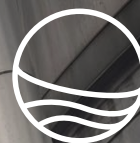


A photograph of a complex industrial facility, likely a power plant or refinery, featuring a dense network of large, metallic pipes and valves. The pipes are arranged in a vertical and horizontal grid, with some sections wrapped in insulation. The background shows a clear blue sky. The image is partially covered by a green gradient at the bottom.

Technology Collaboration Programme by IEA



IEAGHG

Modular Approaches to CO₂ Capture Technologies

Technical Report 2026-03
March 2026
IEAGHG

About the IEAGHG

Leading the way to net zero with advanced CCS research. IEAGHG are at the forefront of cutting-edge carbon, capture and storage (CCS) research. We advance technology that reduces carbon emissions and accelerates the deployment of CCS projects by improving processes, reducing costs, and overcoming barriers. Our authoritative research is peer-reviewed and widely used by governments and industry worldwide. As CCS technology specialists, we regularly input to organisations such as the IPCC and UNFCCC, contributing to the global net-zero transition.

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The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate is twofold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy. The IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics.

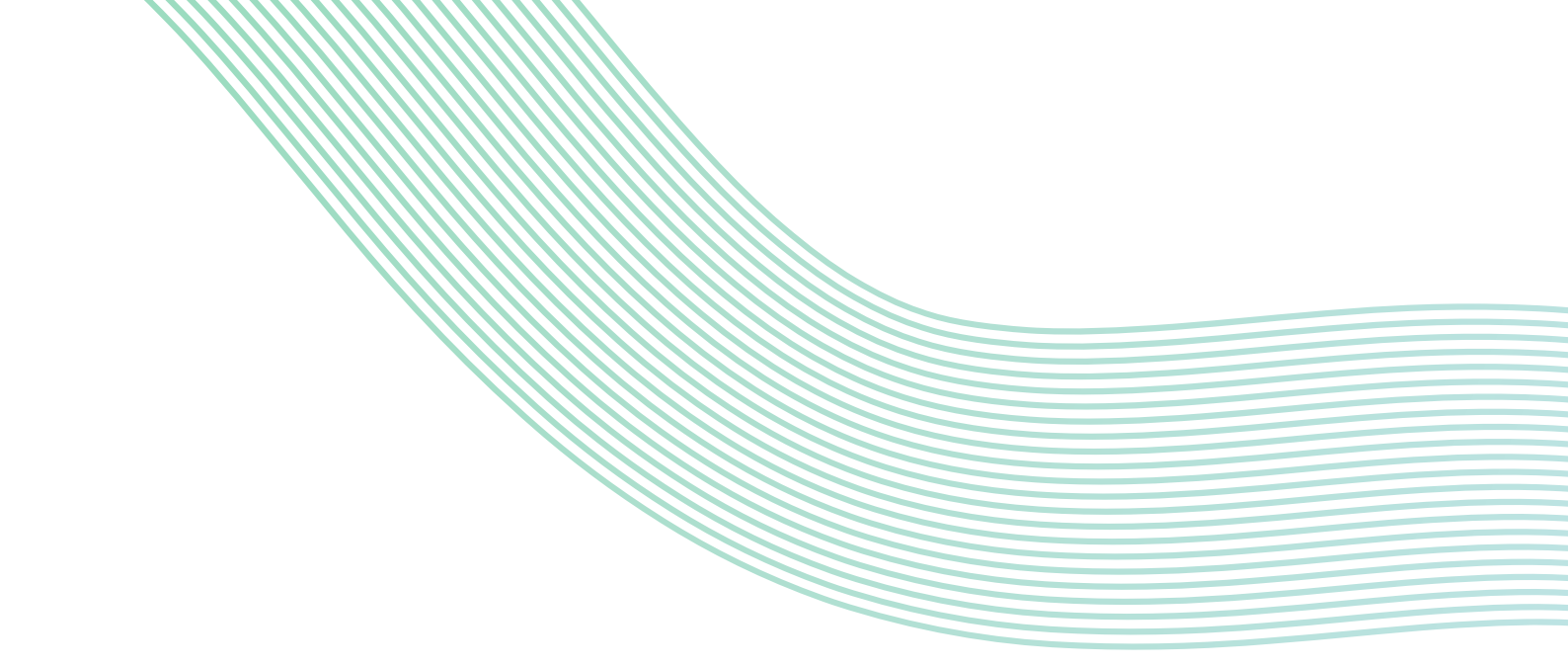
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To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager. The report is also reviewed by a panel of independent technical experts before its release.

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Report Overview:

Modular Approaches to CO₂ Capture Technologies

Introduction

The objective of the study was to explore the status and potential of the modular construction of CO₂ capture plant, targeted at accelerating the deployment of carbon capture, utilisation and storage (CCUS) in the power and industry sectors.

For this study, modular construction¹, prefabrication or off-site construction was defined as *“a process in which a component is prefabricated off-site and is then transported as a completed component to the required location for integration with the plant”*.

Compared to on-site or ‘stick-built’ construction, there are several reported advantages of construction in a more controlled environment, e.g., it can be less prone to delays, can reduce labour costs, can provide uniform quality and optimised performance, can

¹ For clarity, a more nuanced definition is as follows: The terms prefabrication and modular construction are sometimes used interchangeably but they are not the same. Modular construction is just one type of prefabricated construction. Prefabrication, which is very common in the process industries, is any construction process that does not take place on-site. Modular construction, which is the subject of this study, specifically refers to the building of repeated components, or modules, constructed off-site and then assembled on site.

eliminate interference from inclement weather and, with access to superior tools and methods, can reduce overall build time.

A downside might be that modular units are often, by nature, mass manufactured and regular in design and may require a degree of adaptation for a particular application, whereas on-site construction can present a more 'customised' design tailored precisely to the situation required.

Key Messages

Industry Capability and Market Readiness

- A wide range of companies possess commercial and near-commercial experience in modular carbon capture plant design and supply, including major engineering firms, modular plant suppliers and process technology providers.
- There is a diverse portfolio of proven modular designs for capturing up to 100,000 t CO₂/a across multiple industrial sources. Twelve leading suppliers were identified as ready to deliver modular capture projects using proven technologies and established execution capabilities.

Technological Progress and Innovation

- Technical innovation is reducing capture and transport costs, improving efficiency, and increasing technology readiness levels (TRLs).
- Collaboration between process licensors, engineering companies and plant suppliers is optimising cost-effective and standardised modular capture designs.
- New capture technologies that use fewer equipment items and alternative energy sources are particularly suited to smaller-scale², modular implementation.

Application Focus and Process Suitability

- While traditional CCUS efforts have focused on large-scale flue gas emissions, capture from high-CO₂-content streams (e.g. cement, steel blast furnaces, and blue hydrogen) could offer lower specific costs and is now a major focus for modular deployment.
- Modular suppliers are adapting and refining proven process technologies to meet the specific requirements of these concentrated CO₂ sources.

Process Efficiency and Energy Integration

- Capture technologies that produce CO₂ at elevated pressure can reduce compression costs. Advances in solvent-based, physical solvent, and cryogenic systems are enabling such efficiencies in modular configurations.

² For this study, "small-to-medium scale" was broadly considered as being carbon emissions of the order of 100,000 tonnes per annum or less. Carbon capture solutions at capacities as low as 10,000 tonnes per annum were considered.

- Electrifying the capture plant can promote technologies other than “conventional” solvent-based. These innovations are particularly viable at small scales and are helping modular systems overcome traditional economies-of-scale constraints.

Standardisation and Design Flexibility

- Standardised modular designs shorten engineering, procurement, and fabrication timelines without compromising quality or safety.
- Leading suppliers already have standardised plant configurations, supply capability, and experience in modular delivery.
- While most suppliers can tailor designs to client requirements, such modifications can increase cost and delivery time. Early clarity on specifications and deviations is therefore essential during project definition.

Project Configuration and Execution

- Suppliers standardise module sizes to suit road and rail transport. For larger capture capacities, multiple processing “trains” are operated in parallel, or in some cases, larger modules enable a single-train configuration.
- Project execution strategies should determine the optimal number and configuration of capture trains in coordination with the selected supplier.

Cost Estimation and Project Definition

- Accurate cost estimation requires a clearly defined scope covering supplier scope, balance-of-plant, utilities, installation and construction.
- Indicative module prices are useful for preliminary screening but are insufficient for final investment decision (FID) without detailed engineering and project definition since gas composition, required capture, utilities availability and cost, and the ease or not of installation all have an impact on cost.

Deployment Timescales and Project Delivery

- Smaller-scale modular projects are easier to define, cost and deliver, allowing for faster project approvals and reliable quotations.
- Small larger-scale projects may benefit from modularisation, but it may not follow that duplication of smaller-scale modules is a better way to proceed for larger-scale projects. Some larger-scale projects can benefit from a degree of modularisation, such as dressed columns.
- With proper definition and permitting, beneficial operation can be achieved within approximately three years from project initiation.

Strategic Benefits of Modularisation

- As every capture project will differ, decisions on modularisation are best made on a case-by-case basis
- Modularisation should be optimised across all capture project types and sizes. Multiple-train configurations, pre-assembled columns and vessels, and modular pipe-racks can significantly shorten construction time and reduce project risk.

- Modular supply simplifies site activities, enhances safety, reduces waste and offers clear environmental benefits.
- Except where labour costs are exceptionally low and site productivity is high, modular construction should be considered the default approach for carbon capture plant deployment, especially for smaller industrial sites and distributed power generation (large-scale projects can also benefit from a degree of modularisation).

Motivation and Scope

Achieving global net-zero emissions by mid-century will require the large-scale deployment of CCUS technologies across multiple sectors. CCUS must expand well beyond its current deployment base and adapt to a wide variety of industrial contexts. One promising route to accelerating uptake is through the development of modular and standardised CO₂ capture systems, which can reduce costs, shorten deployment timelines and extend the reach of CCUS to smaller emitters.

Global context and outlook. The Global CCS Institute (GCCSI), in its *Global Status of CCS 2025* report, identifies 77 operational CCS facilities worldwide, with a combined capacity to capture and store around 64 Mt CO₂/a. A further 44 Mt CO₂/a of capacity is under construction, and the total announced global project pipeline – including operating, under-construction, and planned projects – now stands at approximately 513 Mt CO₂/a.

To remain consistent with the IEA's Sustainable Development Scenario (SDS), global capture capacity will need to increase to around 840 Mt CO₂/a by 2030 and 5,635 Mt CO₂/a by 2050. This represents an order-of-magnitude scale-up within the next few decades.

Deployment across scales. Achieving these deployment levels will require CCUS to be applied across the full range of emission sources – from large-scale power generation and industrial plants emitting millions of tonnes of CO₂ per year, to small and medium facilities with annual emissions of around 100,000 tonnes or less.

Historically, CCUS development has focused on large-scale installations, reflecting the stronger economies of scale and higher investment returns they offer. However, a substantial share of global emissions arises from smaller industrial sites and distributed power generation. Expanding CCUS to these segments is therefore essential to meeting long-term climate goals. Current international efforts are directed toward reducing the costs of capture, transport, and storage technologies, as well as improving technical performance and modularity.

The Role of Modularisation. Many emission sources stem from standardised and repeatable industrial processes, which are well-suited to modular capture system designs. Examples include:

- Gas turbines and reciprocating engines, typically manufactured in a limited range of standard sizes;
- Lime production facilities, which often follow similar plant configurations; and
- Auxiliary systems such as boilers, heat exchangers and heat pumps, already available as modular components.

The development of modular and standardised CO₂ capture units offers several strategic advantages:

- Accelerated deployment through factory fabrication and simplified site installation;
- Lower capital costs via economies of replication; and
- Enhanced scalability and flexibility, allowing deployment across a wide range of emission sources and industries.

As the global CCUS sector moves from early-stage demonstration to large-scale commercial deployment, modular approaches are expected to play a key enabling role in achieving the rapid expansion required to meet net-zero emissions targets.

Conclusions

This study confirms that modular carbon capture technologies are commercially viable, technically proven and expected to become increasingly cost-competitive through the review of companies with commercial and near-commercial experience in the design and supply of modular capture technology. The reviewed companies could provide modular capture technology with TRLs ranging from 5 to 9, individual module capture capacities ranging from 0.1 ktpa (for pilot plants) to 400 ktpa, and reported lead times of 18 to 24 months. Many of the companies reviewed in this study did not provide cost information due to the great variation in costs between applications as a result of the influence of factors such as gas composition, required capture, utilities availability and cost, and the ease or not of installation. The companies stated that they provide cost information after obtaining information on site-specific conditions and the unit price of utilities.

The growing availability of standardised designs and capable suppliers is enabling rapid deployment across both large and small CO₂ emission sources. Continued innovation in modular process integration, energy efficiency and plant standardisation will further reduce costs and risks. By facilitating faster execution, improving safety and enhancing environmental performance, modularisation represents a key enabler for accelerating global CCUS deployment and achieving long-term net-zero emission goals.

Expert Review

The findings were generally well received, providing a clear and informative overview of relevant suppliers and available technologies within the market.

Some concerns were raised that the report lacked detailed facts and figures, providing limited quantitative data on specific technologies. However, the facts and figures provided align both with information that suppliers were content to have in the public domain and that were verifiable by Costain. The authors emphasised that the report was designed to provide strategic guidance and context ahead of the detailed technical assessments required to compare options prior to approaching commercial organisations in the usual way.

Reviewers broadly endorsed the conclusion that, while the benefits of modularisation should always be evaluated, decisions regarding its application were best made on a case-by-case basis.

Recommendations

Smaller-scale and modular carbon capture systems are subject to similar technical, financial, and regulatory considerations as larger facilities. Accordingly, they should generally be evaluated using comparable assessment frameworks. However, several factors warrant particular attention in the context of smaller-scale deployment:

- **Technology Selection.** Smaller-scale applications increase the relevance of process technologies that lend themselves to modularisation, such as adsorption systems or rotating equipment. These technologies may merit additional development effort and targeted funding to enhance their commercial readiness.
- **Process Simplicity and Cost Balance.** Technologies with relatively few equipment items are particularly suitable for modular implementation. While such simplicity may entail lower capture efficiency or higher operating expenditure, it can offer benefits through reduced capital cost and accelerated deployment schedules.
- **Technology Demonstration and Data Consolidation.** Suppliers should consolidate results from technology trials, including those involving advanced solvents, pilot plants, and semi-commercial facilities. Trials across a range of emission sources are encouraged to demonstrate performance, advance TRLs, and build confidence among potential adopters and investors.
- **Integration with Existing Facilities.** Smaller-scale projects will frequently be implemented as “bolt-on” installations to existing industrial sites, relying on current infrastructure, utilities, control and safety systems, and site operational resources. Accurate investment appraisal requires clear delineation between the modular plant supply and overall project capital expenditure. Depending on project ownership and capability, this assessment may be undertaken internally or with specialist engineering support.
- **Standardisation and Supplier Offerings.** The principal benefits of modularisation – cost reduction and shorter time to operation – depend on adherence to suppliers’ proven, standardised designs, codes, and standards. Modifications to

these baseline designs can significantly reduce the advantages of modular construction. Some suppliers, particularly larger engineering, procurement and construction (EPC) organisations, may offer early guidance on how specific client requirements could affect modular performance and project outcomes.



Modular Approaches to CO₂ Capture Technologies

Costain for IEAGHG

Study Report

1118540-0200-075-07-0001-001 Rev C

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CONTENTS

	<u>Page No.</u>
ABBREVIATIONS	4
EXECUTIVE SUMMARY	8
1.0 INTRODUCTION	11
1.1 Study Definition	11
1.2 Background	11
1.3 Study Objectives	12
1.4 Scope of Work	13
1.5 Basis of Work	15
2.0 MODULAR CARBON CAPTURE	20
2.1 Introduction	20
2.2 Summary and Selection	21
2.3 Air Liquide	26
2.4 Aker Carbon Capture	30
2.5 Axens	35
2.6 Baker Hughes	38
2.7 BASF	41
2.8 Carbon Clean	46
2.9 Chart	50
2.10 Entropy	53
2.11 Fluor	55
2.12 Giammarco-Vetrocoke	57
2.13 Honeywell UOP	59
2.14 Koch Modular	65
2.15 Linde	71
2.16 Mitsubishi Heavy Industries	73
2.17 Pentair	77
2.18 Saipem	80
2.19 Sumitomo	83
2.20 Svante	85
2.21 T.EN	88
3.0 DISCUSSION	91
3.1 Modular Plant - Definition	91
3.2 Suppliers	93
3.3 Cost	96
3.4 Deployment	98
4.0 CARBON DIOXIDE CONDITIONING AND COMPRESSION	101
4.1 Conditioning	101
4.2 Compression	101
5.0 LIQUID CARBON DIOXIDE STORAGE	105
5.1 Storage	105
6.0 RECOMMENDATIONS	108
7.0 CONCLUSIONS	109
REFERENCES	113

ABBREVIATIONS

ACC	Aker Carbon Capture
ANSI	American National Standards Institute
API	American Petroleum Institute
ASCC	Advanced Solvent CO ₂ Capture
ASTM	American Society for Testing Materials
ATR	Autothermal reforming
Bar a	bar absolute
Bar g	bar gauge
BASF	Badische Anilin- und Sodafabrik (<i>De.</i>)
BECCS	Bioenergy with Carbon Capture & Storage
BEIS	(Department for) Business, Energy & Industrial Strategy
BOG	Boil Off Gas
CAP	Chilled Ammonia Process
CAPEX	Capital Expenditure
CCC	Compact Carbon Capture
CCS	Carbon Capture & Storage
CCUS	Carbon Capture Utilisation & Storage
CFB	Circulating Fluidised Bed
CHP	Combined Heat & Power
CNG	Compressed Natural Gas
CO ₂	Carbon Dioxide
DAC	Direct Air Capture
DCS	Distributed Control System
DOE	Department of Energy (US)
DRI	Direct Reduction Iron
EDP	Emergency Depressurisation
EO	Ethylene Oxide
EOP	End-Of-Pipe
EOR	Enhanced Oil Recovery
EPC	Engineering, Procurement and Construction
EPF	Engineering, Procurement and Fabrication
ESD	Emergency Shutdown
ESS	Energy & Sustainable Solutions

E&I	Electrical & Instrumentation
FCC	Fluid Catalytic Cracking
FEED	Front End Engineering Design
FID	Final Investment Decision
FOB	Free On Board
FPSO	Floating Production Storage and Offloading
FW	Foster Wheeler
GS E&C	GS Engineering & Construction
Gt	Gigatonne
HMI	Human-Machine Interface
HP	High Pressure
HPC	Hot Potassium Carbonate
iCCS	Integrated Carbon Capture & Storage
ICS	Industrial Climate Solutions
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
IFP	Institut Français du Pétrole (<i>Fr.</i>)
IFPEN	IFP Energies Nouvelles (<i>Fr.</i>)
IRR	Internal Rate of Return
I/O	Input/Output
kg	kilogram
KM CDR Process™	Kansai Mitsubishi Carbon Dioxide Removal
ktpa	thousands of tonnes (metric) per annum
LNG	Liquefied Natural Gas
LP	Low Pressure
LTCS	Low Temperature Carbon Steel
MCC	Modular Carbon Capture
MCCS	Modular Carbon Capture & Storage
MDEA	Methyl diethanolamine
MEA	Mono-ethanolamine
MHI	Mitsubishi Heavy Industries
MHIENG	Mitsubishi Heavy Industries Engineering
MOF	Metal-Organic Framework
MoU	Memorandum of Understanding
MSP	Mixed Salt Process
Mt	Megatonne (metric)
Mtpa	Megatonne (metric) per annum

MTU	Mobile Test Unit
MTZ	Mass Transfer Zone
MVR	Mechanical Vapour Recompression
MW	Megawatt
MWe	Megawatt electricity
MWth	Megawatt thermal
NCCC	National Carbon Capture Center, Alabama, USA
NDA	Non-Disclosure Agreement
NDT	Non-Destructive Testing
NGL	Natural Gas Liquids
NZE	Net Zero Emissions
NZT	Net Zero Teesside
OEM	Original Equipment Manufacturer
OPEX	Operating Expenditure
PAU	Pre-Assembled Units
PID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
ppmv	parts per million by volume
PSA	Pressure Swing Adsorption
RAM	Rotary Adsorption Machine
R&D	Research & Development
SES	Sustainable Energy Solutions
SFW	Sumitomo Foster Wheeler
SHI	Sumitomo Heavy Industries
SIMOPs	Simultaneous Operations
SMR	Steam Methane Reforming
tpa	tonnes (metric) per annum
tpd	tonnes (metric) per day
tph	tonnes (metric) per hour
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption
T.EN	Technip Energies
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US\$	US Dollar
WtE	Waste to Energy
VAM	Vinyl Acetate Monomer (VAM)

VOC	Volatile Organic Compound
vol.	volume
VSA	Vacuum Swing Adsorption
°C	degrees Celsius
3C	Compact Carbon Capture
3D	DMX™ Demonstration in Dunkirk
€	Euro
£	UK Pound Sterling

1.0 EXECUTIVE SUMMARY

A comprehensive review has identified a large number of companies with commercial and near-commercial experience in the design and supply of modular carbon capture plants. This includes major engineering companies, modular plant suppliers and process technology companies. It shows a wide range of available, proven, modular plant designs for capture of carbon emissions of 100,000 tonnes per annum (tpa) or less from a range of industrial sources. From the leading suppliers evaluated, twelve were considered to be especially of note, in being able to undertake a modular capture project now, or soon, with proven capture technology and project execution abilities.

Technical innovation is reducing the cost of carbon capture and transportation and is increasing Technology Readiness Levels. Modular plant supply is very conventional in industrial and hydrocarbon gas processing and modular carbon capture plants have been demonstrated. New capture technologies are emerging that are particularly suited to smaller-scale plants, by having a small number of equipment items. Process technology suppliers are improving capture plant performance and working with engineering companies and plant suppliers to optimise modular carbon capture plant designs.

To date, carbon capture from large-scale flue gas emissions has been favoured. However, the specific cost of carbon capture is generally lower the greater the feed gas CO₂ content so carbon capture in the steel and cement industries and for “blue hydrogen” may be favoured. Modular plant suppliers are focussing on these sources of carbon dioxide and developing process technology specific to feed gas of high CO₂ content or are modifying existing, well-proven technology. Carbon capture on cement plants for instance is progressing because suitable modular capture plants are now available.

Capture technologies that “produce” carbon dioxide at elevated pressure reduce downstream compression costs. Licensors of solvent-based capture technology have thus demonstrated recent technology and performed trials to show successful operation at elevated regeneration pressure. Physical solvent becomes more significant, by “producing” captured carbon dioxide at elevated pressure. Capture technologies using chilling and partial condensation also “produce” carbon dioxide at elevated pressure, thus reducing the overall capture and transportation cost. All these important developments are being implemented in modular carbon capture plants.

Optimal integration with existing, available utilities is important for all carbon capture. The ability of capture plants to use electrical energy rather than thermal energy promotes

technologies other than “conventional” solvent-based, e.g. partial condensation capture processes are “driven” by electricity. Solvent-based processes are thus being developed to use heat pumps for solvent regeneration. Such technical developments are more feasible and likely for smaller plants. Small-scale modular technology is actually providing lessons for large-scale capture plants. These developments help smaller-scale modular capture to overcome economies of scale and thus be cost-effective.

Modular carbon capture will rely on “standardised” plant designs to minimise the time and cost for engineering design, procurement and fabrication (without compromise to quality and safety) and the time to beneficial operation. The leading companies discussed in this report have suitable plant designs available, plant supply and installation capability and key experience.

Suppliers’ “standard” designs offer lower cost. Designs can (by most) be “tailored” to specific client requirements, but with cost increase. Detailed assessment with a definitive plant specification would be needed to assess the impact of changes to a “standard” plant design. An organisation considering carbon capture must thus understand the basis of a supplier’s design and be clear on requiring “alternative” engineering standards. These can make plant designs bespoke, deviate from supplier’s conventional supply and significantly increase cost and delivery time.

Suppliers “standardise” their modular plant designs(s) based on module sizes to suit road/rail transport containers. For larger capture duties they would employ multiple processing units (“trains”) in parallel. Some suppliers can show capability and experience with much larger modules to have a single “train”. The project execution strategy should identify – with each specific supplier being considered – the optimum number of capture plant “trains”.

Any capture project needs to assess project cost for its specific circumstances rather than deriving broad conclusions from indicative costs. Module supplier scope must be well-defined to obtain a modular plant price quotation. An accurate overall capture cost will then also require “balance of plant” (off the module), utility supply, site installation and more. If module supply is FOB (or similar) then what are the additional costs for installation and associated construction? Suppliers may provide budgetary module costs to aid “screening” but identifying module costs for FID, let alone the total capture investment costs, needs extensive engineering and project execution definition work, much more than this study could address with a generic design basis.

Smaller-scale, modular projects are easier to specify and define, in terms of scope and cost, than major capture projects. This facilitates reliable cost quotations and earlier FID. This can lead to beneficial operation within 3 years (assuming all due regulatory requirements can be met in this time period).

The report shows that adopting modular plant should lead to an increase in carbon capture projects. Capture projects of all duties and carbon sources should consider modularisation, if necessary, by having multiple trains. Modularisation should be maximised as far as possible. Large equipment can be supplied dressed (columns and other large vessels) and pre-assembled piperacks used.

Modular supply simplifies site construction activities, improves site safety and reduces waste, thus having a direct environmental benefit. Other than for very large equipment – less of an issue with smaller-scale plant – the whole plant can be supplied in modular form. Indeed, modular plant supply should be the default approach for all carbon capture projects, other than for the few locations with very low labour costs and good productivity.

2.0 INTRODUCTION

2.1 Study Definition

The IEAGHG Technical Specification [1] defines modular construction, prefabrication or off-site construction as “a process in which a component is prefabricated off-site and is then transported as a completed component to the required location for integration with the plant”. It then notes that “compared to on-site or ‘stick-built’ construction, there are several reported advantages of construction in a more controlled environment, e.g., it can be less prone to delays, can reduce labour costs, can provide uniform quality and optimised performance, can eliminate interference from inclement weather and, with access to superior tools and methods, can reduce overall build time. A downside might be that modular units are often, by nature, mass manufactured and regular in design and may require a degree of adaptation for a particular application, whereas on-site construction can present a more ‘customised’ design tailored precisely to the situation required.”

2.2 Background

From the IEAGHG Technical Specification [1] “With global energy-related CO₂ emissions reaching an all-time high of 36.8 Gt in 2022 and still increasing, the target of 1.5°C is becoming increasingly challenging. Together with other low-carbon technologies, CCUS has and will have a major role in meeting the challenge. CO₂ captured today is 49 Mtpa. The IEA projects (via its Sustainable Development Scenario) this will need to rise to 850 Mtpa CO₂ in 2030 and 5,635 Mtpa CO₂ in 2050.

Energy and climate imperatives dictate that carbon capture will need to be used on all types of plant, on power generation and industrial plant, large and small – from those emitting millions of tonnes of CO₂ a year down to, say, those emitting of the order of 100 000 tonnes per year or maybe less. While the focus of carbon capture has largely been on its application to large-scale plant, reflecting the dominant focus of technology developers on applications that offer stronger economies of scale, a sizeable share of CO₂ emissions from industry and power generation is emitted from small- to medium-scale applications. To help accelerate uptake of CCUS, there are global efforts to lower the costs of technologies along the CCUS chain.

Moreover, certain emission sources come from highly standardised and modularised processes that would lend themselves well to high levels of modularisation of the capture technology, i.e., gas turbines and engines come in specific sizes and certain lime plants

designs are highly standardised. Also, enabling equipment such as boilers and heat pumps might already be modularised and be very useful for capture process applications.”

Modular design is conventional across the process industries. Companies look to provide repeat or near-repeat “standard designs” to greatly minimise engineering, simplify supply chains and thus deliver modular plants quickly and at relatively low cost. This report notes the use of this approach by several leading companies for carbon capture. It notes new technical developments in carbon capture that are being used in modular supply, some of which are especially effective and appropriate. It identifies and broadly evaluates modular CO₂ capture solutions that are commercially available, with TRL of 9 or at least 8, and capture technologies currently in development but which are at a relatively high TRL.

2.3 Study Objectives

From the IEAGHG Technical Specification [1] “Modularisation, the focus of this study, is one of the approaches considered to have the potential to reduce costs as well as offering additional benefits. Along the chain from capture to storage, there are multiple opportunities to modularise systems or components of systems. However, rather than cover the whole process chain, this study will address only the **CO₂ capture, conditioning and compression** elements (hereinafter, **reference to CO₂ capture also includes the conditioning and compression elements**).

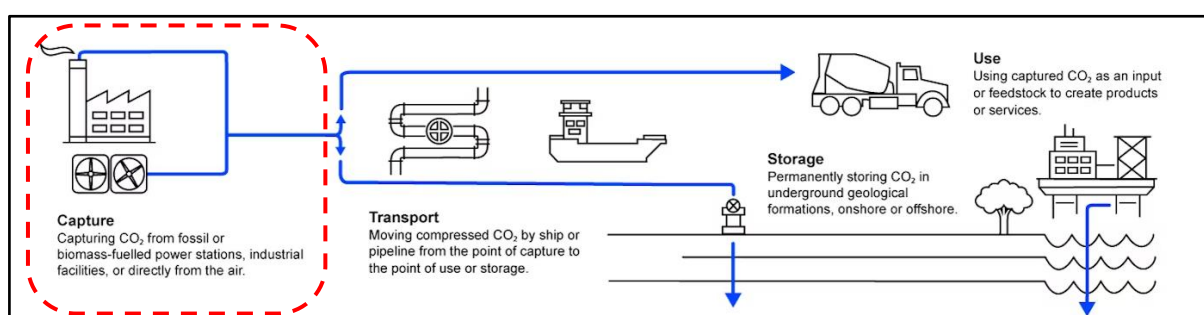


Fig. 1.2.1 Carbon Capture, Transportation, Storage & Use

Some vendors already offer commercially available capture technologies in modular form. The study will assess the need, opportunities, benefits and challenges associated with integrating commercially available modules within current CO₂ capture systems. It will also explore areas of CO₂ capture, both current and still under development, where the potential to modularise has not yet been realised.

There may have been a lack of attention afforded to small- and medium-scale emission point sources due to a perception of relatively higher capital costs. Such sources may also be located in logistically challenging locations, such as small, disperse sites or those with crowded existing infrastructure that would negatively impact the implementation of full-scale capture. The study will consider whether modular technology components or sub-components would have a role in making these emission sources more commercially attractive to finance and operate.”

As per Costain’s proposal [2], assessment of impurity removal upstream of carbon capture is excluded. Most technology and plant suppliers will include conditioning and, in some cases, CO₂ transport in their scope of supply. The breadth of scope offered by a supplier may be a factor in considering and ultimately selecting a modular carbon capture plant supplier.

2.4 Scope of Work

From the IEAGHG Technical Specification [1] the scope of work comprises the following tasks:

2.4.1 Task 1: Information Review

The contractor will undertake a detailed review of the literature, including online vendor sites, to identify what modular components and sub-components are already offered in the commercial domain, what modular components and sub-components are being used or have been used in commercial applications, what modular components and sub-components may be under development and what areas are being considered as having potential for future modular design. Where possible, this review will be augmented by information gathered from discussions with technology suppliers, plant developers and plant operators.

Whilst it is generally assumed that modular components or sub-components are more applicable to medium- and small-scale applications, the contractor will explore whether this supposition is correct or whether, in fact, modular components are relevant regardless of scale.

2.4.2 Task 2

The contractor will undertake a techno-economic analysis of the more promising modular technologies identified. Key performance data for the modular technologies identified will be reviewed and discussed. For example, for capture units, key data will include: type of

technology (solvent, sorbent, membrane, ...); technology readiness level; capture efficiency (rate); scalability and cost.

The analysis will investigate which emission sources would lend themselves to modularised approaches. The use of available modular equipment such as boilers, engines, heat pumps and other auxiliary equipment in the capture plant would also be incorporated into the assessment.

2.4.3 Task 3

The contractor will discuss the need for buildable modules in capture systems and their suitability for their intended application. For example, for capture systems, their need and suitability for application to different industrial, power generation and CCS-enabled hydrogen processes. Essential to the discussion will be the deployment timeline and implications arising from this timeline.

How well current modular components or sub-components have been or may be integrated into the CCS value chain will be reviewed. Opportunities for the deployment of modular units in the CCS value chain will be reviewed. Opportunities for the deployment of modular units in the CCS value chain (CO₂ capture, conditioning and compression) will be identified, their advantages and disadvantages and their commercial viability assessed.

2.4.4 Task 4

An environmental and techno-economic assessment of modular components compared to their 'stick-built' counterparts will be undertaken, considering:

- The environmental impact of the (assumed) shorter systems lifetime of modular components
- The ease of upgrading modular systems while in service to improve their performance; and
- The associated costs and benefits of modular components

2.4.5 Task 5

The findings of the study will be discussed and detailed conclusions drawn, together with recommendations relevant to the CCS technical, financial and policy communities. Suggestions for further study will be made.

2.5 Basis of Work

2.5.1 Introduction

As noted in the IEAGHG Technical Specification [1], CCUS has tended to focus on large-scale plants to capture hundreds of thousands of tonnes a year of carbon dioxide. This is based on achieving lower specific carbon capture cost by economies of scale compared to smaller capture plants. However, a sizeable share of industrial and power generation CO₂ emissions is actually from small- to medium-scale facilities, with carbon emissions in the tens of thousands of tonnes a year rather than hundreds of thousands of tonnes a year. Modular construction may facilitate capture of carbon dioxide from these cost-effectively and in shorter timescales than larger plants which may have such physically large equipment that they are, at least partly, “stick-built” with limited or no modularisation.

Costain’s perspective is based on extensive experience in modular gas processing plant specification, design and supply. This experience highlights that for most processing applications, and site locations round the world, modular supply is cost-effective, assuming modules can be effectively transported and installed at the processing site. Some plants may have such large equipment that “full” modularisation is not appropriate. For carbon capture an absorber column may be in this category. However, even then it could be supplied with all piping, platforms etc. – a so called “dressed” column – and thus as “modularised” as is pragmatic. “Modularisation” is essentially a project execution strategy which runs through a company’s engineering design approach. It would be as unwise to change a business’s approach away from modular plant supply as it would to impose it on an engineering company not greatly experienced in its application. This factor runs through the study work.

The focus of the study was to assess the status of modularisation in carbon capture and the potential benefits that modular design and supply can offer in terms of reduced cost and/or time for project implementation.

Modularisation has been used in industrial gas and natural gas processing for over forty years, especially for smaller-scale gas processing. In air separation, refinery and petrochemical gas processing, NGL recovery and LNG production it is the preferred approach to plant design and supply, other maybe than in parts of the world with low construction labour costs. It will be noted that the most effective way to reduce LNG costs was traditionally by building larger and larger plants or “trains”, so as to realise economies of scale. Today LNG projects (especially on the US Gulf Coast) are installing multiple smaller, “standardised”, modular liquefaction

plants. Of course, the USA is highly focused on process plant supply, with multiple equipment suppliers, is a highly competitive market with excellent transport links and can install modular plant effectively at coastal locations. These factors influenced NGL extraction via modular supply, and now LNG. They are crucial factors in determining the most cost-effective plant supply and installation strategy.

As already noted, some (EPF) plant suppliers specialise in modular plant supply. These are of particular interest where they have aligned their business with carbon capture. Several engineering and EPC companies have a focus and capability in carbon capture and are strong in modular plant design. They have extensive and well-developed supply chains. Whether or how a company interested in carbon capture uses in-house engineering talent, appoints an owner's engineer, relies on selecting and appointing an EPF company or considers an EPC company (with modular plant capability) to provide "turnkey" services are all key considerations for a carbon capture project. This report provides information to provide important guidance to "shape" the thinking of how to approach a carbon capture project.

2.5.2 Capacity

For this study "small to medium scale" was broadly considered as being carbon emissions of 100,000 tonnes per annum (tpa) or less. Carbon capture solutions at capacities as low as 10,000 tpa are considered.

2.5.3 TRL

Technology Readiness Level (TRL) values quoted were mainly obtained from the supplier websites or obtained directly from the supplier. Stated TRL values were reviewed and commented on by Costain to provide as much consistency as possible across the companies considered. In Costain's experience, TRL values are considered by the ultimate operator and their engineering partner based on their experience so stated TRL values in this report should be taken as indicative and for guidance. In some cases, it could be seen that processing solutions are commercially proven and at a TRL of 9 but that there is limited experience of the technology as modular supply. It is important to consider this demarcation. Technology may be proven but whether suppliers have experience and a clear "business model" for modular plant supply is a separate question.

In some cases, companies that were contacted for advice and support were unwilling to cite specific TRL values. TRL values for these suppliers was thus left blank as Costain could only use public domain information for these suppliers whereas others directly supported the study

work and the provision of information. It was ensured that lack of information from specific suppliers in no way reduced the effectiveness of the study as so many suppliers were identified and supported the work and the full range of applicable technologies is effectively covered.

2.5.4 Carbon Dioxide Sources

Most carbon capture projects, studies and evaluations (e.g. Wood report for BEIS (2018) [3]) have focussed on capture from post-combustion flue gases, which are dilute in carbon dioxide content, and conventionally use chemical solvents for carbon capture. However, many sources of industrial carbon emissions are candidates for carbon capture, including gas processing, hydrogen production, steel production, cement production and others. Production of a tonne of cement produces about 0.7 tonnes of CO₂. Production of a tonne of steel produces at least 1.4 tonnes of CO₂. Carbon capture is introducing important changes to conventional industrial practice in these industries. For instance, hydrogen production has traditionally used Steam Methane Reforming (SMR). About 90% of global hydrogen production is obtained this way. However, SMR has either two potential sources of carbon dioxide, with 40% in low pressure flue gas, or if only one source is considered then all carbon dioxide is in low pressure flue gas. Carbon capture is thus expensive. For “Blue Hydrogen” this is promoting auto-thermal reforming (ATR) wherein CO₂ is captured from synthesis gas. The resulting high CO₂ partial pressure means a wider range of capture technologies (than solely solvent-based processes) are applicable to reduce capture costs. Capture technology selection is influenced by feed gas composition, its carbon dioxide content and pressure and by the extent of carbon capture, so that higher carbon dioxide content can make carbon capture more cost-effective. It can thus be seen that selection of the appropriate source of carbon dioxide is important to reducing capture cost. This is being increasingly appreciated in carbon capture projects focussing on processing of carbon dioxide “rich” gases rather than just atmospheric pressure, “dirty” flue gases. This is very significant in focussing efforts on the best opportunities for development and commercialisation of capture technology, including for modular plants.

Direct Air Capture (DAC) is not included in this report as it has quite different technical considerations than industrial emissions, by having such very low CO₂ partial pressure, and thus very high capture costs. The study focussed on solutions that can be shown to be cost-effective and underpinned by supplier offerings and applicable to a wide range of industrial applications.

2.5.5 CO₂ Capture Technologies

This study considered the following CO₂ capture technologies at a wide range of inlet CO₂ concentrations so as to essentially meet the requirements of all industrial carbon emitters:

- **Amine-based absorption:** this is the most “conventional” and widely used CO₂ capture technology. Gas is fed into an absorption column, where a solvent selectively removes CO₂ by chemical reaction. Monoethanolamine (MEA) has traditionally been used but more effective solvents are available, typically using an “activator” added to a Methyl diethanolamine (MDEA) base. These improved solvents lead to lower solvent flow and smaller plant equipment. The CO₂-rich solvent is then fed to a regeneration column, where it is heated to release the CO₂. This solvent regeneration is energy intensive and improved solvents reduce the energy consumption. The regenerated lean solvent, now essentially devoid of CO₂, is cooled and returned to the absorption column.
- **Physical solvent:** process is similar to amine-based absorption but uses the principle of dissolving CO₂ in solvent rather than by chemical reaction. Physical solvent cannot economically achieve very low, i.e. measured in ppmv, CO₂ levels in the treated gas (as chemical solvents can) but is suitable for high carbon dioxide content and high partial pressures. Regeneration can be achieved, at least in part, by reduction of the rich solvent pressure and “flash” of CO₂. This reduces thermal regeneration duty and means that some CO₂ is available at elevated pressure (typically of the order of 10 bar a), reducing the suction pressure on any downstream CO₂ compressor and thus reducing compression duty and cost.
- **Metal-Organic Framework (MOF):** MOFs are crystalline materials composed of metal ions (linkers) connected by organic molecules (nodes), to create a structure with nanoscale pores and a very high specific surface area for adsorption – higher than TSA described below. These pores function as molecular traps to selectively capture CO₂. When the bed of MOFs is “saturated”, it is thermally regenerated to release CO₂.in a comparable way to TSA below. One leading MOF supplier is noted so as to highlight the key aspects of the technology.
- **Temperature Swing Adsorption (TSA):** feed gas is introduced to an adsorbent bed, typically consisting of molecular sieve (of high specific surface area) to physically bind CO₂. Adsorbents for chemical binding are in development. When the bed is saturated, feed gas is routed to a second adsorption bed whilst heat is applied to the first bed to thermally regenerate it and thus release the CO₂. The regeneration gas may then be further processed in a PSA bed system to achieve a CO₂ capture of over 95%. TSA is appropriate for essentially total removal of small levels of CO₂ (no greater than 0.5 vol.% in Costain’s experience), i.e. to ppmv levels, for downstream cryogenic processing, to avoid freezing. It is not a primary technology for carbon capture from gas streams as other technologies would be better, other than for very low CO₂ content streams that would be poor candidates for carbon capture.

- Pressure Swing Adsorption (PSA) or Vacuum Swing Adsorption (VSA): similar to TSA except that regeneration is by pressure reduction (PSA), even to vacuum (VSA) instead of using heat. VSA, supplied by Air Products and funded partly by the DOE, has been demonstrated for carbon capture at the Valero Port Arthur Hydrogen Production facility for over twenty years but has not been taken up elsewhere. PSA is primarily of interest for small-scale applications combined with other technologies that use the ability of PSA to essentially remove CO₂ totally.
- Chilling and condensation. For gas with high carbon dioxide partial pressure, a significant portion of the carbon dioxide can be condensed to liquid. The carbon dioxide rich liquid will likely require distillation and very high purity CO₂ can be produced (99.999% “food grade”). This is the usual route to industrial production of pure carbon dioxide (from very high carbon dioxide content streams such as from amine regenerators). Carbon dioxide “conditioning” to enable cryogenic processing means that no further “conditioning” is required downstream. The percentage of carbon dioxide captured can be relatively low with chilling and partial condensation so further processing of CO₂ rich off-gas may be needed to attain over 90% carbon dioxide capture. Depending on the process configuration CO₂ may be available at elevated pressure and thus, as noted previously, reduce compression duty and cost.

3.0 MODULAR CARBON CAPTURE

3.1 Introduction

3.1.1 Task 1

A detailed review was performed as to what modular components and sub-components are offered commercially for carbon capture (and have been used in commercial applications), what is under development and what applications are being considered as having potential for future modular design and supply. This review made use of public domain information and direct discussions with a comprehensive range of leading carbon capture technology suppliers. Supporting information was sourced from the Global CCS Institute 2023 Technical Report on CCS technologies [4].

The primary focus of Task 1 [2], was “for each of the suppliers identified, collate information gathered, and record the following information in summary form:”

- “Information available
- Source of information e.g. web site, request for information response
- Capture technology e.g. solvent, membrane, adsorption, low temperature, solid sorbent
- Anticipated applications e.g. post-combustion, pre-combustion
- Specialist equipment employed e.g. gas contactors, heat exchangers
- Novel aspects and experience e.g. pilot projects, commercial applications
- Formal relationships between module suppliers and technology (e.g. solvent) providers
- Applicable scale e.g. proposed “standard” capacities, sub-component scale
- Expected delivery time
- Promoted benefits e.g. efficiency, compact footprint, capture performance”

3.1.2 Tasks 2, 3, 4 and 5

In Task 2, 3, 4 and 5 information obtained on each carbon capture technology supplier was developed as discussed in Section 1.4.

Task 1 considered the key requirements for selection of more promising and “representative” modular technology solutions for a wide range of emission sources, broadly considering the requirements of the later Tasks, including performance, TRL, scalability, applicability to various industries and specific cost (as far as it is pragmatic to consider relative cost).

3.2 Summary and Selection

Modular CO₂ capture companies (considered to be “representative” of all potential capture technologies) are summarised below and discussed in more detail (against study requirements) in the following Sections.

The response and good engagement of modular CO₂ capture companies was essential for the study. Costain was able to use both existing and specifically established relationships to obtain some excellent support. It was important to ensure relevant capture technologies be represented, not that every potential plant supplier be represented. Some suppliers did not wish to engage directly. However, the study was very successful in obtaining appropriate information for Costain to present a well-balanced and wide-ranging assessment of relevant and experienced suppliers. The assessment was successful in showing just how advanced modular carbon capture is.

Arising from the table below the particular companies considered were;

- major engineering and EPC companies; MHI, Aker, T.EN and Saipem
- modular supply companies; Honeywell UOP, Koch Modular, Pentair
- technology companies; Carbon Clean, Axens, Chart, Baker Hughes, BASF

Companies progressed are highlighted in CAPITALS.

Note that if information is left “blank” it is because no definitive information was obtained directly from the cited company for this study.

For explanation on TRL values see the more detailed comments on each company in following sections.

Company	Source of Information	CO ₂ Capture Technology	Applications (examples)	TRL (as advised)	Modular Scale (ktpa)	Comments
Air Liquide	Web	PSA and condensation (Cryocap™)	Refinery Hydrogen Syngas Cement Steel	9 (Cryocap™)	100	Air Liquide has much experience in modular cryogenic and low temperature plants but commercialisation of Cryocap™ for carbon capture is limited
AKER CARBON CAPTURE	Web Direct Discussions and Follow-Up	Amine-based absorption	Power generation Refining Hydrogen WtE Cement	7/8 (Just Catch™)	1.5 (MTU pilot) 40, 100, 400 ("Just Catch™")	Well-established carbon capture technology and experience. Joint Venture with SLB to form SLB Capturi, late September 2024 (post study)
AXENS	Web Direct Discussions	Amine-based absorption, and others	Steel noted (but more widely applicable)	8	4 (pilot) 100 (considered fully feasible)	Much experience in technology selection for carbon capture, provision of technology and design and in modular units
BAKER HUGHES	Web Direct Discussions and Follow-Up	Amine-based absorption (& rotating packed beds)	WtE Biomass Cement FCC SMR	5 currently (for rotating packed beds) 7 by 2026	1.6 (demo) 50 to 200 (target)	Compact, modular technology is under development with aim of reducing plant equipment size, footprint and cost
BASF	Web Direct Discussions	Amine-based absorption ("OASE")	Hydrogen Ammonia Cement Lime kilns Power generation WtE	9	16, 32, 132 (planned)	Well-established carbon capture solvent technology, much experience and strategic partnership for project execution with GS E&C

Company	Source of Information	CO ₂ Capture Technology	Applications (examples)	TRL (as advised)	Modular Scale (ktpa)	Comments
CARBON CLEAN	Web Direct Discussions and Follow-Up	Amine-based absorption (& rotating packed beds)	Cement Ammonia Biomass Power generation	9 Cyclone CC currently 6, expected 7 by end 2024	25 to 280 (planned)	Well-established carbon capture technology. Development of compact technology to reduce plant equipment size, footprint and cost
CHART	Web Direct Discussions and Follow-Up	Chilling and condensation (with distillation)	Cement Lime kilns Biomass Power generation	7		Chart noted development plans for 35, 175, 350 ktpa
Entropy	Web	Amine-based absorption	Natural gas Oil & gas Steel Power generation	9 claimed	47	Operator interested in project finance
Fluor	Web	Amine-based absorption	Natural gas Syngas			Established EPC in large-scale carbon capture. No clear advantage over others for modular capture
Giammarco-Vetrocoke	Web	Hot Potassium Carbonate	Power generation Cement Steel Pulp WtE			Established technology supplier in large-scale carbon capture. No clear, major advantage over others for modular capture
HONEYWELL UOP	Web Direct Discussions and Follow-Up	Amine-based absorption, PSA, cryogenic fractionation and others	Natural Gas Refining Hydrogen Power Generation Cement Steel	9 ASCC technology in development and TRL 7	10 to 200	Wide range of carbon capture solutions and much experience in modular plants for gas processing. Can be licensor, EPF or EPC

Company	Source of Information	CO ₂ Capture Technology	Applications (examples)	TRL (as advised)	Modular Scale (ktpa)	Comments
KOCH MODULAR	Web Direct Discussions and Follow-Up	Amine-based absorption	Power generation	9 Depending on capacity may be lower	100	Much experience in modular plants for carbon capture. EPF.
Linde	Web	Amine-based absorption PSA and others	Ammonia Cement Refining Hydrogen Power generation Steel Pulp		2.4 to 10	Experience in modular plants. No clear advantage over others for modular capture
MHI	Web Direct Discussions and Follow-Up	Amine-based absorption	Power generation Shipping WtE Cement Steel Gas turbine	9	0.1 to 66	EPC contractor with well-established carbon capture technology and experience. Note world's largest capture plant at Petra Nova (USA)
PENTAIR	Web Direct Discussions and Follow-Up	Amine-based absorption and CO ₂ liquid	Steam boiler Gas turbine Lime kiln CHP	9	"Small -scale"	Much experience in carbon dioxide processing, liquefaction and capture. Modular plants. EPF
SAIPEM	Web Direct Discussions and Follow-Up	Hot Potassium Carbonate (& enzyme)	Biomass WtE Hydrogen Cement Steel	8	70	EPC contractor with good carbon capture technology and experience. Development of carbon capture solvent
Sumitomo	Web	Hot Potassium Carbonate	WtE Biomass			EPC. No clear advantage over others for modular capture

Company	Source of Information	CO ₂ Capture Technology	Applications (examples)	TRL (as advised)	Modular Scale (ktpa)	Comments
Svante	Internet e-mail	TSA	Power generation Cement	7	160 to 640	
TECHNIP ENERGIES (T.EN)	Web Direct Discussions and Follow-Up	Amine-based absorption	Power generation WTE	7/8	1.5 (pilot) 10 to 200	EPC contractor with well-established carbon capture technology and experience. Technology relationship with Shell to provide CANSOLV

3.3 Air Liquide

3.3.1 Company Overview

Headquartered in France, Air Liquide is a multi-national operating in “gases, technologies and services for Industry and Health” with considerable experience in design and supply of cryogenic and low temperature process plant. Its Engineering & Construction division delivers plants including for CO₂ capture.

3.3.2 Source of Information

Company websites.

3.3.3 Capture Technology

Air Liquide offers a range of CO₂ capture technologies based on capability and experience with semi-permeable membranes and PSA as well as cryogenic technology [6]. For this study, their main differentiator of interest is low temperature processing.

Semi-permeable membranes have been widely used for “bulk” removal of carbon dioxide from gas, including natural gas, in modular plants. To be effective they require feed gas at high pressure and of high carbon dioxide content. The percentage of carbon dioxide captured per membrane stage is relatively low. Product purity is also relatively low unless multiple membrane stages are employed and “residue gas” is compressed, making membrane technology machinery and power-intensive for carbon capture.

PSA can capture carbon dioxide with almost total removal but is normally unsuitable for carbon capture, other than for relatively low feed gas carbon dioxide content. CAPEX is a strong function of actual carbon dioxide removal duty as much of the cost is due to the amount of adsorbent, adsorbent vessel size and the multiple number of adsorbent vessels needed for high capture.

PSA is used to purify hydrogen in hydrogen production plants. The PSA off-gas, whilst at low pressure, can be rich in CO₂ (up to 40 to 50 vol.%) and suitable for carbon capture (though is normally used as fuel gas for methane reforming). By compressing the PSA off-gas a process stream of relatively high CO₂ partial pressure is available. This is amenable to capture by chilling and partial condensation. From expertise in low temperature processing and PSA Air Liquide developed Cryocap™ technology for this and the same technology is appropriate and available for other industries.

Product	Applications	CO ₂ Capture Capacity (ktpa)	Claimed CO ₂ Capture Rate	Cost* (€/tonne CO ₂)
Cryocap™ H ₂	Hydrogen Syngas	100 to 3,300	>99%	30 to 50
Cryocap™ FG	Cement Lime Refineries	100 to 3,300	<98%	40 to 80
Cryocap™ Oxy	Oxyfuel combustion	330 to 5,000	90% to 98%	30 to 50
Cryocap™ Steel	Steel	100 to 1,600	80% to 95%	25 to 60

Table 2.3.1 Air Liquide “Product Range” [4]

*As with all module vendor supplied “cost” values in this report the exact basis is uncertain – what exactly is included? Solely the module supply cost or including installation? What influence from any requirement for bespoke design rather than using the supplier’s “standard” solution, influence of transportation limits on plant capacity and need for parallel process units, how does it include for utilities and energy costs and overall OPEX? etc. Cost values can only be taken as indicative and for broad initial assessment. Cost is also a function of feed gas carbon dioxide partial pressure – the higher it is the lower the specific cost. However, if feed gas requires compression for effective capture, then how a basis such as this is considered in the presented costs is uncertain.

Cryocap XLL technology for CO₂ liquefaction is available in a range of custom plant capacities from 700 to 7,000 tpd CO₂ (230 to 2,300 ktpa).

Cryocap™ technology should be suitable and relatively economical at lower plant capacities. It would be expected to be used more in the future as low temperature carbon capture technology becomes more proven, especially for scenarios where feed gas contaminants can be effectively and economically removed to avoid operating problems downstream due to freezing and/or blockage of the specialist heat exchangers used for low temperature processing. The technology is auto-thermal and more reliant on provision of electrical power rather than heat. This is advantageous if low-cost renewable power were to be available.

Air Liquide offer Rectisol for CO₂ capture by absorption (typically with methanol). This technology has high TRL and is applicable for modular plants as with other solvent-based processes discussed in this report.

3.3.4 Modularity & Standardisation

Air Liquide has experience and capability in design and supply of small-medium scale cryogenic gas processing plants and would be capable of providing CryoCap™ at sizes relevant to the study.

Air Liquide can provide a “full service” for process plant based on its in-house technology via its Engineering and Construction Division.

3.3.5 Applications & Experience

Applications to date include [6]:

- 2015: first industrial deployment of Cryocap™ H₂ technology, Port-Jérôme refinery, France (300 tpd CO₂ i.e. 100 ktpa)
- 2021: Kairos@C project with BASF, Belgium (Antwerp port industrial cluster)
- 2022: Memorandum of Understanding (MoU) signed with Lhoist, France (lime production facility)
- 2022: K6 project with EQIOM, France (cement production facility)

3.3.6 TRL

Based on the Port-Jérôme refinery, France, Cryocap™ H₂ technology can be considered as at least TRL 8, potentially 9, depending on receiving further information on the operating performance of this one plant. Other potential Cryocap applications are at lower TRL.

3.3.7 Discussion

Cryocap™ H₂ technology has been employed on one processing facility, at Port-Jérôme, to remove carbon dioxide from PSA off-gas from hydrogen purification. Such PSA off-gas is normally used as reformer fuel gas, so the PSA off-gas CO₂ content exits in reformer flue gas along with all products of combustion. If this reformer flue gas were processed to capture carbon dioxide then justification for separate PSA off-gas processing would clearly diminish. If flue gas carbon capture not employed then PSA off-gas processing by Cryocap™ H₂ would enable about 60% of the total potential carbon emissions (from a typical steam methane

reformer, SMR) to be captured, with the other 40% of carbon emissions leaving in the reformer flue gas.

Cryocap™ H₂ looks an interesting prospect for retrofit of existing SMRs if overall carbon capture of only about 60% is acceptable. Although the capture rate is low with this approach it may be attractive in terms of low specific capture cost rather than doing nothing and all carbon dioxide emissions going to the atmosphere. The process consumes electrical power rather than steam (such as with solvent-based technologies) so its selection would be influenced by the availability and relative cost of electricity against steam.

3.4 Aker Carbon Capture

3.4.1 Company Overview

Aker Carbon Capture (ACC) was formed as a spin-off from Aker Solutions, which did much to pioneer industrial carbon capture in the 1990s. Its current CO₂ capture technology has been in development since 2005 and offered commercially since 2009. ACC benefits from having developed from an established process plant contractor with a business focus on carbon capture.

ACC is relatively well-established in modular capture solutions having undertaken several small-scale site trials and with large-scale deployment soon to be operational.

In September 2024, ACC entered into a joint venture with SLB (formerly Schlumberger) to combine their respective CO₂ capture businesses as SLB Capturi and to be a world leader in industrial carbon capture.

3.4.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of this report.

3.4.3 Capture Technology

ACC CO₂ capture technologies use solvent-based absorption. As is typical with such technology a CO₂ capture rate of up to 95% is claimed (with CO₂ purity of 99.9% (dry basis)). ACC has developed and commercialised the technology primarily for flue gas processing but discussion with ACC noted it could be competitive more widely including for a feed gas carbon content as high as 20 vol.%.

Technologies and “Product Range” are summarised as [7]:

- Mobile Test Unit (MTU): modular carbon capture plants (test)
- Just Catch™: modular capture plants, offered as 3 distinct “standard” capacities
- Just Catch Offshore™: modular capture plants for offshore applications
- Big Catch™: bespoke (non-modular), large-scale capture, over 400 ktpa.

Product	Modular Capacity (ktpa CO ₂)	Typical Lead Time (months)	Footprint (m)	Comments
MTU	1.5	N/A		6 rental units
Just Catch 40™	40	up to 22	13 x 23	
Just Catch 100™	100	up to 24	19 x 24	
Just Catch 400™	400	24 to 30	30 x 55	
Just Catch Offshore™	120 to 360	20 to 24	"small"	Designed for FPSO applications

Table 2.4.1 Aker CC “Product Range”

ACC’s CO₂ capture process (in their case also including CO₂ liquefaction, intermediate storage and CO₂ export) has been qualified by DNV-GL according to DNV-RP-A203 Qualification Procedures for New Technology and DNV-RP-J201 Qualification Procedures for CO₂ Capture Technology [8].

The “typical” lead times noted above are indicative. As with all suppliers, the particular specific issues for a potential project would need to be considered in detail, based on a clear capture duty, to obtain meaningful data on which to base assessments. The values provided for plant “footprint” are also indicative and for comparison purposes. More definitive values could be obtained from ACC, by a company interested in carbon capture, by providing to ACC a design basis and scope and by defining the “battery limits” of the required modular carbon plant.

3.4.4 Modularity, Standardisation and Cost

Information provided by ACC and in their references show ACC’s experience and that a clear leader in design and supply (via approved European module fabricators) of modular capture solutions. This is especially true with the recent joint venture to form SLB Capturi. A “standard” portfolio of modular solutions has been established for carbon capture capacities of 40 ktpa and above (which is applicable to the duty for this study). ACC has focussed on an “engineer once, supply many” strategy whilst also being able to meet client’s bespoke requirements and engineering standards. Their offering is “standardised” to reduce engineering and procurement, reduce CAPEX and give early deployment. This approach – of having a “standardised” offering whilst being able to “customise” as applicable to client requirements – applies also to other module suppliers. However, some are more amenable to providing bespoke designs than others. Such “customising” inflates plant costs by needing much more engineering, possibly non-“standard” equipment, changing established plant layout and introducing more procurement activity.

The indicative levelised cost of carbon capture for 100 ktpa, as provided by ACC, is €30 to €45 per tonne CO₂ (US\$30 to \$45 per tonne CO₂). This cost includes the Just Catch 100™ facility, liquefaction, temporary storage and financing [9]. It appears optimistic compared to “historical norms” for capture costs, especially for “dilute” flue gas streams with CO₂ content of only 10% or less. Such high-level cost figures should be used with care and only for indicative purposes, as it is difficult to ensure a consistent basis for comparison, for one supplier against another, without specific definition of process duty, scope of module supply, “balance of plant” and application of specific engineering codes and standards, amongst other points.

3.4.5 Applications & Experience

Up to Q4 2023, ACC had commenced 37 studies, 5 FEEDs and 6 supply agreements for Just Catch™ [9]. Applications include [7]:

Product	Modular Capacity (ktpa CO ₂)	Client	Location	Application	Status
MTU	1.5	Risavika Gas Center	Norway	Natural gas	Trial complete
MTU	1.5	Longannet Power	UK	Coal	Trial complete
MTU	1.5	National Carbon Capture Centre (NCCC)	USA	Coal	Trial complete. NCCC used by ACC for testing
MTU	1.5	Dong CHP Equinor oil refinery	Norway	Natural gas & Heavy oil cracker	Trial complete
MTU	1.5	Heidelberg / Norcem	Norway	Cement	Trial complete
MTU	1.5	Klemetsrud WtE	Norway	WtE	Trial complete
MTU	1.5	Preem Refinery	Sweden	Hydrogen	Trial complete
MTU	1.5	Polchar	Poland	Char	Trial complete
Just Catch™	5 x 100	Ørsted	Denmark	Power generation: wood-chip, straw	Under construction (Includes liquefaction, CO ₂ storage)
Just Catch™	1 x 100	Twence	Netherlands	WtE	Commissioning anticipated Q3 2024

Table 2.4.2 Aker CC Modular Experience

3.4.6 TRL

The TRLs of ACC's modular solutions are:

- Mobile Test Unit (MTU): from deployment and testing at client sites (see above), TRL could be considered as 7 or 8, depending on a client's specific feed gas conditions and how well proven the MTU is on similar application.
- Just Catch™: from deployment of MTU (same technology, smaller scale), TRL can be considered as 7 or 8. The facility at Twence could be in operation by the end of 2024 or early 2025 and will provide a very good project reference.
- Just Catch Offshore™: potentially as Just Catch but likely a lower TRL.



Fig. 2.4.1 Aker CC - Just Catch 100, Twence, Netherlands [9]

3.4.7 Discussion

ACC claim 10 years of experience (60,000 operating hours) in modular CO₂ capture plants via MTU trials and operation in 11 industrial sectors including WtE, gas- and coal-fired power plants, refineries and cement.

Considering the study requirements, ACC, with six Just Catch™ units “sold”, has demonstrated ability to provide effective carbon capture, using modular and relatively “standardised”

solutions, including at capture capacities above 100 ktpa. With Just Catch 40™ ACC can offer a “standardised” modular solution at 40 ktpa.

It would be of value to compare ACC proprietary solvent performance and specific energy consumption against other “best in class” solvents as this particular parameter is a valuable guide in ensuring minimal solvent flow, minimal equipment size, low plant CAPEX and low plant energy consumption. ACC claim of the order of 2 GJ/tonne. This is essentially “best in class”, as can be seen in discussion of other solvent technologies.

ACC has developed a business model and business approach for carbon capture. ACC offer full engineering and design capability with established and “standardised” designs for carbon capture. Subsequent to the study ACC entered into a joint venture with SLB (formerly Schlumberger) to form SLB Capturi.

Obtaining operating performance data and results from the Twence Just Catch 100™ facility would be beneficial as an effective “test case”, with a TRL of 9, and at a plant capacity of direct relevance to this modular plant study. When available, from operation under varying feed gas conditions, this data could help validate its applicability.

Twence is required to produce “food grade” CO₂ so demonstrating “conditioning” to high carbon dioxide product purity. Whether this one plant alone could be considered as demonstrating a TRL of 9 for wider industrial applications would need to be addressed with ACC by evaluating technology performance with alternative feed gas conditions, carbon dioxide content and required capture rate.

Subsequent to the study, ACC reached mechanical completion of the world’s first full-scale carbon capture facility in December 2024 at a cement plant, the Heidelberg Materials plant at Brevik, Norway. This Big Catch™ plant, designed to capture 400 ktpa of CO₂, is planned to be operational in 2025. As with Twence, it would be valuable to have operating performance results from this facility.

3.5 Axens

3.5.1 Company Overview

Axens is an IFPEN Group company. It has broad experience and multiple technology solutions for gas processing including carbon dioxide removal. Axens therefore has appropriate proven process technology in their suite of gas processing and gas treating technologies.

3.5.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of this report.

3.5.3 Capture Technology

Axens has over 60 years' experience (including 200 licenced units) in gas sweetening applications and in developing and commercialising advanced solvents for carbon dioxide removal from gas streams. These include AdvAmine™ technology, developed with Total Energies [10].

Axens CO₂ capture technology, DMX™, uses a solvent of two organic compounds which helps reduce regeneration energy duty. From the Axens ERTC presentation (2023), DMX™ solvent gives a CO₂ capture rate of over 90%. As with essentially all chemical solvent technologies, capture rate would increase with higher feed gas carbon dioxide content and could be improved by additional cost (e.g. stripping lean solvent to lower carbon dioxide content). Indeed, Axens note that 99% capture could be economically justified. The regeneration duty of 2.0 to 2.7 GJ/tonne CO₂) [11] is about as low as any solvent technology supplier can claim. This parameter is significant in reducing CAPEX and OPEX compared to “open access” solvents (MEA normally being used for comparison). Solvent regeneration can be performed at above atmospheric pressure (up to 5 bar g) without solvent degradation – a recent technology development also made by other leading solvent licensors. This reduces the CAPEX and OPEX of downstream carbon dioxide compression for transport and sequestration. This is an important overall OPEX and CAPEX saving and it highlights the importance of considering the overall cost of carbon capture and sequestration together, as relatively small additional CAPEX (due to higher pressure regeneration) can reduce downstream carbon dioxide compression substantially to thus reduce overall capture cost. These technology advancements can be adopted into modular capture plants.

3.5.4 Modularity & Standardisation

Axens has supplied “over 500 modular units, both onshore and offshore, providing “tailor-made” designs to client project specifications” [12]. Axens advised that a 100 ktpa modular DMX™ design is effectively now “on the market”.

Axens understands how to manage and maximise modularisation in their plant designs and has valuable experience in design and delivery of pre-fabricated process units including the minimising of large equipment items being supplied loose [12].

3.5.5 Applications, Experience and Cost

A DMX™ demonstration pilot module has performed successfully at the ArcelorMittal steelworks in Dunkirk, France. From April 2023 it has operated continuously, capturing 0.5 tph CO₂ (4.2 ktpa CO₂) from blast furnace gases of 25 vol.% CO₂ [13].

With optimised heat recovery, relatively low carbon capture costs of less than €30/tonne are envisaged for blast furnace applications [14]. As noted by other technology and modular plant suppliers, steel production is a better candidate for carbon capture if able to take advantage of available heat for solvent regeneration.

3.5.6 TRL

From the ArcelorMittal demonstration pilot, Axens claim a TRL of 8 for DMX™ on post-combustion. This would need to be investigated but this pilot is an interesting demonstration that progresses DMX™ in terms of testing and commercialisation.

3.5.7 Discussion

As a leading technology licensor Axens’ solvent performance and process technology appears as good as currently available. They act solely as a licensor and thus require another company to undertake engineering, design and plant supply against Axens’ process design. They have worked especially with T.EN on this basis but can work with established engineering and EPC companies. For small-scale applications having to use another company may put them a little behind those process contractors who have a clear focus on modular design and supply based on their own or third-party technology. This would need to be considered for a particular project application by assessing the potential advantages with Axens’ DMX™ process performance against overall project plant design and delivery.

Axens may soon have further demonstratable evidence to show DMX™ being appropriate for modular carbon capture. Investigation could show effective carbon capture from wider industrial applications by highlighting DMX™ performance for different feed gas conditions, carbon dioxide content and required capture rate. DMX™ is applicable for small-scale applications, potentially including such as industrial boilers and engines. The Dunkirk demonstration plant is a very good reference.

3.6 Baker Hughes

3.6.1 Company Overview

Headquartered in the USA and the UK, Baker Hughes describes itself as “the leading energy technology company”, designing, manufacturing and servicing “transformative technologies”. It offers technologies relevant across the CCUS chain, from capture to storage.

3.6.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of the study and Baker Hughes completion of a specific questionnaire.

3.6.3 Capture Technology

Baker Hughes offers a range of CO₂ capture technologies [15]:

Technology	CO ₂ Removal Route	TRL	Comments
Chilled Ammonia Process (CAP)	Solvent: ammonia-based	7	Elevated pressure regeneration reduces carbon dioxide compression cost and supports direct liquefaction
Mixed Salt Process (MSP)	Solvent: potassium-based with ammonia	7	
Industrial Climate Solutions (ICS)	Pulsing froth gas-liquid contactor	Low	More efficient mass transfer Pre- and post-combustion applications
Compact Carbon Capture (CCC)	Solvent: MEA/other	5 7 on-going	More efficient mass transfer Modular, scalable

Table 2.6.1 Baker Hughes Carbon Capture Technologies

The Chilled Ammonia Process (CAP) is a post-combustion CO₂ capture process which has demonstrated a specific energy consumption of 2.6 GJ/tonne CO₂. The Mixed Salt Process (MSP) has been demonstrated by pilot plant at a capacity 0.25 tpd CO₂ (75 tpa) at a specific energy consumption of 2.0 to 2.3 GJ/tonne CO₂ [4]. It thus appears Baker Hughes can claim solvent-based technologies with performance similar to “best in class”, as offered by others.

Baker Hughes was primarily considered for this study due to its modular offering; Compact Carbon Capture (CCC). Baker Hughes acquired Compact Carbon Capture (3C) in 2020. The

technology uses solvent for absorption. Baker Hughes state they are “solvent agnostic”. By using rotating packed beds (RPBs) for absorption rather than an absorption column, centrifugal forces enable more effective solvent distribution for the absorption of carbon dioxide from feed gas and increased mass transfer between gas and liquid. This facilitates low residence time and smaller equipment. The principle was proposed and trialled – initially as “HiGee” – in the 1980s. The regeneration reboiler is installed in the regeneration vessel. A CO₂ capture rate of 95% is claimed for a flue gas stream of 10% CO₂ concentration. Operation at elevated (above atmospheric) regeneration pressure reduces carbon dioxide compression cost as with other leading capture technologies [16].

Baker Hughes also provides CO₂ compression for post-capture transportation [4]:

- Below 200 bar g: in-line compressor, integrally-gearred compressor and pump
- Above 200 bar g (up to 800 bar g): in-line compressor and HP pump, integrally-gearred compressor and pumps (MP & HP)

3.6.4 Modularity, Standardisation and Cost

CCC has been developed by process intensification principles to reduce key equipment size and weight to facilitate modularisation. Baker Hughes’ information shows that overall plant height is greatly reduced by not having an absorber column or a tall regeneration column. Equipment is installed in containers, with multiple containers in parallel being used for larger capacities. Baker Hughes claims a reduction in plant footprint by up to 75% and 50% lower CAPEX compared to conventional carbon capture. This technology may therefore be especially appropriate offshore [17].

Baker Hughes advised its intent to develop “standard” size modular units in the mid-scale range of 50 to 200 ktpa CO₂. The reference case for inlet flue gas concentration is 10% CO₂ (operating range of 5 to 15%). The manufacturing strategy is currently in development.

3.6.5 Applications & Experience

Baker Hughes list multiple potential applications for their technology - power generation (e.g. WtE, biomass), industry (e.g. cement) and hydrocarbons (e.g. SMR, FCC). At this time, with the current level of technical development, it is not considered feasible to compare Baker Hughes rotating technology against others directly, but it appears relevant to small-scale carbon capture, such as from boilers or engines.

3.6.6 TRL

Baker Hughes advised the TRL of CCC is currently 5 following the successful trial of a 5 tpd (1.6 ktpa) pilot plant. They aim for a TRL of 7 by 2026 via a 15 tpd (5 ktpa) demonstration plant.

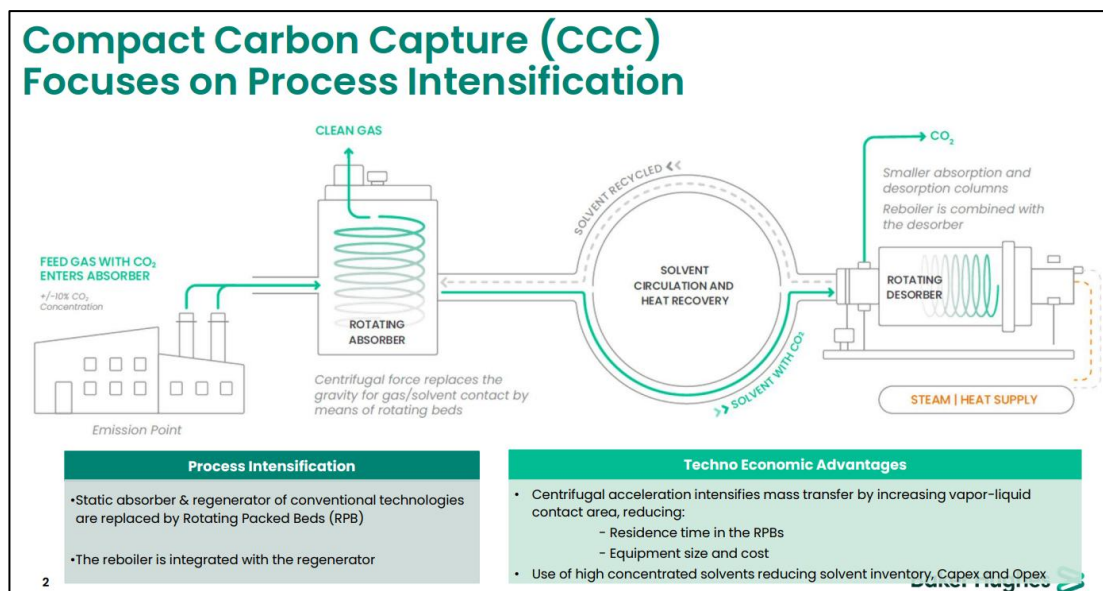


Fig. 2.6. 1 Baker Hughes CCC Process [16]

3.6.7 Discussion

Baker Hughes CCC technology is certainly interesting. When fully proven it could offer a “step change” in reducing capture costs and in reduced physical size of capture facilities to facilitate installation. The purchase of CCC and continued technology development shows commitment to offer carbon capture solutions. As noted, the technology is at a lower TRL than others. It relies on rotating equipment so parallel equipment may be needed to ensure high overall plant availability, at increased CAPEX. More development work is needed to have a fully commercial offering but interested parties should follow Baker Hughes progress. The technology is scalable and, by being compact, could offer opportunities for carbon capture to be implemented where conventional solvent-based capture technology could not be used because of space and footprint limitations.

3.7 BASF

3.7.1 Company Overview

Headquartered in Germany, BASF is one of the largest chemical producers in the world and present in 93 countries. It operates 234 production sites [18].

3.7.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of this report and BASF completion of a specific questionnaire.

3.7.3 Capture Technology

BASF were considered very relevant for this study as so well-established in acid gas treatment and by having developed advanced carbon dioxide removal solutions with a chemical solvent activator based on MDEA (aMDEA) over forty years ago. Since 2011 BASF has delivered its gas treatment technology under the OASE brand. It has experience with 500 operating applications [19]. OASE® blue was developed for large-scale CO₂ capture technology [20].

OASE® blue is applicable for inlet CO₂ concentrations of 3 to 35 vol.%, across many industries including hydrogen, ammonia, LNG, cement, lime kilns and power generation. It is claimed that CO₂ capture rate can be as high as 99%. This would need evaluation on a case-by-case basis. BASF note that high carbon capture is especially attainable for higher feed gas carbon dioxide contents, by use of high performance solvents (that effectively reduce CO₂ levels in “treated gas” to less than 100 ppmv). This applies for other advanced chemical solvents and is influential in selecting carbon capture for higher carbon dioxide content gases.

In commencing the study, it was clear BASF had world-leading solvent and carbon capture technology but is solely a technology licensor.

Of particular interest for the study was how many modular carbon capture facilities, with BASF solvents, have been delivered and are operational.

It has been conventional for BASF to work on the basis of preparing a process design “package” with equipment specifications, PIDs etc. for detailed engineering and management of fabrication by an engineering company. This approach has been undertaken with many engineering companies for BASF aMDEA based solvent for carbon dioxide removal.

3.7.4 Modularity, Standardisation and Cost

In 2022, BASF signed a Memorandum of Understanding (MoU) on a strategic partnership with GS Engineering & Construction (GS E&C) of South Korea, specifically to jointly develop modular solutions for carbon capture facilities [21]. GS E&C is a major international EPC company with established strategic partnerships with experienced Korean module fabricators and recent experience in international EPC projects based on modular design and supply.

BASF advised it could provide a carbon capture plant design for any required capacity. As with other companies in the study it has approached scalability by developing a suite of “standard” modular designs, in this case of 50, 100 and 400 tpd (16, 32 and 132 ktpa) with larger capacities having multiple units based on module transport and weight limitations. The 400 tpd carbon capture (132 ktpa) plant would consist of 7 module blocks. This “suite” of plant capacities is applicable to this study, and it is considered encouraging that specific efforts are being made at relatively small-scale capacities, down to 50 tpd.

The business relationship with GS E&C is primarily aimed at the Asian market. BASF’s commitment to work with other engineering companies would need to be addressed directly with them, though in Costain’s experience BASF has shown no reservations to working with a range of engineering companies via provision of a process design package.

Costain concurs with BASF comments on carbon capture cost being a strong function of inlet CO₂ concentration (specific cost falling with increased concentration). As this parameter varies greatly across different industrial applications caution is needed in comparing alternative capture costs, technologies and suppliers. Capture from flue gas at atmospheric pressure will normally have much higher CAPEX than capture from high pressure synthesis gas.

BASF concurred on all the key benefits of modularisation as proposed for this study (including reduced waste disposal, noise and pollution), also noting (correctly) that if “high value” construction labour (high productivity against competitive rates) and good labour availability the use of modularisation would need assessment against “stick built” plant erection. As with other suppliers the optimal level of modularisation would be considered on a case-by-case basis, with the solvent regeneration system in particular being relatively easily modularised.

An indicative timescale for project implementation and achieving operation is 18 to 24 months, dependent upon CO₂ capture capacity. BASF states it is committed to modular supply to minimise time to beneficial operation. This has supported their strategic partnership with GS

E&C, to offer leading carbon capture technology with established plant design and supply capability by entering into a relationship with a world leader in modular plant supply.

3.7.5 Applications & Experience

BASF has designed many CO₂ removal plants for applications including hydrogen, ammonia, LNG, cement, lime kilns and power generation.

GS E&C has focussed on relatively large capture plants. They have performed a pre-FEED for a modular 400 tpd (132 ktpa) CO₂ capture plant at a WtE incinerator. GS E&C has also performed a technology study and pre-FEED for 1,000 ktpa CO₂ capture facilities. The process flowsheet, engineering line diagrams, materials of construction and plant equipment for carbon capture by amine-based solvent are well understood. With BASF and GS E&C working together it appears they are essentially ready to offer a modular capture solution using proven technology. As noted earlier, BASF is confident that any carbon capture capacity can be considered and that modular design and supply will give lower cost and quicker deployment than “stick-built”.

3.7.6 TRL

BASF's CO₂ capture technology has TRL 9 in many applications, with a large number of commercial scale applications using its solvent technology. However, the TRL for a specific OASE solvent should be confirmed. For example OASE[®] blue has a TRL of no higher than 8. BASF are a leading candidate for consideration, especially with GS E&C with their joint strategic approach to modular carbon capture. Because their joint approach has yet to be commercialised this would indicate a lower TRL than 9.

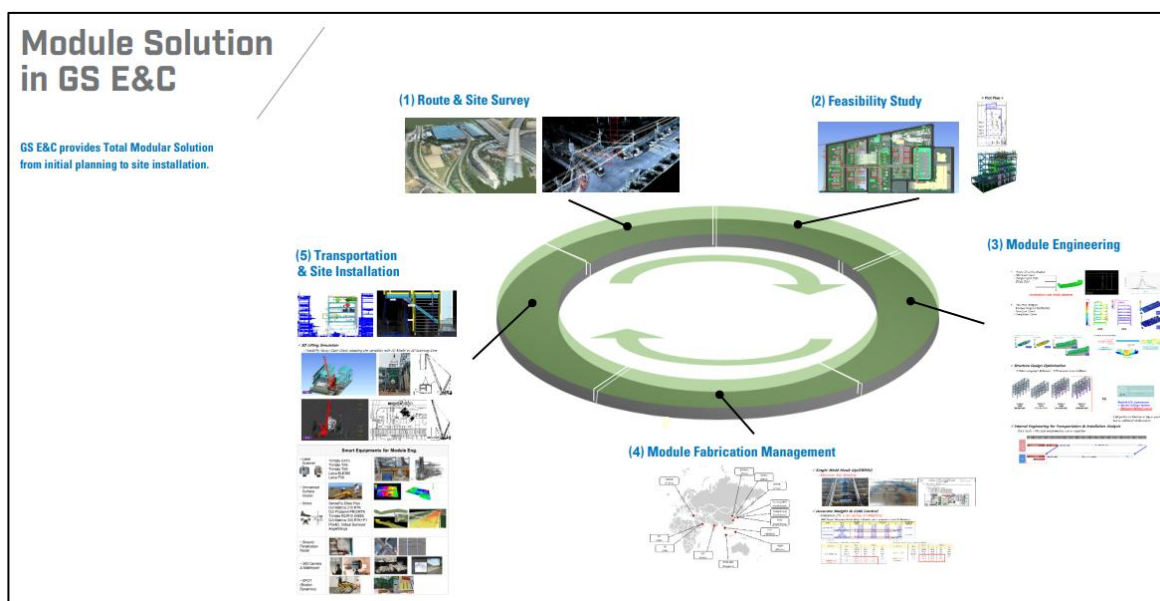


Fig. 2.7.1 GS E&C – CCUS Module Solution [22]

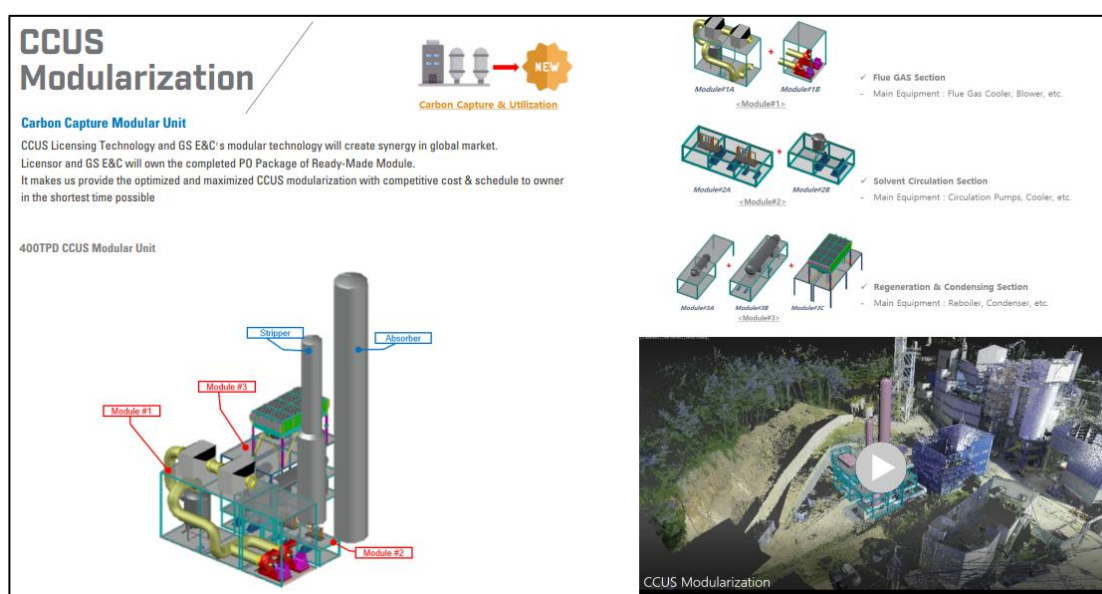


Fig. 2.7.2 GS E&C – CCUS Modularisation [22]

3.7.7 Discussion

BASF and GS E&C show a clear commitment to being able to offer scalable modular carbon capture solutions in the immediate term and for essentially any plant capacity. Their technology offering is relevant for relatively small carbon capture applications as per the study requirements. It could be considered to be at a marginally lower TRL than others who have specific carbon capture reference plants but BASF's extensive experience on a wide range of

projects and applications, when coupled with GS E&C, gives a pairing that is a primary candidate for modular carbon capture.

For a specific carbon capture application GS E&C may need to show focus on the international market, delivery capability and the ability to work to European and US codes and standards if necessary.

3.8 Carbon Clean

3.8.1 Company Overview

Founded in 2009 in India, Carbon Clean is now headquartered in the UK with offices in the USA and Canada [23]. Carbon Clean is focussed on carbon capture and patented technology solutions.

3.8.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for this report and Carbon Clean's completion of a specific questionnaire.

3.8.3 Capture Technology

Carbon Clean's experience with CO₂ capture technology is based on a proprietary solvent. Carbon Clean is thus similar to others in this report whilst also offering "process intensification" solutions:

- Proprietary amine-promoted buffer salt solvents: APBS-CDRMax for industrial CO₂ capture, APBS-CARBex for biogas/RNG upgrading
- Rotating packed beds (RPBs): these give improved mass transfer for CO₂ absorption as discussed for Baker Hughes 3C. Centrifugal forces, as the packed bed rotates, result in more effective solvent distribution than with a trayed or packed column (with rising gas and falling liquid solvent), better mass transfer between the liquid solvent and gas and thus greater absorption of CO₂, decreased residence time and smaller absorption equipment.

Carbon Clean's two especially relevant CO₂ capture offerings are [24]:

- CycloneCC™, modular: reduces overall cost and footprint for the reasons noted above.
- CaptureX semi-modular: captures CO₂ at low to high inlet concentrations, producing CO₂ at 99.5% purity. Delivered 80% prefabricated and containerised.

3.8.4 Modularity, Standardisation and Cost

CycloneCC™ provides fully modular (pre-fabricated) CO₂ capture with modules sized for road transportation.

For 100 ktpa CO₂ capture, stated plant height is 8.2 m with a footprint is 277 m².

CycloneCC™ capacities of 75 to 855 tpd CO₂ (25 to 280 ktpa) are offered as “standardised” designs for a range of CO₂ inlet concentrations (3% to 20%). Parallel modules would be added as processing capacity increases.

Carbon Clean noted that solvent regeneration energy consumption relies on so many variables that a “typical” value may not be representative for a specific application. Carbon capture efficiency of over 90% would normally be considered cost-effective as with other solvent technologies but a higher efficiency could be optimal depending on specific application. As noted elsewhere the optimal carbon capture is influenced by feed gas CO₂ content, process technology, specific design and performance.

Carbon Clean advised its RPB technology means total installed cost and physical footprint can be reduced by up to 50% compared to “conventional capture solutions”. They advise that mechanical completion and commissioning (from first module installation) may be as little as 8 weeks from module supply to site. Others could claim similar timescales as this duration is broadly consistent with Costain experience but the reduced module size for a given duty should benefit CycloneCC™. Claims would need to be investigated, especially what proportion of cost savings is due to the process intensification aspect of the RPB technology and what due to modularisation, as compared to “stick-built” construction.

3.8.5 Applications & Experience

Carbon Clean has technology references for 49 sites around the world using CaptureX semi-modular technology. They claim over 2.4 million operational hours of CO₂ capture over the past decade. Technology applications include “hard to abate” industrial sectors including steel, cement, refinery, EfW and biogas.

Applications of CycloneCC and CaptureX include [23]:

Product	Modular Capacity (ktpa CO ₂)	Client	Location	Application	Status (June 2024)
CycloneCC™	33 to 650	CEMEX	Germany	Cement	Engineering
CycloneCC™	3.4 (pilot)	ADNOC	UAE	Fertiliser	Operational
CaptureX	70	Holcim	Spain	Cement	Engineering
CaptureX	70	Ørsted	Sweden	Biomass CHP	Fabrication delivery
CaptureX	1.6	Tata Steel	India	Steel (blast furnace gas)	Operational

Product	Modular Capacity (ktpa CO ₂)	Client	Location	Application	Status (June 2024)
CaptureX	6.6	NTPC	India	Power generation (coal)	Operational
CaptureX	3.2	Taiheiyo Cement	Japan	Cement	Operational

Table 2.8.1 Carbon Clean CO₂ Capture Technologies & Applications

3.8.6 TRL

As advised by Carbon Clean:

- CycloneCC™: Now operating at TRL 7 with a test campaign set for completion in Q3 2024. The ADNOC pilot facility may be operational by the end of 2024.
- CaptureX: TRL 9

3.8.7 Discussion

Carbon Clean's CaptureX technology is essentially proven. Considering the requirements of this study it is partially modular.

CycloneCC™ technology development and business focus show a clear commitment by Carbon Clean to offer modular carbon capture solutions. The technology could offer a "step change" in reduced capture costs and reduced physical size of capture facilities. It relies on rotating equipment and therefore consideration of parallel equipment, at extra CAPEX, may be needed to ensure high enough plant availability.

Carbon Clean's CycloneCC™ technology has had limited trials. More, at increased gas flow and capture duty would be of clear value. It would be recommended that a prospective client consults with Carbon Clean to verify performance for the potential client's specific gas conditions and carbon dioxide content, especially to verify the advantages and performance of the rotating equipment.

For CycloneCC™, Carbon Clean are equipment suppliers and a prospective client would contact them directly. Carbon Clean would work with preferred engineering companies and fabricators for modular plant delivery. Carbon Clean is actively developing key relationships for execution of capture projects based on CycloneCC™.

For CaptureX, Carbon Clean operates as a technology licensor so a prospective client would obtain a plant design from them to take to an engineering contractor so as to execute EPC. Carbon Clean has preferred EPC companies for CaptureX plant project execution and would recommend these to prospective clients.

Carbon Clean has shown good focus on development of innovative modular technology, especially at relatively large carbon capture applications. Further CycloneCC™ trials would be of great value. Their technology has merit and should be investigated by a prospective client based on a definitive application.

3.9 Chart

3.9.1 Company Overview

Chart is headquartered in Georgia, USA with operations across the USA and engineering and manufacturing in Europe, India and China. In 2020, Chart acquired Sustainable Energy Solutions' (SES) and with it their Cryogenic Carbon Capture™ process. This integrates very well with Chart's business as a provider of modular process solutions, equipment and technology to create what can be considered a total CO₂ capture solution [25].

3.9.2 Source of Information

Information was primarily obtained from the company website, supplemented by discussion for the needs of this report and Chart's completion of a specific questionnaire.

3.9.3 Capture Technology

The Cryogenic Carbon Capture™ (CCC) process captures carbon dioxide by chilling and freezing.

Chart also offers small-scale CO₂ capture via its patented CiCi technology. The process features three stages: drying (moisture removal), scrubbing (VOC and impurity removal) and chilling (facilitating CO₂ capture as gas, liquid or solid).

In 2023, Chart acquired Howden, a leader in Mechanical Vapour Recompression (MVR) technologies as used to reduce energy consumption for solvent regeneration by heat pumping [25], by employing electricity in lieu of thermal energy.

3.9.4 Modularity & Standardisation

Chart advised they are “working towards” having “standard” CCC designs and process modules, available in 100, 500, 1000 tpd units. They advised that as more insight is gained in potential carbon capture markets and industries a “standard” plant design against the “most common capture plant size” could be developed.

For a 100 tpd CCC plant, a footprint of about 20m × 20m was stated. Exactly what this includes, and the overall weight could be provided by more detailed work for a specific application.

Chart Industries has acquired companies that manufacture much of the equipment used in the CCC process (e.g., brazed-aluminium multi-stream heat exchangers, other heat exchangers, cascade refrigeration systems (currently used for natural gas liquefaction), process vessels/tanks, compressors (Howden), air coolers (Hudson)). Chart has manufacturing facilities in many countries, allowing for a localised manufacturing option.

For CCC plants over about 100 tpd some equipment would be too large for off-site fabrication and modularisation.

3.9.5 Applications, Experience and Cost

To date the CCC process has been demonstrated at pilot plant scale in capturing up to 1 tpd of CO₂ with field tests conducted on gas from cement works, coal-fired power plants and natural gas-fired fuel gas [26]. The intended plant capacities stated above as “goals” thus represent significant scale-up and need to be treated with caution.

Feasibility studies are ongoing for CCC applications in multiple industries (e.g., cement, lime, refractory, carbonates, coal-fired power production, natural gas combined cycle power production, biomass-fired combined heat & power plants).

Chart and partners, including the US Department of Energy, are currently in the construction phase of a CCC plant to capture 30 tpd from a cement kiln, Kansas City, MO, USA. Commissioning is expected in the second half of 2025. Results on plant performance would clearly be of interest in advancing CCC.

Chart is currently focusing on design of CCC for gas streams with 5-40% CO₂ but note the technology is applicable for a wider range of CO₂ concentrations. By its nature it would be expected to be applicable to high CO₂ levels including up to 75 – 80% in oxyfuel fired applications.

The “standard” CCC process design is to capture 95% of the CO₂ in the incoming gas. It is stated that a “small” increase in CAPEX and OPEX would enable CO₂ capture up to 98%.

3.9.6 TRL

Chart advise the CCC Process has a TRL of 7 (System/process prototype demonstration in an operational environment) whilst process equipment is “proven” and has a TRL of 9. Process equipment in the CCC process is conventional and easily acquired – often off-the-shelf for

certain scales. The process uses mainly compressors, pumps, and heat exchangers, all of which are common in other industrial processes.

TRL for CCC can be maybe better assessed if and when results from the 30 tpd Kansas City plant are available.

3.9.7 Discussion

Chart's CCC technology is an interesting alternative in using low temperature partial condensation for CO₂ capture, somewhat akin to Air Liquide Cryocap although CCC removes carbon dioxide by condensation and freezing.

Chart's technology may be most cost-effective on applications with high carbon dioxide content as costs should be less strongly influenced than with solvent-based processes.

Based on Chart's technology trials it would be recommended that a prospective client consult with Chart to verify plant performance for the potential client's specific gas conditions and carbon dioxide content. Chart should advise whether they would wish to propose CiCi or Cryogenic Carbon Capture™.

Chart has shown a focus on development of modular technology at the larger end of the potential range of carbon capture applications. This looks to be a potentially significant extrapolation of trials performed to date whereas the technology would seem to have merit at small- to medium-scale and is relevant to this study. It is not yet proven to the extent of other available technologies, especially solvent-based, but it would be interesting to compare Chart's claims for a specific application and to highlight the comparative capture cost.

3.10 Entropy

3.10.1 Company Overview

Based in Canada, Entropy was formed in 2021 as a “clean tech” spin-off from Advantage Oil & Gas [27]. Entropy is not a technology supplier but are worthy of note as their business model is to invest in, own and operate carbon capture facilities if “carbon policy provides a return on investment”.

3.10.2 Source of Information

Information was primarily obtained from the company website. Entropy also participated in limited discussion via e-mail.

3.10.3 Capture Technology

Entropy’s Modular Carbon Capture™ (MCC) solution uses absorption by a proprietary solvent (“Entropy 23”). They claim a thermal energy duty for solvent regeneration of 2 to 2.2 GJ/t CO₂ which is similar to leading solvents and as compared to 3.5 - 4 GJ/t CO₂ with MEA. Licensors noted in this report show a similar “best in class” energy consumption with advanced chemical amine-based solvents.

Entropy and an original equipment manufacturer (OEM) partner have developed integrated Carbon Capture & Storage (iCCS) technology. It is claimed that iCCS can deliver 25% CAPEX savings compared to a retrofit.

3.10.4 Modularity & Standardisation

Entropy’s Modular Carbon Capture & Storage™ (MCCS) technology is claimed to be scalable down to 8 ktpa and “implementable” in less than 2 years from final investment decision [28].

3.10.5 Applications & Experience

Entropy notes its carbon capture solution is applicable for a wide range of industrial emissions associated with ethanol, methanol, natural gas processing, oil production, steel and power generation.

Phase 1 of Entropy’s first MCC application, Glacier (Canada), was delivered in 2022 at a stated cost of US\$31 million. As with all costs the overall scope would need to be clarified. This stated cost looks to be a total project cost. Two CO₂ capture units were installed on Caterpillar 3616

engine-driven compressors: one a retro-fit, the other a new-build. With a capacity of 47 ktpa CO₂, capture rates up to 97% are reported [29]. Entropy state this is the only onstream natural gas based post-combustion capture plant in the world.

3.10.6 TRL

Entropy advised that as operational and “proven,” its solution is TRL 9.

3.10.7 Discussion

Entropy is essentially outside the scope of this report by not offering a carbon capture technology or direct supply solution but is interesting due to its operating experience (and by being able to potentially provide support to a carbon capture venture).

The various claims on solvent performance, cost and project deployment time have not been reviewed in detail as Entropy is not a module supplier. They could be an interesting company for a carbon capture project developer to follow up with.

3.11 Fluor

3.11.1 Company Overview

Fluor provides engineering, procurement and construction (EPC) services globally across sectors including power generation, mining and transport [30].

3.11.2 Source of Information

Information was primarily obtained from the company website.

3.11.3 Capture Technology

Fluor's post-combustion, low pressure CO₂ capture technology, Econamine FG Plus™, uses absorption. Fluor describe the technology as "well suited to capture CO₂ from large, single-point emission sources...including large facilities with CO₂ capture capacities greater than 10,000 tpd" [31]. It is applicable to flue gases with as low as 3% CO₂ and of high oxygen content (up to 15 vol.%) [32].

Fluor's Solvent™ process uses a dry propylene-carbonate solvent to remove CO₂ from gas streams. As a physical solvent it is particularly suited to blue hydrogen applications (high CO₂ partial pressure). It operates by flash regeneration, so no thermal energy is needed for regeneration and CO₂ is thus available at elevated pressure to reduce downstream compression costs.

3.11.4 Modularity & Standardisation

At the large carbon capture capacities Fluor focuses on it works on a bespoke basis with clients to optimise fabrication and construction strategies to minimise cost and schedule [33].

3.11.5 Applications & Experience

Fluor has delivered over 400 CO₂ removal units in natural gas and synthesis gas processing and licensed over 30 Econamine FG™ Plus plants over 30 years [32].

3.11.6 TRL

Costain assessed as 9 based on information found from experience at large plant capacities but uncertain for modular applications.

3.11.7 Discussion

Fluor tend to concentrate on bespoke projects. Whilst Fluor has relevant experience and capability, others noted in this report would seem to have a specific business focus more fully aligned with smaller-scale, modular carbon capture.

3.12 Giammarco-Vetrocoke

3.12.1 Source of Information

Information was primarily obtained from the company website.

3.12.2 Company Overview

Based in Venice, Italy, Giammarco-Vetrocoke describes itself as a “trusted industry leader in capturing CO₂ from industrial emissions, effectively combating climate change” [34]. Giammarco-Vetrocoke noted a master license and engineering agreement with KBR, though it is uncertain if this is exclusive and exactly what it includes. [35].

3.12.3 Capture Technology

Giammarco-Vetrocoke CO₂ capture technology uses Hot Potassium Carbonate (HPC) solvent. This can give over 90% CO₂ removal from flue gas (and CO₂ purity exceeding 99.5%) but as a physical solvent may not offer as high carbon capture as amine-based chemical solvents for gas CO₂ contents below 6 – 7 %. As based on physical solvent, Giammarco-Vetrocoke technologies are applicable to carbon capture from syngas.

Key technologies [36]:

- HPC – Genesys: conventional regeneration (stripping) system.
- HPC – EcoEnergi: stripping section is in two sections including pressure let-down for partial regeneration, giving a 40% reduction in thermal energy consumption compared to the conventional Genesys scheme and CO₂ at elevated pressure so as to reduce downstream compression.
- HPC – NovaFlash: produced steam is recompressed and returned to the stripping column. Thermal energy saving is up to 40-50% compared to HPC – Genesys.
- HPC – VoidCapture: regeneration at sub-atmospheric pressures enables a lower stripping temperature, facilitating use of available waste heat. However, this can mean that CO₂ is available at reduced pressure, which is not desirable in terms of compression duty and cost.

Successful testing of HPC – VoidCapture has been demonstrated in multiple pilot plants.

3.12.4 Modularity & Standardisation

Limited specific information obtained.

3.12.5 Applications & Experience

Giammarco-Vetrocoke has over 70 years of experience in capturing CO₂ from industrial emissions. It has over 400 industrial references [34]. As would be expected with a physical solvent these are mostly on high pressure syngas, including 350 in hydrogen and ammonia.

Giammarco-Vetrocoke technology can be retrofitted into power generation, cement, steel, pulp, glass and WtE plants.

Other applications include:

- Direct Reduction Iron (DRI) Reactor Off-Gas (syngas: a mixture of CO and H₂)
- Natural Gas Sweetening
- Gasification of Waste and Coal
- Recycled Gas from Ethylene Oxide (EO) & Vinyl Acetate Monomer (VAM) Units
- Tail Gas from PSA Units

3.12.6 TRL

HPC – VoidCapture has undergone successful testing at pilot plant level. There are plans to further advance TRL via demonstration plant operating on flue gas from waste incineration.

3.12.7 Discussion

Whilst there can be little doubt that Giammarco-Vetrocoke has much relevant experience and capability, others noted in this report would seem to have business focus more fully aligned with smaller-scale, modular carbon capture.

3.13 Honeywell UOP

3.13.1 Company Overview

Honeywell is one of the 30 Dow Jones companies, based in Charlotte, North Carolina, USA [37]. Honeywell UOP is a wholly owned subsidiary and the world's largest process technology licensor in refining, petrochemical and "sustainable technology markets". It offers commercially proven CO₂ removal and capture solutions and has a wide range of available process technologies from which to select the most appropriate.

Honeywell UOP has extensive experience in modular plant solutions for gas processing and leverages its FastFEED™ and modular execution capability.

3.13.2 Source of Information

Information was primarily obtained from the company website. Honeywell also participated in discussion and provided answers to questionnaire.

3.13.3 Capture Technology

Honeywell UOP was considered an important company for this study by having a range of carbon capture technology solutions (at TRL 9) and a business focus on design and supply of modular process plant. Many engineering companies have used Honeywell UOP process design "packages" and the business model for application of the "packages" is well understood and reliable.

CO₂ capture technologies include:

- Amine Guard / Amine Guard Formulated Solvent. Over 600 operating units worldwide, typically in gas processing and LNG plants. This solvent is applicable to "higher" CO₂ feed gas levels including for capture from synthesis gas on blue hydrogen plants.
- Advanced Solvent (Amine) CO₂ Capture (ASCC). Developed specifically for post combustion flue gas from many years of university research. The first commercial application is being sought. Considered to be applicable at any scale with 3,600 ktpa project being engineered and offered as a modular solution.
- Benfield®: inorganic solvent (hot potassium carbonate with activator) for higher partial pressure applications such as carbon dioxide removal from hydrogen synthesis gas. Over 650 units deployed worldwide.

- Selexol™: physical solvent (polyethylene glycol derivative), typically deployed in gasification (relatively high CO₂ partial pressure) for sources containing sulphur or in oxidative conditions but is also suitable for carbon dioxide removal. Costain is aware of its use on UK LNG “Peakshaving” plants to reduce CO₂ from typically 2 – 3 mol.% to about 0.5 mol.% and to also effect gas dehydration. As a physical solvent regeneration can be performed by rich solvent flash to release CO₂ at elevated pressure – typically of the order of 10 bar a.
- PSA: over 1,100 units deployed worldwide, mostly on hydrogen purification service which includes CO₂ removal. 3 applications for CO₂. Adsorbent technology for CO₂ removal alone is suitable for CO₂ at relatively low levels being reduced to virtually zero, so is something of a “special case” but on hydrogen purification service is applicable as the main objective is to produce hydrogen to 99.9%+ purity.
- Separex™ Membrane Systems: particularly applicable to offshore CO₂ capture and sequestering due to being relatively compact, having low weight and not incurring any effects due to plant movement as with solvent-based technologies. Over 300 units deployed worldwide.
- Orloff low temperature CO₂ fractionation: “Bulk” removal of CO₂ at potentially very large scale with low energy consumption. Modular.

Potential carbon capture technologies can be broadly “screened” by consideration of CO₂ partial pressures. This is a well-accepted and reliable approach. Honeywell UOP can provide essentially all process technologies as summarised below:

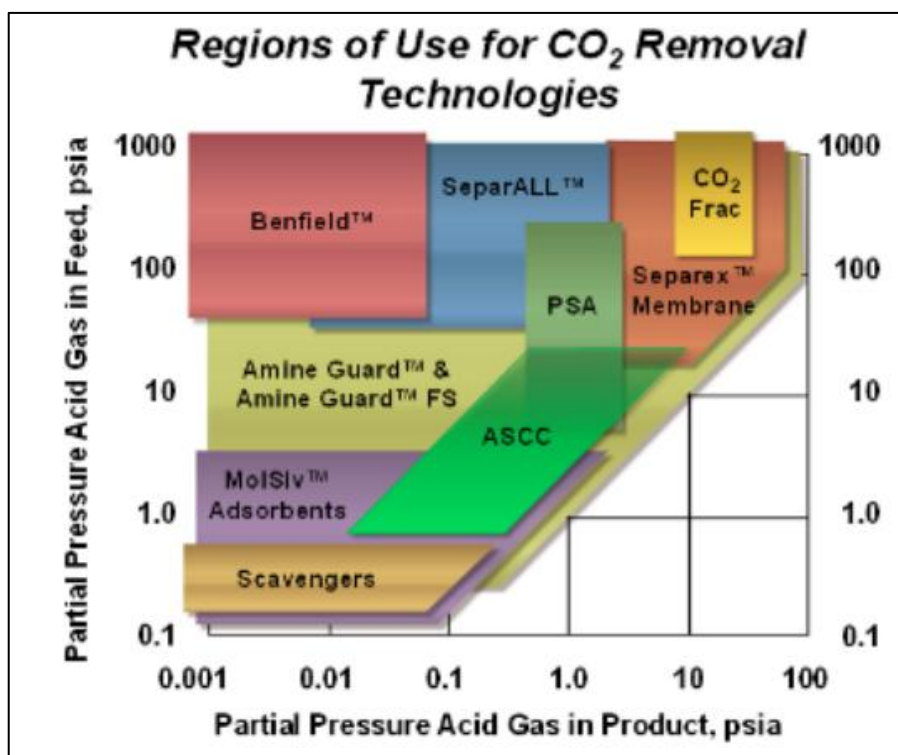


Fig 2.13.1 Honeywell UOP - CO₂ Capture Technology Selection

Honeywell UOP technologies of most relevance to this study are:

- ASCC (TRL 7) for lower CO₂ concentration post-combustion inlet streams. Advantages claimed include:
 - High mass transfer rates require shorter absorber (30% saving on absorber cost).
 - Patented, high efficiency heat exchanger design reduces heat requirements to 2.1 to 2.4 GJ/t CO₂ captured. This compares to 2.4 to 3.7 GJ/t CO₂ for “conventional” solvent alternatives, so providing 10% to 30% OPEX savings. Other leading solvents provide similar performance, but ASCC may be able to achieve 1.8 GJ/t.
 - Potential to use heat pumping rather than thermal energy for regeneration due to relatively low reboiler temperature. Note that others claim similar and increased opportunity to use waste heat at around 100°C.
 - Elevated operating pressure for regeneration delivers CO₂ at 5-6 bar g, reducing downstream carbon dioxide compression requirements due to much reduced compression ratio: savings of CAPEX (30%) and OPEX (40%) are noted and look reasonable. Other leading solvents e.g. OASE, CANSOLV, Axens have similar claims.
- Cryo and Cryo-PSA (TRL 9) for higher CO₂ concentration streams (to deliver a liquid product) such as on hydrogen purification from reforming, FCC, cement. As noted

elsewhere streams with high CO₂ partial pressure can lead to relatively low carbon capture costs. Can be all-electric system with combination of proven technologies: pressure swing adsorption, molecular sieve drying and cryogenic fractionation.

Honeywell UOP is currently developing ASCC as a modular product.

3.13.4 Modularity, Standardisation and Cost

Since the early 1980s, Honeywell UOP has delivered over 1,800 modular process units worldwide in refining, petrochemicals and upstream oil & gas. It has developed strong relationships with key equipment and module fabricators to provide plants directly as well as for EPC contractors.

Honeywell UOP's modular design philosophy is common with others considered and focusses on definition and optimisation of equipment layout to maintain their "standard" module design, minimise change and ensure maximum pre-assembly.

Honeywell UOP has developed an execution philosophy and design approach called FastFEED™. This approach to project execution uses parallel execution of activities in the basic engineering and FEED phases [38] to give accurate cost definition and earlier FID by up to 6 months. Plant operation may thus start 10 months earlier than otherwise. Of course, such figures would have to be assessed on a case-by-case basis but FastFEED™, as a key element of Honeywell UOP business, does show understanding and commitment to modular plant supply. Honeywell UOP considers their approach offers cost and schedule certainty. They fully "buy-in" to modular design for small- to medium-scale carbon capture.

It is difficult to be specific on the capture cost for ASCC as it is dependent on such factors as:

- Inlet flue gas CO₂ concentration
- Type of technology deployed
- Pre-treatment technology and cost considerations
- CO₂ product specifications
- Plant location

Honeywell UOP provided indicative cost figures for different carbon capture technologies which highlighted lower cost for higher CO₂ content feed gas. ASCC, which is appropriate for flue gas, may be US\$55 – 70 per tonne whereas Amine Guard on syngas may be US\$45 – 60 per tonne. These cost values should only be used for broad comparison and "screening" for a

specific project. Economies of scale would have to be considered. The values are as broadly anticipated by Costain for a carbon capture plant alone.

3.13.5 Applications & Experience

As noted, Honeywell UOP has an extensive range of CO₂ capture technology solutions that have been supplied as modular plants.

One technology that is essentially unique is Ortloff low temperature CO₂ fractionation. It provides CO₂ directly as a high purity liquid product. A major world-scale facility, the Century Gas Plant, Sandridge, Texas, USA (8,400 ktpa CO₂) has operated for over 15 years to capture carbon dioxide from high CO₂ content natural gas for enhanced oil recovery (EOR). The same process technology will be deployed at the ExxonMobil Baytown refinery complex (Texas, USA) to capture 7,000 ktpa CO₂ and for Wabash Valley. This technology performs capture and liquefaction at low energy consumption. By producing liquid CO₂ it minimises the cost of carbon dioxide transportation. To date this relatively “novel” technology has only been applied on relatively large projects, but it is especially interesting for blue hydrogen and other carbon capture projects considering feed gas with relatively high carbon dioxide content.

Honeywell UOP has undertaken FEED studies for modular projects including a combination of PSAs and cryogenic capture for blue hydrogen plants (somewhat akin to Air Liquide CryoCap). It has undertaken studies for cryogenic carbon capture units for the cement industry – for applications where carbon dioxide has a sufficiently high partial pressure to capture it by partial condensation.

For smaller scale modular post-combustion capture the relatively new ASCC (enhanced amine) technology is a key focus.

3.13.6 TRL

Honeywell UOP advised that all its CO₂ capture technologies are at TRL 9 as they have been commercially deployed many times at scale. Overall, they account for the capture of 15 million tpa CO₂, about 38% of the world’s current sequestered CO₂.

The only exception to a TRL of 9 is Advanced Solvent CO₂ Capture (ASCC) which is currently at TRL 7. It has been tested for over 8,500 operating hours at the NCCC. The first commercial units are expected to be operating by 2026.

3.13.7 Discussion

Honeywell UOP has demonstrated the ability to provide effective carbon capture, using modular and relatively “standardised” solutions. They can select from a very wide range of applicable technology solutions and have considerable experience in design and supply of modularised solutions. They “bought-in” to all aspects of modularising carbon capture solutions, offering “standard” designs and managing project execution to ensure higher quality and shorter delivery than otherwise. They have a business model and business approach suitable to meeting the needs of carbon emitters and providing modular plants.

3.14 Koch Modular

3.14.1 Company Overview

Koch Industries is a US based conglomerate. It manufactures equipment including to support carbon capture e.g. structured packing for improved mass transfer in absorption [39]. More significant to this study, via Koch-Glitsch, it is a joint-venture partner in Koch Modular Process Systems (“Koch Modular”) which offers modular CO₂ capture technology [40].

3.14.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of this report and Koch’s response to a specific questionnaire.

3.14.3 Capture Technology

Koch Modular’s CO₂ capture offering is based on absorption.

3.14.4 Modularity & Standardisation

Koch Modular was considered for this study by having extensive experience in design and supply of small- to medium- scale modular process plant including for carbon capture, as well as applications in e.g. alternative fuels, petrochemicals, power [41], [42]. Modular plant supply is “usual business” via a well-established supply chain for engineering and fabrication. As with others, Koch Modular fully “bought in” to the requirements of this study with regard to the suitability of modular plant for carbon capture.

Koch’s module dimensions are compatible with the constraints of road transport, typically being limited to 3.7 m x 4.3 m, height up to 27.4 m and weight of 90 tonnes. Process equipment is typically limited to 2.0 m diameter (with off module tanks up to 3.0 m diameter). For larger carbon capture applications, modular plant is applicable other for than free-standing columns, which can be supplied fully dressed.

3.14.5 Applications & Experience

Koch Modular has focussed on providing solutions for carbon capture and has collaborated with multiple academic and industry partners in developing modular CO₂ capture solutions:

- 2009: Koch delivered its first CO₂ capture pilot plant at a coal-fired power station, Wisconsin, USA. It later delivered a larger pilot plant for the same client at a power station

in West Virginia, USA. This pilot unit ran for two years at up to 300 tpd (100 ktpa) CO₂ removal [43].

- 2014: Koch constructed a pilot plant at the University of Kentucky, USA to capture 20 tpd (i.e. 6.6 ktpa) CO₂.
- 2023: Koch announced Project Enterprise, a CO₂ capture demonstration scheme, and delivered and installed modules at the Los Medanos Energy Center's gas-fired power station, California, USA to capture 11 tpd (i.e. 3.6 ktpa) CO₂. The plant uses ION Clean Energy's proprietary solvent (ICE-31) [44].
- 2024: Koch announced a collaboration with PPL Corporation for a "large scale" CCUS pilot project to be located at the Louisville Gas & Electric gas-fired power station in Cane Run, USA. Designed to capture 90 ktpa CO₂, the pilot "aims to refine and prepare the technology for widespread commercial use" [45].

3.14.6 TRL

Koch Modular describes its modular plant offering as TRL 7 but against others it could be considered TRL 8 based on the extensive carbon capture technology testing, the conventional process design for solvent-based absorption and execution of modular plant design and supply being proven and conventional.

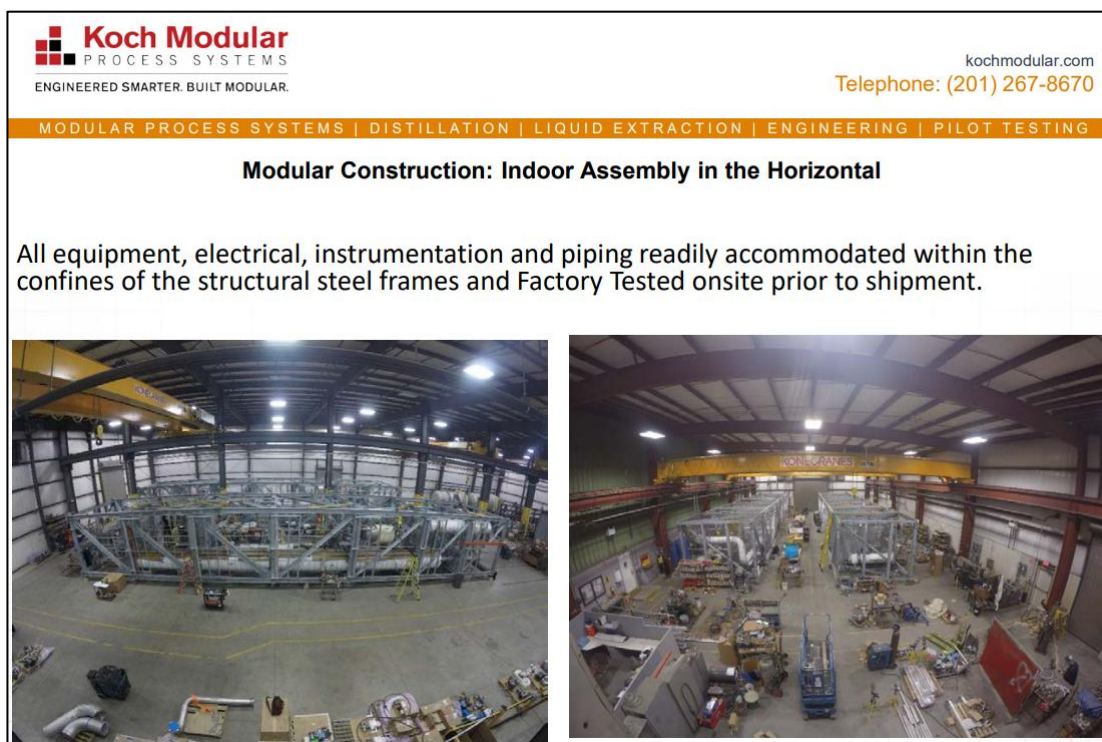


Fig. 2.14.1 Koch Modular – Modular Fabrication Facilities [42]

Transportation: Via Roadway



Fig 2.14.2 Koch Modular – Modular Transportation [42]

Traditional Modular Construction: All equipment and piping readily accommodated within the confines of the structural steel frames.



Commercial Scale System



Pilot Scale System

Fig. 2.14.3 Koch Modular – Modular Construction [42]



Fig. 2.14.4 Koch Modular – Hybrid Modular Construction [42]

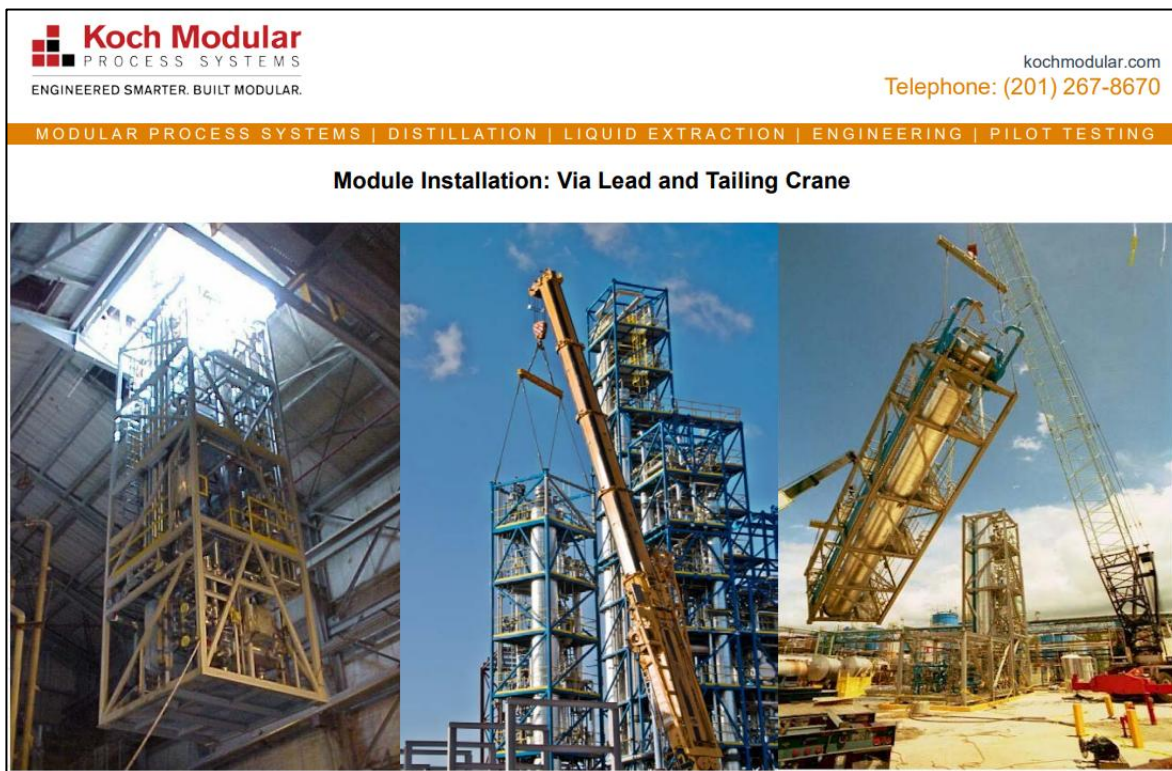


Fig. 2.14.4 Koch Modular – Module Installation [42]



Fig. 2.14.6 Koch Modular – Completed Modular System [42]

3.14.7 Discussion

Koch Modular has effectively demonstrated the ability to provide effective carbon capture, using modular and relatively “standardised” solutions.

Company focus has been on the development of “standardised” capture solutions for small- to medium- plant capacities consistent with equipment such as boilers and engines.

Koch Modular has developed a business model and business approach to meeting the needs of carbon emitters. They offer engineering and design capability with relatively established designs for carbon capture. Whilst they could not necessarily “compete” for the large carbon capture facilities considered so far around the world, they have focussed on developing solutions for smaller-scale projects and are of clear interest against the requirements of this study.

As Koch mainly supplies into the USA and takes a “standardised” approach to supply it would be necessary to consider their ability to work to international engineering codes and specifications, especially for instrumentation and electrical equipment.

It would be valuable to have results from pilot facilities to assess overall TRL and to demonstrate a TRL of at least 8 for a range of alternative feed gas conditions, carbon dioxide content and required capture rate. The performance of its selected solvent against leading solvents offered by licensors would be interesting.

3.15 Linde

3.15.1 Company Overview

Headquartered in Germany, Linde is a major industrial gases and engineering company. Linde has extensive experience in CO₂ purification and liquefaction (modular and large-scale) and also offers CO₂ capture technology [46].

3.15.2 Source of Information

Information was primarily obtained from the company website.

3.15.3 Capture Technology

Linde offers CO₂ capture technology for pre-combustion, oxy-fuel combustion and post-combustion applications [47].

Linde CO₂ capture technologies include [48]:

- For low CO₂ content streams e.g. flue gas
 - Absorption (i.e. scrubbing using an amine-based solution) using BASF OASE® blue or Rectisol
- For medium to high CO₂ content streams e.g. syngas, hydrogen
 - PSA technology and cryogenic separation: HISORP CC
 - Membrane separation: HISELECT

Linde also has experience with CO₂ compression, dehydration and liquefaction.

3.15.4 Modularity & Standardisation

Linde has extensive experience in delivery of modular gas processing plants. It also has a partnership with BASF to deliver modular CO₂ capture solutions using BASF's gas treatment technology, OASE® blue [49]. To date this has resulted in two pilot plants.

3.15.5 Applications & Experience

Linde list CO₂ capture applications in chemicals production (ammonia, ethanol), cement, refining, hydrogen production, power-generation and industry (iron & steel, pulp & paper).

Application	CO ₂ Capture Capacity (tpd / ktpa)	Client	Location	Status
Coal-fired power station	7.2 / 2.4	RWE	Niederaussem, Germany	Operational 2009 to 2017
Research facility	30 / 10	Linde used NCCC for testing	Wilsonville, USA	3,200 h operational time

Table 2.15.1 Linde & BASF CO₂ Capture Applications

3.15.6 TRL

The business link with BASF would appear to reflect a TRL of 8 but this would need verification.

3.15.7 Discussion

Engagement with Linde was limited, and it was unclear that Linde offered any clear advantages for carbon capture over the leading suppliers considered in the study, especially as BASF is considered separately. They have a range of available technologies based on adsorption, as with Axens and Honeywell UOP, and cryogenic capture as with Chart and Honeywell UOP.

3.16 Mitsubishi Heavy Industries

3.16.1 Company Overview

Mitsubishi Heavy Industries (MHI) is a Japanese-based conglomerate. MHI has focussed on CO₂ capture for many years and offers its process technology, design and supply (and EPC if required) fully in-house via its engineering division (MHIENG) [50].

3.16.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of this report and a comprehensive technology summary from MHI.

3.16.3 Capture Technology

MHI's CO₂ capture technology is based on absorption. The KM CDR Process™ was available as long ago as 1990 (primarily for large-scale applications) using KS-1 amine solvent. MHI's offering has been developed into the Advanced KM CDR Process™ and KS-21 respectively [50]. Carbon capture rate is typically above 95% based on cost-optimisation and CO₂ purity is above 99.9% [51].

3.16.4 Modularity & Standardisation

MHIENG has a clear business focus on carbon capture, developing its offering for over 25 years. Its modular CO₂ capture plant (CO₂MPACT) is available in a wide range of "standardised" capacities [51].

Model	Capacity (tpd / ktpa)	Project Stage	Applications
A	0.3 / 0.1	Verification	
B	3 / 1.0	Demonstration	
C	30 / 10	Commercial use and demonstration	Power generation Boiler/furnace Shipping WtE Gas engine
D	100 / 32	Commercial use for small- to medium-scale	Power generation Boiler/furnace Cement Steel Shipping WtE Gas engine
E	150 / 50		
F	200 / 66		

Table 2.16.1 MHI CO₂ Capture Technology, CO₂MPACT [51]

3.16.5 Applications & Experience

The large-scale Advanced KM CDR Process is proven technology having been implemented at 16 sites worldwide with a further 2 under construction. These include Petra Nova (USA), the largest post-combustion CO₂ capture project in the world, capturing 1,400 ktpa from a coal-fired power station [51]. This project has had commercial issues that should be distinguished from technical and operational issues in any consideration of Advanced KM CDR.

MHI has entered into an agreement with Drax Group to install Advanced KM CDR at Drax power station (North Yorkshire, UK) as part of a major Bioenergy with Carbon Capture and Storage (BECCS) project [52].

In 2022, MHIENG announced that its first compact, modular carbon capture plant (CO₂MPACT) had entered full-scale operation at a small biomass power station in Hiroshima, Japan. With a 0.3 tpd (0.1 ktpa) CO₂ capture capacity, the unit has a “standardised” design with a footprint of only 5 m x 2 m (though this value should clearly be “checked” against what scope it includes).

MHIENG noted its 30 tpd “Compact Series” plant design as being suitable for and focussed on carbon capture from gas engines. They currently have a number of operating installations but anticipate many more in the short- to mid-term. This is of direct relevance to this study as it aligns with requirements of having a business focus, development plan and execution for smaller-scale carbon emitters.

MHIENG plans to expand its portfolio of compact CO₂ capture systems and to pursue reductions in installation time and OPEX [50].

In 2023, MHIENG delivered another 0.3 tpd CO₂ capture modular unit to a ceramics facility in Japan [53].

MHIENG has experience in carbon capture with production of pure liquid CO₂.

Based on long experience MHI provided some interesting points regarding modular plant design and associated “compromises” in plant performance and OPEX [51]. These would apply universally in considering optimal project execution and construction strategy and show

that any carbon capture project needs to fully consider project specific issues rather than using indicative values that may be inappropriate against specific project scope and requirements.

For example:

- If the plant operates for many years, then performance inefficiencies (and the excessive operating costs that accrue) may outweigh CAPEX savings over time
- There can be wide differences in gas compositions and carbon dioxide content over time and plants need to be robust to change whilst maintaining capture performance and achieving high availability
- A “standard” design may mean having a plant size larger than is needed (so as to fit a supplier’s “portfolio” of “standard” designs) so equipment size, plant footprint and cost exceed what is appropriate.
- Even with “stick built” plants there can be a significant amount of off-site fabrication. Project execution should consider a “hybrid” approach to optimise the extent of modularity to achieve optimal results.

3.16.6 TRL

TRL of 9 for Advanced KM CDR. For CO₂MPACT the TRL may be as high as 9 due to plants now being in operation. It would be appropriate to obtain more details from MHI to confirm.

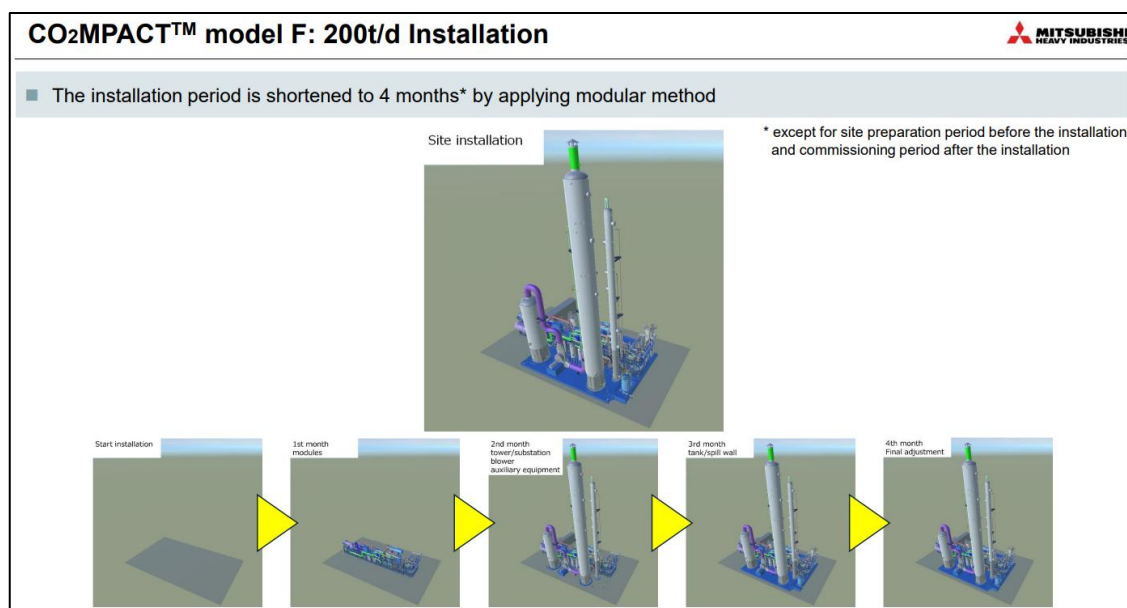


Fig. 2.16.1 MHI CO₂ Capture Installation, CO₂MPACT [51]

3.16.7 Discussion

MHI has demonstrated the ability to provide effective carbon capture at scale, using modular and relatively “standardised” solutions, at capacities much larger than 100 ktpa. For large-scale applications MHI can be considered one of the world leaders in carbon capture with experience developed over many years. Recent technology development provides an advantageous position for smaller facilities.

Business focus has been on the development of “standard” solutions for small- to medium plant capacities including for gas engines. More so than most, MHI has looked to apply its technology on small-scale facilities as well as larger scale and they understand the optimisation of plant engineering and project execution for modular supply. They have a business model and business approach to meeting the needs of carbon emitters effectively. They offer full engineering and design capability.

3.17 Pentair

3.17.1 Company Overview

Headquartered in Denmark, Pentair Union Engineering has worked on carbon dioxide plants – mostly for liquefaction – for over 50 years and describes itself as “specialised in sustainable technologies for capturing, recovering, and purification of carbon dioxide”.

3.17.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of this report.

3.17.3 Capture Technology

Pentair CO₂ capture experience includes:

- Advanced Amine technology for 3 to 25 vol.% CO₂ content, noted as being e.g. gas turbines, lime kilns [54]. Solvent is highly concentrated MEA. This includes “NOxFlash” technology [55]. Thermal regeneration can be by flue gas heat, eliminating the need for steam, though this is potentially valid for regeneration systems in general.
- FlashCO₂: for medium-rich CO₂ concentration sources (up to 50 vol.% CO₂) e.g. syngas, to deliver high-purity liquid CO₂. This uses a combination of conventional physical absorption (chilled methanol) and CO₂ liquefaction technologies. Overall CO₂ removal is 92% (limited by the evaporating temperature of refrigerant used in condensing CO₂).

Pentair’s main experience is in small-scale carbon capture using “open access” solvent. Therefore, plant performance, including energy consumption, should be evaluated against the leading solvent licensors and plant suppliers. Pentair noted they could design and supply to a client specified solvent if required (but would need to consider process performance warranties).

Pentair also delivers conventional liquid CO₂ plants to 99.999 vol.% CO₂ purity (“food grade”).

3.17.4 Modularity & Standardisation

Pentair has extensive experience in modular design and supply having delivered over 350 amine-based CO₂ extraction plants worldwide, over a range of industries, and a total of over 2,000 plants for processing CO₂ rich gas. Most carbon capture plants are on gas engines and steam reformers [55]. About 50 of these plants use “high concentration amine”.

In discussing “standardisation” Pentair advised that each unit is designed to the client’s specific requirements. It is considered this is no different to most other suppliers in that Pentair has established plant designs and layouts (to save engineering time and simplify equipment procurement) but that as an engineering company is “flexible” to meeting client requirements.

Modules are manufactured at Pentair’s own fabrication facility in China. This is considered beneficial to minimising cost whilst maintaining quality of fabrication. Pentair is fully capable of working to international engineering codes and standards.

Timeline from order to plant operation was indicated as typically being 2 years. This would need to be assessed in more detail against project specific requirements. It is a reasonably typical indicative duration. It would be feasible to reduce this duration for a relatively “standard” design.

For a 12 tph CO₂ unit (100 ktpa CO₂), “indicative” plant footprint was stated as 30 m x 20 m. As with other suppliers the exact scope to which this footprint applied would need to be evaluated.

3.17.5 Applications & Experience

Amongst hundreds of projects Pentair can show capture applications including power generation (heavy oil steam boilers, natural gas-fired combustion engines) and lime kilns, with many plants having been in operation over 25 years.

In 2021, Pentair delivered (with BEIS support) the UK’s first industrial scale CO₂ capture plant (40 ktpa CO₂) at Tata Chemicals Europe Winnington (UK) Combined Heat and Power (CHP) site, for £20 million [56]. This looks a good project reference against the study requirements.

Pentair noted they do not provide indicative costs for capture plants due to the influence of gas composition, required capture, utilities availability and cost, and the ease or not of installation.

3.17.6 TRL

As the technology has been deployed at industrial scale, TRL is 9.

3.17.7 Discussion

Pentair has demonstrated the business focus and ability to provide effective carbon capture, using modular and relatively “standardised” solutions. The Tata Chemicals Europe carbon capture project in the UK demonstrates Pentair’s technical and project execution capability and provides an interesting reference for modular plants of similar capacity.

Pentair has experience with “standard” carbon capture solutions for small- to medium-scale plant capacities consistent with equipment such as boilers and engines.

Solvent performance should be evaluated against licensed solvent technologies to ensure it offers low regeneration energy and low solvent loss rates without solvent degradation and/or potential corrosion concerns.

Pentair offer engineering and design capability with established designs for carbon capture by solvent, focussing on smaller-scale projects. They also have “standardised” solutions for carbon dioxide liquefaction to 99.999% purity. Smaller-scale carbon capture is essentially “normal business” for Pentair, and the company has both engineering and procurement expertise with module fabrication being in-house.

3.18 Saipem

3.18.1 Company Overview

Headquartered in Italy, Saipem is a well-established major international engineering contractor and “global leader in CCUS, providing comprehensive solutions across the entire CO₂ value chain” [57].

3.18.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of this report.

3.18.3 Capture Technology

Saipem has undertaken carbon capture projects using a range of technologies and both open-art and licensed solvents. It is now actively focussed on offering a modular CO₂ capture technology, Bluenzyme™ 200 [58]. This uses potassium carbonate solution containing carbonic anhydrase enzyme (a natural catalyst) to increase the reaction rate for CO₂ absorption and thus enhance capture performance. This is akin to solvent activators as with Axens, BASF/GSEC, Honeywell UOP and others and gives a similar regeneration energy duty to the leading solvents.

Saipem advised that Bluenzyme™ 200 can achieve high selectivity and thermal stability for CO₂ capture. This would need to be evaluated and confirmed. As with physical solvents in general, thermal regeneration occurs at relatively low temperature (85°C), so steam may not be needed if low-grade heat is available. Because of the relatively low regeneration temperature and low regeneration energy duty Saipem noted that heat pumping may be cost-effective, i.e. use of (renewable) electricity rather than thermal energy.

3.18.4 Modularity & Standardisation

Saipem has performed design work at CO₂ capture capacity of up to 200 tpd (66 ktpa), to justify Bluenzyme™ 200 as a modular ‘plug & play solution’ [58]. Process and plant design has been “proven” on 30 tpd (10 ktpa) facilities operating in Canada (see below). The proposed 200 tpd capacity is considered by Saipem as aligning with “market demand”.

Saipem is well-versed in modular plant supply and its project execution so as to maximise quality and safety. Saipem bring established plant delivery experience to their pre-engagement of the equipment supply chain and fabrication yard. They claim their approach to and

methodology for execution enables plant delivery in as little as 18 months. As with other modular plant suppliers considered in this report, plant design and delivery plans would need considering on a case-by-case basis for a potential client's application, site limitations, potential for energy integration, use of "standardisation" to reduce engineering and to simplify the supply chain. Saipem are confident on the merits of modular plant design as against "stick built" for carbon capture.

3.18.5 Applications & Experience

The Bluenzyme™ 200 design has been developed for a wide range of flue gas CO₂ concentrations associated with emitters such as biomass, WtE, hydrogen, cement and steel. Saipem notes the technology and plant design suits a wide range of flue gas concentrations as the regeneration equipment capacity and design is based on the quantity of carbon dioxide captured not the feed gas composition (which essentially only affects absorption equipment). Of course, this statement is valid for all solvent capture technologies. It is important in understanding how regeneration equipment and modules can be "standardised" whilst absorption equipment is often of physical dimensions and weight that makes transportation more challenging.

A 30 tpd (10 ktpa) Bluenzyme™ facility is in operation at a pulp mill in St. Félicien, Quebec, Canada, giving 95% capture. It would be recommended that this plant performance is considered in some detail in evaluating Bluenzyme™. Saipem can also cite data from pilot and demonstration trials performed in development of the solvent.

Saipem advised that they do not provide indicative, high-level costs for CO₂ capture facilities due to the great variation in costs between applications. Costs depend significantly on site-specific conditions and the unit price of utilities. This approach seems appropriate and prudent due to the small number of built and operating Bluenzyme™ facilities and the limited representative technical and cost data.

3.18.6 TRL

Saipem advised that current Bluenzyme™ TRL is 8 with work ongoing to achieve a TRL of 9. The validity of this would need considering against a specific plant design and as to whether operating plants sufficiently "prove" the technology. Advanced technical solutions like using heat pumping would have a marginally lower TRL.

3.18.7 Discussion

Saipem has comprehensive engineering and design capability in modular plant design and supply and in EPC plant contracting internationally. They have a clear focus and business plan for modular carbon capture plant based on development of their own solvent technology.

Saipem has achieved successful plant operation. However, by currently only having one plant in operation they did not wish to provide indicative performance or cost data that may be inapplicable or misleading for a client's specific case. They were enthusiastic to provide a potential client with further demonstratable evidence of Bluenzyme™ 200 for modular carbon capture. Investigation could show effective carbon capture and competitive plant cost for a range of industrial applications, different feed gas conditions, carbon dioxide content and required capture rate. The process technology is applicable for modular solutions for small- to medium-scale applications, industrial boilers and engines. The “standard” plant capacity of 200 tpd is relatively large for some potential industrial applications but aligns well with the requirements of this study.

3.19 Sumitomo

3.19.1 Company Overview

Sumitomo Group is a Japanese-based conglomerate. It offers CO₂ capture technology via its Sumitomo Heavy Industries (SHI) division which acquired Amec Foster Wheeler's (FW) energy business in 2017 to form SFW [59].

3.19.2 Source of Information

Information was primarily obtained from the company website.

3.19.3 Capture Technology

Sumitomo CO₂ capture technologies include [60]:

- SFW Oxy+: oxy-fuel-based post combustion capture technology
- SFW Cal+: calcium looping technology for sectors including power generation, cement and steel
- SFW HPC+: Hot Potassium Carbonate (HPC) modular CO₂ capture technology via partnership with Capsol [61] for energy and industrial applications e.g. WtE, biomass

3.19.4 Modularity & Standardisation

SFW HPC+ modular CO₂ capture technology (from Capsol) consists of [62]:

- CapsolGT: gas turbine applications
- CapsolGo: demonstration unit
- CapsolEOP: end-of-pipe (EOP) applications

3.19.5 Applications & Experience

For SFW Oxy+, a 30 MWth CO₂ capture and storage demonstration plant was built and operated in Ponferrada, Spain. A FEED for a full-scale (300 MWe) plant was later completed [60].

SFW Cal+ was developed using experience from over 500 Circulating Fluidised Bed reactors (CFBs) [60].

3.19.6 TRL

Not considered in detail.

3.19.7 Discussion

Engagement with Sumitomo was limited. It was unclear whether Sumitomo would offer clear advantages over the leading suppliers considered in the study.

3.20 Svante

3.20.1 Company Overview

Formed in Canada in 2007, Svante describes itself as “a leading CO₂ capture and removal solutions provider” [63]. Svante head office is in Burnaby, near Vancouver.

3.20.2 Source of Information

Information was primarily obtained from the company website, supplemented by specific discussions for the needs of this report.

3.20.3 Capture Technology

Svante’s CO₂ capture technology uses a Metal-Organic Framework (MOF) adsorbent (provided by BASF) which undergoes thermal regeneration. Svante’s key development for carbon capture is high-capacity adsorbent with rotary adsorption machines (RAM) so as to combine a novel capture technology with process intensification. This minimises equipment and overall plant size and weight. This facilitates modular supply.

Svante advised that key merits of using MOF adsorbent include “fast kinetics” in capturing CO₂, so high CO₂ adsorption capacity is high. This leads to relatively low adsorbent weight (as compared to molecular sieves). Comparing with molecular sieve adsorbent technology this means that overall adsorbent loading approaches equilibrium due to a short Mass Transfer Zone (MTZ). The MOF adsorbent has high selectivity between carbon dioxide and nitrogen, high tolerance to water, low thermal regeneration energy duty and high stability in the presence of oxygen and acid gases.

The MOF technology is considered “most effective” at flue gas CO₂ concentrations above 8 vol.% and especially above 10 vol.% CO₂. The CO₂ product purity exceeds 95%. As the process operates at a slight negative pressure (-0.15 bar g), regeneration temperature can be lower than for conventional amine-based capture processes so there is increased opportunity to use waste heat.

3.20.4 Modularity & Standardisation

Svante has designed 2 “standard” sizes of rotary contactors. The URSA 1000 and URSA 2000 units can capture 500 tpd and 2,000 tpd CO₂ (160 and 640 ktpa) respectively. Contactors are reported as being of 14 m and 24 m diameter respectively.

The rotary contactors are manufactured by a “third-party” for site assembly. Plant scalability would be achieved by adding further contactors. It would be expected that rotary contactors could be designed and specified for lower capture capacities if a demand.

Svante advised that CO₂ capture costs depend significantly on site-specific factors, e.g. energy integration at the host site (steam, electricity, and cooling). Costs are currently projected at between US\$60 to US\$110 per tonne. Care should be exercised in using these costs to compare with other capture technologies as the cost basis, financial data used and scope of supply may not be comparable. By indication, for relatively high CO₂ content streams some technology suppliers report capture costs of US\$40 per tonne but note costs of over US\$100 per tonne for other applications. This highlights that Svante technology would need to be properly compared on a like-for-like carbon capture basis.

The above costs reflect the development level of the process technology, and the project applications to date. Svante expects CAPEX reductions as they progress the technology and gain operating experience from deployment. This would be expected and could make Svante MOF technology an interesting candidate for small-scale capture.

3.20.5 Applications & Experience

The CALF-20 MOF is produced by BASF and shipped to Svante's production facilities in Canada. It is coated on to a laminate to create a patented architecture of structured adsorbent of very large surface area. Adsorbent filter vessels are delivered to site complete and ready to be installed.

At the end of adsorbent operating life, the adsorbent filters can be returned to Svante for recycling. It is understood, using comparison with molecular sieve, silica gel and alumina, that adsorbent capacity will notably reduce after several thousand thermal regeneration cycles. The MOF life, how to maximise it, and what feed gas processing and clean-up would be needed, would be an important consideration with this technology.

As with any adsorbent technology, contaminants that can reduce adsorbent capacity would need managing and mitigating. Ensuring stability of the MOF adsorbent would be important to ensure the integrity of downstream equipment including the filtration equipment needs.

Svante has three pilot plants currently in operation: two in Canada (power generation, cement), one in USA (power generation flue gas). The latter unit (25 tpd), at Bakersfield, CA is a modular design and would be an interesting reference project.

3.20.6 TRL

Svante advised that filter technology, contactor technology and other critical elements are currently at TRL 7. The first commercial-scale plant is currently in FEED and is expected to start up in 2027.

3.20.7 Discussion

Svante's MOF based technology is interesting. The technology is clearly in development but close to being commercially available. It could provide significant modular cost reduction.

It would be recommended that a prospective client consult with Svante in detail so as to identify performance for the potential client's specific gas conditions and carbon dioxide content. Technical experience and operating experience should be used to check regeneration system design and performance, effect of contaminants and adsorbent stability. Particular attention should be given to scale-up and any empirical data used for design and that it is fully relevant.

Svante has focussed on developing modular technology at the larger end of the potential range of carbon capture applications. The technology may actually be best focussed on smaller-scale applications.

Svante's supply chain and relationships with key equipment suppliers should be reviewed.

Overall, MOF technology is of significant interest. It could offer key advantages but requires a development programme to increase TRL. A prospective project would need to ensure it is proven and appropriate for the specific application. It would be reasonable to anticipate MOF technology being built and operational before 2030 and demonstrating cost advantages.

3.21 T.EN

3.21.1 Company Overview

Headquartered in France, Technip Energies (T.EN) is one of the world's leading engineering contractors. A feature of T.EN's gas processing business is the development (and patenting) of in-house process technology and focussed conceptual design capability. International experience runs across the full range of design and project development services from early engagement to project delivery and construction [64].

3.21.2 Source of Information

Information was primarily obtained from the company website. T.EN also participated in discussion (including completion of questionnaire supplied).

3.21.3 Capture Technology

T.EN has undertaken many carbon dioxide removal projects using a range of technologies. Of late, it has progressed 'Canopy by T.EN' which uses well-proven Shell Catalysts and Technologies CANSOLV CO₂ capture technology (amine-based solution) [65]. As with other leading solvents this has low regeneration energy and "fast kinetics" in absorbing CO₂. Regeneration is performed at elevated pressure of up to 4 bar a so as to reduce downstream CO₂ compression cost. Applicable inlet CO₂ concentration can be very low (flue gas such as gas turbine exhaust) to medium/high as with hydrogen-rich syngas. Whilst CO₂ capture efficiencies of up to 99% can be achieved, T.EN advised the economic optimum is typically in the range 90-98% with higher values appropriate for higher CO₂ inlet concentration. As expected with selective amine solvent the regenerator outlet CO₂ concentration is over 99.9%. With CANSOLV technology and focussed development of "standardised" design and production, T.EN is aiming to optimise plant CAPEX and reduce OPEX in line with the objectives of this study work.

3.21.4 Modularity & Standardisation

'Canopy by T.EN' is offered in a range of capacities [65]:

- Pilot: 1.5 ktpa modular CO₂ capture plants (test)
- C10, C100, C200: 10, 100, 200 ktpa modular CO₂ capture plants
- Marine: offshore modular CO₂ capture plants
- C+: bespoke, large-scale CO₂ capture.

T.EN has supplied many gas processing and carbon dioxide removal plants. T.EN fully understand and supports modularisation. It has extensive experience with multiple fabricators (particularly in Asia) and advises that its 2,000 fabrication partners are regularly assessed.

Typical delivery time was cited as around 26 months. As with all stated delivery times this would need to be considered on a case-by-case basis

3.21.5 Applications & Experience

T.EN refer to scores of carbon capture plant conceptual evaluations, basic engineering studies and FEEDs.

T.EN is a member of the Carbon Capture Alliance to build facilities to capture 2 million tpa CO₂ via the Net Zero Teesside (NZT) Power project, UK. As the time of completing this report this project was approaching FID.

In Q1 2024, T.EN initiated an EPF (Engineering, Procurement and Fabrication) contract for Carbon Centric for CO₂ capture at the Rakkestad waste incineration plant, Norway [66]. Modular Canopy C10 technology will capture 10 ktpa of CO₂ at a capture rate of over 90%. The plant will feature extensive heat integration to reduce energy consumption. The project will be delivered as a “capture-as-a-service” offering via Kanfa, a Norwegian design and engineering company with experience in CO₂ capture pilots and modular process systems [67].

Information provided is from T.EN’s experience. Shell’s CANSOLV has been licensed and used on capture projects prior to ‘Canopy by T.EN’.

3.21.6 TRL

T.EN advised their pilot plant (1.5 ktpa) can be considered fully proven. Modular Canopy technology solutions (10, 100, 200 ktpa) are at TRL 7 with large-scale deployment ongoing. As Shell CANSOLV is relatively well-proven across a range of capture projects the TRL for modular plant can be considered as 8 and will possibly be 9 by the end of 2025.

3.21.7 Discussion

T.EN has demonstrated experience in design and supply of gas processing facilities and in the engineering, design and supply capability to provide effective carbon capture, using modular and relatively “standardised” solutions at a range of plant capacities.

T.EN has developed a business model and business approach for carbon capture by offering full engineering and design capability and by linking with Shell Catalysts and Technologies to provide capture technology solutions and plant supply using CANSOLV technology. This offering combines T.EN's capabilities with a leading and well-established technology solution for a wide range of industrial sectors. Carbon capture technology solutions for smaller-scale are available.

4.0 DISCUSSION

4.1 Modular Plant - Definition

Modular design and supply conventionally means that all major equipment, piping and valves, all instrumentation, electrical equipment and cabling are provided on the module.

The following scope points should be considered in detail for any modular design project;

- Control – modules may be provided with control such as by PLC (in a purged control panel) or other HMI
- Termination of process and service lines at module edge
- Termination of instruments at in/out terminals of control cabinet
- Termination of electrical connections at junction box(es)
- Confirmation of insulation supply
- Clarification on interconnecting pipework between modules (and its support)
- Free issue items such as pressure relief valves to be installed off-module
- Clarification on initial charge of any chemicals and consumables

The following are normally excluded from module supply projects;

- All utilities – heat, electricity, plant and instrument air, purge nitrogen etc.
- Flare
- Effluent treatment
- All off-module structural engineering
- Civil engineering
- Design and supply of any facilities outside the module limits including process and services pipe racks
- Isolation valves at module limits
- Supply and installation of instrumentation items and cabling off-module
- Supply and installation of electrical distribution and control, lighting, earthing, lighting protection
- Supply and configuration of main plant DCS
- Design and supply of ESD/EDP systems
- Analyser systems and associated buildings
- Design and supply of safety equipment such as flame and gas detectors, fireproofing, fire monitors or hydrants, deluge system
- Any buildings

- Plant erection
- Plant commissioning
- Spare parts

It is therefore important to understand and accurately define the module supplier's scope of supply.

In general, modular plant supply is most appropriate where equipment items are relatively small but have such a significant amount of interconnected pipework between the equipment items that "stick-building" would be onerous. Plants using pressure or thermal regeneration have a large number of valves for adsorber vessel changeover from on-line to regeneration (or standby). These are an excellent application for modular supply. Adsorbent vessels could be installed on the module depending on their size and weight. As the vessels are relatively heavy and interconnecting feed gas pipework around the vessels can be relatively large, off-module installation can be better.

Low temperature process plants are normally supplied as modules with all low temperature equipment and piping in a steel plate and frame "cold box". This would be appropriate for carbon capture even though operating temperatures are likely to be above -50°C. Any required mechanical refrigeration systems are supplied in modular form.

Many of the capture technology solutions put forward rely on absorption. Typically, the absorber and regeneration columns are of a physical size and weight that mean they need to be free-standing. If so, these columns can be supplied "dressed" and therefore are essentially modular, with all necessary platforms, ladders and instrumentation pre-installed for minimal on-site installation activity. The lower part of such columns may actually be supplied on modules (with flanged column bodies) to meet transport limits, with upper column sections supplied for site installation. Costain applied this approach for absorber columns forty years ago. Individual module suppliers would need to review their methodology and demonstrate how their "standard" design minimises site installation.

The size and nature of solvent regeneration equipment, i.e. compact heat exchanger and pumps lend themselves to modular design. Any intermediate solvent storage would likely be best located off-module.

Modular plants suit water cooling as air cooling requires much greater footprint. Air coolers could be supplied as discrete items by the carbon capture module supplier, but the best

approach would need to be considered in design as air coolers could be located some distance away.

As far as possible on modular installation projects piperacks should be provided in modular form to minimise site installation, pipe-welding and non-destructive testing (NDT). Whilst module suppliers may provide process modules ready as “plug and play” solutions it is important to maximise all aspects of modular design to minimise all site activities, not only construction and installation but including “hook-up” of piping, electrics and instrumentation.

Module safety relief valves may need to be supplied “free issue” for site installation to ensure discharges free drain to relief / flare.

4.2 Suppliers

All twelve of the companies selected as representative of modular plant suppliers have a clear business objective to provide solutions to lower the cost of carbon capture via modular plant supply [4]. All are experienced and align with study requirements. All could provide confidence to underpin TRL values from actual plant operation.

All companies could show experience across a range of gas processing technologies [7], [12], [17], [24], [38], [44], [45], [50], [52], [53], [54], [55], [57], [58], [64], [65], [66] and the application of modular design supply to achieve;

- Improved overall quality, much less rework and reduced overall fabrication time compared with on-site working. Modular construction is much less likely to incur delays.
- Better planning and scheduling of plant fabrication and installation, again minimising delays and providing certainty to the overall capture project.
- Much improved site safety due to reduced construction activity, major equipment handling and site movements. The relative ease of module installation should mean that all plant installation activities can be performed in a short “time window” whilst existing, surrounding plant is off-line. Stick-built construction makes this essentially impossible and entails much more “live plant” working with the consequent need to manage hazardous operations under procedures and permit to work management. Module supply can thus provide a major improvement to a capture project.
- Much reduced site environmental impact due to avoidance of waste materials normally associated with equipment installation. Disposal of solid or liquid waste can be a major issue in construction, and this is greatly minimised. Emissions to the atmosphere and

noise associated with construction are greatly reduced. As with site safety issues, module supply can thus provide a major improvement to a capture project.

- Much smaller equipment “laydown” area and much less equipment storage and handling. Ensuring availability of land for equipment “laydown” for construction can be a major cost. This is another issue, along with the safety and environmental benefits of having modular plant, that can easily be unappreciated in considering modular plant supply against stick-built.
- Much improved organisation on site due by module supply.
- Minimal interruption due to adverse weather.

Essentially all companies highlighted how they minimise engineering design, procurement activity and fabrication time by having a portfolio of “standard” modular designs for specific feed gas carbon dioxide content, partial pressure and capacity. Modularisation goes hand-in-hand with having a suite of plant capacities, equipment type/size and optimised layouts around this equipment so that module design is essentially “fixed”.

Most identified plant capacity could be easily scaled by the addition of further identical modules to increase processing capacity.

For smaller-scale modular plant there is great incentive to use;

- An “engineer once, supply many times” approach
- “Industry standards for engineering design and equipment specification
- “Standard” process flowsheets and P&IDs
- Pre-selected suppliers for equipment, piping, valves, instruments
- Pre-selected, quality assured and verified fabricators

This approach facilitates the supply of modules to site, installation, hook-up of piping, electrics and instrumentation/control to DCS, commissioning and having the plant operational in less time than the conventional approach of “stick-built”. Use of pre-selected suppliers and fabricators also simplifies the “supply chain”. The regular use of reliable suppliers and fabricators builds relationships, improves quality, gives assurance in project management and delivery and helps minimise cost.

In the main, experience in maximum module size and weight limitations means suppliers limit module dimensions to what is transportable. For smaller-scale carbon capture “standard” container-size modules, especially for solvent regeneration, are applicable. However, this

should be taken up with suppliers on a case-by-case basis so as to optimise modularisation, construction work and overall time to first operation. For instance, use of a coastal fabricator can enable module limits to be dictated more by sea-going dimension limits than “standard” road transportation limitations. If transport dimensions can be set by road widths to the construction site (and access within the site) being wider than “standard” this could be influential.

There may be some compromise by using modular carbon capture plant designs, which by their nature will tend to be more “standardised” than bespoke designs:

- Performance and plant efficiency: it might be that a “standardised plant” is less able to efficiently cope with feed gas changes due to equipment design or by being limited on such parameters as solvent flow. It thus incurs greater OPEX over its operating life than savings in initial CAPEX.
- A “standardised” plant design may be over-sized against the specific capture duty and incur unnecessary CAPEX.

Overall plant build time and time to first operation can be reduced by modular supply, potentially significantly, by at least several months. However, this should be evaluated on a case-by-case basis as it relies on the level of “standardisation” applied by the supplier (and/or the need for a more bespoke approach). Module suppliers should be consulted on the potential savings in deployment time against any potential “downsides” of accepting a “standard” plant design due to e.g. over-sized or non-optimised equipment or acceptance of “industry” codes and standards (which are often USA based, such as ASTM, ANSI, API). This may raise a question on project engineering codes and standards and the ability of a supplier to work with alternatives. An exercise would be needed to ensure that departure from supplier “norms” would not disrupt savings in CAPEX, engineering time or fabrication time. Suppliers are well versed in considering such points to ensure their proposals and commercial offers are aligned with client requirements of plant performance, CAPEX, ease of installation and overall timescale for deployment.

Of course, the smaller the capture plant capacity the less significant any “downsides” in performance or efficiency by using modular plant supply.

Detailed assessment of available space is always needed for modular plant supply into “brownfield” environments.

It may be interesting to consider how modular plant suppliers and EPF companies work in NGL extraction, which has been a highly “standardised”, modular supply business since the 1980s, especially in the USA. Process simulation and engineering assessment is used to identify any “downside” in “standard plant” performance and evaluated against the improved delivery time obtained with the “standard plant” approach. Many of the module suppliers noted in the report supply extensively into the USA and understand this “modus operandi”. A potential client should put the onus on the module suppliers to show that their technical and commercial offers are optimised against clear requirements, including the client/s economic criteria if it is possible to provide this.

Any prospective carbon capture project needs to be clear on participant’s willingness to use a supplier’s “standard plant” offering and understand in detail what this entails.

4.3 Cost

All the technology providers considered in this report advised that modular designs would normally reduce CAPEX significantly versus a conventional “stick-built” design. Modularisation can also improve predictability of project cost for the technology suppliers scope of supply as construction costs are not included.

Modular plant does require more structural steel (for the module base and frame) so has an additional cost to “stick-built” construction. However, this sum typically represents no more than several % of the module supply cost and is typically a small consideration in comparison to the benefits that modular supply can bring. There are no other “additional” costs.

It proved difficult to obtain comprehensive and consistent cost data from suppliers. Costain noted a lack of consistent costs in the public domain (for techno-economic assessment of smaller-scale carbon capture), other than general points to reflect that modularisation can make carbon capture cost comparable to larger facilities. In other words, the use of modular design and supply can go against expected “economies of scale” to make smaller-scale capture facilities more cost-effective, as per the study requirements.

There are many reasons why obtaining relevant cost data is prohibitive. All suppliers noted that they would need to consider a specific project to be able to provide reliable cost information and to have a clear scope breakdown as discussed in Section 3.1 above.

Unit CO₂ capture cost is highly variable and dependent upon a range of parameters, typically including:

- Inlet gas CO₂ concentration
- Inlet gas pre-treatment
- Type of CO₂ capture technology deployed
- CO₂ treatment requirements
- CO₂ product specifications
- Availability of existing and/or “standard” modular design to align with capture duty
- Availability of utilities and opportunity for integration with existing for e.g. waste heat
- Engineering standards
- Site transport and/or lifting limitations
- Scope considered – any effect of location on plant design or plant installation, does capture cost include for any off-sites (such as CO₂ transport and/or storage), module foundations and installation, integration with main plant systems, ‘client costs’, operating and maintenance costs and others
- Financial basis, amortisation time, interest payments

Carbon capture cost is a strong function of inlet CO₂ concentration (cost falling with increased concentration). As this parameter varies significantly across different industrial applications caution is needed in comparing alternative capture costs, technologies and suppliers. Atmospheric pressure flue gas will normally have much higher CAPEX than capture from synthesis gas.

A very important aspect with smaller-scale carbon capture is that modular units could be ‘plug and play’. In other words, all that is needed for operation is the carbon capture process plant, installed on prepared foundations and with piping, instrumentation and electrical systems connected up. Such a plant would use existing on-site utilities, DCS, safety systems such as existing flare and firewater system, buildings, existing operations and maintenance staff etc. Whereas a carbon capture plant capturing hundreds of thousands of tonnes of CO₂ or more would essentially be a greenfield installation, with a significant investment in land, a much smaller (modular) capture facility would rely on existing infrastructure. This gives greatly reduced specific cost than otherwise and makes smaller plants cost competitive against larger capture plants.

Aker Carbon Capture [9], Axens [14] and Honeywell UOP provided indicative capture costs with the first two indicating that for 100 ktpa a value as low as US\$30 per tonne may be viable.

Honeywell UOP reflected a slightly higher cost would be expected. Costs and cost comparisons between technology providers should be treated with caution. As noted, indicative cost values, with little regard for feed gas conditions, capture performance and other issues, can be misleading. Some note very low costs for some applications and over US\$100 for others, highlighting the need for adequate project scoping before considering costs to be any better than 30 – 40% accuracy. When the scope of modular supply and “balance of plant” is understood, all site installation, construction and end client costs resolved then costs for CO₂ transport, storage and OPEX will need to be considered, plus OPEX values.

Suppliers tend to cite in US\$ and converting directly to local currency can be invalid. US plant costs reflect a highly competitive supply market and US fabrication. This may not be applicable for other localities and hence the need for third party engineering support unless the end client has sufficient in-house capability.

Even if a prospective client and/or capture plant operator considered that sufficient cost data for project assessment is available in-house or has been provided by initial dialogues with suppliers, or by basic engineering work or even FEED, valid costs for progress to FID can only really be obtained by requesting proposals. Via proposals suppliers can take a sufficiently detailed approach to provide salient and reliable information. Module costs can change significantly due to external factors and the suppliers current “order book”.

4.4 Deployment

Suppliers provided indicative timelines for modular plant supply and justifications for using modular technology to reduce overall project timescale. However, it is difficult to provide indicative time values. What is key is that all suppliers have a business approach to use already developed plant designs, specifications and drawings to minimise engineering work, and to use established equipment types and dimensions for modular supply. Some have progressed this to have “standardised” designs and established equipment and piping layouts with module fabricators so as to simplify equipment procurement, minimise change and have clear project execution so as to minimise delivery.

Suppliers should be able to provide high-level information on plant performance and cost and deployment from an initial process duty specification. This enables them to select the appropriate technology, identify plant performance and perform initial equipment sizing. Clearly the more “standard” the process duty the better suppliers can provide reliable information on

module scope, sizes and weights, indicative cost for their scope of supply and anticipated module delivery schedule.

Large-scale CO₂ capture design, supply and installation projects are like all high-value engineering and construction projects in the processing and power industries. They typically undergo process studies and initial techno-economic evaluation to identify capture performance and costs so as to evaluate process technologies and the suppliers to progress. This phase of work should consider execution strategies so as to have an indicative timeline to beneficial operation. Most operating companies will require engineering support to consider all aspects outside of the plant supplier and or EPC contractor's scope so as to determine overall safety, environmental, technical, interface and construction aspects. Project cost-estimates would typically be considered +35/-15% at this stage.

Further work to refine project costs from the best candidate suppliers would be carried out before considering selection of one or more companies to perform FEED. Depending on the scope a typical FEED may require of the order of 9 months execution time (by the supplier) so as to provide a project cost estimate to an accuracy of +/-10%, suitable for proceeding to FID.

Taking the above into account, it would typically require 2 – 3 years until a major project would be sanctioned. From that point it would typically then be 2 – 3 years before a capture plant gave beneficial operation.

This study focusses on modular capture plants of smaller-scale than discussed above. The smaller-scale means that a different approach can be taken. The companies discussed in this report have the experience and capability to provide a +35/-15% cost estimate for their scope of supply relatively quickly. By providing modules, interfaces with plant and utility systems can be readily defined and the scope of supply – what is included in the high-level cost estimate provided – is clear. There should be much less need for engineering support by a “third-party” as the modular carbon capture plant supplier should provide that support. This could be a key factor for a potential project. Some companies noted in the report are essentially international engineering contractors with full plant installation and even EPC capability. Others are more “pure play” modular plant suppliers. How the question of “third-party” support is handled is a key question to any prospective carbon capture plant operator.

Smaller-scale projects and modular plant design should mean that FEED activities are much reduced. Again, this depends on the capability of each candidate carbon capture plant supplier to provide a comprehensive proposal on an acceptable commercial basis. If carbon capture is

a “one-off” project this could be handled by the eventual plant operator depending on their technical capability. Some will want to use “third-party” engineering and project execution consultants or contractors. As with all projects, sufficient time must be spent for all parties to evaluate and define a clear scope for the modular plant supplier so as to agree the commercial conditions for project execution.

It was noted that a “major” project would require 2 – 3 years until sanction. For smaller projects, of lower value, the use of experienced plant supply companies could mean FID of less than 12 months. By then applying “standardised” design, with its much-reduced engineering and procurement, and having suitable commercial conditions to favour project execution, modules could be supplied to site in under 18 months with beneficial plant operation achieved in under 2 years.

It will thus be noted that the key benefit of modular plant supply is not only in reduced execution time but in the selection of appropriate technology and plant supply by putting greater responsibility on the module supply company, so as to achieve FID sooner. In this way, whereas a major capture project may require 4 – 5 years to sanction (and in many cases this would be considered optimistic) a smaller-scale project should be based on potentially achieving beneficial operation within 3 years (assuming that all due regulatory requirements can be met in this time period).

5.0 CARBON DIOXIDE CONDITIONING AND COMPRESSION

5.1 Conditioning

“Conditioning” is an integrated part of “carbon capture” for most carbon capture suppliers.

Carbon dioxide dehydration conventionally uses TEG or adsorbent (alumina, silica gel or molecular sieve) to meet required water content specification, typically < 20 ppmv. Dehydration modular plant design and supply is conventional and has a TRL of 9 for both TEG and adsorption.

Dehydration by adsorption normally consists of a single pre-assembled module containing the feed and regeneration gas “changeover” valves and pipework. There are two adsorbent vessels, one for operation and the other for regeneration. The module will also contain the regeneration gas heater (often electric at small capacities), plus regeneration gas cooler and a front-end knock-out drum, if needed, to ensure liquid not carried over to the adsorbers. If needed to remove contaminants the dehydration module can also include a de-oxidation vessel containing catalyst. A hydrogen injection point would be located upstream.

A protective layer of silica gel on top of the adsorbent is conventional so as to remove solvent and other contaminants that could reduce adsorbent performance. A water wash system may be installed as part of the carbon capture system (if solvent based) to minimise contaminants in feed gas to CO₂ conditioning.

Regeneration is by feed gas. The use of silica gel and alumina enable a lower regeneration temperature to be employed and should be able to meet the required water content specification.

Dehydration by TEG may need two modules depending on capacity as more discrete equipment items including heat exchangers, pumps, regeneration column condenser and reboiler. The absorber column and regeneration column (preferably “dressed” with all piping, ladders and platforms installed) may be located off-module, depending on plant capacity.

5.2 Compression

5.2.1 Introduction

Captured CO₂ may be destined for sequestration at a pressure in excess of 150 bar a. Most carbon capture projects are based on sequestration due to consideration of large-scale

projects, capturing hundreds of thousands of tonnes a year or more. For the small- to medium-scale capture projects in this study it is more likely that captured CO₂ is routed to liquefaction plants. These typically operate at about 15 bar a (to use ammonia or refrigerants such as R410a for condensing CO₂). If captured CO₂ from a small- to medium-sized plant is compressed for transport it is likely to be compressed to a “moderate” pressure to be sent to a central gathering “hub” for CO₂ to then be sent onwards.

Some carbon capture technologies, as discussed in consideration of suppliers, produce liquid CO₂ that can be pumped directly. In considering the eventual CO₂ destination, capture technology that produces CO₂ liquid is more likely to be justified for small- to medium-scale than on larger plants because it simplifies and reduces the cost of onward CO₂ transportation. Each potential project should consider this in overall technology selection and economic assessment.

The CO₂ compression duty can thus be;

- Compression from capture plant into a liquefaction plant
- Compression from capture plant into a pipeline
- Recompression to enable transportation through the pipeline
- Compression into a geological formation for sequestration (at reservoir pressure)

Transportation through the pipeline, so as to avoid CO₂ liquid formation, should be at an operating pressure of over 100 bar a (depending on level of impurities) so the CO₂ is a supercritical fluid – above the critical point (and also termed “dense phase”). The CO₂ physical properties then resemble those of a liquid rather than a gas. The CO₂ is in effect essentially incompressible and is effectively pumped rather than compressed. The power consumption to increase pressure is thus relatively low.

Carbon dioxide has a relatively high molecular weight so is relatively easy to compress and the maximum pressure ratio for each compressor stage can be relatively high. This leads to high heat of compression and the need for interstage cooling. There is also a significant reduction in volumetric flow per stage which dictates the number of compressor stages and the interstage cooling so as to limit temperatures to maximise efficiency and limit power consumption.

Depending on the duty, and especially suction and required discharge pressures, CO₂ compression can be performed by oil-free reciprocating, screw or centrifugal compressors. For high discharge pressures (and relatively large flow), typical of carbon dioxide

sequestration, multistage centrifugal and integrally geared machines are favoured for efficiency reasons though these can be relatively complex and have high CAPEX and relevance for small- to medium-scale carbon capture projects is questionable. For small- and medium-scale carbon capture plants, both reciprocating and screw machines can be employed. Reciprocating machines can achieve relatively high pressure as shown below but may require a parallel machine to ensure sufficiently high availability. Screw machines are limited on discharge pressure.

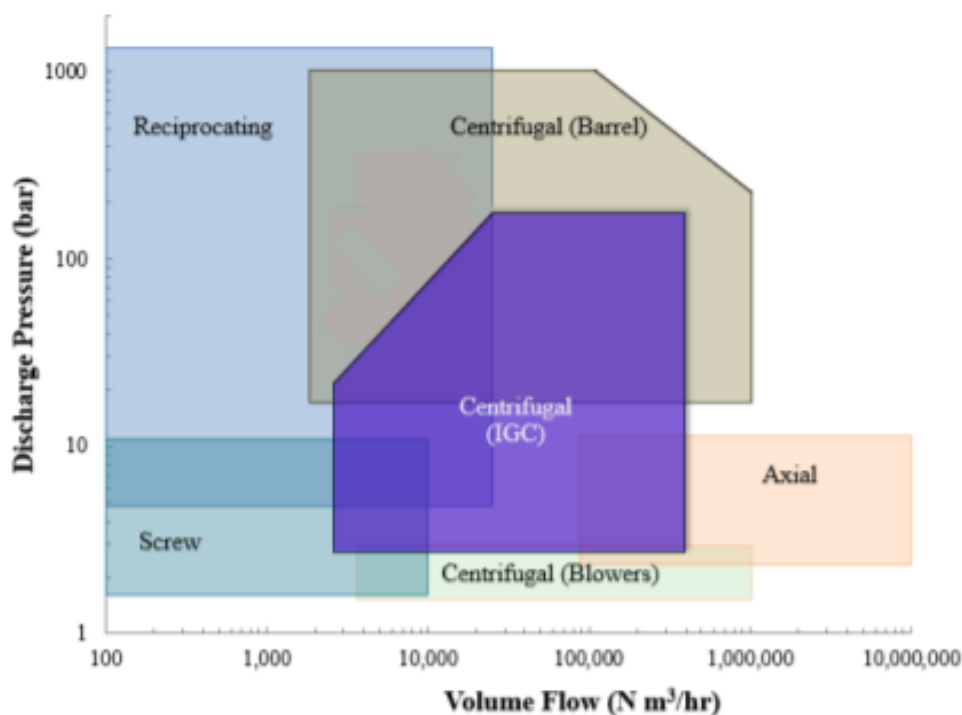


Fig. 4.2.1 Compressor Selection

5.2.2 Machinery Standards

Any engineering and design project would need to establish the engineering standards to be used for compressors (and CO₂ pumps). On large-scale EPC projects these tend to be well-defined and universally applied across the project, based on international and local standards, engineering contractor “selection based on value engineering principles, client and specific site practice and preferences and the experience of the overall engineering team”. Such practice is arguably overbearing for a relatively small carbon capture project.

“Minimum” technical standards (along with statutory standards) will need to be established.

Compressors should be specified based on “Manufacturers Standards” which should themselves be aligned with API, i.e. API 618 for reciprocating machines and API 617 for axial, centrifugal and integrally geared machines. Pumps should be specified based on API 610 for

centrifugal machines and API 674 for reciprocating machines. Particular attention should be paid to instrumentation and electrical system conformity to ensure aligned with existing site practice.

5.2.3 Suppliers

The extent to which compressors could be supplied as “packaged” process modules, containing all necessary equipment including suction drum, interstage knock-out drums, coolers (based on using cooling water), anti-surge protection and relief valves, and being fully piped, wired and instrumented, would need to be considered specifically with suppliers against the carbon dioxide flow, conditions and required duty.

A range of experienced compressor and pump suppliers is provided below. This is not necessarily fully comprehensive but reflects those focused on carbon capture and transportation, what has been developed and installed and the technology development efforts being made for carbon capture applications.

- Baker-Hughes – centrifugal and integral gear compressors [68], [69]
- Siemens – compressors and pumps [70]
- Atlas Copco - reciprocating, screw and centrifugal/integral gear compressors [71], [72]
- Ebara Elliott Energy - centrifugal, multistage centrifugal and axial compressors. Hybrid compressor/centrifugal pump for CO₂ compressed to dense phase [73]
- MAN Energy Solutions - axial, integrally geared, centrifugal, screw compressors [74], [75], [76], [77]
- Ruhrpumpen - carbon dioxide pumps, reciprocating and centrifugal [78]

6.0 LIQUID CARBON DIOXIDE STORAGE

6.1 Storage

For small-scale carbon capture it is likely that carbon dioxide will be liquefied for transport.

Review of the supplier information discussed earlier will note that liquefaction of carbon dioxide (such as from amine regeneration columns) is conventional to produce food grade carbon dioxide, of 99.99%+ purity. “Raw” carbon dioxide is compressed to about 15 bar g so that cooling against evaporating ammonia or a refrigerant such as R410a will condense CO₂ for purification by distillation. Typical carbon dioxide removal from a distillation system with a refrigerated condenser is of the order of 85% so a carbon dioxide rich overheads stream will need to be recycled. This can be used for thermal regeneration of CO₂ dehydration facilities.

The below considers a carbon dioxide storage system for about 65,000 tpa of CO₂. Storage tank operating pressure of 15 bar g is typical to maintain the CO₂ as liquid under high-level refrigeration. Subcooled liquid CO₂ is pumped to road or rail tankers operating at a pressure slightly higher than the storage pressure so that vapour from liquid CO₂ flashing can be returned to the storage system.

Four vessels, each of approximately 100 m³ capacity operating at 15 bar g at -27°C. Vessels typically have a foam or vacuum-perlite insulation system to minimise BOG.

The storage vessels have a diameter of 3 m and length of 23.3 m. At this size they can be shop built for transportation to site. They would normally be installed horizontally but can be installed vertically where space is at a premium. The required “footprint” for horizontal vessels, including export pumps would be of the order of 375 m² whereas vertical vessels would only require about 70 m².

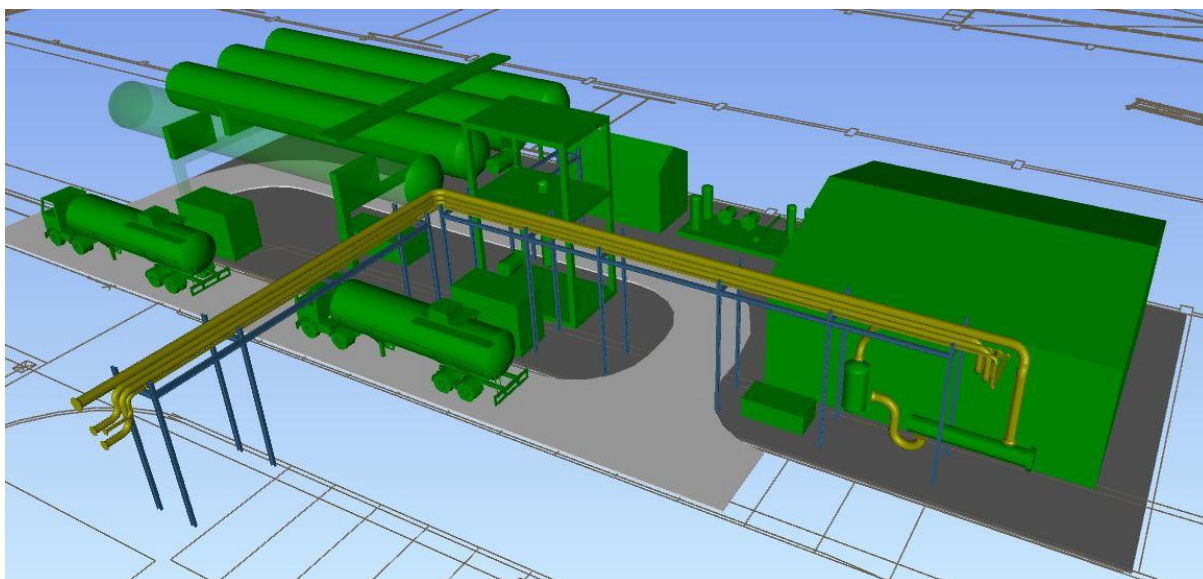


Fig. 5.1.1 Horizontal CO₂ Storage

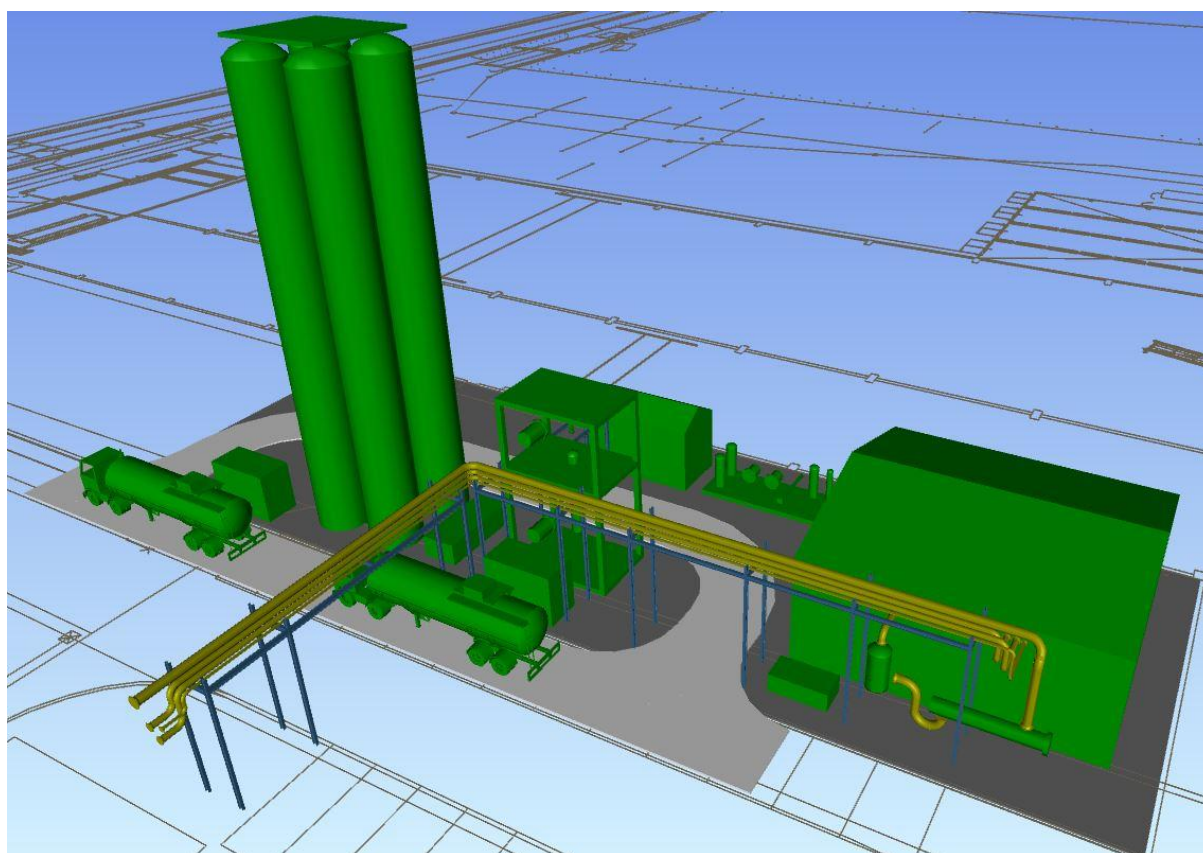


Fig. 5.1.2 Vertical CO₂ Storage

At 65,000 tpa of CO₂ four vessels provide approximately 2 days of CO₂ production, based on being 85% full. Maximum permissible fill level is typically 95%.

- Liquid CO₂ rundown flow to storage of about 7 m³/h
- Storage tank boil-off is typically 0.1 % per day of the nominal capacity
- Typical road tanker capacity of 20 m³ so a road tanker will be filled every 3 hours, i.e.
- Tanker boil-off is typically 0.1% of the nominal capacity
- Typical road tanker loading rate of 50 m³/h

Vessel mechanical design pressure of 17.5 bar g with lower design temperature of -46°C. 6°C.

Storage vessel material selection is based on the minimum design temperature in the absence of a corrosive service so LTCS and specifically SA-516 Gr.60 is typical. Liquid export pumps, liquid loading and vapour return arms and equipment in the BOG/flash gas recycle system can all use LTCS.

Modular design could be applied to maximise the use of pre-assembled pipework.

Two road tanker loading bays would be needed to avoid waiting time for driver/operators.

7.0 RECOMMENDATIONS

Smaller-scale and modular carbon capture essentially exhibits the same technical, financial and regulatory issues as larger capture facilities and should be considered in essentially the same way other than for points as below;

- Consideration of smaller-scale carbon capture (than what is considered conventional) means that process technology that lends itself to modularisation e.g. adsorption or rotating equipment becomes of greater interest and may justify more development and funding.
- Consideration of smaller-scale carbon capture means that process technology that lends itself to modularisation by having few equipment items will be of increased interest. The relative simplicity may lead to reduced performance and maybe higher OPEX than other technologies but can be a route to lower CAPEX.
- Suppliers should consolidate the results of trials of new technology (including advanced solvents), pilot and semi-commercial plants, and perform trials on a range of emission sources to help demonstrate technology, increase TRL and increase industry confidence.
- Smaller-scale projects, by their nature, will often be “bolt-ons” to existing processing facilities and thus reliant on existing site infrastructure, energy supplies, instrumentation and control systems, safety systems (including fire protection and flaring) and even existing site operating and maintenance resource. In evaluating overall project cost it will be essential to ensure proper demarcation of the modular plant supply and CAPEX against total project cost. Depending on the individual project developer this aspect of investment appraisal may be performed “in-house” or with third-party engineering support.
- As noted throughout this report, the key benefits of employing modular technology arise from using a supplier’s “tried and tested” offering. Cost savings and reduced time to beneficial operation depend on minimal change to a suppliers’ “standard” offering. This especially means acceptance of proposed project codes and standards. Some suppliers, especially larger EPC companies, can be flexible and advise “upfront” the influence of specific client requirements and changes. For some suppliers the major benefits of modular design may be negated if changes to their normal ways of working are imposed.

8.0 CONCLUSIONS

A comprehensive review was performed of companies with good experience in the design and supply of modular carbon capture plants. A wide range of process technologies were considered to show that carbon capture from many industrial sources is feasible.

To date, carbon capture from large-scale flue gas emissions has been favoured. However, the specific cost of carbon capture is generally lower the greater the feed gas CO₂ content so carbon capture in the steel and cement industries and for “blue hydrogen” may be favoured. Modular plant suppliers are focussing on these sources of carbon dioxide and developing process technology specific to feed gas of high carbon dioxide content or are modifying existing, well-proven technology. Carbon capture on cement plants for instance is progressing because modular capture plants are now available.

Technologies that “produce” carbon dioxide at elevated pressure reduce downstream compression costs. Licensors of solvent-based capture technology have thus demonstrated technology for this. Physical solvent becomes of more significance, by “producing” carbon dioxide at elevated pressure. Capture technologies using chilling and partial condensation “produce” carbon at elevated pressure thus reducing overall capture cost. All these important developments are being implemented in modular capture plants.

Whilst carbon dioxide capture by absorption in solvent is the most widely employed technology choice, alternative process technologies, some with much fewer equipment items, could be more appropriate at relatively small-scale, easier to modularise and more cost-effective, especially if they can use lower cost energy sources such as waste heat or renewable electricity.

From identifying experienced modular plant suppliers who could show high TRL (with successful design and supply execution and with beneficial plant operation), and to be fully representative of technology suppliers and carbon capture opportunities, twelve companies were considered in relative detail. All twelve have proven technology and project execution experience and are focussed on cost reduction in carbon capture by using modular plant design and supply.

Companies considered included;

- major engineering and EPC companies; MHI, Aker, T.EN and Saipem
- modular supply companies; Honeywell UOP, Koch Modular, Pentair
- process technology companies; Carbon Clean, Axens, Chart, Baker Hughes, BASF

Some offer more capability for carbon capture than the above summary may reflect e.g. Honeywell UOP has a wide range of process technology solutions for license, Saipem has developed solvent technology, T.EN use well-established Shell technology, both MHI and Aker have many years of experience and Koch Modular and Pentair have key experience with smaller-scale modular design and supply.

Suppliers' ability to "standardise" was considered – so as to minimise the cost and time for engineering design, procurement activity and fabrication (without any compromise to quality and safety). As engineering and project management costs are relatively independent of plant capacity it is especially important for smaller-scale capture projects to minimise these by "standardisation" so as to minimise plant cost and to facilitate beneficial plant operation sooner. The leading companies discussed in the report have suitable plant designs, plant supply and installation capability.

For smaller-scale modular plants there is greater incentive, compared to major carbon capture projects to employ;

- an "engineer once, supply many times" approach to reduce engineering cost and time
- "Industry standards" for engineering design and equipment specification
- "standard" process flowsheets and engineering line diagrams
- pre-selected vendors for equipment, bulks, instrumentation etc.
- pre-selected, quality assured, verified fabrication shops

Bespoke plant designs that are "tailored" to specific feed gas and capture duty may offer better performance, but this matters less for smaller-scale applications. Suppliers' "standard" designs should offer significantly lower CAPEX. Depending on the supplier, it may be possible to "tailor" designs to an extent without significant cost increase. For capture plants using absorption for example, regeneration equipment can be "standardised" whilst bespoke design and sizing of the absorber might be appropriate. Consideration of bespoke design against a supplier's "standard" design can only be assessed on a case-by-case basis and with a definitive plant specification that takes all factors into account, including scope of supply, feed gas conditions, capture duty, utility availability and utility cost, plant location and ease of equipment/module transportation and installation, appropriate engineering standards etc.

Even though process duties can be relatively similar from one capture project to another, each potential project should be considered against its own specific, unique circumstances rather

than drawing general conclusions on carbon capture cost. With any cost assessment it should be fully clear what is included. The module supplier may cite for design and supply, not including for any aspects of utilities supply and plant installation. Investors need TIC and how this is developed from a module supply cost needs engineering and project execution work.

Some suppliers “standardise” based on module sizes to suit road/rail transport containers and would employ multiple units in parallel if necessary whereas others work on the basis of being able to manage and supply larger modules.

Design and supply of modular carbon capture plant is relatively mature. Many plant suppliers can show high TRL from operating experience. Some have alternative designs in development which will have TRL values of 7 and greater in the future. Such developments include improved solvents to permit higher pressure regeneration (up to about 5 bar a) and thus lower downstream CO₂ compression cost, lower thermal regeneration duty and/or lower temperature with the prospect of heat pumped regeneration, scale-up of low temperature process technology (that uses electricity rather than thermal energy) and other techniques. Two companies, Carbon Clean and Baker Hughes, have progressed rotating equipment development for intensive gas/solvent contact to reduce absorber size and weight to reduce cost.

It is important to evaluate capture technology solutions and supplier offers on the basis of total net cost including carbon dioxide production and transportation. This factor can mean capture technologies that produce elevated pressure carbon dioxide being more relevant, for example technologies using partial condensation with “product CO₂” at elevated pressure.

A key benefit of modular plant supply is not only reduced execution time but also greater responsibility on the module supply company so as to achieve FID much sooner. In this way, whereas a major capture project may require 4 – 5 years to sanction (and in many cases this would be considered optimistic) a smaller-scale project should be based on potentially achieving beneficial operation within 3 years (assuming that all due regulatory requirements can be met in this time period).

The report shows that adopting modular plant should lead to an increase in carbon capture projects. Capture projects of all duties and carbon sources should consider modularisation, if necessary, by having multiple trains and by maximising modularisation as far as possible. Large equipment can be supplied dressed (columns and other large vessels) and pre-assembled piperacks used.

Modular supply simplifies site construction activities, improves site safety and reduces waste, thus having a direct environmental benefit. Other than very large equipment – less of an issue with smaller-scale plant – all the plant can be supplied in modular form. Indeed, modular plant supply should be the default approach for all carbon capture projects, other than for the few locations with very low labour costs and good productivity.

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