRESSION AND PIPELINE COSTS

GLOBAL CCS INSTITUTE

COMPRESSION





CO_2 density jumps at the critical pressure, forming dense liquid (aka dense phase) CO_2.

Dense phase CO_2 required when CO_2 injected into geological storage formations, to maximise use of pore space.

As CO_2 typically captured at/near atmospheric pressure (~1 bar) we use compressors to boost the pressure.

Above the critical pressure, a pump can be used, as the dense phase CO_2 is mostly incompressible (little volume change).

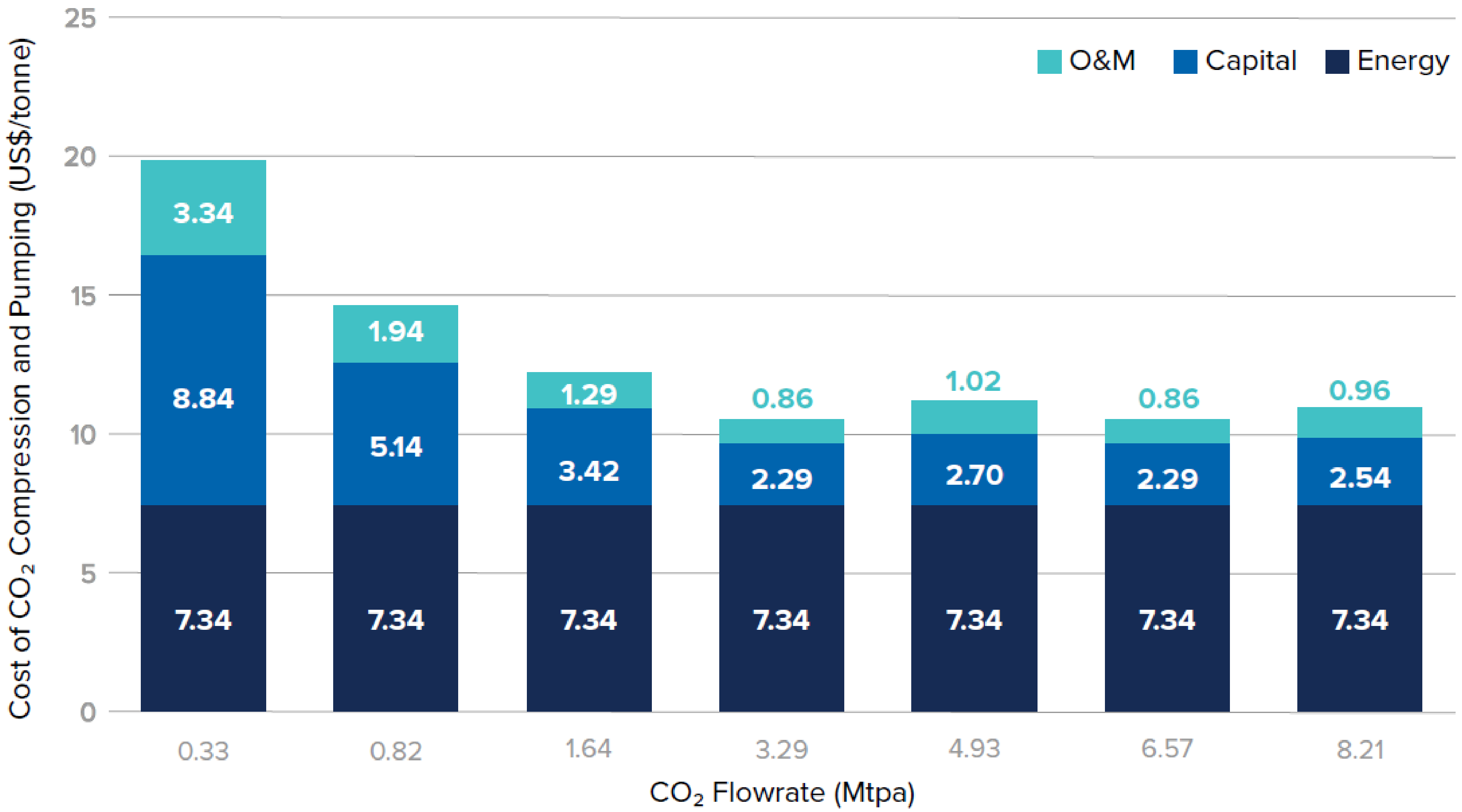
As a gas is compressed to higher pressures, it gets hotter. Hotter gas has a higher volume, which increases energy consumption.

CO_2 compressors are multi-stage (4-8 stages). This divides the compression into smaller parts, allowing the gas to be cooled after each stage, reducing energy consumption.

Water is removed in concert with compression, both through condensation and later with a dedicated dehydration step.

COMPRESSION

CO_2 compressor for Santos' Moomba CCS Project
Source: Baker Hughes



Above 3.3 Mtpa, a 2nd compressor train is required (compressors max out at 40 MW). Hence costs jump up again.

Energy consumption per tonne is constant always – no economies of scale.

Ideal scale is ~3 Mtpa of CO_2. Supported by CCS networks to build volumes.

GLOBAL CCS
INSTITUTE

CO_2 PIPELINES

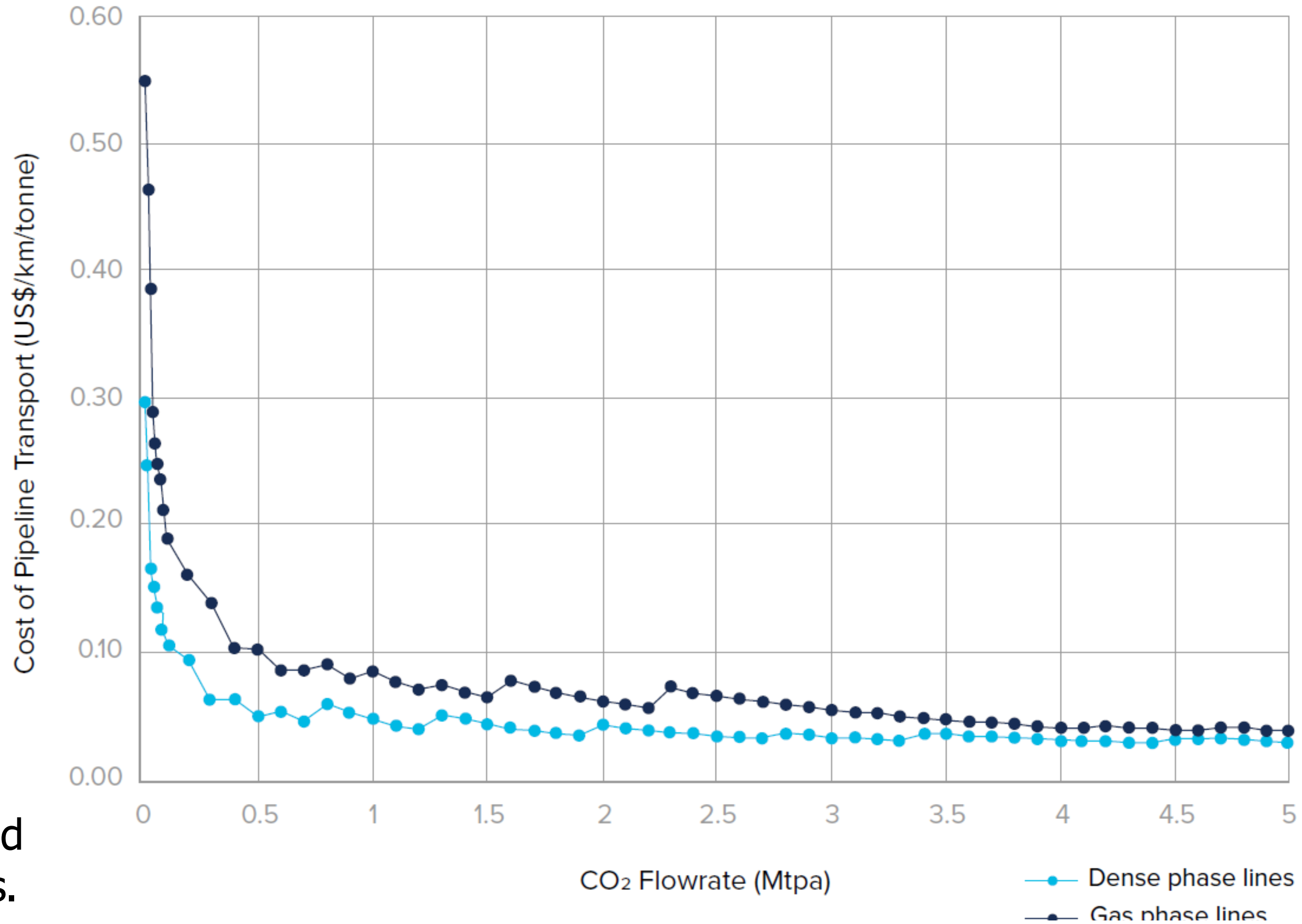
CO_2 pipeline being installed in Rotterdam, Netherlands
Source: Porthos Project

Most CO_2 pipelines are made of conventional steel. Similar to natural gas pipelines, though usually rated for higher pressures.

Dense phase CO_2 pipelines are lower cost (per tonne of CO_2) for all flows. Despite being more expensive per km than gas phase CO_2 pipelines (thicker walls to withstand higher pressures), they can transport much more CO_2 due to the higher CO_2 densities.

Gas-phase CO_2 pipelines have their place for transporting CO_2 from capture plant to compression station.

Economies of scale run out at around 1-1.5 Mtpa. Networks facilitate these volumes.



Cost of CO_2 pipelines for gas-phase (< 73.8 bar) and dense-phase transport.

Cost given in US$/km/tonne – the cost depends on CO_2 tonnage but also on length.

Above are for onshore pipelines – offshore will cost more.

CO_2 LIQUEFACTION AND SHIPPING COSTS

OVERVIEW OF CO_2 LIQUEFACTION AND SHIPPING

CO_2 Liquefaction and Shipping: A Critical Step in CCS Value Chains

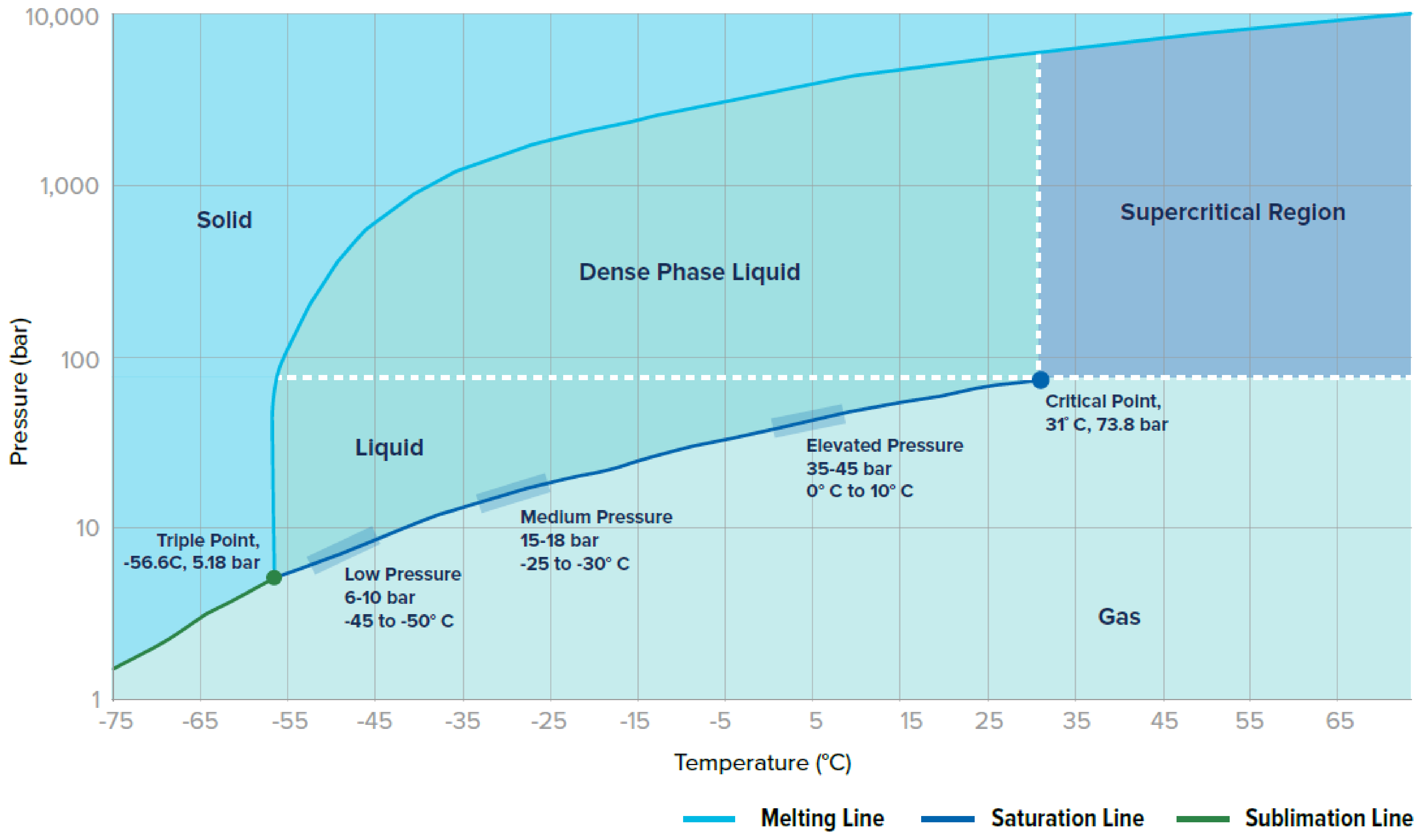
Why liquefaction?

- ✓ Higher Density & Lower Costs
- ✓ Long-Distance Viability
- ✓ Moderate Pressure Advantage

CO_2 Shipping costs

- ✓ Shipping Pressure: Low Pressure (LP), Medium Pressure (MP), and High Pressure (HP)
- ✓ Ship Size
- ✓ Energy Consumption

CO_2 pressure-temperature phase diagram

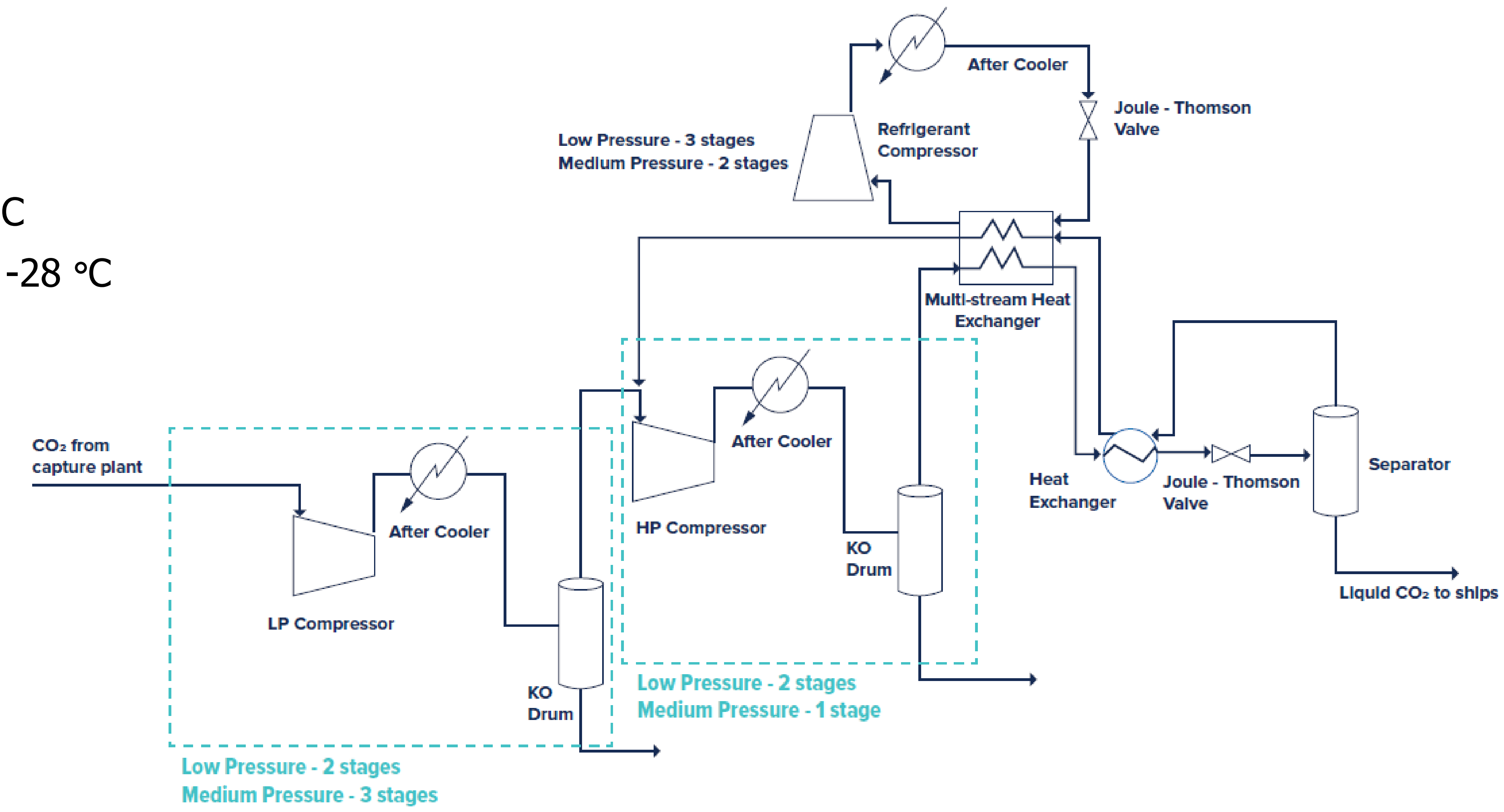


GLOBAL CCS INSTITUTE

LIQUEFACTION PROCESS OVERVIEW

Major Cost Drivers:	**Values in this study:**
• Initial CO_2 pressure →	1 bar
• Transport pressure →	Low Pressure: 6 bar and -53 °C Medium Pressure: 15 bar and -28 °C
• Flow rate →	0.5, 1, 1.5, and 2 Mtpa
• Stream impurities →	Out of Scope

Pre-cooled Linde Hampson System



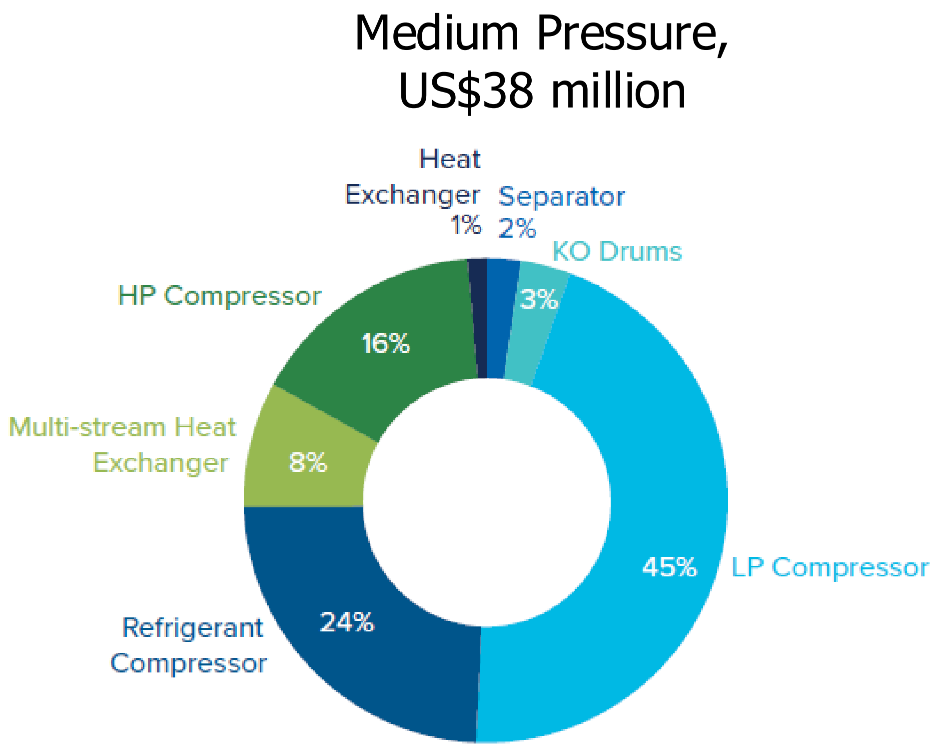
Process Flow:

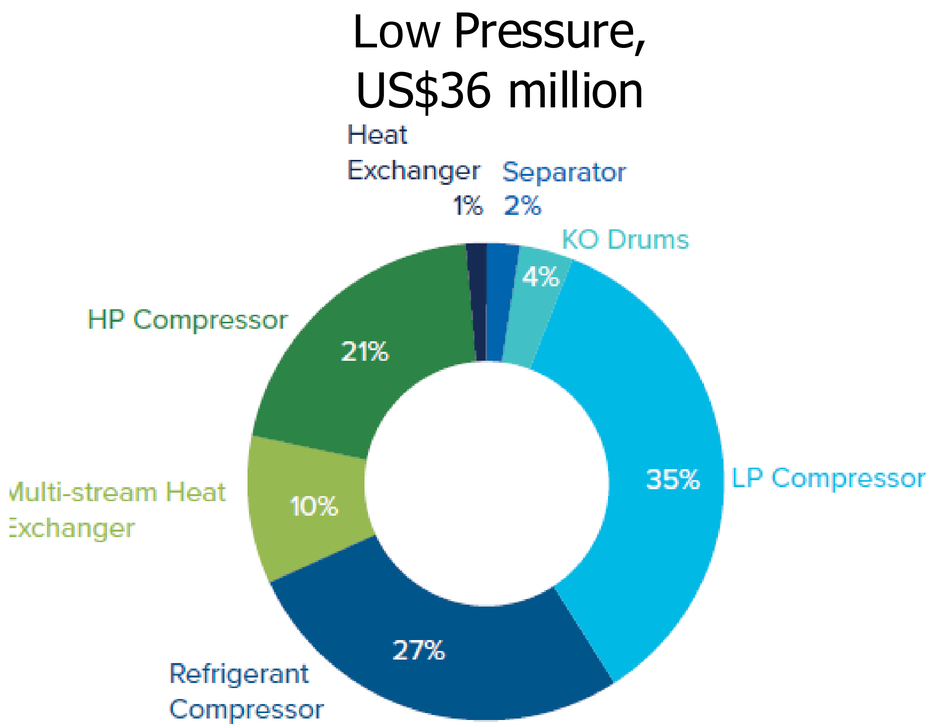
- Multi-stage Compression: increases CO_2 pressure incrementally.
- Heat Exchangers: reduce CO_2 temperature to achieve liquefaction.
- Knockout (KO) Drums: ensure gas purity by removing impurities and liquids.
- Refrigerants: Using advanced refrigerants, such as ammonia, improves cooling efficiency and reduces energy consumption.

COST ANALYSIS OF CO_2 LIQUEFACTION SYSTEMS (1/2)

Capital Costs:

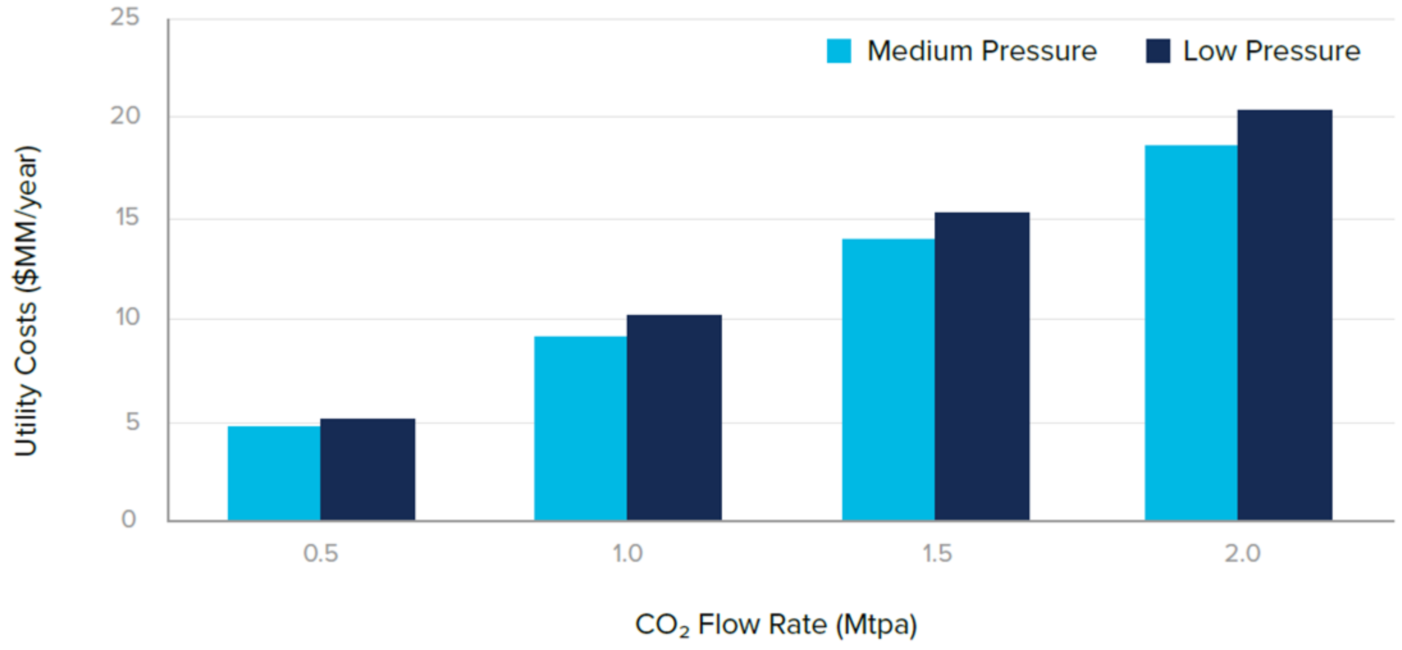
Liquefaction Annualised Capital Cost Breakdown by Equipment at 1 Mtpa for medium-pressure and low-pressure liquefaction.


Medium Pressure,
US$38 million


Low Pressure,
US$36 million

Operating Costs:

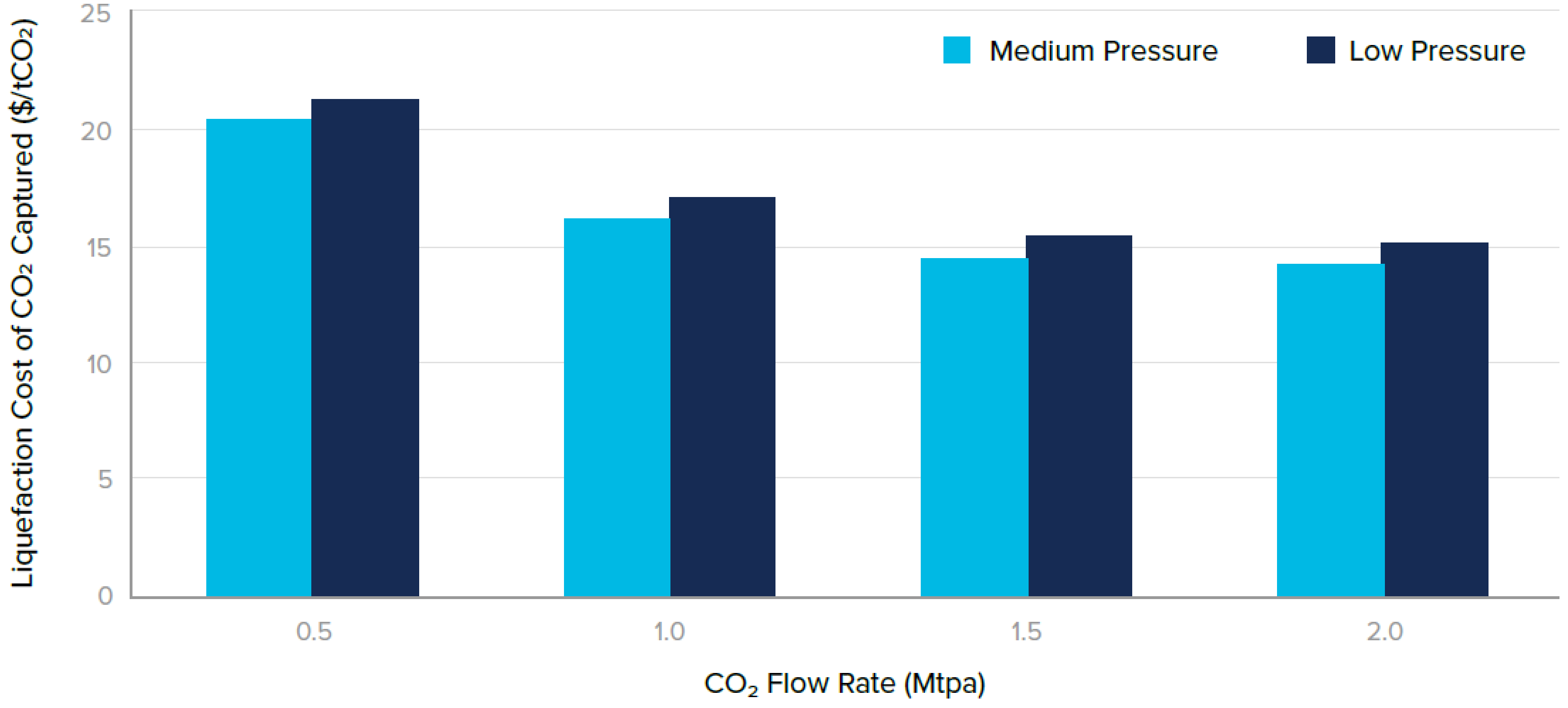
- Utility costs are the major contributor (electricity and cooling water).
- Medium-pressure systems offer ~10% energy savings compared to low-pressure systems.



COST ANALYSIS OF CO2 LIQUEFACTION SYSTEMS (2/2)

Economies of Scale

- Costs per tonne of CO_2 decrease as flow rates increase from 0.5 Mtpa to 2 Mtpa.
- Higher flow rates improve cost efficiency due to better utilisation of infrastructure.



CO_2 SHIPPING COSTS IMPLICATION

Ship Size:

- ***Flow Rate*** (0.50 Mtpa to 2 Mtpa)
- ***Distance*** (500 km, 1,000 km, 1,500 km, and 2,000 km)
- ***Round-trip Voyage Duration***
- ***Storage and Liquefaction Constraints***

Ships modelled in the medium-pressure Scenario 1 case (limited to 10,000 tonnes)

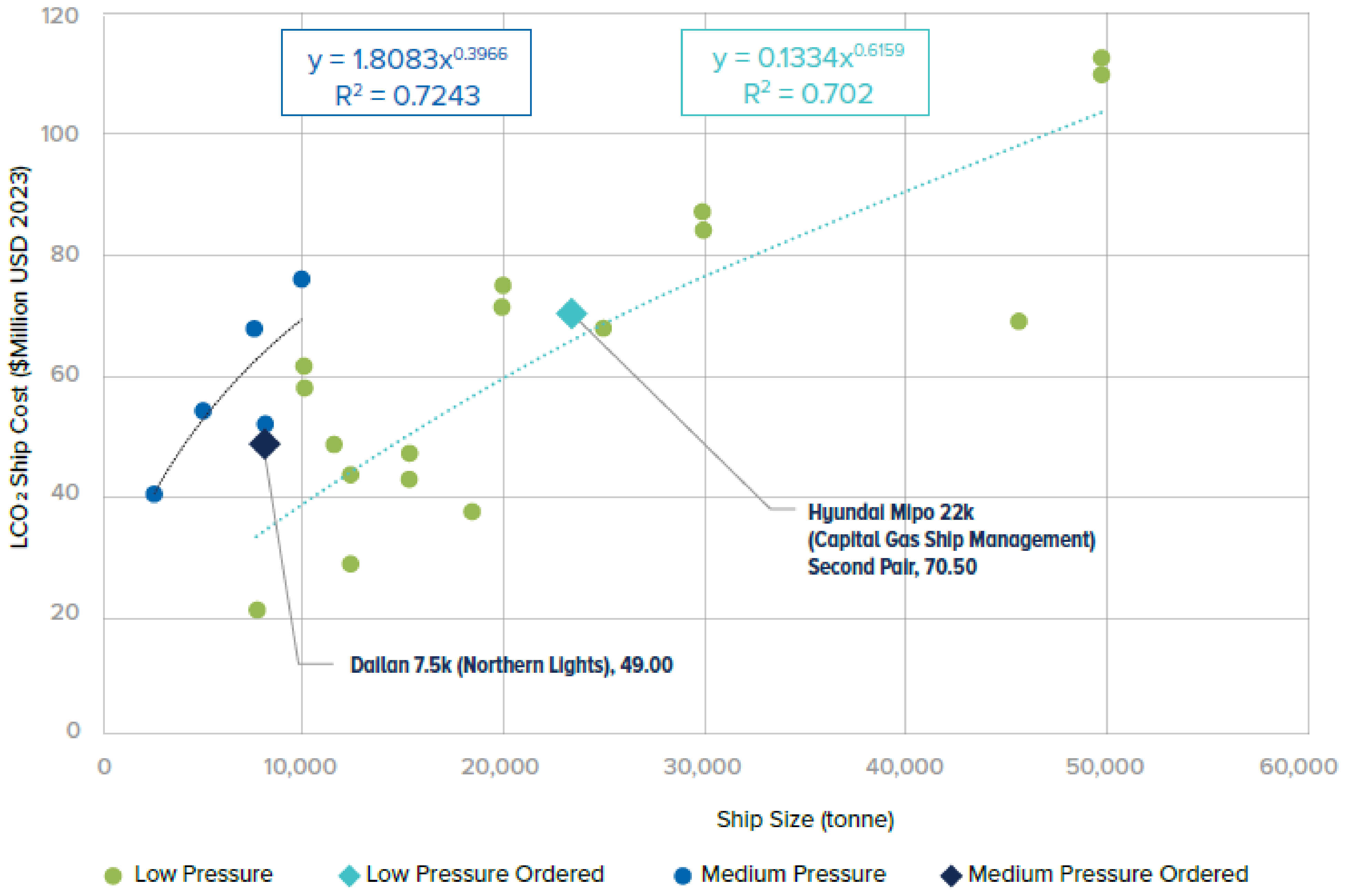
Distance (km)	Flow Rate			
	0.5 Mtpa	1 Mtpa	1.5 Mtpa	2 Mtpa
500	1×6,000	1×10,000	2×8,000	2×10,000
1,000	1×8,000	2×8,000	3×8,000	3×10,000
1,500	1×10,000	2×10,000	3×10,000	4×10,000
2,000	2×6,000	3×8,000	4×10,000	5×10,000

Ships modelled in the medium-pressure Scenario 2 and low-pressure Scenario 3 (both limited to 50,000 tonnes)

Distance (km)	Flow Rate			
	0.5 Mtpa	1 Mtpa	1.5 Mtpa	2 Mtpa
500	1×6,000	1×10,000	1×15,000	1×20,000
1,000	1×8,000	1×15,000	1×25,000	1×30,000
1,500	1×10,000	1×20,000	1×30,000	1×40,000
2,000	1×15,000	1×25,000	1×40,000	1×50,000

- ***Scenario 1*** –The ship sizes for medium pressure do not exceed 10,000 tonnes for all flow rates and distances.
- ***Scenario 2*** – The ship sizes for medium-pressure range from 2,000 to 50,000 tonnes, depending on flow rate, distances, storage and liquefaction limitation, and round-trip voyage duration.
- ***Scenario 3*** – Similar to Scenario 2, but applies low-pressure conditions.

SHIP COSTS



Cost estimations from studies for liquified CO_2 vessels. Data Points sourced from a Global CCS Institute database, built upon the initial data sourced from an Element Energy study (2018)

ROLE OF SHIP SIZE IN COST EFFICIENCY

- **Medium-Pressure (≤10,000 tonnes) – Top Chart**
  - Small ship size → more trips → higher costs
  - Costs rise sharply for long distances (2,000 km)
  - Not viable for large-scale transport
- **Medium-Pressure (≤50,000 tonnes) – Middle Chart**
  - Larger ships reduce per-tonne costs
  - Cost increase is more gradual
  - Improved efficiency over longer distances
- **Low-Pressure (≤50,000 tonnes) – Bottom Chart**
  - Lowest transport costs across all distances
  - More stable cost trends, even at lower flow rates
  - Most cost-effective for long-haul, high-volume CO₂ transport

OVERALL SHIPPING COSTS

- “Intermediate Storage” costs increase with distance, becoming a major factor at longer transport ranges.
- “Ship” costs depend on size and pressure level, with low-pressure, larger ships offering the best cost efficiency.
- “Liquefaction” and “conditioning” costs vary by pressure scenario, with low-pressure requiring more energy input.
- “Loading and Unloading” has a negligible impact on overall costs.

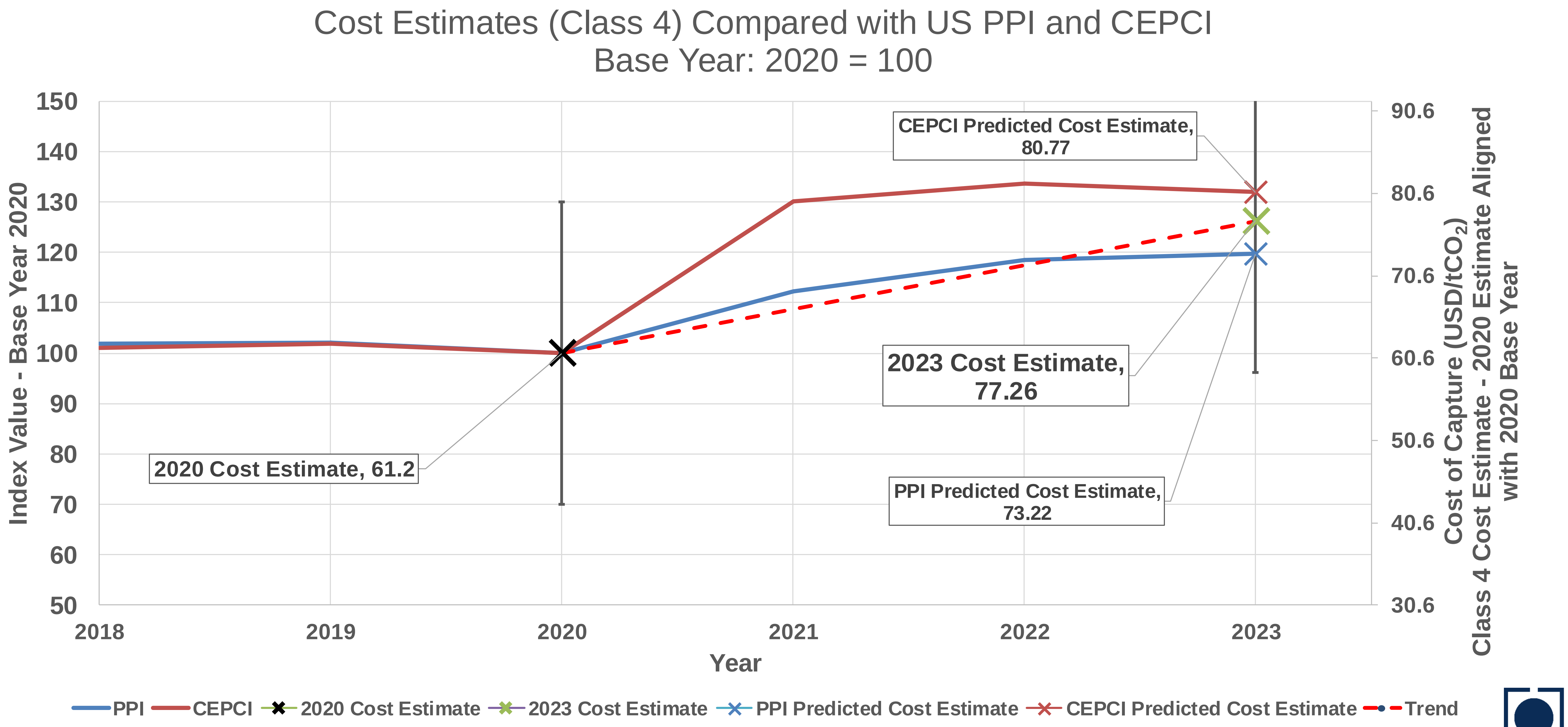
GLOBAL CCS INSTITUTE

THANK YOU

QUESTIONS?

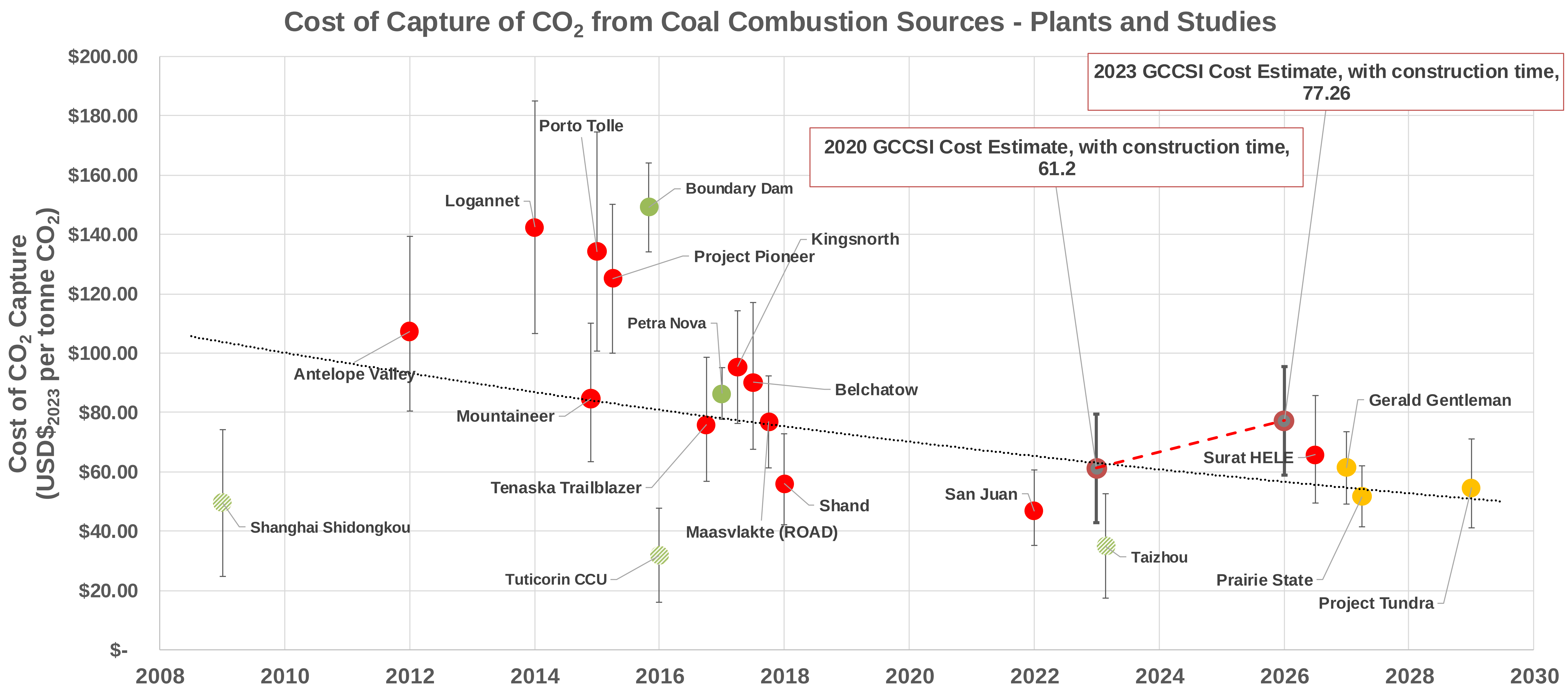
GLOBAL CCS INSTITUTE

INFLATION AND OUR ESTIMATES



GLOBAL CCS INSTITUTE

ESTIMATES AGAINST TRENDS



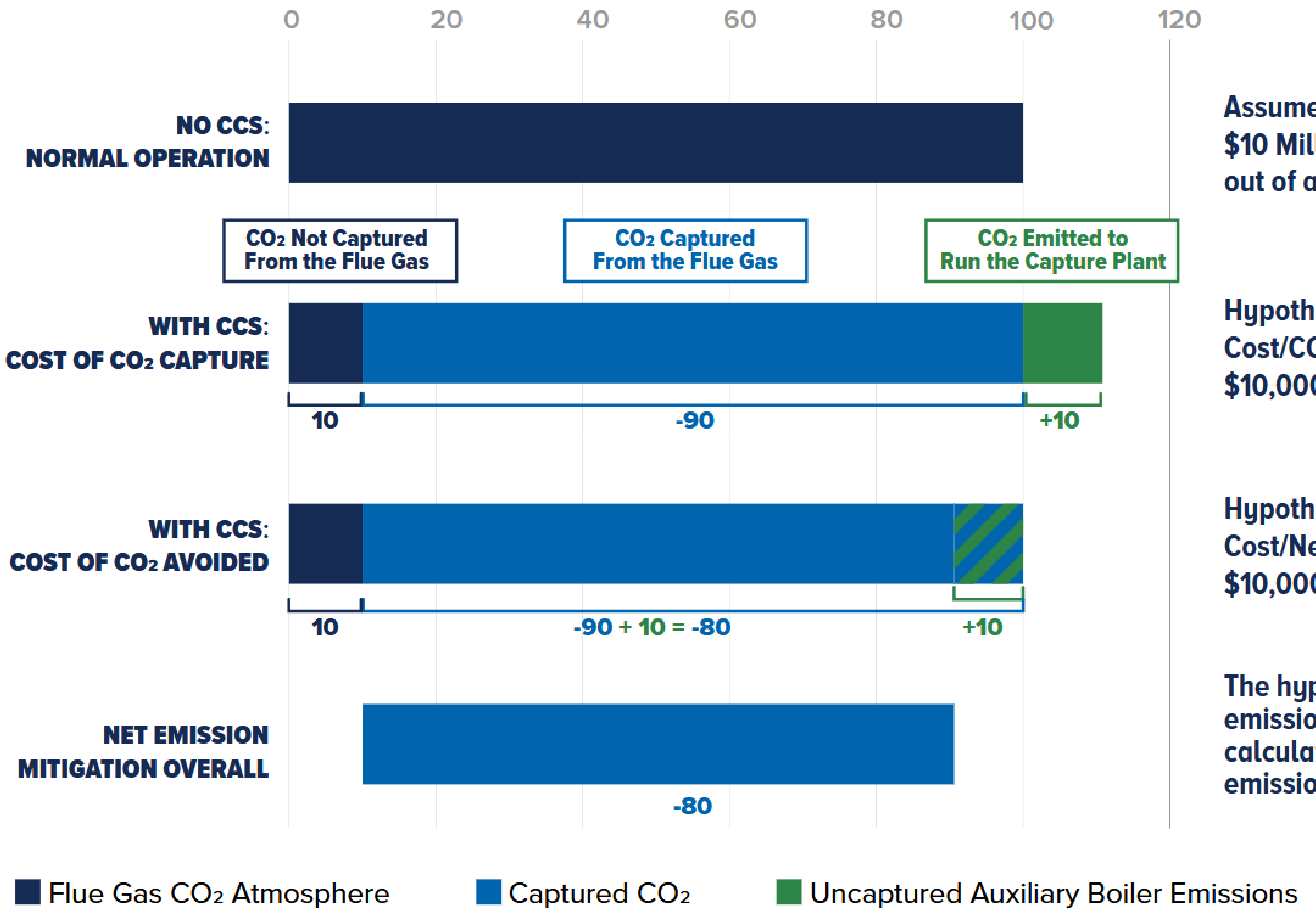
Cost of Capture of CO_2 from Coal Combustion Sources - Plants and Studies

2023 GCCSI Cost Estimate, with construction time, 77.26

2020 GCCSI Cost Estimate, with construction time, 61.2

GLOBAL CCS INSTITUTE

COST OF CAPTURE VS AVOIDED



Assume a hypothetical plant costs \$10 Million to capture 90,000 tpa of CO$_2$ out of a 100,000 tpa CO$_2$ flue gas stream

Hypothetical costs of CO$_2$ Captured
Cost/CO$_2$ Captured from Flue Gas =
\$10,000,000/90,000 = \$111.11/tCO$_2$

Hypothetical costs of CO$_2$ Avoided
Cost/Net Impact =
\$10,000,000/80,000 = \$125/tCO$_2$

The hypothetical Net Impact to emissions is the same under both calculation methods. A reduction in emissions by 80,000 tpa

GLOBAL CCS INSTITUTE