



GLOBAL CCS
INSTITUTE

TECHNICAL REPORT

STATE OF THE ART: CCS TECHNOLOGIES 2026

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FOREWORD

Carbon capture and storage (CCS) is a crucial tool in addressing global greenhouse gas emissions and tackling climate change. Scaled deployment of advanced CCS technologies is urgently needed to meet emissions targets across industries such as cement, steel, chemicals, natural gas, and power generation.

CCS project activity continues to grow, with new projects under construction and in operation that use advanced technologies across the value chain. The uptake of these technologies, however, must continue to accelerate to address today's sources of emissions and the removal of CO₂ from the atmosphere.

The 2026 *“State of the Art: CCS Technologies”* compendium continues the aim of our past editions: connecting technology developers and providers with decision-makers, project developers, and designers. Technology firms across the CCS landscape are represented, emerging and established, all seeking to further drive innovation in performance, reliability, energy efficiency, and, most importantly, cost. The entries in this edition cover a range of methods in capture, transport, and storage to accelerate the development of the full CCS value chain.

The *“State of the Art: CCS Technologies”* compendium showcases the breadth and depth of CCS technology ready for deployment and already deployed today, as well as technologies in the process of reaching full commercial readiness.

The current CCS technological capabilities and upcoming future developments submitted here show the strong capabilities ready to support the scale-up of CCS to meet our decarbonisation targets and accelerate the overall deployment of CCS globally. We hope you find this publication useful in your endeavours, as designers, developers, or advocates.

Hugh Barlow
Global CCS Institute
July 2026

Acknowledgements

We are grateful for the contributions and support of all the submitters who have provided content to this publication.

We are also grateful for the Members of the Global CCS Institute, whose Membership enables the Institute to develop catalytic thought leadership pieces, publications such as this Technology Compendium, our annual Global Status Report and a variety of other publications that can be found on [our website](#).

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EDITOR'S NOTES

The Global CCS Institute ("The Institute") is an international think tank whose mission is to accelerate the deployment of carbon capture and storage, a suite of technologies to tackle climate change and deliver climate neutrality.

The Institute produces the *State of the Art: CCS Technologies* ("The Technology Compendium") annually to provide a platform for technology owners and providers to share their solutions, and allow developers, proponents, and interested parties to discover the field's state-of-the-art offerings. This is in accordance with our mission to accelerate the deployment of CCS globally.

The Technology Compendium is a free-to-enter publication, and technology providers collaborate with the Institute to provide their information to the Technology Compendium for review and publication. The technologies presented in the 2026 Technology Compendium represent a non-exhaustive picture of the overall landscape of CCS technologies. Where there has been no submission received for the 2026 Technology Compendium, there is no presence within the Compendium. The Institute is aware of other CCS technologies not mentioned in this Technology Compendium, established and emerging, and we are working to include these technologies in future editions.

If you wish to make a submission to the next edition of the Technology Compendium, please contact us via techcompendium@globalccsinstitute.com.

Disclaimer

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Technology Readiness Level (TRL)

In this publication, the TRL of various technologies has been reported as a part of the submission. The guidance provided to submitters for TRL assessment is provided in Table 1. For inclusion in the 2026 Technology Compendium, a Technology must have a TRL of 5 or above.

Table 1: TRL Guidance Provided for 2026 Technology Compendium Submissions

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

Key Data Table

The Key Data Table is a section of the Technology Submission Template used to outline the capabilities of individual technologies presented on parameters of interest. For Capture Technologies, the parameters are fixed, however for Capture Enabling, Transport, and Storage Technologies the parameters can be adjusted to better reflect the parameters of interest for each technology. The only required parameter across all submissions is the TRL, assessed against the guidance in Table 1.

Definitions of Note for the Key Data Table:

Capture Percentage (%): This is the percentage of CO₂ captured from the inlet stream to a capture technology. A facility may have more than one source of CO₂ emissions – when considering capture percentages, only the specific source directed to a capture plant is considered.

Source CO₂ Purity Range: This is the range of CO₂ concentrations for which a technology is suitable for deployment. This is generally in mol%.

Energy Consumption (GJ or kWh(e)/tCO₂): This is the energy involved in the operation of a technology across the entire system of capture. This can be electric power. This value may include the net effect of waste heat recovery systems or other energy integration. Where these systems may have an impact, but the impact depends on the host site, this is noted.

Specific Regen. Energy (GJ or kWh(e)/tCO₂): This is the "specific regeneration energy". This data point is the amount of energy required to capture CO₂ and regenerate a technology for continuous operation. No waste heat recovery or other energy recovery is included in this data point. No pretreatment upstream or post-treatment downstream of a capture unit is included in this data point.

Front Cover Image: The Ravenna CCS plant at the Casalborsetti Gas Plant, Italy. Image courtesy of Eni / Snam

Foreword Image: The Glacier Gas Plant in Alberta, Canada. Image courtesy of Entropy.

CAPTURE



The Brevik CCS facility, in Brevik, Norway. Image courtesy of Heidelberg Materials and carbon capture technology provider SLB Capturi



AIR LIQUIDE

CHEMICAL ABSORPTION – FLUE GAS AND SYNGAS AMINES



SUMMARY

Air Liquide has designed and installed over 85 amine units globally, leveraging its extensive operational experience and partnerships with key solvent providers to deliver optimised amine-based CO₂ removal. Amine technology is recognised as a leading solution for CO₂ removal due to its ability to efficiently capture CO₂ from a wide range of gases.

Air Liquide's engineers have extensive experience in optimised process design, selecting the right solvents, and integrating amine units into existing processes. In addition to our design and engineering capabilities, Air Liquide also operates several amine units worldwide. This operating experience gives Air Liquide a unique understanding of the challenges and opportunities associated with amine-based CO₂ removal.

With over 35 years of partnership with BASF and over 30 OASE-based amine units designed and built worldwide, Air Liquide is also able to build on BASF's vast know-how of amine chemistry, trace component handling and emission control for OASE-based projects.

BENEFITS

- Technology provides low operating costs and high reliability
- Process configuration can be tailored to optimise CAPEX and OPEX
- Possibility of using waste heat from adjacent units or thermal oil instead of steam
- Fully referenced in all applicable scales and different applications
- Process uses inexpensive, available and chemically stable solvent

Technos

CHEMICAL ABSORPTION	
SYNGAS AMINE WASH	FLUE GAS AMINE WASH
Heat driven CO ₂ removal	
Syngas from SMR, ATR, POx	SMR, Power plant, Pulp & Paper, Waste Incineration, Boilers, BECCS, Cement

Source / application

KEY DATA

TRL	8 - 9	Capture Rate Range (tpd)	150 - 5,000	Capture Efficiency (%)	99%+
Source CO ₂ Purity Range	3 - 25%	Energy Consumption (GJ/tCO ₂)	1 - 2.8 (heat)	Specific Regen Energy (GJ/tCO ₂)	~
Number of Commercial Plants	85+	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	- Flue Gas: SMR, Boilers, Fired heaters, Waste incineration, Refineries (FCC), BECCS, Power plant, Pulp & paper - Syngas: H₂ production (SMR, POX, ATR) & Syngas with ~15% to 35% CO₂. Oxo-syngas with 3% to 15% CO₂				

SYNGAS AMINE WASH

Air Liquides Syngas Amine Wash technology offers highly energy-efficient processes such as BASF OASE® white. The process configuration is tailored according to treated gas requirements and CO₂ product specification as well as optimised CAPEX and OPEX.

CO₂ specifications in the treated gas < 20 ppm are achievable, making this process ideal for CO₂ removal upstream of any coldbox or ammonia process. CO₂ capture rates from syngas of >99% can be achieved to produce a decarbonised hydrogen product.

Characteristics:

- 99.7% availability
- CO₂ at up to 2.3 bara, purity of up to 99.9%
- CO₂ specifications in the treated gas < 20 ppm achievable
- Heat-integration with the upstream gas generation possible to reduce or completely avoid using steam to drive the regeneration

Main applications:

- Syngas from Steam Methan Reforming
- ATR or POx

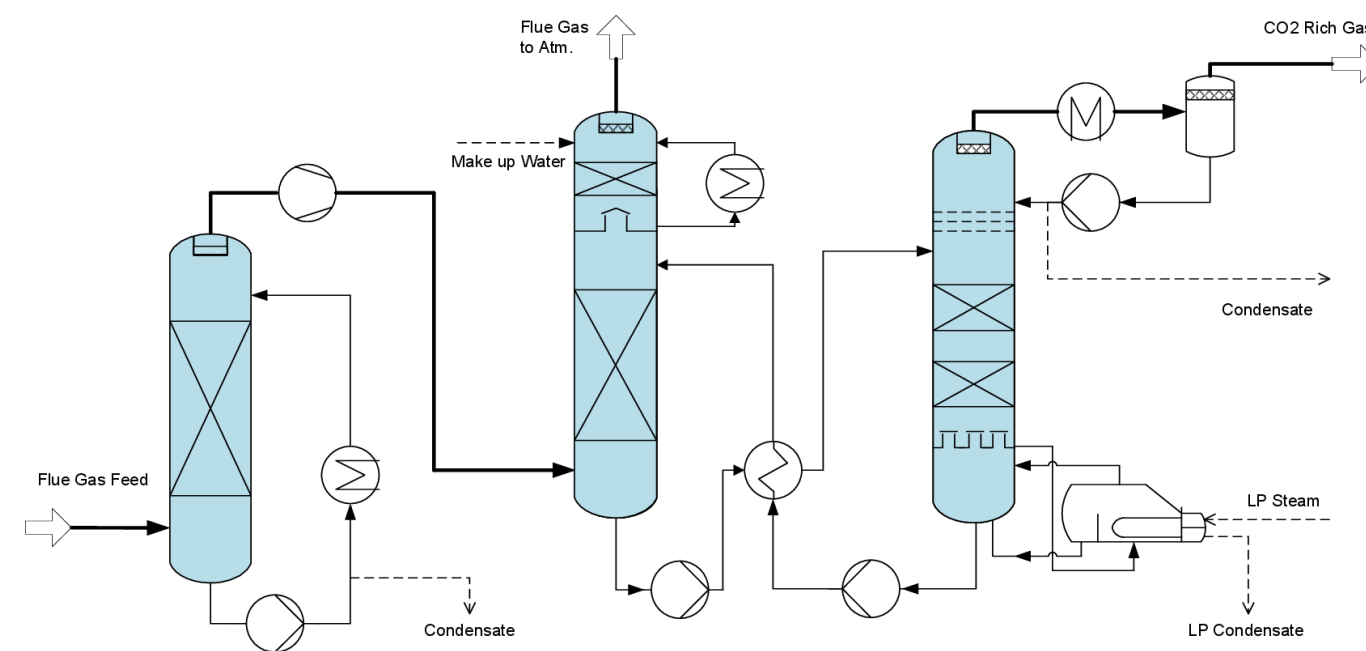
FLUE GAS AMINE WASH

The Flue Gas Amine Wash technology is an energy efficient solution using highly stable, low maintenance solvents based on proprietary second generation amines such as BASF's OASE® blue. CO₂ capture rates of up to 99% can be achieved irrespective of the feed's CO₂ content, and a CO₂ product specification of up to >99.9% can be reached. Up to 1,500,000 Nm³/h of flue gas or 5,000 tpd CO₂ can be treated in a single train. Trace components such as particles and SO_x are handled in the upstream pretreatment. The required heat duty can be provided by LP Steam or thermal oil. For optimal emission control, BASF's OASE® aerozone, a proprietary and patented design proven to reduce aerosol driven emissions and amine losses from the CO₂ capture process, can be applied.

Characteristics:

- Max 16% O₂ in flue gas
- 99.7% availability
- CO₂ purity of up to 99.9% and low O₂, at up to 2.5 bara w/o compression
- Particles & SO_x handled upstream of amine wash
- OASE® aerozone for emission control

Main Applications: Flue gases or off gases from industrial sources with CO₂ content 3% to 25% - (SMR, cement/lime, steel blast furnace, refineries (FCC), biomass power plant, pulp & paper)



AIR LIQUIDE CRYOCAP™ (H₂, FG, OXY & STEEL)



SUMMARY

Air Liquide has developed Cryocap™, a patented technology that uses cryogenic processes to capture CO₂. Being a combination of various Air Liquide proprietary technologies, Cryocap™ can be adapted to various applications and has the potential to not only reduce the CO₂ emissions by up to 99% but also to recover other valuable molecules such as H₂, CO, and CH₄ from the feed gas. To date, Cryocap™ is the only operational full-scale cryogenic carbon capture technology with an industrial reference (Port Jerome, France) in the CCS market worldwide. For over 10 years, the Port Jerome site has demonstrated steady operation and performance parameters, no interruptions in the H₂ production, and a CO₂ availability of more than 99%+.

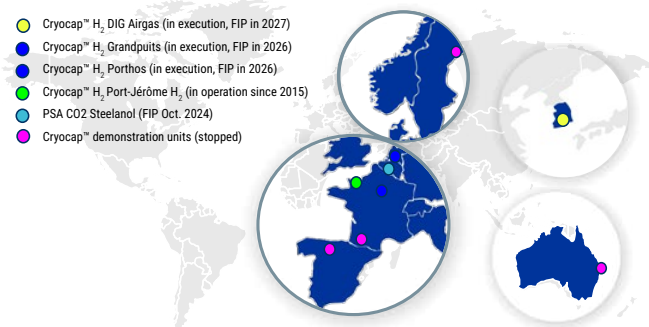
BENEFITS

- Minimised overall carbon footprint: high CO₂ recovery (92 - 99%+)
- High intrinsic process efficiency: most efficient technology bricks and operation close to triple point
- Safety and no toxicity: no by-product formation, solvent-free, no toxic or flammable gases used
- Matches the end specifications and high CO₂ product purity: meeting stringent CO₂ specifications (>99.9%v)
- Favours synergies and optimised space: 1-step capture and liquefaction, compact design & flexible configuration
- Improved productivity: for some applications (H₂ and steel), H₂ production can be increased by up to 20%
- HSE friendly
- Skidded: main equipment delivered skidded for lower installation cost

KEY DATA

TRL	7 - 9	Capture Rate Range (tpd)	300 – 10,000+	Capture Efficiency (%)	99%+
Source CO ₂ Purity Range	15 - 95 %v	Energy Consumption (GJ/tCO ₂)	0.4 – 2	Specific Regen Energy (GJ/tCO ₂)	~
Number of Commercial Plants	2	Number of Pilot Plants	4	Modular (Y/N)	Yes
Target Industries	• H₂ : H₂ production (SMR or ATR) • FG: Flue gases or off-gases with CO₂ content >= 15% (SMR, cement/lime, steel blast furnace, refineries (FCC), waste incineration/biomass power plant, pulp & paper) • Oxy: Cement/Lime, Power plant, any applications with CO₂ concentration >50% • Steel: Iron and Steel Production				

Air Liquide Cryocap™ references



CRYOCAP™ H₂

Cryocap™H₂ uses cryogenic purification to separate the CO₂ from the Pressure Swing Adsorption (PSA) off-gas, containing typically 40-70+%v CO₂. The PSA off-gas is compressed, dried and sent to a cryogenic unit, where the CO₂ is separated from the other components by a combination of partial condensation and distillation. A pure liquid CO₂ flow is produced from the cold process. The non-condensed gases are recycled through a membrane system to recover H₂ and CO₂. The residual gas, composed of CO and CH₄, is recycled to the H₂ production plant either as feedstock or as fuel gas. The CO₂ product is either revaporised to be then compressed up to the final pressure (gaseous or supercritical product) or extracted in liquid state.

Characteristics:

- Avoided CO₂ cost reduction: up to 40% compared to MDEA
- Hydrogen extra production: of + 12-20%

CRYOCAP™ FG

Cryocap™FG is a separation process based on the combination of adsorption and cryogenic separation. The flue gas is first compressed, dried and sent to a PSA (Pressure Swing Adsorption). The PSA pre-concentrates the CO₂ in the off-gas, which is then compressed and sent to a cold process. There, the CO₂ is separated from the other PSA off-gas components and purified by a combination of partial condensation and distillation. Part of the impurities removed in the cryogenic process are recycled to the inlet of the plant. The CO₂ product is either compressed up to the final pressure (gaseous or supercritical product) or recondensed and extracted in liquid state. The pressurised nitrogen from the PSA is expanded to recover energy.

Characteristics:

- PSA-assisted CO₂ condensation
- Smart impurities management (including NO_x removal)

CRYOCAP™ OXY

Cryocap™Oxy uses oxy-fuel combustion exhaust as a feedstock. The flue gas issued from the cement or lime or power plant is first treated in a pre-treatment unit, which aims to cool the gas and remove the SO_x, HF, HCl, part of the NO_x, and dust. Then, the gas is compressed and dried before entering the cryogenic purification unit. In the cold section, CO₂ is recovered and purified by a combination of partial condensation and distillation, with both light and heavy components (O₂, Ar, CO, N₂, remaining NO_x) being removed from the CO₂ down to ppmv or sub ppmv level. The purified CO₂ can be produced either gaseous and then compressed to the final pressure, or produced directly as liquid.

Characteristics:

- Enriched flue gas above 50% CO₂
- Smart impurities management (including NO_x removal)

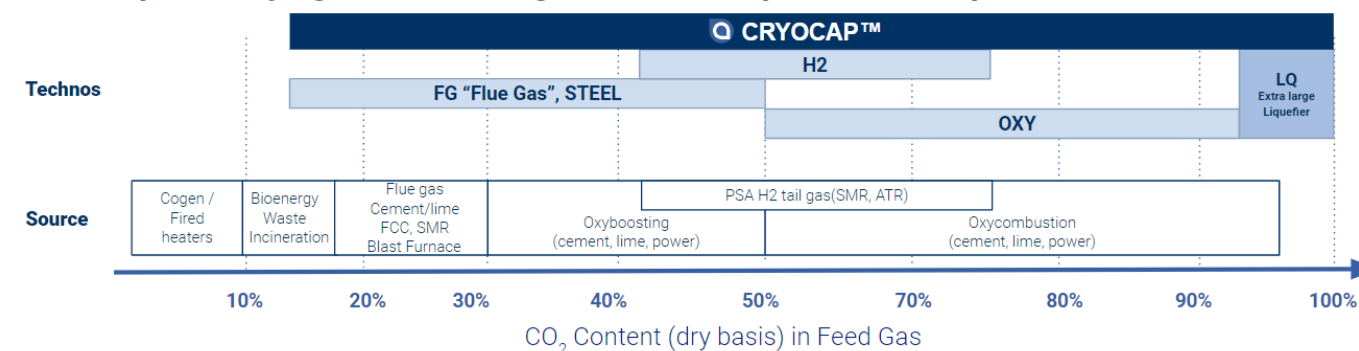
CRYOCAP™ STEEL

Cryocap™Steel was designed to specifically capture CO₂ from steel making plants with flue gases containing CO₂ in the 20-50% range. The gas is first compressed, dried and sent to a PSA (Pressure Swing Adsorption). The PSA pre-concentrates the CO₂ in the off-gas while producing a CO rich stream. The pre-concentrated CO₂ stream is compressed and sent to a cold process. There, CO₂ is recovered and purified by a combination of partial condensation and distillation, with both light and heavy components (NO_x, O₂, Ar, CO, N₂) being removed from the CO₂ down to ppmv or sub ppmv level. The purified CO₂ can be produced either gaseous and then compressed to the final pressure, or produced directly as liquid. The pressurised CO-rich stream from the PSA unit is either recycled to the blast furnace or used to produce fuels.

Characteristics:

- Compact and flexible footprint: compressors, PSA and cold-box can be located in three different plots

Air Liquide cryogenic offerings for CO₂ capture and liquefaction





AIR LIQUIDE

PHYSICAL ABSORPTION: RECTISOL™ AND RECTICAP™



SUMMARY

Air Liquide’s Rectisol™ and Recticap™ state-of-the-art physical absorption technologies use cryogenic methanol to remove acid gases and CO₂ from feed gas. Air Liquide draws on its extensive experience and technological expertise from the operation of multiple Rectisol™ units, more than 110 units installed worldwide, and a demonstration plant, to test and implement new innovations.

BENEFITS

- One of the highest energy efficiencies for the removal of CO₂ and/or acid gases (H₂S, COS, etc.) in separate product streams
- Rectisol™ can treat the most severe impurities that stem from gasification, and deliver ultra high purity syngas for downstream catalytic applications such as the production of Sustainable Aviation Fuels
- Recticap™ delivers one of the highest energy efficiencies for CO₂ removal on low carbon H₂ or NH₃ applications
- More than 110 references worldwide, and know-how from Air Liquide’s own operated plants and demonstration unit

Technos	PHYSICAL ABSORPTION	
	RECTICAP™	RECTISOL™
Source / application	Highest efficiency - adapted to large scale low-carbon syngas applications	
	Low-carbon H ₂ or NH ₃ Production	Biomass / MSW gasification for H ₂ , MeOH, SAF Production

KEY DATA

TRL	9	Capture Rate Range (tpd)	1,000 - 10,000	Capture Efficiency (%)	Up to 99%+
Source CO ₂ Purity Range	20 - 30%	Energy Consumption (GJ/tCO ₂)	0.2 GJ/tCO ₂ (elec) + 0.1 GJ/tCO ₂ (heat)	Specific Regen Energy (GJ/tCO ₂)	~
Number of Commercial Plants	110+	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Rectisol™ : • NG-based Low carbon H₂ or NH₃ • Biomass-based / MSW-based gasification for the production of Sustainable Aviation Fuels (SAF) / H₂ / MeOH / NH₃ • Solid carbonaceous-based applications such as IGCC, Chemicals Recticap™: • Carbon capture & syngas bulk CO₂ removal for production of decarbonised hydrogen and ammonia/urea				

RECTISOL™

Harmful acid gases contained in raw gases from gasification are removed by absorption with a physical solvent (cold methanol).

Rectisol™ is the leading process when it comes to the purification of gasification-based syngas for hydrogen production, catalytic applications (production of syngas, methanol, ammonia, or Fischer-Tropsch), or syngas for power production. Using an energy efficient solvent in combination with optimised heat integration, the Rectisol™ process has extremely low operating costs and high availability.

Various configurations are possible, to optimise the capital intensity or energy consumption in accordance with the project or client’s conditions.

Characteristics:

- CO₂ removal rate: down to 5 ppm
- Sulphur (H₂S + COS): < 0.08 ppm
- Special setups for removal of mercaptans, metal carbonyls and BTX available
- All harmful contaminants within the acid gas can be safely processed in a SRU
- Separate CO₂ and SRU-suitable gas product streams

Main Applications: Syngas from solid carbonaceous materials, biomass or oil residue gasification

RECTICAP™

Recticap™ is a streamlined Rectisol™ concept optimised for CO₂ removal from ATR based applications such as low carbon H₂ or NH₃. The process has been tailored for CO₂ capture at large capacities (> 300,000 Nm³/hr syngas) and moderate to high pressures (> 25 bar).

Recticap™ removes only CO₂ from the raw hydrogen / syngas, thus combining the efficiency of the Rectisol™ process with reduced capital expenditures. The technology allows for capture rates in excess of 99% from syngas.

Various configurations are possible for project specific optimisation of energy demand and CO₂ capture performance.

Characteristics:

- Recticap™ delivers one of the highest energy efficiencies for CO₂ removal on low carbon H₂ or NH₃ applications
- High availability: 99.7%
- > 99% purity, dry CO₂ product ready for pipeline transport / sequestration
- > 300,000 Nm³/hr syngas

Main Applications: Syngas from Steam Methane Reforming, ATR or POx



SUMMARY

Building on 60 years of experience and continuous innovation, Axens provides CO₂ capture solutions as well as a comprehensive range of flue gas pre-treatments and CO₂ conditioning processes. To address challenges of capturing CO₂ from flue gases, Axens and IFPEN developed the DMX™ process, a breakthrough CO₂ post-combustion capture process based on absorption using a proprietary demixing solvent.

The DMX™ solvent consists of a mixture of two organic compounds in aqueous solution, which separates (demixes) into two phases under certain conditions of temperature and CO₂ partial pressure in the regeneration section. Only the CO₂-rich phase has to be regenerated, which significantly reduces the energy required for solvent regeneration.

The DMX™ Technology has been successfully demonstrated through a large-demonstration plant at ArcelorMittal's steel mill in Dunkirk. It is now proven, robust and ready for commercial deployment.

BENEFITS

Main benefits of DMX™ process are the following:

- Versatile and flexible process applicable to multiple types of flue gases origins, compositions and flowrates.
- Low energy consumption down to 1.8 GJ/tCO₂.
- Thermally stable solvent with low degradation rate.
- High capture rate (up to 99%) and high purity of produced CO₂ (>99.8%).
- CO₂ produced readily under pressure up to 5 barg, for significant compression cost-savings.
- 30% reduction of CO₂ capture cost compared to MEA based technologies.
- Customised design fitting the site, operational and available utilities constraints.
- Available for a wide range of unit sizes (stick built, Modular or Mobile pilot).
- Support on the full value chain: pre-treatment, capture, conditioning and close collaboration with EPCs and compressor vendors for integrated offer.

KEY DATA

TRL	8	Capture Rate Range (tpd)	From pilot to tailor made large scale unit	Capture Efficiency (%)	90 - 99%
Source CO ₂ Purity Range	1 - 30%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	1.8 - 2.7 Typical heat req.
Number of Commercial Plants	1	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Power generation, Steel mills, Refineries, waste incinerators as well as chemical, cement, lime, glass, paper, aluminium production plants				

PRECONDITIONING SECTION

Upstream of the carbon capture process a dedicated preconditioning section shall be foreseen to cool down the Flue gases, optimise the Heat Recovery, overcome the pressure drop across the Carbon Capture Unit and remove the dust and the impurities such as SO_x and NO_x if present in high quantities. Axens, with its Danish subsidiary Flowvision offers technologies to address all these pollutants.

Relying on this know-how, and DMX™ solvent's high tolerance to flue gas impurities, including O₂, particulates, and acid gases such as NO_x and SO_x, Axens is capable of supplying a fully integrated and optimised pre-conditioning section tailored to each specific application.

CARBON CAPTURE PROCESS DESCRIPTION

The DMX™ process, originally developed for CO₂ capture on coal power stations flue gases and steel mill gas is also applicable to capture CO₂ from industrial emitters such as refineries, lime producers, waste incinerators as well as chemical, cement, glass, paper or aluminium production plants.

The DMX™ solvent removes CO₂ from the flue gas in the absorber to achieve a CO₂ recovery of 90 - 99% depending on the needs.

The CO₂-rich solvent is preheated in the lean/rich solvent exchanger to reach conditions at which the solvent forms two phases: one CO₂-rich phase and the other, CO₂-lean phase.

The CO₂-lean phase is separated in the decanter and directly routed back to the absorber. Only the CO₂-rich phase is regenerated, resulting in a considerable reduction in reboiler steam consumption.

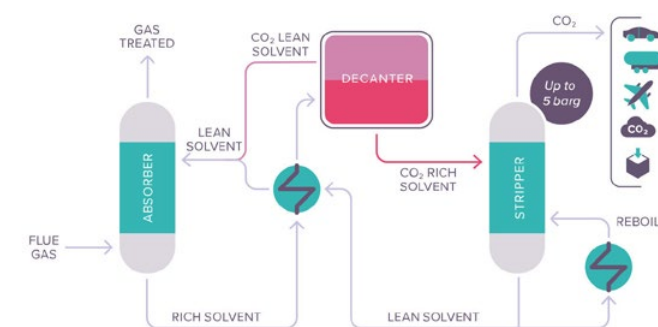


Figure 1: DMX™ Process Concept & PFD

The regeneration of the CO₂-rich phase is performed under pressure, up to 5 barg, thanks to its thermal stability. This significantly reduces down-stream compression needs and lowers transport costs, supporting large-scale decarbonization. The DMX™ solvent is also far less corrosive, allowing the use of carbon-steel equipment, which results in substantial CAPEX savings.

Low steam energy consumption at the reboiler can be achieved, varying typically in the range of 1.8 - 2.7 GJ/tCO₂, depending on the CO₂ concentration of the flue gases and the targeted capture rate. This energy penalty can be further reduced with electrification of the process, valorisation of waste heat and optimised heat integration with the site environment.

DEVELOPMENT AND TECHNOLOGY READINESS LEVEL

The DMX™ demonstration unit has been developed under the EU H2020 “3D” project with 11 partners—including ArcelorMittal, Axens, IFPEN, and Total Energies. It has operated for two years, capturing 0.5tCO₂/h (or 4,000 TPA) from the blast furnace gas.

The 3D demonstration unit, installed at ArcelorMittal's steel mill, has successfully showcased the full potential of DMX™ carbon capture technology. It highlights its exceptional operability, outstanding solvent stability, low energy consumption, and consistent delivery of high-purity CO₂ even under varying CO₂ concentrations.

Beyond demonstrating technical excellence, this project also investigates the full-scale capture, conditioning, transport, and storage of 1 MTPA of CO₂. It contributes to developing a CO₂ hub in Dunkirk, connected to storage facilities such as those planned for Northern Lights (or Longship).

Capitalizing on this successful demonstration, Axens is leading the way in large-scale deployment of DMX™, while driving continuous innovation to make CO₂ capture even more efficient, cost-effective, and sustainable.

CO₂ CONDITIONING

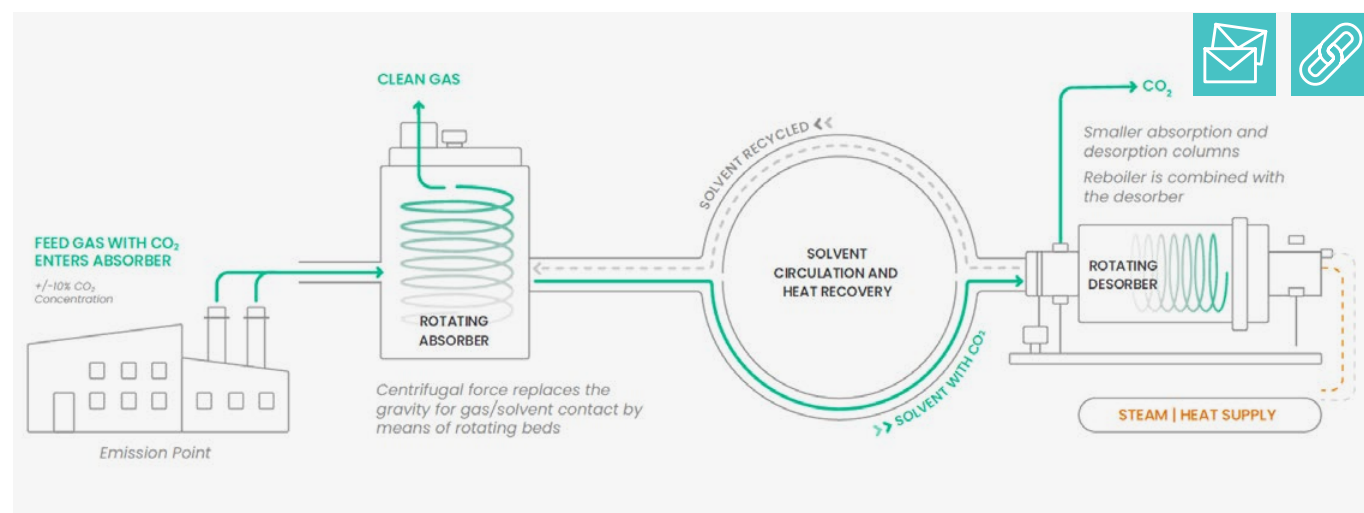
The purification of the captured CO₂ plays a critical role in enabling its safe and efficient transport, utilization or permanent storage.

Most common impurities are sulfur compounds, oxygen and water but other contaminants such as mercury or chloride may also be present.

Axens offers a complete portfolio of in-house products (catalysts and adsorbents) together with technologies to remove contaminants from CO₂ and ensure compliance with required specifications.

Axens' diverse solutions, know-how in process design and close collaboration with compressor suppliers ensure an optimised design of the CO₂ conditioning chain tailored for each project.

Baker Hughes BAKER HUGHES COMPACT CARBON CAPTURE (CCC)



SUMMARY

Compact Carbon Capture (CCC) is a pioneering technology development in the Baker Hughes CCUS portfolio. CCC employs the Rotating Packed Bed (RPB) technology, a novel process intensification that utilises centrifugal acceleration to intensify mass transfer reducing the equipment size and cost. CCC is developed for post-combustion applications and for small to medium sizes of emissions.

By using RPB technology, CCC drastically increases the vapor-liquid contact area, overcoming the traditional hydraulics limitations. Compared to conventional solvent-based systems using static equipment, CCC's enhanced mass transfer results in reduced residence time in the absorber and the regenerator requiring much smaller equipment. CCC also proposes the regenerator and the reboiler integrated into one unique equipment, which results in a further reduction of the plant's footprint.

CCC is currently validated at TRL 5 in a pilot- of 1.7 ktpa CO₂ at Equinor's test facilities in Porsgrunn, Norway. Further development is ongoing, with a demonstration plant at 5 ktpa scale currently under development.

BENEFITS

- Significant CAPEX reduction through process intensification and optimised equipment design
- Reduced footprint and equipment size, delivering a compact system architecture
- Lower solvent inventory, translating into reduced operating costs
- Reduced electricity consumption for CO₂ compression, enabled by regeneration at higher pressure
- Shorter project lead times enabled by a modular and standardised design approach, simplifying logistics and minimizing on-site civil works for accelerated deployment.



Pilot plant (1.7 ktpa), picture taken before moved to Equinor's test facilities in Porsgrunn, Norway

KEY DATA

TRL	5*	Capture Rate Range (tpd)	~	Capture Efficiency (%):	95%
Source CO ₂ Purity Range	4 - 25%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂):	~
Number of Commercial Plants	~	Number of Pilot Plants	1*	Modular (Y/N):	Yes
Target Industries	Fossil Fuel-Based Power Plants, Waste to Energy & Biomass Power Plants, Cement Plants, Refineries and Petrochemical Complexes				

* A demonstration plant at 5 ktpa scale is currently under development to meet TRL 7

Compact Carbon Capture has transformed the process equipment used in post-combustion carbon capture by introducing rotation and high G-forces to capture CO₂.

ABSORPTION SECTION

In the Cross Flow Absorber, the G-forces are created in several cross-flow rotating packed beds. CO₂-lean solvent is distributed from the inner axis and horizontally flung outwards in the direction of the wall of the column, while the flue gas moves vertically from the bottom to the top. Mass transfer takes place between the flue gas and the solvent in a cross-flow type arrangement.

Due to the rotation of the packed bed within the column that induces high centrifugal forces, the solvent is accelerated when it hits the packing structure, forming small droplets. This generates a large vapor-liquid contact area compared to conventional static mass transfer which relies on gravity. The larger contact area between gas and liquid results in a faster mass transfer of CO₂ from the flue gas into the solvent droplets, resulting in a much shorter absorber column height compared to conventional columns.

The short contact time allows for the operation with highly viscous solvents that improve the process efficiency. Higher concentrated solvents result in higher absorption rates. When this is combined with the compactness introduced by the process intensification, a considerably lower solvent inventory is needed, resulting in smaller capacity and size of pumps and other equipment in charge of solvent handling.



Cross Flow Absorber (CFA)

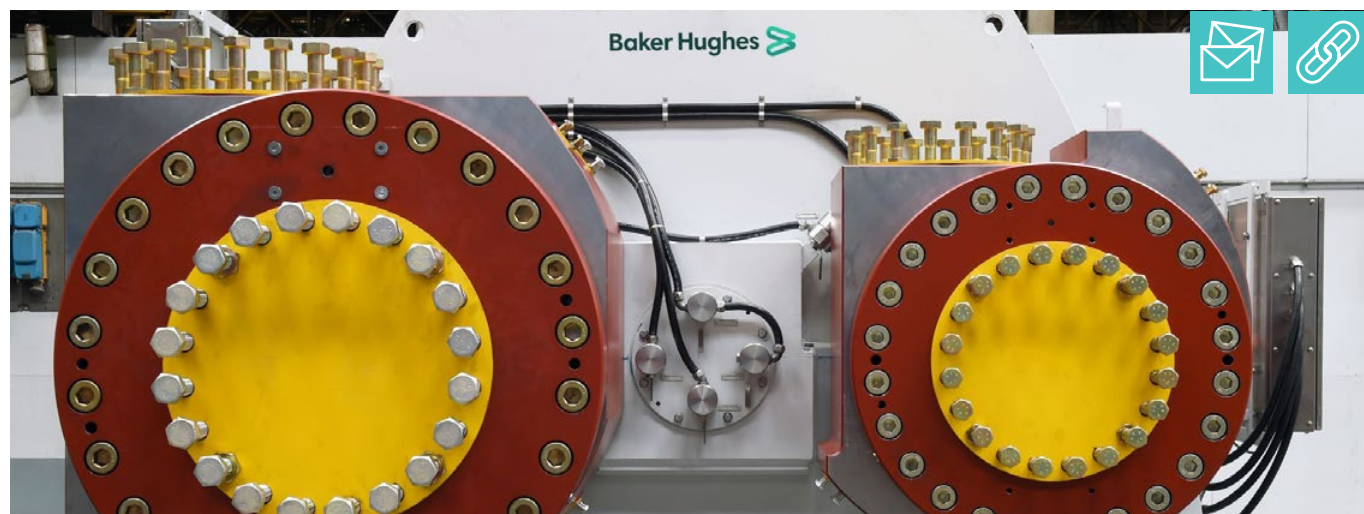


Rotating Desorber Wheel (RDW)

REGENERATION SECTION

The Rotating Desorber Wheel is a compact equipment combining the reboiler and stripper, that can operate at higher pressures and can handle highly viscous solvents. High-speed rotation of the desorber unit introduces turbulence and high G-forces to the solvent regeneration, which are advantageous for mass and heat transfer, resulting in a very compact equipment. The Rotating Desorber Wheel can be described as a lightweight pressurised shell-and-tube heat exchanger where the "hot-side" tube bundle rotates to generate the centrifugal force required to produce small solvent droplets. Instead of a static regenerator column with attached reboiler in a conventional solvent-based system, CCC will have a single compact rotating bed/flash drum that heats the rich solvent and flashes off CO₂ to generate a high purity (>99%) CO₂ product stream.

Baker Hughes **BAKER HUGHES** **HOT POTASSIUM CARBONATE**



SUMMARY

Baker Hughes, in collaboration with Giammarco Technologies, is advancing the commercialization of Hot Potassium Carbonate (HPC) technology for post combustion carbon capture. Giammarco Technologies' HPC process, built on decades of operating experience, is integrated with Baker Hughes' turbomachinery solutions to enhance system performance, leveraging decades of expertise and a global installed base of more than 5,000 compression and turbine units.

These solutions support cost effective and reliable decarbonization across a range of energy and industrial sectors, including waste to energy, biomass power generation, pulp and paper, and cement and lime production. The proven HPC process uses a sustainable, thermally stable solvent that enables robust operation without complex solvent degradation management while minimizing environmental risk. The solvent is commercially available and non proprietary, reducing both supply chain and operational risk.

HPC technology is designed for retrofitting into existing facilities with minimal disruption to operations, while providing strong operational flexibility. It enables CO₂ capture rates of 95%+ and enables extensive heat integration. This includes opportunities to support downstream CO₂ compression and liquefaction, district heating, or fully electrified plant configurations. Multiple process options allow effective utilization of available heat sources, improving overall energy efficiency and reducing operating costs.

BENEFITS

Our HPC solution is a mature, commercially proven technology with decades of operating experience. It has been deployed across more than 400 industrial projects and demonstrated in post combustion capture application through thousands of hours of pilot-scale testing. Key advantages include:

- A sustainable, stable, and readily available solvent that minimises environmental risk
- Energy efficient capture enabled through integration with Baker Hughes' compressor expander trains and turbomachinery for post combustion applications

- Multiple process configurations designed to accommodate diverse energy mixes and maximise heat recovery, thereby reducing capture costs
- Modular, packaged solutions that shorten delivery timelines, simplify maintenance, and are supported by comprehensive lifecycle services
- Fully integrated, customised solutions are delivered to reduce the cost of carbon capture, with end to end project execution across the full lifecycle—from technology screening and FEED through execution, commissioning, startup, and long term operation and maintenance.

KEY DATA

TRL	7	Capture Rate Range (tpd)	100 tpd+	Capture Efficiency (%)	95%
Source CO ₂ Purity Range	-	System Energy (GJ/tCO ₂)	-	Specific Regen. Energy (GJ/tCO ₂)	-
Number of Commercial Plants	400	Number of Pilot Plants	1*	Modular (Y/N)	-
Target Industries	Coal and NG power plants; WtE; Oil & Gas; Steel industry; Cement Industry				

* Additional pilot plants to be deployed in post-combustion capture applications

A typical HPC capture configuration comprises flue gas compressor–expander, gas to gas heat exchanger, CO₂ absorber and stripper, and lean–rich solvent heat exchangers among key equipment. Flue gas is compressed to the conditions required for CO₂ capture, where CO₂ is selectively removed via chemical absorption using the hot potassium carbonate solvent. The pressurised CO₂ lean flue gas is then expanded to recover energy before discharge to the stack while the CO₂ rich solvent is heated, and steam stripping releases CO₂ at the top of the stripper column. The regenerated solvent is subsequently cooled and recycled to the absorber.

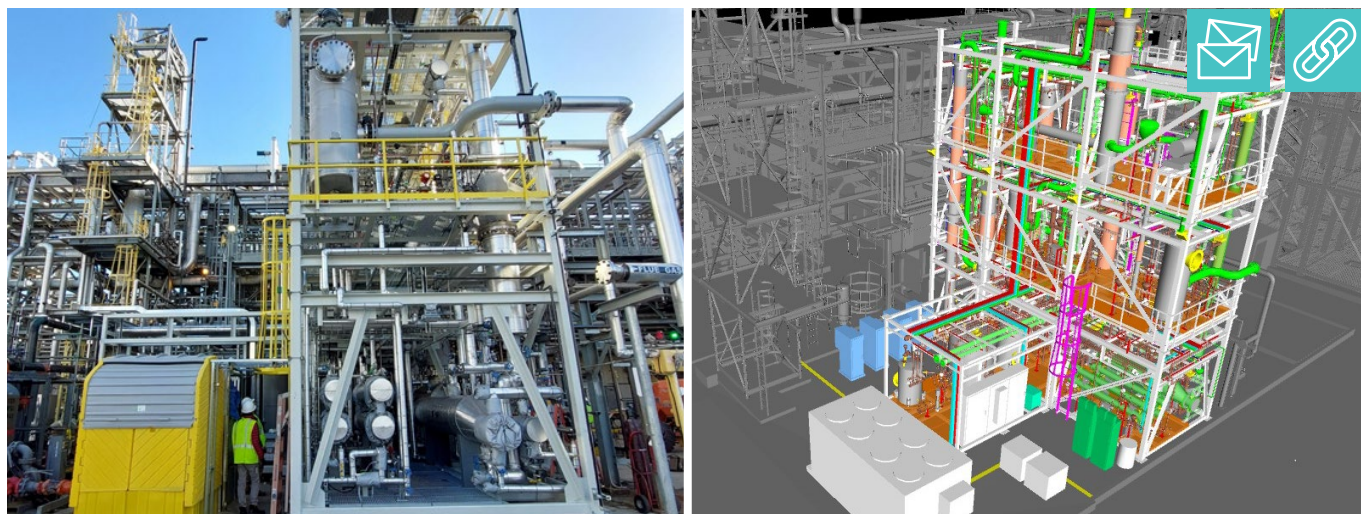
Multiple process solutions are tailored to project specific requirements to optimise capital and operating expenditures, including the generation and utilization of surplus heat. This is achieved by integrating Giammarco Technologies' HPC process schemes with Baker Hughes' world class turbomachinery. Representative process schemes include:

- HPC thermal integration: featuring Giammarco Technologies HPC-Genesys® this represents the simplest scheme and allows to maximise the heat recovery from the process whilst minimizing capital expenditure. Therefore, it represents the preferred solution in situations where effective thermal integration with other utilities is prioritised, such as for waste-to-energy and biomass power generation facilities seeking to deliver district heating in the form of domestic water production.

- HPC thermal saving: featuring Giammarco Technologies HPC-NovaFlash® or HPC EcoEnergi® schemes, where the steam produced from boiling the solvent is directed to a flash step and recycled back to the stripping column after recompression, thus reducing reliance on external heat. This configuration is particularly suitable in situations where reducing operational expenditure is a priority and a source of steam is available
- HPC thermal independence: featuring Giammarco Technologies HPC-Electron® scheme, this solution allows the HPC capture system operating using electricity alone by integrating mechanical vapor recompression turbomachinery. It is ideal in situations where a thermal source is unavailable and modifying existing plants for steam-powered capture is challenging, such as cement and lime production facilities

Each solution can be further customised through different absorption and stripping arrangements (single stage, split stream, or dual stage), to meet CO₂ product specification and conditioning, thermal energy reuse strategies, and integration with downstream CO₂ compression and liquefaction systems. When combined with Baker Hughes' turbomachinery, including radial and axial compressors, high temperature energy recovery systems, the HPC solutions achieve high performance, reliability, and operational flexibility.

Baker Hughes **BAKER HUGHES** **MIXED-SALT PROCESS (MSP)**



SUMMARY

Baker Hughes uses the Mixed-Salt Process (MSP) for CO₂ capture under license from SRI International. SRI International received support from the US Department of Energy's Office of Fossil Energy and National Energy Technology Laboratory (NETL) for the development of this technology. MSP is a post-combustion carbon-capture process that uses a novel solvent formulation, which is based on potassium carbonate and ammonium salts. Both chemicals are low-cost, inorganic commodity chemicals, and readily available on the market. The inorganic solvent used by MSP is tolerant to flue gas contaminants (such as SO_x, NO_x, and O₂), unaffected by thermal and oxidative degradation, results in lower emissions, lower toxicity, and higher CO₂ regeneration pressure compared to conventional amine-based solutions. MSP has been demonstrated at the capacity of 0.25 tpd at the SRI's campus in USA. MSP was demonstrated using real flue gases and a 10 tpd pilot-scale plant at the National Carbon Capture Center in USA in the period 2025/26.

BENEFITS

The benefits of MSP comprise:

- Reduced reboiler energy consumption of 2.0 – 2.3 GJ/ton CO₂
- Uses inexpensive, industrially available chemicals (potassium and ammonium salts)
- Stable reagent. Unlike amine-based solvent systems, it does not suffer from thermal and oxidative degradation
- Tolerant towards oxygen in flue gas and to contaminants such as SO_x and NO_x
- Regenerates CO₂ at elevated pressure, thus requiring less compression energy for the downstream CO₂ product
- Reduced auxiliary electricity loads

KEY PROJECTS

- **Development of Mixed-Salt Technology for CO₂ Capture from Coal Power Plants (US DoE: DE-FE0012959):** A bench-scale study of MSP technology aiming the demonstration of TRL:4. It comprised: i) the desing and construction of bench-scale testing set-up, ii) the execution of experimental research, and iii) the study of thermodynamics; Tested capture capacity: 0.25 tpd ; Period: 2014 – 2018.
- **Engineering-Scale Demonstration of the Mixed-Salt Process (MSP) for CO₂ Capture (US DoE: DE-FE0031588):** Demonstration of MSP technology using industrial flue gas and a pilot plant deployed in relevant industrial environment (NCCC) for demonstration of TRL: 6. It comprised: i) the desing and construction of the pilot plant facility, ii) the execution of test campaigns, and iii) the derisking of MSP process; Tested capture capacity: 10 tpd; Period: 2018-2026

KEY DATA

TRL	5 - 6	Capture Rate Range (tpd)	1,000+	Capture Efficiency (%)	95
Source CO ₂ Purity Range	>4%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.3
Number of Commercial Plants	~	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Coal and NG power plants; WtE; Oil & Gas; Steel industry; Cement Industry				

MSP is a post-combustion technology that is applicable to a wide range of flue gases. It uses an aqueous blend of ammonium and potassium-based salts to absorb CO₂ from flue gases at ambient pressure and temperature. The high CO₂ cyclic loading of MSP solvent reduces the consumption of water during plant operation. The stability of the inorganic solvent used by MSP is not affected by oxygen and shows high tolerance to acidic trace components present in the incoming flue gas. The process is characterised by very low emissions and produces little-to-no toxic waste. The application of a proper process design could also allow the formation of by-products, e.g., ammonium sulfate, with a commercial value.

A simplified process flow diagram of the MSP technology is depicted in the accompanying figure and the process can be described as seen below.

Inlet flue gas first undergoes cooling to 20 - 30 °C in a direct contact cooler (DCC) and subsequently enters Absorber 1, where it contacts the mixed salt solvent counter-currently. The mixed salt solvent in Absorber 1, which has a higher concentration of ammonium-based species than potassium-based species (high ammonia/potassium ratio), performs the bulk removal of CO₂, absorbing 60-80% of the CO₂ in the flue gas. The remaining CO₂ is absorbed in Absorber 2, which operates with the mixed-salt solvent with a lower ratio of ammonium-based species to potassium-based species than that of the solvent feed of Absorber 1. Absorber 2 performs the trim removal of CO₂ to achieve an overall CO₂ capture rate of more than 90% and reduces the ammonia slip from Absorber 1. The operation of absorption columns at relative high temperatures and atmospheric pressure minimises the chilling duty needs and enhances the reaction kinetics. Furthermore, it makes feasible the application of MSP to geographic zones with high temperatures.

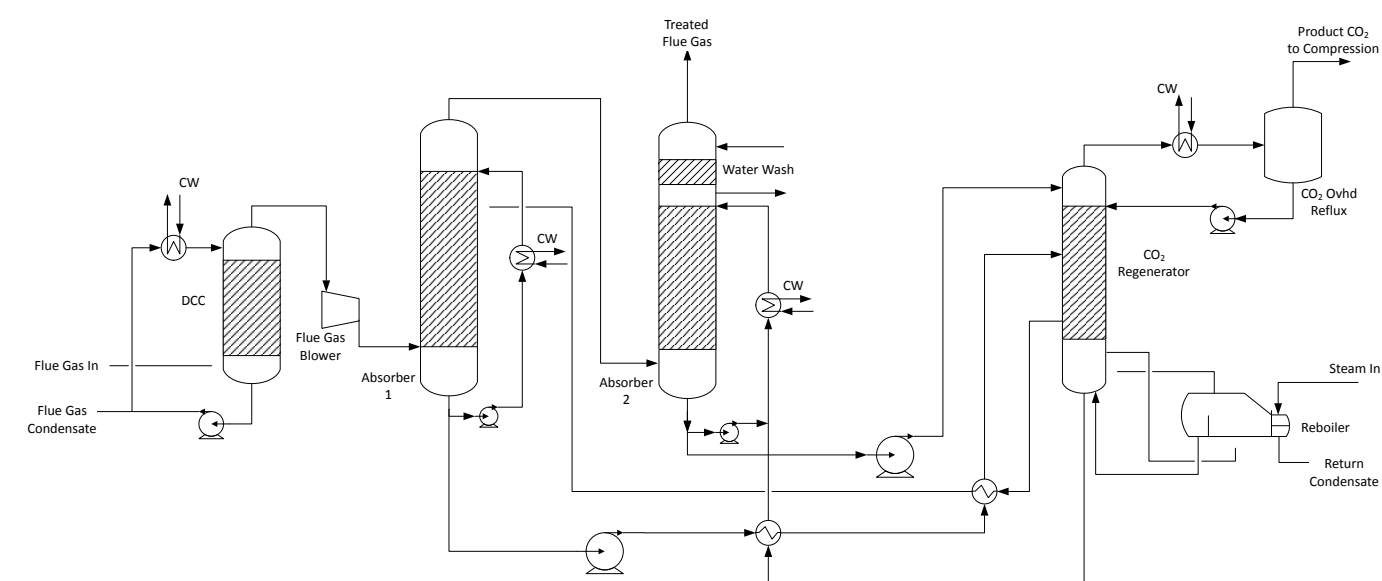
A water wash located at the top of Absorber 2 further reduces the ammonia content in the treated flue gas to ensure the compliance with ammonia emission limits and the recovery ammonia.

Both absorbers operate with liquid recycle using heat exchangers to remove the heat of reaction and keep the solution at the optimum temperature for efficient absorption and minimum ammonia slip. The CO₂-rich solvent collected from the absorbers is sent to the regenerator for regeneration via an integrated rich-lean heat exchanger network that is designed to recover sensible heat.

Heat is supplied to the regenerator via a reboiler located at the bottom of the column. The increase in temperature releases CO₂ as a gas and regenerates the mixed-salt solvent to be returned to Absorber 1 and Absorber 2. CO₂ is released at an elevated pressure of 10 - 20 bar(a) from the regenerator column, which serves to reduce the downstream CO₂ compression power requirements. Furthermore, it provides a good quality raw CO₂ product free of toxic impurities that simplifies the final purification stages.

The CO₂-lean mixed salt solvent is drawn from the lower-middle stage of the column and sent back to Absorber 1 to perform bulk CO₂ removal. Near the bottom of the regenerator where the temperature is higher, ammonia is vaporised, resulting in a lean solvent with low ammonia/potassium ratio, which is returned to Absorber 2 where it performs the trim removal of CO₂ and reduces ammonia losses.

MSP process desing give emphasis on the solvent management. The consumption of chemicals (make-up) and generation of wasted water are limited throught the use of recovery subsystems. This results in a strongly sustainable carbon capture solution.



A simplified process flow diagram of the MSP technology.



CARBON CLEAN
CAPTUREX™



SUMMARY

CaptureX™ is a semi-modular post combustion carbon capture technology developed by Carbon Clean for deployment across a range of industrial applications. The system delivers high purity CO₂ capture across a wide range of flue gas profiles, with a semi-modular design that enables fast installation, reduced onsite activity, and integration into existing and future facilities.

CaptureX™ plants are optimised using APBS-CDRMax® solvent, enabling high capture efficiency and energy performance. Each installation is configured according to site-specific flue gas characteristics, with scalable capacity and capture rates of up to 95%. The technology has reached Technology Readiness Level (TRL) 9 and has been commercially deployed since 2016. The technology has also been validated at large scale test centres, including Technology Centre Mongstad in Norway and the National Carbon Capture Center in the US, and has accumulated more than 3 million tonnes of CO₂ capture cumulatively across all technology references.

BENEFITS

- **Semi-modular design:** ~80% prefabricated, reducing on-site works, installation time, and integration complexity, while supporting repeatable quality and faster commissioning.
- **Engineered-to-order:** Systems are configured for project-specific CO₂ capacities and flue gas compositions, supporting low, medium, and high-concentration streams with consistent performance.
- **Proprietary solvent performance:** APBS-CDRMax® enables high CO₂ capture efficiency, with reductions in energy demand of 10-25%, corrosion rates by a factor of 20, and degradation by a factor of 10 relative to conventional solvents.
- **High purity CO₂ output:** Produces CO₂ at up to 99.5% purity, suitable for utilisation or storage.
- **Operational track record:** Technology is at TRL 9, with commercial deployment since 2016.

KEY PROJECTS

CaptureX™ has been deployed across a range of industrial environments, demonstrating robust performance under varying flue gas compositions and operating conditions.

- **NTPC (2023):** Long term operation at the 500 MW Vindhyachal Super Thermal Power Station, capturing 20 TPD of CO₂ for catalytic conversion to methanol using green hydrogen, demonstrating integration with utilisation pathways.
- **Taiheiyo Cement Corporation (2021):** 10 TPD CO₂ capture demonstration at the Kumagaya plant, validating capture from cement kiln flue gas.
- **Tata Steel (2021):** Deployment at Jamshedpur, capturing 5 TPD of CO₂ directly from blast furnace gas for onsite reuse.
- **Tuticorin Alkali Chemicals and Fertilisers (2016):** A commercial scale CCU deployment capturing ~60,000 tCO₂/yr at >90% efficiency, with on-site utilisation for soda ash production.

KEY DATA

TRL	9	Capture Rate Range (tpd)	50 - 5,000 (bespoke available)	Capture Efficiency (%)	90%+
Source CO ₂ Purity Range	3 - 20 mol%	System Energy (GJ/tCO ₂)	Varies with Source CO ₂ Purity	Specific Regen. Energy (GJ/tCO ₂)	Subject to flue gas
Number of Commercial Plants	50*	Number of Pilot Plants	1	Modular (Y/N)	Semi-modular
Target Industries	Energy, industrial power, gas turbines, industrial emitters (cement, steel and energy from waste), e-Fuels and maritime.				

* CycloneCC™, CaptureX™ and proprietary solvent references (biogas)

CaptureX™ is a standardised post-combustion carbon capture product line developed by Carbon Clean for larger-scale industrial and power applications. It is designed to enable repeatable deployment with reduced engineering complexity, cost uncertainty, and delivery risk.

By combining established solvent chemistry with a pre-engineered system design, CaptureX™ reduces the need for fully bespoke systems. This approach shortens project timelines and improves cost predictability, addressing key barriers to large-scale carbon capture deployment.

CaptureX™ is optimised for medium-to-large-scale emitters where throughput, reliability, and standardisation are required. The system is applicable across power generation, cement, steel, refining, and chemical production. Its configurable design enables adaptation to site-specific conditions while retaining the benefits of standardisation. Systems can be deployed as single or multiple trains, enabling both phased implementation and full-site decarbonisation.

APBS-CDRMAX® SOLVENT TECHNOLOGY

CaptureX™ uses Carbon Clean's APBS-CDRMax® solvent, an amine-promoted buffer salt (APBS) formulation that combines the high kinetic reactivity of amines with the low regeneration energy of buffer salts. The result is a fast-acting, high-capacity solvent that delivers consistently higher performance than conventional amine-based systems.

The solvent chemistry enables efficient removal of CO₂ from flue gases with concentrations typically ranging between 3% and 20% by volume. APBS-CDRMax® produces CO₂ with a purity of ≥99.5% (dry basis), suitable for both utilisation and storage applications. It reduces regeneration energy requirements while providing greater stability and lower corrosivity.

Comprehensive testing and commercial operation have provided validation data on the performance of APBS-CDRMax®, including:

- Up to 20x lower corrosion and 10x lower degradation rates relative to conventional solvents
- 10-25% lower energy demand for CO₂ capture and solvent regeneration
- Up to 5x longer solvent life with significantly reduced make-up requirements
- Solvent emissions at parts-per-billion (ppb) levels

These characteristics are associated with reduced operating costs, improved system reliability, and reduced environmental impact over the asset lifecycle. The availability of high-purity CO₂ also enables integration with downstream utilisation pathways, including synthetic fuels and chemical production.

COMMERCIAL DEPLOYMENT SPOTLIGHT: NTPC VINDHYACHAL

The deployment of CaptureX™ at NTPC Limited's Vindhyachal Super Thermal Power Station represents a commercial-scale demonstration of post-combustion carbon capture integrated with utilisation. The project is installed on a 500 MW coal-fired unit (Unit-13) and captures approximately 20 tonnes of CO₂ per day directly from flue gas.

The project, executed by NTPC Energy Technology Research Alliance (NETRA), uses CaptureX™ semi-modular technology to extract CO₂ from coal-derived flue gas under continuous operating conditions. Following more than two years of operation, the project has demonstrated stable performance.

A key milestone was achieved in 2025 with the production of the first methanol derived from captured CO₂. The captured CO₂ is catalytically hydrogenated using green hydrogen, demonstrating an integrated carbon capture and utilisation (CCU) pathway. This confirms the feasibility of combining carbon capture with utilisation to produce low-carbon fuels and chemicals, supporting emerging circular carbon economy models.

The Vindhyachal deployment is part of a broader programme by NTPC to explore carbon capture and utilisation technologies across its fleet. The project highlights the applicability of semi-modular capture systems in retrofitting existing power infrastructure and provides a basis for scaling similar configurations across other point sources.



CARBON CLEAN CYCLONECC™



SUMMARY

CycloneCC™ is a modular post-combustion carbon capture technology developed by Carbon Clean for hard-to-abate sectors, including steel, cement, power generation, maritime, and energy-intensive applications such as gas turbines and behind-the meter power supply for data centres. The system utilises Rotating Packed Beds (RPBs) to intensify gas-liquid contact, replacing conventional packed columns. This reduces equipment size and associated balance-of-plant requirements, with reductions in total installed cost and physical footprint up to 50% relative to conventional amine-based systems. The CycloneCC™ C1 Series has a capture capacity of up to 100,000 tonnes of CO₂ per year. Its modular design enables phased deployment and integration with existing industrial processes. Factory acceptance testing has been completed, confirming readiness for commercial deployment. In 2025, Carbon Clean commissioned a Global Innovation Centre in Mumbai, India, including pilot-scale units and laboratories for solvent development and testing to accelerate next generation carbon capture research and scale-up.

BENEFITS

- CycloneCC™ has a footprint up to 50% smaller than conventional carbon capture plants, with key equipment sizes reduced by up to 10x.
- Rotating packed beds (RPBs) replace conventional packed columns, reducing steel requirements by approximately 35% and overall plant height by up to 70%.
- Units are prefabricated and skid-mounted, enabling delivery as road truckable modules and reducing costs associated with transport, logistics, site preparation and installation.
- Total installed cost is reduced by up to 50% relative to conventional carbon capture systems.
- Carbon Clean's APBS-CDRMax® solvent reduces energy demand by 10-25%, lowers corrosion rates by a factor of 20, reduces degradation by a factor of 10, and extends solvent lifespan by up to five times compared to conventional solvents.

KEY PROJECTS

In 2025, Carbon Clean completed the first industrial deployment of CycloneCC™ at Fertiglobe's nitrogen fertiliser plant in Abu Dhabi, achieving ~4,000 operating hours and progressing the technology to TRL 7. Captured CO₂ was utilised in urea production.

A collaboration with Aramco and SAMSUNG E&A deployed CycloneCC™ to capture CO₂ from natural gas turbine exhaust streams (3–3.5% CO₂), supporting validation in low-concentration applications. SAMSUNG E&A provided engineering, procurement, and construction (EPC) services. The unit continues to generate operational data under industrial conditions.

The CycloneCC™ C1 Series has also completed factory acceptance testing, supporting commercial readiness.

Through partnerships with MODEC and projects with JSW Steel and BHP, CycloneCC™ is advancing across industrial, maritime, and offshore applications.

KEY DATA

TRL	7	Capture Rate Range (tpd)	75 - 855 per CycloneCC™ train	Capture Efficiency (%)	90%+
Source CO ₂ Purity Range	3 - 20 mol%	System Energy (GJ/tCO ₂)	Varies with source CO ₂ purity	Specific Regen. Energy (GJ/tCO ₂)	1.9 - 2.9 GJ/tCO ₂ subject to flue gas
Number of Commercial Plants	50*	Number of Pilot Plants	3	Modular (Y/N)	Y
Target Industries	Energy, industrial power, gas turbines, industrial emitters (cement, steel and energy from waste), e-Fuels and maritime.				

* CycloneCC™, CaptureX™ and proprietary solvent references (biogas)

CycloneCC™ is a modular post-combustion carbon capture system developed by Carbon Clean, designed for deployment in space- and cost-constrained industrial applications. The system adopts a modular, plug-and-play, 'lego-block' configuration, enabling phased installation for small-to-midsize industrial emitters.

CycloneCC™ intensifies conventional solvent-based carbon capture by combining two proven process intensification technologies:

1. Rotating Packed Beds (RPBs)
2. Carbon Clean's amine-promoted buffer salt solvent (APBS-CDRMax®)

Together, these technologies enhance gas-liquid contact, mass transfer and process efficiency relative to conventional packed column systems.

ROTATING PACKED BEDS (RPBS)

CycloneCC™ utilises RPBs for the key column operations in a conventional solvent capture process. RPBs contain a disk of packing material which rotates about its axis. This generates a centrifugal force significantly higher than the force of gravity relied on by conventional columns with packing, while more effective in the mass transfer of CO₂ from flue gas to solvent.

Under greater force, the droplets and solvent films that form on the bed's packing material are substantially finer than in conventional columns, increasing the available surface area of solvent for a given volume. This results in faster and higher mass transfer efficiency between the gas and liquid phases.

The dramatic improvement in absorption efficiency allows the RPB to be 10x smaller than a traditional column, achieving the same results.

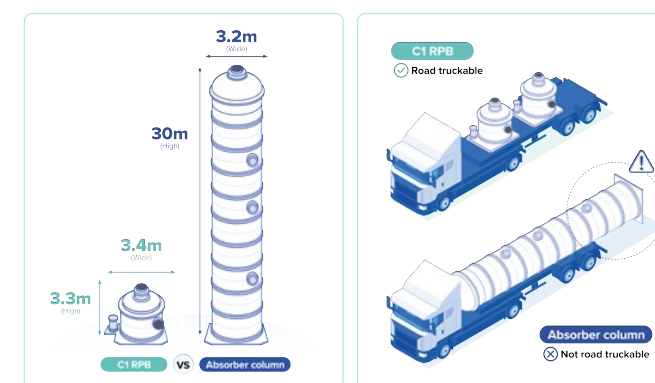


Figure 1: Delivery of Rotating Packed Beds in comparison to columns

The combination of RPBs and the APBS-CDRMax® solvent provides:

- Smaller equipment sizes at equivalent performance – using RPBs in the absorber and stripper results in more than one order of magnitude reduction in equipment size.
- Better mass and heat transfer between the liquid and gas phases through thinner liquid films produced by a centrifugal force.

- More intense turbulent flow relative to conventional columns.

When paired with APBS-CDRMax® solvent, RPBs also reduce heat requirements and improve efficiency of heat transfer, cutting costs for solvent regeneration. Additionally, degradation and corrosion rates are lowered, unlocking savings in solvent make-up and waste disposal, while energy efficiency is improved by the reduced need to pump coolant around the unit.

AI-driven remote monitoring and optimisation further enhance the efficiency of CycloneCC™, ensuring seamless operation with lower energy consumption. Its modular, cost-effective design makes it easy to integrate into existing and future facilities, allowing businesses to scale carbon capture gradually while meeting decarbonisation targets sooner.

APBS-CDRMAX® SOLVENT

Carbon Clean's APBS-CDRMax® solvent is a proprietary formulation combining amines with buffer salts, intended to retain high reaction kinetics while reducing regeneration energy requirements.

The solvent chemistry allows for rapid removal of carbon dioxide from flue gases with CO₂ concentrations ranging between 3% and 20% by volume. APBS-CDRMax® produces CO₂ with a purity of ≥99.5% by volume on a dry basis. It reduces regeneration energy requirements and provides both greater stability and lower corrosivity than conventional solvents.

Comprehensive testing and commercial operation have provided validation data on the performance of APBS-CDRMax®, including:

- Up to 20x lower corrosion and 10x lower degradation rates relative to conventional solvents
- 10-25% lower energy demand for CO₂ capture and solvent regeneration
- Up to 5x longer solvent life with significantly reduced make-up requirements
- Solvent emissions at parts-per-billion (ppb) levels

DATA CENTRE AND DISTRIBUTED POWER GENERATION

CycloneCC™ is being developed for application in behind-the-meter, lower-carbon power systems for data centres, based on gas-turbines with carbon capture. Demonstration of CycloneCC™ on a natural gas turbine exhaust streams (3–3.5% CO₂) has validated performance in low-concentration conditions relevant to these applications.

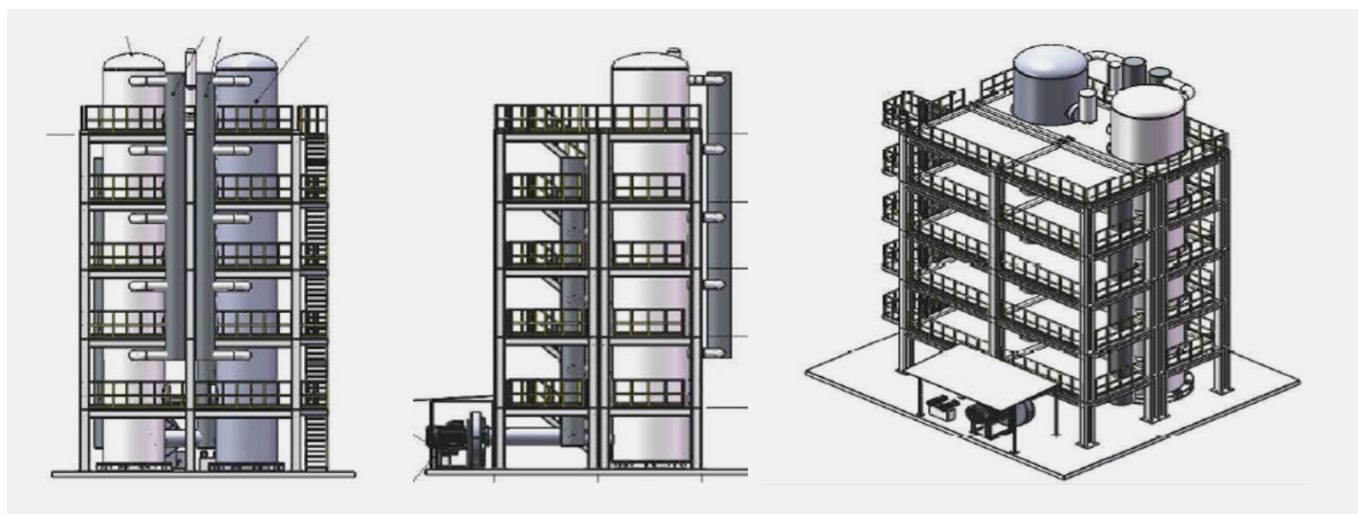
The modular configuration allows multiple units to operate in parallel, supporting incremental scaling aligned with data centre expansion, as well as deployment across larger data centre campuses.

The technology is compatible with a range of gas turbine models, and plant capacity is flexible. Carbon Clean can develop multiples of a 30-100MW power plus CCUS asset within an approximately 18-month timeframe.



CHINA NATIONAL PETROLEUM CORPORATION

DIRECT AIR CAPTURE



SUMMARY

Direct Air Capture (DAC) is a technology that extracts CO₂ directly from the atmosphere, first conceptualised in the 1990s and now globally acknowledged for its technical viability. As a crucial complement to fixed-source carbon capture methods, DAC serves as a "safety net" technology to achieve net-zero emissions by addressing dispersed or legacy CO₂ sources. Unlike traditional systems tied to industrial sites, DAC operates independently, capturing atmospheric CO₂ (currently ~420 ppm) through chemical adsorption or absorption processes. The captured CO₂ can be permanently stored underground or used for producing green fuels.

CNPC launched a metric-ton-scale DAC pilot in 2023, validating technical feasibility through continuous operation. A 200-ton-per-year demonstration plant, set to become China's largest DAC facility, is under construction and expected to launch by June 2025.

BENEFITS

- **High-efficiency Adsorbent Material:** Utilises novel amine-based composite adsorbents with superior CO₂ selectivity and resistance to hydrothermal degradation.
- **Enhanced Fluidised Bed Technology:** Gas-solid fluidization design improves mass transfer efficiency, enabling seamless integration of adsorption-regeneration processes and overcoming limitations of traditional fixed-bed intermittency.
- **Steam-assisted Temperature Swing Adsorption:** Cyclic steam temperature modulation reduces regeneration energy consumption by over 30% while maintaining adsorbent structural stability.
- **Modular Design:** Standardised containerised units enable distributed deployment, adapt to varying carbon sources, and cut construction time by 50%.



KEY DATA

TRL	6	Capture Rate Range (tpd)	0.5- 1	Capture Efficiency (%)	> 50%
Source CO ₂ Purity Range	0.04 mol%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	3-5
Number of Commercial Plants	~	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Direct Air Capture				

BACKGROUND AND MATERIAL DESIGN INNOVATIONS

Current direct air capture (DAC) technologies face critical limitations in balancing high adsorption capacity with low energy consumption. Conventional solid amine adsorbents suffer from poor cycling stability and vulnerability to humidity, while metal-organic frameworks (MOFs) struggle with moisture sensitivity, formability challenges, and slow regeneration kinetics. To address these issues, this project proposes a groundbreaking composite adsorbent that synergises the merits of solid-state amines and MOFs through a rationally engineered hierarchical structure.

Guided by the principle of "structure determines performance" and the thermodynamic essence of molecular interactions, an in-situ self-assembly modulation strategy was developed. This approach leverages the interconnected macroporous architecture (pore size: 50–200 μm) and ultrahigh porosity (>85%) of a polymer scaffold to host microporous active components (pore size: 0.5–2 nm). The macroporous framework ensures rapid gas diffusion, while the embedded amine-functionalised MOF nanoparticles (e.g., MIL-101(Cr)-NH₂) provide high-density CO₂ binding sites. Crucially, covalent bonding between the amine groups and the MOF-polymer interface enhances structural integrity, achieving a balance between hydrophobicity (water contact angle: 130°) and CO₂ selectivity (CO₂/N₂ selectivity: 250 at 400 ppm).

Traditional binder-assisted molding methods often block pores and degrade adsorption kinetics. By optimizing the self-assembly process, the team eliminated binders and achieved monolithic adsorbent pellets (2–3 mm diameter) with preserved porosity (>90% of powder form) and mechanical strength (crush resistance: >15 MPa). This innovation resolves the long-standing trade-off between formability and performance, enabling scalable manufacturing.

ADSORPTION PROCESS OPTIMIZATION

Capturing CO₂ from ultra-dilute air (~400 ppm) demands processing vast air volumes (≥1,700 m³ per kg CO₂). Conventional fixed-bed systems incur prohibitive pressure drops (ΔP: 5–10 kPa/m), leading to excessive fan energy consumption. To overcome this, a low-pressure-drop fluidised bed adsorption process was engineered, capitalizing on the adsorbent's high abrasion resistance (mass loss: <0.1% after 500 cycles) and tunable particle density (0.8–1.2 g/cm³).

In the fluidised state, the adsorbent particles exhibit chaotic motion, creating dynamic gas-solid contact channels. This reduces ΔP by 40–60% (to 2–4 kPa/m) compared to fixed beds while enhancing heat and mass transfer efficiency (volumetric mass transfer coefficient: 0.15–0.3 s⁻¹). Computational fluid dynamics (CFD) simulations confirmed uniform temperature distribution (±1.5°C across the bed) and minimised channeling effects. Field tests demonstrated a CO₂ capture rate of 1.2–1.5 kg/m³·h under ambient conditions, with <5% capacity loss after 1,000 adsorption-desorption cycles.

REGENERATION PROTOCOL DEVELOPMENT

Slow regeneration kinetics and oxidative degradation remain key bottlenecks in DAC systems. Conventional temperature-swing processes using hot air or resistive heating suffer from slow heating rates (<2°C/min) and amine oxidation (capacity loss: 20–30% per 100 cycles). To address this, a steam-assisted "four-step" temperature-swing regeneration protocol was developed:

- **Step 1: Pre-Purging** – Low-pressure steam (100–110°C, 0.1 MPa) displaces residual air, creating an oxygen-free environment.
- **Step 2: Rapid Heating** – High-temperature steam (130–150°C, 0.2 MPa) penetrates the adsorbent bed, achieving heating rates >10°C/min.
- **Step 3: Vacuum Desorption** – A two-stage vacuum system (10 kPa → 1 kPa) strips CO₂ from binding sites while maintaining steam partial pressure to prevent amine dehydration.
- **Step 4: Quench Cooling** – Controlled steam reduction and convective cooling (30°C/min) rapidly reset the adsorbent to adsorption temperature (25–35°C).

This protocol achieves full regeneration within 15 minutes (vs. 60–90 minutes in conventional systems) with minimal thermal degradation. X-ray photoelectron spectroscopy (XPS) analysis confirmed <2% amine oxidation after 1,000 cycles, while thermogravimetric analysis (TGA) revealed stable decomposition temperatures (>200°C). The integrated process reduces regeneration energy consumption to 1.8–2.2 GJ/tCO₂, approaching theoretical thermodynamic limits.

SYSTEM INTEGRATION AND SCALABILITY

The synergy between the composite adsorbent, fluidised bed adsorption, and steam-assisted regeneration is considered into a coherent DAC framework. Pilot-scale tests (10 tCO₂/year capacity) demonstrated a system energy consumption of 2.4–2.8 GJ/tCO₂, outperforming state-of-the-art liquid amine systems (4–6 GJ/tCO₂). Lifecycle analysis projects a levelised cost of \$120–150/tCO₂ at commercial scale, with further reductions achievable through heat recovery optimization.

CO₂SORB – EFFICIENT HIGH-PRESSURE CO₂ CAPTURE



SUMMARY

Natural gas serves as an energy source and a vital feedstock for various industries. Production of natural gas presents the challenges of separating CO₂ at high pressure. At high pressure, the performance of the pressure swing adsorption (PSA) process drops due to a reduction in the selectivity and capacity of adsorbents.

Novel adsorbent CO₂SORB from CO₂CRC and its research partners demonstrated a significant improvement in CO₂ working capacity and selectivity over the original parent material, under the feed pressures of up to 50 bar and CO₂ concentrations of 7 - 40%. Thus, CO₂SORB adsorbent enables the PSA system to handle 3 to 4 times higher flow rates or reduces the size of the PSA unit, up to a third or a quarter compared to units using the parent material at the same feed flow rate. Additionally, the improved selectivity of CO₂SORB allows for more effective separation between CO₂ and methane, leading to increased methane revenue and reduced CO₂ and methane emissions. Therefore, CO₂SORB is ideal for integration into PSA systems for CO₂ capture from natural gas or high pressure CO₂ separation.

BENEFITS

CO₂CRC's CO₂SORB adsorbent has been developed to remove CO₂ efficiently from high-pressure natural gas. Here are the major benefits of CO₂SORB:

- CO₂SORB is a robust material with high working capacity, making the PSA process more compact than commercial adsorbents.
- High selectivity of CO₂SORB provides high purity of methane-rich and CO₂-rich streams, significantly reducing the methane loss. Thus, it provides better OPEX and reduces greenhouse emissions due to both methane and CO₂. Moreover, more revenue can be achieved with less methane loss (higher methane production).
- Lower footprint and lower energy requirements for regeneration as compared to the solvent technology.
- With demonstrated performance at 50 bar, CO₂SORB had the potential to take advantage of the high pressure of raw natural gas from the gas well and reduce the compression energy requirements downstream.
- CO₂SORB is non-toxic and non-hazardous and, unlike amine-based solvents, does not lead to the corrosion of the equipment.

KEY DATA

TRL	4 - 5	Capture Rate Range (tpd)	0.01 - 0.025	Capture Efficiency (%)	>70% - Can be higher if run in series
Source CO ₂ Purity Range	7 - 40%	Energy Consumption (GJ/tCO ₂)	Depends on CO ₂ % in the gas and gas pressure	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Potential for high pressure (up to 50bar) CO ₂ capture from oil and gas and/or hydrogen operations. Can be applied for pre-combustion emission and post combustion emission.				

The performance of the adsorption technology depends on the ability of the adsorbent surface to adsorb the desired gas from the gas mix selectively and the adsorbent's ability to desorb the gas with the change of conditions, e.g. temperature (temperature swing), pressure (pressure swing) or moisture (moisture swing). For natural gas processing, separation of hydrogen from syngas, the pressure swing adsorption (PSA) takes advantage of the high pressure of the gas streams. Thus, for high-pressure applications, the adsorption process provides significant energy savings with respect to conventional amine-based absorption. The development of CO₂SORB targets to reduce the CAPEX and OPEX of the CO₂ capture process. In addition to working capacity and selectivity, physical properties (hardness and stability under cyclic operations) are important, as shown in Figure 1.

TECHNOLOGY DEVELOPMENT

CO₂CRC's research and development program for CO₂ separation from natural gas started in 2016 in collaboration with its research partner. The adsorbents were compared based on a few performance criteria such as material cost, isotherms, capacity, and selectivity for application in high pressure natural gas. Sorbead WS was selected to be the benchmark adsorbent for a stage-gated Otway Capture Project at CO₂CRC's Otway International Test Centre (OITC) for field testing with natural gas from a buttress well at OITC.

A new process recipe was developed to produce the novel adsorbent material CO₂SORB with the size, shape, packing density, crushing strength, adsorption capacity and selectivity. All CO₂SORB samples were developed and characterised in the lab environment. CO₂ and CH₄ isotherms were measured using volumetric apparatus (ASAP 2050, Micrometric, USA). BET surface area, pore width distribution and volume of CO₂SORB were determined by measuring N₂ isotherm at the temperature of 77 K (-196.15°C) with 3Flex. The adsorbent structure was characterised with X-ray Powder Diffraction (XRD) and element analysis within the adsorbent samples was conducted using energy-dispersive X-ray spectroscopy (EDS).

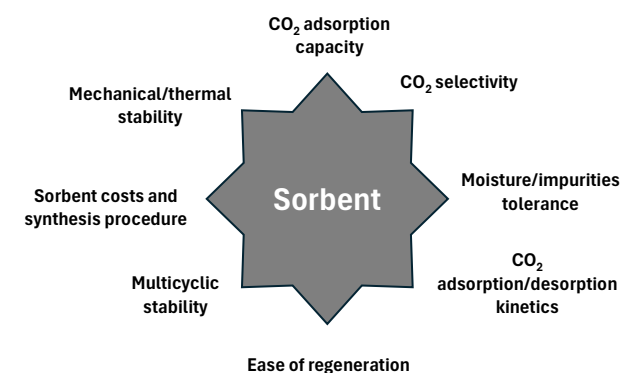


Figure 1

IMPROVED PERFORMANCE

The measured isotherms of CO₂ and CH₄ for the scaleup sample (Figure 2) indicate much higher working capacity compared with the benchmark commercial material, Sorbead. The better adsorption characteristic means using the developed material can potentially reduce capital costs via smaller equipment and less material.

Four CO₂SORB samples were studied for four different feed CO₂ concentrations ranging from 10-40%. The working capacity and selectivity were calculated based on 30% CO₂ feed concentration at 50 bar and desorption pressure at 1 bar with 95% CO₂. Test results showed that the CO₂SORB series achieved much higher CO₂ working capacity and selectivity than Sorbead and previous generation CO₂CRC's adsorbent, Otway HY (Figure-3). The binary selectivity for all samples was calculated to be greater than 1, indicating that the PSA process is suitable for the gas separation application.

NEXT STEPS

After establishing a superior performance of CO₂SORB, the next step is to scale up the pilot testing of CO₂SORB adsorbent in a full PSA system, progressing to a higher TRL level up to commercialisation. The CO₂SORB formulation and testing can also be expand to other potential applications in syngas treatment, which is commonly used in the blue hydrogen production industry, such as from steam methane reforming (SMR) and coal gasification. CO₂CRC is looking for potential funding and collaboration opportunities to test and showcase CO₂SORB technology in different industrial applications and environmental conditions.

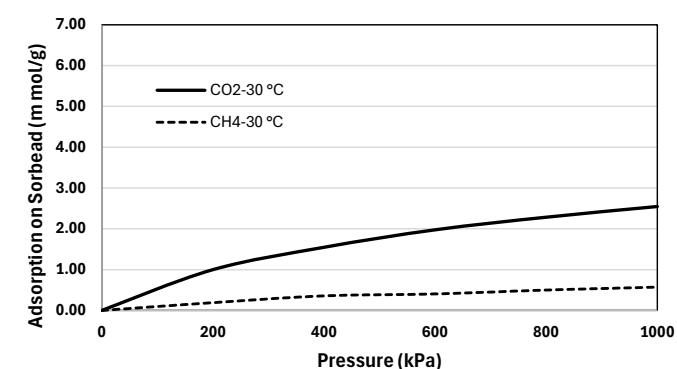


Figure 2

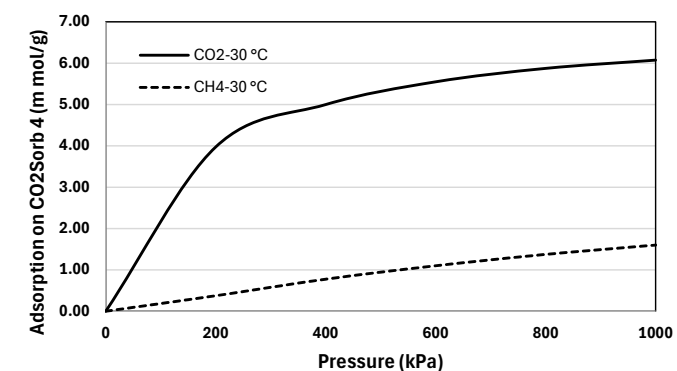
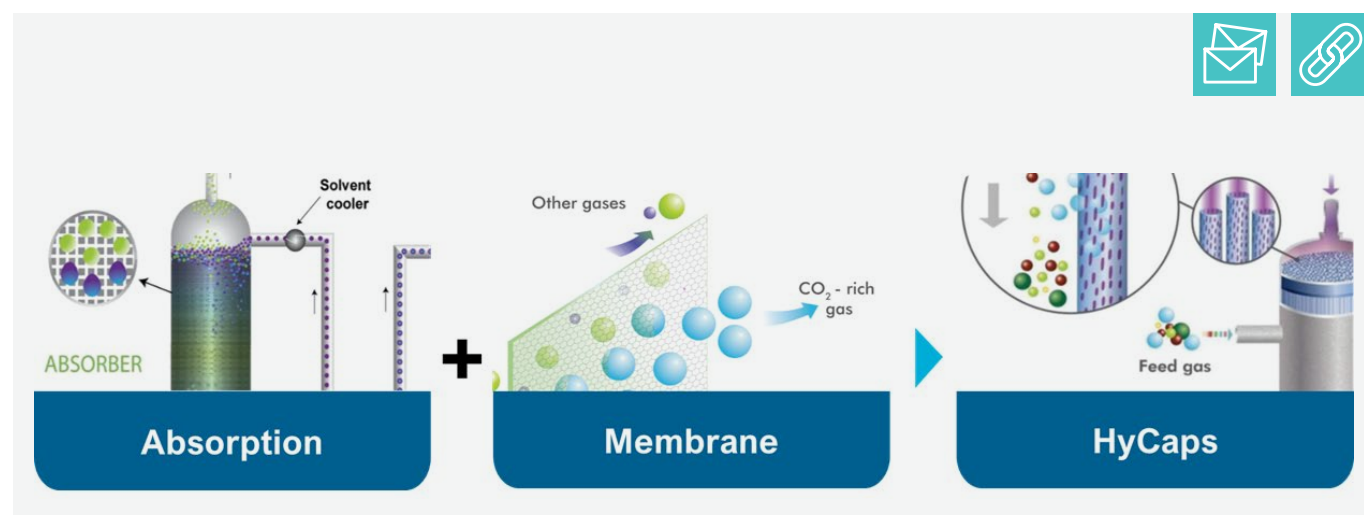


Figure 3



SUMMARY

Operating since 2003, CO₂CRC is a global leader in carbon capture, utilisation, and storage (CCUS) research. The organization collaborates with national and international experts, managing interdisciplinary and inter-institutional research projects. With well-established relationships spanning over a decade, CO₂CRC enjoys strong international brand recognition and boasts an excellent health and safety record. Additionally, CO₂CRC develops and tests next-generation low-emission technologies through commercially relevant, first-of-a-kind demonstrations.

CO₂CRC Ltd., in collaboration with its research partners in Australia, has developed a hybrid CO₂ capture technology called HyCaps. This innovative approach combines solvent absorption and membrane separation in a single process, harnessing the benefits of both methods to achieve efficient carbon capture. The HyCaps process has demonstrated its effectiveness in capturing carbon dioxide while significantly reducing energy requirements. Additionally, HyCaps is modular and scalable, which can be designed with smaller footprint compared to conventional amine solvent processes for CO₂ absorption. This makes it suitable for retrofitting existing plants, thereby facilitating faster implementation of carbon capture, utilisation, and storage (CCUS).

BENEFITS

- With an interfacial area of 2,700 to 4,000 m²/m³, HyCaps offers over ten times the specific surface area of conventional packed columns, (250 to 700 m²/m³), thus reducing the equipment size and footprint.
- Membrane's configuration flexibility and modularity enable the capture process to be accommodated and retrofitted in limited site space.
- HyCaps enables separate and independent control of liquid and gas phase flow. This functionality helps to eliminate or reduce operational issues, such as foaming, liquid channelling, and liquid entrainment in conventional solvent columns.
- In the HyCaps, gas is not in direct contact with the solvent, the chemical degradation of the solvent due to the impurities in the gas is potentially lower than in conventional packed columns, where gas and liquid phases are in intimate contact.
- The HyCaps process operates at a lower temperature than conventional packed beds and eliminates the need for solvent boiling during regeneration, reducing energy use and thermal degradation of the solvent.

KEY DATA

TRL	6 - 7	Capture Rate Range (tpd)	50 - 500 for pilots	Capture Efficiency (%)	90%
Source CO ₂ Purity Range	>3.5%	System Energy (GJ/tCO ₂)	Depends on CO ₂ % in inlet	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	5	Modular (Y/N)	Yes
Target Industries	Power, industry, oil and gas, hard-to-abate sectors and other post-combustion CO ₂ emissions including small footprint operations (onboard shipping, remote/offshore platform, etc.)				

HyCaps is a hybrid technology that combines mature solvent technology with membrane technology to overcome inherent limitations while retaining or enhancing their advantages.

A typical flowsheet of the HyCaps process is similar to that of conventional solvent CO₂ capture systems, but the HyCaps module replaces the conventional packed columns for absorption and solvent regeneration. The process involves the transfer of CO₂ from the gas mix through a hollow-fiber membrane, where it is chemically absorbed into a solvent. In solvent regeneration with HyCaps, the physical separation of the solvent and gas phases by the membrane enables CO₂ to be drawn from the enriched solvent phase into the gas phase. This enables solvent regeneration to be achieved at temperatures lower than conventional packed columns, and the solvent regeneration can be achieved without boiling of the solvent. Hence, in HyCaps CO₂ capture, there is no reboiler in the regeneration section of the process. By avoiding solvent boiling, the HyCaps process significantly reduces the energy demand for solvent regeneration.

TECHNOLOGY DEVELOPMENT

CO₂CRC Ltd and its research partners have successfully demonstrated the potential of HyCaps technology for both post-combustion and pre-combustion carbon capture scenarios in the Australian industry. This novel technology represents over a decade of laboratory research and was successfully tested in various pilot plant industrial trials. CO₂CRC has been developing novel technologies to reduce the cost of CO₂ capture. The compact design of HyCaps is illustrated in Figure 1, which displays the demonstration test skid of HyCaps alongside skids for solvent and adsorbent technologies CO₂ capture. In HyCaps process, the solvent regeneration operating temperature ranged between 90 to 102 °C, well below the solvent vaporisation temperature of 105 °C. Hence, the pilot plant proved that carbon capture and solvent regeneration could occur without a bulk solvent phase change.

To ensure rapid scale-up of HyCaps technology, the membrane-based HyCaps modules chosen were based on commercially available membranes originally developed for other gas separation applications. Therefore, the technology can be rapidly scaled up and adopted by industry and expanded without the need for membrane material development or the construction of sophisticated membrane fabrication facilities, reducing time to commercialisation. It is also important to note that ongoing developments on advanced solvent and/or advanced membrane systems can be transferred seamlessly to the HyCaps module to make HyCaps a more advanced system – a further benefit of the system that will ensure its future relevance to the industry.

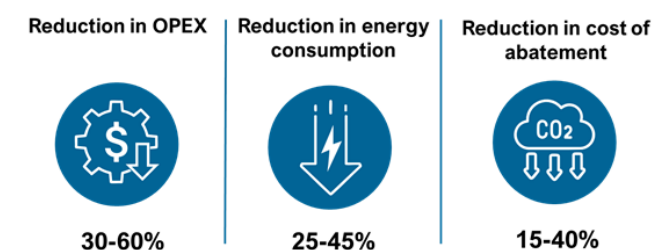
COST EFFECTIVE TECHNOLOGY

Initial techno-economic analysis done for the CO₂ capture with 18% CO₂ in the flue gas indicates the cost-effectiveness of HyCaps technology. HyCaps modules have greater surface area per volume as compared to the conventional packed columns. As a result, HyCaps modules have a reduced overall equipment dimension. The reduction in equipment size couple with HyCaps design with less auxiliary supporting equipment is also a factor in HyCaps' reduced CAPEX. Avoiding solvent boiling and lower operating temperature results in low energy demand for regeneration, and the low-quality heat/waste heat from the plant can be utilised within the system, making the whole regeneration a low OPEX process. Compared to the conventional solvent process, the solvent regeneration energy requirement of HyCaps is about 25-45% lower. HyCaps requires low-quality steam for regeneration, potentially reducing energy costs further. Overall, there can be 30-60% reduction in OPEX and 15-40% reduction in cost of abatement as compared to conventional packed column solvent technology.

The Hybrid HyCaps is a new approach to carbon capture technology that offers clear advantages in terms of energy requirement and footprint compared to traditional methods. This technology has been demonstrated at three different industrial pilot plants in Australia. It has proven to be deployment-ready to effectively address carbon emissions from industrial sources, including the hard-to-abate sector. HyCaps is a modular, compact, and scalable solution that can be applied to both post-combustion and pre-combustion CO₂ capture processes. Due to its compact design, flexible orientation, and easy installation, HyCaps is suitable for any industry with limited space, including mobile process platforms such as FPSO and ship-based processes.

NEXT STEPS

HyCaps has achieved a technology readiness level (TRL) 6 with successful pilot demonstrations in different industrial environments. HyCaps is a cost competitive CO₂ capture technology and is ready for scale up and large-scale demonstration. As a next step, CO₂CRC is working on a scaled-up design for the equipment and is looking for potential funding and collaboration opportunities to test and showcase HyCaps technology in different industrial applications and environmental conditions.





COOL PLANET TECHNOLOGIES

ADVANCED MEMBRANE CAPTURE TECHNOLOGY



SUMMARY

Cool Planet Technologies provides emitters with a modular, energy-efficient membrane capture solution designed for simple end-of-pipe retrofits. The compact, scalable, system significantly reduces the cost and energy required to capture CO₂ from industrial flue gases, while offering high reliability, fast start-up, and rapid response for operational flexibility. Cool Planet is collaborating with Holcim and is in the final stages of commissioning a 10,000 tpa plant at its Höver cement plant in Germany, with start-up planned for mid-2026. Cool Planet is also working with other industrial emitters to develop plants ranging from 50,000 tpa to 1,100,000 tpa, which are currently in the planning and design stages. The investors in Cool Planet are Taranis Carbon Ventures, Eni Next, Neva SGR, Audacy Ventures, CRH Ventures and BlueScopeX.

BENEFITS

Cool Planet's proprietary membrane technology has been designed and built from the outset to be scalable, robust and reliable to meet the requirements of heavy industry:

- **50% lower cost per tonne:** Intrinsically lower CAPEX and OPEX compared to existing solutions.
- **60% lower energy:** Passive process uses less energy
- **Highly compact and modular:** The technology has a footprint a fraction of the size of existing solutions and has a low profile. Ideal for tight retrofits with minimal crange.
- **Proven technology:** 15 years of R&D, 5+ industrial pilots and 12+ years of continuous operation.
- **Fully electrical:** Can be powered by renewable electricity.
- **Chemical free:** No harmful emissions.
- **Fast start and response:** Allowing intermittent and batch industrial processes.
- **Upgradable:** Can be upgraded to the latest membrane versions.

KEY PROJECTS

Membrane Module Demonstration: Cool Planet successfully demonstrated its 3rd Generation industrial-scale membrane module in 2025 at capture rates of up to 37,000 tpa, derisking the scaling prior to the module's incorporation into the capture plant currently being commissioning at Höver.

Membrane and Module Manufacturing: Cool Planet is building a large-scale facility in Austria to manufacture membranes and lower-cost 4th-generation modules for current and future projects.

Commercial Operations and Industry Scaling: Cool Planet's technology is ready for commercial deployment. The company is already planning and designing plants from 50,000 tpa up to 1,100,000 tpa, with first operations planned for the early 2030s.

Cool Planet has developed an energy efficient, scalable, reliable, modular capture system based optimised around the class leading PolyActive™ membrane and a patented, highly efficient, compact, modular membrane housing, built around a standard ISO container frame. The capture solution can be deployed in a scalable manner ranging from a few thousand tonnes per annum (tpa) to installations in excess of 1,000,000 tpa.

The PolyActive™ thin-film composite membrane was developed by Helmholtz Hereon (Germany's leading membrane-focused R&D institute) specifically to remove CO₂ from industrial flue gases. Built to be robust and optimised for both selectivity and permeability, it uses a solution-diffusion transport mechanism where CO₂ moves through the membrane by pressure-gradient-driven diffusion. Since no chemical reaction occurs within the membrane, PolyActive™ is resilient to typical flue-gas contaminants such as NO_x and SO_x. It is also tolerant of variable operating conditions, making it suitable across a wide range of industrial applications and climates. Rapid response times accommodate operational fluctuations, enabling flexible operation even in intermittent or cyclical processes.

This is an end-of-pipe solution that processes the flue gas without affecting the operation of the host plant, although some level of plant integration can typically lead to further energy efficiency gains. The incoming flue gas is typically cooled and scrubbed to remove particulates. Other components can be processed through the membrane and are not typically removed. The pressure of the gas is then raised slightly before being processed through the passive membrane stage or stages depending on the percentage of CO₂ in the incoming gas. The membrane stages are capable of delivering 95% pure CO₂. If a higher purity is required for pipeline transport, sequestration or use, then an integrated, energy optimised cryogenic purification or liquefaction stage can be added. Since no chemicals are utilised in the process, there are no capture-related produces that require subsequent removal.

The capture plant uses standard, industry proven equipment around the proprietary membrane stage making the plant simple, efficient and reliable. Energy recovery and optimisation also is integrated into the capture process.

A COMPLETE CAPTURE SOLUTION

The Cool Planet team have decades of experience in the design and build of large complex plants across a range of industries including industrial gasses, oil and gas and transportation networks. From first concept through commissioning, the Cool Planet team works side-by-side with emitters to deliver fit-for-purpose plants at low unit cost. Cool Planet can also support customers in building the capture, offtake and sequestration/utilisation chain.

Cool Planet also provides ongoing operational support, system management and monitoring, performance optimisation and maintenance services for the project on an ongoing basis.

PILOT TESTING

The membrane technology was successfully piloted at an EnBW coal-fired power plant in pilot projects in 2014, 2018 and 2019, followed by a successful programme in 2022 at Holcim's Höver cement plant. Long-term membrane performance has also been proven through 12 years of continuous operation at the world's first algae bioreactor. Further testing programmes in steel and cement are ongoing.

KEY DATA

TRL	8	Capture Rate Range (tpd)	10 - 10,000+	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	Prefer >10%	System Energy (GJ/tCO ₂)	Low. Industry dependent	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	2	Number of Pilot Plants	5+	Modular (Y/N)	Yes
Target Industries	Cement, Lime, Refining, Steel, Smelting, Coal-fired Power, Waste to Energy, Paper & Pulp, Soda Ash etc.				



ENTROPY INC

INTEGRATED CARBON CAPTURE (iCCS™)



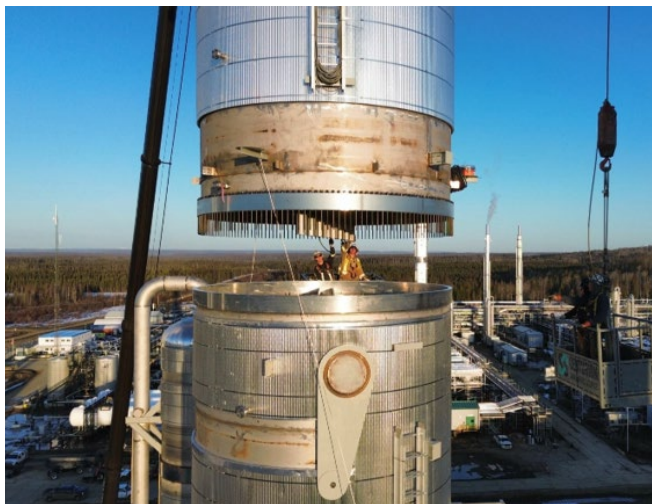
SUMMARY

Entropy is a global leader in carbon infrastructure and industrial decarbonization. Backed by Brookfield Asset Management (\$15 billion Global Transition Fund) and the Canada Growth Fund (\$15 billion fund), Entropy's scale-up-driven technology development has progressed from a first-of-kind 40 tonne per day (t/d) capture project on a single reciprocating engine to construction of a 500 t/d (~200k tpa) gas-plant decarbonization project.

Building on four years of commercial post-combustion CCS deployment on reciprocating engines, Entropy is constructing the world's first clean firm power facility using CCS on a natural gas turbine. Located in Saddle Hills County, Alberta, the project will deliver always-on power with low-carbon emissions at <100 kg CO₂e/MWh (life cycle analysis) from a 15-MW Solar T130 turbine, supplying power to a 425 MMcf/d gas-processing facility and exporting surplus decarbonised power to the Alberta, AESO electricity grid.

BENEFITS

- **Proven Performance:** Four years of commercial CCS operation, delivering confidence in performance, cost certainty, and on-time delivery. Demonstration of retrofit and greenfield applications on natural gas combustion (3-6% CO₂ flue gas)
- **Energy-Efficient Integration:** Waste-heat recovery and low-carbon power reduce operating costs and heat duty while enabling high CO₂ recovery across diverse flue-gas conditions with minimal parasitic load.
- **Scalable & Modular:** iCCS™ enables accelerated deployment, lower development risk, and the ability to scale projects incrementally as needs evolve.
- **Full-Stack:** A single platform for technology, capital, and execution, simplifying commercial structures, accelerating timelines, and materially reduced delivery risk.



KEY DATA

TRL	9	Capture Rate Range (tpd)	40 - 3,000+	Capture Efficiency (%)	90 - 99%
Source CO ₂ Purity Range	3 - 99%	System Energy (GJ/tCO ₂)	0	Specific Regen. Energy (GJ/tCO ₂)	2.4 ¹
Number of Commercial Plants	3	Number of Pilot Plants	0	Modular (Y/N)	Yes ²
Target Industries	Natural Gas, Thermal Oil, Ethanol, Methanol, Steel Production, Power Generation				

¹ 2.4 GJ/t gross regeneration duty, all of which is provided via waste heat integration in active projects to date

² modular construction scalable for applications 1 Mtpa+

Entropy invests in and develops integrated carbon infrastructure including capture, transport and storage as well as low carbon power systems designed for reliable, bankable, and scalable decarbonization across industrial and power sector applications. The company is differentiated by real world commercial operating experience and a portfolio of carbon infrastructure projects advancing from construction into long term operation - demonstrating that large scale CCS is achievable today.

INTEGRATED CARBON INFRASTRUCTURE AND CLEAN, FIRM POWER

Entropy provides full stack carbon infrastructure combining post combustion CO₂ capture, compression, transport, and permanent geological sequestration. Power system integration—including waste heat capture, steam integration, and low carbon power supply—reduces operating costs and improves the efficiency and commercial viability of CCS installations.

Standardised iCCS™ configurations—Thermal, Recip, and Turbine—support deployment across boilers, reciprocating engines, and gas fired turbines, enabling broad applicability across industrial and power generation environments.

The technology architecture supports a wide range of CO₂ stream conditions and configurations, enabling deployment across gas processing, gas fired power, chemicals, thermal oil operations, and other emission intensive industrial sectors. Modular design limits bespoke engineering, reduces deployment risk, and allows incremental scaling from tens of thousands to hundreds of thousands of tonnes of CO₂ per year. Systems are also proven on widely deployed industrial reciprocating gas compression engines, supporting broad North American retrofit potential.

Continuous commercial operation informs ongoing design and operational improvements, allowing the platform to evolve based on real system behavior rather than theoretical or pilot scale data.

Glacier Project Highlights

Location	Alberta, Canada
Emission Type	Post-combustion natural gas
Emission Sources	Reciprocating engines & gas turbines
Construction Time	18 months
Uptime Availability	99%

GLACIER PHASE 2 – ALBERTA, COD MID-2026

Glacier is a fully integrated carbon infrastructure development at a natural gas processing and power generation site in Saddle Hills Country, Alberta. Commercial capture systems have operated since 2022 (iCCS Recip™), with a major expansion entering service mid 2026 (iCCS Recip™ and iCCS Turbine™).

The development captures CO₂ from natural gas compression and integrated power generation, delivering material site wide abatement. Glacier includes the world's first commercial natural gas turbine with integrated post combustion carbon capture, providing reliable, low carbon power under long term contract while significantly reducing emissions intensity.

Upon completion, the decarbonised gas plant will reduce emissions by 86%, while supplying low carbon electricity to both site operations and the AESO grid. The facility demonstrates the technical and commercial viability of full stack CCS where industrial operations and grid connected clean power intersect.

BELLE PLAINE HUB – SASKATCHEWAN, OPERATING

Belle Plaine is a large-scale CCS hub designed to serve industrial emitters in southern Saskatchewan, Canada. The project comprises CO₂ transport and storage infrastructure, sequestering up to 450 t/d (>150k tpa), with operations commencing in Q2 2026.

Leveraging access to deep saline storage formations and extensive subsurface characterization, the Belle Plaine hub provides more than 20 million tonnes of long-term CO₂ storage capacity.

BOW VALLEY CARBON COCHRANE – ALBERTA, UNDER CONSTRUCTION

The Bow Valley Carbon Hub provides regional sequestration capacity through infrastructure that moves CO₂ from the Cochrane Extraction Plant to a dedicated local storage site. First injection is scheduled for mid 2027. The hub enables cost effective carbon storage access for industrial emitters and is designed to expand over time as regional demand grows.

U.S. EXPANSION: CCS ENABLED CLEAN FIRM POWER

Entropy's CCS platform is in the design phase of multiple U.S. clean firm power developments, including Net Power's Project Permian in West Texas.

Project Permian is intended to accommodate up to 1 GW of CCS enabled clean firm power capacity across multiple phases. Phase 1, with final investment decision targeted for 2026 and commercial operation as early as 2029, is expected to provide approximately 80 MW of ERCOT-connected generation. All captured CO₂ from Phase 1 is intended to be delivered and permanently sequestered in support of enhanced oil recovery. Generated electricity is intended to be sold under long term power offtake agreement to industrial and commercial customers seeking the benefit of low-carbon power to reduce their GHG footprint and meet emissions reductions objectives.

These projects demonstrate the scalability of CCS-enabled clean firm power and highlight its role in accelerating carbon infrastructure deployment across North America.

FLUOR[®]

FLUOR ECONAMINE FG PLUSSM



SUMMARY

Fluor's Econamine FG Plus (EFG+) technology is an industry recognised, proven, and cost-effective process to remove carbon dioxide (CO₂) from low-pressure and post-combustion gas streams. Over the last four decades, 30 EFG+ units have been built worldwide to capture CO₂ from gas streams derived from a variety of fuels such as natural gas, coal, light fuel oil, heavy fuel oil, and LPG. The solvent formulation is specially designed to recover CO₂ from low-pressure gas streams. The EFG+ solvent has been proven to be successful on flue gases containing as low as 3.5 vol percent (dry) CO₂.

BENEFITS

- Significant improvements were made over the past 20 years to improve energy consumption (reduced by 36 percent), reduce solvent degradation (reduced by 3 to 6 times), and improve the environmental signature (solvent, ammonia, and VOC emissions are all drastically reduced).
- The main ingredients in the EFG+ solvent are readily available, inexpensive, and are produced by multiple qualified solvent manufacturers. This provides the licensee with the ability to source solvent on a competitive basis, rather than being fixed to a 'single source' arrangement.
- Our Advanced Solvent Maintenance System, the result of significant development work and successfully proven in practice, is key to maintaining trouble-free operation in the presence of oxygen and other contaminants, improving both solvent hygiene and environmental signature of the process, and significantly reducing solvent losses compared to more conventional thermal reclaiming systems.
- The proprietary absorber water wash system minimises slip of solvent and other components into the treated flue gas, resulting in low atmospheric emissions.

KEY PROJECTS

- Northeast Energy Associates (Bellingham, Massachusetts): The Bellingham EFG+ plant had continuous commercial operation from 1991 to 2005 on a flue gas flow from a NGCC power plant.
- E.ON Demonstration Plant (Germany) - Capture Pilot plant in Wilhelmshaven, Germany
- Confidential Power Plant - FEED for >1,000 TPD plant
- Federated Co-Operatives Refinery Complex (Canada)
- Federated Co-Operatives Renewable Diesel Complex (Canada)

KEY DATA

TRL	9	Capture Rate Range (tpd)	Up to 20,000	Capture Efficiency (%)	95%
Source CO ₂ Purity Range	>3%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	30	Number of Pilot Plants	~	Modular (Y/N)	~
Target Industries	Power Generation, Cement, Steel, Glass, Pulp & Paper, Reformers in Chemical/Oil & Gas facilities, Waste to Power				

PROVIDING PROFESSIONAL AND TECHNICAL SERVICES

Fluor is building a better world by applying world-class expertise to solve its clients' greatest challenges.

Fluor's 30,000 employees provide professional and technical solutions that deliver safe, well-executed, capital-efficient projects to clients around the world. We take pride in our long history of successful execution of thousands of projects and our extensive successful track record in the execution of carbon capture projects.

Fluor provides engineering, procurement, and construction (EPC) services to carbon capture projects including CO₂ compression and transportation. Additionally, Fluor has the unique ability to be the technology licensor and EPC for any carbon capture project using EFG+. Our carbon capture project experts focus on the delivery of innovative, reliable, and cost-efficient project solutions built on more than 110 years of EPC and maintenance experience and 30 years of experience in carbon capture.

PROJECT EXPERIENCE

Northeast Energy Associates (Bellingham, Massachusetts): The Bellingham EFG+ plant had continuous commercial operation from 1991 to 2005 (more than 120,000 hours of operation over 14 years). The carbon capture plant's profile is as follows:

- Capacity: 330 tpd CO₂ captured
- 40 MW flue gas flow from NGCC power plant
- CO₂ Concentration: 3.5 percent v/v
- O₂ Concentration: 13-14 percent v/v
- Product Usage: food grade CO₂
- On Stream Factor: 98.5 percent in 2004
- 100 percent air cooled

E.ON Demonstration Plant (Germany). Fluor and E.ON Kraftwerke (E.ON) were partners in developing a slipstream carbon capture pilot plant in Wilhelmshaven, Germany. The construction phase included demonstration of new materials and techniques for erection of process columns, installation of several energy saving process systems, installation of extensive instrumentation suitable for testing and R&D and incorporation of remote monitoring capability.

Federated Co-Operatives Refinery Complex. Fluor was the selected carbon capture licensor and produced licensor design packages for two units designed to capture CO₂ from flue gases produced by existing steam methane reformers and new auxiliary boilers.

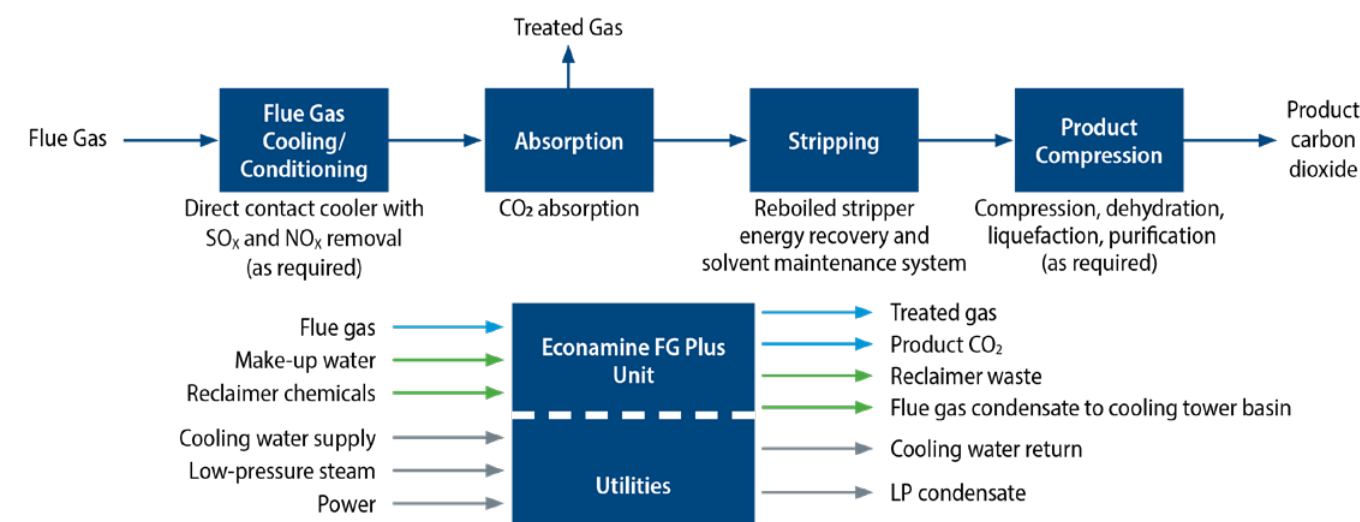


Figure: A typical EFG+ block flow diagram of the process is shown below.

FLUOR[®] FLUOR SOLVENTSM



SUMMARY

The Fluor SolventSM technology is applicable for pre-combustion carbon capture applications using propylene carbonate as the physical solvent. The process is applicable to feed gas with 3.5 barg and higher CO₂ partial pressures. Fluor Solvent plants have been designed for natural gas and syngas production with feed gas rates up to 250 kNm³/h (220 MMscfd) and pressures up to 138 barg with CO₂ content varying from 12 to 53 volume percent. Particularly suited to blue hydrogen projects seeking an all-electric capture solution.

BENEFITS

- **Low Operating Temperature.** The solvent's CO₂ holding capacity increases with lower temperature, requiring less circulation. Solvent performance proven at -20°C.
- **Regeneration.** Lean solvent is produced by successive pressure letdown, followed by vacuum pressure or solvent stripper. External heating is not required.
- **Selectivity.** Dry gas product of either blue hydrogen or methane have minimal losses, minimised by vapour recycle.
- **Propylene carbonate has favorable treating properties:** high solubility for CO₂, low heat of solution of CO₂, low solvent vapor pressure, low solubility for light hydrocarbons and low viscosity.
- **Low solvent freezing temperature** makes the process suitable for cold climate operation, requiring minimum winterization.
- **The solvent is non-hazardous**, chemically non-reactive to natural gas components.
- **Solvent does not degrade or foam**, requiring minimal operator attention.
- **The solvent absorbs water** in the feed gas, producing a dry gas meeting the pipeline specification

KEY PROJECTS

- **Terrell County (Texas):** The Fluor Solvent plant, located in Terrell County, Texas, was originally built in 1960s. The plant was designed to treat natural gas to meet 2 volume percent CO₂ specification. The original plant was designed to treat 250 kNm³/h (220 MMscfd) feed gas with 53 volume percent CO₂ at 63 barg pressure. Currently, the gas plant is processing about 136 kNm³/h (120 MMscfd) of feed gas with 36 volume percent CO₂ at 46 barg. The process uses four flash stages for solvent regeneration, with the last stage operating under vacuum pressure. A small amount of refrigeration is used on the rich solvent to lower the solvent temperature. The process unit has been successfully operating for over 50 years. The same equipment is used without any corrosion problems.
- **Woodward Oklahoma** (Oklahoma; pictured on first page): The Fluor Solvent plant was built for ammonia production. The process was used to treat 168 kNm³/h (148 MMscfd) syngas operating at 130 barg. The process removes CO₂ from 22 volume percent to 200 ppmv CO₂ to meet the syngas specifications.

KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	Up to 95%
Source CO ₂ Purity Range	12 - 53%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	12	Number of Pilot Plants	~	Modular (Y/N)	~
Target Industries	Natural Gas Processing, Hydrogen Plants, Ammonia Plants				

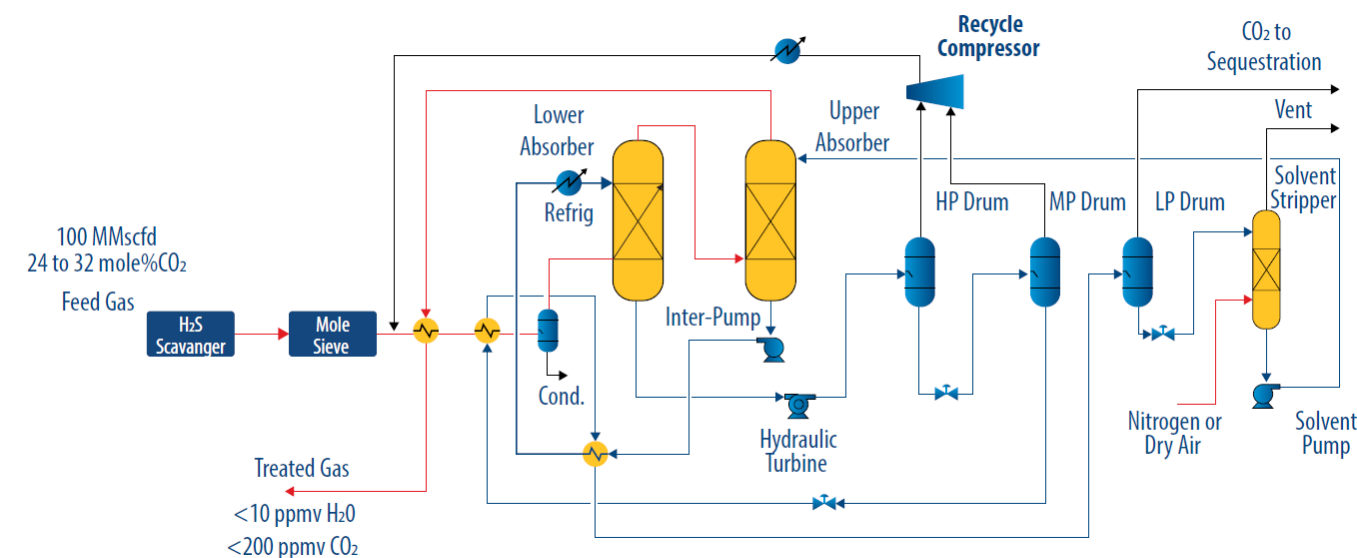


Figure 1: Fluor Solvent's Improved Process

Fluor has improved the process for treating high pressure and high CO₂ gases. The process is configured to take advantage of the energy potential of feed gas CO₂ content. Feed gas is treated in a Sulphur scavenger to produce a Sulphur free feed gas.

- Two absorber design: the upper absorber produces a semi-lean solvent to be cooled and re-used in the lower absorber.
- Refrigeration generated from flash solvent cools the feed gas and the semi-lean solvent, which helps with regeneration.
- Hydraulic turbine recovers power from the pressure letdown while producing cooling.
- Flash gases are recycled to the absorber to minimise hydrocarbon losses.
- Dry air or nitrogen for stripping to produce an ultra-lean solvent.
- Applicable for CO₂ capture from hydrogen plant syngas to produce a blue hydrogen product.

PROVIDING PROFESSIONAL AND TECHNICAL SERVICES

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Fluor provides engineering, procurement, and construction (EPC) services to carbon capture projects including CO₂ compression and transportation. Additionally, Fluor has the unique ability to be the technology licensor and EPC for any carbon capture project using Fluor Solvent. Our carbon capture project experts focus on the delivery of innovative, reliable, and cost-efficient project solutions built on more than 110 years of EPC and maintenance experience and 30 years of experience in carbon capture.



SUMMARY

FrostCarbon, Inc. (an equity carve-out of Carbon America) has developed FrostCC®, a patented point-source cryogenic carbon capture technology designed to eliminate the high cost, complexity, and secondary emissions concerns of conventional solvent-based systems. The process utilises standard industrial equipment—compressors, expanders, pumps, and heat exchangers—and requires no solvents, chemicals, water supply, or thermal energy. FrostCC® achieves up to 99% CO₂ capture with product purity exceeding 99.9%+ and meeting pipeline specs, while simultaneously removing co-pollutants including NO_x, SO_x, heavy metals, and particulates from the flue gas. The commercial product leverages mature commodity equipment and low-cost materials in standardised, modular trains engineered for high-volume manufacturing. Its compact footprint and fully electric load enable straightforward retrofitting of existing plants with minimal host site disruption.

BENEFITS

- **Low Cost:** Anticipated to be one of the lowest levelised cost of capture of any technology
- **Non-Invasive and Easy to Integrate:** Its electric-only load, small footprint, and high modularity enable nondisruptive, drop-in retrofits. No additional CO₂ compression needed.
- **Ultraclean:** High capture efficiency, product purity, and co-pollutant removal.
- **Robust and Reliable:** The capture system is insensitive to contaminants and does not degrade. The process leverages inherently predictable phase-change physics.
- **Rapid Scalability:** Existing supply chains and simple integration enable rapid manufacturing and project timelines. Full-scale capacity is achieved through replication of standardised trains.
- **Water Generating:** Produces significant quantities of cleaned water, a valuable co-product at constrained sites.

KEY PROJECTS

- **R&D at Colorado Test Facility:** Over 2500 hours of testing have been performed across a range of concentrations and rates at our laboratory-scale system. Custom, empirically-validated models enable confident technology scaling and enhancement. Testing in Colorado achieved TRL 5 in 2022.
- **National Carbon Capture Center (NCCC) Pilot Plant:** An engineering-scale system of the fully integrated process, capable of capturing 1000 tonnes of CO₂ per year using natural gas combustion flue gas, was operated in 2024 at NCCC, their first cryogenic capture pilot. The demonstration achieved >1000 operating hours at 90-99% capture efficiency elevating FrostCC® to TRL 6.
- **Commercial Demonstration Plants:** FrostCarbon is pursuing deployment of initial commercial trains in 2028-2029, achieving TRL 8, with normal operations achieving TRL 9 shortly thereafter.

KEY DATA

TRL	6	Capture Rate Range (tpd)	100 - 1,000 per train*	Capture Efficiency (%)	95 - 99%+
Source CO ₂ Purity Range	4 - 40 mol%	System Energy (GJ/tCO ₂)	1 - 2 (elec)	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	First in 2028 - 2029	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Gas power, coal power, pulp & paper, cement, steel, waste-to-energy, biomass, natural gas boilers, and other industrial greenhouse gas emitters				

* Multiple standardised trains deployed in parallel to achieve full scale

TECHNOLOGY DESCRIPTION

BACKGROUND AND DEVELOPMENT

FrostCC® functions based on the thermodynamic principles of a reverse Brayton cycle, integrated with a novel CO₂ capture-and-recovery process that leverages phase-change phenomena at low temperatures, leading to a breakthrough in cost-effective cryogenic carbon capture system design. The success and speed of the R&D program can be heavily attributed to the simplicity of the FrostCC® process, which relies on only conventional industrial equipment (unlike other cryogenic technologies) and predictable underlying physics (unlike sorption-based processes). Furthermore, the design process has fundamentally prioritised minimizing technical risk, system cost and energy, and development timeline.

FrostCC® has rapidly progressed from concept to pilot-scale validation (TRL 6) within only ~5 years. The technology was first conceptualised in 2019 under Carbon America, followed by proof-of-concept testing in 2020 (TRL 3), core process testing completed in 2022 (TRL 5), and testing of the fully integrated pilot plant completed in 2024 (TRL 6). The accelerated development timeline reflects the use of predictable physical phase-change processes and established equipment, enabling rapid scale-up with minimised technical risk. The imminent deployment of the first commercial trains will soon advance the technology to TRL 8+. In 2025, Carbon America performed an equity carveout of FrostCC® assets and intellectual property to formally launch FrostCarbon as an independent technology-focused business unit.

CAPTURE PROCESS DESCRIPTION

FrostCC® compresses, cools, and expands flue gas, causing the CO₂ to "frost" — transitioning directly from gas to solid in a process known as desublimation. The CO₂ deposits as a solid on the heat exchanger surfaces, and the heat exchangers are periodically cycled to melt the solid CO₂ into a highly pure liquid. This liquid CO₂ can remain a liquid or be converted into gas or supercritical fluid at any pressure with minimal equipment or energy needs.

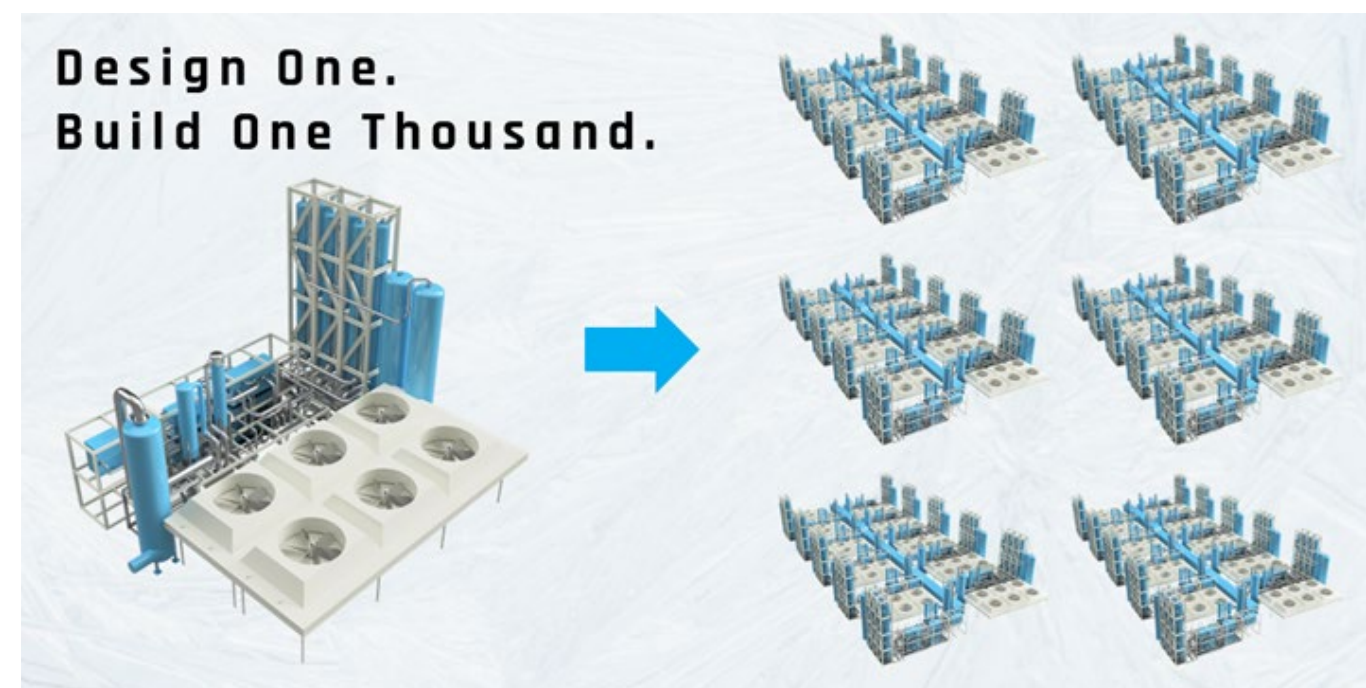
The CO₂-lean exhaust gas leaves the frosting heat exchanger and is circulated back through the system as the auto-refrigerant. The system consists of standardised, skid-based equipment that can be factory-manufactured and shipped to sites for final installation which reduces construction time, complexity, and cost. These mature equipment types include compressors, expanders, pumps, standard heat exchanger types, piping, and valves.

MODULAR DESIGN

FrostCC® is designed around a modular, standardised "train" architecture, where each train represents a repeatable, factory-built unit with consistent performance characteristics. This "design one, build one thousand" philosophy enables rapid manufacturing, continuous cost reductions through replication, and minimises engineering variability and field construction compared to bespoke systems. Multiple trains are deployed in parallel to scale capacity, allowing facilities to align capital deployment with project timelines, reduce upfront risk, and scale capture capacity in step with operational or regulatory needs. By leveraging identical, well-characterised units, FrostCC® reduces integration risk, accelerates project timelines, and ensures predictable performance as projects scale from initial deployment to full commercial capacity.

NEXT STEPS

FrostCarbon is currently pursuing several large-scale commercial demonstration projects across various emitter types and establishing strategic partnerships with host sites, clean energy buyers, carbon market participants, equipment manufacturers, and engineering firms. For general inquiries or interest in commissioning a Pre-FEED study, please see our contact page on our website, www.frostcarbon.com

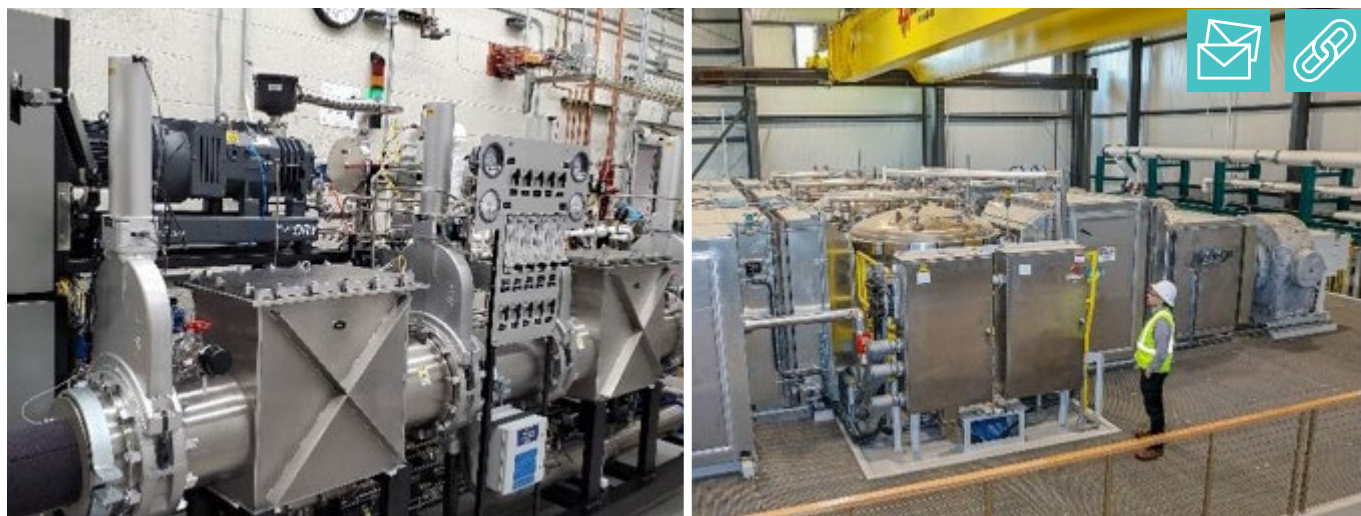




GE VERNOVA

GE VERNOVA

GE VERNOVA DIRECT AIR CAPTURE



SUMMARY

Direct Air Capture (DAC) is a cornerstone of global net-zero pathways, serving both as a vital Carbon Dioxide Removal (CDR) strategy, a source of climate-neutral CO₂ for synthetic fuels, and a technology to remove legacy CO₂ emissions. GE Vernova is advancing this field through proprietary solid sorbent technology developed at our Advanced Research Center. Our innovative approach utilises low-temperature thermal vacuum swing adsorption (TVSA), which reduces energy intensity, enhances water management, and provides modular scalability. By collaborating with key U.S. government agencies, GE Vernova has established a position as one of the leaders in DAC innovation. We remain committed to delivering high-efficiency carbon management solutions that address the dual requirements of atmospheric decarbonization and circular carbon utilization for a more sustainable industrial future.

BENEFITS

GE Vernova's DAC technology offers several key advantages for large-scale carbon management:

- **Proprietary Solid Sorbent:** Internally developed materials, binders and coating process help to deliver enhanced performance and a more competitive cost profile.
- **Enhanced Water Management:** Enhanced process reduces water consumption and incorporates the potential for water recovery.
- **Reduced Energy Intensity:** High-efficiency adsorbent materials and enhanced regeneration cycles significantly lower overall power requirements.
- **Modular Scalability:** The flexible architecture allows for rapid scaling and seamless integration into diverse industrial and geographic environments.

KEY PROJECTS

GE Vernova scales its DAC technology through a rigorous New Product Introduction (NPI) process, systematically de-risking deployment for our customers. Key development milestones include:

- **Lab Scale:** Demonstrates 1 kg/day capture capacity to validate fundamental system engineering and sorbent performance.
- **Test Facility:** A 10-tonne/year system configuration for comprehensive testing of sorbents, processes, and integrated system controls.
- **Deep Sky Project:** An outdoor operational pilot capturing up to 1,500 tonnes/year, focused on validating product reliability and performance in real-world environmental conditions.

KEY DATA

TRL	5	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	~
Target Industries	Direct Air Capture				

GE Vernova's DAC technology utilises advanced solid adsorbents within a batch-operated, two-step adsorption and desorption cycle. During the initial phase, adsorption occurs at ambient temperature and pressure. The subsequent desorption phase releases concentrated CO₂ by employing a temperature-vacuum swing adsorption (TVSA) mechanism, operating at temperatures between 80°C and 100°C under vacuum conditions. This process is housed within a modular system architecture, ensuring both operational efficiency and flexible deployment across various scales. By combining high-performance chemistry with a scalable mechanical configuration, GE Vernova provides a robust solution tailored for the evolving requirements of the global carbon capture industry.

DAC PROCESS

The GE Vernova DAC system is comprised of modular contactor units that can be customised based on geographic location, ambient environmental conditions, and specific capacity requirements. These contactors are coated with a proprietary solid sorbent material developed to facilitate an efficient carbon capture cycle. The process is divided into four distinct operational phases: adsorption, desorption, transport, and cooling as shown in Figure 2.

Adsorption: The cycle begins with the adsorption phase, where high-efficiency fans draw ambient air through the contactor. As the air passes over the solid sorbent, CO₂ molecules are selectively captured at atmospheric temperature and pressure while the CO₂-depleted air exits the unit. This phase continues until the sorbent reaches its saturation point, a threshold dictated by the specific sorbent isotherm, which meets capture efficiency before transitioning the system to the next stage.

Desorption: Once saturated, the system enters desorption mode, where the contactor is sealed from the surrounding environment. A vacuum system evacuates the unit to remove residual air, preventing the dilution of the captured CO₂ and ensuring high purity. And the contactor is heated to facilitate the release of the CO₂ and the regeneration of the sorbent material, leveraging thermal energy to break the chemical bonds between the sorbent and the carbon dioxide.

Transport: Following the successful release of the CO₂, the concentrated CO₂ is compressed to meet the necessary specifications for downstream handling. This high-purity stream is then transported to its destination, where it can be utilised as a feedstock for industrial products and synthetic fuels or directed toward permanent geological sequestration.

Cooling: To prepare the system for the subsequent capture cycle, the contactor must return to its configured operating temperature. This is achieved during the cooling phase, where cold water is circulated through the unit to dissipate residual heat from the sorbent and contactor structure. This thermal management step restores the sorbent's adsorption capacity, ensuring the system is ready to begin the next cycle with enhanced efficiency.

GE VERNOVA ADDED VALUE

GE Vernova mission is to develop a technologically differentiated, economically viable DAC solution. The strategy relies on three pillars; Innovate, Industrialize, and Integrate. Innovate involves the cutting-edge research in sorbent materials, which are the cornerstone of DAC, directly influencing operational performance, energy efficiency, and overall project economics. Industrialize leverages GE Vernova decades of expertise in plant configuration and optimization in combined cycle gas turbine to develop a highly improved DAC plant. Additionally, GE Vernova leverage its global supply chain and strategic alliances to make DAC economically viable. Integrate involves leveraging the DAC ecosystem, aiming to avoid unused calories.

This unique combination of material science and large-scale engineering provides a distinct advantage in deploying reliable, high-efficiency carbon management solutions.

GE Vernova is working with development partners to advance larger-scale DAC projects in the United States, Canada, and Europe, while also exploring opportunities for unique integrations with BECCS, data centers, and others that create mutual advantages.

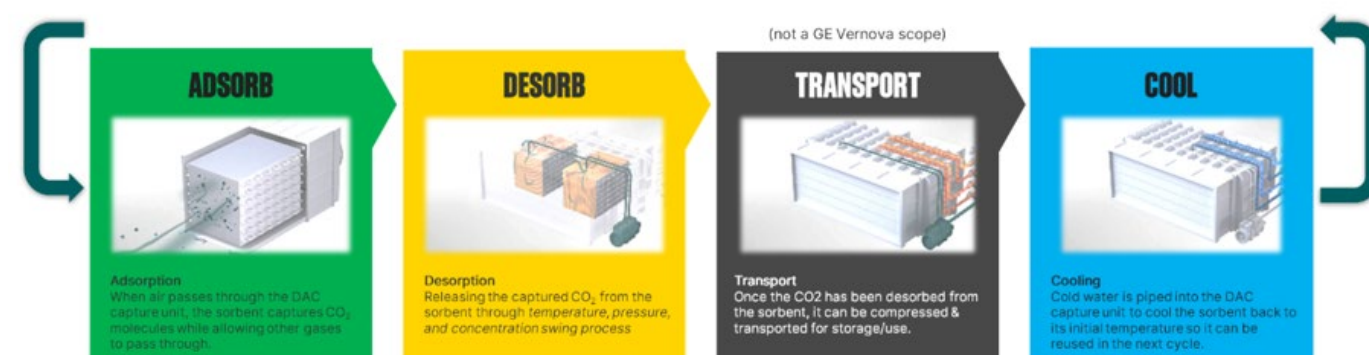
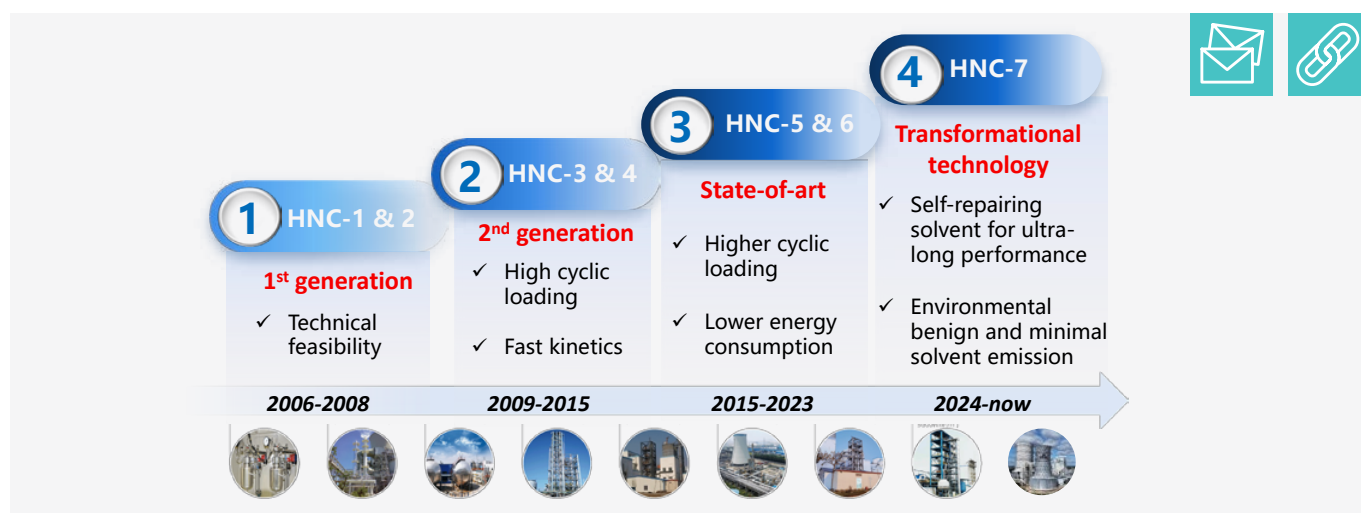


Figure 2: GE Vernova DAC process steps. Please note that the Transport step is not in GE Vernova scope

HUANENG HNWWC-7 CO₂ CAPTURE TECHNOLOGY

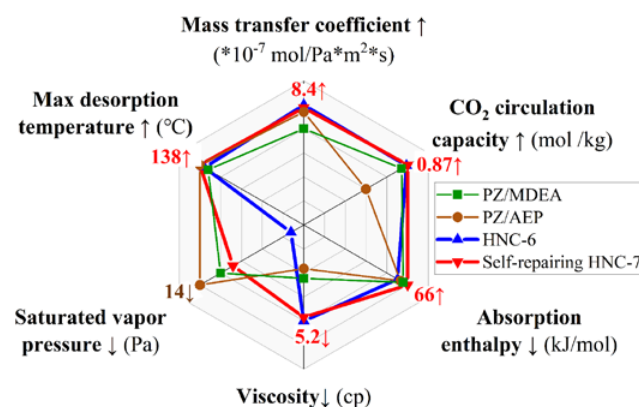


SUMMARY

CERI is currently a leading supplier of carbon capture technology in China. Through over 20 years of research, CERI has established an independent intellectual property system for CCUS technology. CERI has developed a series of commercial absorbents designated as HNC-1 through HNC-7. The HNC-5 solvent has been validated for over 20,000 hours at the Shanghai Shidongkou 120,000 tons/year CO₂ capture facility. Advanced HNC-6 absorbent featuring higher cyclic capacity and lower energy consumption has been conducted long-term performance validation for over 2,000 hours at the Huaneng Yangpu NNGC 2,000 tons/year CO₂ capture pilot plant. To address the challenges of absorbent degradation, the self repairing solvent, HNC-7, was developed and applied in the world's largest-scale 1.5 million tons/year CCUS demonstration project. It achieves a carbon capture rate of 91.4%, reduces capture heat consumption to 2.2 GJ/t, and requires only 0.82 t/t CO₂ of steam consumption, demonstrating excellent scalability and operational economy.

BENEFITS

- Targeted design of molecules with inherent resistance to degradation, achieved by screening and incorporating functional groups that enable antioxidant chain reactions.
- Significant reduction in degradation rate through the synergistic action of the main absorbent, self-repairing products, and auxiliary additives.
- An absorption enthalpy of only 66 kJ/mol, a high CO₂ cyclic capacity of ~2 mol/kg solvent, and a maximum desorption temperature of up to 138°C.
- At CO₂ concentration of 4vol.% and 90% CO₂ capture efficiency, the CO₂ desorption energy consumption is reduced by 28% compared to a PZ/AMP solution. It exhibits excellent thermal and oxidative stability during tests exceeding 1000 hours.



Comparison of kinetic and thermodynamic parameters for HNC absorbent. $\uparrow$: higher is better; $\downarrow$: lower is better.

KEY DATA

TRL	9	Capture Rate Range (tpd)	3 - 5,000	Capture Efficiency (%)	90 - 97%
Source CO ₂ Purity Range	3 - 20%	System Energy (kWh/tCO ₂)	50-150	Specific Regen. Energy (GJ/tCO ₂)	2.2 - 2.6
Number of Commercial Plants	3	Number of Pilot Plants	4	Modular (Y/N)	Yes
Target Industries	Coal and natural gas fired Power, Steel, cement and waste to energy plants				



MILLION-TON SCALE CCUS PROJECT APPLICATION

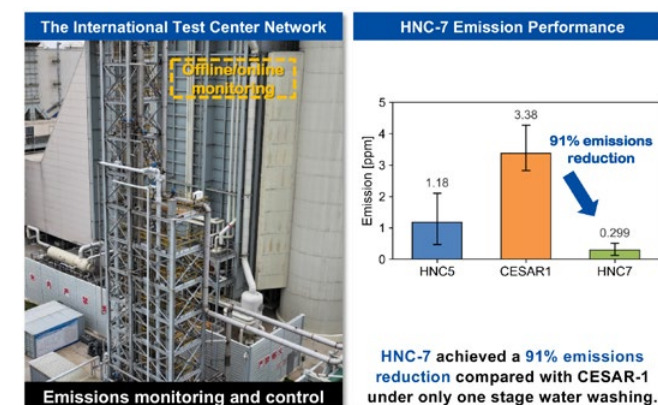
The self-repairing HNC-7 absorbent developed by CERI has undergone long-term testing in laboratory-scale and pilot-scale CO₂ capture units and is successfully applied in the world's largest 1.5 million tons/year coal-fired power carbon capture demonstration project in September 2025. During operation, the absorbent exhibits stable performance, achieving a CO₂ capture rate >90%, an average capture energy consumption of 2.2 GJ/t CO₂, and a CO₂ production rate of 200 t/h, representing a globally leading level. Estimates indicate that the absorbent consumption per ton of CO₂ captured is less than 0.3 kg, and the comprehensive capture cost (including annualised CAPEX) is as low as 220 RMB/t CO₂. This represents a reduction of over 15% compared to mainstream international technologies. The technology holds significant potential for widespread application across the energy, chemical, and power sectors, facilitating the marketization of emission reduction technologies and generating revenue through technology transfer.

By lowering carbon capture costs, improving capture efficiency, and minimizing secondary pollution, this technology contributes to energy conservation, emission reduction, and the transition to a green economy. On one hand, the reduced specific energy consumption and replenishment demand decrease energy usage and chemical emissions, lessening the environmental burden associated with raw material consumption and waste disposal. On the other hand, by enhancing the affordability of emission reduction for industrial sectors (such as power, steel, cement, chemicals, and biomass), it can accelerate the achievement of regional and national emission reduction targets, promoting the diversified implementation of pathways towards carbon neutrality.



AI-DRIVEN PLATFORM FOR R&D OF CO₂ ABSORBENTS

CERI has constructed an integrated intelligent R&D platform for new materials, incorporating molecular modeling, automated experimentation, machine learning, and high-throughput screening technologies. This platform establishes a closed-loop workflow for absorbent development, ranging from virtual screening and performance prediction to experimental validation. It has been applied to the structure-property prediction of CO₂ absorbents and the screening of new materials, significantly shortening R&D cycles and improving development success rates. Starting from molecular structures, a high-dimensional descriptor feature space is constructed, and machine learning models are utilised to predict CO₂ absorption capacity under specific operating conditions. Rapid validation and model feedback iteration are then conducted via an automated experimental platform, enabling precise screening and performance optimization. Concurrently, a proprietary high-throughput automated development system for CO₂ absorbents has been developed. This system integrates precision liquid handling, physical property parameter detection modules, absorption reaction modules, online gas analysis with automatic recording, and automated instrumentation. It enhances R&D efficiency by more than approximately 10 times compared to manual experimentation.





ION CLEAN ENERGY ICE-31® CO₂ CAPTURE SYSTEM



SUMMARY

ION Clean Energy's ICE-31 post-combustion CO₂ capture technology has demonstrated transformational performance at the engineering-scale and large pilot-scale by capturing between 95% to over 99% of CO₂ with extremely low emissions, unprecedented solvent stability and low energy requirements. ION's ICE-31 technology is particularly well suited to high oxygen environments, like natural gas-fired power generation, where the solvent's resistance to oxidative degradation shines, resulting in the extremely low emissions that minimise the adverse environmental impact typically seen with implementation of other amine-based technologies.

BENEFITS

- **Unprecedented Solvent Stability & Extremely Low Emissions:** Excellent stability and resistance to oxidative degradation extends the life of the solvent without losing capture efficiency. The frequency of solvent reclamation, replacement and disposal are decreased, and as a result, this leads to better operability, less waste and improved carbon intensity evaluations. Emissions from the ICE-31 solvent also fall below detectable levels of current Continuous Emissions Monitoring Systems. This minimises the adverse environmental impact typically seen with implementation of other amine-based capture technologies.
- **High Capture Efficiency:** ION's ICE-31 solvent has consistently demonstrated capture efficiency between 95% to over 99% of CO₂ emissions, and steady-state operations with less than 200 ppm of CO₂ in the exhaust gas.
- **Lower Energy Requirements:** ION's ICE-31 solvent is energy efficient and has low energy requirements to regenerate the solvent. As a result, operating costs are minimised while capture efficiency rates of more than 95% are maintained.

KEY PROJECTS

- **ICE Blocks™ Standardised, Modular CO₂ Capture Units:** ICE Blocks are standardised CO₂ capture units that provide all the benefits of ION's ICE-31 capture system, but for CO₂ emissions sources as small as 35,000 tonnes per year. The modular design and high-volume production efficiency of ICE Blocks reduce CAPEX through reduced onsite labor risk leading to optimised economics and increased customer value. ICE Blocks are available in three sizes for a range of CO₂ flue gas concentrations and all base unit configurations include the carbon capture island modules, flue gas ducting, CO₂ compression and dehydration, and evaporative cooling system. ION also offers additional modular add-ons for other required balance of plant systems. With ICE Blocks, ION provides a single source contract with a fully wrapped project and performance guarantee.

KEY DATA

TRL	8	Capture Rate Range (tpd)	10 - 10,000	Capture Efficiency (%)	95 - 99%+
Source CO ₂ Purity Range	3 - 20%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.4 - 2.8
Number of Commercial Plants	6	Number of Pilot Plants	6	Modular (Y/N)	Yes*
Target Industries	CCGT power generation and industrial processes				

*ICE Blocks standard units are modular

EXTREMELY LOW EMISSIONS

The Enterprise emissions were continuously monitored out of top of the absorber using a Proton-Transfer-Reaction Time-of-Flight mass spectrometer (PTR-TOF-MS) during the long-term steady-state portion of the campaign. PTR-TOF-MS is the state-of-the-art technology for continuous emissions monitoring and can detect and quantify calibrated compounds at the parts-per-billion (ppb) level. ION measured the additive emissions of volatile organic compounds (VOC) (quantified as methane equivalent) to be approximately 1 ppb during the steady-state testing across a wide range of flue gas temperatures. Extractive emissions sampling was also performed by a third party, where VOC emissions were found to be at or below the limit of detection for the extractive sampling method.

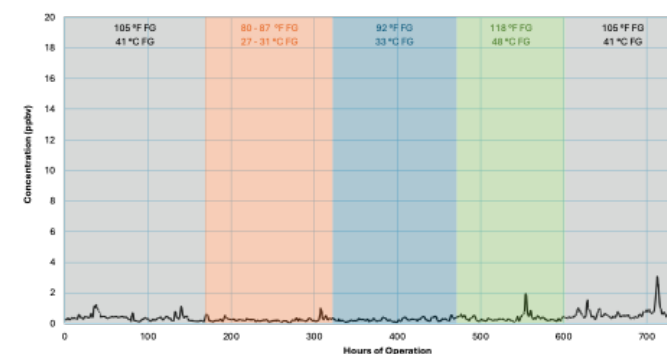
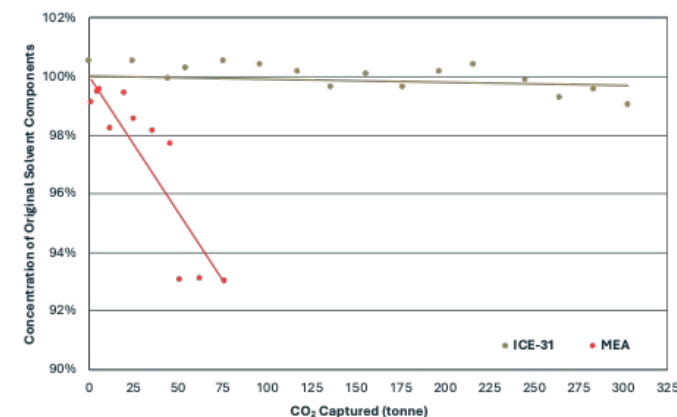


Figure 1: VOC emissions as methane at Enterprise during the long-term steady-state portion of the campaign. The temperature of the flue gas entering the absorber is shown at the top of the graph.

ICE-31 STABILITY

After a year of continuous operation using the same batch of ICE-31 solvent, ION extended operations with the spent solvent for an additional 30-day demonstration period under commercial operating conditions, requiring only minimal solvent addition and reclamation.

Composition was remarkably stable for solvent components; the only accumulation was 0.0002 wt%/day of heat stable salts. Any additional reclamation to remove HSS and return ICE-31 to exact starting composition would occur during major planned maintenance outages at a cadence of 5-20 years. The plot below shows the stability as compared to the virgin MEA at Enterprise, where you see a steep decline of MEA components almost immediately, whereas ICE-31's original solvent components are stable at near 100%.



LOWER ENERGY USE: SRD VERSUS CAPTURE

Figure 2: ICE-31 Stability during 30-day demonstration testing, with a Year aged ICE-31 compared to MEA in the same pilot plant; 100% Represents the Sum of All Active Solvent Components.

EFFICIENCY

ICE-31 is uniquely formulated for high capture efficiency with minimal increase to the Specific Reboiler Duty (SRD) even at net-zero emissions from an NGCC stack. Under optimal conditions, SRD increases only 2-3% over baseline values while a similarly optimised MEA facility increases 8% over baseline values when achieving net zero. Moreover, ION has proven these results at pilot facilities where even under drop-in conditions, there was only a 4% SRD penalty when going from 90% to 98% capture efficiency. Due to ICE-31's stability, ION can drive leaner solvent loadings, which results in higher capture efficiency with the ability to achieve over 99%.

ENTERPRISE PILOT AT CALPINE'S LOS MEDANOS ENERGY CENTER

A first-of-its-kind pilot designed and built to ION's specifications to demonstrate the empirical performance of ICE-31 on a 1 MWe (10 tpd) slipstream of combined-cycle gas turbine (CCGT) flue gas from a commercially dispatched power plant in Pittsburg, CA, USA. ION has been operating the Enterprise pilot and has accumulated over 6,000 hours of ICE-31 testing including parametric studies, dynamic and long-term operations to demonstrate key performance indicators. This collaboration feeds directly into ION's partnership with Calpine to implement CO₂ capture onto their Sutter Decarbonization Project in Northern California. The Enterprise project has received significant funding for development through U.S. Department of Energy programs.



K2-CO₂



SUMMARY

K2-CO₂ delivers fully integrated turnkey Carbon Capture Use & Sequestration (CCUS) solutions targeting small and medium scale industrial emitters. Our portfolio includes turnkey solutions to satisfy from the exit of combustion source to the exhaust stack including **carbon capture** integrated with **flue gas treatment, waste heat recovery, and reuse or sequestration**. These solutions integrate into an existing process without impacting the production, resulting in a reduction of environmental emissions, overall energy impact, and CO₂ footprint.

Our team leverages its extensive experience as industrial flue gas treatment integrators to offer a safe, energy-efficient, “bolt-on” carbon capture system utilising Hot Potassium Carbonate (HPC) solvent with the needed conditioning for sequestration or reuse. The HPC-solvent process for CO₂ capture, licensed by Giammarco Technologies, with worldwide exclusive for Glass, is used globally in industries such as chemical plants. K2-CO₂ has extended the usefulness to lower CO₂ concentrations, making it suitable for most combustion-derived flue gas, with specific focus on the glass industry, where carbon capture represents one of the key decarbonisation pathways for hard-to-abate industrial processes.

BENEFITS

- **No Upstream Process Modifications:** Our systems integrate into existing processes without upstream modification of conditions or fuel required and include Use and/or Storage, providing tailored solutions to the unique process and site.
- **Energy Efficient:** Energy demands for heating/cooling and expansion/compression are minimised through energy re-use throughout the process.
- **Cost Effective:** Minimal changes to combustion process, waste heat recovery, and solvent regeneration provide a cost-effective solution for CCUS in small to medium size emitters.
- **Continuous Compliance:** Highly effective air pollution control technology is integrated for other flue gas pollutants.
- **Safe and Environmentally Friendly:** Hot Potassium Carbonate (HPC) is a non-flammable, nontoxic, stable and inexpensive solvent, eliminating the need for harmful and corrosive amine-based capture processes.

KEY DATA

TRL	7	Capture Rate Range (tpd)	20 - 400	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	1	Modular (Y/N)	~
Target Industries	Glass, Cement, Biomass to Energy, Steel, Waste to Energy				

The K2-CO₂ process comprises of a dry section and wet section connected in series.

The dry section is comprised of the Air Pollution Control system and heat recovery states to meet the heat needs required by the carbon capture process.

This section can utilise existing air pollution control equipment on-site with the integration of heat recovery stages or can be provided as new equipment. It must be noted that the flue gas can exit the system by bypassing the wet section via an exhaust stack to **maintain continuous emission compliance** in the event of an emergency or maintenance on the wet system.

The wet section is comprised of a deSO_x process, CO₂ absorption, and CO₂ cooling and concentration.

The deSO_x process provides further removal of contaminants and additional conditioning of the flue gas stream to begin the CO₂ recovery process.

The absorption section, utilising the well-known carbon capture technology of Hot Potassium Carbonate (HPC), absorbs CO₂ from the flue gas stream into the HPC water solution. The remaining flue gases, which have already been treated in the dry section, are emitted to the atmosphere.

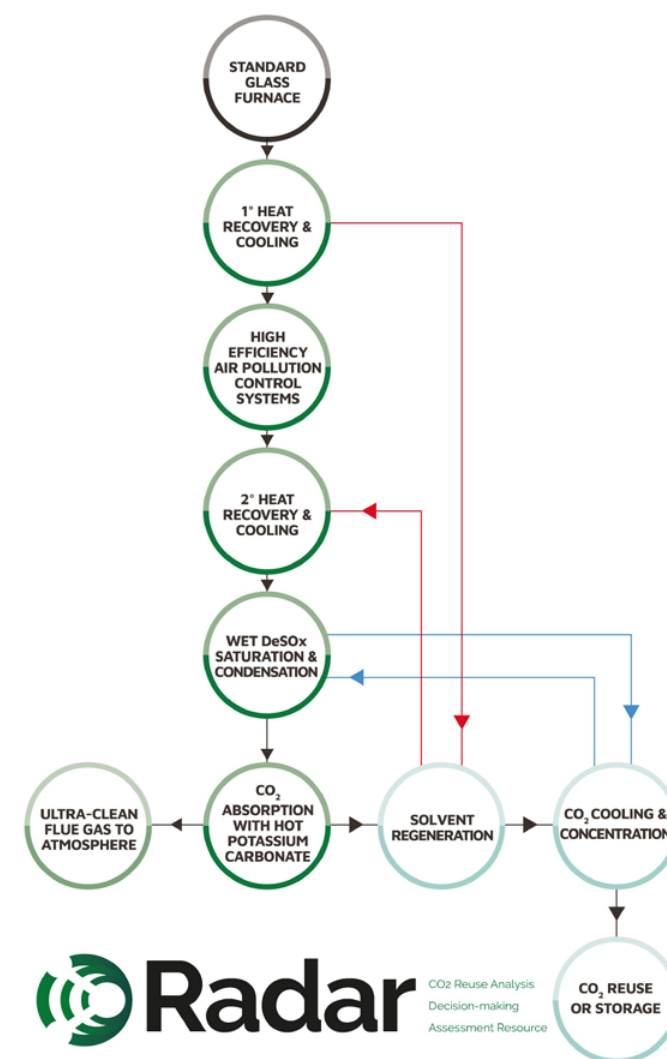
The CO₂-rich HPC solution is then heated to release the highly concentrated CO₂ product in a stripping process. The HPC solution is regenerated and injected into the absorber in a loop system, requiring no continuous make-up of the solution.

The CO₂ is collected, conditioned, and sent for the chosen use or storage solution for the process. The captured CO₂ can be sent to the conditioning plant, designed to deliver the desired CO₂ quality, pressure and temperature for use or storage: underground, for enhanced oil recovery or mineralisation.

The conditioning **technology is adapted to the effective needs** and can cover from simple storage/delivery in gas phase to purification and liquefaction or compression to supercritical conditions.

The K2-CO₂ HPC process is a classic absorption/stripping process but is operated at relatively low pressures (typically 0.5-5 barg) and integrates all possible heat recovery stages. The process is **designed to have zero external heat needs**, making it less energy-intensive than other CCUS technologies, including those utilising a similar solvent or amine-based systems. It can be applied to a wide range of industrial processes such as glass, steel, biomass/waste incineration.

HPC technology has been chosen against Amines for several reasons, safe for people and the environment, non-volatile, stable, inexpensive, and based on a non-proprietary, readily and worldwide available basic component. The technology is currently being advanced through industrial initiatives including a **Cardinal Glass Industries project** aimed at integrating a high-efficiency CO₂ capture within industrial glass production



RADAR® SERVICE

K2-CO₂ delivers feasibility studies that can include the RADAR® service. With the RADAR®, we give the customers a complete overview of the multiple possible opportunities for the final destination of the CO₂, including transport, storage, valorisation, use. K2-CO₂ continuously updates a database with more than 140 different reuse technologies, pipelines, multi-modal shipment routes, storage hubs, sequestration wells. This allows the emitters to have complete view over the business case for their CCUS projects.

DOBBY™ MOBILE DEMONSTRATION PLANT

K2-CO₂ has developed a mobile demonstration unit available for rental. The system, called DOBBY™, captures 1-2 tpd from flue gas streams up to 500 Nm³/h and down to 7% CO₂ content. It is fully automatised and instrumented to evaluate and optimise the capture parameters, so to reach capture efficiency of 95% and above. It also include a unique pre-treatment stage and can take raw, untreated gases. It's completely mobile and suitable for travelling overseas.



LINDE

ADVANCED AMINE-BASED POST-COMBUSTION CO₂ CAPTURE (PCC)



SUMMARY

Post-Combustion CO₂ Capture (PCC) is a mature option to capture CO₂ from flue gas streams. With the OASE® blue technology, CO₂ is removed from the flue gas through chemical scrubbing with an aqueous amine-based solvent. It can be implemented downstream of existing assets without interfering with upstream processes. For new assets, advanced plant integration concepts and optimised total costs of ownership can be accomplished.

The optimal design of turnkey facilities using OASE® blue technology has been jointly developed by BASF and Linde. It leverages BASF's capabilities in high-performance gas treatment technologies and Linde's strength and proven track record in design and delivery of turnkey industrial plants. This results in an optimal interplay of solvent, process design, equipment, and plant integration. In combination with our solid track record in large-scale gas treatment plants, this high-performance CO₂ capture technology ensures low risk in EPC projects.

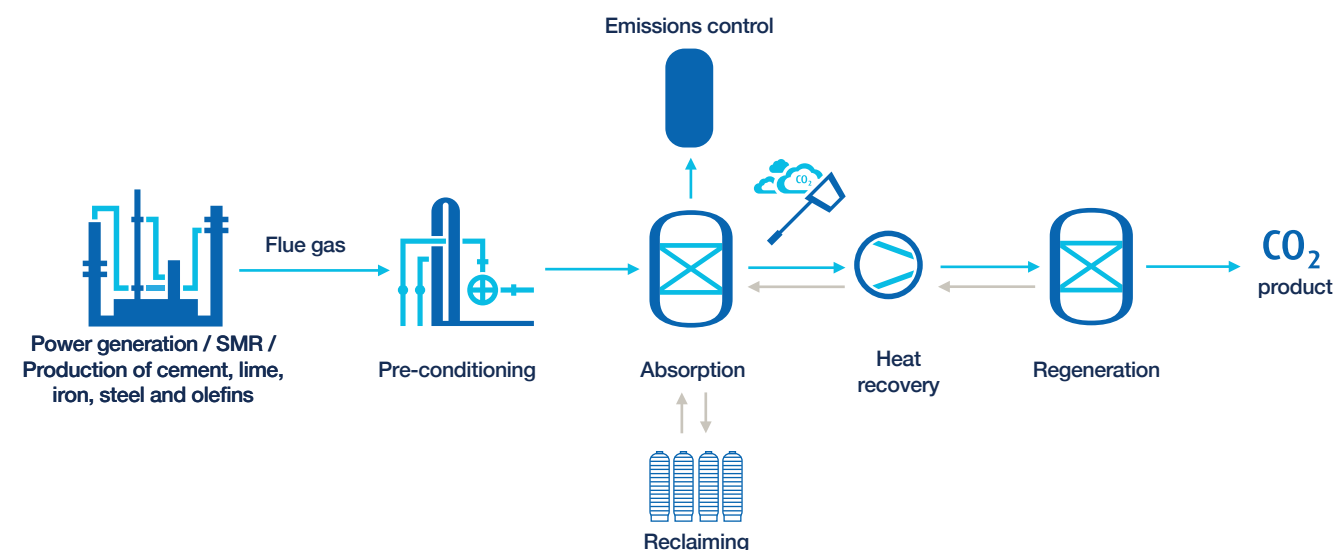
HIGHLIGHTS

- Compact footprint
- High CO₂ capture rate even at low CO₂ concentrations
- With a final CO₂ product purity of 99.9 vol% (dry), a further purification step may not be necessary
- 20% lower energy consumption and 20% lower circulation rate compared to MEA solution
- Low solvent degradation rate even at elevated oxygen content in flue gas, and therefore low solvent consumption rate
- Different options for energy and heat integration
- Unique emissions control technology for minimum environmental impact
- > 500 OASE® gas treatment plants in operation for different applications
- > 65,000 hours of operational experience with OASE® blue
- Reference plants in Germany and the United States

KEY DATA

TRL	9	Capture Rate Range (tpd)	200 - 7,000	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	3 - 25%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.5 - 3.2
Number of Commercial Plants	>60	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Cement & lime, power generation (natural gas, biomass, coal), iron & steel, petrochemical, oil & gas				

TECHNOLOGY DESCRIPTION



OASE® blue post-combustion CO₂ capture (PCC) process

OASE® is a registered trademark of BASF SE

KEY PROJECTS

- The joint venture of Heidelberg Materials and Linde received a building permit for a CO₂ capture and liquefaction plant at Heidelberg Materials' site in Lengfurt, Germany. With the achievement of this major milestone, building activities have commenced.
- A major 10-megawatt carbon capture pilot project for City Water, Light and Power (CWLP) in Springfield, Illinois, is on track to start up later this year. The Linde/BASF Advanced Post-Combustion CO₂ Capture Technology used in this project is a major step in demonstrating how capture technologies can be successfully integrated into industrial facilities to reduce CO₂ emissions.



LINDE AMINE WASH PRE-COMBUSTION CO₂ CAPTURE

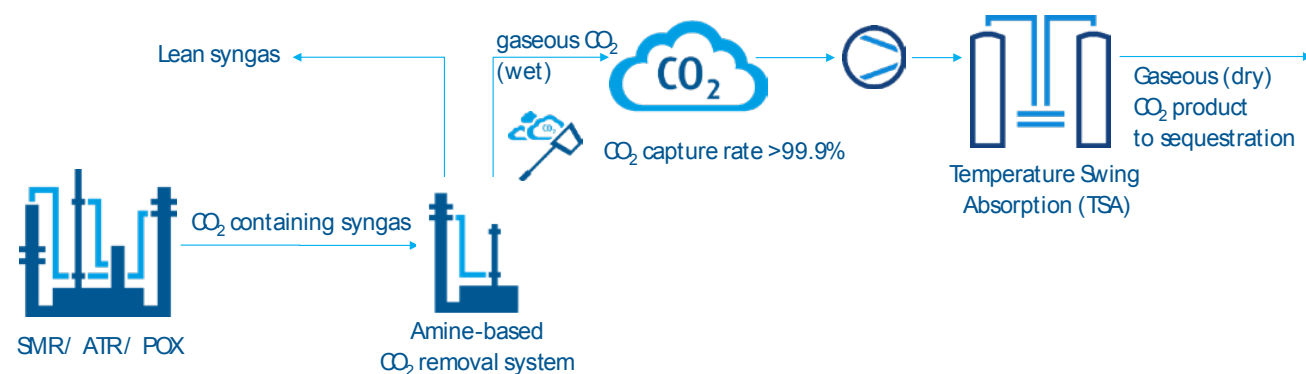


SUMMARY

Amine wash processes are the standard for CO₂ removal from steam methane reforming (SMR)-based hydrogen, syngas, and ammonia plants. CO₂ capture from syngas is a proven technology, which achieves a CO₂ recovery rate of 99.9%. Further advantages include a low investment and favorable operating costs. Amine wash units can be installed in various areas of a plant, from low- to high-pressure applications. They are also suitable for advanced CO₂ removal as well as simultaneous removal of CO₂ and Sulphur. Amine wash units can also be combined with other Linde technologies, such as the Linde Ammonia Concept (LAC™), or with cryogenic processes for carbon monoxide production.

BENEFITS

- State-of-the-art process
- Compact design
- Favorable design for low- and high-pressure applications
- Compatible for CO₂ removal and/or Sulphur removal



Amine wash-based CO₂ capture process from syngas

KEY DATA

TRL	9	Capture Rate Range (tpd)	20 - 2,000+	Capture Efficiency (%)	99.9%
Source CO ₂ Purity Range	2 - 40 vol%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	1.0 - 3.0
Number of Commercial Plants	>60	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Natural gas, oil and gas, chemical				



LINDE CO₂ PSA



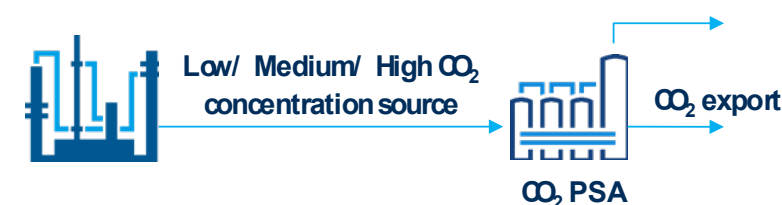
SUMMARY

Linde's pressure swing adsorption (PSA) system is an efficient technology for the recovery of CO₂ from process gas streams at a wide concentration range, as shown in the figure below. In many cases, PSA technology is a more cost-effective alternative to conventional washing systems due to its lower investment and operating costs.

In the iron and steel industry, PSA technology can be used to efficiently remove CO₂ in direct reduction or blast furnace off-gases. The process removes maximum amounts of CO₂, yet leaves valuable gas components, such as H₂, CO, and CH₄ in the gas stream for further processing. A stand-alone CO₂ PSA unit can achieve a product purity of up to 95 vol%, with unit capacities ranging from a few MMSCFD/thousand Nm³/h to around 450 MMSCFD/500,000 Nm³/h.

HIGHLIGHTS

- Mature and robust purification technology
- Negligible electricity consumption
- No steam required for regeneration (thereby no additional CO₂ generation)
- No solvents are applied, so therefore no negative environmental impact due to the emission of solvent traces in exhausts or in the CO₂ product
- No extra cost for solvent makeup and handling
- Low CAPEX and OPEX technology



Typical CO₂ PSA process design for efficient capture of CO₂ from process gas

KEY DATA

TRL	9	Capture Rate Range (tpd)	10 - 5,000	Capture Efficiency (%)	99%
Source CO ₂ Purity Range	>7%	System Energy (GJ/tCO ₂)	0 ¹	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	>15	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Iron & steel, (petro-)chemical, cement & lime, oil & gas, hydrogen				

¹ If feedgas is at elevated pressure



LINDE

HISELECT® POWERED BY EVONIK MEMBRANES

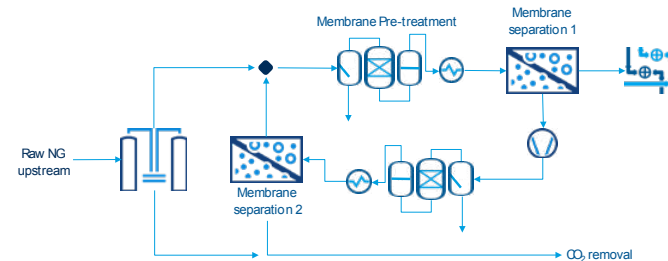


SUMMARY

The HISELECT® membrane was originally developed with a focus on the natural gas and process gas industries. For natural gas resources with sour and acid fractions, membranes are an excellent alternative to conventional amine wash systems for acid gas removal. Driven by partial pressure difference, the HISELECT® membrane works like a semi-permeable barrier and separates the feed gas into a low-pressure permeate, rich in the gas to be removed or recovered (such as CO₂) and a high-pressure retentate with a low concentration of these components. The membranes demonstrate high selectivity for CO₂, irrespective of high hydrocarbon (HHC) content and CO₂ partial pressure. Additionally, strong resistance to unsaturated hydrocarbons, mechanical robustness, and high resistance to hydrogen sulfide (H₂S) result in low maintenance requirements. Aside from natural gas sweetening, HISELECT® membrane technology can also be applied in hybrid solutions with pressure-swing or temperature-swing adsorption units to efficiently remove CO₂ or other contaminants.

HIGHLIGHTS

- Low CAPEX and OPEX with high operational flexibility
- Rapid return on investment
- High separation capacity and high selectivity for maximum recovery rates and high purities
- Ability to tailor membrane capacity and selectivity to customer requirements
- High volume efficiency due to optimised packing of hollow fiber membranes
- Production flexibility with wide feed stream condition range and supporting temperatures up to 212°F/100°C and pressures up to 2,900 PSI/200 bar
- Resistant to CO₂ partial pressure of up to 725 PSI/50 bar
- Robust and stable performance over time under harsh operating conditions, reducing need for overdesign
- Reduced pre-treatment effort due to excellent resistance to heavy hydrocarbons and plasticisation
- Mechanical resistance to process fluctuations during operation



Typical process design of a gas processing unit with HISELECT® for natural gas acid removal.

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KEY DATA

TRL	9	Capture Rate Range (tpd)	>10	Capture Efficiency (%)	85 - 95%
Source CO ₂ Purity Range	>2%	System Energy (GJ/tCO ₂)	0 ¹	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	>20	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Natural gas				

¹ If feedgas is at elevated pressure



LINDE HISORP® CC



SUMMARY

HISORP® CC is a sophisticated carbon capture solution that combines Linde's proprietary adsorptive and cryogenic technologies. It takes a toolbox approach, prioritizing the reduction of carbon footprint while minimising total costs, especially for industries with high CO₂ emissions. HISORP® CC can be applied to pre- and post-combustion carbon capture for a variety of emissions sources. The technology is flexible in terms of scale, covering all relevant industrial sizes, CO₂ feed concentration, CO₂ export product state (gaseous, liquid, or supercritical form), and all purity levels, from industrial and sequestration grade to high-purity food & beverage grade.

Typical applications of HISORP® CC include blue hydrogen production; removal of CO₂ from CO₂-rich flue gases from cement, lime, or steel production; and CO₂ removal from sour gas sources.

BENEFITS

- All major process units within the HISORP® CC Toolbox have been built by Linde for decades, making it a mature and well-referenced carbon capture technology
- Design is based on maximised modularisation with pre-manufacturing and workshop testing to minimise transportation and installation costs
- 100% driven by electrical power with no steam required unless beneficial for rotating equipment driver selection
- Flexible cooling design minimises fresh water consumption
- An optimised cryogenic purification design requires no external refrigeration to produce gaseous CO₂
- No consumption, handling, makeup, or emission of chemical washing agents nor disposal of their degradation products results in minimised OPEX for consumables and a lower environmental impact

KEY PROJECT

Equinor and Linde have started front-end engineering design (FEED) for their joint H2M Eemshaven low-carbon hydrogen project in the Netherlands. Equinor will procure carbon transport and storage capacity and provide low-carbon hydrogen to the market, while Linde will build, co-own, and manage the facilities for hydrogen production using natural gas from the Norwegian continental shelf with CO₂ capture and storage. In excess of 95% of the CO₂ captured will be safely and permanently stored beneath the Norwegian offshore seabed. The objective is to construct a facility in the Eemshaven industrial area capable of producing low carbon hydrogen by 2029 with onshore hydrogen pipelines set to be commissioned in both the Netherlands and Germany.

KEY DATA

TRL	9	Capture Rate Range (tpd)	100 - 10,000+	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	10 - 80 mol%	System Energy (kWh/tCO ₂)	30 - 300	Specific (Regen.) Energy (kWh/tCO ₂)	40 - 400*
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	~
Target Industries	Cement & lime, hydrogen, oil & gas, (petro-)chemical, iron & steel				

* Based on CO₂ product battery limit pressure of 7 barg

TECHNOLOGY DESCRIPTION

HISORP® CC – CO₂ CAPTURE FOR BLUE HYDROGEN PRODUCTION

The toolbox approach of HISORP® CC shows its advantages for the production of blue hydrogen with steam-methane reforming (SMR), autothermal reforming (ATR), partial oxidation (POX), or gasification. By optimally combining pressure-swing-adsorption (PSA), temperature-swing-adsorption (TSA), HISELECT® membranes, compression, and cryogenic purification, hydrogen recovery is maximised with minimal carbon intensity. HISORP® CC can be retrofitted to existing SMRs and ATRs and applied in the syngas or the tail gas route of the H₂ PSA. Alternatively, for new-build ATR and POX reactors, HISORP® CC is used for carbon capture in the tail gas route, providing reliability and availability, and enhancing H₂ production while reducing specific energy consumption for CO₂ removal.

Highlights

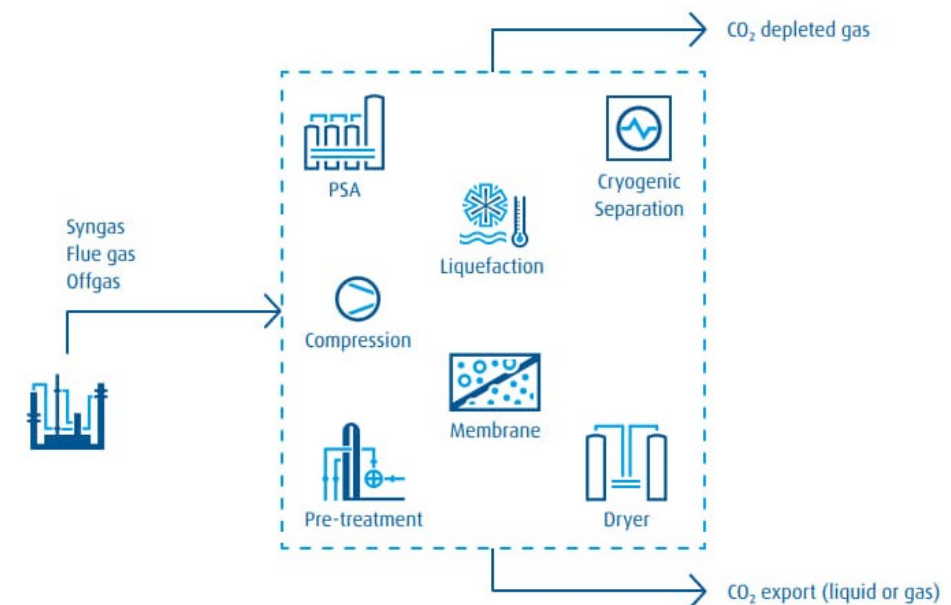
- Linde's in-house technologies are combined for blue hydrogen production, including PSA, TSA, HISELECT® membranes, and cryogenic purification
- Individual concepts for different feed streams in hydrogen production plants
- Flexibility in size and scale, ranging from 100 to more than 10,000 tpd CO₂
- CO₂ capture rate of more than 99.5% with potential for increased hydrogen production

HISORP® CC – CO₂ CAPTURE FROM CO₂-RICH FLUE GASES AND OXYFUEL PROCESSES

A large portion of industrial CO₂ emissions are released through flue gases at atmospheric pressures, often carrying a high CO₂ concentration of more than 15%, making them a perfect fit for HISORP® CC. This is particularly relevant for hard-to-abate CO₂ sources, such as flue gases from cement and lime production, and for flue gases from steel production via the blast furnace or direct reduction route, flue gases of SMR for hydrogen production, and other high-content CO₂ streams from oxyfuel processes. Flue gases often contain a high amount of various trace impurities, such as NO_x, SO_x, O₂, volatile organic compounds, aldehydes, and heavy metals that require special treatment steps. In these applications, HISORP® CC core equipment (PSA, TSA, compression, cryogenic purification) is combined with advanced traces impurity treatment and direct-contact cooling (DCC), and CO₂ is captured and purified in accordance with common CO₂ specifications for sequestration, like Northern Lights or Aramis.

Highlights

- Combines Linde's in-house technologies for carbon capture from CO₂-rich flue gases: tailored and advanced impurity removal steps, PSA, TSA, and cryogenic purification
- Individual HISORP® CC concepts for different flue gas sources with flexibility in size and scale from around 100 to more than 10,000 tpd CO₂
- CO₂ capture rate ranging from typically 95% up to 98% from CO₂-rich flue gases and oxyfuel processes
- Includes advanced pre-treatment for trace impurity removal (e.g., NO_x, SO_x, heavy metals) from flue gases



The Linde HISORP® CC toolbox



LINDE

RECTISOL WASH UNIT

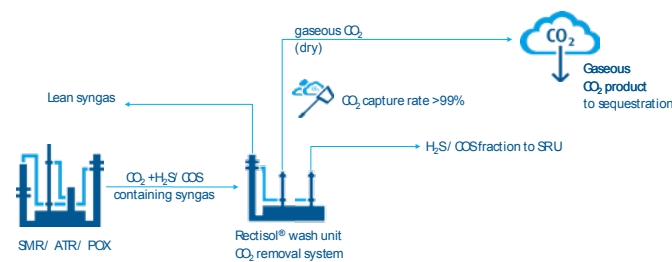


SUMMARY

Linde's Rectisol wash unit is able to extract sour gas from syngas. The technology has been proven over decades and is adjustable to the actual needs and requirements of plant operators. The process can handle feed gases from different sources and adjust the CO₂ purity in the treated gas with respect to requirements from downstream units. Rectisol technology is used for selective removal of CO₂ and sulphur. The process can be designed for CO₂ capture, where about 99% of the incoming CO₂ can be captured Sulphur and water free. The sulphur is enriched in the acid gas fraction, which can, for example, be routed to a sulphur recovery unit (SRU). Linde's Rectisol Wash Unit can be integrated with other Linde gas processing technologies, e.g. downstream cryogenic processes (e.g. CO production), the Linde Ammonia Concept LAC™, or with PSA units.

HIGHLIGHTS

- State-of-the-art process
- Used for the treatment of feed-gases containing sulphur and CO₂
- Treated syngas (Sulphur < 0.1 vppm, CO₂ adjusted, water free)
- Water- and sulphur-free CO₂ product for further processing
- Capacities from small-scale plants (30,000 Nm³/h feed gas) up to high one-train capacity plants (2,000,000 Nm³/h feed gas)
- Application pressure from 20 up to 80 bar and higher
- Easy solvent handling (chemically stable, low cost, and readily available on the market)
- Enhanced trace component handling
- Low product losses (H₂ and CO)
- The sulphur-rich tail gas from the SRU can be deSulphurised within the Rectisol Wash Unit without the need of an additional wash system and additional equipment

Typical Rectisol process design for CO₂ capture from syngas

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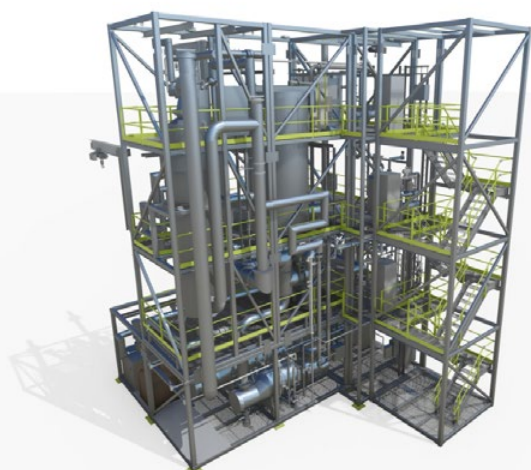
KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~99%
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~100	Number of Pilot Plants	~	Modular (Y/N)	No
Target Industries	Syngas				



MANTEL

CARBON CAPTURE



SUMMARY

Mantel Capture, Inc. is pioneering a new class of high-temperature carbon capture technology using molten salts. Mantel's molten borate technology captures CO₂ at high temperatures (600-800°C), the conditions found inside boilers, kilns, and furnaces. This allows for efficient energy recovery through steam production, making it a good fit for any industrial site utilising steam, heat, or electricity. By reducing capture costs more than 50% compared to conventional methods, the system is ideal for decarbonising hard-to-abate industrial sectors, including power generation.

Mantel's technology is modular, scalable, and designed for seamless integration with existing industrial infrastructure. The company is currently demonstrating this breakthrough technology in its 2,000 tpa project in Quebec, proving its commercial viability and setting the foundation for broader deployment.

BENEFITS

- **Lower Cost:** Compared to incumbent carbon capture technologies, Mantel's systems reduce levelised costs of capture, compression, transport and storage by more than 50%.
- **Compact footprint:** Mantel's system is approximately half the footprint of an amines system due to its compact absorber and ability to operate without flue gas pre-treatment or CO₂ post treatment.
- **Minimal energy demand:** The system has a capture penalty of 0.1 GJ per tonne of CO₂ capture, generating steam with efficiencies comparable to industrial boilers. This allows facilities to maintain near-full energy output with minimal parasitic load.
- **High-Purity CO₂ Output:** The process produces bone-dry CO₂ at high purity, making it suitable for storage or utilisation applications without additional processing.

KEY PROJECTS

- **Pulp & Paper Demonstration:** This project is located at Kruger's Wayagamack paper mill in Trois Rivières, Quebec. Phase I, captures 2,000 tpa and generates 1 MWth of steam for the mill. A planned Phase II will capture from the site's lime kiln and increase capture capacity up to 4,000 tpa.
- **Oil & Gas Deployment:** A 60,000 tpa project generating 10 MWth of steam for Steam Assisted Gravity Drainage (SAGD) at an upstream oil & gas site in Canada has entered the Front-End Engineering Design (FEED).
- **Feasibility Studies:** Mantel is conducting feasibility studies for carbon capture systems across a wide range of industries and geographies including power generation, refineries, and chemicals.

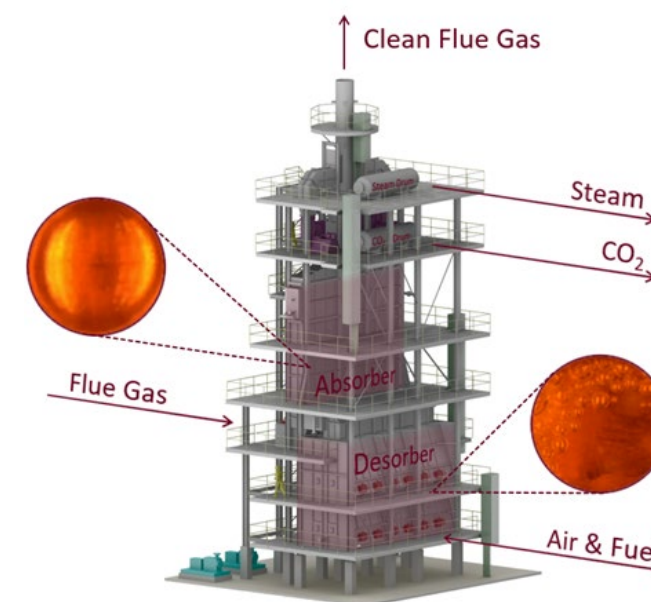
KEY DATA

TRL	7	Capture Rate Range (tpd)	150 - 5,000+	Capture Efficiency (%)	95 - 99%
Source CO ₂ Purity Range	1 - 40%	System Energy (GJ/tCO ₂)	0.1	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	1	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Power Generation, Pulp & Paper, Oil & Gas, Steel, Cement, Chemicals, Hydrogen, Other Hard-to-decarbonise				

THE ONLY HIGH-TEMPERATURE, LIQUID PHASE CAPTURE PROCESS

Molten borates are a newly discovered class of materials for carbon capture. The distinct feature of these materials is that they are liquid phase at high temperatures (600 - 800°C), making them capable of efficiently capturing CO₂ at the conditions found inside boilers, kilns, and furnaces. The improved efficiency of high temperature operation comes from utilising the heat of reaction. Capturing CO₂ generates a large amount of energy, as absorption and adsorption are exothermic processes. CO₂ capture can occur at low temperatures after heat recovery or at high temperatures before heat recovery. Low temperature capture is inefficient because heat is consumed during regeneration, and the energy generated on capture is wasted, as it is low quality heat. For high temperature CO₂ capture, energy is required for regeneration, but the energy generated on capture can be efficiently recovered as high-quality heat and passed through the heat recovery section to generate steam. Mantel is proving that energy and cost savings can go hand in hand. Mantel's system captures CO₂ while recovering valuable process heat as clean steam, creating a closed energy loop where nothing is wasted.

Past attempts to leverage this high-temperature benefit have been limited by the use of solid materials. Unlike solid-phase sorbents, Mantel's molten borates do not suffer from sintering or performance degradation over repeated cycles and have demonstrated over 1000 cycles with less than a 0.1% change in performance. This inherent durability ensures that the molten borate materials consistently deliver stable performance, providing reliable and long-term carbon capture capability. By combining high temperature and liquid phase operation, Mantel's molten borates enable new process designs that increase thermal efficiency 50x, and reduce the cost of carbon capture and storage by more than 50%.



INDUSTRIAL IMPLEMENTATION AND PLANT-LEVEL BENEFITS

At the plant level, Mantel's technology offers significant operational advantages over traditional carbon capture systems, enabling simpler and more cost-effective integration into industrial sites. One major benefit is reducing the incremental thermal energy requirement typically associated with carbon capture. Mantel's system directly burns fuel and captures CO₂ simultaneously, integrating both carbon capture and steam generation into a single, efficient unit. By generating steam at efficiencies comparable to conventional industrial boilers, Mantel's system imposes nearly zero additional energy demand on the host facility. This dual-function capability enables industrial plants to reduce reliance on existing boiler equipment. Facilities could eliminate or place approximately one-third of conventional boilers into standby, maintaining fuel consumption and steam generation, while lowering maintenance expenses, and minimising equipment wear, thus providing significant operational flexibility and substantial cost savings. Alternatively, power generation facilities could even increase energy output while achieving near full decarbonisation. With this unique dual-purpose functionality as both a CCS system and a steam boiler, facilities can achieve significant emissions reductions without sacrificing efficiency.

Mantel's unique operations also allow for significantly streamlined plant integration and smaller footprints. The high-temperature absorption process eliminates the need for extensive flue gas pre-cooling & pretreatment equipment required by conventional carbon capture technologies. Further, molten borates exhibit high tolerance to impurities, eliminating the need for pre-capture SO_x and NO_x scrubbing. Additionally, Mantel's system directly produces high-purity CO₂, compatible with transport, storage or utilisation requirements, eliminating the need for post-capture purification, which typically involves additional equipment and energy-intensive processes like dehydration and removal of residual gases. Additionally, the increased reaction efficiency at elevated temperatures allows for significantly smaller core absorption equipment, typically an order of magnitude smaller than half the size of comparable amine-based systems.

The streamlined nature of the Mantel system results in fewer components, simpler maintenance, and lower overall operating complexity. These plant-level benefits not only decrease initial investment costs but also substantially reduce long-term operational costs, ensuring Mantel's solution remains economically attractive for diverse industrial applications.



MITSUBISHI HEAVY INDUSTRIES

KM CDR PROCESS™ / ADVANCED KM CDR PROCESS™



SUMMARY

KM CDR Process™/ Advanced KM CDR Process™ is an amine-based CO₂ capture technology for post-combustion flue gas developed jointly by Mitsubishi Heavy Industries (MHI) and The Kansai Electric Power (KEPCO). It is a robust and commercially proven technology that features a unique absorbent with low regeneration energy and low degradation and emissions. MHI has provided the KM CDR process™ for industrial and power projects on varying flue gases since 1999. Up to now, MHI has provided licensing, engineering, and/or full EPC services for 18 commercial KM CDR Process™ /Advanced KM CDR Process™ projects all over the world, with two more units under construction. MHI's technology has been proven and used on natural gas, fuel oil, and coal-fired flue gas. MHI is working to expand the application of this technology to various power generation facilities such as Diesel engine, and Biomass fired boilers, as well as industrial plants such as cement, steel, pulp and paper, Oil & Gas, and Waste to Energy, and marine engines.

BENEFITS

- **Commercially Proven:** Used on Natural gas, Heavy oil, and Coal-fired flue gas for many purposes such as Urea, Methanol, EOR and other general usage.
- **Environmentally Friendly:** Improved amine emission reduction system significantly reduces amine emissions compared to conventional systems.
- **Flexible to Gas Load:** Proprietary Auto Load Adjustment Control (ALAC) system quickly and smoothly ramps CO₂ production.
- **Updated Technologies (KS-21™):** Reduced OPEX by lowered amine degradation. Reduced amine emission by stabilised solvent.

KEY PROJECTS

- **Petra Nova (2016):** Used to enhanced oil recovery in U.S. oil fields. CO₂ capture from coal fired power plant flue gas (capacity: 4,776 t/d). Delivered to the U.S. for the first time. One of the largest delivery records in the world.
- **Ravenna CCS (2024):** Used for injection into a depleted offshore gas field owned by Eni. CO₂ capture from gas turbine (capacity: 89 t/d) delivered to Europe for the first time.
- **Bangladesh Chemical Industries (2024):** Used to increase production at a urea plant in Bangladesh. CO₂ capture from SMR natural gas-fired combustion flue gas (capacity: 240 t/d). First delivery of Advanced KM CDR Process™.
- **Heidelberg Materials UK's Padeswood (2025):** Used for injection into depleted gas fields beneath Liverpool Bay. UK's first CO₂ capture plant for the cement facility (Capacity 2,700 t/d)

KEY DATA

TRL	9	Capture Rate Range (tpd)	100 - 5,000*	Capture Efficiency (%)	>90%
Source CO ₂ Purity Range	<1 - >30%	System Energy (GJ/tCO ₂)	ND	Specific Regen. Energy (GJ/tCO ₂)	ND
Number of Commercial Plants	20	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Power, Biomass, LNG Liquefaction, Refinery, Cement, Steel, Waste to Energy, Pulp & Paper, Shipping				

* No restrictions from under 1 ton to over tens of thousands

KM CDR PROCESS™ OVERVIEW

The KM CDR Process™ has been developed for more than 30 years. In 1991, the first pilot plant (2 t/d) was installed at the Nanko Power Station of KEPCO, and the first plant (210 t/d) for SMR flue gas of Petronas' fertiliser plant was delivered in 1999.

After that, a 1 t/d pilot plant was installed in the MHI's R&D Center (2002) with the aim of applying it to the flue gas of coal-fired boilers. Following the durability demonstration tests at 10 t/d (2006-2008) and 500 t/d (2011-2015) in 2016, then the world's largest CO₂ capture plant (4,776 t/d) was delivered for the CO₂-EOR project in Texas, USA.

KM CDR PROCESS™ FEATURES

Low Regeneration Energy

MHI and KEPCO have developed a proprietary amine solvent (KS-1™) that features low regeneration energy and enables an energy-saving regeneration process by optimizing heat exchange between the absorption and regeneration towers, resulting in a significant reduction in energy consumption.

Amine Emission Reduction System

Some flue gas contains aerosols such as SO₃ ammonium sulfate and others which increase the loss of solvent. We have reduced the loss of solvent significantly compared with the conventional system by applying an original emission reduction system.

Automatic Load Adjustment Control System

The proprietary Automatic Load Adjustment System (ALAC) enables the capture rate to change quickly. Even if the CO₂ concentration in the flue gas greatly fluctuates, the rated CO₂ capture rate and capture amount can be maintained under optimum steam consumption.

Long-Term Commercial Operation

Since the first machine was delivered in 1999, the machine has been in commercial operation for more than 20 years. It is used to capture CO₂ from natural gas, heavy oil, and coal-fired flue gas for general industrial applications such as urea, methanol, and EOR.

ADVANCED KM CDR PROCESS™ FEATURES

MHI and KEPCO have developed a new solvent, KS-21™, for the purpose of saving energy and reducing amine emissions. A pilot test at Nanko Power Station in 2019, and a durability demonstration test was conducted at TCM in Norway in 2021. The process performance was evaluated and data necessary for the environmental impact assessment were obtained. As a result, superior energy-saving performance, and solvent durability with lower amine emissions than KS-1™ were confirmed.

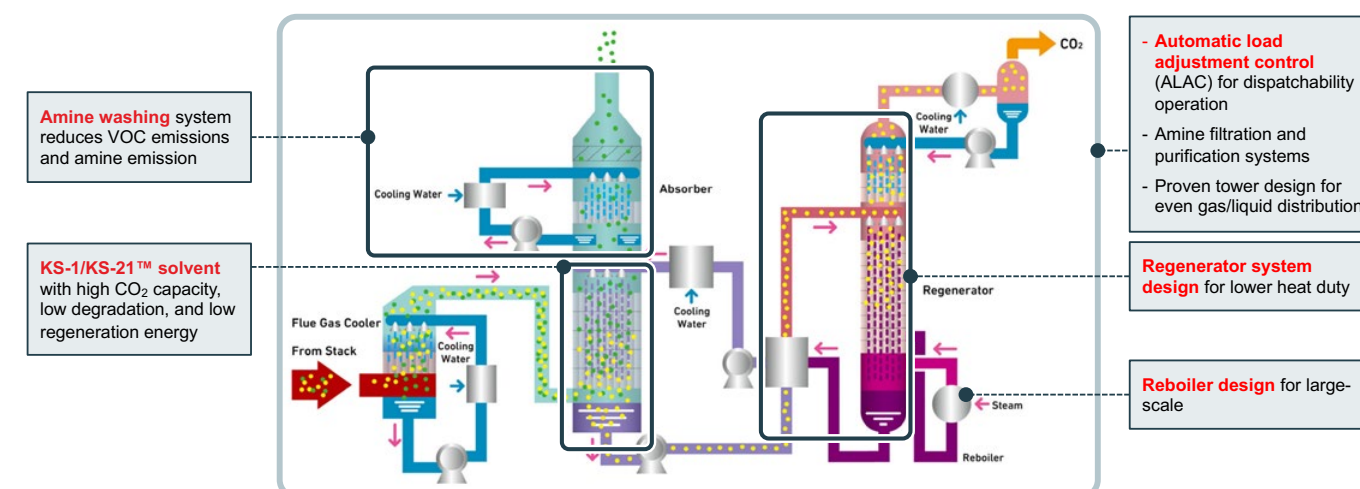
Parameters Relative to KS-1™	KS-1™	KS-21™
Volatility	100	<70
Thermal Degradation rate	100	<50
Oxidation rate	100	<50
Heat of absorption	100	Slightly lower

PROSPECTS FOR FUTURE

In 2022, ExxonMobil and MHI have formed a technology alliance to deploy MHI's leading CO₂ capture technology as part of ExxonMobil's end-to-end carbon capture and storage (CCS) solution for industrial customers. At present, various development programs are underway, and new improved technologies will be provided soon.

COMPACT CO₂ CAPTURE SYSTEM: CO₂IMPACT™ SERIES

The model adopts a mass-produced full-module concept based on standard design for decarbonisation of a wide range of industries as a middle size class.





SUMMARY

NX CryoCOOL™ is NextChem's solvent-free carbon capture and purification technology, developed to address CCS applications at various CO₂ feedstock concentrations. Based on a hybrid process combining cryogenic separation and physical adsorption, NX CryoCOOL™ enables the recovery of CO₂ as a high-purity stream, suitable for direct liquefaction, transport, or permanent storage.

Within the CCS value chain, NX CryoCOOL™ is positioned as a separation-driven solution that integrates capture, purification, and conditioning within a single process configuration also allowing for high efficiency liquefaction if needed. Fully electrified by design, NX CryoCOOL™ reduces process complexity compared to conventional solvent-based systems and expands the range of viable decarbonization pathways for CO₂-rich industrial gas streams.

BENEFITS

- **Solvent-Free and Fully Electrified Capture:** Solvent-free and fully electrified NX CryoCOOL™ eliminates solvents and steam regeneration, integrates low-carbon power, and achieves competitive power-per-ton CO₂ capture efficiency.
- **Integrated Capture, Purification and Conditioning:** NX CryoCOOL™ integrates CO₂ separation, purification, and conditioning within a single cryogenic process configuration, enabling direct delivery of a high-purity CO₂ stream for downstream handling.
- **Flexible CO₂ Product Delivery:** NX CryoCOOL™ delivers CO₂ in gaseous or liquid phase at battery limit, enabling flexible integration with transport, storage, or utilization infrastructures.
- **Operational Flexibility:** NX CryoCOOL™ can be adapted to different feed conditions and compositions by integrating the core system with the required conditioning sections.

KEY PROJECTS

- **Hail & Ghasha:** Following final investment decision, the Hail & Ghasha project is under construction as a large scale low carbon gas development incorporating CO₂ capture and management, with NX CryoCOOL™ referenced as a cryogenic CO₂ separation solution for CO₂ rich gas streams.



Hail & Ghasha offshore gas development under construction (image courtesy of ADNOC).

KEY DATA

TRL	9	Capture Rate Range (tpd)	>400	Capture Efficiency (%)	>95
Source CO ₂ Purity Range	>15	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	100 - 400
Number of Commercial Plants	1	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	~				

TECHNOLOGY OVERVIEW

NX CryoCOOL™ uses a two-stage separation concept that combines CO₂ pre-concentration via adsorption with cryogenic purification to produce a CO₂ stream suitable for downstream handling.

By coupling adsorption-based bulk separation with cryogenic purification in a single process scheme, partnering on the collaboration with Linde, NX CryoCOOL™ enables an integrated pathway from CO₂-rich gases to a high-purity CO₂ product, deliverable in gaseous or liquid phase depending on project requirements and downstream logistics.

SYSTEM FLEXIBILITY ACROSS DIFFERENT FEED GASES

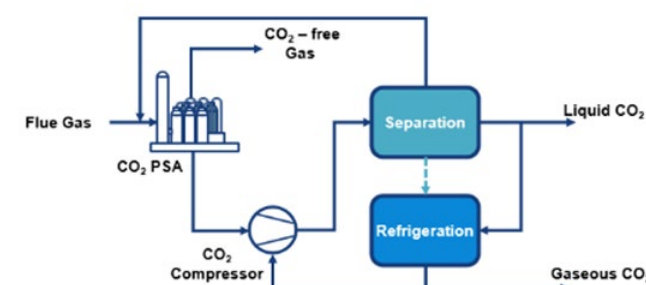
NX CryoCOOL™ is designed as a highly flexible CO₂ capture system that can be easily adapted to treat different types of gas feeds with minimal modifications. Thanks to its modular layout and robust separation concept, the same core process can be applied to flue gas, syngas, and tail gas streams.

FLUE GAS APPLICATIONS

When applied to flue gas, NX CryoCOOL™ treats large volumes at low CO₂ loads (from 15%mol CO₂).

In the adsorption section, the incoming CO₂-rich gas is conditioned and sent to a dedicated PSA units, where CO₂ is selectively captured. This step generates a concentrated CO₂ stream (with a recovery >95%), while the remaining gas is discharged as treated gas. Pre-concentration is essential because it reduces the gas flow to the cryogenic section, maximizing energy efficiency.

In the second stage, the CO₂-rich stream is routed to an integrated cryogenic section that removes light impurities and upgrades the CO₂ to specification through controlled cooling and phase-change separation. NX CryoCOOL™ leverages a self-refrigerated cryogenic concept, using CO₂ as the working refrigerant to avoid external refrigerants and maintain a compact, electrified process architecture. Appropriate gas conditioning is included to ensure stable cryogenic operation and CO₂ can be recovered either in liquid or gaseous phase.

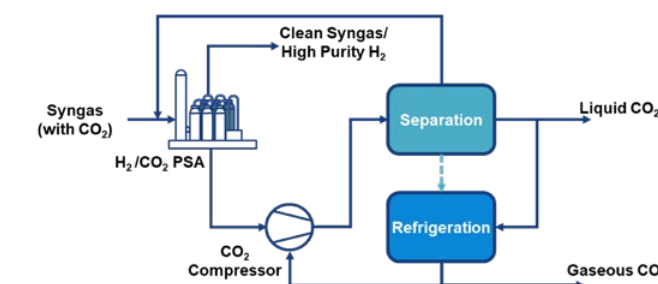


SYNGAS APPLICATIONS

For syngas applications, NX CryoCOOL™ is capable to operate as a pre-combustion carbon capture. NX CryoCOOL™ treats the raw syngas stream to selectively separate CO₂ from H₂, coupling H₂ and CO₂ PSA units, delivering a CO₂-rich stream to the subsequent cryogenic separation at elevated pressure and Clean Syngas/High Purity H₂ according to plant requirements.

The CO₂ gas stream is compressed to the optimal pressure range and directly routed to the cryogenic separation section, where CO₂ is purified and liquefied if needed.

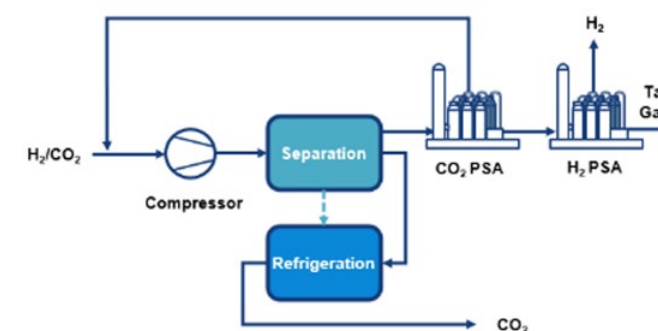
This configuration enables efficient separation and purification of CO₂, delivering a liquid product compatible with common transport specifications, while minimizing syngas losses.



TAIL GAS APPLICATIONS

In the tail gas configuration, NX CryoCOOL™ processes streams mainly composed of CO₂ and hydrogen.

The pressurised feedstock is further compressed and sent to the cryogenic separation section, where CO₂ is liquefied and recovered. The CO₂ is then vaporised and flashed to provide the needed frigorities. Later it is delivered as the principal product. Downstream, the CO₂ PSA generates a CO₂ rich stream, which is recycled within the process, and an H₂ rich stream, which is routed to a dedicated H₂ PSA unit. In this section, hydrogen is recovered, while the CO₂ product is recycled to meet the required specifications. This configuration enables effective recovery of both CO₂ (>95%) and hydrogen (>80%) while maintaining a simple and flexible process layout suitable for variable tail gas compositions. The process is fully electrified and characterised by high energy efficiency.



NEXTCHEM

NX DECARB™



SUMMARY

MAIRE, through NEXTCHEM and its Integrated E&C arm, offers a uniquely integrated approach to carbon capture, combining proprietary process technologies with proven EPC execution. NEXTCHEM's NX Decarb™ portfolio delivers advanced solutions for CO₂ capture, while MAIRE brings decades of experience in designing and constructing large, complex industrial plants worldwide. This synergy has enabled the delivery of landmark projects, including Italy's first industrial scale PCCS plant and major net zero gas developments with integrated CO₂ recovery. NX Decarb™ is NEXTCHEM's technological value proposition for post combustion carbon capture integrating third party licensed technologies. NX Decarb™ maximises heat integration and energy recovery to reduce steam demand also by enabling partial or full electrification of the capture system through proprietary energy recovery concepts.

BENEFITS

- **Reducing Utility Consumption:** Cuts utility consumption at source by maximizing heat integration within the capture system, reducing reliance on external energy utilities and improving the economic viability of CCS projects.
- **Increasing Heat Recovery:** Increases heat recovery through advanced system-level integration, turning available thermal energy into a valuable resource to enhance overall carbon capture efficiency.
- **Amine Carbon Capture Electrification:** Enables electrification of amine carbon capture, eliminating CO₂ emissions from steam generation and enabling integration with low-carbon electricity.
- **Flexible & Retrofit-Ready Deployment:** Enables retrofit-ready carbon capture, reducing implementation risk and accelerating deployment across existing industrial plants.

KEY PROJECTS

- **ENI Casal Borsetti:** Delivered South Europe's first CCS demonstration plant at Casal Borsetti, recovering waste heat via HRSG to enable CO₂ capture from gas compression exhaust and permanent offshore storage.
- **NFL Vijaipur:** Delivered an EPC LSTK post-combustion CO₂ recovery unit at NFL Vijaipur, India, capturing 160 KTPA of CO₂ to support fertiliser production.
- **Marcegaglia Ravenna:** Delivered FEED for the AdriaticCO₂ CCS project, integrating an Energy Recovery System to reduce energy demand and improve CO₂ conditioning efficiency for transport.
- **GPIC Sitra:** Delivered an EPC LSTK post combustion CO₂ recovery plant at GPIC Sitra, Bahrain, completed on a fast track schedule of 27 months with zero lost time accidents.

KEY DATA

TRL	9	Capture Rate Range (tpd)	100 - 5,000	Capture Efficiency (%)	>95
Source CO ₂ Purity Range	>1	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	6	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Power, Biomass, LNG Liquefaction, Refinery, Cement, Steel, Waste to Energy, Pulp & Paper, Shipping				

TECHNOLOGY OVERVIEW

NX DECARB™ is NEXTCHEM's integrated solution for post-combustion carbon capture, combining a proven amine-based CO₂ capture technology with advanced energy-efficiency and heat-integration systems. Rather than a standalone capture unit, NX DECARB™ is designed as a platform that integrates carbon capture with energy optimization to improve overall plant efficiency and operability.

The core of NX DECARB™ is a third-party licensed amine absorption process, based on the absorber–regenerator configuration widely recognised as the most mature and reliable solution for post-combustion CO₂ capture. This core technology enables high capture efficiencies from low-pressure flue gas streams generated by gas compression, refining, fertilisers, cement, and other hard-to-abate sectors.

What differentiates NX DECARB™ is the systematic integration of proprietary and tailored auxiliary systems aimed at maximizing energy recovery and minimizing operating costs. These include optimised flue gas conditioning, advanced heat exchangers, and dedicated energy-recovery solutions such as Heat Recovery Steam Generator (HRSG) systems and its proprietary Energy Recovery Systems (ERS). By valorizing waste heat from hot exhaust gases and improving thermal integration within the capture process, NX DECARB™ significantly reduces steam demand and overall energy intensity.

Through the combination of a selection of a robust amine capture core and advanced energy-efficiency solutions, NX DECARB™ enables industrial-scale decarbonization projects that are both technically solid and economically optimised.

ENERGY PERFORMANCE

Energy consumption represents the main barrier to the large scale deployment of post combustion carbon capture, particularly in industrial applications where steam demand for solvent regeneration can significantly impact operating costs and plant efficiency. For this reason, NX DECARB™ has been developed with energy performance as a primary design driver, addressing site specific conditions through alternative and flexible energy integration solutions.

NX DECARB™ adopts different energy recovery concepts depending on the characteristics of the flue gas available at battery limits. When high temperature exhaust gases are available, the system can be configured with a Heat Recovery Steam Generator (HRSG) to recover sensible heat and generate steam directly used for solvent regeneration.

This approach allows a substantial reduction—or even elimination—of imported steam, significantly lowering the overall energy penalty of the capture unit, as demonstrated in industrial retrofit applications.

When lower-grade waste heat is available, NX DECARB™ can be configured with dedicated Energy Recovery Systems (ERS).

The ERS is an energy integration solution designed to recover and redistribute this available thermal energy within the carbon capture system, supporting solvent regeneration through optimised thermal coupling of process sections and significantly reducing, or in some cases eliminating, reliance on external energy utilities.

These systems focus on maximizing heat integration within the capture process and between the capture unit and the host facility, improving thermal efficiency and reducing specific regeneration energy without relying on direct steam generation.

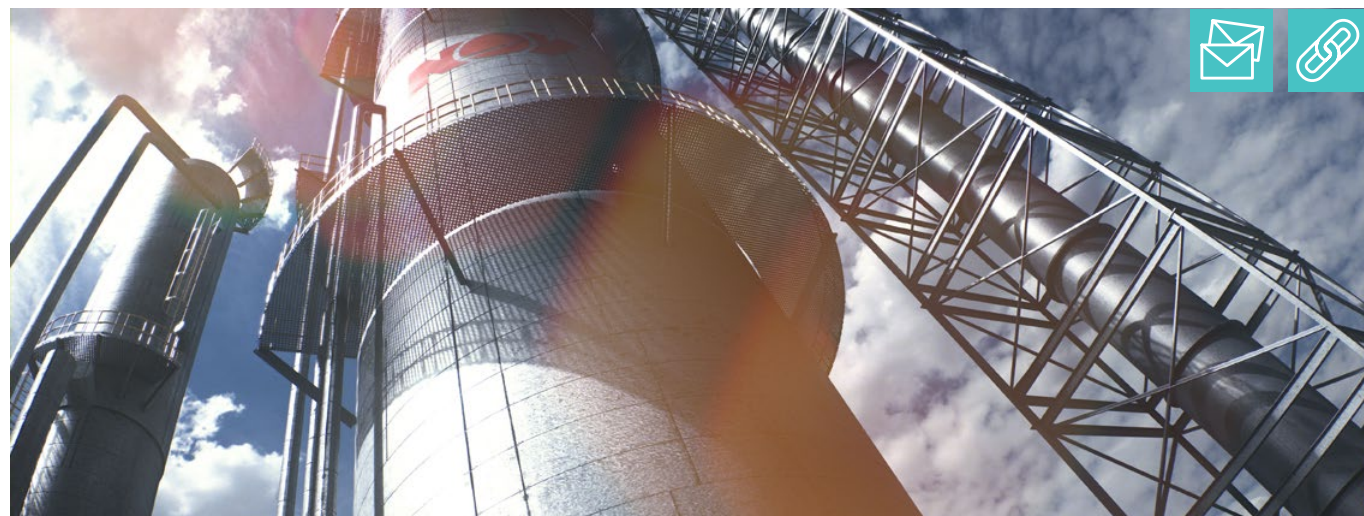
By offering alternative energy integration schemes tailored to site specific conditions, NX DECARB™ enables optimised CCS deployment across a wide range of industrial configurations, from retrofits to large-scale hub-and-cluster developments.



NX DECARB™ industrial application - Energy integrated post combustion carbon capture at the Casal Borsetti site (Italy) (image courtesy of ENI)



NOV – CO₂ CAPTURE AND CONDITIONING CAPTURE



SUMMARY

Carbon capture, utilisation, and storage (CCUS) is essential for meeting emission targets, allowing industries to continue vital processes with reduced environmental impact. Safety in CO₂ handling during transportation and storage is critical. We enhance and re-purpose oil and gas technology and expertise for the energy transition. NOV supports carbon capture projects with technologies like CO₂ conditioning and fiberglass ducting for flue gas gathering, ensuring optimal capture and corrosion protection. We help our customers to select the best capture technology and verify CO₂ volumes for carbon offset and tax credit reporting.

NOV's Process Systems group provides leading technologies for oil, gas, and water treatment. With decades of global expertise, we design and execute custom carbon capture and CO₂ conditioning systems. As your corrosion protection partner, we offer flexibility and optimal project economics through our global presence and experience.

BENEFITS

We are a one-stop shop, offering capabilities to support throughout the entire value chain. These benefits include:

- Established execution and global supply chain models featuring local, low-cost fabrication and decreased delivery times
- Experience in standardised systems and equipment packages to drive efficiency
- Precision with large-scale projects mitigates risk and lowers costs associated with engineering design and project management
- Research and development activity to keep customers involved with the latest CCUS technology advancements



KEY DATA

TRL	9	Capture Rate Range (tpd)	68 - 2,700	Capture Efficiency (%)	90 - 95%
Source CO ₂ Purity Range	4 - 25%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	All CCUS applications				

Our post combustion carbon capture portfolio offerings vary from fully customisable and bespoke solutions, providing a wide range of design flexibility for demanding applications, to a more standard modular offering, reducing the amount of stick build required on-site to enable faster deployment of carbon capture. We offer proprietary amine-based solvent carbon capture technology for post combustion applications. Other solvents can be assessed for use based on client needs.

The following product offerings provide carbon capture systems tailored for efficient application of size and flexibility.

POST-COMBUSTION CAPTURE PRODUCT OFFERINGS

Summit Solution™ Offering



Our Summit Solution provides a full range of design flexibility to meet demanding applications with CO₂ emissions of up to 1 Mtpa utilising solvent-based technology. This offering allows for full integration to maximise the existing capacity of support systems and reduce operating costs. Furthermore, the footprint and orientation of equipment can be specifically designed to meet more challenging settings.

Peak Solution™ Offering



Our Peak Solution provides a limited range of design flexibility to decrease project time and cost. This offering allows for product size ranges to match site requirements and provides flexibility to integrate with existing plant utilities and support systems.

It's tailored to applications ranging from 50,000 - 200,000 ktpa of CO₂ emissions utilising solvent-based technology. Additionally, the footprint and orientation of equipment can be specifically designed to meet site requirements.

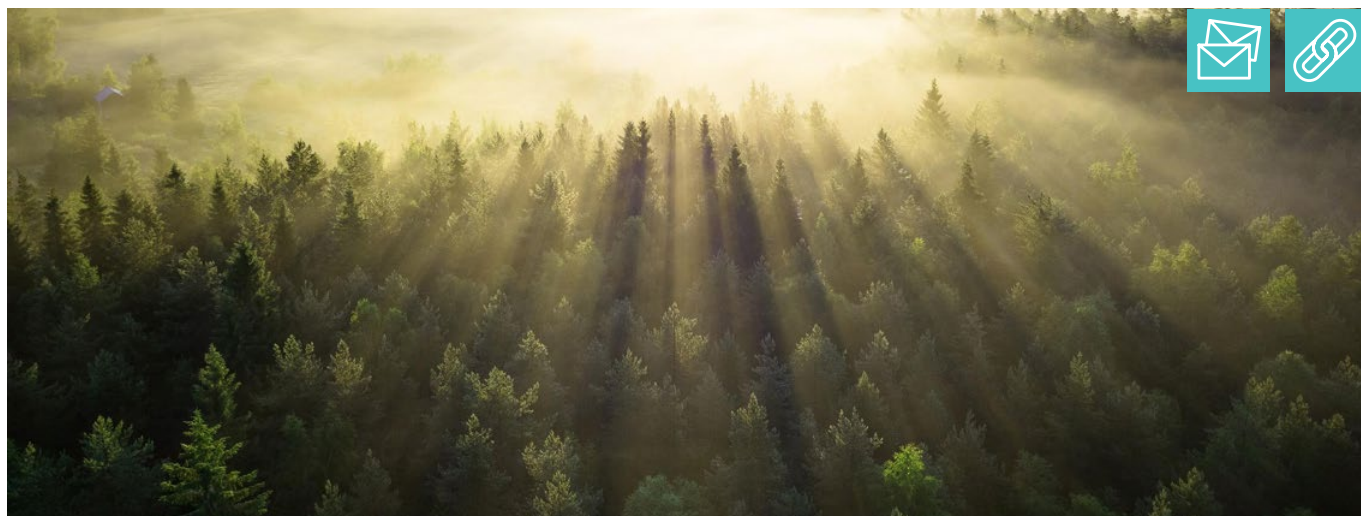
Ascent Solution™ Offering



Our Ascent Solution uses standardisation and technologies best suited to client needs. The offering utilises a proprietary amine-based solvent carbon capture technology for post combustion applications to meet gas capacities between 25 and 70 ktpa of CO₂. This set of standardised solutions can fit site needs while decreasing project time and cost.

NOVONESIS

ENZYMATIC POST-COMBUSTION CARBON CAPTURE



SUMMARY

At Novonesis, we harness the incredible power of enzymes for effective and sustainable carbon capture. Enzymes are one of our planet's tiniest yet mightiest agents of change. When we leverage their power with science, we create biosolutions that transform the way we all produce, consume and live.

For millions of years, nature has controlled CO₂ using enzymes known as carbonic anhydrases. These efficient biocatalysts facilitate the conversion of gaseous CO₂ into water-dissolved bicarbonate, and vice versa. Each enzyme molecule enables 1,000,000 catalytic reactions per second, until equilibrium is reached between gaseous CO₂ and dissolved bicarbonate.

Novonesis and Saipem have united to provide carbon capture solutions based on enzyme technology. Saipem has developed the enzymatic process, including the enzyme, and brings over 60 years of EPC expertise for carbon capture processes and equipment. Novonesis produces and supplies the enzymatic solution for large-scale use, ensuring a cost effective and reliable enzyme supply.

BENEFITS

Enzymatic carbon capture is **reliable**

- Requires less equipment, lowering the risk of potential downtime
- Involves no prototype equipment – everything is built at scale
- Avoids the risk of more stringent regulatory requirements

Enzymatic carbon capture is **efficient**

- Yields high purity CO₂ (≥ 99%)
- Can capture > 95% of CO₂ in flue gas
- Runs on less costly, low-grade residual heat
- Involves less equipment to build, operate and maintain
- Higher tolerates flue gas contaminants

Enzymatic carbon capture is **sustainable**

- Uses a non-toxic, biodegradable solvent
- Produces no toxic waste and forms no toxic aerosols



KEY DATA

TRL	8	Capture Rate Range (tpd)	200+	Capture Efficiency (%)	95%
Source CO ₂ Purity Range	5%+	System Energy (GJ/tCO ₂)	0.55	Specific Regen. Energy (GJ/tCO ₂)	*
Number of Commercial Plants	1	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Suitable to all industries with post-combustion emissions of any kind, especially to sites that have access to low-grade residual or geothermal heat above 85°C				

* Specific Regen. Energy varies with CO₂ concentration in flue gas (Hot utility at 85°C, no steam required)

BIOSOLUTIONS MAKES BUSINESS BETTER

Novonesis already helps more than 30 different industries boost efficiency and sustainability with biosolutions. Biosolutions enable the production of more and better products with fewer resources while helping to address key global challenges such as healthier lifestyles, balanced food systems, and climate change. They have the potential to reduce global CO₂ emissions by approximately 4,300 million tonnes by 2030, equivalent to 8% of global emissions.

Novonesis and Saipem's unique partnership combines Novonesis' cutting-edge enzyme production expertise with Saipem's unmatched carbon capture processes and equipment know-how. Saipem supplies the carbon capture process and equipment; we supply the enzymes that optimise the process.

Enzymes are proteins found everywhere in nature that catalyse biological processes by efficiently transforming specific substances. Whether it's humans, plants or microbes, enzymes are the life forces behind making sure every living organism in nature stays alive, functions well, and thrives. We produce our enzymes through fermentation, where microbes generate the enzymes. After fermentation, the enzymes are separated, purified, and concentrated into a solution ready for use.

CHALLENGES IN CONVENTIONAL CARBON CAPTURE TECHNOLOGY

While amine-based carbon capture is a proven process, its reliance on toxic chemicals introduces significant uncertainties. The high temperatures required make the process costly, with amines carrying a 20-30% energy penalty for CO₂ capture. Even with improvements, efficiency gains are expected to reach only 10-20%. The process also generates toxic by-products requiring additional handling, increases equipment and maintenance costs, and poses health risks for workers.

REDEFINING CARBON CAPTURE

This innovative biocatalytic enzyme based technology enables CO₂ energy stripping at lower temperatures, significantly reducing energy consumption, and eliminating need for costly, steam-intensive processes. Instead, it operates with minimal energy input from the plant, leading to up to 20% lower energy costs when waste heat is available.

The enzymatic carbon capture process is very similar to the established post-combustion process – it simply replaces toxic amines with biocatalytic enzymes. And, it requires less equipment.

The novel catalysed solvent solution offers strong chemical stability, non-toxicity, non-volatility and low-grade temperature regeneration.

The catalyst is an enzyme type used by all living organisms to regulate CO₂. Called carbonic anhydrase, this biocatalyst is used in the absorber, along with carbonate. When the flue gas passes through the absorber, the enzyme converts the CO₂ to bicarbonate, binding it in the bicarbonate. When the circulating bicarbonate fluid reaches the stripper, it must be heated to only 75°C to release the CO₂ – rather than the 120-150°C required for amine-based carbon capture.

DEVELOPMENT HIGHLIGHTS

Saipem and Novonesis are offering both “CO₂ Solutions by Saipem” to the market and “Bluenzyme,” a standardised, modular turnkey solution that reduces implementation from 3 years to 1.5 years (see Saipem listing for details). Already being deployed in several projects, Bluenzyme has the potential to make a significant impact in industrial-scale carbon capture.

For instance, **Hera Group** are implementing Italy's first industrial-scale CCS project for a waste-to-energy plant in Ferrara. Using the Bluenzyme™ enzymatic technology, the system will capture 90% of the CO₂ emissions (64,000 tons/year) from one of the plant's two lines and store them in depleted Adriatic gas fields. The process operates at lower temperatures, maximizing energy efficiency by utilizing waste heat and renewable sources. Supported by €24 million from the EU Innovation Fund, the plant is expected to be operational by 2028, contributing to Hera's Net Zero 2050 strategy and advancing scalable CCS applications in hard-to-abate sectors.

Ren-Gas has selected the Bluenzyme™ technology for the carbon capture unit at its Tampere e-methane plant, marking Finland's first industrial-scale post-combustion carbon capture facility. The plant will capture 40,000 tonnes of biogenic CO₂ annually for e-methane production. Bluenzyme™ will reduce the operational complexity for hard-to-abate industrial sectors and is applied to post-combustion emissions from new or existing plants.

ABOUT NOVONESIS

Novonesis is leading the era of biosolutions.

By leveraging the power of microbiology with science, we transform the way the world produces, consumes and lives. In more than 30 industries around the world, our biosolutions are already creating value for thousands of customers and benefiting the planet. Our 10,000 people worldwide work closely with our partners and customers to transform business with biology.

Let's better our world with biology.

NUADA ADSPIRE PROCESS



SUMMARY

Nuada is a carbon capture solutions provider poised to decarbonise heavy industries through Adspire, its next-generation point-source capture technology that redefines carbon capture and addresses the energy, cost, and integration challenges of conventional approaches. The technology combines advanced solid sorbents, named Metal-Organic Frameworks (MOFs), with mature vacuum pressure swing adsorption (VPSA) technology to separate CO₂ from flue gases, using pressure rather than heat. This combination represents a step change in carbon capture innovation and yields a fully electrified process that enables seamless integration and slashes the associated energy penalty by up to 90% compared to incumbent solutions. Adspire has been successfully pilot-tested in cement, biomass, and waste-to-energy facilities and further demonstration projects have been lined up. Nuada is advancing the first commercial application of its proprietary Adspire carbon capture process.

BENEFITS

- **Ultra-Energy-Efficient:** The energy penalty for carbon capture is reduced by up to 90% compared to incumbent solutions, drastically lowering operating costs.
- **Seamless Integration:** A pure end-of-pipe and fully electrified solution that requires no heat or steam. This results in lower balance of plant costs while preserving the autonomous operation of the primary process.
- **Small Footprint:** A compact, low-footprint capture solution driven by high-capacity media and rapid process cycles, enabling reduced equipment costs and a retrofitting option for space-constrained sites.
- **Dynamic Operation:** Rapid capture and release cycles provide flexibility to address operational challenges, such as flue gas fluctuations, or facilitate quick startups and shutdowns.

KEY PROJECT

- **Nuada Scout at Buzzi Unicem:** Nuada built, deployed and successfully tested a pilot plant of 1tpd scale at Buzzi Unicem's cement plant in Monselice, Italy.
- **UNICORN Project:** Nuada deployed and successfully trialed a second pilot plant asset (1tpd) using waste incineration flue gases at the Translational Energy Research Centre (TERC) in Sheffield, United Kingdom.
- **Nuada Scout at enfinium Ferrybridge:** Nuada deploys and operates one of its pilot plants at enfinium's Ferrybridge-1 waste-to-energy facility in West Yorkshire, UK. The project commenced in June 2025 and will run for at least six months.
- **Nuada Scout at MLC Singleton Birch:** Nuada and MLC partnered to pilot Nuada's solution and validate a scalable pathway to net-zero lime production at MLC's Singleton Birch facility in the UK.

KEY DATA

TRL	6 - 7	Capture Rate Range (tpd)	Up to 4,000	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	>5%	System Energy (GJ/tCO ₂)	0.3 - 0.7	Specific Regen. Energy (GJ/tCO ₂)	0.3 - 0.7
Number of Commercial Plants	0	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Cement, Lime, Waste to Energy, Biomass Incineration, Steel, Chemicals, Oil & Gas				

Nuada's patented carbon capture process, Adspire, combines the unique properties of a bespoke MOF sorbent material with vacuum technology. This innovative combination distinguishes Adspire from traditional carbon capture methods that depend on thermal regeneration processes. The weak interaction and absence of chemical bonds between the MOF capture media and CO₂ molecules minimise the energy required for regeneration. Building on this, Nuada engineered a "heatless" process that uses vacuum pressure to regenerate the MOF filters. This innovation drastically reduces the energy penalty for CO₂ separation down to 0.3 GJ per tonne, delivering significant OPEX savings.

Nuada's technology is designed for point-source carbon capture as an end-of-pipe (EoP) solution that can be readily deployed at the back end of industrial processes. During the carbon capture process, the hot CO₂-rich flue gas undergoes initial conditioning, whereby the flue is cooled to super-atmospheric conditions and certain impurities are reduced. The conditioned flue gas is then directed to a bank of compact adsorption columns loaded with the highly selective MOF filter media, where the CO₂ in the flue gas contacts the MOF filter in a unique contacting sequence and selectively adsorbs to its surface. Other gases, such as nitrogen and oxygen, pass through the filters and return to the flue stack. Once the MOF filters are suitably saturated, they are regenerated via vacuum (no heat needed), releasing a high-purity CO₂ stream ready for downstream operations.

DISRUPTIVE INNOVATION, SEAMLESS INTEGRATION

Adspire is a fully electrified EoP process that can be seamlessly deployed at site, permitting autonomous and dynamic operation of both the capture plant and the primary process. By eliminating thermal demands, complex process integration can be avoided which leads to reduced balance of plant costs. The 'solventless' nature of the system further reduces costs by removing fugitive emission control systems and permitting the use of less specialised fabrication materials.

The compact and modular nature of the Adspire process provides an attractive retrofitting option for emitters, particularly with existing sites with spatial restrictions. The profile of the adsorption columns is an order of magnitude lower than solvent absorbers. The potential for standardisation also provides a pathway for rapid, low-cost deployment with flexibility for capacity expansion.

This relative ease of integration combined with the ultra-energy-efficient separation, translates into a substantially lower cost-of-capture.

FROM SUCCESSFUL PILOTS TO COMMERCIAL UNITS

Successful pilot trials in cement, biomass and waste-to-energy sites have demonstrated outstanding capture performance and validated the versatility of Nuada's capture platform. Additional pilot trials at lime and waste-to-energy facilities are planned through 2026/7. Building on these early successes and the inherent scalability of the technology, Nuada is deploying its first commercial-scale MOF-VPSA capture plant at a European energy production facility.





PETRONAS

MEMBRANE BOX CONTACTOR (MBC)



SUMMARY

A KEY TO ACHIEVING NET ZERO TARGETS

PETRONAS, pioneering as the first Oil and Gas company in Southeast Asia to commit to net zero emissions by 2050, introduces a groundbreaking solution in carbon capture technology: the Membrane Box Contactor (MBC). This fully modularised technology seamlessly integrates the strength of solvent-based absorption with the adaptability of membranes. MBC's innovative design boasts a revolutionary 50% reduction in overall volume. More than just its size, the MBC signifies impact, offering new avenues for industries tackling decarbonization challenges, particularly in hard-to-abate sectors. With its compact and flexible nature, MBC empowers companies to scale their carbon capture efforts in line with their decarbonisation ambitions. Implementation is no longer synonymous with daunting infrastructure projects; MBC's swift setup and minimal operational disruption makes carbon capture not only feasible but also accessible, and remarkably cost-effective for industries.

BENEFITS

- **Minimises Overall Carbon Footprint:** MBC's state-of-the-art multi-cartridge membrane contactor modules, achieve an impressive 50% reduction in the overall volume while maintaining high carbon capture efficiency, all within a compact design.
- **Tailored Solutions for Every Need:** MBC offers unparalleled scalability, allowing seamless adjustments to match the unique requirements of our clients. MBC's adaptable nature ensures flexibility by catering to clients' evolving operational needs.
- **Cost-Effective Carbon Capture:** With lower CO₂ compression costs due to solvent regeneration pressure at 5 barg and reduced solvent circulation by up to 30%, MBC delivers competitive capture costs of US\$ 75 per tonne of CO₂, with a target of less than US\$ 50 per tonne of CO₂ by 2030.
- **Innovative and Reliable:** Separation of gas and solvent minimises foaming and chemical use, while differential pressure control improves durability and ensures stable long-term performance..

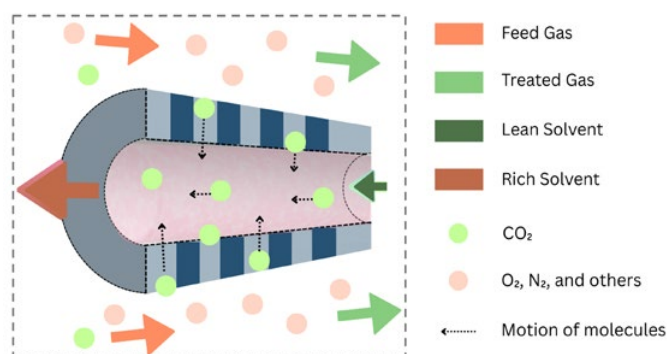


Figure 1: Cross Sectional of Hollow Fibre Membrane in MBC

KEY DATA

TRL	7	Capture Rate Range (tpd)/module	10 - 1,000	Modular (Y/N)	Yes
Source CO ₂ Purity Range	3 - 30%	Energy Consumption (GJ/tCO ₂)	<2.9	Capture Efficiency (%)	>90%
Number of Commercial Plants	~	Number of Pilot Plants	4	Pressure Drop	<0.1 bar
Target Industries	Refineries, Hard-to-abate industries (Cement, Steel, Petrochemicals, Fertilisers and Power Plants)				

Carbon Capture and Storage (CCS) technology plays a critical role in combating climate change. Despite its benefits, widespread adoption faces challenges. Traditional CCS systems require significant space for installation, posing issues for industries with limited land or optimised facilities. Integrating large-scale CCS systems into existing industrial sites can also be costly and disruptive, making it less attractive for many businesses.

PETRONAS' Membrane Box Contactor (MBC) technology is poised to transform the CCS landscape. With over 20 times higher mass transfer area compared to conventional systems, this innovation delivers high efficiency. It enables a compact separation system with a 75% reduction in height, 40% reduction in weight, and 25% lower solvent usage. Beyond physical improvements, PETRONAS' modular technology offers scalability and operational simplicity, addressing challenges such as flooding and foaming.

Its versatility, demonstrated through compatibility with a wide range of solvents, ensures adaptability across different markets. In collaboration with the Dalian Institute of Chemical Physics, MBC enhances CO₂ separation performance, achieving over 90% capture efficiency. It also reduces solvent usage and lowers regeneration energy consumption by 25% compared to conventional amine packed bed column systems.

PETRONAS' proprietary design further reduces CO₂ capture costs through integrated box design, streamlined solvent circulation, and integrated intercooler heat exchanger systems, all optimised for efficiency and cost-effectiveness.

In a landscape where sustainability and economic viability are essential, PETRONAS leads with transformative CCS solutions that set new benchmarks for environmental performance and commercial excellence.

PROCESS DESCRIPTION

The process starts with a conditioning step of the flue gas from the point source emission (3-30% CO₂), whereby the flue gas is cooled down to between 40°C and 60°C via a combination of Waste Heat Recovery Unit (WHRU) and Direct Contact Cooling (DCC) if available where SO_x, NO_x and fine particulates are removed.

As shown in Figure 2, the MBC integrates key units such as the DCC, absorber, and water wash within a compact enclosure. The use of internal baffles and cost-effective structural materials simplifies the design while reducing footprint and installation complexity.

After cooling, the absorption of CO₂ from the cooled flue gas takes place in the MBC absorber where this gas stream is in contact with the semi-lean amine solvent. Gas flows into the membrane shell side counter-current with semi-lean solvent which is fed into the tube side of the MBC absorption module.

The counter current flow configuration enables the leanest solvent to come into contact with flue gas near the gas exit of the module, maintaining high CO₂ concentration gradient between the flue gas and solvent throughout the module, which is translated into better CO₂ removal efficiency.

The depleted gas is released to the atmosphere through water wash section; while the CO₂ rich amine is heated and sent to the regenerator which operates at up to 5 barg. Additional heat is added in the reboiler to favour the release of the absorbed CO₂. Two streams leave the regenerator: the CO₂ rich gas stream which can either be sequestered to storage or utilised to a higher value product, and the semi-lean amine. The semi-lean amine is then recycled back into the MBC absorber. The CO₂ recovered has purity more than 98%.

The flow rate of the feed gas, and the solvent can be varied independently depending on the process conditions and requirements, providing the system with higher flexibility for any changes in process inputs as compared to the conventional tall absorption columns.

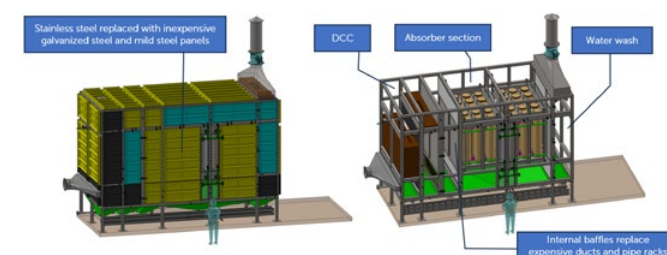


Figure 2: Internal Configuration of the Membrane Box Contactor

PROOF POINT: PETRONAS'S CARBON CAPTURE DEMO PROJECT

MBC Capture technology is currently being deployed for a carbon capture demonstration project at one of PETRONAS's facilities, with a capacity of 10 TPD, a significant stride towards embracing low-carbon solutions. By leveraging MBC technology, PETRONAS aims to achieve substantial cost reductions in its capture processes, with anticipated equipment savings of 27% and energy cost savings of 30%. This strategic initiative highlights PETRONAS' dedication to environmental sustainability, prioritizing emission reduction at its core operations.

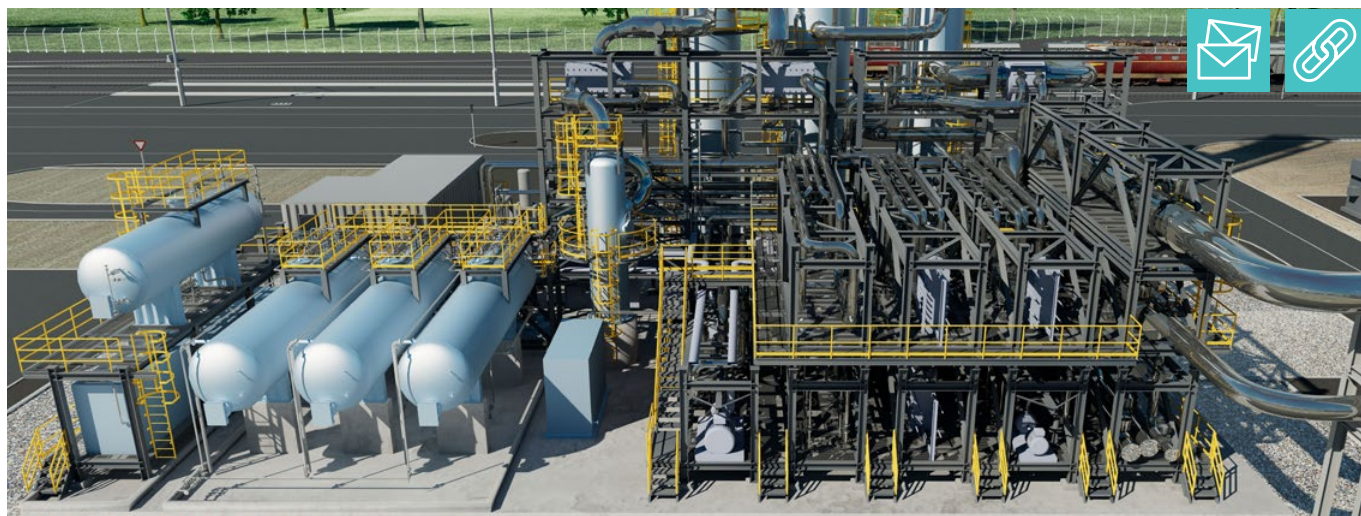
PROOF POINT: MBC'S FIRST COMMERCIAL PROJECT

MBC is progressing towards its first commercial deployment, with a project in Canada currently advancing through FEL-2 and targeting Final Investment Decision (FID) in Q3 2026. This milestone marks a significant step in the commercialisation journey, building on the successful demo, which has demonstrated the technology's readiness for real-world, cost-competitive carbon capture. The project reflects growing confidence in MBC as a scalable solution for global deployment.



SAIPEM

CO₂ SOLUTIONS BY SAIPEM / BLUENZYMES™



SUMMARY

In an era where sustainable technological solutions are paramount, Saipem's CO₂ Solutions emerges as a beacon of innovation. Our enzymatic carbon capture technology, pioneered through decades of research and development, offers a superior approach to mitigating industrial CO₂ emissions. This technology is designed to be both environmentally friendly and economically viable, aligned with Saipem's commitment to advancing the global transition towards a greener future. By harnessing the power of nature with cutting-edge engineering, we provide a scalable, effective solution for industries striving to achieve their carbon neutrality goals.

BENEFITS

- **Environmentally Friendly:** Utilises a non-toxic, non-volatile carbonate solvent, minimising ecological impact.
- **Cost-Efficiency:** Reduces operational costs through low-grade heat for solvent regeneration and a simplified process that lowers CAPEX and OPEX.
- **Operational Simplicity:** A streamlined process requiring fewer pieces of equipment enhances usability and maintenance.
- **High Tolerance:** The solvent is inert to SO_x and NO_x, offering superior resistance and more flexibility in various industrial environments.
- **Risk Mitigation:** Eliminates many hazards associated with traditional carbon capture methods, providing a safer, more reliable solution.

KEY PROJECTS

- **St-Félicien Facility, Quebec, Canada** (Since 2019 - Ongoing): Successfully tested commercial scale enzymatic carbon capture from lime kiln exhaust, capturing over 95% CO₂ at 30 tpd. Now in commercial operations.
- **The ACCESS Project, EU's Horizon 2020** (since 2022 - ongoing): Advancing novel high-intensity contactors to TRL7 in Norway, Sweden, and Poland, offering cost-effective solutions.
- **Parachem Industrial Demonstration, Quebec, Canada** (2017-2019): Showcased enzymatic carbon capture in chemical production, highlighting integration and environmental benefits. Ran over 3,000 hours.
- **Valleyfield Pilot Plant, Canada** (2015-2017): Validated the technology at TRL-7, capturing 10 tonnes of CO₂/day over 2,500 hours.

KEY DATA

TRL	8	Capture Rate Range (tpd)	200+	Capture Efficiency (%)	95%
Source CO ₂ Purity Range	5%+	System Energy (GJ/tCO ₂)	0.55 (electricity)	Specific Regen. Energy (GJ/tCO ₂)	Varies with influx CO ₂ concentration*
Number of Commercial Plants	1	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Suitable to all industries with post-combustion emissions of any kind, especially to sites that have access to low-grade residual or geothermal heat above 85°C				

*Hot utility at 85°C (hot water only, no steam required)

CO₂ SOLUTIONS ENZYMATIC PROCESS TECHNICAL OVERVIEW

CO₂ Solutions by Saipem™ process technology revolutionises carbon capture through enzymatic mechanisms, offering unmatched efficiency and environmental compatibility. This meticulously designed system captures CO₂ with minimal energy input and maximum environmental stewardship and safety.

Role of Enzyme in Capture

Carbonic Anhydrase is an efficient and naturally occurring catalyst that converts CO₂ into bicarbonate ions, accelerating carbon capture. Adapted to industrial conditions, its application in decarbonisation demonstrates a bio-inspired solution to face environmental challenges, making enzymatic solutions the preferred choice in the industry.

Simply Better

Enzymatic carbon capture technology simplifies the process by eliminating high-pressure absorbers, solvent recovery systems, and thermal regenerators. Leveraging enzymatic efficiency reduces energy-intensive steps and costly equipment, making carbon capture more accessible and sustainable and lowering capital and operational expenditures.

- **Quench Tower:** The initial step cools flue gas, condenses water vapour, and removes particulates and contaminants to prepare the gas for efficient CO₂ absorption.
- **Absorber Column:** Core of capture process where flue gas interacts with a solvent blend containing a carbonate and 1T1 Carbonic Anhydrase enzyme that boosts CO₂ absorption kinetics at low pressure.
- **Desorber Column:** This is the final stage, where the CO₂-laden solvent is heated at a low temperature under a mild vacuum to release pure CO₂ for collection. This is environmentally sustainable and economically advantageous. Steam is not required.

Operational Advancements and Sustainability

Saipem's technology uses a non-volatile and inert solvent catalysed with Carbonic Anhydrase to decrease energy for CO₂ capture and regeneration, cutting costs by simplifying the process and yielding an environmentally sustainable and economically viable capture solution.

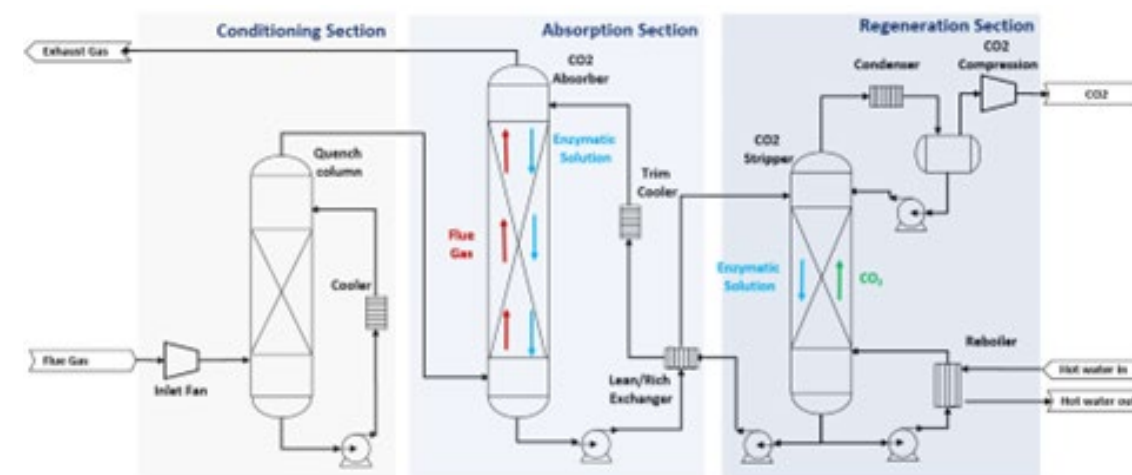
BLUENZYMES™ : REVOLUTIONIZING RISK MANAGEMENT

For operators keen on minimising project execution risks while enhancing operational efficiency, Bluenzyme™ represents a groundbreaking solution. This product line embodies the culmination of Saipem's enzymatic carbon capture technology in a modular, easily deployable format tailored to industrial applications' diverse needs.

Bluenzyme™'s Distinct Advantages

- **Risk Mitigation:** With its stable, non-toxic and non-volatile solvent, Bluenzyme™ significantly reduces the risks associated with chemical handling, exposure and license-to-operate. This feature uniquely benefits operators in industries where safety and environmental compliance are paramount.
- **Operational Flexibility:** Bluenzyme™ units offer unparalleled adaptability, designed to fit into existing industrial setups without extensive modifications. This plug-and-play approach minimises downtime and facilitates a smoother transition to carbon capture solutions, addressing a key concern for operators regarding operational disruption.
- **Cost Efficiency:** The modular nature of Bluenzyme™ products streamlines the implementation process, reducing capital and operational expenses. Using low-grade heat for solvent regeneration further enhances the economic appeal of Bluenzyme™, offering a cost-effective alternative to more energy-intensive solutions.
- **Environmental Impact:** In line with Saipem's commitment to sustainability, Bluenzyme™ units are engineered to have a minimal environmental footprint. By maximising CO₂ capture efficiency and minimising solvent waste, Bluenzyme™ supports operators in achieving their environmental and sustainability goals.

Bluenzyme™ stands out as a symbol of innovation and safety in carbon capture technology, offering a robust solution for discerning operators focused on risk reduction and operational excellence. Saipem's enzymatic carbon capture process, epitomised by Bluenzyme™, paves the way for a more sustainable industrial future, reducing the environmental impact of CO₂ emissions while maintaining economic and operational viability.





SHELL CATALYSTS & TECHNOLOGIES

ADIP ULTRA CARBON-CAPTURE TECHNOLOGY



SUMMARY

Shell Catalysts & Technologies offers ADIP* ULTRA, an amine-based high-capacity CO₂-capture and gas-treating technology for high-CO₂ process streams. The ADIP family is deployed at more than 500 Shell and non-Shell sites worldwide, with a strong track record of cost-effective, deep CO₂ removal in natural gas applications. ADIP ULTRA builds on this operating base with an optimised solvent formulation and a next-generation process design derived from decades of operating data and learnings. As an optional enhancement, ADIP ULTRA can be deployed with latest-generation absorption column internals (Shell Turbo Technologies), which increase mass transfer and hydraulic capacity to enable high capture rates and deep treated-gas specifications while reducing solvent circulation and regeneration duty.

BENEFITS

Shell's ADIP ULTRA captures CO₂ cost-effectively from high-CO₂ gas streams. Proven at 1-mtpa scale, it helps improve capex, opex and performance through:

- lower absorber capex via latest generation column internals (Shell Turbo Technologies), enabling higher capacity and/or smaller absorber diameters;
- lower regeneration energy from optimised solvent design and data-driven modelling (up to 30%, design dependent);
- flexible line-ups that meet treated-gas specifications while minimising installed and operating cost;
- robust operation with low foaming risk and no solvent degradation, reducing waste from solvent breakdown; and
- a non-corrosive, non-toxic solvent system, reducing materials-of-construction constraints and HSE burden.

KEY DATA

TRL	9	Capture Rate Range (tpd)	100 - 3,000+	Capture Efficiency (%)	99.5%+
Source CO ₂ Purity Range	1–35 vol%	System Energy (GJ/tCO ₂)	Design Specific	Specific Regen. Energy (GJ/tCO ₂)	Design Specific
Number of Commercial Plants	+500	Number of Pilot Plants	N/A	Modular (Y/N)	Yes*
Target Industries	Natural Gas and LNG, Hydrogen Manufacturing (including Blue H ₂) and Refining				

KEY PROJECTS

Quest 1-million-t/y CCS project

The commercial-scale Quest CCS facility in Canada captures > 1 mtpa of CO₂ from the Scotford upgrader's hydrogen manufacturing units, with > 99% uptime, better-than-projected reliability, cost and storage performance, and operating costs of approximately \$25/t CO₂ (with an estimated up to 30% lower cost if built today). ADIP ULTRA treats the three hydrogen-unit process gas streams; the captured CO₂ is then dehydrated and compressed, transported about 75 km by pipeline, and injected for permanent storage in a deep saline formation approximately 2 km underground. Since start-up in 2015, Quest has captured more than 10 million tonnes of CO₂.

ADIP technology has been applied in gas treating since the 1950s. In 2000, Shell introduced ADIP-X, incorporating a significantly upgraded solvent system that delivered a step change in CO₂-removal capability. The latest generation, ADIP ULTRA (2017), extends this performance through an optimised solvent and updated process design intended to lower the cost of CO₂ capture. Relative to earlier ADIP generations, ADIP ULTRA can achieve equivalent treated-gas specifications with reduced equipment size and energy demand, including a shorter absorber column, lower solvent circulation, a slimmer regenerator and a smaller reboiler (Figure 1).

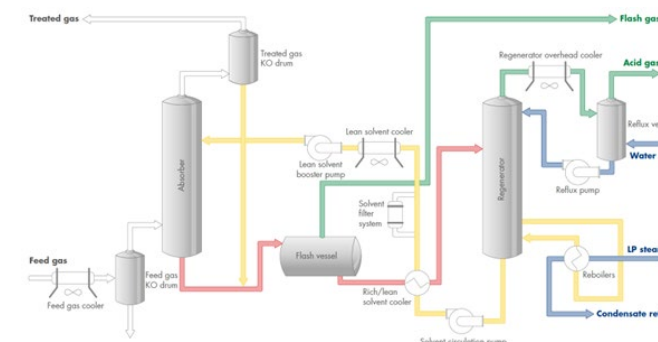


Figure 1. The Shell ADIP ULTRA process.

As an optional enhancement, ADIP ULTRA can be deployed with Shell's absorption column internals (Shell Turbo Technologies) to increase contact efficiency and expand the operating window. At column scale, gas flows upwards counter-current to the descending solvent. Within each tray element, gas and liquid are distributed through multiple cocurrent contacting boxes and then separated, improving phase contacting and liquid distribution (Figure 2). The resulting increase in effective interfacial area and mixing drives higher mass-transfer rates and raises hydraulic capacity. In practical terms, Shell Turbo Technologies can enable operation at higher inlet CO₂ concentrations and increase capacity by up to 80%, or alternatively reduce absorber diameter by up to 35% and total column weight by up to 50%.

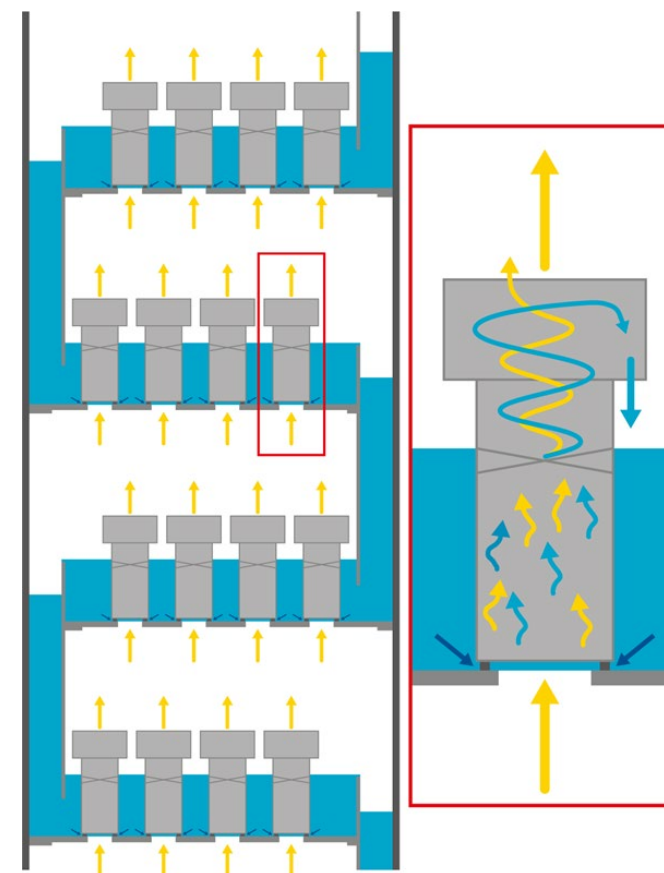


Figure 2. With Shell Turbo Technologies, the trays are designed to improve phase contacting and liquid distribution.

ADIP ULTRA solvent comprises methyl diethanolamine (MDEA) as the primary amine, piperazine as the reaction-rate promoter, and water. The formulation is designed to provide high CO₂-loading capacity at low circulation rates, which can reduce absorber diameter and pumping duty versus conventional aqueous MDEA systems. For both grassroots units and revamps, these characteristics translate into potential reductions in total installed cost and regeneration energy. The solvent is also engineered for stable operation, with low hydrocarbon solubility and low propensity for foaming, fouling, corrosion and degradation, supporting reliable performance over extended run lengths.

The process line-up can be configured to match CO₂-removal targets, feed composition and utilities – for example, using a hot-flash configuration in place of a conventional regenerator where appropriate. These variants are based on established design options and are applied within the Shell Blue Hydrogen Process, supporting selection of an energy- and cost-effective configuration for project-specific requirements.

* ADIP is a Shell trademark.



Carbon Capture Alliance



SHELL CATALYSTS & TECHNOLOGIES AND TECHNIP ENERGIES ALLIANCE CANSOLV CO₂ CAPTURE SYSTEM



SUMMARY

Shell and Technip Energies bring together proven carbon capture technology and global project delivery capability to help clients turn decarbonisation ambitions into investable projects. At the core is the amine-based post-combustion CANSOLV® CO₂ Capture System, with more than a decade of commercial operating experience across power and industrial applications. Canopy by T.EN™ powered by Shell CANSOLV builds on this foundation as a flexible, integrated suite of modular and bespoke carbon capture offerings, supporting scalable deployment across industries, geographies, and project sizes. Together, we help clients progress carbon capture projects with greater confidence, from concept through delivery. We are by your side, making decarbonisation possible and realising ambitions. Confidence. Captured.

BENEFITS

- **Proven performance:** CANSOLV technology has more than 12 years of continuous commercial operation at scale, across 3 industrial sites, delivering high capture efficiency, wide turndown capability, high-purity CO₂ product, and strong solvent stability.
- **Integrated expertise:** CANSOLV technology is delivered by our fully aligned alliance, uniting licensed technology, engineering, integration, and project execution excellence across the asset life cycle.
- **Competitive carbon capture:** Canopy by T.EN™ powered by Shell CANSOLV provides high-value productised, modular approaches and ready-to-deploy solutions, for retrofit and greenfield developments across diverse plant sizes, CO₂ concentrations, and industrial sectors, with focus on constructability, schedule, and risk reduction.
- **Committed collaboration:** We work closely with clients to optimise technology deployment, energy integration, construction approaches, and continuous improvement, reducing capital and operating costs while enhancing project confidence.

KEY DATA

TRL	9	Capture Rate Range (tpd)	250 to 20,000+	Capture Efficiency (%)	98%+
Source CO ₂ Purity Range	2 - 30%	System Energy (GJ/tCO ₂)	Design Specific	Specific Regen. Energy (GJ/tCO ₂)	Design Specific
Number of Commercial Plants	3	Number of FEEDs	21	Modular (Y/N)	Yes
Target Industries	Large-scale gas-fired power facilities, petrochemical and refineries, gas processing facilities, waste to energy, hard to abate (cement, steel), waste/biomass power facilities				

KEY PROJECTS

- **BP Net Zero Teesside Power, UK:** The EPC phase is now in progress by the Technip Energies and GE Vernova consortium, including Balfour Beatty, with Shell Catalysts & Technologies as licensor, for 2-mtpa CO₂ capture at one of the world's first commercial-scale gas-fired power stations with integrated CCS.
- **Carbon Centric Rakkestad, Norway:** Our alliance delivered a C10 modular solution for the Rakkestad energy-from-waste plant. The standardised approach reduced cost, schedule, and on-site labour, enabling successful start-up in 2025.
- **Heidelberg Materials, Canada:** Following a successful piloting campaign, the alliance was awarded a FEED project to capture 1.5 mtpa CO₂ from cement production and an integrated heat and power facility.
- **Humber Zero, UK:** Shell's CANSOLV technology is being deployed for both VPI Immingham CCGT and Phillips 66 Refinery to deliver one of the world's largest CCS projects, accounting for almost a fifth of the UK Government's 2030 target for captured carbon.

The CANSOLV® CO₂ Capture System is a proprietary amine-based post-combustion carbon capture technology developed by Shell and delivered globally through the Shell Catalysts & Technologies and Technip Energies alliance. It uses a regenerable solvent to selectively capture CO₂ from flue gas and release it as a high-purity product suitable for transport, storage, or utilisation.

Designed for retrofit and greenfield applications, the technology supports a wide range of flue gas compositions, flow rates, and capture capacities, providing a flexible solution for industrial clusters and standalone CCS projects.

PROVEN PERFORMANCE FROM LONG-TERM OPERATIONAL EXPERIENCE

The CANSOLV CO₂ Capture System benefits from more than a decade of commercial operating experience, providing performance assurance that is critical for CCS investment decisions.

In 2014, the SaskPower Boundary Dam coal-fired power station in Canada became the first in the world to use CCS at large commercial scale. The plant now has more than 11 years of operation, with capacity to capture up to 1 mtpa CO₂. Learnings from this first-of-a-kind deployment continue to support ongoing technology development and broader CCS deployment.

The technology has also been retrofitted at the Brother CISA chemical facility in South Africa, capturing 170 tpd of high-purity CO₂ with zero downtime and minimal operational support since 2013.

In 2025, the Carbon Centric Rakkestad facility started up successfully, capturing 10 ktpa of CO₂ for utilisation in the food and beverage industry and demonstrating a commercial pathway for small-scale capture in energy-from-waste.

These references are complemented by extensive piloting across sectors, informing improvements in solvent formulation, process efficiency, emissions management, and operability.

COMBINED KNOWLEDGE FOR COMPETITIVE CARBON CAPTURE

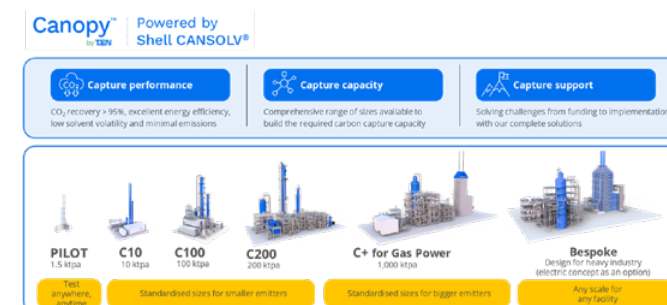
As an alliance, we translate proven performance into deployable products and solutions. Canopy by T.EN™ powered by Shell CANSOLV provides a flexible, integrated suite of modular and bespoke carbon capture offerings, with the CANSOLV CO₂ Capture System at the core.

These solutions support investment decisions by reducing execution risk, improving cost control, enhancing delivery certainty, and enabling scalable deployment across industries and geographies.

The latest offering, C+ for Gas Power, is a modular, productised solution designed for integration with leading gas turbine frames. Built on experience from major gas power CCS projects, C+ combines configurable design parameters with repeatable architecture to support faster deployment.

*CANSOLV is Shell trademark

Available as a nominal 1 mtpa module aligned with ~350 MW combined cycle output, C+ provides a scalable building block for larger installations. By moving away from bespoke design, it reduces installation time, simplifies engineering, and optimises sparing and margins, supporting greater predictability, lower execution risk, and more consistent cost outcomes.



INTEGRATED EXPERTISE FOR CONTINUOUS INNOVATION AND IMPROVEMENT

Shell Catalysts & Technologies and Technip Energies have worked as an alliance since 2012, advancing the technology to meet evolving industry needs, improve performance, and reduce capital and operating costs.

This innovation focus includes adapting the CANSOLV CO₂ Capture System to customer-specific energy integration needs. For example, steam supply can be a constraint for carbon capture deployment in the cement sector. To address this challenge, the alliance has developed a fully electrified configuration for customers replacing steam-based solvent regeneration with electric boilers and heat pumps, reducing reliance on fired heaters and enabling integration with low-carbon electricity sources where available.

COMMITTED COLLABORATION WITH SUPPORT ACROSS THE PROJECT LIFE CYCLE

Every successful project is a journey. With integrated technology and execution capabilities, we support clients from early concept and feasibility through FEED, execution, and long-term operations, helping simplify complexity and maintain collaboration across the project life cycle.

To support operational facilities, Shell CANSOLV Connect is included with all products from the alliance. Building on Shell's CatCheck™ platform, used for more than 20 years in catalyst performance remote monitoring, this digital solution provides continuous performance visibility and data-led insights to help sustain operational confidence, identify optimisation opportunities, and support ongoing value delivery throughout the asset life cycle.

With proven technology, scalable offerings, and integrated delivery support, the Shell and Technip Energies alliance helps clients move carbon capture from ambition to execution with confidence.

SLB CAPTURI ADVANCED CARBON CAPTURE™



SUMMARY

SLB Capturi offers a portfolio of cost-effective, proven carbon capture technologies, tailored to meet the diverse needs across industrial sectors and energy solutions. The modular approach ensures seamless integration and customization, empowering the emitter to achieve their carbon reduction and removal goals efficiently.

SLB Capturi's standardised and modularised carbon capture plants, Just Catch™, is designed for easy fabrication, transportation and installation. This unlocks other advantages, such as compact design, short delivery time and low cost. The range of modular Just Catch™ units covers sizes of 100,000 and 400,000 tpa, with the possibility to add multiple units to scale the capture capacity.

SLB Capturi provides process designs and technology licenses for large-scale industrial carbon capture plants under the Big Catch™ concept. These large-scale industrial carbon capture plants are optimised to project specific requirements and cover capacities from 400 tpa into the millions.

BENEFITS

- Highly energy-efficient capture process with innovative heat integration solutions.
- Includes proprietary Advanced Carbon Capture™ (ACC™) emission control to prevent the formation of amine mist; this nearly eliminates emissions of amine and amine degradation products.
- The ACC™ CO₂ capture process, 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.
- SLB Capturi's proprietary ACC™ solvents show very low solvent degradation, meaning low corrosion, low amine make-up requirements, low emissions of amine degradation products, low demand for amine reclamation, and low production of reclaimer waste.

KEY PROJECTS

- Delivered: Twence CCU [capture capacity: 0.1 Mtpa]- Modular Just Catch™ 100 delivered to Twence's waste-to-energy plant in the Netherlands.
- Delivered: Heidelberg Materials Brevik CCS [capture capacity: 0.4 Mtpa] – Big Catch™ delivered to Heidelberg Materials' cement plant in Norway.
- Ørsted Kalundborg CO₂ Hub CCS [capture capacity: 0.5 Mtpa] - Delivering five Just Catch™ units to Ørsted's Asnæs and Avedøre bioenergy plants in Denmark.
- Hafslund Celsio Oslo CCS [capture capacity: 0.4 Mtpa] – Delivering Just Catch™ 400 to Hafslund Celsio's waste-to-energy facility at Klemetsrud, Norway.
- Mobile Test Units (MTU): Since 2008, the MTU has validated SLB Capturi's technology across a range of industries. To date, 14 different flue gases have been tested and verified with SLB Capturi's MTUs.

KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	8	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Cement, bio/waste-to-energy, pulp and paper, gas-to-power, in addition to refining and process industries				

SLB Capturi's carbon capture technology has robust patent protection and is based on a health, safety and environmentally (HSE) friendly solvent portfolio developed with the aim of no harm to workers on site, surrounding communities or the environment, along with high energy efficiency. It can be applied to both existing and new build plants, and has extensive real-world validation, with data across a range of carbon emitting industries.

Energy optimisation is critical for carbon capture as it significantly reduces energy consumption. At SLB Capturi, energy optimisation, heat integration, and waste heat recovery are prioritised areas. The company offers highly effective solutions for energy optimisation, tailored to specific industrial applications and site-specific conditions.

PROPRIETARY AND PROVEN TECHNOLOGY

The Advanced Carbon Capture™ (ACC™) proprietary solvents were developed in an eight-year R&D program (SOLVit) together with industry and research partners. Numerous solvent mixtures were tested across energy consumption, robustness, toxicity, material compatibility, and – most importantly – HSE performance. The SOLVit program resulted in energy-efficient solvents and reduced solvent consumption and thus reduced OPEX. Compared to traditional amines, SLB Capturi's proprietary solvents also minimise degradation products, which can have an impact on corrosion and the need for maintenance. The ACC™ capture technology, including the ACC™ solvents and ACC™ Emission System, has been tested and verified on flue gases from gas-fired and coal-fired power plants, cement kilns, waste-to-energy, pulp & paper, hydrogen, char manufacture and smelting, with more than 90,000 hours of operating experience from the US, UK, Germany, Scotland, Sweden, Poland, and Norway, with additional industrial-scale commercial operations in the Netherlands and Norway.

ADVANCED CARBON CAPTURE™ PROCESS

The main stages of the ACC™ process include the Direct Contact Cooler (DCC), the absorber and desorber columns, the reboiler, the reclaimer, the energy saver, the flue gas fan, and a liquefaction unit with optional proprietary advanced heat integration.

Flue gas from the emitter is extracted downstream of any existing emission control units through the flue gas fan and is pre-treated in the DCC. The DCC cools the flue gas and removes any acid gases such as SO₂, HCl, and HF.

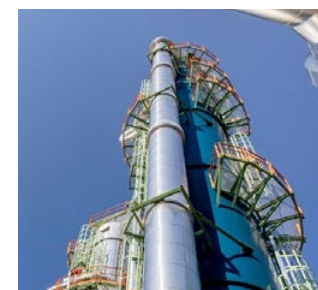
Condensed water from the flue gas exits the DCC as a bleed stream.

Flue gas from the DCC is routed to the CO₂ absorber downstream of the booster fan. The absorber consists of a CO₂ absorption section in the lower part of the column, and a water wash section with emission control in the upper part of the column. In the absorption section, flue gas contacts the lean amine solvent in a countercurrent flow, absorbing CO₂. In the upper part of the column, advanced emission control including the ACC™ Anti-Mist design cools and cleans the CO₂-lean flue gas of traces of amines and potential degradation products, thus effectively preventing emissions of amine and any degradation products as aerosols. CO₂-lean flue gas is either emitted from the absorber stack or returned to the existing flue gas stack downstream of the flue gas extraction point.

CO₂-rich amine solvent is drained from the absorber and regenerated using steam. The steam is condensed in a reboiler and returned as hot condensate. The increase in temperature during the indirect heating of rich solvent strips the CO₂ from the solvent. The resulting lean amine is returned to the absorber for reuse in the capture process, while CO₂ exits the top of the desorber. The energy saver consists of a proprietary process that reduces the steam consumption in the reboiler. The CO₂ is then compressed and fed into a regional CO₂ pipeline or compressed and liquified for transport by ship or truck. The ACC™ proprietary technology enables internal heat recovery from compression that also reduces the overall steam requirement for the carbon capture plant. To maintain high solvent performance, a reclaimer is included to intermittently remove impurities and degradation products, generating a small amount of concentrated liquid waste. This needs to be disposed of batch-wise as chemical waste. Due to the low degradation rate of the ACC™ solvents, along with a properly designed DCC, the amount of reclaimer waste from the ACC™ process is very low compared to standard plants using generic solvents such as MEA.

INNOVATION AND TECHNOLOGY DEVELOPMENT

Research, innovation, and technology development are key drivers of competitive advantage, and SLB Capturi has an active program focused on reducing costs, developing and qualifying new capture technologies, and improving capture project economics. This includes capture efficiency, modularization, and the implementation of digital capabilities.



TWENCE CCU

Waste-to-energy, Netherlands
Just Catch™ 100
Capacity: 100,000 TPA



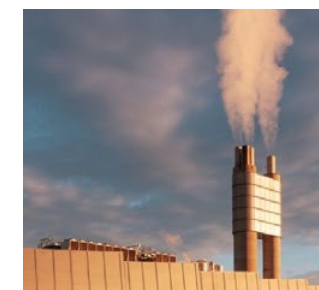
BREVIK CCS

Cement plant, Norway
Big Catch™
Capacity: 400,000 TPA



KALUNDBORG CCS

Biomass Power stations, Denmark
5 x Just Catch™ 100
Capacity: 500,000 TPA



OSLO CCS

Waste-to-energy, Norway
Just Catch™ 400
Capacity: 400,000 TPA



SUMMARY

SFW's Cal+ solution based on the Calcium Looping (CaL) capture technology, is a scalable and retrofitable post combustion CO₂ capture technology. The solution is built on SFW's experience of delivering over 500 commercial Circulating Fluidised Bed (CFB) units. SFW Cal+ is a multi-product, cost- and environmentally effective and highly adaptable solution for the decarbonization of hard-to-abate industrial sectors. In particular, the solution serves the energy from waste (EfW) or waste to energy (WtE), cement, iron & steel, and pulp & paper industries.

BENEFITS

- CO₂ capture efficiency higher than 90%
- Added value in the form of co-production of green electricity and carbon-free lime
- Captures other acid gases and can treat high temperature flue gases
- Commercially available, scalable, and cost-effective components
- Can be applied to numerous large-scale CO₂ emitters such as cement, EfW / WtE, iron & steel and other carbon intensive industrial plants.
- Oxygen synergy and sector coupling with green hydrogen and Power to X (P2X) plants.



Calcium Looping 1.7 MW demo plant completed in La Pereda, Spain. The pilot plant was commissioned in 2012 with demonstrated capture efficiency of over 90%

KEY DATA

TRL	6 - 7	Capture Rate Range (tpd)	>50	Capture Efficiency (%)	90 - 95%+
Source CO ₂ Purity Range	>5%	System Energy (GJ/tCO ₂)	Dependent on plant integration level	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	3	Modular (Y/N)	No
Target Industries	Cement, EfW / WtE, iron & steel and other carbon intensive industrial plants.				

CALCIUM LOOPING

Calcium Looping or CaL utilises a natural and non-toxic sorbent, calcium, to capture and release high purity CO₂. The energy required to capture CO₂ is supplied via the oxyfuel combustion of sustainably sourced bio-residues and/or waste-derived fuels.

CaL creates added value for industrial plant operators in the form of circular economy applications, decarbonizing energy generation and enabling sector coupling opportunities. In essence, CaL addresses scope 1,2 and 3 emissions. CaL is supplied either as a tail-end configuration, capturing CO₂ and producing energy and lime, or as an integrated configuration in which the capture system exchanges material and heat streams with existing industrial units.

As such, CaL can be integrated to any industrial emission source, especially those with an existing lime cycle in operation such as cement, steel, and pulp and paper. The sorbent purged from the capture system, a mixture of lime and valuable minerals, is a viable feedstock for the green manufacturing of construction materials.

As in oxyfuel applications, CaL provides synergy with green hydrogen plants, whereas cheap and available by-product oxygen is utilised for the carbon capture process. This leads to reductions in capture costs and the efficient synthesis of carbon negative fuels and materials.

CaL is a multiproduct technology which drives project feasibility due to numerous potential revenue streams, such as excess electricity, high quality heat, waste gate fees, carbon removal credits, calcined lime and hydrogen or nitrogen from the oxygen production plant.

Calcium Looping has been tested and demonstrated since 2012 under industrial operating conditions at the La Pereda power plant, Spain (see picture left). Sumitomo SHI FW has supplied the demonstration unit and continues to support innovation and process improvement via ongoing demonstration projects.

FEATURED PROJECTS:

1.7 MW CaL demo plant in LaPareda, Spain

Supplied and commissioned by Sumitomo SHI FW in 2012, the plant (see picture left) demonstrated a CO₂ capture efficiency of over 90%. The plant has continued to operate flexibly for over 5,000 hours under different process conditions to optimise the technology.

CaLby2030² project for hard-to-abate sectors

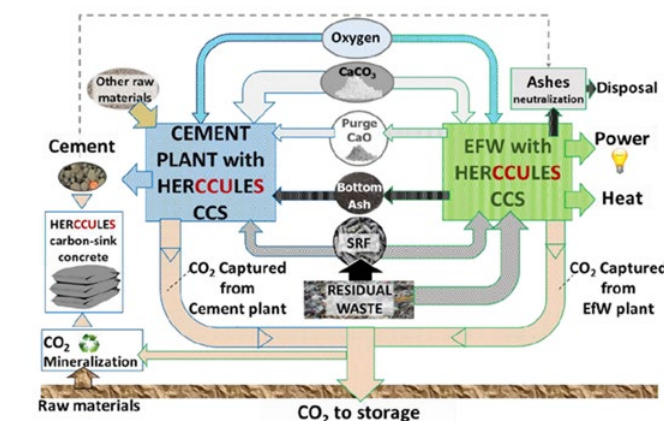
Sumitomo SHI FW is involved in the design of three integrated CaL pilot plants tailored for operation in relevant industrial environments across Europe. The pilot campaigns will be carried out with the aim of exceeding 90% CO₂ capture rates and even approaching 99% in specific configurations. The results of the demonstration activities will be utilised for process scale-up towards commercial-scale for Thomas Zements integrated cement plant in Karsdorf (Germany), Alleima's Sandviken steelworks plant (Sweden), Hunosa's La Pereda power plant (Spain) and IREN's waste to energy plant (Italy).

¹ <https://www.herccules.eu/>

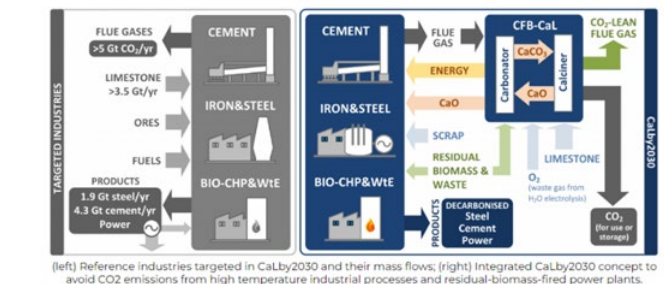
² <https://www.calby2030.eu/>

HERCCULES¹ project for WtE plants

SFW will engineer a new CaL carbon capture demonstration plant to be installed at the Milan Silla-2 WtE plant, owned and managed by a2a Ambiente, a member of the a2a group. The plant is one of the largest Italian waste management facilities that handles around 550,000 tons of municipal solid waste and non-hazardous special waste per year. The demonstration plant will operate for up to 4,000 hours and the project will conclude with the engineering and design of a commercial-scale facility.



Sector coupling opportunity and material flows enabled by CaL capture system (Source: HERCCULES¹ project)



CaL industrial cases examined in the CaLby2030 project (Source: CaLby2030 project²)

Funded by the European Union under the Horizon Europe Framework Program (Project name: CaLby2030; grant number: 101075416), (HERCCULES, grant number:101096691). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them."



SUMITOMO SHI FW (SFW) SFW HPC+ SOLUTION



SUMMARY

SFW HPC+ is a liquid solvent carbon capture solution based on the well-proven Hot Potassium Carbonate (HPC) process. The solution enables capture rates of over 90% from industrial stacks. HPC uses a widely available, lowcost, safe, and environmentally friendly solvent.

The SFW HPC+ solution enables lower energy consumption in the capture process than comparable post-combustion capture technologies. The carbon capture plant can be powered with electricity only or a combination of power and steam, giving more flexibility in implementation, whereas the low-grade heat is recovered in the form of district heating.

BENEFITS

- HPC is a well-proven carbon capture technology with hundreds of references and decades of operational experience in the chemical and Oil & Gas industries.
- Potassium carbonate is a low-cost solvent with low makeup need, reducing the solvent management cost of the carbon capture plant.
- HPC solvent does not pose risks to environment or health, facilitating simpler permitting.
- SFW HPC+ solution enables flexible configurations of electricity-only and combined electricity-and-steam operation based on available energy
- SFW HPC+ can be implemented to new plants or retrofitted to various industrial emitters.
- SFW HPC+ solution has low energy penalty for capture by utilizing various heat recuperation systems, enabling cost-effective operation and minimizing the effect on host plant.
- SFW HPC+ recuperates the consumed energy to be utilised in a form of e.g. district heating, creating extra revenue for the host plant operator
- SFW HPC+ achieves high capture rate over 90% and produces high purity CO₂ product suitable for subsequential utilization.



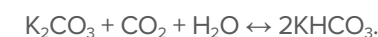
Sumitomo SHI FW (SFW), together with partner Capsol Technologies ASA, and Swedish energy company Vaxjö Energi AB collaborated on a testing campaign to demonstrate carbon capture technology based on the Hot Potassium Carbonate (HPC) process.

KEY DATA

TRL	7	Capture Rate Range (tpd)	>50	Capture Efficiency (%)	80 - 95%
Source CO ₂ Purity Range	>5%	System Energy (GJ/tCO ₂)	1.5 - 1.7	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Biomass and Waste to Energy Plants				

HOT POTASSIUM CARBONATE, HPC

SFW HPC+ capture technology starts with the cooling and compression of flue gas to enhance CO₂ absorption. The capture system removes CO₂ and regenerates the solvent via the following reversible reaction:

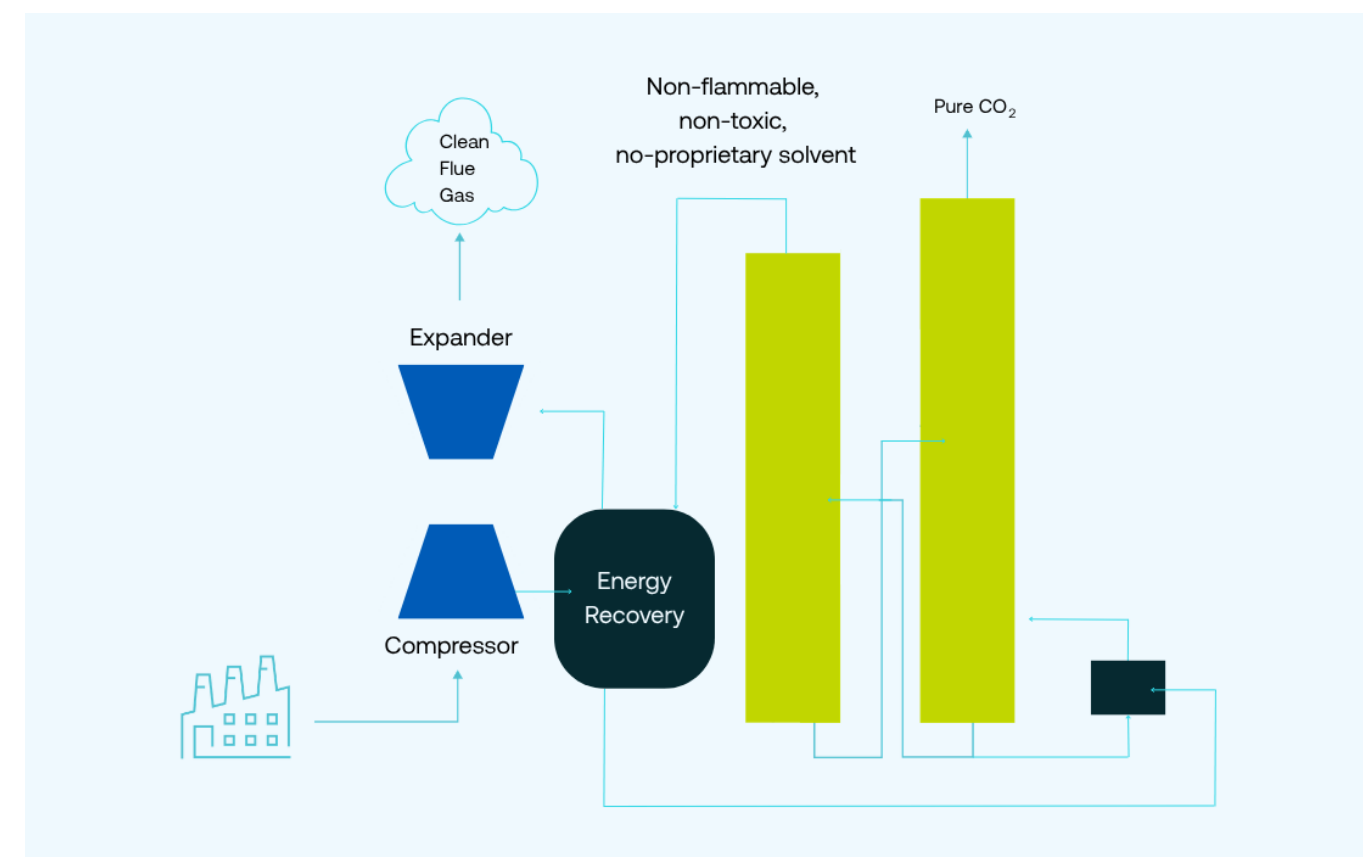


Expanding the CO₂ depleted flue gases over an expander recovers a large part of the compression energy. The heat recuperated from the flue gas and product CO₂ streams is used internally in the capture system and also exported to be utilised in low-temperature consumption points, e.g. district heating network.

The SFW HPC+ plant is aimed at producing biogenic CO₂ from retrofitting biomass and waste to energy plants with carbon capture, creating potentially negative emissions or providing biogenic CO₂ for e-fuel synthesis.

The carbon capture plant can also be delivered as part of a new biomass or waste-to-energy plant, or be retrofitted to existing incineration lines without any major modifications needed at the existing site.

SFW collaborates with Capsol Technologies ASA as a carbon capture technology partner, gaining access to Capsol's CapsolEoP® solution for efficient HPC carbon capture plants. SFW and Capsol Technologies collaborated on two demonstration campaigns in the Nordics over eight months utilizing CapsolGo® mobile carbon capture unit, at an Energy-from-Waste and a biomass-to-energy plant. This collaboration highlights how SFW and Capsol work together to advance HPC deployment.



Schematic of HPC solution (Source: Capsol Technologies AS)



SUMMARY

SFW has developed the oxy-fuel technology for fluidised bed power plants since 2003, known as SFW Oxy+. The fundamental principle of oxy-fuel is to replace the nitrogen in air with CO₂-rich recirculated flue gas during energy production. When compared with post-combustion CO₂ capture solutions, the CO₂ concentration of flue gas from SFW Oxy+ boiler is inherently high. The SFW Oxy+ can be divided into three sub-products: Oxy-enriched, Flexi-combustion and full Oxy depending on the targeted CO₂ purity level.

BENEFITS

Oxy-Enrichment

- Targets to elevate CO₂ concentration of flue gas to at least > 30% (dry gas)
- Combustion air is only partially replaced by the mixture of oxygen and recirculated flue gas
- Optimal solution if limitation exist on O₂ availability
- Applied in new boilers or retrofit of existing plants

Flexi-mode

- Boiler and auxiliaries dimensioned to operate in both air- and oxy-modes
- Targets to elevate CO₂ concentration of flue gas to > 90% on dry basis, depending on fuel
- Allows higher plant generation capacity in oxy mode compared to air-fired mode offsetting carbon capture costs
- Applied in new boilers or retrofit of existing plants

Oxy+

- Same targeted CO₂ concentration than with Flexi-combustion
- More compact design than flexi-combustion
- Applied in new boiler plants



Featured project: Carbon capture and storage demonstration plant with Endesa and CIUDEN during 2009-2017. Design for a full-scale 300 MWe plant was developed as part of the project.

KEY DATA

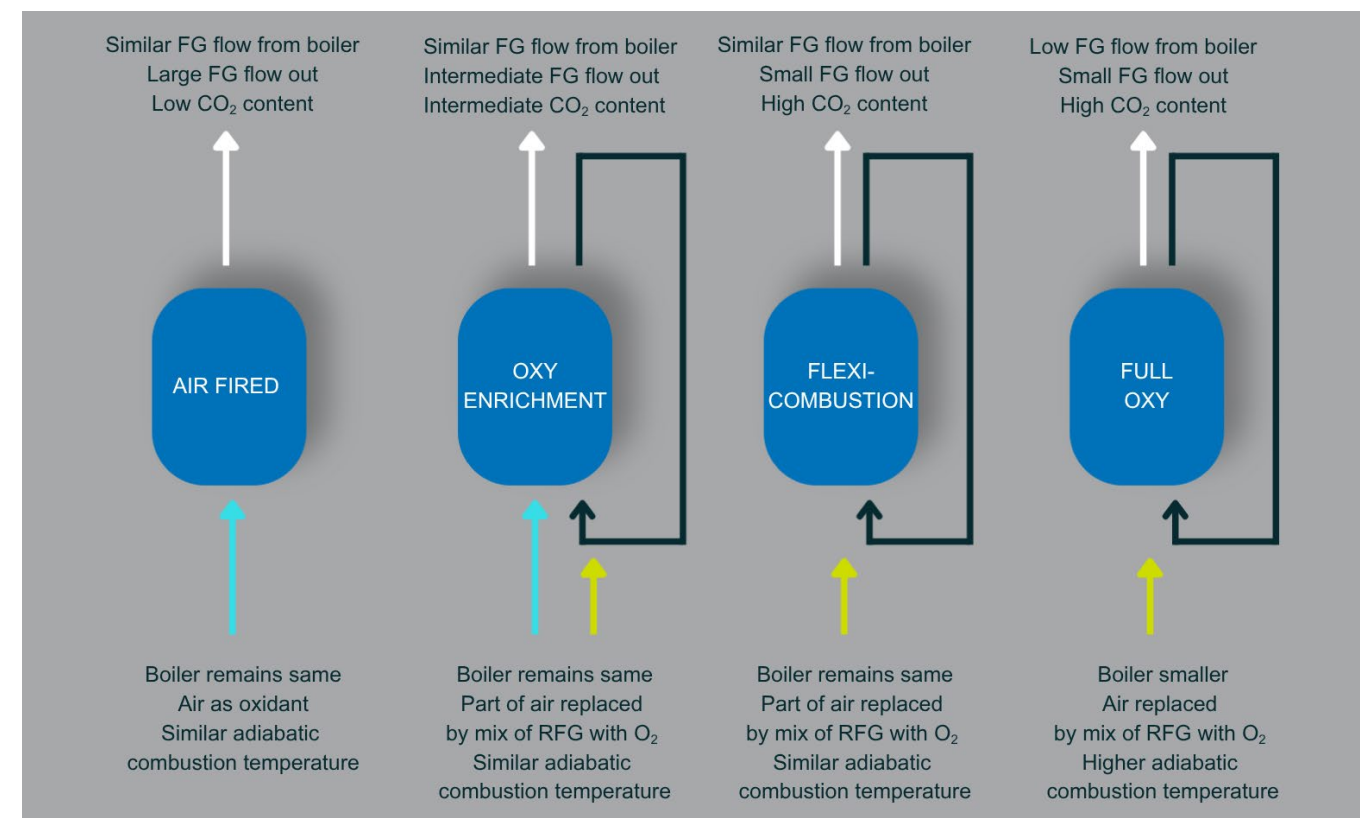
TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	>99.9% Oxyfuel boiler, 95% from integrated plant
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~ 0.6 – 1.7*	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	1	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Biomass and Waste to Energy, chemical and e-fuel plants				

* Including O₂ production plant and CO₂ compressions and liquefaction

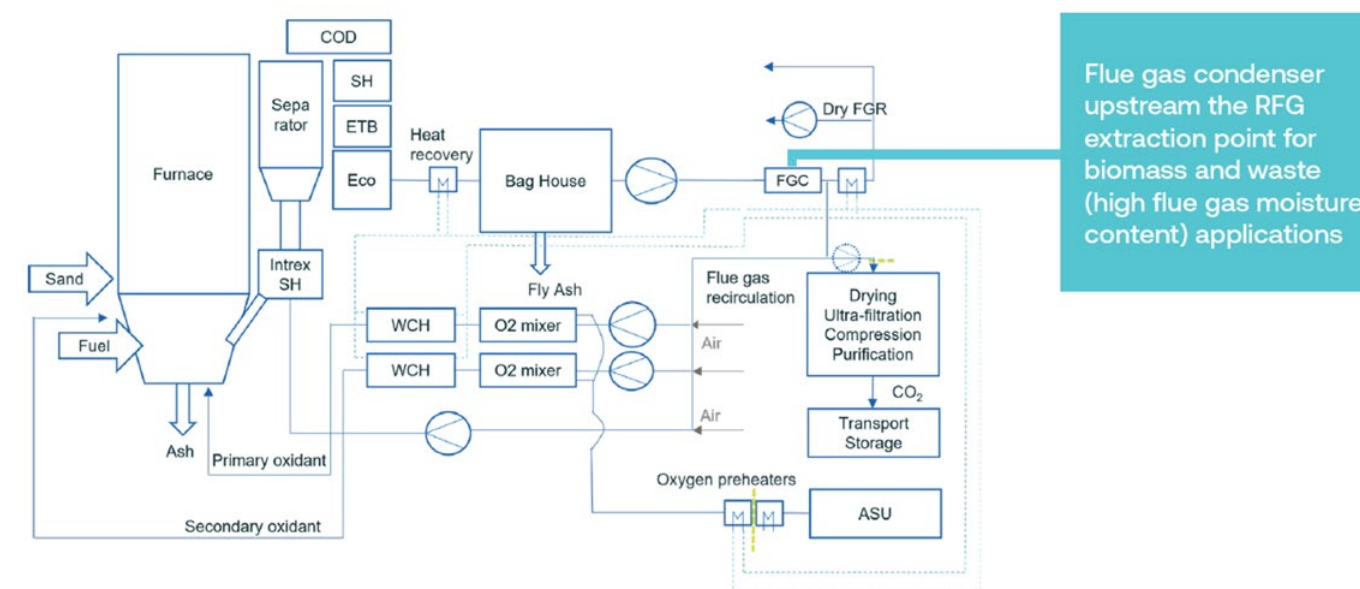
SFW OXY+ GENERIC PROCESS DESCRIPTION

In SFW Oxy+, CO₂-rich recirculated flue gas is mixed with oxygen. This mixture is called oxidant. The O₂-content of the oxidant is a process variable that is used to control process temperatures together with the amount of recirculated flue gas.

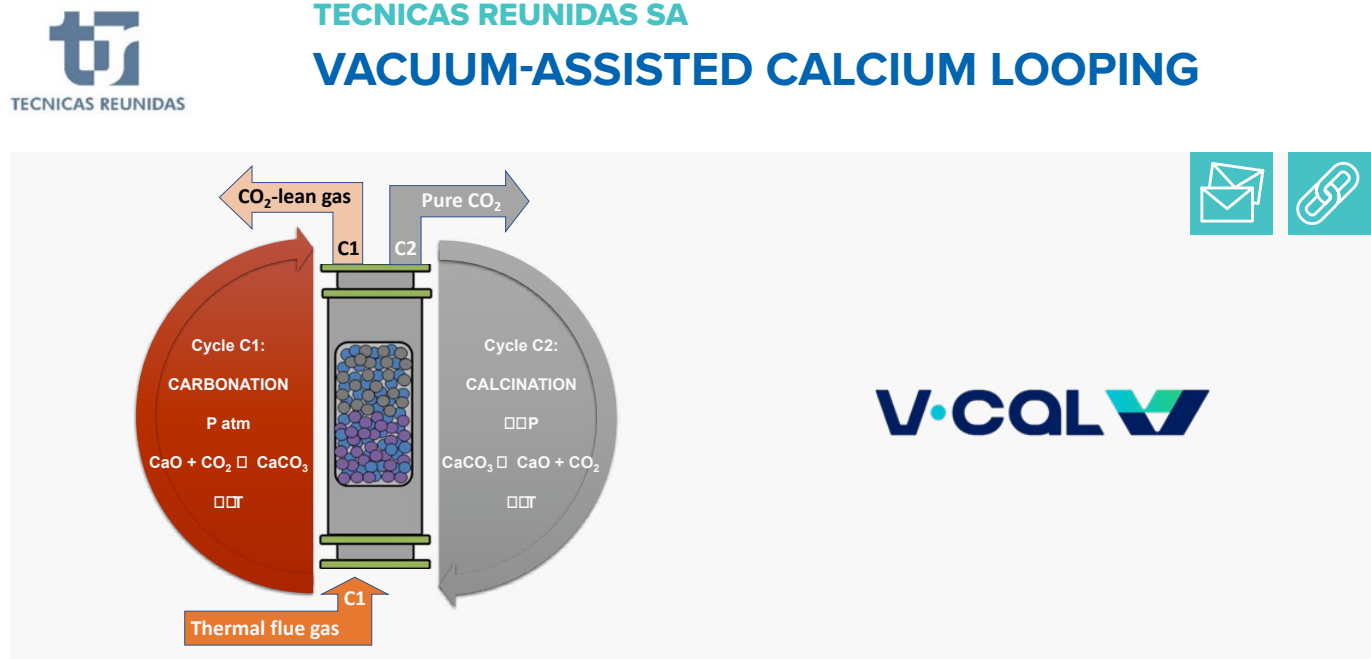
The technology was demonstrated at the scale of 30 MWth at the Fundacion Ciudad de la Energia (CIUDEN), Spain. This was followed by commercial development with partners to complete the FEED (Front End Engineering Design) activities and develop a readily available 300 MWe SFW Oxy+ power plant design. SFW's R&D and engineering experts continue to develop the solution and adapt innovations linked into our existing designs.



SFW Oxy+ comparison



SFW Oxy+ flow diagram



SUMMARY

Vacuum-assisted Calcium Looping is a groundbreaking technology for CO₂ capture from a wide range of industrial emissions. V-CaL is based on a fixed-bed reactor filled with calcium oxide, which undergoes carbonation-calcination operational cycles to capture carbon dioxide from incoming flue gas and release it with a purity of nearly 100%.

The innovation over traditional Calcium Looping is that the calcination step is conducted under near-vacuum conditions to release the CO₂, resulting in significant energy savings. In fact, for flue gas temperatures above 700°C, V-Cal does not require external heat in any step of the cycles. In addition, neither flue-gas desulphuration nor CO₂ purification units are required. Therefore, V-CaL technology offers benefits that are highly suitable for energy-intensive, hard-to-abate industries and can be adapted to treat an extensive range of flue volumes.

BENEFITS

- **Low cost:** V-CaL requires CaO, an accessible and inexpensive material, as feedstock, standard fixed-bed reactors, and a simple balance of plant.
- **Highly energy-efficient:** By iterating exo- and endothermic reactions in adiabatic conditions, it limits the required external energy to capture from flue gas.
- **Pure CO₂ produced:** does not require a purification unit.
- **Sulphur robust:** does not require a prior flue gas desulphurisation unit.
- **Scalable:** As a modular technology, V-CaL can adapt to a wide range of required capture volumes.
- **Easy integration:** does not require a radical industrial process disruption to be implemented.

KEY PROJECTS

- **CDTI-Misiones - Hy2DEC:** a national R&D project to investigate novel technologies for the decarbonisation of Spanish industry. In this project, TRL for VCaL was raised from 3 to 5.
- **CDTI-PID - VCaL:** A national technology development project to advance Vacuum-assisted Calcium Looping from TRL 5 to 7 by designing and integrating a demonstration plant to capture CO₂ from the flue gas of a ceramic industry.

KEY DATA

TRL	5	Capture Rate Range (tpd)	~	Capture Efficiency (%)	>92%
Source CO ₂ Purity Range	>25%	System Energy (GJ/tCO ₂)	< 1	Specific Regen. Energy (GJ/tCO ₂)	0.15
Number of Commercial Plants	~	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Any intensive industry, e.g. cement, ceramic, steel, petrochemical, power				

CALCIUM-LOOPING TECHNOLOGIES

Calcium Looping (CaL) is an emerging CO₂ capture technology that employs solid looping cycles at elevated temperatures and uses CaO as a CO₂ sorbent. CaL offers several advantages over established CCS technologies, including reduced costs and energy penalties associated with CO₂ capture, a high availability of calcium-based sorbents, and potential synergy with energy-intensive industries such as cement and steelmaking plants.

CaL systems have been extensively studied in configurations comprising interconnected fluidised beds. However, the purity of CO₂ is of critical importance in CaL systems, as impurities such as dust, O₂ from oxy-calcination, and mainly traces of SO₂ from the oxy-calcliner can significantly impact purification, costs, and applicability.

V-CAL DESCRIPTION

In the innovative Vacuum-assisted Calcium Looping (V-CaL) process, which Tecnicas Reunidas is currently developing and has recently filed for patent, the capture and production of nearly pure CO₂ is straightforwardly achieved. In this process, the industrial flue gas is injected into a single-bed reactor packed with CaO. If the temperature is above approximately 700°C, the CaO bed is carbonated with the CO₂ contained in the gas. The use of a packed bed eliminates the need for dust-cleaning equipment. At this point, the bed is saturated with CaCO₃ and its temperature has risen to around 850°C due to the exothermic carbonation.

In the second process step, the flue gas intake is stopped, and a partial pressure swing of CO₂ is applied (to reach partial pressures around 0.1 atm), which induces the calcination of CaCO₃ back to CaO, releasing nearly pure CO₂ (impurities << 0.1%) out of the reactor, ready to be stored or pressurised. This endothermic calcination results in the adiabatic cooling of the bed solids, returning them to the initial temperature of approximately 700°C. Thus, provided that the incoming flue gas temperature is above 700°C, no external thermal energy input is required, unlike other CaL systems (e.g., lime and cement, with >4 GJ/t CO₂). As the calcination proceeds, traces of other gases are hardly detected in the exhaust from the decomposing CaCO₃ (e.g., inert gases << 0.1%), demonstrating that the process yields 99.99% pure CO₂ and eliminating the need for a subsequent purification unit.

An example of V-CaL robustness is its proven ability to endure up to 1.5 years of carbonation-calcination cycles while maintaining a capture efficiency above 92%. This capability significantly reduces operational costs associated with reactant provision and maintenance shutdowns.

Furthermore, extensive experimental analysis of the capture process for treating flue gases containing up to 1 g/L of SO₂ as an impurity has shown that V-CaL remains unaffected. Even in long-term tests, only sub-ppm levels of sulphur are detected during calcination, thereby maintaining CO₂ purity at 99.99% and capture efficiency above 92%.

FINAL REMARKS

In conclusion, Vacuum-assisted Calcium Looping (V-CaL) emerges as a promising carbon capture technology, offering high energy efficiency and low costs for producing nearly pure CO₂, while eliminating the need for a prior desulphurisation step or a downstream purification unit.

Thanks to its characteristics, V-CaL can be directly integrated into various high-temperature off-gas, hard-to-abate industrial sources, such as metallurgical processes with electric-arc furnaces, cement production, or power generation. Additionally, it is adaptable to a wide range of treated flue gas volumes due to its modularity and scalability.

ACKNOWLEDGEMENTS

This technology has been developed in close collaboration with the Carbon Science and Technology Institute (INCAR) of the Spanish Council for Scientific Research (CSIC)



Figure 1. Picture image of the TRL-5 V-CaL prototype.



TONEXUS

TX-1 SERIES CARBON CAPTURE SOLVENTS



Absorption Solvents Type	Regeneration Energy Consumption (GJ/t)	Operating Loss (kg/tCO ₂)	Anti-Degradation Capability(min)
MEA	3.9-4.2	1.5-2.9	13
World-Class	2.5-2.6	/	/
a	~2.5 (2.1)	0.4-0.8 (Low Energy Consumption)	270
Tonexus TX-1 Series b	~2.7 (2.4)	0.3-0.7 (Balanced Type)	456
c	~3.5	0.8-1.5 (Economical Type)	1224

SUMMARY

The TX-1 series is a high-performance chemical solvent specifically optimised for CO₂ capture from low-partial pressure, high-oxygen, and high-impurity industrial flue gas in steel, cement, power generation, waste incineration, marine exhaust and other sources. Developed based on a function-oriented design approach, the solvent exhibits excellent resistance to oxidative degradation, high net CO₂ loading capacity and regeneration energy consumption as low as 2.1 GJ/tCO₂. Its customised product portfolio—TX-1a (low-energy consumption type), TX-1b (balanced type), and TX-1c (cost-effective type)—can be flexibly tailored to accommodate different steam prices and operating conditions. Proven in 5 industrial projects, the solvent is highly mature and ideally suited for large-scale carbon capture applications.

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BENEFITS

- **Benefit One:** 35–40% lower regeneration energy consumption compared with conventional MEA (Monoethanolamine) and significant reduction in steam cost.
- **Benefit Two:** 21 times higher oxidation resistance compared with MEA, 2–3 times longer operational life, the solvent consumption is 0.4 - 0.8 kg per ton of CO₂.
- **Benefit Three:** Suitable for complex industrial flue gases: high oxygen, high dust, sulfur-containing, maintains stable CO₂ capture efficiency (85-95%).
- **Benefit Four:** In combination with the TXio process, 30–90% reduction in pretreatment wastewater, 30–60% lower alkali consumption.

KEY PROJECTS

- **Project One:** Vietnam cement kiln flue gas carbon capture project: For 20–22% CO₂ cement kiln gas, annual capacity 25,000 tonnes. Fits high-oxygen, low-partial-pressure conditions; solvent lifespan more than three times that of MEA. Regeneration energy consumption is 20% lower than the design value, and carbon dioxide purity exceeds 99.97%.
- **Project Two:** China multiple 10,000-ton marine carbon capture solvent projects: For low-concentration, highly dynamic marine exhaust, Tonexus supplies shipboard solvents adapted to limited space and fluctuating conditions, ensuring stable capture efficiency.
- **Project Three:** China steel plant flue gas carbon capture project: For 18–20% CO₂ boiler gas, annual capacity 50,000 tonnes. Uses TX-1 solvent for high-oxygen, low-partial-pressure gas, with regeneration energy consumption of 2.5 GJ/tCO₂ under traditional processes.

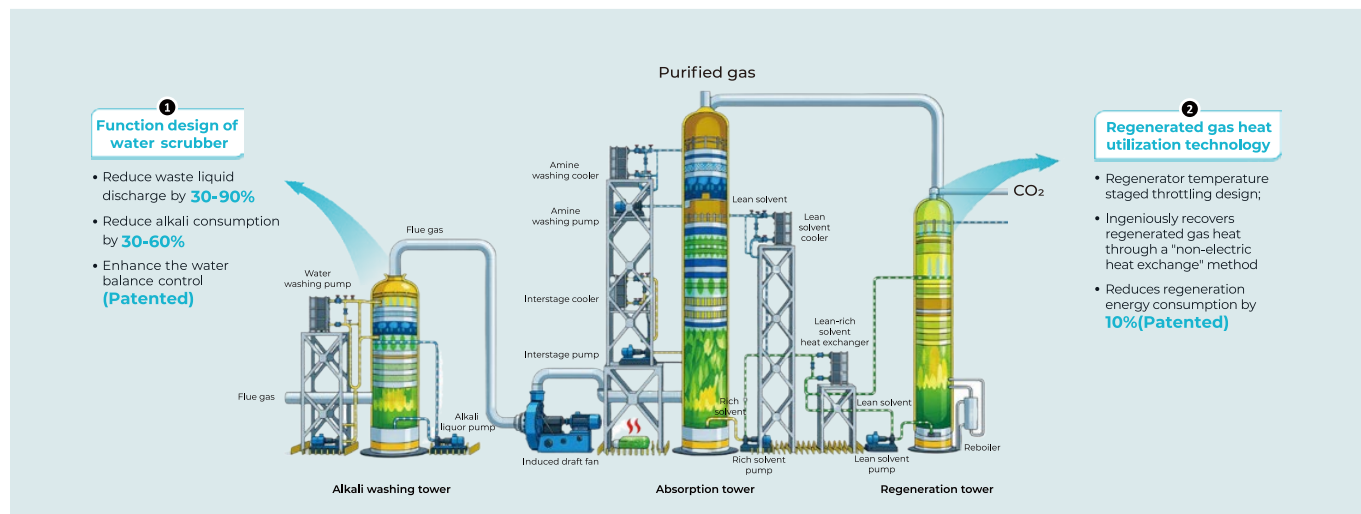
KEY DATA

TRL	9	Capture Rate Range (tpd)	200	Capture Efficiency (%)	90
Source CO ₂ Purity Range	18 - 22%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.1 - 2.5
Number of Commercial Plants	4	Number of Pilot Plants	2	Modular (Y/N)	~
Target Industries	Steel, cement, power generation, marine exhaust, waste incineration and other sources				



TONEXUS

TXIO CO₂ WET CAPTURE PROCESS



SUMMARY

This technology is an innovative wet CO₂ capture process specifically designed for industrial flue gases with low CO₂ partial pressure. Its core lies in achieving intelligent water balance control through regeneration gas scrubbing and secondary spray, while efficiently recovering latent heat within the system to reduce energy consumption. The process is suitable for complex flue gas conditions from coal-fired power plants, cement, steel, waste incineration, marine and other industries. When combined with dedicated solvents, it can reduce steam energy consumption by approximately 35–40% while significantly lowering wastewater discharge. Currently, the technology has completed pilot-scale testing and has been successfully applied in industrial projects. Its technical maturity level (TRL) has reached level 9, making it ready for large-scale promotion.

BENEFITS

- **Benefit One:** Modular pretreatment tower: 30–90% less wastewater discharge, 30–60% lower alkali consumption, liquid–gas balance control support.
- **Benefit Two:** Scrubbed gas from the absorber passes through an separation stage, reducing ammonia slip losses.
- **Benefit Three:** Regenerator top latent heat recovery process enhances system liquid balance control, recovers heat, and optimises tower temperature distribution.
- **Benefit Four:** MVR design for non-capture system heat source.

KEY PROJECTS

- **Project One:** A large-scale carbon capture project for a major building materials company, involving multiple coordinated gas sources (including lime kiln gas and dryer exhaust), with oxygen content of 6–10% and high dust levels. Combining solvent-enhanced mass transfer design with a conventional process to achieve a capture rate exceeding 97%.
- **Project Two:** CO₂ Capture System for Basic Oxygen Furnace Gas at Rizhao Steel. 150,000 tons per year BOF gas CO₂ capture device, with the maltreatment process based on Tonexus patented technology. The process innovatively adopts a function-segmented design concept, reducing annual operating costs by approximately \$600,000 compared with conventional designs and significantly improving overall project economics.

KEY DATA

TRL	9	Capture Rate Range (tpd)	450	Capture Efficiency (%)	90
Source CO ₂ Purity Range	13%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.3
Number of Commercial Plants	1	Number of Pilot Plants	1	Modular (Y/N)	~
Target Industries	Coal-fired power plants, cement, steel, waste incineration, marine and other industries.				

The “wet CO₂ capture process integrating liquid balance control and in-system heat utilization,” developed by Tonexus, is an innovative carbon capture solution specifically designed for industrial flue gases with low CO₂ partial pressure, such as those from coal-fired power plants, cement, steel, waste incineration, marine and other industries.

By optimizing internal energy integration and water resource management, the technology significantly enhances the economic performance, operational stability, and environmental sustainability of wet CO₂ capture processes.

CORE PROCESS INNOVATION

The core of this technology lies in the deep integration and reconfiguration of conventional wet carbon capture unit operations. The key innovations include:

INTELLIGENT LIQUID BALANCE CONTROL SYSTEM

The Process innovatively incorporates an additional regeneration gas scrubbing tower and a secondary scrubbing tower. Overflow scrubbing water from the pretreatment unit is used to pre-cool the high-temperature regeneration gas, reducing the downstream cooling load; meanwhile, the heat-absorbed scrubbing water is re-sprayed into the outlet flue gas, enabling dynamic regulation of system liquid balance through evaporation. This significantly enhances the system's adaptability to varying operating conditions (particularly when using high-concentration absorbents), reduces the strong dependence of conventional processes on inlet–outlet gas temperature differentials, and improves overall operational flexibility.

EFFICIENT IN-SYSTEM HEAT INTEGRATION

Through proprietary heat exchanger design and process optimization, efficient recovery of the latent heat from the regenerator top gas is achieved. The recovered heat is utilised for internal preheating or to support liquid balance control, thereby reducing the demand for external cooling and heating utilities. When combined with the company's independently developed low-regeneration-energy TX-1 series solvents, the overall system steam consumption can be reduced to approximately 2.1 GJ/tCO₂, representing a reduction of about 35–40% compared with conventional MEA-based processes.

FUNCTIONAL MODULAR DESIGN OF THE PRETREATMENT UNIT

The purification and cooling functions of the conventional alkali washing tower are decoupled. The alkali scrubbing section is dedicated to removing impurities such as SO_x, while the cooling section operates independently. This design prevents continuous generation of large volumes of alkaline wastewater during cooling. According to engineering data, it can reduce wastewater discharge by 30–90% and lower alkali consumption by 30–60%.

TECHNICAL ADVANTAGES AND BENEFITS

Significant operating cost reduction

The combination of low-regeneration-energy solvents and highly efficient heat integration is key to reducing capture costs. For a cement plant project capturing 300,000 t CO₂ per year, simulations show that steam cost savings alone can reach several 6 million dollars annually.

Superior Environmental Advantages

The technology significantly reduces wastewater discharge and alkali consumption, while measures such as enhanced gas–liquid separation effectively minimise solvent slip losses, mitigating secondary environmental risks.

High adaptability to diverse operating conditions

The process, together with the TX-1 solvents, is particularly suited for complex industrial flue gases with high oxygen, high dust, and sulfur content. It has been validated in 10,000-ton-class demonstration projects across cement, steel, power, waste incineration and other industries, consistently achieving high capture efficiency (exceeding 97% in some cases).

Increases operational reliability of the system

The improved liquid balance control enhances process flexibility and stability, supporting long-term, automated, and smooth operation of the carbon capture device.

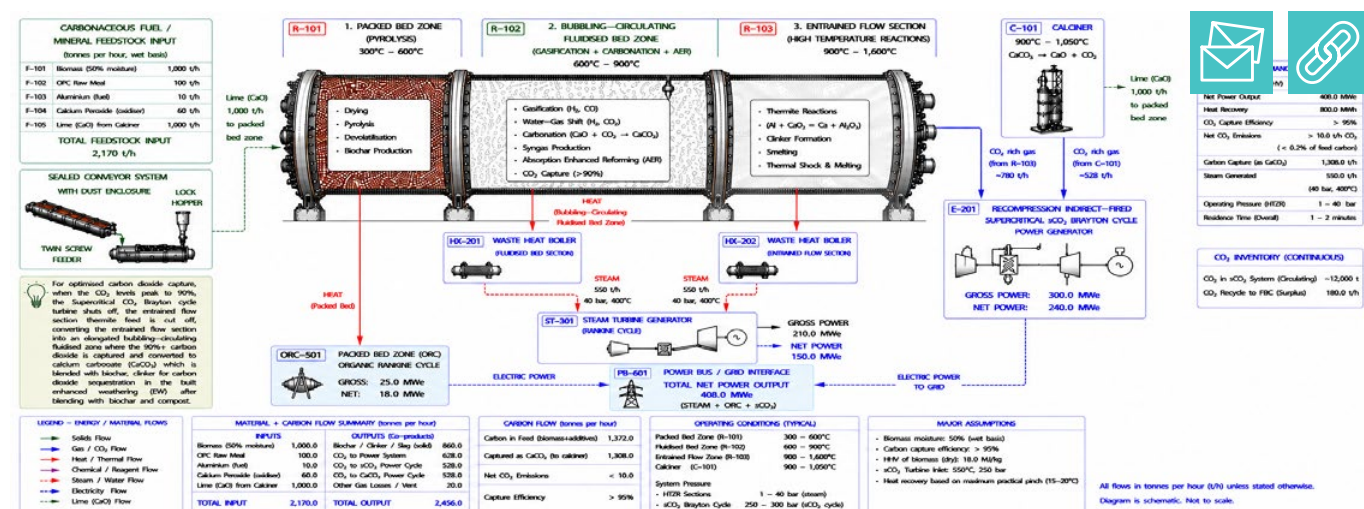
SUMMARY

Tonexus patented solution is not merely an improvement of a single unit, but a highly integrated, customised approach encompassing solvent chemistry, system process design, and heat and material management. It directly addresses the pain points of conventional wet CO₂ capture—high energy consumption, difficult liquid balance, and excessive wastewater—achieving simultaneous enhancements in energy efficiency and environmental performance. This provides a competitive, cost-effective option for large-scale industrial carbon capture.



AEL CCS

HORIZONTAL TRINARY ZONE REACTOR (HTZR)



SUMMARY

The process begins with the calciner converting limestone (CaCO_3) into lime (CaO) which is transferred to the packed bed zone. Concurrently the carbonaceous material, enters the 300°C – 600°C packed-bed pyrolysis zone and the mineral feedstocks are subsequently added. Whilst a small portion of the biochar is discharged, the material then moves into a bubbling-circulating fluidised bed zone operating at 600°C – 900°C for gasification, syngas generation, absorption enhanced reformation (AER) and carbonation reactions. Sequentially, the final entrained-flow high-temperature section (900°C – 1,600°C) supports Ordinary Portland Cement (OPC) clinker formation and/or pig iron smelting. For the terminal carbonation, the entrained flow section's thermite feed is stopped and the bubbling-circulating fluidised bed zone overlaps this extended area. The carbon dioxide (CO_2) is captured as calcium carbonate (CaCO_3) which is blended with biochar, clinker for sequestration in the built environment and/or mineralisation for enhanced weathering (EW) applications including peatland restoration prior to blending with biochar.

BENEFITS

- Benefit One:** Waste heat from the packed bed zone is recovered in the Organic Rankine Cycle (ORC) unit, whilst the waste heat streams from the bubbling fluidised zone-entrained flow sections are channeled by heat exchangers coupled to thermal power generation.
- Benefit Two:** A supercritical carbon dioxide (SCO_2) Brayton cycle turbine powered by concentrated CO_2 streams from the entrained flow section and calciner.
- Benefit Three:** Combining net zero power production Carbonaceous fuel conversion flexibility, P-t-X, Bioenergy with Carbon Capture and Storage (BECCS) technologies within a single multi-zone platform.
- Benefit Four:** Open sourcing of the AEL CCS Horizontal Trinary Zone Reactor (HTRZ) post commercialisation at the AEL CCS Scotland Greenhouse Gases Capture Hub & Centre of Excellence Q4 2028

KEY DATA

TRL	6	Capture Rate Range (tpd)	30,000	Capture Efficiency (%)	95%+
Source CO_2 Purity Range	<01–99%	System Energy (GJ/t CO_2)	<1	Specific Regen. Energy (GJ/t CO_2)	~1.2–1.5
Number of Commercial Plants	0	Number of Pilot Plants	3	Modular (Y/N)	No
Target Industries	Carbonaceous fuel combustion, hard-to-abate industries for CO_2 retrofits and greenfield newbuilds. Research, development and demonstration (RD&D) for internal combustion engines (ICEs) and direct air capture applications.				



AIRHIVE

DIRECT AIR CAPTURE (DAC)



SUMMARY

Direct Air Capture (DAC) is an innovative technology designed to mitigate the rising levels of atmospheric CO_2 by capturing it directly from the air. Airhive is developing a fast, energy efficient and low-cost DAC technology that will rapidly scale to accelerate the deployment of carbon capture. Airhive's technology employs fluidisation to provide rapid CO_2 removal via our low-cost, non-toxic metal oxide-based sorbent. Our approach is designed for rapid scalability by (i) leveraging proven industrial processes, (ii) minimising energy requirements, and (iii) employing abundant, sustainable sorbents. The technology consists of a horizontal fluidised bed reactor where particles of mineral-based sorbent mix rapidly with fluidising air to capture CO_2 , resulting in CO_2 -free air exiting the reactor. The carbonated solids are then circulated into a connected electro-calciner, where it is regenerated, yielding pure CO_2 for utilisation or storage and refreshed sorbent for successive cycles of carbon capture.

BENEFITS

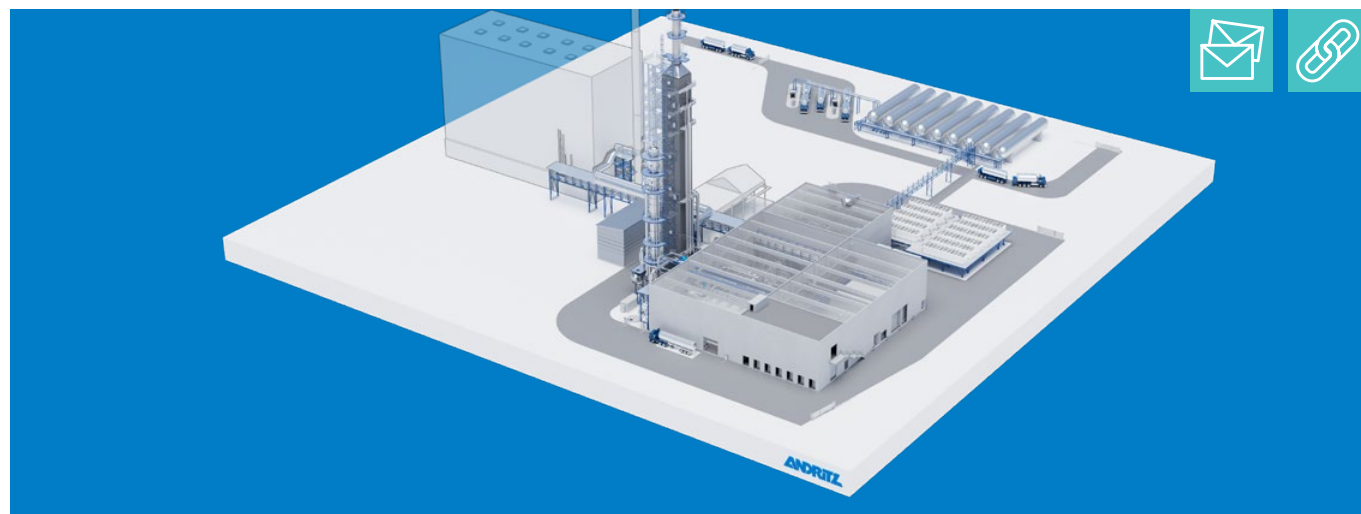
The Airhive DAC system is:

- Fast:** The nano-structured sorbent removes 99% of CO_2 from the air in <0.1 seconds.
- Sustainable and easy to scale:** The technology is built on existing industrial equipment and supply chains, configured in new ways for DAC. The naturally abundant mineral sorbent is widely available, non-toxic and can be reused for many cycles of carbon removal.
- Low-cost:** Estimated cost at pilot scale is <\$400 per net t CO_2 with pathways to estimate at-scale costs of <\$100 per net t CO_2 .
- Energy efficient:** The system is targeted at 1.5 MWh/t CO_2 , and can be fully powered by low carbon energy. It also has in-built thermochemical energy storage potential, allowing it to run when there is no external energy source available.

KEY DATA

TRL	6+	Capture Rate Range (tpd)	3.8 tpd/reactor	Capture Efficiency (%)	>97%
Source CO_2 Purity Range	0.04%	System Energy (GJ/t CO_2)	3.6 GJ/t CO_2 (1 MWh/t CO_2)	Specific Regen. Energy (GJ/t CO_2)	~
Number of Commercial Plants	0	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Chemicals, Food and Beverage, Green Fuels, CDR credit buyers				

ANDRITZ AG ADVANCED AMINE CARBON CAPTURE



SUMMARY

ANDRITZ has developed an innovative and robust carbon capture offering that uses a blend of well-proven amines to achieve the highest CO₂ removal rate with low energy consumption. This advanced amine solution has been tested in our demonstration and pilot plants and is at the center of our advanced post-combustion carbon capture solution. The overall technological solution is mature, commercially available for large-scale installations, offers high removal rates of over 95%, and produces a high-purity CO₂ product of up to 99.9%. The design is well-suited for new, as well as for existing installations, providing our customers with the option to further operate their assets while reducing their CO₂ footprint. Depending on the project-specific conditions, the ANDRITZ team will make the best possible use of wasted process heat and consider the addition of heat pumps to further optimise the energy needs of the CO₂ capture process. ANDRITZ has a wide offering ranging from feasibility or FEED studies to complete EPC solutions, including liquefaction and/or P2X schemes, ensuring that the offerings meet the needs of our various industrial customers.

BENEFITS

- **High Removal Rate:** Achieves more than 95% CO₂ removal from flue gases, ensuring a significant reduction in greenhouse gas emissions.
- **High Purity CO₂ Product:** Produces CO₂ with up to 99.9% purity, reducing the need for further purification.
- **Energy Integration:** Integrates wasted process heat and heat pumps to optimise energy demand.
- **Seamless Integration:** Designed to be also integrate into existing industrial sites, extending the lifetime of the assets.
- **Comprehensive Service:** Offers a range of services from feasibility or FEED studies to full-scale EPC projects, tailored to meet the specific needs of various industries.
- **Extended Scope:** Provide fully integrated P2X solutions (from Green Hydrogen, Carbon Capture to e-Fuel synthesis).
- **Long Term Service Agreements (LTSA):** ANDRITZ takes care of maintenance and service for our carbon capture projects.

KEY PROJECTS

- **FEED studies (Finland & Denmark): Westerngy: WtE industry. Size:** 25t/hour. **ARGO: WtE Size:** 50t/hour. Kredslob: Using BASF OASE®blue technology on WtE & biomass incl. CO₂ compression for pipeline transport. Size: 70t/hour.
- **Pre-FEED studies (Finland): Vantaan:** Study for two WtE lines, incl. CO₂ compression and extensive district heating utilization. Size: 78t/hour. Joensuu: Study for an e-Methanol (MeOH) plant by P2X Solutions. Size: 5.5t/hour (40t/year).
- **Pilot Project (Austria, Germany): voestalpine/K1-MET:** Collaboration in the iron and steel industry. **Rohrdorf:** First demo plant in the German cement industry. Size: 2t/day. Executed multiple pilots in cement, iron & steel, biomass & WtE in Sweden, Germany & Spain.
- **Mobile Test Units (MTUs):** are available for rental or purchase utilizing Amine or HPC. Also, a combined Multi-Solvent pilot that operates on Amines & HPC in the same unit.

KEY DATA

TRL	8	Capture Rate Range (tpd)	As per need	Capture Efficiency (%)	90%
Source CO ₂ Purity Range	4 - 30%	System Energy (GJ/tCO ₂)	11 - 3.3	Specific Regen. Energy (GJ/tCO ₂)	2.5 - 2.8
Number of Commercial Plants	0	Number of Pilot Plants	9	Modular (Y/N)	Yes
Target Industries	Pulp & Paper, Iron & Steel, Cement, Biomass, Energy from Waste/Waste to Energy				

ANDRITZ AG ENHANCED HOT POTASSIUM CARBONATE



SUMMARY

ANDRITZ and CATAcarb® have partnered to offer an energy-efficient and eco-friendly CO₂ removal solution targeting flue gas emissions. This end-to-end solution combines ANDRITZ's EPC capabilities with CATAcarb's hot potassium carbonate (HPC) technology to provide a turnkey option for climate change mitigation. CATAcarb HPC is a proven technology with over 150 units in operation worldwide, backed by 60 years of design expertise and 40 million operating hours of CO₂ removal. ANDRITZ offers a comprehensive service ranging from feasibility and FEED studies to full-scale EPC projects, tailored to meet the specific needs of various industries. This ensures that clients receive a fully integrated solution that addresses their unique requirements, from initial concept through to project completion. ANDRITZ provides both standard and tailor-made solutions based on customer needs and offers a fully integrated P2X solution.

BENEFITS

- **Safe Operations & Eco-Conscious:** The process is non-volatile and contamination-free, ensuring a secure and clean environment. The system is fully closed, preventing any environmental contamination.
- **Clean Output:** No solvent is present in the final product, making it eco-friendly and safe for use.
- **Energy Saver:** It requires low energy for solvent regeneration, making it highly efficient.
- **High Capture Rate:** The process achieves over 90% efficiency in capturing CO₂.
- **High Purity CO₂:** The process captures high purity (>99%) CO₂.
- **Comprehensive Service:** Offers a range of services from feasibility or FEED studies to full-scale EPC projects, tailored to meet the specific needs of various industries.
- **Full Integration:** Provide fully integrated P2X solutions (from Green Hydrogen, Carbon Capture to e-Fuel synthesis).

KEY PROJECTS

- **Mälarenergi 6 (Sweden) WtE:** The study is for a large-scale carbon capture plant treating flue gases from a Waste-to-Energy line in VÄSTERÅS region (Sweden). The study covers the integration of an HPC CATAcarb® CO₂ capture process for a nominal capacity of about 48 tonnes/hour. While maximizing recovered energy for district heating and using available on-site utility steam, the Mälarenergi unit optimises all benefits of the CATAcarb HPC process while minimizing external electricity needs.
- **Schwenk (Latvia) Cement plant:** The FEL-2 study is for a large-scale carbon capture plant treating flue gases from a Cement kiln in Broceni (Latvia). The study covers air quality control system (AQCS), Hot Potassium Carbonate (HPC) CATAcarb® CO₂ capture process, liquefaction, and heat integration for a nominal capacity of about 100 tonnes/hour. Leveraging CATAcarb proprietary vapor recompression technology, the all-electric design maximises efficiency with an energy requirement of 0.8 GJ/ton of captured CO₂.

KEY DATA

TRL	9	Capture Rate Range (tpd)	As per need	Capture Efficiency (%)	90%
Source CO ₂ Purity Range	>8% vol	System Energy (GJ/tCO ₂)	0.7 - 1.8	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	150	Number of Pilot Plants	6	Modular (Y/N)	Optional
Target Industries	Pulp & Paper, Iron & Steel, Power (WtE, Biomass, CHP), Cement, Gas Processing				



ARMENT OPTIPERM™ CARBON



SUMMARY

Ardent's advanced membrane technology offers a solvent-free, modular, scalable, and cost-effective CO₂ capture solution with low energy demand, suitable for small and large emission sources alike. With approximately 10,000 hours of operation across multiple pilot projects in a wide variety of industries, including steel, kiln, petrochemical, oil and gas, and waste-to-energy our Optiperm™ platform is proving its reliability in the field. Technical partners praise its ease of use, making Optiperm™ the ideal solution for a range of customers and industries, including those with limited CCS experience. Built on 30+ years of experience developing and commercializing new membrane technologies in various applications, Ardent ships over 1,000 units annually, setting the stage for rapid commercial deployment in the carbon capture space. Ardent works with companies across the carbon value chain to support end-to-end solution development.

BENEFITS

- **Low Cost, Even at Small Scale:** The modular nature of Optiperm™ membranes enables a low cost of capture, even at very small scale (< 50,000 tpa), where traditional technologies cannot compete.
- **Solvent Free, Fully Electrified:** Optiperm™ offers a chemicals-free easy-to-use capture solution for customers with no access to steam or water or that want to avoid permitting, HS&E and emissions issues associated with solvents.
- **Low Energy, Low Footprint:** Operation at low pressure without the need for regeneration cuts energy use by up to 40% compared to incumbent capture solutions, reducing both overall capture costs and system footprint.
- **Reduced Retrofit Complexity:** Optiperm™'s modular membrane configuration supports integration into existing industrial sites where footprint, utility access, and process disruption can limit conventional capture approaches.

KEY PROJECTS

Optiperm™ pilots are operational across multiple industries, with more on the way:

- **Kiln:** Our pilot at RHI Magnesita has been operating for over a year, demonstrating the technology's ease of use and suitability for cement, lime and other kiln operators seeking alternatives to solvent-based solutions.
- **Petchem:** OMV operated an Optiperm™ pilot for over 800 hours, successfully demonstrating the technology in a refinery application. Results from this work were published at ADIPEC 2025.
- **Oil & Gas:** Following successful lab trials, two US oil & gas partners have integrated Optiperm™ pilots into their operations.
- **Steel:** voestalpine has operated a pilot for over a year, with an additional steel customer launching in summer 2025.
- **Other:** Ardent has an operational Waste-to-Energy deployment, expanding Optiperm™ Carbon validation into another industrial flue gas application

KEY DATA

TRL	5 - 7	Capture Rate Range (tpd)	10 - 2,000+	Capture Efficiency (%)	Up to 95%
Source CO ₂ Purity Range	3 - 30+	System Energy (GJ/tCO ₂)	Design Specific	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	6	Modular (Y/N)	Yes
Target Industries	A wide variety of industrial use cases and smaller point sources such as small boilers, fired heaters, reciprocating engines, and waste-to-energy applications				



ARMENT PERMOVAL™ CARBON



SUMMARY

With over 30 years of experience developing and commercialising membrane technologies for difficult industrial separations, Ardent designs systems for applications where space, weight, energy use, and operational reliability are critical. Permoval™ Carbon membranes target ultra-low concentration CO₂ applications, including direct air capture and CO₂ capture from enclosed, inhabited spaces. In this application, Ardent's membranes are used as gas/liquid contactors to facilitate CO₂ transfer between gas streams and liquid absorbents, reducing ambient CO₂ concentration from 500 ppm to 9 ppm. This technology combination enables a space-, weight-, and energy-efficient solution that avoids the need for steam regeneration and supports the use of selected non-toxic absorbents, offering reduced maintenance and operational expenses compared with amines or scrubbers. The same membrane contactor approach is also informing Ardent's NGCC-focused development work for hybrid membrane-solvent carbon capture.

BENEFITS

- **Space and Weight Efficient:** Enables a hybrid solution designed to minimise space and weight requirements, both essential characteristics for enclosed space applications.
- **Reduced Regeneration Burden:** Removes the need for a steam regeneration step, eliminating associated temperature or pressure swing equipment and enabling a highly energy-efficient continuous process.
- **Selected Non-Toxic Absorbents:** Supports the use of selected non-toxic absorbents such as ionic liquids, reducing HS&E constraints associated with other solvents.
- **Low Maintenance:** Designed for simple operation with limited maintenance requirements. Broader membrane field experience supports confidence in membrane durability, while absorbent lifetime depends on the selected ionic liquid, operating conditions, and application profile.

KEY PROJECTS

- **Australian Defence Science & Technology Group:** Permoval™ Carbon has been evaluated with the Australian Defence Science & Technology Group for enclosed space CO₂ capture applications. The hybrid membrane contactor/liquid absorbent system was piloted in April 2022
- **Performance demonstration:** Testing demonstrated ambient CO₂ reduction from 500 ppm to 9 ppm using Permoval™ Carbon membranes as gas/liquid contactors with liquid absorbents.



KEY DATA

TRL	6	Capture Rate Range (tpd)	~	Capture Efficiency (%)	95+
Source CO ₂ Purity Range	500 - 2000 ppm	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Enclosed space applications, including submarines, spacecraft, mining, and other inhabited enclosed environments				



ARK CAPTURE SOLUTIONS HYBRID CARBON CAPTURE



SUMMARY

ARK Capture Solutions' patented Hybrid Carbon Capture Technology captures low-concentration point-source flue gases containing 4% to 15% CO₂ (solutions are also available for higher concentrations).

ARK delivers end-to-end capture solutions, providing CO₂ at the purity required by the customer and meeting the most stringent use and transport specifications. The process requires neither heat nor solvents and operates autonomously. With a compact footprint, commercial-scale units can be integrated into most existing industrial sites without modification.

While optimised for dilute streams, the technology also handles higher CO₂ concentrations. Its modular architecture enables the simultaneous treatment of multiple inlet streams with different CO₂ concentrations, providing high operational flexibility.

BENEFITS

- **Low Capture Cost:** Significantly reduced CAPEX and OPEX, thanks to (1) unique process integrations, (2) a modular design and (3) an autonomous data-driven asset.
- **Demonstrated in real conditions:** Fast upscaling development in real conditions, backed by three pilots. Strong partnerships to upscale the technology in line with the industry needs.
- **Universal solution:** Flexible technology suitable for all types of concentration, compatible with all plant configurations and all the transport modes. The CO₂ captured reaches a suitable grade for utilization and/or storage.

KEY PROJECTS

- **Prototype A:** First prototype of 1tpa, built in a R&D setup, in order to continuously improve the technology.
- **Prototype B:** Fully automated pilot of 50tpa, tested on various industrial flue gases and real conditions. Available for renting or for joint projects.
- **CO₂DISRUPT:** Mobile 1,000tpa industrial demonstration unit, tested at three industrial sites (Aperam – Industeel (ArcelorMittal) – Cinergie). Project awarded and supported by the SPW.
- **FEED Studies ongoing**

KEY DATA

TRL	6-7	Capture Rate Range (tpd)	>1	Capture Efficiency (%)	99%
Source CO ₂ Purity Range	4 - 98%	System Energy (GJ/tCO ₂)	0.4 - 2.4	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Power, Steel, Glass, (Petro)Chemistry, Waste-to-Energy, BECCS				

THE “STATE OF THE ART: CCS TECHNOLOGIES” COMPENDIUM SHOWCASES THE BREADTH AND DEPTH OF CCS TECHNOLOGY READY FOR DEPLOYMENT AND ALREADY DEPLOYED TODAY



ATOCO

DIRECT AIR CAPTURE (DAC) BASED ON RETICULAR MATERIALS



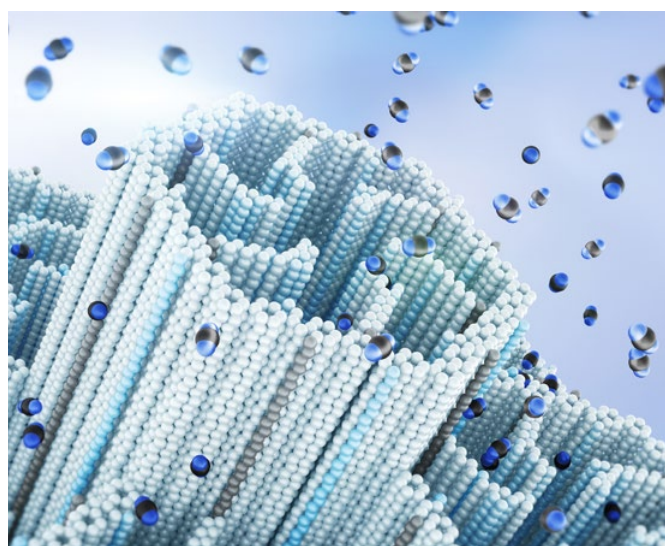
SUMMARY

Atoco develops advanced Direct Air Capture (DAC) adsorbent modules designed to remove CO₂ directly from the atmosphere at ultra-low concentrations. The technology leverages proprietary, humidity-stable, solid-state reticular materials that combine high CO₂ selectivity, superior working capacity, and rapid adsorption and desorption kinetics, enabling efficient operation under real-world environmental conditions.

Unlike conventional DAC technologies that rely on high-temperature regeneration or complex air pre-conditioning, Atoco's solutions capture CO₂ directly from humid air without pre-drying. The materials regenerate at temperatures as low as 40°C, enabling integration with low-grade ambient or waste heat, and significantly reducing energy consumption and operating costs. Designed for durability and long operational lifetimes, Atoco's DAC solution supports modular deployment and scalable atmospheric carbon removal across diverse geographies and climates.

BENEFITS

- **No Pre-Drying Required:** Captures CO₂ directly from humid air without energy-intensive air conditioning or drying.
- **Energy-Efficient CO₂ Capture:** Regeneration at temperatures as low as 40°C enables integration with ultra-low-grade ambient or waste heat.
- **High DAC Capacity:** Superior solid-state CO₂ uptake and rapid adsorption/desorption kinetics support high annual capture throughput.
- **Long-Lasting Performance:** Robust crystalline reticular structures maintain stability and capture capacity over tens of thousands of cycles.
- **Water-Free:** Solid-state sorbents eliminate water use for CO₂ capture, cooling, or regeneration, making the system well suited for deployment in arid regions and reducing operational complexity and cost.



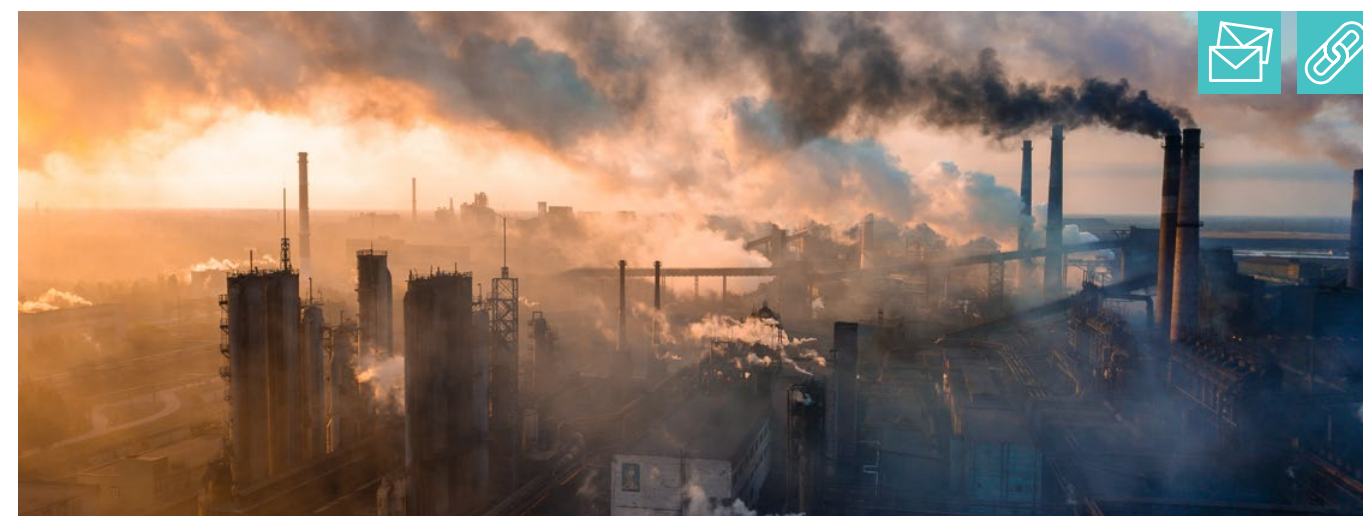
KEY DATA

TRL	6	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	>=0.04%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Carbon Dioxide Removal, Power-To-X (efuels), Data Centers, Greenhouses, Water Carbonation, Light and Heavy Industry, and Commercial operations that are difficult to decarbonise.				



ATOCO

POST COMBUSTION CARBON CAPTURE (PCC) BASED ON RETICULAR MATERIALS



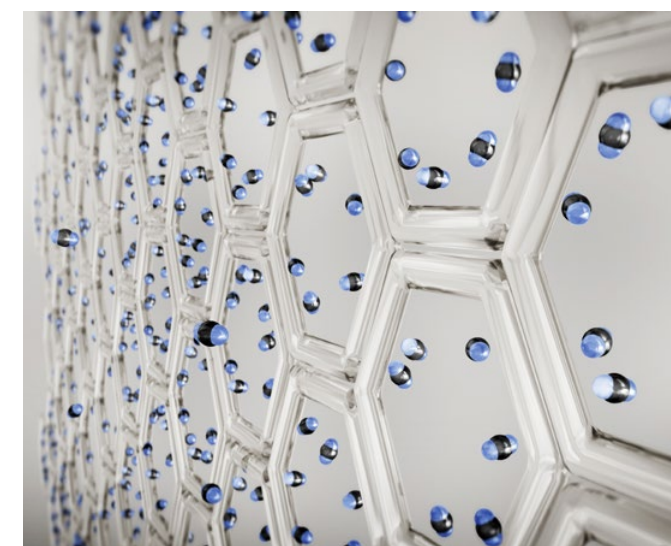
SUMMARY

Atoco develops next-generation post-combustion carbon capture adsorbent modules based on nano-engineered reticular materials. Founded by Nobel Laureate Prof. Omar Yaghi, the inventor of reticular chemistry, Atoco leverages atomically precise material design to optimise CO₂ selectivity, working capacity, and regeneration energy consumption. Atoco's proprietary materials are engineered to perform efficiently in low-concentration CO₂ environments (1–10%) and maintain superior performance in humid conditions, where conventional solvent and solid-state sorbent technologies face significant cost and energy penalties.

Atoco's solid-state solutions eliminate liquid solvents and avoid flue gas pre-drying. The materials regenerate at low temperatures, enabling the use of low-grade waste heat when thermal swing is applied, or operate in pressure swing configurations without heating, with both approaches significantly reducing energy consumption.

BENEFITS

- **Energy-Efficient CO₂ Capture:** Pressure swing requires no heating; thermal swing operates at low temperatures using low-grade waste heat.
- **No Pre-Drying Required:** Eliminates energy-intensive flue gas drying, lowering auxiliary energy demand and operational complexity.
- **High CO₂ Capture Capacity:** Record CO₂ uptake and rapid adsorption/desorption kinetics enable ultra efficient cycling and higher annual capture volumes.
- **Performance at Low CO₂ Concentrations:** Highly selective reticular materials enable efficient capture at concentrations as low as 1%.
- **Long-lasting Performance:** Robust solid-state technology ensures stable operation over tens of thousands of capture cycles.



KEY DATA

TRL	6	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	1 - 20%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Power Generation, Oil and Gas, Cement, Light and Heavy Industry, Chemical Production, Waste-To-Energy, On-Board Carbon Capture for Maritime Shipping				



BABCOCK & WILCOX

BRIGHTLOOP™ LOW-CARBON INTENSITY HYDROGEN PRODUCTION



SUMMARY

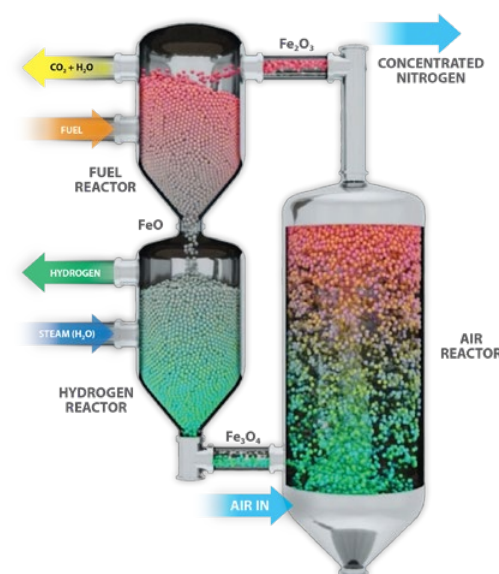
Babcock & Wilcox's BrightLoop™ chemical looping technology can use a variety of fuel stocks to produce hydrogen, syngas, steam, liquid fuel or methanol, and/or power while also producing a stream of concentrated CO₂ for sequestration and storage or other uses.

The patented BrightLoop process is based on the oxidation and reduction of an iron-based oxygen carrier TranspO₂rt™ particle and can produce separated streams of hydrogen and CO₂ from gas and solid fuels – including biomass, coal, waste fuels, natural gas, biogas, or others. In this process, fuel reacts with the TranspO₂rt™ particles in a fuel reactor, forming combustion byproducts, predominantly CO₂, while reducing the oxygen-carrier particles. The reduced oxygen-carrier particles then move to a hydrogen reactor where they react with steam to partially oxidise the particles and generate a stream of hydrogen.

The oxygen-carrier particles are then transported to an air reactor where they are regenerated with air back to their original state. The fuel and hydrogen reactors use moving bed technology while the air reactor uses fluidised-bed technology, both well-proven technologies with which B&W has extensive experience. Other emissions can be controlled using B&W's complete suite of environmental control technologies.

BENEFITS

- Hydrogen from solid fuels – can utilise a variety of solid or gaseous fuels as feedstock.
- High rate of carbon captured – inherent CO₂ isolation supports sequestration or utilisation without the expensive post combustion capture equipment and operation.
- Competitive hydrogen cost – lower levelised cost of hydrogen when compared to other hydrogen production methods.
- High quality hydrogen – production from steam produces higher quality as compared to separating hydrogen from fuel.
- Scalable for a range of applications – accommodates both large and small applications.



KEY DATA

TRL	6	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Oil & Gas, Refineries, Power Utilities, Iron & Steel, any medium to heavy industrial facility				



BABCOCK & WILCOX

OXYBRIGHT™ OXYGEN COMBUSTION



SUMMARY

B&W's OxyBright™ oxy-combustion process can be used to generate steam and power using a variety of fuels, including coal, natural gas, biomass, oil, and others. In the oxy-fuel process, combustion air is replaced with nearly pure oxygen and recirculated CO₂. Nitrogen that would normally be conveyed with the air through conventional air-fuel firing is excluded and the resulting flue gas consists of nearly pure CO₂. The non-recirculated flue gas leaving the boiler is cleaned using conventional particulate and sulfur removal systems and sent to the compression purification unit (CPU) where a high-purity CO₂ stream is produced that is suitable for transportation or other uses.

Combining B&W's OxyBright technology with biomass-fired technology, such as our bubbling fluidised-bed (BFB) boiler, along with carbon capture and sequestration, energy is produced with a net-negative carbon intensity. Biomass such as forest litter, construction and demolition waste, or agricultural byproducts, can fuel our BFB boiler. BECCS (bioenergy production with carbon capture and sequestration) is a highly scalable technology and is an emerging innovative solution to decarbonise emission-intensive industries.

BENEFITS

- The combustion process produces a concentrated CO₂ stream suitable for sequestration or other beneficial uses; no post-combustion equipment is required.
- Applicable to a variety of fuel sources.
- Can be retrofitted on existing plants or designed for new steam generation installations.
- Net-negative carbon intensity when biomass is the fuel source and is combined with carbon capture and storage (BECCS).

KEY PROJECTS

- B&W provided oxy-fuel technology for use with coal on the U.S. Department of Energy's FutureGen 2.0 demonstration project in Illinois, which was to be a retrofit of a 167 MW coal-fired power plant. Although construction began in 2014, the project was canceled in 2016 due to redirection of DOE funding support. B&W has continued to develop oxy-fuel technology and it is ready for full-scale commercialization and deployment.
- B&W has been selected for and is engaged in numerous BECCS studies for our OxyBright, BFB biomass and flue gas treatment (FGT) technologies.

KEY DATA

TRL	8	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	2	Modular (Y/N)	No
Target Industries	Utility Power, Medium to Heavy Industry, Waste/Biomass to Energy				



BABCOCK & WILCOX

SOLVEBRIGHT™ POST-COMBUSTION CARBON CAPTURE



SUMMARY

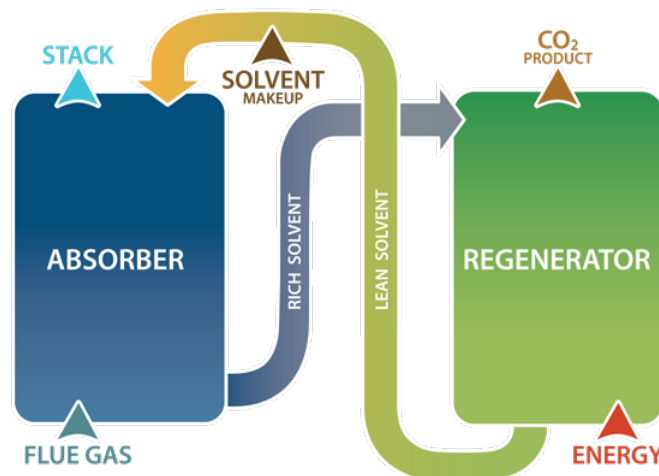
B&W's SolveBright™ regenerable solvent absorption technology scrubbing process came from decades of decarbonisation research and development.

The SolveBright carbon dioxide scrubbing system is a post-combustion carbon capture technology that captures CO₂ directly from flue gas in an absorber using a regenerable solvent. The CO₂-rich solvent is sent to a regenerator where it is heated, and the CO₂ is released as a concentrated stream for compression and storage or beneficial uses. The CO₂-lean solvent is then recycled to the absorber for reuse.

While B&W's solvent compared favorably with more than 100 competing solvents during our extensive testing procedures at the National Carbon Capture Center, a major advantage of the SolveBright process is solvent flexibility, which allows customisation of an optimal CAPEX and OPEX solution for each application. SolveBright can be used with a variety of solvents and we have the expertise and ability to use a wide range of potential solvents.

BENEFITS

- Solvent flexibility, allowing us to customise an optimal CAPEX and OPEX solution for each application.
- Knowledge of solvent scrubbing solutions for carbon capture since 2005; we understand the process, the equipment and the innovation behind the various types of solvents used.
- Experience across a wide range of industries with various fuels and combustion processes: from utilising waste and biomass as fuels to industries such as cement, steel, chemical, oil and gas, pulp and paper, food and beverage, and many others looking for reliable decarbonisation partners.
- Total solution support, from feasibility studies, pre-FEED and pilot unit definition, FEED studies, to full-scale plants, tailored to the customers' specific needs.



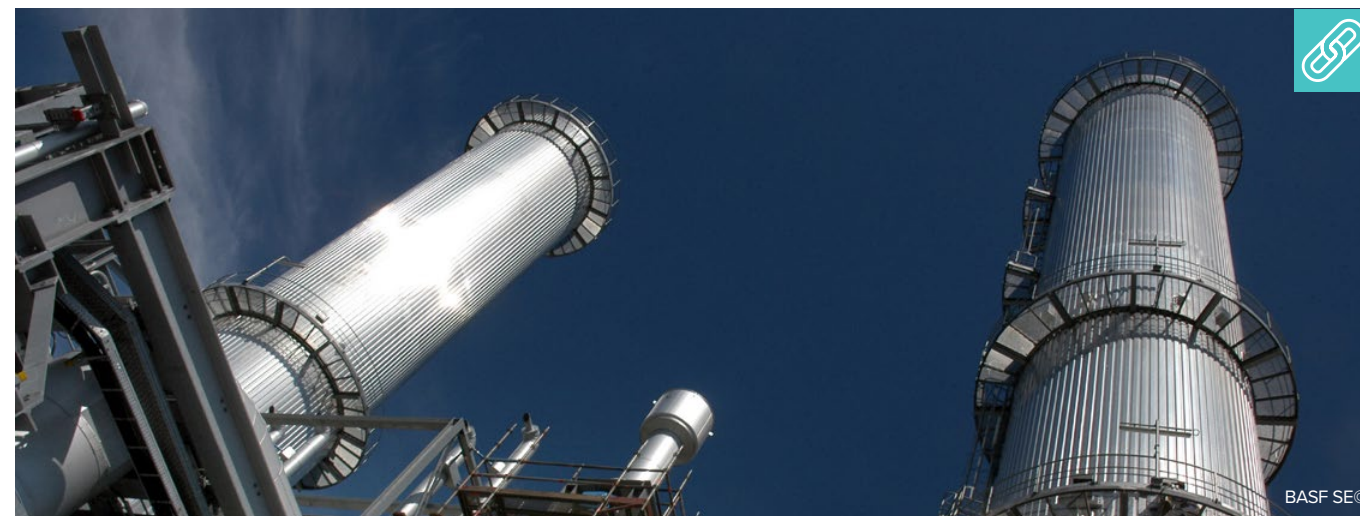
KEY DATA

TRL	8 - 9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	No
Target Industries	Utility Power, Medium to Heavy Industry, Waste/Biomass to Energy				



BASF OASE® GAS TREATING EXCELLENCE

OASE® blue



SUMMARY

At BASF, we create chemistry for a sustainable future. With more than 50 years of experience and 500+ reference plants worldwide, BASF offers customers amine-based gas treating solutions under the OASE® brand name for a variety of applications.

OASE® blue is a proven post combustion CO₂ capture technology based on innovative BASF's chemistry. Its **advanced solvent** demonstrates low energy consumption, low solvent losses and an exceptionally flexible operating range for flue gas with a wide range of composition, making it well-suited for both carbon capture storage and utilization (CCUS) applications.

BENEFITS

- **Project execution and commercial flexibility:** Non-exclusivity, plant design and troubleshooting, performance warranties
- **Global solvent supply:** In house solvent production and robust global supply chain to ensure consistent availability and quality
- **Customised solution:** CAPEX and OPEX optimised designs enabled by OASE® connect digital platform
- **Digitalization:** Solvent health monitoring with OASE® digilab
- **Environmental management:** Equipped with patented OASE® aerozone® design to reduce aerosol & vapor driven emission and amine losses

REFERENCES

Pilot & Demonstration

- RWE Niederaussem, Germany
- National Carbon Capture Center, USA
- CSSC Power (Group) Corporation Limited (CPGC), China: CO₂ capture pilot unit for marine engine exhaust gas
- City, Water, Light & Power (CWLP), USA: One of the largest CO₂ capture demonstration units for coal based power plant (200 tpd)

Operational: Commercial CCU Application

- Solvay-SIAD, Italy: Lime kiln and Process gas
- Messer, Austria: Lime kiln
- Linde-Heidelberg Materials CAP2U, Germany: Cement

Front End Engineering Design (FEED) Studies

- Southern Company's Natural Gas Combined Cycle and CO₂ capture project in USA, in joint collaboration with GE Vernova, Linde and Kiewit
- Kredslob Waste-to-Energy and Biomass Power Plant CO₂ capture project in Denmark with ANDRITZ
- Forestal del Atlántico's Triskelion e-MeOH project in Spain

KEY DATA

TRL	9	Capture Rate Range (tpd)	10 - 10,000	Capture Efficiency (%)	>95
Source CO ₂ Purity Range	3 - 40%+	System Energy (GJ/tCO ₂)	-	Specific Regen. Energy (GJ/tCO ₂)	as of 2.2*
Number of Commercial Plants	3	Number of Pilot Plants	4	Modular (Y/N)	Yes
Target Industries	Cement, Power Generation (Coal/Natural Gas), Blue Hydrogen/Ammonia, E-fuels, Waste-to-Energy, Marine				

*Excluding any waste heat recovered at CO₂ compression or flue gas upstream CO₂ Absorber



BASF OASE® GAS TREATING EXCELLENCE

OASE® green



SUMMARY

At BASF, we create chemistry for a sustainable future. With more than 50 years of experience and 500+ reference plants worldwide, BASF offers customers amine-based gas treating solutions under the OASE® brand name for a variety of applications.

OASE® green is a proven technology for capturing CO₂ for biogas application i.e conventional biogas upgrading with a targeted CO₂ slip of 2-5 vol.% CO₂ in the treated gas as well as for bio-LNG (liquefied biomethane) with a targeted CO₂ slip of <50 ppmv in the treated gas.

The design and configuration of the OASE® green unit can be customised depending on the customer's requirements, both CAPEX and OPEX optimised designs are possible. All designs are energy-efficient and show **very low methane losses and high CO₂ purity**.

BENEFITS

BASF provides:

- Non-exclusive access to OASE® green technology for customers and engineering companies
- Unique licensing model integrated with OASE® solvent sales produced and supplied by BASF
- Customised design, operating and analytical manuals
- Performance warranties
- OASE® connect digital platform for plant design and performance monitoring
- OASE® digilab with the capability to analyse the composition of OASE® green solvent in near real time

Latest Improvements

- BASF has recently re-engineered the formulation of the OASE® green solvent as well as optimised the technology to offer more operational benefits

KEY DATA

TRL	9	Capture Rate Range (tpd)	-	Capture Efficiency (%)	>99
Source CO ₂ Purity Range	40 - 50%+	System Energy (GJ/tCO ₂)	-	Specific Regen. Energy (GJ/tCO ₂)	2.0 - 2.5*
Number of Commercial Plants	8	Number of Pilot Plants	-	Modular (Y/N)	Yes
Target Industries	Biogas upgrading*, Bio-LNG				

* Process and configuration specific.

REFERENCES

Operational

Feed gas capacity: 3000-6000 Nm³/h

- Biogas upgrading plant in India: Produced from agricultural residues for use as compressed biogas (CBG)
- Biogas upgrading plant in Germany and USA: Produced from biomass for use in biorefinery



BASF OASE® GAS TREATING EXCELLENCE

OASE® purple



SUMMARY

At BASF, we create chemistry for a sustainable future. With more than 50 years of experience and 500+ reference plants worldwide, BASF offers customers amine-based gas treating solutions under the OASE® brand name for a variety of applications.

OASE® purple technology has proven its versatility and reliability in natural-gas applications, where it is used for the removal of acid gases such as CO₂ and H₂S. It offers broad range of solutions, including bulk and selective acid gas removal for sales gas and deep acid gas removal for liquefied natural gas (LNG) applications. Leveraging BASF's extensive technical experience and reference plants in these applications, OASE® purple designs can be **tailored to a wide range** of feed gas and product specifications; while optimizing CAPEX and OPEX in line with project requirements. BASF's design capabilities also extend to **floating** application, supported by established operational references.

BENEFITS

- Designed to handle CO₂, H₂S, COS and mercaptans removal with high operational flexibility
- Customised solution for greenfield, revamp, debottlenecking and solvent swap projects, supported by OASE® connect digital platform
- Flexible collaboration with engineering partners, contractors and customers for project delivery
- Superior energy efficiency and performance warranties
- Global solvent availability and technical support
- Operational knowhow in plant troubleshooting
- Quick solvent health monitoring with OASE® digilab
- Maximizing operational benefits with BASF Durasorb® adsorbents for efficient removal of contaminants
- Expertise in Computational Fluid Dynamics (CFD) and maritized design for floating application

REFERENCES

Operational

- Acid gas removal unit (AGRU) integrated with one of the world largest carbon capture and storage (CCS) sequestration sites
- Global presence and proven track records in mega LNG plants with >7 mtpa LNG per train
- Floating application: PETRONAS PFLNG DUA, Malaysia and Eni Coral South FLNG, Mozambique

Under Construction

- Several large scale LNG and sales gas plants in Africa, Asia and North America
- Qatar Energy North Field Expansion Project
- Nearshore and deep-sea FLNG plants

KEY DATA

TRL	9	Capture Rate Range (tpd)	up to 7,000+	Capture Efficiency (%)	99.9
Source CO ₂ Feed Range (vol%)	0.05 - 40%+	System Energy (GJ/tCO ₂)	-	Specific Regen. Energy (GJ/tCO ₂)	0.7 - 4.0*
Number of Commercial Plants	160+	Number of Pilot Plants	-	Modular (Y/N)	Yes
Target Industries	Sales gas, LNG, Floating Liquefied Natural Gas (FLNG), Floating Production, Storage, and Offloading (FPSO)				

*Process and configuration specific



BASF OASE® GAS TREATING EXCELLENCE

OASE® white



SUMMARY

At BASF, we create chemistry for a sustainable future. With more than 50 years of experience and 500+ reference plants worldwide, BASF offers customers amine-based gas treating solutions under the OASE® brand name for a variety of applications.

OASE® white is a proven technology for removing CO₂ and H₂S from synthesis gas (syngas). It has been widely used in industrial ammonia, hydrogen and syngas production. Known for its versatility and reliability, OASE® white consistently meets the requirements across a wide range of feed compositions. OASE® white also plays a key role in **low carbon energy** solutions, supporting blue hydrogen and blue ammonia production through highly efficient CO₂ capture rate up to 99.99 mol% while meeting the CO₂ purity requirement for carbon capture and storage (CCS). With its superior energy consumption and flexible design configurations, OASE® white remains a leading choice for large-scale production.

BENEFITS

- Collaboration with reputable technology licensors and engineering partners, integrated into their technology packages with performance warranties
- Proven track records in diverse applications i.e. steam methane reforming (SMR), autothermal reforming (ATR), partial oxidation (POX), pressure swing adsorption (PSA) tail gas, direct reduction iron (DRI), gasification and specialty chemicals
- Experience with revamps for plant debottlenecking and energy optimization
- Customised solution with CAPEX and OPEX optimised designs enabled by OASE® connect digital platform
- **Innovation: Low-low pressure (LLP) flash configuration with even better energy efficiency than best-in-class two-stage absorption process**

REFERENCES

Demonstration

- Tomakomai CCS Demonstration Project, Japan

Operational

- Multiple world scale SMR based ammonia plants, including capacity >3000 mtpd
- DRI steel plants in India, Saudi Arabia and UAE

Under Construction

- World scale ATR based ammonia and hydrogen projects in Australia and USA respectively

Front End Engineering Design (FEED)

- HyNet Low Carbon Hydrogen Production Plant (HPP1), UK

KEY DATA

TRL	9	Capture Rate Range (tpd)	20 - 4,000+	Capture Efficiency (%)	99.9
Source CO ₂ Feed Range (vol%)	3 - 40%+	System Energy (GJ/tCO ₂)	-	Specific Regen. Energy (GJ/tCO ₂)	0.6 - 3.6*
Number of Commercial Plants	300+	Number of Pilot Plants	-	Modular (Y/N)	Yes
Target Industries	Ammonia, Hydrogen, Syngas, Steel, Low carbon fuels				

*Process and configuration specific



CAPSOL TECHNOLOGIES ASA

FULL-SCALE CO₂ CAPTURE SOLUTION



SUMMARY

Capsol Technologies provides carbon capture solutions designed to reduce emissions from industrial facilities and power generation. The company's portfolio includes CapsolEoP®, a full-scale end-of-pipe carbon capture system for large industrial plants and CapsolGT®, a solution tailored for simple-cycle gas turbines. The company offers CapsolGo® mobile demonstration units to de-risk customer's flue gases and test the capture performance on-site.

All technologies use the safe, widely available hot potassium carbonate (HPC) solvent, and Capsol's integrated heat recovery to improve energy efficiency and reduce operational costs compared with conventional amine systems. The technology solutions are fully electric, require minimal water use, and are designed for end-of-pipe integration with existing facilities, resulting in minimal plant modifications. Through demonstration campaigns, engineering studies, and project partnerships across Europe and North America, Capsol supports industries including cement, biomass, energy-from-waste, and power generation in progressing from technology validation to full-scale carbon capture deployment.

BENEFITS

- **Energy-efficient carbon capture:** Industry leading low energy requirements for carbon capture, often below 1,0GJ/tonnes of CO₂.
- **Flexible integration:** Can be applied as a fully-electric system (typically in cement or steam exporting power plants) or with heat integration (e.g. district heating plants)
- **Leading HPC knowledge in post-combustion:** Over 20,000 hours of flue gas operation through demonstration testing on cement, biomass, energy from waste and others, de-risking and validating capture performance.
- **Safe and scalable solvent technology:** Utilises non-toxic hot potassium carbonate (HPC), offering low solvent degradation, reduced environmental impact, and easier permitting.

KEY PROJECTS

- **Stockholm Exergi BECCS Project:** Large-scale bioenergy with carbon capture and storage project deploying Capsol's technology. The facility is expected to capture 800,000 tonnes of CO₂ annually when operational in 2028.
- **US gas turbine projects:** Capsol is involved in multiple gas turbine projects intending to integrate CapsolGT® for additional net power output when applied for simple cycle turbines.
- **Industrial Engineering studies:** Capsol has conducted more than 30 engineering studies for carbon capture projects across cement, lime, metals, biomass, refining, and waste-to-energy sectors.
- **R&D development platform:** Demonstration units also support technology testing and optimization from Capsol's Technology and R&D Center in Norway.

KEY DATA

TRL	7 - 8	Capture Rate Range (tpd)	100 - 5,500	Capture Efficiency (%)	90 - 95%
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	0.7 - 1.5	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	3	Modular (Y/N)	No
Target Industries	Cement, Biomass, Energy from Waste/Waste to Energy, Lime, Pulp and Paper, Power Generation, and Process Industries.				



CAPTIVATE TECHNOLOGY MUF-16 ADSORBENT

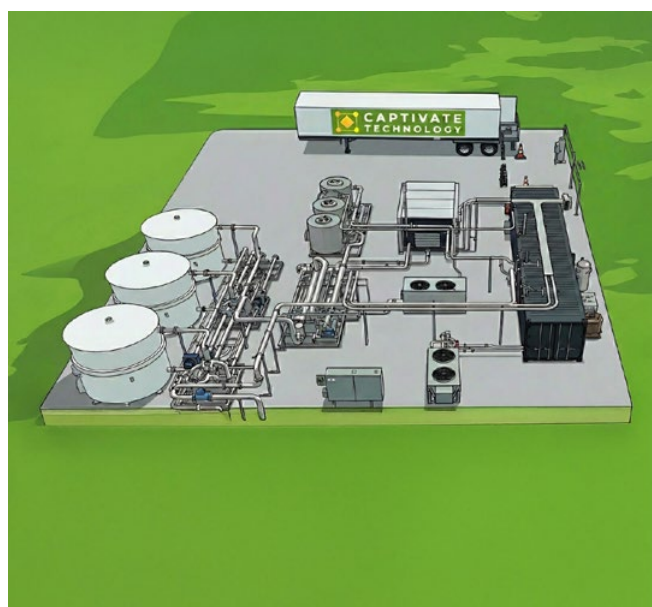


SUMMARY

Captivate Technology has commercialised a porous, solid-state adsorbent that selectively sieves carbon dioxide from crude biogas and flue gas streams. This metal-organic framework, known as MUF-16, captures CO₂ using a conventional pressure-swing adsorption process. The system generates a high-purity stream of carbon dioxide suitable for storage or industrial use. In biogas applications, it produces renewable natural gas with purity and recovery rates exceeding 98%. MUF-16 is a low-cost material that remains stable in the presence of water vapor and common impurities, contributing to a long operational lifetime. Because the process operates at low feed pressures, energy consumption is significantly reduced compared to incumbent methods. Captivate is currently moving toward full-scale operation alongside industrial partners, offering a practical business case driven by low capital and operating costs and the ability to extract maximum value from both methane (as RNG) and carbon dioxide streams.

BENEFITS

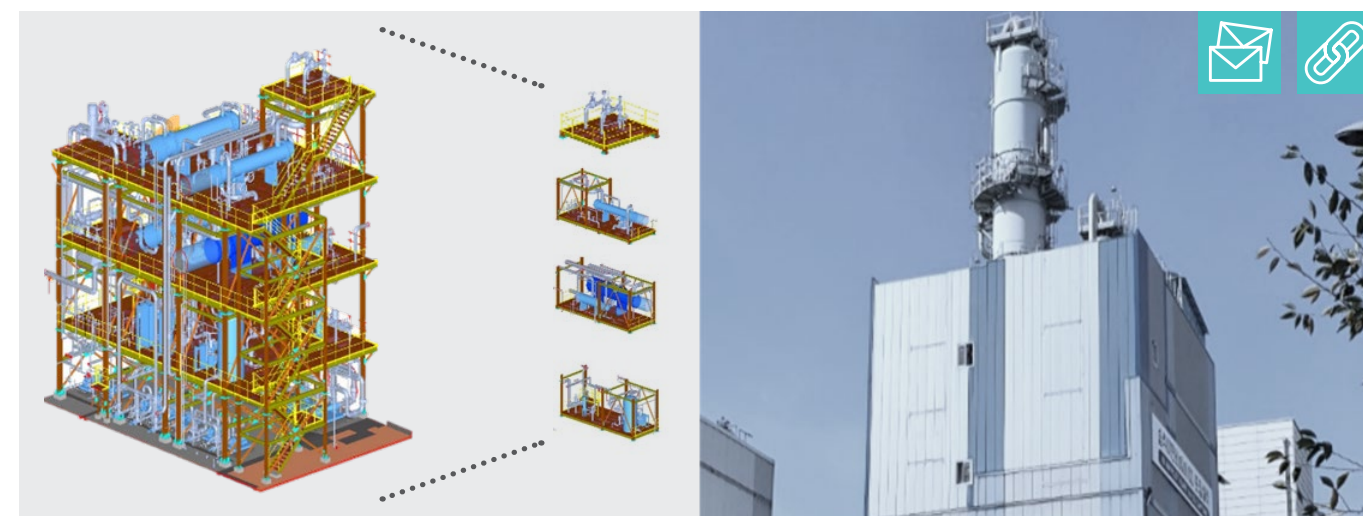
- Robust, inexpensive and easily-handled solid-state adsorbent
- High selectivity for CO₂ over other gases such as nitrogen and methane
- Tolerant of impurities such as acid gases with no unwanted side-reactions
- Maintains carbon capture performance with humid gas streams.
- Low energy penalty for CO₂ desorption and recycling due to weak physisorption interactions
- Short cycles times are possible owing to the rapid uptake and release kinetics
- Compatible with conventional pressure-swing adsorption processes
- Applicable to wide range of flue gases and biogas
- Full technical support provided by Captivate's team



KEY DATA

TRL	5	Capture Rate Range (tpd)	1 - 1,000	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	>4%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	<1
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Fossil combustion, cement, geothermal, SMR, biogas, syngas, built environment, gas-fired engines and turbines				

CARBONCO CARBONCAP™ CO₂ CAPTURE TECHNOLOGY



SUMMARY

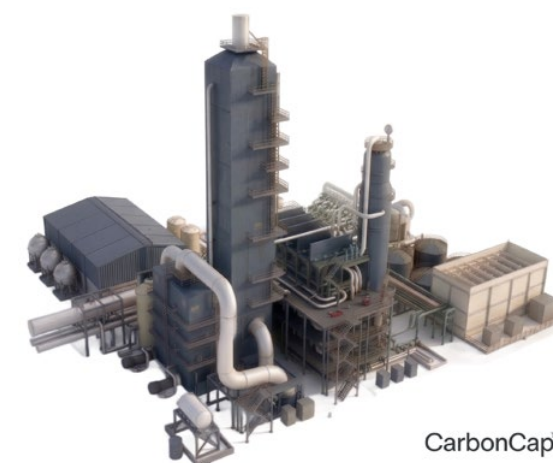
CARBONCO is a leading technology provider specializing in post-combustion carbon capture through its proprietary amine-based solvent. As a specialised licensor, CARBONCO delivers cost-effective, customised designs using optimal standardised engineering models. With extensive global experience and operational know-how, its cutting-edge technology is ready for deployment across all scales, ranging from small-scale modular (2 TPD) to large commercial projects (over 1M TPA).

Through strategic partnerships with major CCUS stakeholders, CARBONCO's solutions have been rigorously validated across diverse operational environments. By integrating advanced engineering with state-of-the-art solvent technology, CARBONCO empowers industries to meet climate targets efficiently.

The CARBONCO R&D Center drives continuous innovation, focusing on energy efficiency, operational stability, and solvent performance. Through pilot testing and system integration studies, the center ensures that CAROBNCO's carbon capture systems remain scalable, reliable, and future-ready for the global energy transition.

BENEFITS

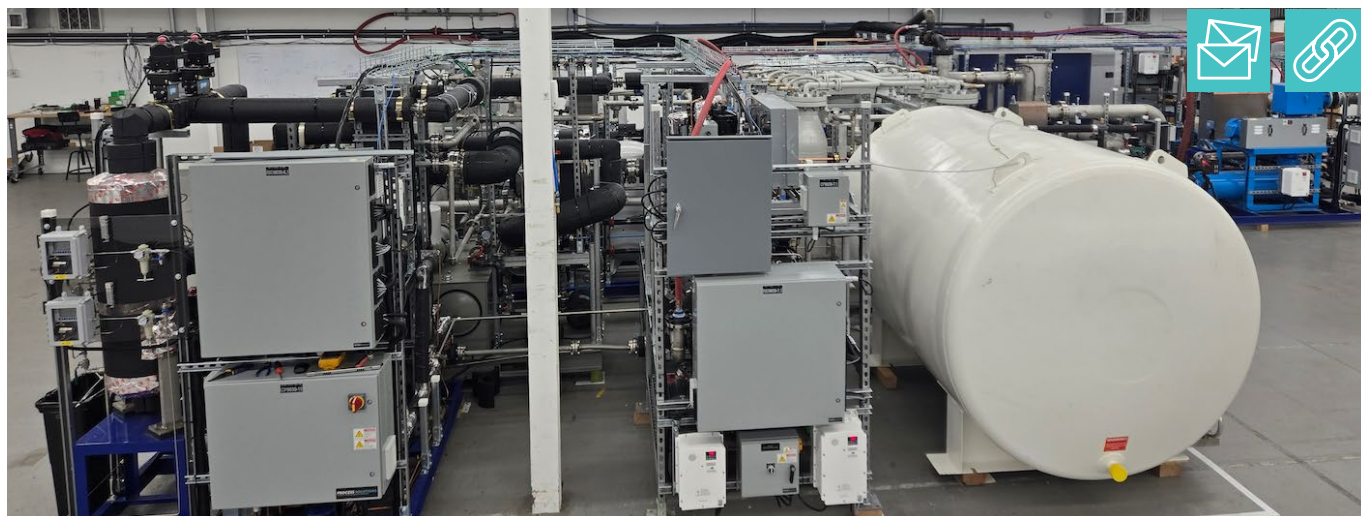
- **Proven Operational Reliability:** long-term reliability through over 10 years of continuous operation at a commercial-scale facility in South Korea.
- **High Efficiency & Purity:** Achieves 90% CO₂ recovery rate and 99.9%+ CO₂ purity, meeting the most stringent industrial specifications.
- **High Performance:** Maintains competitive energy consumption through continuous process innovation, achieving ≤ 2.3 GJ per tonne of CO₂ captured.
- **Diverse Portfolio of Solvents:** Provides flexibility to meet specific customer requirements through a diverse solvent portfolio, including proprietary in-house developed solvents.



KEY DATA

TRL	9	Capture Rate Range (tpd)	2 - 4,000	Capture Efficiency (%)	>90%
Source CO ₂ Purity Range	>3%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	<2.3
Number of Commercial Plants	1	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Oil&Gas, Power Plant, Petrochemical, Waste-to-Energy, Cement, Steel, Glass & Chemicals, Fertiliser & Urea				

DISTRIBUTED CARBON CAPTURE™



SUMMARY

CarbonQuest provides distributed carbon capture solutions for small-to-medium sized applications, using modular, containerised solid sorbent technology. CarbonQuest's primary markets are capture from biogas; oil and gas infrastructure including compressors; low carbon power generated by natural gas systems (fuel cells, engines); and industrial boilers in multiple segments, including re-use of CO₂ in the food and beverage market. System sizes range from 1000 tpy or 2 MW, up to 300,000 tons of CO₂/yr or up to 100MW in low carbon power applications.

The technology does not require large towers, there are no toxic chemicals or water in the process, and the modular approach allows for ultimate flexibility on site. The solution is also versatile to work with gas heating and power systems: our current projects include distributed carbon capture™ with boilers (heating), CHP, RICE engines, and fuel cells (power or heating + power).

BENEFITS

- **Modular & Expandable:** modular systems can be stacked for larger applications by using parallel systems to achieve up to 300,000 tons/year or up to 100 MW of power.
- **Economic Value:** Can reduce cost of onsite power up to 24%. Significant value over electrification. Value stack can include tax incentives and CO₂ sales.
- **Distributed:** proven track record of projects in remote areas (compressors) and smaller applications (food & bev or biogas) that are not well suited for larger amine solutions.
- **End-to-end Solution:** For each client to take care of the CO₂ offtake. Our offtaker MOUs span every region of the US and multiple options from monetizing CO₂ on the market to sale into green concrete or SAF, and mineralization and sequestration. We handle transportation logistics and co-location options.

KEY PROJECTS

- **Project One:** 5 smaller projects that capture CO₂ from boilers in New York. These projects were built to prove out the technology in a commercial setting, demonstrating that solid sorbents and small physical footprint can capture CO₂.
- **Project Two:** capture engine emissions from a pipeline compressor station in Alberta, Canada to highlighting new materials (MOFs) and ability to address emissions in remote locations for oil & gas infrastructure.
- **Project Three:** a beverage ingredient maker that captures and re-uses the CO₂ onsite. The CO₂ is purified by CarbonQuest to ISBT beverage grade standard. Lower CO₂ cost for customer + security of supply.
- **Project Four:** 3 Fuel cell+carbon capture energy hub projects coming online in 2027. These projects provide 5MW of power each while reducing CO₂ emissions from the gas-fueled fuel cell. A solution for utilities and smaller data centers.

KEY DATA

TRL	8 - 9	Capture Rate Range (tpd)	2 - 822	Capture Efficiency (%)	92 - 97%
Source CO ₂ Purity Range	4 - 99	System Energy (GJ/tCO ₂)	1 - 2.9	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	10	Number of Pilot Plants	~	Modular (Y/N)	Y
Target Industries	Low carbon power for data centers and industrials; biogas; oil&gas; district/campus energy; industrials; food & beverage onsite re-use				

CATACARB® HOT POTASSIUM CARBONATE



Over 65 years of expert HPC CO₂ removal design for
200+ UNITS WORLDWIDE IN 35 COUNTRIES

SUMMARY

The CATACARB® process provides an efficient, reliable and environmentally responsible method for capturing CO₂ without modifying upstream technologies. For over 65 years, CATACARB has specialised exclusively in hot potassium carbonate (HPC) CO₂ capture. CATACARB technology is available via direct licences or select partnerships. The process includes optimised HPC design using a database from over 200 licensed plants and 40,000,000 plant operating hours, optional proprietary performance additives, and ongoing technical support. CATACARB additives enhance the process by significantly improving efficiency, providing corrosion protection enabling carbon steel construction, and reducing plant footprint, lowering both CAPEX and OPEX.

Exxon Sabic's EO plant in Gregory, Texas, one of the world's largest, uses CATACARB to capture 260 kta at a 90% CO₂ capture rate. Pemex's ammonia plant in Cosoleacaque, Mexico, uses CATACARB to capture 1.25 mtpa at a 99.6% capture rate. Many CATACARB units have supplied high-purity CO₂ to the beverage industry since the 1990s.

BENEFITS

CATACARB prioritises health and the environment. The HPC solution is non-volatile and the process forms no carcinogens. There is no solvent in the high-purity final product.

CATACARB HPC with performance additives inhibits corrosion, allowing carbon steel construction. The additives increase CO₂ removal efficiency by 30–40% compared with basic HPC and do not degrade, thereby minimising solution make-up and reducing OPEX. These qualities enable a smaller footprint and lower CAPEX.

Compared with other technologies, low energy requirements for solvent regeneration and reduced steam demand allow an electricity focus when needed. CATACARB is a fully closed system and can recover heat for district heating.

CATACARB has extensive experience and leverages data from ongoing support to over 150 clients in 35 countries, totalling 40,000,000 plant operating hours.

KEY DATA

TRL	9	Capture Rate Range (tpd)	1 to 10,000+	Capture Efficiency (%)	90 - 95%
Source CO ₂ Purity Range	>8%vol	System Energy (GJ/tCO ₂)	0.7 - 1.8	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	202	Number of Pilot Plants	2 (flue gas)	Modular (Y/N)	Optional
Target Industries	Power, Steel, Cement, Refining & Petrochemical, Waste-to-Energy, BECCS, Pulp & Paper, Gas Processing, and Industrial Flue Gases				

KEY PROJECTS

Stockholm Exergi's biomass CHP plant Värtaverket in Stockholm, Sweden, has licensed CATACARB HPC technology. Only CATACARB provided the Enhanced HPC PDP for 800 kta CO₂ capture and only CATACARB provides ongoing HPC support. Commissioning planned in 2028.

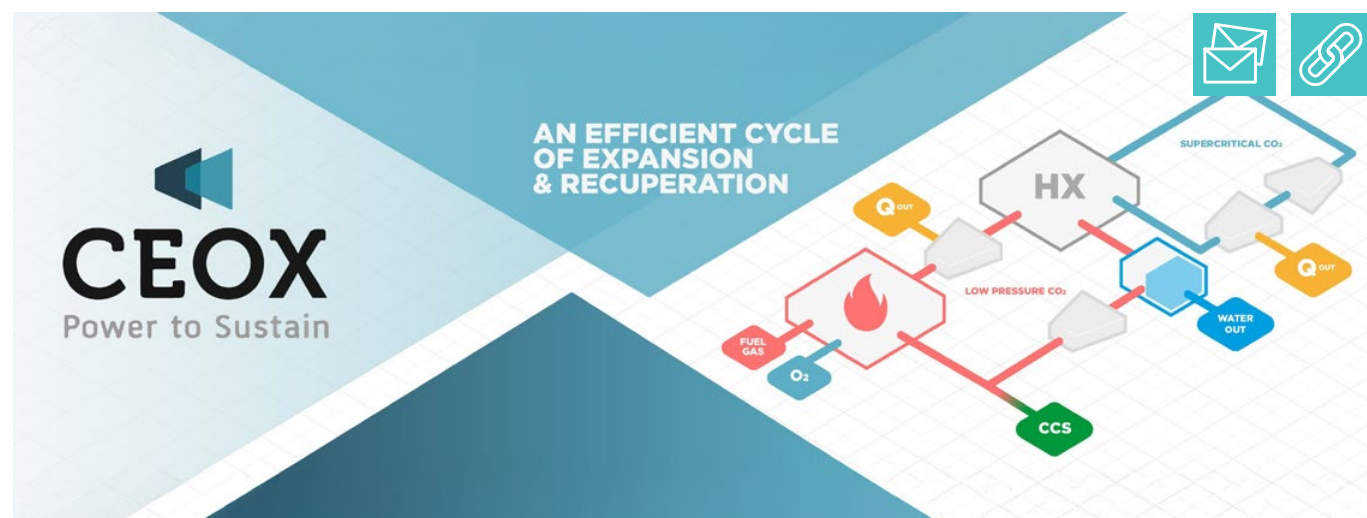
KEZO's waste-to-energy plant in Hinwil, Switzerland, selected CATACARB HPC for a ~1 tpd post-combustion CO₂ unit targeting 90% capture, with CATACARB and Sulzer demonstrating flexible, energy-efficient operation. Commissioning planned in 2026.

Karbon Korea's fully electric demonstration unit, built in 2023, captures 1.5 tpd of CO₂ with 90–96% capture at multiple South Korean sites using CATACARB HPC technology, design and support.

Schwenk's cement plant in Brocēni, Latvia, a 2025 FEL-2 study with Andritz, applies Enhanced HPC for an all-electric CO₂ capture plant, targeting 0.8 GJ/tonne at 100 tonnes/hour.



CEOX POWER WITH INHERENT CAPTURE TECHNOLOGY



SUMMARY

CEOX is a power-with-inherent-capture technology. It uses oxy-combustion with a nested supercritical CO₂ power generation loop. Every element of the CEOX cycle uses fully mature equipment with decades of operational experience. The only new technology is the thermodynamic power generation cycle itself.

CEOX offers emissions-free power generation with 100% inherent capture of CO₂. The pressurised CO₂ outflow is high-quality and ready for disposal via CCS. Power is generated via a semi-closed combustion loop with CO₂ recycle, nested with a closed supercritical CO₂ loop.

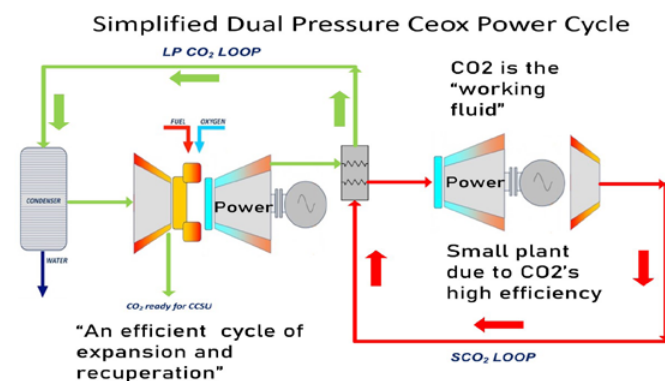
The post-oxy-combustion mix of CO₂ and water is inherently contained at pressure within the process, eliminating the need for CO₂ capture and compression. CEOX has application for any hydrocarbon power and heat generation, where a CCS network is available to dispose of the CO₂.

BENEFITS

- **No new technology:** Its dual pressure design permits the use of proven materials and available equipment, meaning a CEOX system is present day technology ready for implementation now.
- **Emissions free:** CEOX delivers emissions-free industrial power and heat in any application where a CCS network is present to facilitate CO₂ disposal.
- **Efficient:** CEOX uses supercritical CO₂ to generate its power which does >50% more work than steam when converting heat into power. This enables high efficiency, lower cost, and smaller power plants.
- **Low CO₂ capture cost:** CEOX adds value to an industrial process by integrating high availability power with CO₂ capture at no extra cost for capture.
- **Highly Economic:** Efficiency >15% better than industrial normal and still at no extra cost for CO₂ capture.

KEY PROJECTS

- **CEOX Concept Basis of Design:** 2017 Thermodynamic modelling, supply chain validation, NIST validation and independently peer reviewed engineering study.
- **Project One:** CEOX is currently in FEED for a 50MWe modular power plant to pave the way for developing a full-scale demonstration plant.



KEY DATA

TRL	5	Capture Rate Range (tpd)	700 tpd / 50MWe	Capture Efficiency (%)	>99%
Source CO ₂ Purity Range	N/A	System Energy (GJ/tCO ₂)	N/A	Specific Regen. Energy (GJ/tCO ₂)	N/A
Number of Commercial Plants	0	Number of Pilot Plants	0	Modular (Y/N)	Yes
Target Industries	All thermal industrials incl: LNG, Water desal, Blue H ₂ , Ammonia, Methanol, CCS cluster CO ₂ compression, Petrochemicals, Oil and Gas process, Direct air capture, SMR, ATR etc.				



CRYOCOLLECT CARBOLIQUE



SUMMARY

The Carbolique process, developed by CryoCollect, is a patented technology designed to capture and valorise carbon dioxide from CO₂-rich streams that produces high-purity, food-grade liquid CO₂. Carbolique transforms what is typically a waste stream into a valuable resource. Its flexible design allows integration with various industrial sources and different gas compositions (minimum 80% CO₂) and impurity levels.

The process involves multiple purification and liquefaction stages, including compression, drying, condensation using natural refrigerants, and distillation. Initially, the gas is compressed and dehydrated, followed by removal of volatile compounds through low-temperature condensation and washing. The purified CO₂ is then cooled to cryogenic conditions to be liquefied and separated from other gases such as methane and nitrogen. Carbolique is a modular process that ensures efficient CO₂ recovery with minimal losses and high product quality.

BENEFITS

- **In-house Expertise:** CryoCollect has a deep know-how in gas treatment and cryogenic processes, supported by multiple patents and demonstrated by several projects in France and around the world.
- **Proven Track of Record:** Carbolique brings 7 years of industrial experience with 14 operational plants across France producing high-purity, food-grade liquid CO₂. It has demonstrated reliable performance, operational robustness, and consistent product quality.
- **Modular Approach:** Carbolique plug-and-play architecture enables straightforward integration into existing industrial sites. Its modularity provides flexibility for various capacities.
- **Energy Efficiency:** Carbolique process achieves a specific energy consumption below 0.25 kWh per kg of pure liquid CO₂.

KEY PROJECTS

- **Methavie (Commissioned in October 2022):** Equipped with Carbolique's technology, this unit produces up to 5,000 tonnes per year of pure, certified food-grade liquid CO₂ from methanization off-gas, supplying the local market with a reliable, low-carbon source of CO₂.
- **Medoc (Largest installed unit):** The largest plant of this technology currently installed in France, designed to produce over 10 000 tonnes of liquid CO₂ per year from methanization off-gas. Its configuration demonstrates the scalability of Carbolique's process for higher-capacity installations.
- **Fermentation Off-Gas Purification:** The project involves the recovery and purification of 100 TPD fermentation off-gas to produce food-grade LCO₂. The facility is planned for commissioning in February 2027. CryoCollect is in charge to perform the engineering studies and complete process and plant design for this facility.

KEY DATA

TRL	9	Capture Rate Range (tpd)	5 - 240	Capture Efficiency (%)	99.9%+
Source CO ₂ Purity Range	>80%	System Energy (GJ/tCO ₂)	<0.9	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	14	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Bio Gas, Oxy-Combustion, Anaerobic Digestion, Bio Ethanol, Land Fills, Etc.				



DECARBONTEK

FIBERSORB™-DAC FOR DIRECT AIR CAPTURE



SUMMARY

Decarbontek's Fibersorb™-DAC technology is a direct air capture (DAC) solution that integrates high-performance adsorbent materials into mechanically robust fibre contactors. These structured modules exhibit excellent air flow dynamics and high CO₂ adsorption capacity, which enables efficient carbon capture from ambient air. The fibres demonstrate strong stability under cycling conditions and can be regenerated at low temperatures (below 100 °C), which significantly reduces energy demand compared with high-temperature systems. Fibre regeneration can be driven by flexible energy sources, including renewable electricity and industrial waste heat, making the process adaptable and energy-efficient for scalable carbon removal applications.

BENEFITS

- **Structured Modular Design:** High performance solid adsorbents designed for DAC are shaped into fibres and wound into structured contactors with superior mass and heat transfer rates.
- **Low Regeneration Temperature:** The adsorbent fibres can be regenerated at temperatures below 100 oC, allowing energy efficient operation.
- **Passive DAC:** The novel adsorbent fibres enable efficient passive DAC, eliminating energy intensive fans.
- **Ideal for Mobile Applications:** Decarbontek's DAC process can be powered by renewable electricity, making it ideal for mobile applications.



KEY DATA

TRL	5	Capture Rate Range (tpd)	0.01 - 1,000	Capture Efficiency (%)	>99%
Source CO ₂ Purity Range	0.04%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Transportation, Food and Beverage, Oil & Gas, Green Fuels, Climate Control, Green Houses				



DECARBONTEK

SPK™ MOF CARBON CAPTURE PROCESS



SUMMARY

Decarbontek's SPK™ CO₂ capture process is an advanced post-combustion solution that significantly lowers the cost of carbon capture. This technology delivers over 30% CAPEX reduction and more than 70% OPEX reduction compared to conventional solvent-based systems.

SPK™ is built on several key innovations. First, it uses DCF-1, a low-cost, high-performance MOF sorbent designed to match the price of conventional molecular sieves while offering superior CO₂ adsorption. Second, structured, helically wound Fibersorb™ MOF fibre contactors enhance mass transfer, reduce pressure drop, and enable compact system design. Third, the contactors regenerate through a fast, low temperature process that leverages low-grade waste heat, dramatically reducing energy consumption. Alternatively, Decarbontek's SPK™ process can also be powered by renewable electricity.

BENEFITS

- **Zero Emission and Degradation:** Solid, stable DCF-1 MOF adsorbent does not degrade.
- **Significant CAPEX Savings:** DCF-1 MOF is synthesised from abundant raw materials, enabling low-cost manufacturing and a reliable supply chain.
- **Compact and Modular Design:** DCF-1 MOF adsorbent is shaped into advanced fibre contactors and packed into structured modular devices.
- **Significant OPEX Savings:** By regenerating via waste heat rather than conventional steam methods, the SPK™ process can cut OPEX more than 70% compared with amine systems without waste heat recovery.



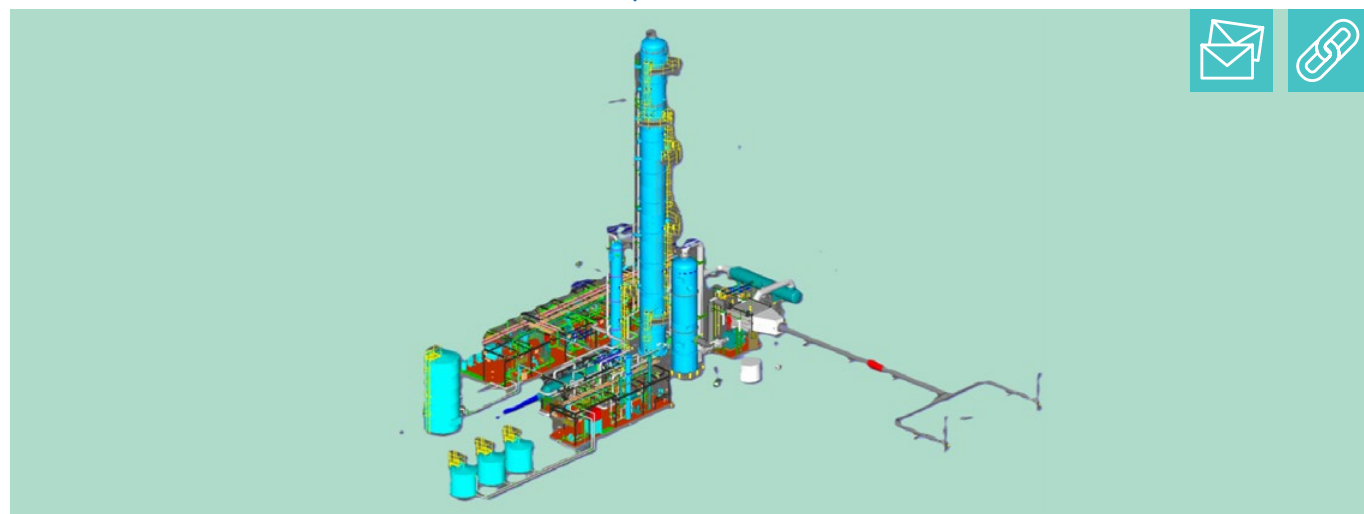
KEY DATA

TRL	5	Capture Rate Range (tpd)	0.1 - 1,000	Capture Efficiency (%)	>90%
Source CO ₂ Purity Range	4 - 50%	System Energy (GJ/tCO ₂)	< 1.7	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Power Plants, Refineries, Chemical Manufacturing, Cement, Oil & Gas, Transport, Maritime				



DELTA CLEANTECH

LOW-COST DESIGN CARBON CAPTURE TECHNOLOGY, CARBX®



SUMMARY

Since 2004, Delta CleanTech (DELTA) has been globally recognised as a leading technology provider for industrial Post-Combustion Carbon Capture and Solvent Reclamation focused on “Capturing Sustainability”. This means delivering innovative, commercially sustainable, and socially beneficial solutions for micro, small, and medium scale modular carbon capture and solvent reclamation projects.

In addition to providing engineering services, DELTA’s patented and proprietary solutions include CarbX modular carbon capture systems, PureRX modular solvent reclaimers, and SolvX licensed open-access solvents

As the newest member of the Scovan Group of Companies, DELTA is located in Calgary, Alberta, Canada and now able to provide end-to-end carbon capture solutions, from owner’s engineering to full lump sum turnkey EPFC services with aftersales support.

BENEFITS

- **Scalability:** Modular systems available from 1–1,200 TPD.
- **Simplicity:** Integrated solvents and modular systems simplify design and operation.
- **Affordability:** Pre-engineered modules and open-access SolvX solvents reduce CAPEX and OPEX.
- **Performance:** Captures CO₂ from 2.5–70% concentration with efficiencies up to 99%.
- **Open-Access Solvents:** Commercially available SolvX solvents with no royalty fees.
- **Engineering Expertise:** Experienced carbon capture specialists backed by Scovan’s full engineering, procurement, fabrication, and construction (EPFC) capabilities.
- **Commercially Proven:** Technology Readiness Level (TRL) 9 technology ready for deployment.

KEY PROJECTS REFERENCES

- Over 10 projects successfully commissioned over the past 10 years.
- Recently commissioned CO₂ capture plant for a major Canadian Oil and Gas Company.
- Multiple small to large-scale front-end engineering and design studies (FEED) studies from 1 TPD to 1,200 TPD on plants including Natural Gas turbines, Refineries, Coal Plants, Bio Plants, Steel, Cement NG Boilers, and Reciprocating Engines.

KEY DATA

TRL	9	Capture Rate Range (tpd)	1 - 1,200	Capture Efficiency (%)	Up to 99%
Source CO ₂ Purity Range	2.5 - 70%	System Energy (GJ/tCO ₂)	1 - 3.5	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	10	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	All industrial sources with proper pre-treatment if applicable				



EQUATIC

ELECTROLYTIC SEAWATER MINERALIZATION



SUMMARY

Equatic uses renewable-powered seawater electrolysis to accelerate the ocean’s natural capacity to remove carbon dioxide from the atmosphere and store it permanently. In the process, seawater flows through proprietary electrolyzers that split it into hydrogen, oxygen, acidic, and alkaline streams. The alkaline stream reacts with atmospheric CO₂, converting it into stable dissolved bicarbonate ions and solid carbonate minerals that can remain stored for thousands of years. To safeguard marine chemistry, the acidic stream is neutralised with alkaline rocks before the treated water is returned to the ocean. The system also generates carbon-negative hydrogen as a valuable clean fuel co-product. By combining durable carbon storage with measurable, verifiable removal and useful hydrogen production, the process offers a scalable pathway for climate mitigation, supports emerging clean energy markets, reduces ocean acidification, and contributes to long-term global decarbonization efforts.

BENEFITS

- **Permanent Carbon Storage:** Equatic converts atmospheric CO₂ into stable dissolved bicarbonate and solid carbonate minerals, enabling durable storage that can last for more than several thousands of years in the ocean without risk of rapid re-release.
- **Carbon-Negative Hydrogen Production:** The process generates hydrogen as a valuable co-product, offering a clean fuel that can decarbonise heavy industry, shipping, and energy systems while simultaneously removing carbon from the atmosphere.
- **Scalable, Verifiable Climate Solution:** Designed for coastal deployment and powered by renewable energy, the technology offers measurable, monitorable carbon removal with potential for gigaton-scale impact globally.

KEY PROJECTS

- **Pilot Demonstrations:** Equatic operates pilot plants at the Port of Los Angeles and the Tuas Desalination Plant in Singapore, each removing about 100 kg of CO₂ per day. These early facilities validate core technology components: seawater intake, electrolyzer design, gas processing, and control systems, while proving scalability and low energy demand.
- **Equatic-1 Demonstration Plant:** Equatic-1 is a modular demonstration plant under construction in Singapore with a capacity of approximately 3,650 tonnes of carbon removal per year. It builds on pilot learnings, uses advanced oxygen-selective anodes, and will demonstrate improved unit costs and ISO-standard MRV practices.
- **First Commercial Scale Deployment:** The first full commercial plant will remove 109,500 tonnes of CO₂ per year and produce carbon-negative H₂.

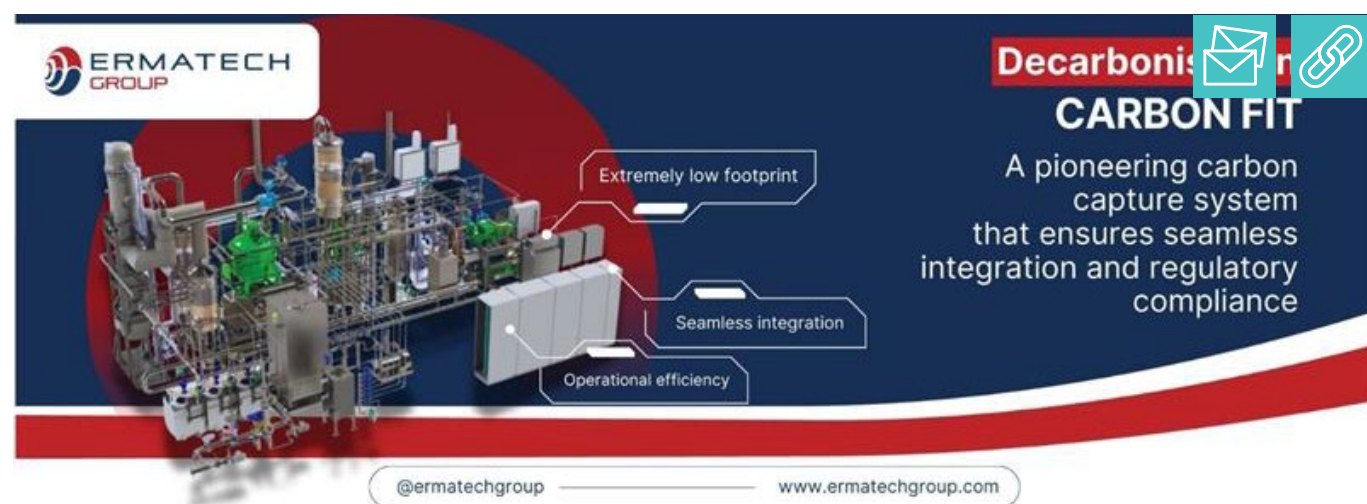
KEY DATA

TRL	7	Capture Rate Range (tpd)	0.1 - 300	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	7.2	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Industrial decarbonization sectors that demand clean hydrogen and high-integrity CO ₂ removal credits				



ERMA TECH GROUP

CARBON FIT



SUMMARY

The ERMA FIRST CO₂ Capture and Storage system (Carbon Fit) employs the post-combustion chemical absorption technique using amine-based solvents, a mature and highly efficient method for separating CO₂ from exhaust gases. It has been purpose-built for maritime applications, where compactness, rapid mass transfer, and operational robustness are critical, while remaining equally suitable for small to medium land-based emitters with CO₂ capture needs up to 20,000 tonnes (or more, combining multiple units). The system employs CO₂ absorption in a dedicated Rotating Packed Bed (RPB) absorber, maximizing gas-liquid contact and reducing equipment footprint, followed by solvent regeneration in a stripping column where CO₂ is desorbed. The recovered CO₂ stream is then compressed, purified, and cooled downstream to produce liquefied CO₂ meeting food-grade purity standards (99.9% purity), enabling safe storage or commercial utilization.

BENEFITS

- **High capture efficiency:** Amine-based absorption can remove a large fraction of CO₂ from flue gas, enabling substantial emissions reduction
- **Compact design:** The use of a Rotating Packed Bed absorber intensifies mass transfer, significantly reducing equipment size and making the system **suitable for space-constrained maritime installations**.
- **Technology maturity and reliability:** Post-combustion amine absorption is a proven industrial technology, ensuring predictable performance, operability, and ease of integration with existing exhaust systems.
- **High-purity CO₂ product:** The downstream compression, treatment, and cooling train delivers liquefied CO₂ of food-grade quality, for reuse or commercial valorization.

KEY PROJECTS

- **Project One:** The Carbon Fit has been tested at a dedicated pilot plant testing campaign with successful results between February – October 2025.

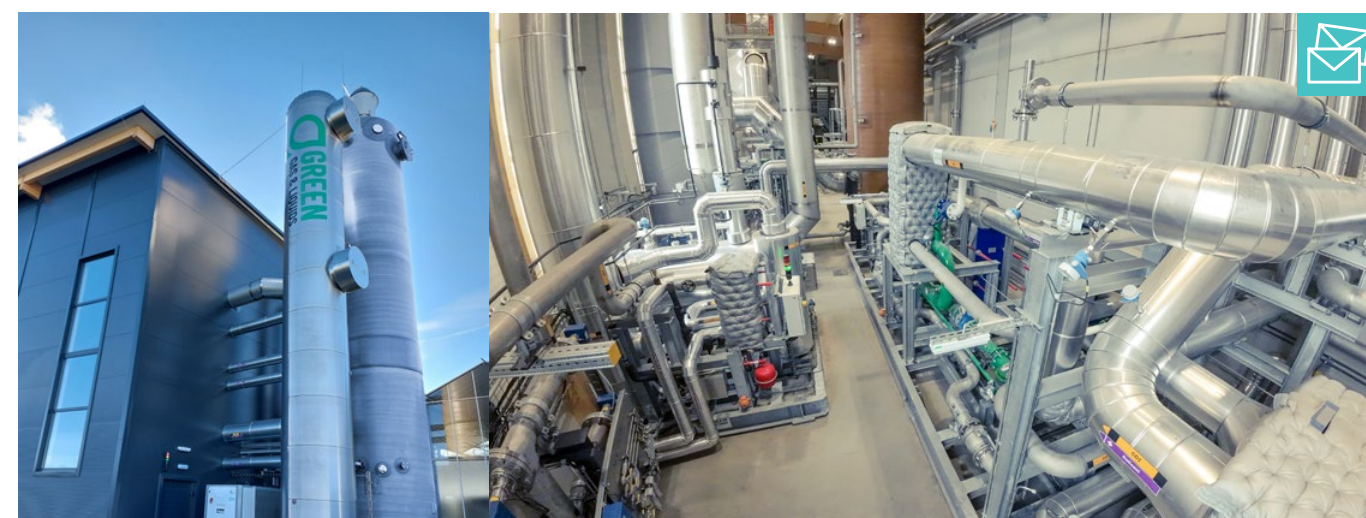
KEY DATA

TRL	8	Capture Rate Range (tpd)	12 - 60	Capture Efficiency (%)	70
Source CO ₂ Purity Range	3 – 12%	System Energy (GJ/tCO ₂)	5.3	Specific Regen. Energy (GJ/tCO ₂)	3.5
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Maritime, small to medium land-based emitters with CO ₂ capture needs up to 20,000 tonnes (or more, combining multiple units)				



GREEN GAS & LIQUIDS

GALLOXOL®



SUMMARY

Galloxol® Carbon Capture Technology by Green Gas & Liquids BV is a solvent-based (bio-) CO₂ capture system based on accelerated salt technology. Unlike conventional amines, its non-toxic solvent has zero vapour pressure — emitting zero solvent traces in both the atmosphere and the product CO₂ stream, eliminating liquefaction steps and simplifying environmental compliance. The system operates through a continuous absorption/desorption cycle which, coupled with advanced heat integration, minimises operating costs. Galloxol® is supplied as a modular, skid-mounted system, enabling rapid deployment and integration with existing boiler installations. Product CO₂ is purified up to 99.9%, based on downstream end-use quality standards. Commercial installations have been operating since 2019 across the Netherlands, Italy, and Austria in various non-petrochemical applications.

BENEFITS

- **Non-toxic solvent:** The bio-degradable nature of the solvent makes it easy to deploy directly in applications close to food and beverage production or in the proximity of residential areas without the risk of environmental concerns.
- **CO₂ quality:** The CO₂ produced is free from any trace of the solvent and achieves high purity levels even without undergoing expensive CAPEX liquefaction steps.
- **Modular design:** Its modular skid design allows for fast installation, minimal footprint and adaptable layout with easy integration to a range of energy systems.
- **Advanced Heat integration:** Its heat integration allows to reduce OPEX and increase efficiency of overall process.

KEY PROJECTS

- **Mersch Gartenbau, Austria 2025:** Latest modular design deployed for CO₂ capture installation with significant improvement in process efficiency and long term operational
- **FNX Liquid Natural Gas S.L, Italy 2022:** Carbon capture deployed for biogas upgrading from bioLNG.
- **Wijnen Square Crops, The Netherlands 2022:** Second installation of the Carbon Capture technology, powered by Galloxol® to capture CO₂ from a steam generating biomass boiler for the horticultural sector.
- **Duurzame Energie Sirjansland (DES), The Netherlands 2019:** world's first commercial Carbon Capture installation for horticulture is installed. Flue gases from the biomass-fired boiler are directed to the Galloxol® system to obtain pure Biogenic CO₂ (99%) utilised in greenhouses to enhance photosynthesis and increase yields.

KEY DATA

TRL	9	Capture Rate Range (tpd)	12-120	Capture Efficiency (%)	>85%
Source CO ₂ Purity Range	6-18%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	4	Number of Pilot Plants	0	Modular (Y/N)	Yes
Target Industries	Non-petrochemical power (Biomass, WtE, CHP): Horticulture, District heating, Food & Beverage				

Honeywell

HONEYWELL ADVANCED SOLVENT CARBON CAPTURE (ASCC)

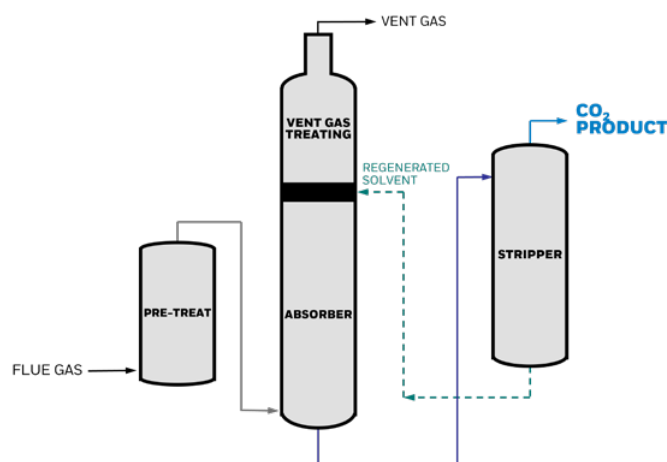


SUMMARY

Honeywell UOP's Advanced Solvent Carbon Capture (ASCC) is a second-generation amine scrubbing process for low-concentration, high-volume flue gas streams from power generation, cement, steel, refining, pulp and paper, and other industrial sources. ASCC scrubs CO₂ in an absorber column using proprietary solvent AZ-108. The enriched solvent passes through a patented heat-exchange train and is regenerated in a high-pressure stripper; lean solvent recirculates for continuous CO₂ absorption, achieving >95% CO₂ capture efficiency across diverse flue gas compositions.

BENEFITS

- Up to 30% lower CAPEX through reduced absorber footprint.
- Low regeneration energy: 2.1 GJ/MT of CO₂.
- High-pressure stripping (6–8 barg) eliminates downstream CO₂ compression, reducing CAPEX and OPEX.
- Modular configurations: Up to 500 KMTA with standard designs at 100 KMTA and 2 MMTA.
- All-electric operation available via eASCC.
- 20+ years of development; 8,500+ hours tested at the National Carbon Capture Center (2–15% CO₂) and 2,650+ hours at Technology Centre Mongstad processing 200 tpd from FCC and power generation.
- Comprehensive warranty and performance guarantees.
- Full life-cycle support from feasibility through FEED, commissioning, startup and operations.



KEY DATA

TRL	8	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	2 - 25%	System Energy (GJ/tCO ₂)	1.8 - 2.4	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Power, Steel, Cement, Refining & Petrochemical, Waste to Energy, BECCS, Pulp & Paper, Gas Processing, & Industrial Flue Gases				

Honeywell

HONEYWELL AMINE GUARD™ PROCESSES

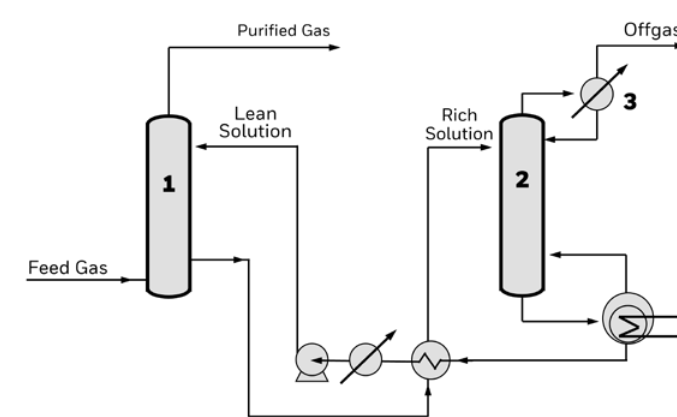


SUMMARY

Honeywell UOP Amine Guard processes pair high-performance UCARSOL solvents with proven engineering expertise to remove acid gases from high-volume streams including natural gas, syngas, gasification off-gas, and blast furnace gas. CO₂ and H₂S are scrubbed in an absorber column using application-specific UCARSOL solvent. The rich solvent is regenerated via heat exchange and stripping, with lean solvent recirculated for continuous CO₂ absorption. In addition to CO₂ and H₂S, plus COS and other sulfur species, delivering treated gas to specification.

BENEFITS

- UCARSOL solvent portfolio allows tailored regeneration energy for specific process conditions.
- Two-stage configurations available for reduced energy consumption.
- Minimal hydrocarbon, H₂, and CO losses owing to low solvent solubility.
- Flash-only regeneration option for bulk CO₂ removal improves energy efficiency.
- Waste heat can typically supply stripping steam requirements.
- TRL 9 with 400+ units in commercial operation worldwide since the 1990s, including Amine Guard FS.
- Full life-cycle support from feasibility through FEED, commissioning, and operations.



KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	400+	Number of Pilot Plants	~	Modular (Y/N)	No
Target Industries	Coal or Biomass Gasification, Hydrogen or Ammonia Syngas, (Synthetic) Natural Gas, GTL Front End Treatment				

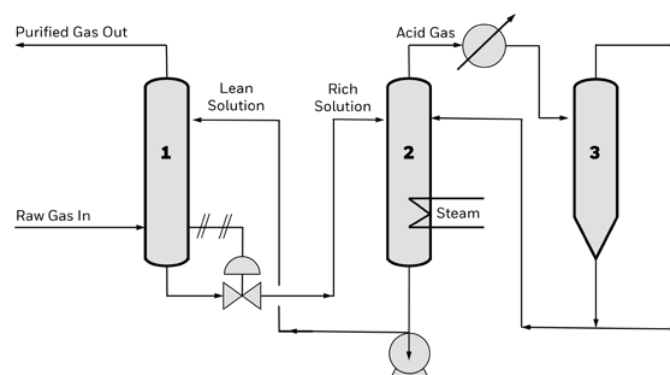
Honeywell
HONEYWELL
BENFIELD™


SUMMARY

Originally developed at the U.S. Bureau of Mines in the 1950s, the hot potassium carbonate (HPC) process has been continuously refined by Benson, Field, and subsequently Honeywell UOP. The Benfield process treats high-volume gas streams containing CO₂ and H₂S—including natural gas, ammonia and hydrogen syngas, gasification off-gas, flue gas, and partial oxidation streams. It employs a thermally regenerated, activated and inhibited HPC solution with proprietary additives for enhanced performance and corrosion prevention, removing CO₂, H₂S, and other acid gas components.

BENEFITS

- LoHeat and HiPure configurations reduce energy consumption or achieve ultra-low acid gas residuals, respectively.
- Regeneration energy optimised through tailored additive selection for the potassium carbonate solution.
- Waste heat can typically supply stripping steam requirements.
- TRL 9 with 700+ units operated worldwide since the 1960s—spanning ammonia and hydrogen production, 50+ natural gas plants, and direct iron ore facilities.
- Full life-cycle support from feasibility through FEED, commissioning, and operations.
- Available as engineering packages or modular solutions.



KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	700	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Power, Steel, Cement, Refining & Petrochemical, Waste to Energy, BECCS, Pulp & Paper, Gas Processing, & Industrial Flue Gases				

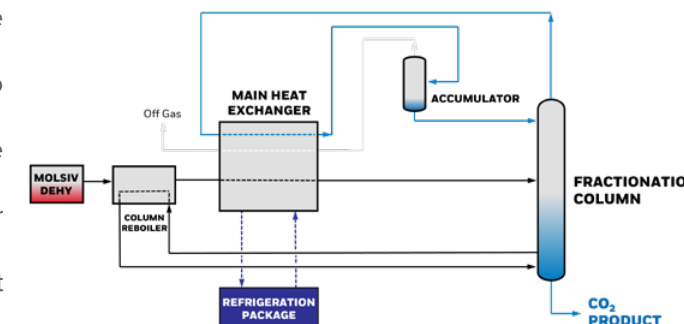
Honeywell
HONEYWELL
CRYOGENIC FRACTIONATION


SUMMARY

Honeywell UOP's CO₂ Fractionation technology is an all-electric, solvent-free solution that captures CO₂ as a high-purity liquid product. Using precisely controlled temperature and pressure, it separates materials by boiling point to isolate specific chemicals from industrial process streams—serving NGL recovery, LPG/LNG production, refinery off-gas processing, and carbon capture. For CCUS, CO₂ condenses into liquid while remaining gases pass through. The Ortloff® Dual Refrigerant CO₂ Fractionation (DRCF) delivers bulk CO₂ removal with simultaneous liquid product recovery and reduced energy consumption.

BENEFITS

- 100% electrically driven — no steam required; compatible with renewable power
- High-purity liquid CO₂ product — ready for pumping to transport/storage pressure
- Compact footprint — lower equipment count vs. amine systems
- Flexible integration — combines with Selexol™, PSA, or membranes.
- TRL 9 — 400+ commercial units — proven since 1976 at industrial scale
- Full lifecycle support — feasibility through FEED, commissioning, and operations



KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	400+	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Blue Hydrogen, Blue Ammonia, Steam Cracker, Steel, Cement, Refining & Petrochemical, and Gas Processing				

Honeywell HONEYWELL POLYBED™ PRESSURE SWING ADSORPTION (PSA)

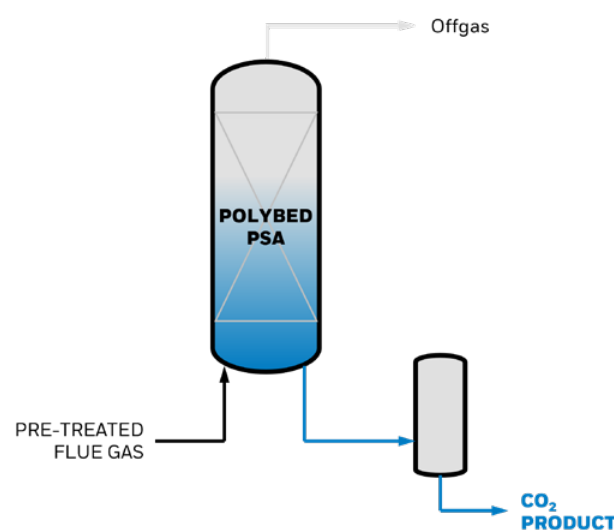


SUMMARY

The Polybed® CO₂ Pressure Swing Adsorption (CO₂ PSA) system delivers high-purity hydrogen or carbon dioxide (99.9+ mol-%) from diverse gas streams through cyclic pressurization and depressurization over selective adsorbent beds. Unlike traditional multi-unit schemes, PSA removes all impurities in a single step with minimal utility consumption. Systems comprise 4 to 16+ adsorber vessels in staggered cycles, using proprietary adsorbents and patented void-gas recovery for maximum yield. Commercially proven since 1966, with 1,180+ units delivered worldwide. Honeywell's CO₂ PSA can be integrated seamlessly with Cryogenic Fractionation process in a variety of schemes to maximise the CO₂ product recovery and to produce high quality CO₂ product such as food grade with appropriate post-treatment.

BENEFITS

- Automatic operation.
- Push-button startup and shutdown.
- On-stream factors in excess of 99.8%.
- Compact units requiring small plot space.
- Skid-mounted and modularised units to mitigate cost and installation time .
- All impurities for H₂ production are removed in a single step.
- Proven TRL 9 technology with more than 1,150 units having begun commercial operation since 1966.
- PSAs can also be designed to purify CO₂ in post combustion capture service as well as CH₄, He, N₂, and Cl purification.
- Honeywell UOP expertise and support spanning the project life cycle from conceptual and feasibility studies, through Front End Engineering Design (FEED), commissioning startup and services during the operational life.



KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	1,180+	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Blue Hydrogen and Ammonia, Steam Cracker, Steel, Cement, Refining & Petrochemical, and Gas Processing				

Honeywell HONEYWELL POLYSEP™ MEMBRANES

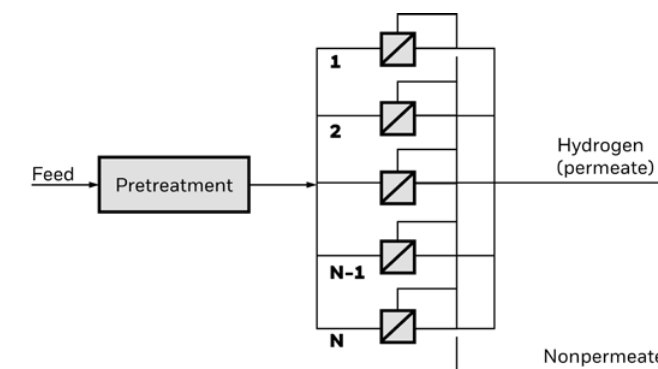


SUMMARY

Honeywell Polysep™ systems leverage advanced composite membrane technology and polymer science for hydrogen recovery, purification, and rejection. The Polysep membranes deliver optimised permeability, selectivity, and contaminant resistance across diverse process conditions. Applications span refinery streams (catalytic reformer off-gas, hydrotreater/hydrocracker purge, FCC off-gas), petrochemical processes (ethylene, ammonia, and methanol off-gases), and synthesis gas from steam reforming, partial oxidation, and gasification. Modular skid-mounted units house proprietary hollow-fiber cartridges in series or parallel configurations, optimised for mechanical integrity and flow distribution. High packing density minimises footprint and cost. The pressure-driven process requires minimal moving parts and operator involvement.

BENEFITS

- Automatic startup.
- Integrated capacity and product purity controls.
- Automated depressurization, turn-up, and turn-down.
- Proprietary counter-current-flow hollow-fiber bundles maximise separation driving force and minimise membrane area.
- Pressure-driven process with minimal moving parts, utilities, and operator intervention.
- TRL 9 with 85+ commercial units since 1985; largest unit processes 350+ MMscfd of synthesis gas.
- Full life-cycle support from feasibility through FEED, commissioning, and operations.



KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	85+	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Refining & Petrochemical, Waste to Energy				

Honeywell

HONEYWELL SEPARALL™

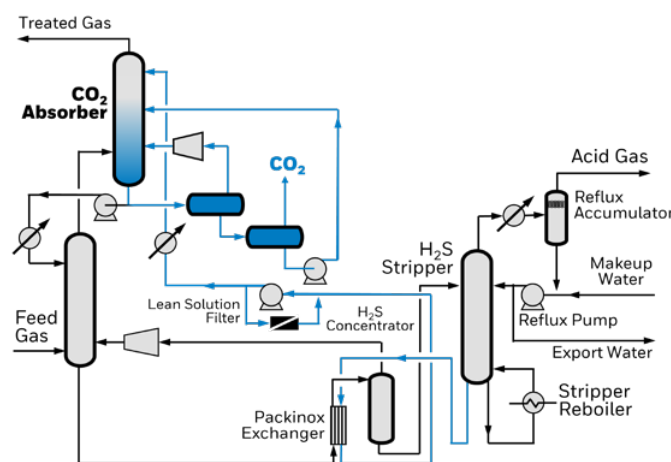


SUMMARY

Honeywell UOP's SeparALL™ process, commercially proven since 1965, uses the Selexol™ physical solvent—dimethyl ethers of polyethylene glycol—to remove acid gases via partial-pressure-driven absorption. Applications include coal and biomass gasification, natural gas processing, ammonia and hydrogen syngas, hydroprocessing, synthetic natural gas, chemicals, fertiliser production, and molecular sieve regeneration for CNG, LNG, and GTL front-end treatment. Ideally suited for selective removal of H₂S and COS and/or CO₂ to very low residual levels, with independently optimizable sulfur and CO₂ capture. The process can be tailored for bulk or trace acid gas removal.

BENEFITS

- CO₂ removal efficiency up to 99%.
- >99% on-stream availability with simple, reliable operation.
- Rapid startup: plants brought online within 2–3 hours.
- Chemically inert Selexol solvent resists degradation—no reclaiming, purging, or corrosion inhibitors required.
- Reclaiming and/or purging of solvent is not required.
- Low corrosivity without the use of corrosion inhibitors.
- TRL 9 with 110+ units in commercial operation worldwide since the 1960s.
- Full life-cycle support from feasibility through FEED, Commissioning, startup and operations.



KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	110	Number of Pilot Plants	~	Modular (Y/N)	No
Target Industries	Blue Hydrogen, Blue Ammonia, Steam Cracker, Refining & Petrochemical, and Gas Processing, Biomass & Coal Gasification				

Honeywell

HONEYWELL SEPREX™ MEMBRANE SYSTEMS

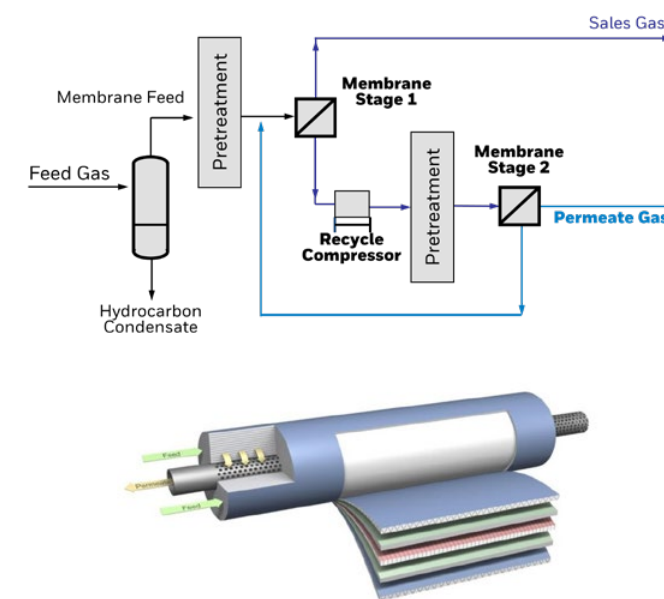


SUMMARY

Seppure® membrane systems provide bulk removal of CO₂ and water from natural gas, with proportional H₂S co-removal. Hybrid configurations—membranes for bulk CO₂/H₂S removal followed by solvent polishing—offer an economically attractive route to tight specifications. Designed for high partial-pressure CO₂ service, Separex systems are compact, lightweight, and well suited to remote and offshore locations. The single-stage design has no moving parts, requires minimal maintenance, and delivers rapid startup/shutdown with high reliability. Honeywell UOP modular designs further reduce footprint and installed cost for offshore applications.

BENEFITS

- Operationally simple: minimal rotating equipment, no chemical reagents, and minimal servicing requirements.
- Prefabricated skid delivery minimises cost and plot space.
- TRL 9 with 150+ units in commercial operation worldwide since 1981.
- Full life-cycle support from feasibility through FEED, commissioning, and operations.



KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	150	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Gas Processing, Biogas Upgrading, Renewable Natural Gas				

Immaterial IMMATERIAL CARBON CAPTURE USING MONOLITHIC MOF



SUMMARY

To meet the commitments of the Paris Climate Agreement, while continuing to provide power, housing, and infrastructure for a growing global population with ever-increasing digital needs, it is imperative that we deploy low cost carbon capture systems for power generation, steel, cement, and other critical manufacturing processes.

Immaterial is uniquely positioned as a technology provider to offer a solution that meets these needs. Building on and enhancing the Nobel prize-winning chemistry of metal-organic frameworks, MOFs, we are able to produce game-changing materials in a unique, patent-protected “monolithic” embodiment with high density and tunable physical form that overcomes the challenges associated with powder MOFs in industrial applications. We have also developed unique, patented, process technology that maximises the efficacy of this unique form of MOF to offer the most cost-effective carbon capture solution.

BENEFITS

- **Low total capture cost:** The low capital and operating costs enable a total cost of capture that is extremely competitive and strengthens the business case with current market pricing in EU and US whilst avoiding significant capex.
- **Small footprint:** The intensified process using swing adsorption with our patented m-MOF shrinks the footprint compared to liquid amine scrubbing by up to 75%, making the technology ideal for sites where space is at a premium.
- **No secondary emissions:** Our densified solid sorbents eliminates the risk of secondary emissions of liquids or vapours.
- **Versatile and controllable:** With excellent turndown and rapid start-up and shut-down times, the technology is ideal for plants where operating regimes can vary and low cost is imperative.

KEY PROJECTS

- **Piloting from 2024:** We have a pilot operating since mid 2024 running technology development and materials demonstration.
- **Demonstrating at scale 2026:** Our purpose-built demonstrator goes live on partner sites demonstrating the full capture process at scale from late 2026, with deployment at priority sites in our target sectors.

KEY DATA

TRL	5	Capture Rate Range (tpd)	1 - 3,000	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	3 - 20%	System Energy (GJ/tCO ₂)	Depends on use case	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	-	Number of Pilot Plants	1	Modular (Y/N)	Optional
Target Industries	Cement, Steel, Power Generation, Refining, Chemicals, Glass, Energy from Waste				

ionada IONADA HOLLOW FIBER MEMBRANE CONTACTOR



SUMMARY

Ionada is a deep tech company developing modular, cost effective carbon capture solutions for small to medium sized emitters underserved by conventional CCS technologies. Its proprietary platform, iDeCarbon™, integrates hollow fiber membrane contactors (HFMCs) with proven amine solvents to intensify gas-liquid contact, enabling high CO₂ capture efficiency in compact, containerised units. Compared with traditional packed column systems, Ionada's technology delivers up to 50% reduction in footprint and weight and up to 30% lower energy consumption, making it suitable for space and heat constrained environments.

Ionada targets a range of applications including Waste to Energy plants, maritime onboard carbon capture, offshore installations such as FPSOs, and oil & gas midstream assets, where retrofit flexibility, low energy penalty, and compact design are critical. The technology has been validated through a 1 ton per day pilot operating for over 1,500 hours, and Ionada is advancing toward larger demonstrations and commercial deployment in support of industrial decarbonization goals.

BENEFITS

- **Compact footprint:** Up to 50% smaller and lighter than conventional amine tower systems, enabling deployment in space constrained sites.
- **Lower energy consumption:** up to 30% reduction in energy use per ton of CO₂ captured, supported by efficient heat integration.
- **Modular and scalable:** Containerised design allows rapid installation, easy scale out, and stepwise capacity expansion.
- **Retrofit friendly:** Minimal disruption to existing infrastructure across industrial, marine, and offshore assets.
- **High capture efficiency:** Demonstrated 85–95% CO₂ removal under real operating conditions.

KEY PROJECTS

- **MiniPlant Pilot (2023):** Ionada deployed its first hollow fiber membrane contactor (HFMC) carbon capture MiniPlant at Halliburton Labs. The pilot achieved over 90% CO₂ removal across a range of inlet concentrations.
- **Automated Test Station – ATS (2024):** An ATS unit was designed and operated to systematically qualify HFMC modules, control logic, solvent behavior, and operating envelopes. This platform enabled accelerated stress testing and generated a robust engineering dataset to assess reliability.
- **1 TPD Pilot System (2025):** Ionada completed an industrial scale 1 ton per day pilot processing natural gas genset flue gas. The system operated for 1,500 continuous hours with over 50% uptime, achieving over 85% CO₂ capture efficiency, validating integrated performance and readiness at TRL 6.

KEY DATA

TRL	6	Capture Rate Range (tpd)	1.0 TPD	Capture Efficiency (%)	85 - 95%
Source CO ₂ Purity Range	4 - 20%	Electrical Power (GJ/tCO ₂)	0.2 - 0.4	Specific Regen. Energy (GJ/tCO ₂)	2.0 - 3.0
Number of Commercial Plants	N/A	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Waste-to-Energy, Maritime, Offshore (FPSOs), Oil & Gas, Distributed Emission Sources				

CARBON CAPTURE FOR WASTE TO ENERGY



SUMMARY

Capturing carbon dioxide (CO₂) from the flue gas produced in hard-to-abate industries and properly storing it (a process called carbon capture and storage or CCS) is a key component of most governments' net-zero strategies. Thermal treatment of waste, known as Waste to Energy (WtE) is an example of a hard-to-abate industry.

The reason is that waste must be handled and the alternative treatment option, landfill, has a worse climate-change impact than WtE. This is true even without the inclusion of CCS, as municipal solid waste landfills release methane, which has far larger greenhouse gas (GHG) potential than CO₂.

Kanadevia Inova develops and manufactures carbon dioxide capture technologies such as amine scrubbing. Amine scrubbing is ideal for capturing CO₂ from flue gas while producing high-quality CO₂.

BENEFITS

- Optimised for capturing CO₂ from the waste to energy industry with hard-to-abate emissions.
- Can be applied to existing and new facilities.
- The solvent of the scrubbing process is cycling in the process.
- No external energy supply needed if it can be connected to the water steam cycle of the Waste to Energy plant

KEY PROJECTS

Protos CC (UK) by Encyclis

The two-line carbon capture facility will be sited immediately next to the WtE plant. It will capture a mixture of biogenic and fossil CO₂ which are released in the combustion of non-recyclable waste at Protos ERF. While WtE facilities are the most climate-friendly waste management option for treating non-recyclable materials, when combined with carbon capture and storage (CCS) technology, Protos ERF will become a negative emitter. Kanadevia Inova's advanced technologies will reliably capture large quantities of CO₂ from the flue gas which will be permanently and securely stored in depleted gas reservoirs under Liverpool Bay through the HyNet Northwest network.

KEY DATA

TRL	9	Capture Rate Range (t/d)	Up to 1,000	Capture Efficiency (%)	90 - 95%
Source CO ₂ Purity Range	~10%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	1	Number of Pilot Plants	2	Modular (Y/N)	N
Target Industries	Thermal treatment facilities (known as Waste to Energy - WtE)				

CHEMICAL LOOPING COMBUSTION (OXY-FUEL COMBUSTION)



SUMMARY

Chemical looping combustion (CLC) is an advanced oxy-fuel combustion technology that enables efficient capture of CO₂ by using metal oxides instead of directly contacting with air. In CLC process, the fuel reacts with metal oxide provided in the fuel reactor to produce CO₂ and H₂O while reducing the metal oxide to its metallic form. By simply condensing the water vapor, highly concentrated CO₂ can be separated. Due to these technological features, CLC enables highly concentrated CO₂ separation and reduces the formation of pollutants such as NO_x without additional carbon capture and denitrification units, thus significantly reducing capital and operational costs.

KEPCO Research Institute (KEPCO RI), the research institute of Korea Electric Power Corporation, has developed the world's largest NG-fueled 3 MWth CLC pilot plant which was successfully operated with 99.5% fuel conversion, 96.6% CO₂ selectivity and NO_x emissions below regulatory limits.

BENEFITS

- Highly concentrated CO₂ over 90vol% can be separated without additional capture units, while simultaneously generating energy (steam, electricity, and heat).
- Due to the flameless oxy-fuel combustion process, it significantly reduces NO_x formation.
- The use of oxygen carriers to provide pure oxygen results in significant saving in capital and operational costs by eliminating air separation.

KEY PROJECTS

In November 2024, the world's first and largest NG-fueled 3 MWth chemical looping combustion steam generation pilot plant was successfully operated with 99.5% fuel conversion and 96.6% CO₂ selectivity at the Ulsan Yongyeon Industrial Complex. It was jointly designed by KEPCO RI and the Korea Institute of Energy Research (KIER), and constructed by Hyundai Heavy Industries Power Systems (EPC). Based on the 3 MWth plant operation results, the design of a 100 MWth commercial boiler and power system was completed as the next phase of demonstration.

KEY DATA

TRL	6	Capture Rate Range (tpd)	15	Capture Efficiency (%)	>96%
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	No
Target Industries	Industrial Gas boiler, Combined Heat and Power, Power plant, Biogas				



KEPCO

POST-COMBUSTION CARBON CAPTURE



SUMMARY

KEPCO Research Institute (KEPCO RI), the research institute of Korea Electric Power Corporation, has been at the forefront of carbon capture technology development since the early 2000s to mitigate emissions from power generation.

In 2002, KEPCO RI developed Korea's first 2 TPD post-combustion CO₂ capture process for a NG power plant. Building on this, a 200 TPD CO₂ capture plant applying its proprietary solvent (KoSol) was commissioned at Boryeong coal-fired power plant in 2013 and has been in stable operation up to now.

With the fuel transition from coal to NG, KEPCO RI has expanded its technology to accommodate NG power plants. Since 2021, KEPCO RI has been developing high-efficiency & low-energy proprietary solvents (KoSol-L) and processes for NG power plant. And a 10 TPD scale CO₂ capture plant for Ulsan NGCC power plant was built in Oct. 2024 and is currently in operation.

BENEFITS

- Achieved low solvent regeneration energy consumption of 2.3 - 2.5 GJ/tCO₂ at a 10 MW post-combustion capture plant for coal-fired power plant.
- Compared to commercial MEA solvents: 80% reduction in solvent loss, 60% lower degradation, and 90% decrease in corrosion — achieving world-class durability and cost-effectiveness
- Captured CO₂ purity exceeds 99.9%, currently utilised for dry ice, beverage and agricultural applications
- Based on successful track records, two new commercial plants (> 200 TPD scale) have been constructed and operated successfully at power plant and petrochemical sites

KEY PROJECTS

- In 2013, KEPCO RI constructed a 10 MW (200 TPD) wet scrubbing CO₂ capture plant at the Boryeong coal-fired power plant using its proprietary KoSol technology. The plant recorded over 30,000 hours of continuous operation and the captured CO₂ is used for industrial CO₂ supply and CCU technology applications.
- In Dec. 2024, a 1MW(10TPD) wet scrubbing CO₂ capture plant — the largest of its kind for NG power plant in Asia — was commissioned at Ulsan NGCC power plant. Integrated operation with CO₂ compression and liquefaction systems is underway. Captured CO₂ will be supplied to nearby industries and used in CCU research facilities, contributing to carbon utilisation and added value.

KEY DATA

TRL	9	Capture Rate Range (tpd)	200 - 300	Capture Efficiency (%)	>90%
Source CO ₂ Purity Range	>3%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.3 - 2.5
Number of Commercial Plants	3	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Oil & Gas, Power plant, Petrochemical, Waste-to-Energy, Cement, Steel, Glass & Chemicals				



LEILAC LTD.

LEILAC



SUMMARY

Leilac is a strategic technology partner enabling future-proof cement and lime. Leilac's patented indirect heating technology separates the heat source from the chemical reaction in the processing of cement and lime. This creates two key process improvements:

- Energy Flexibility:** The Leilac technology is compatible with conventional, alternative and low-carbon fuels, including full electrification of the high temperature heat required for calcination. Hybrid-electric options are designed to enable lowest cost energy use and grid balancing services.
- Carbon capture:** Process carbon dioxide unavoidably released from the raw material is kept pure—uncontaminated by flue gases or air—enabling efficient capture at high purity without additional chemicals or energy-intensive processes.

Leilac's modular technology is designed to be retrofitted to existing assets with minimal downtime and deliver immediate benefits to producers, while providing a capture ready future-proof solution. Leilac also aims to enable scalable carbon dioxide removal solutions through the application of zero emissions lime to direct air capture and ocean acidification reduction

BENEFITS

- Carbon capture:** The Leilac technology naturally produces unavoidable process CO₂ emissions as a high purity (98%) stream—enabling potentially lowest cost abatement of carbon liabilities and new revenues from carbon trading or CO₂ sales.
- Fuel switching:** Enabling full use of low-cost and low-carbon alternative fuel.
- Electrification:** Full or hybrid electric heating options to unlock low-cost electrification.
- Grid balancing:** Enabling new revenue streams from the demand response capability of hybrid heating and helping to stabilise electricity grids without interrupting production.

KEY PROJECTS

Leilac's technology has been demonstrated through multiple pilot projects, delivering over 12,000 hours of operation.

The Leilac-1 project, located at Heidelberg Materials' cement plant in Lixhe, Belgium, successfully demonstrated indirect calcination of both limestone and cement raw meal at industrial temperatures. The project achieved direct separation of process CO₂ at 98% purity, with no observable air ingress or loss of containment.

With a global network of partners, Leilac is developing multiple first-of-a-kind commercial projects across the cement, lime and carbon dioxide removal sectors. The Leilac technology is being developed as an industry-wide solution to be deployed through a non-exclusive technology licensing model.

KEY DATA

TRL	6	Capture Rate Range (tpd)	Unlimited. >70 TPD	Capture Efficiency (%)	95%
Source CO ₂ Purity Range	>95%	System Energy (GJ/tCO ₂)	0 - 0.6 (nth of a kind)	Specific Regen. Energy (GJ/tCO ₂)	0
Number of Commercial Plants	0	Number of Pilot Plants	5	Modular (Y/N)	Yes
Target Industries	Carbon Dioxide Removal				



MESSER

CARBON CAPTURE TECHNOLOGY



SUMMARY

MESSER's carbon capture portfolio utilises advanced amine-based solvents to efficiently capture CO₂ from flue gases. The system achieves high capture rates even at low CO₂ concentrations (>4%), delivering CO₂ purity exceeding 99.9% while meeting specifications for transport, utilization, or storage. Its scalable design accommodates capacities from 60 to 3,000 tpd, making it suitable for a wide range of industrial applications. Flexible energy integration, including the use of process heat, can significantly reduce or even eliminate additional thermal energy demand. Proprietary solvent formulations are highly resistant to oxygen degradation, enhancing process efficiency and solvent lifetime. In addition to post-combustion carbon capture, MESSER supports oxyfuel-based decarbonization concepts through its industrial gas expertise and oxygen supply capabilities. The company also provides CO₂ purification and liquefaction solutions for raw CO₂ streams originating from a wide range of capture technologies, including amine-based systems, oxyfuel combustion, membrane separation, hot potassium carbonate (HPC) processes, and other industrial CO₂ capture systems. By transforming emissions into high-purity CO₂ products, MESSER delivers a reliable and sustainable pathway for industrial decarbonization.

BENEFITS

- **Carbon Capture as a Service approach:** Under the new brand ZeCarb®, Messer also offers "Carbon Capture as a Service" (CCaaS), enabling industries to achieve net-zero targets. Leveraging decades of expertise, ZeCarb provides a scalable CCUS approach along the full value chain - tailored for "hard-to-abate" sectors.
- **Financial & planning security:** With our Carbon Capture as a Service (CCaaS) approach, emitters can stay focused on their core business while ZeCarb® manages the entire CCUS value chain — from capture to sequestration. This turnkey solution ensures cost-effectiveness, financial and planning security, and a reliable foundation for long-term strategic decisions.
- **300+ installed carbon capture plants worldwide:** Emitters benefit from Messer's global expertise in carbon capture. With 70 years of experience building carbon capture plants, we offer proven reliability and deep technical know-how.

Different CO₂ sources: Benefit from single-source solution for carbon capture, with services tailored to your specific needs. We are capable of capturing CO₂ from a wide range of sources and capacities, including cement, bio-waste energy, steel, glass, blue hydrogen, and more.



KEY DATA

TRL	9	Capture Rate Range (tpd)	60 - 3,000	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	4 - 100%v	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	300+	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Cement, Bio- & Waste to Energy, Steel, Glass, Pulp & Paper, Lime Production, Gas-to-Power, Blue Hydrogen				



MTR CARBON CAPTURE

POLARIS® MEMBRANES



SUMMARY

MTR's carbon capture technology and the Polaris® membrane were developed over the past two decades with significant support from the U.S. Department of Energy (DOE). This modular, environmentally-friendly capture process has been demonstrated through a series of eight field trials beginning in 2009 and culminating with MTR's commercial demonstration unit, a 150 tonnes/day (TPD) capture plant which began operation in 2025. This system – the largest membrane post combustion capture plant in the world – recovers up to 90% of the CO₂ in the flue gas from a coal-fired power plant and produces pipeline-quality liquid CO₂. MTR is currently engaged in commercial projects (engineering studies, Pre-FEEDs, FEEDs, and piloting activities) for power and industrial sectors in Europe, North America and Asia. At the time of publication, MTR is commissioning its first commercial capture plant in Taiwan.

BENEFITS

- The Polaris membrane is a clean approach to carbon capture. It produces no secondary emissions and requires no hazardous chemicals handling or storage, potentially making permitting easier.
- Polaris membranes are an all-electric capture process that use no steam. This avoids the use of natural gas boilers that generate additional CO₂ emissions requiring larger capture plants.
- Polaris membrane systems are a modular technology with a flexible plant footprint and a low profile (no tall, heavy towers). It is ideal for use in retrofits with limited space or in populated urban areas.
- Polaris membranes recover water from flue gas, and therefore have a lower water demand than solvent-based capture approaches.

KEY PROJECTS



Project One: The 150 TPD demonstration plant at the Wyoming Integrated Test Center started operation in early 2025 and is scheduled to run for at least a year. It captures CO₂ from coal-fired flue gas and produces pipeline quality liquid CO₂.

Project Two: A commercial MTR capture system at the TSMC Taichung Zero Waste Plant will start operation in late 2025 in Taiwan.

KEY DATA

TRL	8	Capture Rate Range (tpd)	30 - 3,000	Capture Efficiency (%)	50 - 95%
Source CO ₂ Purity Range	8 - 30%	System Energy (kWh/tCO ₂)	300 - 400	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	1	Number of Pilot Plants	6	Modular (Y/N)	Yes
Target Industries	Coal Power, Cement and Lime Kilns, Steel Plants, Waste-to-Energy, Refineries, OTSG, Hydrogen Plants (SMR)				



NEG8 CARBON ELECTROSTATIC DAC TECHNOLOGY



SUMMARY

NEG8 Carbon is a Waterford, Ireland based deep-tech company with a patented electrostatic Direct Air Capture (DAC) technology that removes CO₂ directly from the atmosphere. NEG8's unique electrostatic solid sorbent DAC technology has been developed to operate using low-grade industrial waste heat at a regeneration threshold of 65 °C, significantly below conventional solid sorbent systems. NEG8's electrostatic DAC technology eliminates the high-temperature regeneration inputs required by incumbent solid sorbent and liquid solvent systems, vastly reducing the costs associated with DAC.

Integrating NEG8's modular technology with heat streams that are currently dissipated without productive use in industrial plant unlocks additional carbon capture capability in a range of Industrial Decarbonisation industries including Sustainable Aviation Fuel (eSAF), Methanol production, cement, data centres, geological storage.

BENEFITS

- **Low Energy Consumption:** NEG8 Carbon's DAC technology has industry leading energy consumption of 0.5 to 0.75 MWh/t CO₂ when combined with waste heat.
- **Low Temperature:** 65 °C regeneration temperature reduces energy requirements and makes integration with industrial cooling processes facile.
- **Extended Sorbent Lifespan:** Sorbent is stable for years rather than months owing to indirect heating of sorbent with lightweight heat exchanger and low regeneration temperature.
- **Water Positive:** System produces rather than consumes water, providing valuable additional commodities in arid regions.
- **Heat Reuse:** Hyperscale AI Data centres with immersion cooling; both single phase and two phase heat rejection streams are compatible with NEG8 Direct Air Capture technology. Simultaneously improving power usage efficiency (PUE) and water usage efficiency (WUE) through water harvesting and carbon capture.

BENEFITS

- **eSAF Project UK:** NEG8 Carbon is partnered as technology supplier for a major project in the UK to develop large-scale Sustainable Aviation Fuel (eSAF) production using a low-carbon energy source. This paves the way for economic production of eSAF at scale, which is critical for decarbonisation of the aviation industry. The CO₂ provided via DAC will be combined with green hydrogen and nuclear-generated electricity to create eSAF. NEG8 Carbon's DAC technology is particularly suitable for this project as it uses low-carbon heat and electricity from nuclear, which greatly reduces the cost and increases efficiency of the DAC process.

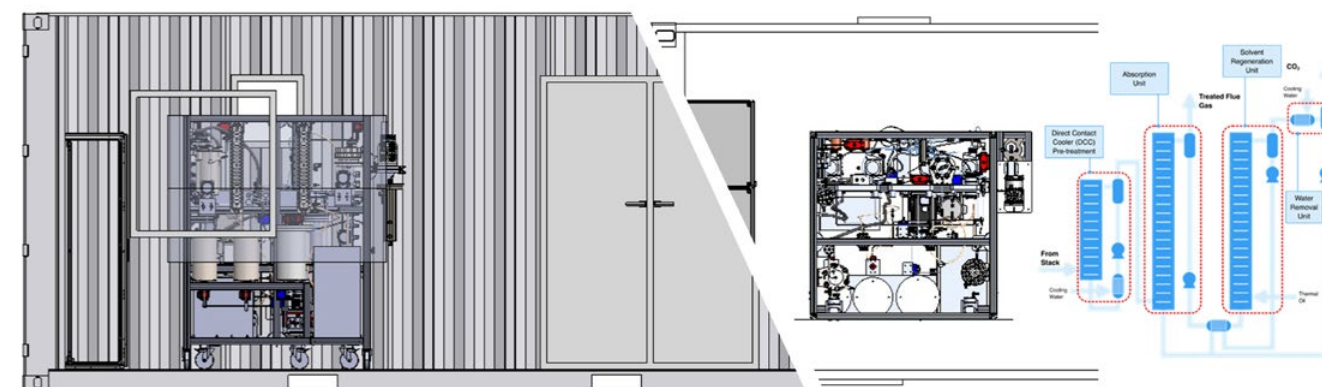


KEY DATA

TRL	5	Capture Rate Range (tpd)	1	Capture Efficiency (%)	60 - 90%
Source CO ₂ Purity Range	0.04	System Energy (GJ/tCO ₂)	6.5	Specific Regen. Energy (GJ/tCO ₂)	4.7
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	eSAF, Methanol Production, Cement, Data Centres, District heating, eMethanol, eMethane / Synthetic Natural Gas				



NET4CO₂ NETCAP – MODULAR CARBON CAPTURE



SUMMARY

NetCap by NET4CO₂ is a modular, scalable carbon capture technology that integrates CO₂, SO_x, and NO_x removal into a single, compact system. Its core innovation is a unique bidimensional absorber design featuring plates with interconnected mixing chambers. This design enhances gas-solvent interaction, increasing absorption rates and mass transfer by up to 50 times, making it highly efficient for low-concentration flue gases. The system enables absorption units with a volume under 0.8 m³/tonne CO₂, eliminating the need for large absorption columns.

The system's modular structure ensures scalability without compromising performance, allowing efficient CO₂ capture despite fluctuations in gas velocity and concentration. It utilises a high-efficiency structured absorber and amine-based solvents, enhancing heat transfer, stabilizing the solvent, and optimizing regeneration while reducing excess solvent use.

NetCap is currently operating in an industrial setting in the glass industry in Porto, Portugal, treating ~50 kg/day of flue gas. Deployment in oil refining is planned for second half of 2026 to validate performance at ≥20% CO₂.

BENEFITS

- **Integrated 2-in-1 system:** Combines CO₂, SO_x and NO_x removal in a single, efficient unit.
- **Compact and modular design:** Scalable system, maintaining equipment size and footprint reduction.
- **High-efficient structured absorber:** Provides mass transfer rates 10 to 50 times higher than conventional CO₂ capture technologies.
- **Flue gases** with CO₂ concentrations between 0.5% and 20%, validated with industrial gases from the ceramic and glass industries.
- **High CO₂ capture performance:** Achieves at least 90% CO₂ capture and >99% CO₂ purity.

KEY DATA

TRL	7	Capture Rate Range (tpd)	2E-4 – 7E-3	Capture Efficiency (%)	>90%
Source CO ₂ Purity Range	0.5 – 20%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Glass, Ceramics, Chemicals, Food and Beverage, Pharmaceuticals, Plastics, and Biogas.				



NITTO MEMBRANE-BASED CARBON CAPTURE SYSTEM



SUMMARY

Nitto is developing a membrane-based, post-combustion carbon capture technology that separates the GHG CO₂ from the benign exhaust gas components. By combining proprietary polymer design and membrane modulation, this technology offers a compact, energy-efficient solution to reduce Scope 1 emissions. Pilot demonstration testing of Nitto's membrane-based carbon capture concept has started in 2023 for one of Nitto's own boiler units. Built upon Nitto's four decades of experience in the manufacture of water treatment membranes, the volume production of the gas separation membrane elements is on track to begin by early 2027 with several additional pilot demonstration projects in operation in 2026.

Nitto is currently constructing a mobile, containerised membrane skid for onsite carbon capture field demonstrations.

BENEFITS

- **Compact & Modular:** From a demonstration skid with few membrane elements to industrial scale operations, Nitto's modular CO₂ separation systems require smaller footprints compared to incumbent CCUS technologies.
- **Energy Efficient:** Improved membrane selectivity and throughput lowers both OpEx and CapEx of Nitto's fully electrified decarbonization technology.
- **Low-Maintenance Design:** Nitto's carbon capture system is solvent & chemical-free, enabling save operation without the need of system regeneration.
- **Flexibility:** Whether non-continuous operation or aiming for lower CO₂ purity with reduced system complexity, Nitto's membrane-based carbon capture design offers flexibility with high performance.

KEY PROJECTS

- **Project One:** 300 tpa pilot demonstration of a two-stage membrane system to separate the CO₂ from the exhaust of a natural gas-powered boiler unit (picture above).
- **Project Two:** Scheduled a small-scale demonstration at a chemical manufacturer with a one-stage membrane carbon capture system with subsequent mineralization of the separated CO₂ to form calcium carbonate.
- **Project Three:** Scheduled a small-scale pilot project at a beverage company to capture the CO₂ from an emission stream followed by the liquefaction of the CO₂ to consider purifying the gas to food-grade quality.

KEY DATA

TRL	7	Capture Rate Range (tpd)	0.1 - 300	Capture Efficiency (%)	50 - 95%
Source CO ₂ Purity Range	3 - 60%+	System Energy (GJ/tCO ₂)	Appl. specific	Specific Regen. Energy (GJ/tCO ₂)	N/A
Number of Commercial Plants	0	Number of Pilot Plants	7+	Modular (Y/N)	Y
Target Industries	Small to mid-size point-source emissions such as boilers, heaters, CHP, fuel cells, etc. up to 300 tpd of CO ₂				

DISRUPTIVE MOF-BASED CO₂ CAPTURE TECHNOLOGY



SUMMARY

Disruptive CO₂ capture technology powered by proprietary MOFs and delivered through a selected partner ecosystem.

novoMOF's technology delivers **significant CAPEX and OPEX savings**. Our unique materials enable smaller, less capital-intensive capture units with reduced energy demand and the potential to cut total capture costs by 50% or more compared to amines. With low-temperature and low-pressure regeneration, our solution slashes operational costs while offering **superior performance in humid conditions**, eliminating the need for costly flue gas drying. Designed for flexible deployment, it ensures adaptability across different flue gases and industrial setups.

Building on proprietary industrial-scale MOF materials and advances in a field recognised by Nobel Prize-winning research, novoMOF enables next-generation carbon capture systems, supporting deployment across industrial applications.

Piloting for your specific CCUS project is available through our selected partners.

BENEFITS

- **Lower OPEX:** Reduced energy consumption significantly lowers operating costs. This is driven by 2–3x lower energy demand due to low-temperature and low-pressure regeneration capability.
- **CAPEX Savings:** Enables smaller, less capital-intensive capture units adaptable to various flue gases and capture processes (TSA, VPSA, PSA, TVSA).
- **Compact & Cost-Effective Capture Units:** Smaller, modular systems reduce infrastructure investment.
- **Solid Materials-Based Systems:** Non-liquid systems ensure simpler operations and fewer safety concerns.
- **Optimised for Humid Conditions:** No need for expensive flue gas drying.
- **Sustainability:** High-stability solid sorbents from green materials. No solvent-related decomposition products.



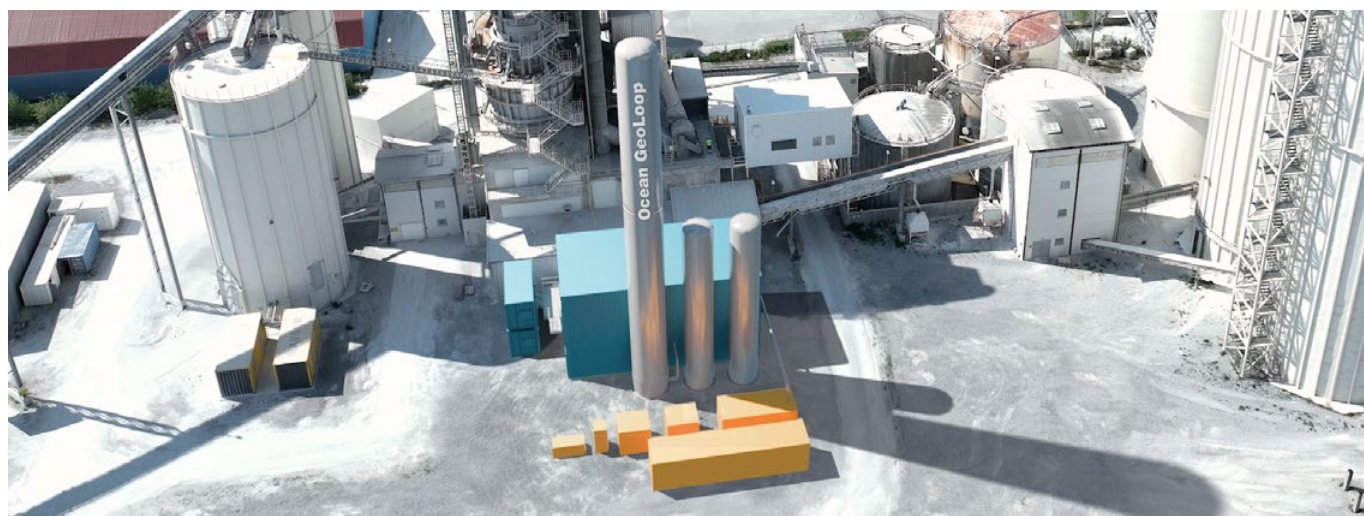
KEY DATA

TRL	6	Capture Rate Range (tpd)	1 - 4,000	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	1 - 25%	System Energy (GJ/tCO ₂)	Design specific	Specific Regen. Energy (GJ/tCO ₂)	<1
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Waste-to-Energy, BECCS, Cement, Steel, Aluminum, Biogas, Glass, Pulp & Paper, Automotive, Maritime				



OCEAN GEOLOOP

CARBON CAPTURE BY NATURE



SUMMARY

Ocean GeoLoop's carbon capture technology offers a clean, chemical-free, flexible and universal low-cost alternative that relies on well-known and robust gas separation principles. Ocean GeoLoop offers simultaneous CO₂ capture and effective removal of harmful components (acidic gases, heavy metals, particles, etc.). The technology exhibits superior energy efficiency by means of smart plant design and integrated energy recuperation elements. The basic process is all-electric and does not require heat input to function, but can harness available waste heat to lower the electrical input requirements. Avoiding the use of chemicals and elevated temperatures, this process has a significantly reduced risk of reactive contaminants in the product CO₂-stream. The technology has been demonstrated in an industrial setting on a scale of 1,000 tons per annum.

BENEFITS

- The base design is all-electric and does not require heat. This is advantageous in cases where local heat sources are insufficient to cover reboiler duty required by chemical methods, or in cases where the available thermal energy is valuable. The method can still benefit from available waste heat to lower electrical duty.
- Water-based process without toxins, amines or other harmful chemicals.
- Energy recuperation elements, combined with smart plant design and dynamic, real-time optimisation of parameters maximises performance while minimizing energy use.
- Fully autonomous, intelligent operation combined with an HSE-friendly profile lowers the need for manual supervision.

KEY PROJECTS

- Owning and operating a 100 tpa scale carbon capture test rig on the premises of the research institute SINTEF, and a 1,000 tpa pilot plant at the paper mill of Norske Skog Skogn, Norway.
- Completed feasibility study for a 10,000 tpa carbon capture plant at the lime kiln of NorFraKalk AS in Verdal, Norway. Planned for realization of demo plant.
- Signed CA that targets the ambition of the Grenland region in Norway to become the world's first climate positive industry region by 2040.
- Involved as sole carbon capture agent in several research projects driven by SINTEF, including various CCU initiatives such as the recently funded (1.2 million EUR) "CO₂Value" project.

KEY DATA

TRL	6	Capture Rate Range (tpd)	>30	Capture Efficiency (%)	>90%
Source CO ₂ Purity Range	>10%	System Energy (GJ/tCO ₂)	0.7	Specific Regen. Energy (GJ/tCO ₂)	N/A
Number of Commercial Plants	0	Number of Pilot Plants	2	Modular (Y/N)	Optional
Target Industries	Lime, cement, waste/bio-to-energy, selected oil & gas applications				



PENTAIR

ADVANCED AMINE TECHNOLOGY



SUMMARY

Pentair's carbon capture technology enables businesses to capture carbon dioxide (CO₂) from industrial processes and convert it into a valuable by-product. The solution is based on proven, industry tested solvents and technologies, including absorption using monoethanolamine (MEA) & Pentair's Steamlite technology, both well understood solvents with years of operational experience.

The solution is designed as a modular system, comprising CO₂ capture and liquefaction. The capture stage, based on Advanced Amine Technology (AAT), increases CO₂ concentration prior to liquefaction and is offered at capacities of up to 300 tonnes per day (TPD). The liquefaction stage compresses and liquefies the captured CO₂ for transport to utilization or storage and is offered at capacities of up to 2,400 TPD.

Pentair's long standing expertise ensures robust design choices, reliable operation, and high purity liquid CO₂ exceeding 99.999% (v/v), meeting food grade and Northern Lights specifications.

BENEFITS

- **Two proven amine solvent systems incl. Pentair's Steamlite technology**, supported by decades of industrial use and established ATEX, HSE, and emissions standards.
- **Reduced steam consumption** through solvent and process design, supporting lower operating costs and improved energy efficiency.
- **In-house proprietary technologies** to mitigate NO₂-related solvent degradation and minimise carry-over into the CO₂ product, as well as to support solvent maintenance and reclaiming.
- **Access to 90+ years of experience** in CO₂ capture, translating proven know-how into robust design choices and reliable operation for food-grade CO₂ production.

KEY PROJECTS

Tata Chemicals:

Location: United Kingdom.

Capacity: 40,000 tons of CO₂ annually, resulting in ~10% carbon reduction.

Utilisation: Used for sodium bicarbonate production.

Flue gas source: Gas engine.

Year of installation: 2021.

Major Industrial Gas Company:

Location: Australia & Europe.

Capacity: 55,000 tons of CO₂ annually.

Utilisation: Food-grade applications.

Flue gas source: Biomass.

Year of installation: (Australia) 2017 & (Europe) 2022.

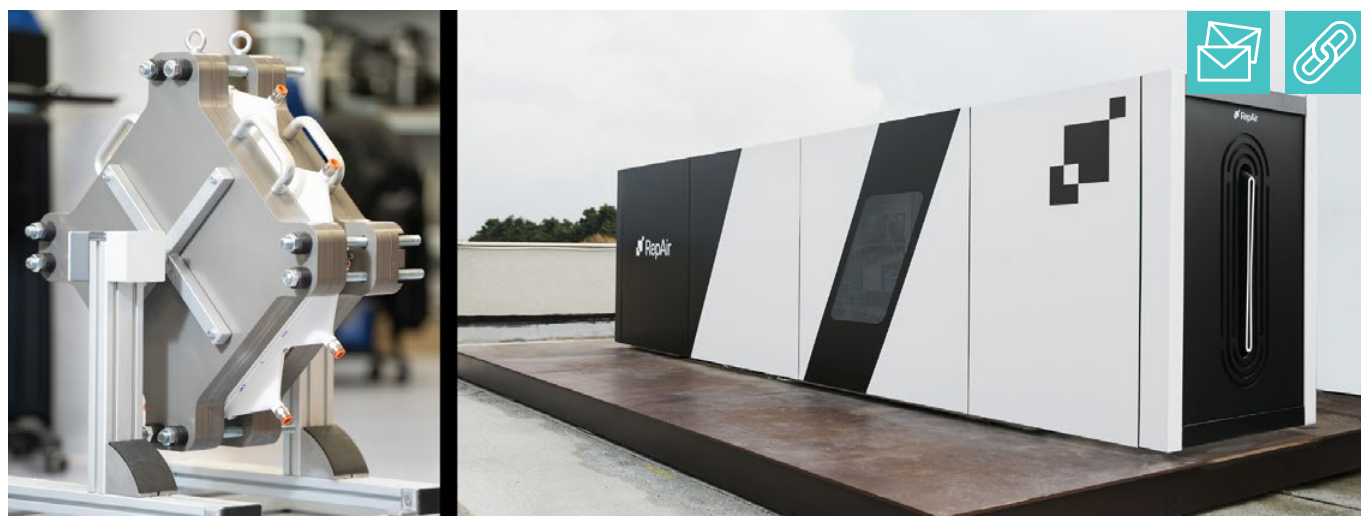
KEY DATA

TRL	9	Capture Rate Range (tpd)	300	Capture Efficiency (%)	90%+
Source CO ₂ Purity Range	3 - 25%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	350+	Number of Pilot Plants	2	Modular (Y/N)	N/A
Target Industries	Heavy Industry, Chemicals, Waste-to-Energy, Biomass-to-Energy, Power Generation				



REPAIR

ELECTROCHEMICAL CARBON CAPTURE



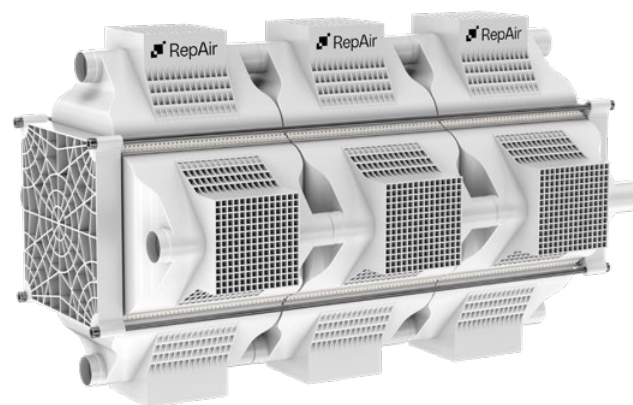
SUMMARY

RepAir is developing a fully electrochemical, solid-state carbon capture technology that operates like a battery and is engineered like a fuel cell. The system selectively captures and releases CO₂ from gas streams using electricity alone, eliminating solvents, sorbents, and thermal regeneration. By integrating capture and release into a single modular electrochemical stack, RepAir replaces complex absorber–stripper systems with a compact, scalable product.

The technology has been validated in field conditions on both Direct Air Capture (DAC) and diluted point-source streams (at 1% and 3–5% CO₂), delivering >97% CO₂ purity at industry-leading energy consumption. Built from abundant materials and designed for mass manufacturability, RepAir's stack-based architecture enables rapid deployment, flexible operation, and seamless integration with industrial and power-generation assets.

BENEFITS

- **Structural Energy Advantage:** Fully electrochemical separation eliminates thermal regeneration, steam extraction, and adsorption cycles. Capture and release occur within a single device at ambient conditions, reducing parasitic load and simplifying integration.
- **Solid-State Simplicity:** No solvents, no liquid handling, no chemical degradation, and no consumables. The system avoids corrosion, solvent makeup, and waste, enabling cleaner operation and lower maintenance complexity.
- **Designed for Flexible Assets:** Electrically driven operation allows response time in seconds
- **Modular, Manufacturable:** Built from stackable electrochemical cells using fuel-cell-like production processes, enabling scalable deployment, compact footprint, and CAPEX reduction at volume.



ElectraStack

KEY DATA

TRL	6	Capture Rate Range (tpd)	~	Capture Efficiency (%)	70 - 90%
Source CO ₂ Purity Range	0.04 - 5	System Energy (GJ/tCO ₂)	1.6 - 2.2	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Aluminium smelters, Gas turbines, CHP plants, Hot steam and water boilers, Gas Compressors, DACCS, DACCU, Copper smelting				



SKYTREE

STRATUS V1.1



SUMMARY

The Skytree Stratus V1.1 is an advanced Direct Air Capture (DAC) system optimised for Carbon Dioxide Removal (CDR) and permanent sequestration. Utilizing a proprietary dual chamber, moving bed temperature vacuum swing adsorption (TVSA) process, the platform achieves high-purity CO₂ capture while reducing energy consumption by up to 50% compared to legacy designs. Currently at TRL 8, the modular units are engineered for scalable deployment in diverse climatic conditions and can be integrated with low grade waste heat, external cooling, or geothermal energy, effectively lowering the energy intensity by 70% compared to the fully electric baseline. By delivering a continuous, high-purity CO₂ stream (>99%), Stratus V1.1 serves as a reliable, energy-efficient front-end for geologic storage and mineralization projects. This modular architecture allows for rapid capacity expansion, supporting large-scale carbon management strategies and the global transition to net-negative emissions.

BENEFITS

- **Enhanced Energy Efficiency:** The proprietary dual chamber architecture optimises the TVSA process, reducing energy consumption by 50% and allowing for a 70% reduction in energy intensity when integrated with waste heat or geothermal sources.
- **Superior Stream Purity:** Delivering CO₂ at a purity exceeding 99%, the system provides a high quality feedstock that meets the stringent requirements for geologic storage, mineralization, and reliable long term sequestration.
- **Climatic and Operational Versatility:** Engineered to perform across diverse global environments, the modular design ensures consistent capture rates while supporting rapid, scalable deployment at diverse sequestration sites without the need for extensive pipeline infrastructure.
- **Strategic Heat Integration:** By utilizing low grade thermal energy and advanced heat pump recovery, the Stratus V1.1 minimises the electrical burden of DAC, significantly lowering the levelised cost of capture for large scale carbon management.

KEY PROJECTS

- **Project Concho (USA):** Selected for the world's first 100% wind-powered DAC park in Texas. In partnership with Return Carbon, Greenalia, and Verified Carbon, this project targets large-scale sequestration with an initial deployment phase exceeding 100 million Euro starting in 2029.
- **EDF Strategic Partnership:** Skytree secured this project following a competitive tender against 60 global DAC providers. Partnering with Return Carbon and EDF, the initiative targets a 50 ktpa capacity by 2029 for permanent carbon management.
- **ASX Oil & Gas Client:** Selected to co-locate our modular DAC technology with one of Australia's leading and operational CCS projects today. Targeted sequestration capacity is 170 ktpa at scale, commencing with 10 ktpa commercial deployment by 2028 to produce negative emissions.

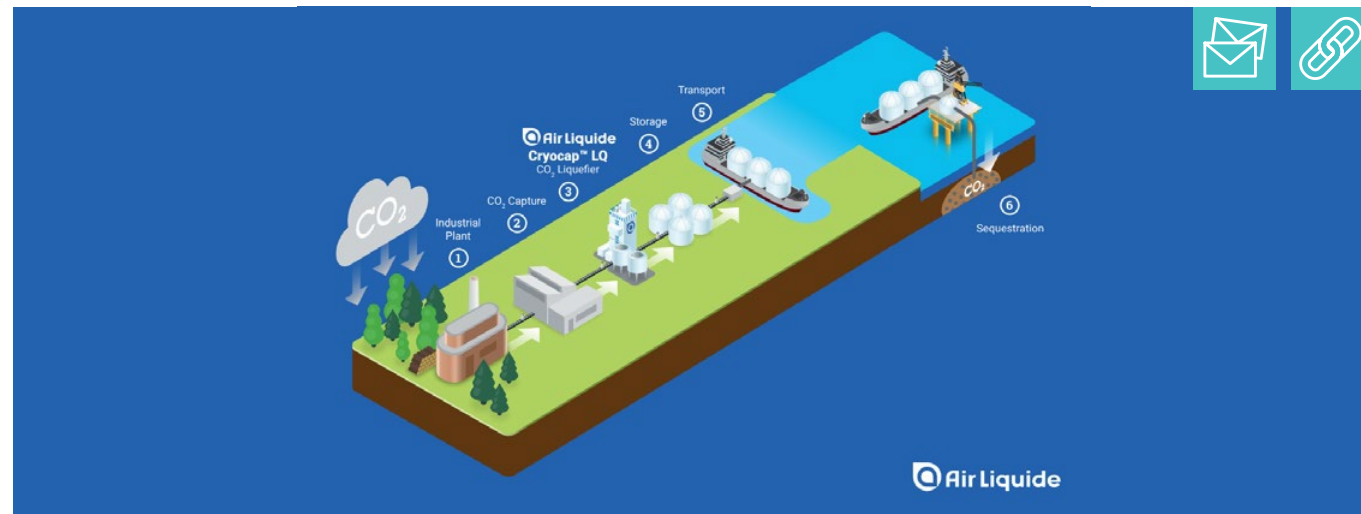
KEY DATA

TRL	8	Capture Rate Range (tpd)	2.5 - 10	Capture Efficiency (%)	98%
Source CO ₂ Purity Range	>0.04%	System Energy (GJ/tCO ₂)	3.6 - 10.8	Specific Regen. Energy (GJ/tCO ₂)	9
Number of Commercial Plants	6	Number of Pilot Plants	6	Modular (Y/N)	Yes
Target Industries	Carbon Sequestration (Storage & Mineralization), E-fuels, Green Chemicals, Horticulture, Food & Beverage, Water Treatment				

CAPTURE ENABLING



AIR LIQUIDE CRYOCAP™ LQ (EXTRA LARGE CO₂ LIQUEFIER)



SUMMARY

Air Liquide has developed Cryocap™ LQ, specifically designed to liquefy large volumes of CO₂. The solution allows the aggregation of CO₂ from various emitters utilising possibly different types of carbon capture technologies. On top of liquefying CO₂, Cryocap™ LQ also allows the removal of moisture and other compounds (such as O₂) to meet CO₂ sink specifications. The technology is able to reduce specific energy consumption throughout the process by 40% compared to traditional industrial CO₂ liquefaction processes, while ensuring very high CO₂ recovery. The technology is especially suited for CO₂ industrial hubs and basins where the CO₂ needs to be transported via ships, trucks, or trains. Cryocap™ LQ is a chemical free, HSE-friendly solution. As a single compressor is used for both the feed and the cycle, it is also a very compact and cost effective solution.

BENEFITS

- Large scale capacities
- HSE-Friendly
- Highly compact and flexible design
- High recovery and lower specific energy consumption
- Single centrifugal compressor (1 machine for CO₂ compression and refrigeration cycle)

KEY PROJECTS

- 2022/2023 - Industrial pre-FEED and FEED for 7000 tpd in Belgium (Antwerp@C)
- 2023/2024 - Industrial pre-FEED and FEED for 3700 tpd in France (Dartagnan)
- 2025 - Execution of 3500 tpd in Sweden (Stockholm Exergi), largest CO₂ liquefier worldwide

KEY DATA

TRL	7	Capture Rate Range (tpd)	700 - 10,000+	Capture Efficiency (%)	97%+
Source CO ₂ Purity Range	95%v+	Energy Consumption (GJ/tCO ₂)	0.2 - 0.5	Specific Regen Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	CO ₂ Liquefaction				

TECHNOLOGY DESCRIPTION

CRYOCAP™ LQ

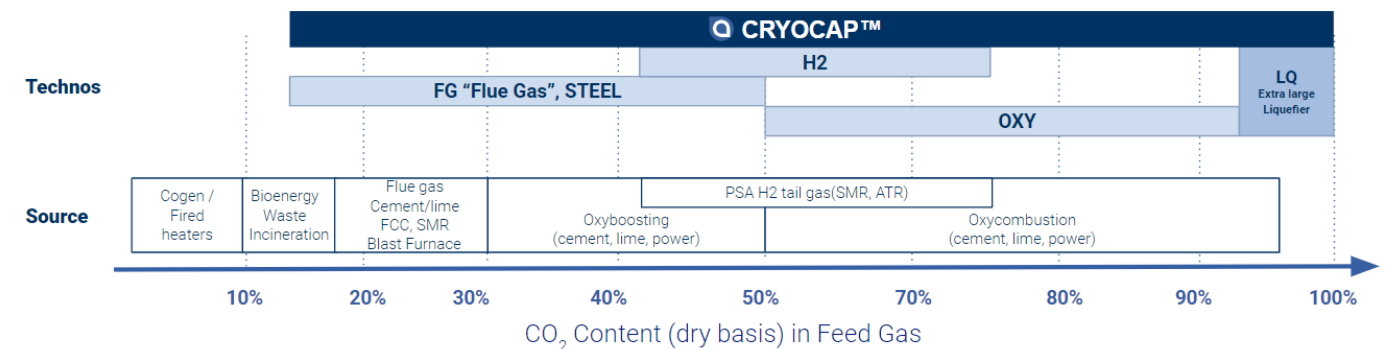
The Cryocap™ LQ process is proposed as an industrial solution to compress, liquefy, and purify the raw CO₂ stream resulting from upstream units. The CO₂ feed gas is compressed in the feed/recycle compressor, dried at an intermediate pressure and then compressed again. The compressed gas is cooled down and then routed to the cold process. In the cold process, the high-pressure, dry CO₂ is cooled down and split into various streams.

One of these streams is purified by distillation in the Stripping Column to produce the liquid CO₂ product, which is routed to the unit's battery limits. The remaining streams are expanded to different levels and vaporised in the main heat exchanger, providing the refrigeration load required for the liquefaction of the CO₂. Once vaporised, these streams are recycled at ambient temperature to the feed/recycle compressor. This configuration makes it possible to handle the compression of the feed gas and the refrigeration with a single compressor (so called self-refrigerated cycle).

Characteristics:

- Very low OpEx
- HSE friendly
- From low pressure to high pressure CO₂ product
- Compact solution

Air Liquide cryogenic offerings for CO₂ capture and liquefaction





TECHNOLOGY DESCRIPTION

The water to be treated is pre-heated and sent to an evaporator, where the water is boiled-off to leave behind a concentrated brine, which can then be recycled or disposed of safely. The boiled-off water is condensed and returned to the process for reuse, so that no liquid waste is discharged into the environment. At the core of the evaporator is the plate heat exchanger where the corrugated plate pattern gives high turbulence and shear forces.

This provides a “self-cleaning effect”, and helps to reduce fouling and scaling, which are primary risks in wastewater evaporation. The streams to be treated are generally corrosive, thus requiring high grade materials such as titanium or duplex steel and Alfa Laval has a deep expertise in material selection. The evaporation systems are available as pre-assembled modular systems or customised solutions and Alfa Laval has supplied more than 1000 evaporation systems within different industries, of which more than 100 in wastewater applications.

SUMMARY

Solvent degradation in amine-based carbon capture plants can take place in the absorber/desorber via thermal degradation or oxidative degradation as a result of chemical reactions with the impurities present in the flue gas or from the impurities caused by corrosion of the carbon capture plant materials. Dirty Amine is then directed to Proprietary Amine reclamation to remove formed solids.

In CCUS like many other industrial processes wastewater streams are generated. Those polluted and contaminated waters represent a cost for treatment, discharge or offsite disposal as well as an environmental concern. This is where an evaporation/ZLD system comes in: to treat and minimise this wastewater. The technology helps to recover and reuse both water and valuable chemicals already at the source, at the production facility.

BENEFITS

- Treat wastewater streams to secure compliance with discharge limits & ZLD requirements
- Close the water loop in the scrubber system: by reusing the water coming out of the ZLD system
- Recover up to 99% water for reuse
- Solids for reuse, or minimal disposal cost
- High liquid circulation rates
- Corrosion resistance
- Compact design
- Access heat transfer surface and highly flexible and adaptable system
- High shear stress (turbulence)
- Self-cleaning effect
- Up-time and CIP efficiency significantly improved

KEY PROJECTS

- **Cement CCUS Plant:** Alfaflash has been recently selected for a commercial Cement CCUS with capacity Of 800ktpa for the reclamation system.

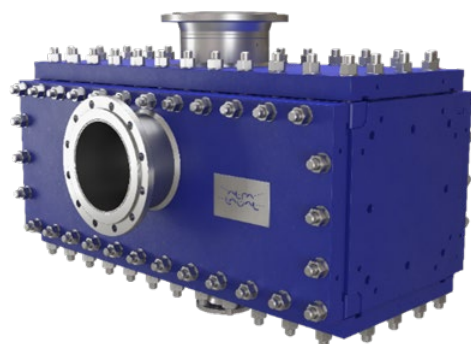
KEY DATA

TRL	9	Number of Commercial Plants	30	Consumed power (kW/t)	30 - 60
Water evaporation capacity (kg/h)	1,500 - 6,000	Modular (Y/N)	Yes		
Target Industries	CCUS, Data Centers, Energy, HVAC, Steel, Pulp and paper, Water and Waste Water treatment				



ALFA LAVAL

COMPABLOC STRIPPER REBOILER



SUMMARY

The main energy cost in solvent-based CO₂ capture is the steam needed for solvent regeneration in the stripper reboiler. Therefore, selecting a right reboiler that minimises the temperature difference between the solvent's boiling point and steam is crucial.

Alfa Laval's Compabloc heat exchanger has a proven track record for this role. Its innovative, fully welded plate design delivers exceptional thermal efficiency, significantly reducing steam consumption and operational costs. The compact, horizontal assembling saves valuable space, while the robust, corrosion-resistant materials ensure reliable performance even with aggressive amine solutions. Compabloc's low-fouling characteristics and easy maintenance access minimise downtime, supporting continuous and efficient operation.

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BENEFITS

- **High thermal efficiency:** Up to four times larger heat transfer coefficient compared to shell-and-tube, resulting in higher heat recovery between the hot and cold streams, reducing the energy required for solvent regeneration.
- **Compact design:** Saves space, reducing installation costs.
- **Low temperature approach:** Can achieve a very close temperature approach (as low as 3°C), maximizing energy recovery and improving overall process efficiency.
- **Accessible for inspection and mechanical cleaning.**
- **Robust and reliable:** Laser-welded plates to optimise reliability. Wide choice of plate materials. More than 30.000 units delivered worldwide.

KEY PROJECTS

- **Gas Plant CCUS:** With 0.2Mtpa capture capacity and operational since 2023, utilising Compabloc in the reboiler position.
- **Coal Power Plant CCUS:** With 1Mtpa capture capacity and operational since 2014, this project is FOAK CCUS project utilising Compabloc in the reboiler position.
- **Natural Gas-fired power plant CCUS:** With 0.86Mtpa capture capacity and operational since 2018, utilising Compabloc in the reboiler position.

KEY DATA

TRL	9	Max design pressure (barg / psig)	Up to 60 / 870	Number of Commercial Plants	>100
Modular (Y/N)	Yes	Max temperature (°C / °F)	Up to 370 / 698		
Target Industries	CCUS, Power, Cement, Oil & Gas, Refineries				



ALFA LAVAL

TL35B LEAN/RICH INTERCHANGER



SUMMARY

The lean/rich position in carbon capture processes is crucial for both operational and capital efficiency. Optimizing heat recovery between the hot rich and cold lean solvent streams at this point significantly reduces external steam demand, lowering OPEX, while also allowing for smaller equipment and reduced CAPEX.

Alfa Laval's gasketed plate heat exchangers TL35B are ideal for lean/rich interchanger duties, offering exceptional thermal efficiency and a compact footprint that saves valuable space. Their advanced design enables a close temperature approach, maximizing energy recovery and further reducing operational costs. Built with corrosion-resistant materials, these exchangers ensure long-lasting performance even in demanding amine environments, and are easy to maintain and clean. With proven reliability and flexibility to adapt to changing process needs, Alfa Laval delivers the trusted technology required for efficient and sustainable carbon capture. Our new T45B will soon be released for larger-scale projects.

BENEFITS

- Fewer units and lower costs: Superior efficiency reduces the number of heat exchangers needed, cutting installation costs.
- Energy savings: They enable a hotter rich solvent to enter the stripper column, which lowers the reboiler's heat duty and steam consumption. This also means a smaller reboiler is required.
- Optimised cooling: Maximizing heat recovery from lean to rich solvent results in a colder lean solvent. This reduces the flow rates of cooling media, eases the load on the lean solvent cooler, and minimises its size.

KEY PROJECTS

- CCUS for Coal-fired power plant: With 1Mtpa capture capacity and operational since 2014, this project is FOAK CCUS project utilising TL35B heat exchangers in L/R position.
- CCUS for Coal-fired power plant: With 1.4 Mtpa capture capacity and operational since 2017, this project utilises TL35B in L/R position.
- Steam Methane reformer: With 0.75Mtpa capture capacity is currently under construction. This project utilises TL35B in L/R position.

KEY DATA

TRL	9	Max design pressure (barg / psig)	Up to 30/535	Number of Commercial Plants	>15 (CCUS plants)
Modular (Y/N)	Yes	Max temperature (°C / °F)	Up to 210/410		
Target Industries	CCUS, Data Centers, Energy, HVAC, Steel, Pulp and paper, Water and Waste Water treatment				

TECHNOLOGY DESCRIPTION

GASKETED HEAT EXCHANGERS FOR L/R

Gasketed plate heat exchangers (GPHEs), offer several key advantages in the lean-rich solvent interchanger, making them a highly efficient and cost-effective choice for this application.

First, they have a low capital expenditure (CapEx) compared to shell-and-tube heat exchangers. Their compact design requires less material and a smaller footprint, reducing both initial investment and installation costs.

Another major advantage is their full cleanability. Since the unit can be fully disassembled, operators have direct access to all heat transfer surfaces, allowing for thorough cleaning. This is particularly important in solvent applications where fouling or scaling can reduce efficiency over time.

GPHEs are also easy to maintain and repair. Individual plates or gaskets can be replaced without the need for a full unit shutdown, minimizing downtime and operational disruptions.

Flexibility is another key benefit. These exchangers allow for the addition or removal of plates to adjust the heat transfer area (HTA), making it easy to optimise performance based on process variations. This adaptability can lead to significant long-term savings.

When it comes to material compatibility, GPHEs support a wide range of gasket materials, including EPDM, HNBR, and HeatSealA, ensuring chemical resistance to different solvent compositions and operating conditions. This helps enhance durability and operational reliability.

Finally, one of the most critical advantages is maximum heat recovery efficiency. GPHEs achieve extremely low approach temperatures and the lowest possible pinch points, maximizing energy recovery between the lean and rich solvent streams. This improves overall process efficiency and reduces energy consumption, which is especially valuable in solvent-based applications.

In summary, GPHEs provide a cost-effective, flexible, and highly efficient solution for the lean-rich solvent interchanger, making them a preferred choice in many industries.



SUMMARY

In solvent based carbon capture processes, the main energy consumer is the steam required for solvent regeneration/CO₂ desorption in the stripper reboiler, leading to higher fuel consumption and emissions. Recovering the energy from hot flue gas to generate low pressure steam or hot water upstream of the direct contact cooler (DCC) will significantly reduce both energy use and emissions. With a proper energy recovery design, the external energy demand to produce steam can be reduced by up to 50%.

Alfa Laval's Ziepack hybrid technology, featuring advanced gas-gas and gas-liquid heat exchangers, is well-suited for Waste-Heat-Recover (WHR) applications. Ziepack units are customizable in size, plate gap, and metallurgy, with dimensions up to 12 meters in length, 4 meters in diameter, and a weight of approximately 46 tons. Ziepack is ideal for amine-based carbon capture and is also suitable for other CCS processes, such as the Hot Potassium Carbonate.

BENEFITS

- **High energy efficiency:** It's excellent heat transfer performance, makes it ideal for demanding distillation, absorption, and stripping applications.
- **Low pressure drop:** It's unique design minimises pressure drop, which reduces energy consumption and operational costs.
- **Compact design:** It's high capacity allows for installation at the top of columns, saving space and reducing installation costs.
- **Robust and durable:** Made from corrosion-resistant materials, it ensures long service life and reliability even in harsh process conditions.
- **Easy installation and maintenance:** Modular construction allows for quick installation and easy access for maintenance and inspection.

KEY DATA

TRL	9	Max design pressure (barg / psig)	34/493	Capacity (MW)	1- 15
Pressure drop (kpa)	<1	Max temperature (°C / °F)	450/842		
Target Industries	Carbon Capture & Refining				

TECHNOLOGY DESCRIPTION

Ziepack heat exchanger maximises the generation of low-pressure steam for use as an energy source in the stripper reboiler, reducing investment costs and removing fuel consumption for a new steam boiler. It also lowers the investment required for DCC equipment, as the flue gas enters the DCC at a much lower temperature and thus reduces volumetric flow rate. The lower the flue gas inlet temperature to the DCC, the more steam is produced by the WHR system, further decreasing boiler and DCC investment costs. The limit to how much flue gas cooling can be achieved in the WHR system is set by the steam saturation pressure and temperature required in the stripper reboiler.

Operating at a higher stripper pressure helps reduce both the reboiler duty and the CO₂ compressor capacity. However, higher stripper pressure causes the solvent to boil at a higher temperature, and since most CO₂ capture solvents are temperature sensitive, the optimal stripper pressure is determined by the maximum allowable temperature to prevent severe solvent degradation.

MATERIAL DETAILS

A wide range of plate materials is available, including stainless steels such as 304, 316, and 904L. Advanced alloys like 254SMO and Duplex are also supported, ensuring compatibility with demanding process environments. The Ziepack shell can be fabricated from either carbon steel or stainless steel, further enhancing its adaptability.

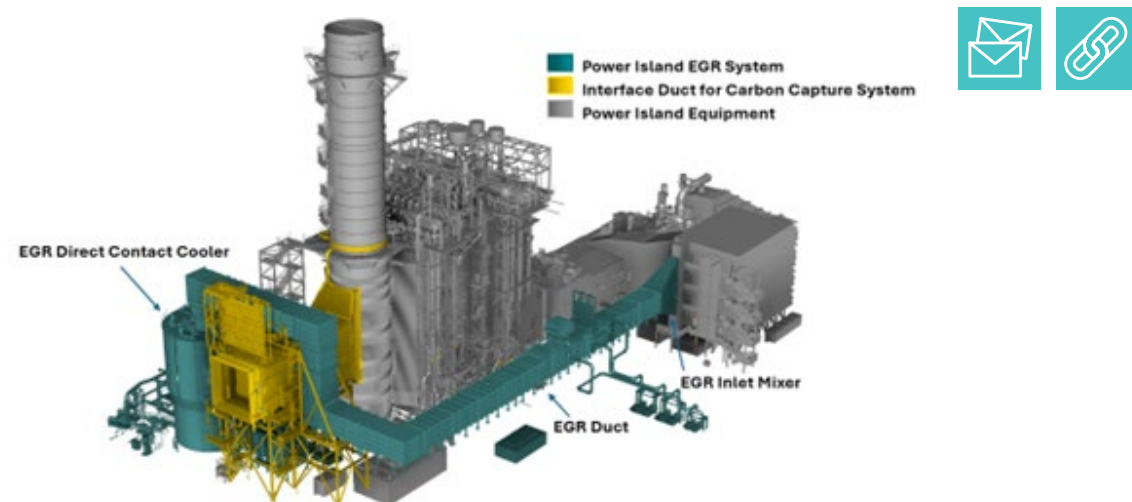




GE VERNOVA

GE VERNOVA

GE VERNOVA CARBON CAPTURE SOLUTIONS



SUMMARY

GE Vernova is a key player in the power industry, providing a wide range of integrated renewable, gas-fired, nuclear, grid, and digital technologies. GE Vernova is committed to deploying diverse technologies to reduce emissions while laying the groundwork for long-term innovation aiming to deliver decarbonised* electric power. GE Vernova has the knowledge and expertise to provide innovative and competitive solutions for integrating carbon capture with generating assets and has developed a portfolio of technologies configured to enhance performance and reduce the cost of carbon capture plants (CCP). These solutions include exhaust gas recirculation (EGR), elimination of CCP blowers, steam integration, upgrades for gas turbines (GT), steam turbines (ST), and heat recovery steam generators (HRSG), along with advanced control systems and digital capabilities for monitoring, reporting, and verification.

BENEFITS

- **Reduced CapEx:** By reducing exhaust gas flow volume to CCP, EGR decreases the size and CapEx of the CCP. Additionally, providing steam through steam integration further reduces CCP CapEx by eliminating the need for an auxiliary boiler.
- **Lower OpEx:** Reduced energy demands and decreased oxidative amine degradation contribute to lowering operational costs.
- **Improved plant performance:** EGR increases the net output and part load efficiency of natural gas combined cycle (NGCC) plants equipped with carbon capture technology. Additionally, steam integration reduces the auxiliary boiler size or, in some cases, eliminates it, thereby enhancing overall plant efficiency compared to the bolt-on solution.
- **Enhanced capture:** EGR increases CO₂ concentration in exhaust gas, which boosts capture efficiency and reduces specific energy requirements.

KEY DATA

TRL**	5 - 7*
Target Industries	Utility Power Generation, Industrial Power Generation, Data Center Power Generation

* Decarbonization as used herein is intended to mean the reduction of carbon emissions on a kilogram per megawatt hour basis

** TRL can differ based on the GT frame and project

KEY PROJECTS

- **Net Zero Teesside Power (NZE Power):** NZE Power aims to be the world's first commercial gas-fired power station integrated with a full scale CCP, capable of generating 740+ MW of flexible, dispatchable and low-carbon power, capturing up to two million tonnes of CO₂ per year which will be transported and stored by the Northern Endurance Partnership (NEP). NZE will demonstrate the first commercial use of GE Vernova's EGR system and CCP blower elimination which will boost plant performance, reliability and availability, while also reducing cost. In addition, the facility includes early steam extraction at start-up and extended steam extraction at shut-down to comply with local CO₂ capture regulations.

TECHNOLOGY DESCRIPTION

EXHAUST GAS RECIRCULATION (EGR)

EGR functions by redirecting a portion of the exhaust flow from the HRSG back into the gas turbine inlet. By decreasing the volumetric flow of exhaust gas directed to the CCP, EGR effectively reduces the size and CapEx of the CCP and associated infrastructure. The significant reduction in CCP size with EGR is primarily in the direct contact cooler (DCC) system and the absorption system, which make up the majority of the CCP CapEx. Prior to mixing with the incoming air at the gas turbine inlet, the EGR flow is cooled and cleaned in the EGR DCC. The EGR DCC is capable of separating and removing impurities like NO_x, SO_x, ammonia (NH₃), particulate matter, and liquid carryover.

EGR increases the concentration of CO₂ in the exhaust gas, allowing the CCP to capture the same amount of CO₂ from exhaust gas while treating a smaller volume of gas. In addition, compared to the non-EGR scenario, EGR improves CCP performance and lowers reboiler duty by increasing the CO₂ concentration in exhaust gas to CCP. This results in less steam extraction and improved NGCC output.

EGR is advantageous not only for the solvent-based carbon capture system but also for other technologies, such as cryogenic systems, membranes, and sorbent adsorption techniques. This results from the elevation of CO₂ partial pressure in exhaust gas, enhancing system efficiency and reducing exhaust gas volume, thereby decreasing the number of units or modules required.

ELIMINATION OF CCP BLOWER

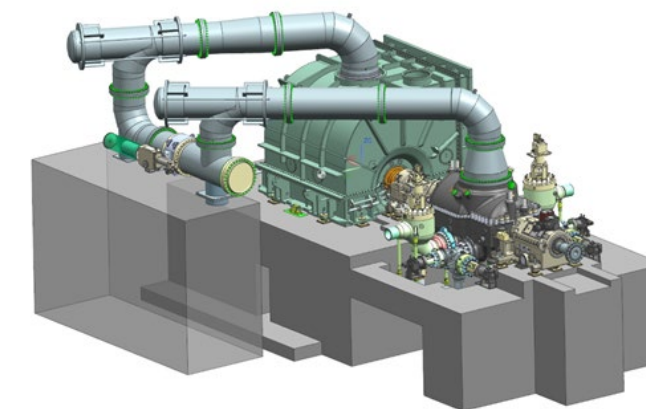
Operating GT and HRSG at higher backpressure eliminates the need for blowers by using the GT to move exhaust gas through the CCP and EGR systems. This simplifies the control system, reduces the CapEx and footprint, and improves performance, reliability, and availability.

STEAM INTEGRATION

The CCP reboiler requires a significant amount of steam to desorb CO₂ from the solvent. Steam can be generated by additional installed auxiliary boilers in a bolt-on solution, or by steam extraction from the bottoming cycle.

A bolt-on solution entails the installation of additional external auxiliary boilers to supply steam to the CCP, resulting in increased CCP size, overall site fuel consumption and emissions, along with reduced site efficiency.

Steam integration, on the other hand, extracts the steam from the steam bottoming cycle. Steam extraction sources are selected based on compatibility with CCP reboiler conditions and typically include low-pressure superheat and intermediate pressure (IP) / low pressure (LP) crossover (shown in image below). By using these steam source, GE Vernova reduces the impact on existing NGCC operations and efficiency.



GAS TURBINE, STEAM TURBINE AND HRSG UPGRADES

A variety of component upgrades and modifications are available to further improve plant performance. Retrofitting GE Vernova's gas turbines, steam turbines, and HRSGs can significantly enhance output, heat rate, reliability, and maintainability. A thorough evaluation of available upgrades and modifications helps mitigate part or all of the NGCC parasitic load associated with CCP.

CARBON CAPTURE CAPABLE CONFIGURATION

To future-proof new unit NGCCs for decarbonization, GE Vernova has developed a Carbon Capture Capable new unit configuration to reduce the future CapEx and outage time required to retrofit carbon capture. This configuration includes a steam turbine with large steam extraction capability, provisions for future EGR, provisions to remove the CCP blower, a stack engineered for future carbon capture installation, reserved space for future equipment, and controls and electrical provisions.

DIGITAL MONITORING, REPORTING & VERIFICATION

GE Vernova provides software to enable the energy transition. CERius™ is a centralised cloud application that automates higher accuracy greenhouse gas (GHG) emission data collection and provides insights to operationalise carbon abatement project accounting.



LINDE HITREAT™ CO₂ LIQUEFACTION



SUMMARY

CO₂ liquefaction can be an additional process step attached to a CO₂ capture and processing plant. For example, when CO₂ is purified by means of cryogenic separation (rectification), CO₂ liquefaction is involved. In addition, CO₂ liquefaction might be required because of the CO₂ logistics concept when transporting it via road trailers, trains, or ships.

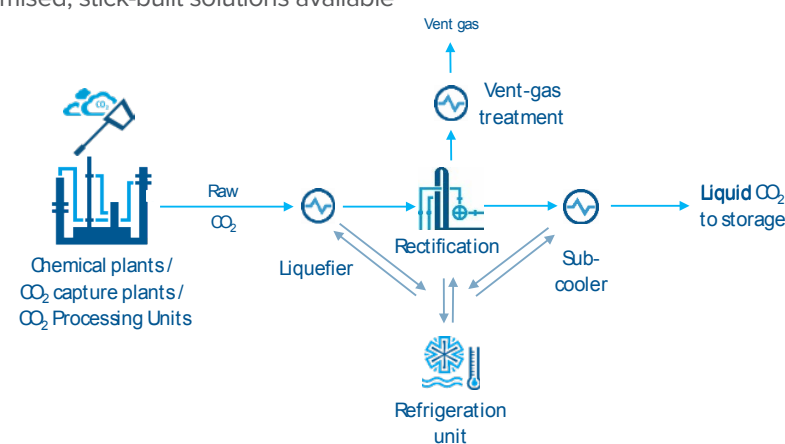
Linde's largest liquefaction plant, in operation since 2015, is producing approximately 1,350 tons of CO₂ per day. The CO₂ is used in enhanced methanol and urea production. Additional large-scale plant references can be found in Norway and the United States for carbon capture and storage (CCS) and food applications, respectively. Depending on local needs, the integration concept, safety considerations, and cost efficiency, different refrigerants can be considered for use in the refrigeration unit.

BENEFITS

- Mature and robust technology
- Various options for refrigerants available
- Extended reference list at various product capacities
- Standardised and skid-mounted modules as well as large-scale customised, stick-built solutions available

KEY PROJECTS

- Linde signed a contract with global fertiliser manufacturer Yara to build the world's largest carbon dioxide liquefaction plant in Sluiskil, the Netherlands.
- The project is now in a construction phase.



Typical CO₂ liquefaction process design

KEY DATA

TRL	9
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LINDE HITREAT™ CO₂ TREATMENT



SUMMARY

Linde's CO₂ Processing Unit (CPU) is applied to purify CO₂-containing gas streams to provide typical CO₂ product specifications for a variety of industrial applications. Typical CPU feed gas streams are CO₂-rich gases generated from CO₂ capture processes, flue gases from oxy-fuel combustion processes, and CO₂-rich off-gases from chemical plants, such as ammonia, ethylene oxide, methanol, or ethanol plants. As shown in the figure, an extended toolbox of processes and technologies allows for the removal of different trace components, such as sulphur- or nitrogen-containing compounds, hydrocarbons, heavy metals, and air gases.

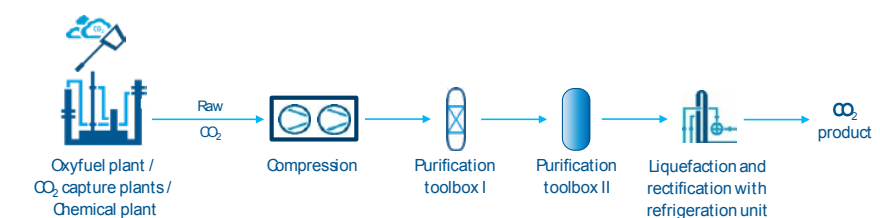
Linde initially developed and commercialised the CPU technology to treat oxy-fuel flue gases at an oxy-fuel lignite-fired power plant at Schwarze Pumpe, Germany. More recently, Linde's CPU has been considered for oxy-fuel projects in the cement industry. Mature CO₂ processing technologies in combination with Linde's track record in large-scale gas-treatment plants ensure low-risk EPC projects for clients.

BENEFITS

- Mature and robust purification technology
- Reference plant in Schwarze Pumpe, Germany, for treatment of oxy-fuel flue gases
- Multiple EPC and Linde operation references for production of food-, chemical-, and electronics-grade CO₂
- Standardised and skid-mounted modules as well as large-scale customised, stick-built solutions available

KEY PROJECTS

- The CO₂ capture and processing plant downstream of an oxyfuel cement process at an existing plant in Mergelstetten is in pre-commissioning phase. Operation is planned to begin in Q3 2026.
- Linde, Sabic, and Scientific Design signed a memorandum of understanding (MoU) related to decarbonisation of petrochemical plants. The goal is to establish sustainable chemicals production.



Typical CO₂ Processing Unit (CPU) design

KEY DATA

TRL	9	Capture Rate Range (tpd)	100 - 12,000	Capture Efficiency (%)	95 - 99.5%
Source CO ₂ Purity Range	70 - 75%	System Energy (kWh(e)/tCO ₂)	100 - 250	Specific Regen. Energy (kWh(e)/tCO ₂)	~
Number of Commercial Plants	>20	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Oxyfuel combustion, chemical plants, CO ₂ capture facility				



SUMMARY

CO₂ liquefaction is a critical enabler for large scale CCS, defining how efficiently captured CO₂ can be transported, stored, or utilised. As projects scale up toward hub and cluster configurations, conventional liquefaction technologies face growing limitations in capacity, efficiency, and complexity.

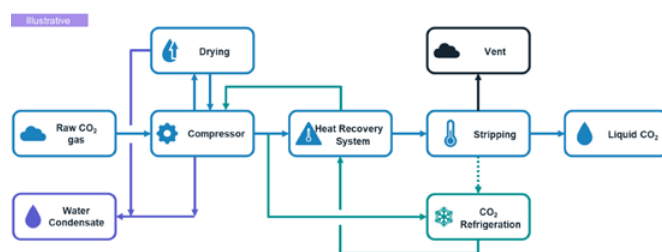
NX CLIQ™ is NEXTCHEM's self refrigerated CO₂ liquefaction solution, developed to enable efficient and scalable CCS infrastructures. By using CO₂ itself as the refrigerant and maximizing heat integration, NX CLIQ™ overcomes the constraints of traditional ammonia based systems, reducing equipment count and improving energy efficiency. Designed for medium and large scale applications, NX CLIQ™ supports the development of integrated CO₂ value chains and real world decarbonization projects, leveraging MAIRE's proven experience in delivering complex industrial plants worldwide.

BENEFITS

- **Large-Scale Single-Train Deployment:** Enables large-scale CO₂ liquefaction in single-train configurations, overcoming the scalability limits of traditional ammonia-based systems and supporting hub-based CCS developments.
- **Flexible CO₂ Product Specifications:** Provides liquid CO₂ at different pressure and temperature levels, delivering a product compatible with conventional transport, storage, and utilization specifications across the CCS value chain.
- **Self-Refrigerated CO₂ Liquefaction:** Eliminates the need for external refrigerants by using CO₂ itself as the refrigerant, simplifying the process configuration and reducing operational complexity and environmental footprint.
- **High Efficiency & Reduced Energy Consumption:** Delivers high-efficiency CO₂ liquefaction with very low specific energy consumption and high CO₂ recovery, improving overall system performance compared to conventional liquefaction technologies.

KEY PROJECTS

- **IRIS:** Agioi Theodoroi Refinery: Selected NX CLIQ™ as the CO₂ liquefaction technology for the IRIS CCS project, enabling efficient and scalable CO₂ liquefaction to support transport and storage within a hub-based CCS configuration.



- **NX CLIQ™:** conceptual view illustrating the configuration of NX CLIQ™ as a self-refrigerated CO₂ liquefaction loop. CO₂ used as refrigerant is recycled back to the compressor to avoid any CO₂ losses.

KEY DATA

TRL	9	Capture Rate Range (tpd)	>400	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	<115
Number of Commercial Plants	~	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	CCS hubs, transport & storage, large-scale CCUS				

TECHNOLOGY DESCRIPTION

TECHNOLOGY OVERVIEW

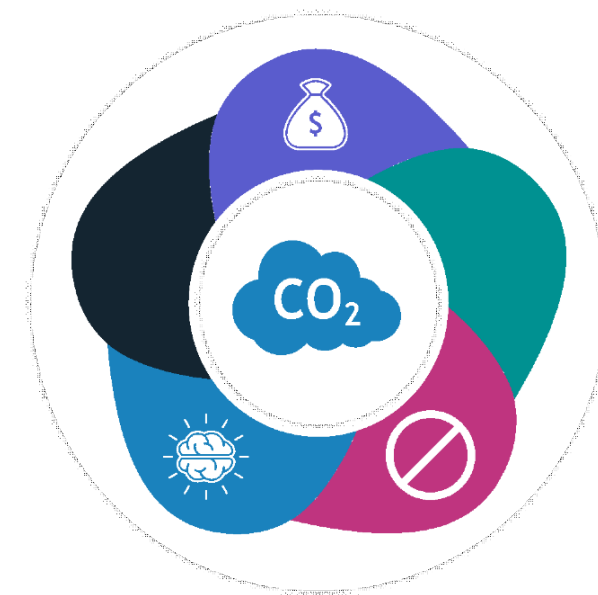
NX CLIQ™ is NEXTCHEM's proprietary CO₂ liquefaction technology, designed to convert compressed CO₂ into a liquid state through a self-refrigerated process configuration. The technology is based on the use of CO₂ itself as the refrigerant, enabling liquefaction without the need for external refrigeration media.

In NX CLIQ™, CO₂ compression, purification, refrigeration, and liquefaction are integrated within a single, closed process loop characterised by a high degree of thermal integration. Purification is an intrinsic part of the process and includes both the removal of non-condensable components and the dehydration of the CO₂ stream, ensuring product quality compatible with cryogenic operation and downstream handling. By coupling these functions within one thermodynamically optimised architecture, NX CLIQ™ maximises internal heat recovery while minimizing auxiliary systems and dedicated refrigeration equipment.

The process is designed to deliver liquid CO₂ at different pressure and temperature conditions at battery limit, allowing flexibility in how the product is transferred to downstream systems. This capability enables NX CLIQ™ to accommodate different logistics and handling requirements while maintaining optimised energy performance compared to conventional liquefaction schemes based on external refrigeration.

WHY USING CO₂ AS A REFRIGERANT?

Using CO₂ as a refrigerant offers several technical, economic, and environmental advantages, making it an attractive choice for modern CO₂ capture and liquefaction systems. From a cost perspective, carbon dioxide is inexpensive and readily available, especially in CCUS applications where it is already present in large quantities. In terms of environmental impact, CO₂ has a low global warming potential and, unlike ammonia, does not pose risks to ecosystems in case of accidental release due to toxicity. Safety is another key benefit: CO₂ is non-flammable, non-toxic, chemically inert, and compatible with common construction materials, enabling simpler plant design and less stringent safety requirements. Although ammonia generally provides higher thermodynamic efficiency, the performance gap can be significantly reduced through careful process optimization when using CO₂. Finally, CO₂ enables the integration of refrigeration and liquefaction within a single, closed loop, unlocking valuable process synergies and reducing overall equipment complexity.



SYSTEM INTEGRATION AND SIMPLICITY AS A DESIGN DRIVER

In complex industrial systems, performance is often determined less by individual components than by how effectively they are integrated into a coherent whole. In CO₂ liquefaction, fragmented process architectures—characterised by separate refrigeration loops, multiple compressors, and numerous interfaces—can introduce unnecessary complexity that affects operability, reliability, and lifecycle performance.

NX CLIQ™ is built around a design philosophy that prioritises integration and simplicity from the outset. By combining CO₂ compression, refrigeration, and liquefaction within a single self-refrigerated loop, the technology minimises the number of rotating machines and reduces the interfaces between subsystems. This integrated configuration simplifies plant layout and control logic, limiting interactions that can otherwise lead to operational constraints or reduced availability.

Rather than adding layers of equipment to manage complexity, NX CLIQ™ embeds functionality directly into the process architecture. The result is a liquefaction solution that is easier to operate, more robust over time, and better suited to continuous, industrial-scale service, where reduced system fragmentation naturally translates into simpler maintenance strategies across the lifecycle. In this context, simplicity is not a consequence of reduced scope, but a deliberate design choice that enhances reliability and supports the long-term operation of integrated CO₂ value chains.

TYPICAL APPLICATION CONTEXT

NX CLIQ™ is particularly suited for CCS projects where captured CO₂ must be conditioned for transport and storage at medium- to large-scale, including hub-based configurations and ship-based CO₂ logistics. The technology is optimised to interface with carbon capture systems, delivering high-purity CO₂ streams and to support integration with pipeline networks, intermediate storage, and export terminals.



NOV – CO₂ CAPTURE AND CONDITIONING

POST-COMBUSTION CAPTURE FIBERGLASS DUCTING



SUMMARY

Corrosion resistance is crucial in carbon capture technology, particularly in the post-combustion capture process, due to the presence of corrosive gases such as carbon dioxide (CO₂) and other impurities in the flue gas. These gases can lead to the formation of corrosive compounds such as carbonic acid, which can degrade the materials used in the capture equipment, leading to reduced efficiency, increased maintenance costs, and potential safety hazards.

For more than 60 years, NOV's Fiber Glass Systems (FGS) business unit has provided fiberglass duct systems, piping, and tanks in a variety of applications and industries around the world. From the start of the carbon capture processes, our high-temperature fiberglass ducting with capabilities up to 325°F (162°C) can reduce post-combustion capture costs.

BENEFITS

- **Corrosion and Chemical Resistance:** Flue gas in post-combustion carbon capture processes often contains corrosive compounds such as Sulphur dioxide and nitrogen oxides, which can lead to corrosion in costly metallic ducting. Fiberglass ducting, with its high resistance to corrosion, is an excellent choice for maintaining structural integrity and longevity in this environment.
- **Temperature Resistance:** Fiberglass ducting can withstand high temperatures without deforming or degrading.
- **Lightweight and Easy to Install:** The lightweight nature of fiberglass is easier to install than heavy metallic alternatives, contributing to cost-effectiveness and efficient installation.

KEY PROJECTS

- **American Electric Power (AEP) Mountaineer Station:** In 2009, FGS, in support of Alstom Power, Inc., completed the structural design, fabrication and delivery of one 10-ft diameter x ~77-ft-tall filament-wound FRP scrubbing vessel and over 1,300 linear feet of 48-in. to 60-in. diameter filament-wound FRP ductwork, comprising the integral portion of the world's first demonstration project to capture and store CO₂ from an existing coal-fired power plant.
- **Tomato Greenhouse in Utah:** FGS provided 10-ft diameter insulated ducting to transport CO₂ captured from a Pacific Northwest power plant to an adjacent tomato greenhouse for CO₂ fertilization for crops.
- **North Dakota Coal-Fired Power Plant:** Installed in 2010, FGS designed and manufactured 21-ft diameter ducting from each absorber, joining at a common wye and exiting at 30-ft diameter.

KEY DATA

TRL

9

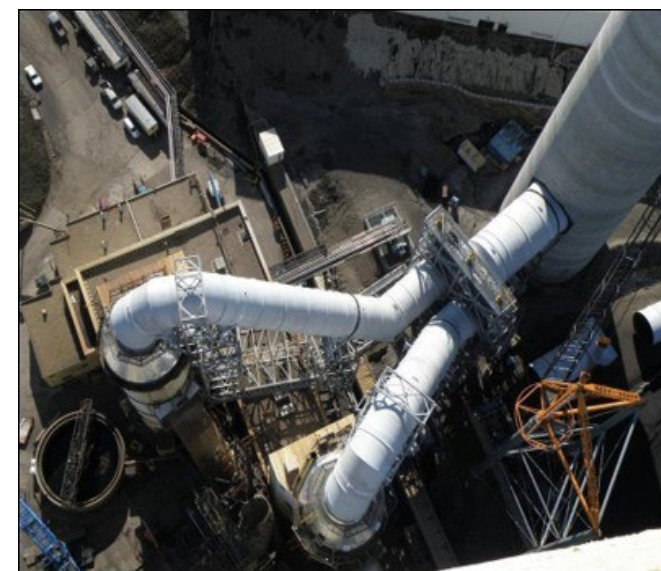
TECHNOLOGY DESCRIPTION

Designing with Fiberglass-Reinforced Plastics (FRP) requires a unique knowledge of composite materials, environmental conditions, chemical properties, ASTM and ASME specifications, and familiarity with specialised fabrication and construction practices. We design and manufacture complete duct systems, including ductwork, hoods, dampers, anchors, hangers, guides, and expansion joints. Cylindrical sizes designed, manufactured, and assembled include duct and components from 4 in. ID to 16 ft ID. We also have the unique capability of designing and manufacturing largescale ductwork systems ranging from 18 ft ID to 48 ft ID, either at your job site or from one of our facilities.

Our proprietary large-diameter winding equipment and highly trained field construction personnel assemble and install fiberglass ducting instead of costly high alloys, providing a long-lasting and corrosion-resistant solution for post-combustion capture.



American Electric Power (AEP) Mountaineer Station



North Dakota Coal-Fired Power Plant



NOV – CO₂ CAPTURE AND CONDITIONING

TRIETHYLENE GLYCOL (TEG) GAS DEHYDRATION



SUMMARY

Most carbon capture processes produce wet CO₂ gas streams that must be dehydrated to meet transportation and storage standards. Dehydration removes water vapour, preventing the formation of corrosive carbonic acid, which can damage carbon steel used in pipelines, pump stations, and storage facilities. Strict safety measures in handling and transporting CO₂ are crucial for public confidence and the adoption of CCUS technologies.

Efficient CO₂ dehydration is vital for the safe and effective transport of CO₂ from capture sites to storage locations. Various mature dehydration technologies are available, each with unique advantages and challenges. The choice of technology depends on factors like CO₂ source, operational scale, energy needs, cost, and water content requirements. Different transportation methods (pipeline, truck, rail, ship) have specific water content and gas purity specifications, influencing the selection of the appropriate dehydration technology. Implementing these technologies will enhance CCS project viability.

BENEFITS

Triethylene glycol (TEG) is an absorption-based gas dehydration method that uses a liquid solvent to selectively absorb water from the CO₂ stream. Known for its high dehydration efficiency, commercial viability, and cost-effectiveness, TEG results in a relatively higher water content level than other dehydration technologies. Typically, TEG is recommended for water specifications down to 50 ppmv.

As a leading global provider of CO₂ dehydration technology and equipment, NOV has expertise in deploying CO₂ dehydration systems worldwide. As a corrosion protection partner, we can help you assess which technology best suits any given application to ensure the CO₂ is safe and does not cause corrosion issues downstream. NOV ensures the CO₂ meets pipeline and transport specifications. This safeguards the transport and sequestration infrastructure, thereby increasing the longevity and safety of the project.



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KEY DATA

TRL	9	CO ₂ Feed Capacity	10 - 5,000 ktpa	Modular (Y/N)	Yes ¹
Source CO ₂ Purity Range	Saturated	Fast Startup Times	No		
Number of Commercial Plants	100+	Water Outlet Content	50 - 600 ppmv		
Target Industries	All CCUS applications				

¹ Specific size ranges have the option of modularity



NOV – CO₂ CAPTURE AND CONDITIONING

TEMPERATURE SWING ADSORPTION (TSA) GAS DEHYDRATION



SUMMARY

Most carbon capture processes produce wet CO₂ gas streams that must be dehydrated to meet transportation and storage standards. Dehydration removes water vapour, preventing the formation of corrosive carbonic acid, which can damage carbon steel used in pipelines, pump stations, and storage facilities. Strict safety measures in handling and transporting CO₂ are crucial for public confidence and the adoption of CCUS technologies.

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BENEFITS

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KEY DATA

TRL	9	CO ₂ Feed Capacity (ktpa)	10 - 5,000	Modular (Y/N)	Yes
Source CO ₂ Purity Range	Saturated	Fast Startup Times	Yes		
Number of Commercial Plants	10+	Water Outlet Content	<1 - 50 ppm		
Target Industries	All CCUS applications				

TECHNOLOGY DESCRIPTION

SORBEAD®

BASF Sorbead® technology is a TSA process that involves passing the CO₂ gas stream through a Sorbead® aluminosilicate gel bed, which has a high affinity for water molecules. The Sorbead® system is then regenerated through heat. It offers a relatively low energy, low cost, and simple method for dehydration. The ease of regenerating the Sorbead® bed in a cyclic manner while achieving a low water content in the dried CO₂ makes this process appealing.

Typically, Sorbead® dehydration is recommended for water content specifications of 5 to 50 ppmv.

MOLECULAR SIEVE

Molecular sieve TSA technology employs zeolite microporous structures, which selectively adsorb water molecules based on size and polarity. The dehydration process involves the adsorption of water molecules onto the surface of the molecular sieve material. Molecular sieve systems are regenerated by using heat to desorb the water molecules. The ease of regenerating the molecular sieve in a cyclic manner while achieving very low water content in the dried CO₂ makes this process an appealing solution for certain applications. Molecular sieve technology can achieve very dry CO₂ gas, which is beyond what is typically required for various means of CO₂ transport. However, it is more expensive than the other technologies. Typically, molecular sieve dehydration is recommended for water content specifications of <1 ppmv.

INTEGRATED DEOXYGENATION OPTION

The CO₂ streams from a post-combustion carbon capture system usually contain varying levels of oxygen. Most pipeline transport specifications are placing tight control on oxygen concentrations in addition to moisture. The presence of oxygen in CO₂ at certain levels can cause challenges in reservoir formations associated with storage and enhanced oil recovery. Oxygen can react with hydrogen sulfide and elemental Sulphur to create corrosion issues downhole. Most storage and utilisation applications require proper control of oxygen levels.

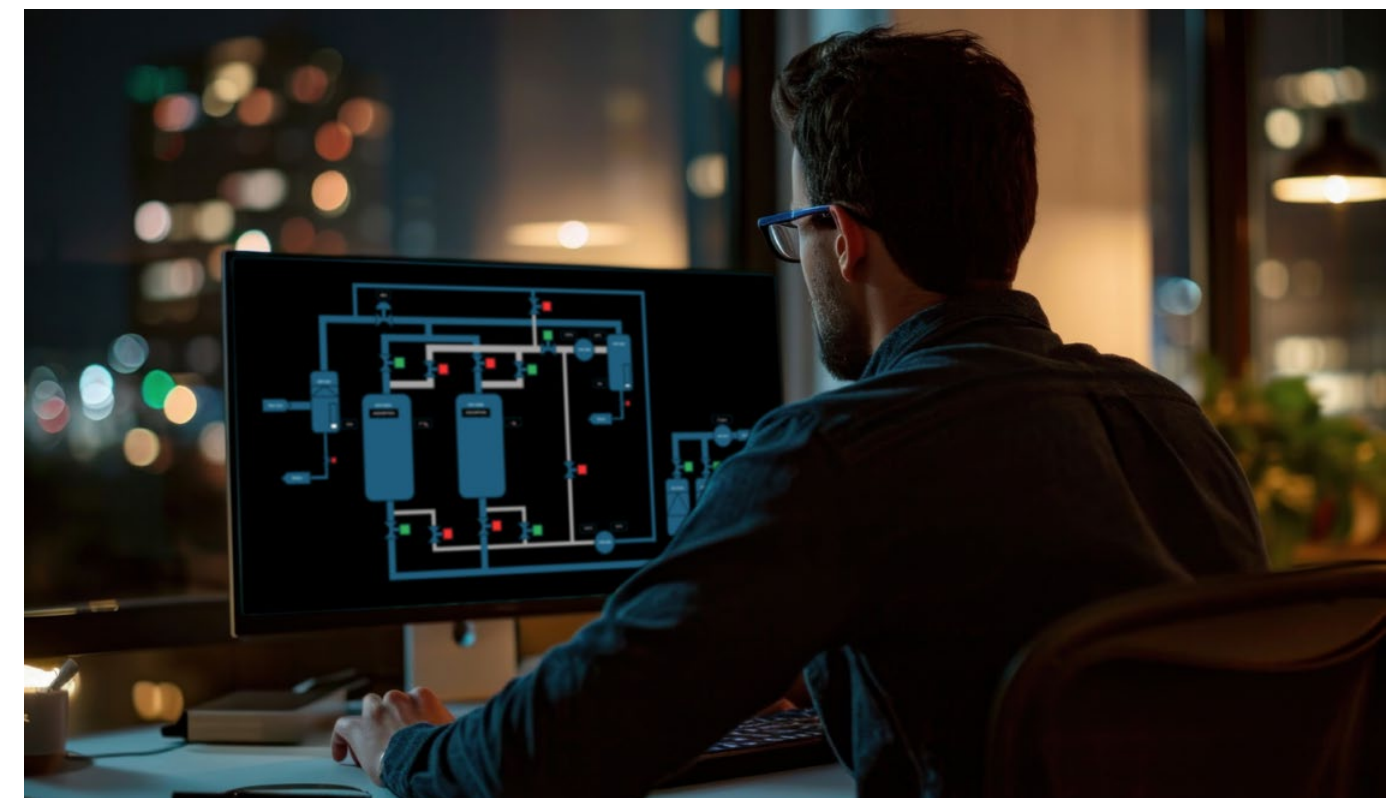
Elevated oxygen in the CO₂ stream must be removed before transport to meet pipeline specifications. NOV's CO₂ deoxygenation process removes oxygen from CO₂ via a catalytic bed with hydrogen. The CO₂ reacts with hydrogen to form a water byproduct. NOV provides integrated deoxygenation and dehydration systems.

SMART BED™ DEHYDRATION CONTROL SYSTEM

The Smart Bed™ Dehydration Control system introduces an advanced methodology for managing temperature swing adsorption (TSA) units. This innovative control system enables real-time monitoring of adsorption beds, optimising the switch from adsorption to desorption based on system needs instead of relying on traditional timer-based controls.

With Smart Bed Dehydration Control, desiccant media bed adsorption time is extended, reducing the frequency of regeneration cycles.

This improvement leads to cost savings, decreased energy consumption and longer desiccant media lifespan—all while maintaining your outlet gas dehydration specifications.



VAISALA

VAISALA

MGP241 MULTIGAS CO₂ INSTRUMENT FOR CCUS

SUMMARY

RADICALLY SMARTER CO₂ MEASUREMENTS FOR CARBON CAPTURE

The MGP241 measures carbon dioxide and humidity directly in the gas flow within point-source and direct air carbon capture processes, and in both carbon storage and carbon utilisation projects. With direct installation into the process, no moisture removal or other sample treatment is required.

Unlike traditional gas analysers, Vaisala's MGP241 requires no expensive calibration gases, needs significantly less maintenance, and offers a minimum 10-year lifespan in heavy-duty use. Its compact size and in-situ design allow for competitive pricing – around a third of the cost of the most common solutions on the market.

The MGP241 is a plug-and-play instrument that employs patented CARBOCAP® infrared technology for simultaneous measurement of gases, while automatically compensating for sensor drift, sensor aging, and any cross-interference effects. As a fast response in-situ probe, the MGP241 delivers real-time measurements that are essential for efficient process control.

BENEFITS

- **Heavy-duty performance:** The compact MGP241 is the smartest solution for process CO₂ measurement. From carbon capture to general industrial use, it's built to endure and excel in the harshest environments.
- **Superior reliability:** Exceptionally compact, lightweight and operationally optimised, the MGP241 is field-proven and IP65-rated, and requires only minimal maintenance and calibration.
- **Plug-and-play + high connectivity:** Radically easier installation and seamless integration into your existing operational systems, from SCADA to the Vaisala Indigo platform, with minimal effort.
- **Low TCO, high ROI:** Requires only a fraction of the investment compared to typical industry solutions.

KEY PROJECTS

- **Cool Planet Technologies:** Proving the efficiency of new, modular, membrane-based carbon capture technology.
- **Octavia Carbon DAC:** The world's second ever DAC + geological storage plant uses the CARBOCAP technology to measure and verify capture, from approximately 430 ppm up to 99.99% CO₂.
- **CapsolGO modular CCS platform:** Helping to optimise and maintain a high capture rate in a hot potassium carbonate-based CCS process.
- **Niterra Regional CCU™:** Continuous measurement of raw and post-capture CO₂ in a closed loop operation spanning from local factories to CO₂ reuse, hydrogen production, and methanation for reuse as fuel for the same factories.
- **Carbonaide decarbonises concrete & construction industries:** Ensuring permanent CO₂ sequestration in concrete blocks in a highly effective and robust carbonization process for precast concrete manufacturers.

KEY DATA

TRL	9	Modular (Y/N)	Yes
Number of Commercial Plants	Several	Number of Pilot Plants	> 5
Target Industries	Cement, biomass, power generation, waste incineration, CO ₂ separation from RNG, direct air capture		

TECHNOLOGY DESCRIPTION

The MGP241 is an in-situ probe that measures CO₂ and humidity and is specifically designed to bring a new level of transparency and verification to CCUS projects. It delivers always-on data at roughly one-third of the cost of commonly used measurement solutions.

The MGP241 measures carbon dioxide and humidity in point-source and direct air carbon capture processes, as well as in a wide range of utilization and storage projects.

ENSURING YOUR CAPTURE PROCESS OPERATES AT PEAK CAPACITY

A key challenge today is to make measurement in CCUS projects as transparent and efficient as possible, leaving no room for guesswork or sugarcoated results.

To achieve this, the MGP241 operates directly in the gas stream and provides real-time measurement data, enabling timely and informed decisions about your capture process.

NEW LEVEL OF TRANSPARENCY IN CCS

Without the ability to measure captured carbon, it would be problematic to determine whether and how much carbon has been captured. This is particularly important for pilot projects that need to be evaluated before commercialisation, and for industrial processes that need to verify their carbon capture claims – for both financial and sustainability reasons, as well as for carbon trading.

The MGP241 offers continuous, accurate measurement of captured carbon, which is essential for process optimization, building stakeholder trust, and demonstrating a genuine commitment to sustainability.

The MGP241 even helps generate new profit streams by enabling the sale of carbon dioxide for further use or permanent storage.

CONTINUOUS AND DIRECT PROCESS MEASUREMENT

The MGP241 measures directly in the process without the need for drying or other sample treatment. This simplifies installation and minimises the physical footprint compared to traditional gas analyser.

Its rapid measurement cycle takes only seconds, providing direct real-time measurement data for process control and monitoring. CO₂ measurements can be shown in either wet-basis or dry-basis values.

Built-in temperature and pressure compensation algorithms, and the CARBOCAP infrared technology ensure extremely stable and reliable measurements across a wide range of process conditions and environments.

The MGP241 can also be made to fit into small-scale setups, using a flow through adapter with a G 1/8" inlet and outlet.

2-IN-1 MEASUREMENT, PATENTED TECHNOLOGY

The MGP241 measures carbon dioxide (CO₂) and humidity (H₂O vapor) in demanding conditions. It measures CO₂ and humidity in vol-% or ppm units, or alternatively dewpoint temperature (Td) and frostpoint temperature (Tf).

The patented CARBOCAP infrared technology enables simultaneous detection of multiple gases unlike more traditional non-dispersive infrared technologies.

This allows compensation for sensor drift, sensor aging, and cross-interference effects between measured gases. Calibration gases are not required for routine operation; a functional check and drift check every 12 months is recommended.

POWERFUL CONNECTIVITY

The MGP241 offers both digital and analog connectivity. It uses the Modbus RTU protocol for digital connectivity and 4–20 mA analog outputs for CO₂ and H₂O vapor concentrations, as well as a 4–20 mA analog input for external pressure or temperature signal used for compensation.

The MGP241 readily connects to various Vaisala Indigo transmitter host devices, from the top-of-the-line Indigo500 to the Indigo300, and the award-winning Indigo80 handheld.

For easy access to configuration, diagnostics, calibration and adjustment, the MGP241 probe can also be connected to the Vaisala Insight PC software suite.

BACKED BY 90 YEARS OF MEASUREMENT EXPERIENCE

As a specialist manufacturer of carbon dioxide sensors, Vaisala has pushed the boundaries of measurement reliability and accuracy with truly robust technology since 1936 – on Earth and Mars.

Users of the MGP241 are spread around the globe, in applications such as cement manufacture, waste incineration, direct air capture (DAC), oil & gas CCS, and more.

THREE CUSTOM USE CASES

- Incoming CO₂ monitoring: 0 to 35% CO₂ range at 1% accuracy.
- High-concentration CO₂ output monitoring: 90 to 100% CO₂ range at 1% accuracy
- DAC monitoring: 0 to 1000 ppm CO₂ range at 3ppm accuracy (also possible in combination with Vaisala GMP343 CO₂ probe).

KEY SPECIFICATIONS

- Measurement range: 0 to 100 vol-% CO₂ | 0 to 25 vol-% H₂O
- Accuracy: ±1 vol-% @ 90 to 100 vol-% CO₂
- Temperature range: -40 to +60°C
- Pressure range: -500 to +500 mbar (gauge)
- Output types: 3x 4-20 mA | Modbus RTU
- Auto-calibrating IR gas measurement
- IP65-rated construction
- Operates on 24V DC power
- No consumables
- Only minimal maintenance needed



ABB

CO₂ IMPURITY MONITORING SOLUTION FOR CCUS



SUMMARY

CCUS operations need a broad range of measurements that require a suite of highly sensitive equipment. ABB provides a fully integrated solution for CO₂ impurity monitoring and compliance. Because no single device fits all needs for this diverse measurement challenge, ABB's solution comprises three components – ACF5000 CCUS, Sensi+ CCUS and GCP100 – delivered in a fully equipped, single solution, analyzer shelter with a modular design. Built on ABB's decades-long experience, the solution simplifies procurement, reduces engineering effort, and ensures measurement consistency across the CCUS chain.

ACF5000 CCUS: Flexible multicomponent FTIR/FID analysis with an ideal balance of speed and precision.

Sensi+ CCUS: Ultra fast laser-based detection using OA-ICOS, an advanced form of CEAS, to prevent pipeline rejection and protect infrastructure.

GCP100: Gas chromatography for non-IR active gases (H₂, N₂, Ar) at the lowest detection ranges.

Completing the full package, ABB's global service network, enhanced by powerful digital tools, delivers maximum uptime for CCUS installations.

BENEFITS

- **Optimal technology:** Best-in-class performance for each component.
- **Streamlined installation, commissioning and preventive maintenance:** Our service professionals work alongside your teams to optimise and troubleshoot, maximizing availability and performance.
- **Ease of use:** No need for complex laboratory analyser requiring intensive maintenance, calibration, or specialised lab operators.
- **Advanced digital tools:** Associated digital solutions ensure maximum uptime across systems installed worldwide.
- **One brand:** ABB is a one-stop shop for complete, end-to-end analyzer systems, leading the way in delivering flexible, fully customizable analytical solutions.



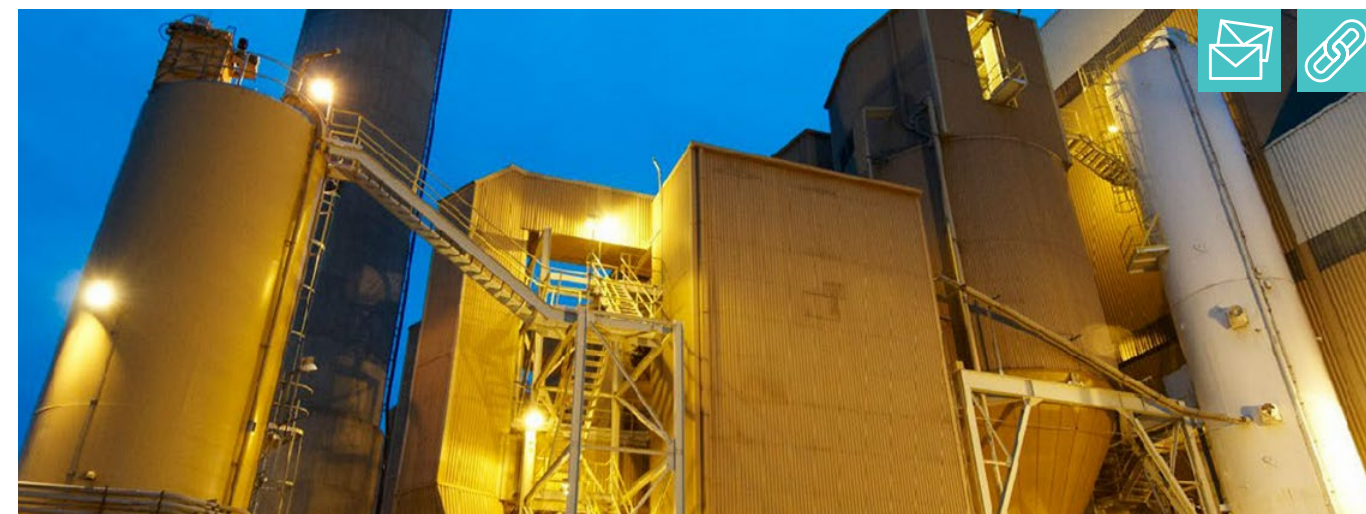
KEY DATA

TRL	9	
Target Industries	Emitting industries (steel, cement, power generation, WtE, chemical and other) and CO ₂ transport operators	



BABCOCK & WILCOX

FLUE GAS PRE-TREATMENT



SUMMARY

Acid gases degrade the solvents used in a post-combustion carbon capture system. B&W offers a complete suite of environmental control technologies to control sulphur dioxide (SO₂), sulphur trioxide (SO₃) – which can form aerosols and cause loss of CO₂ capture solvents – hydrogen chloride (HCl), and hydrogen fluoride (HF) in the pre-capture flue gas stream, as well as technologies for other pollutants such as metals and particulates. Nitrogen oxides (NO_x) are also detrimental for CO₂ capture solvents and can lead to hazardous degradation products in the process. CO₂ scrubbing may also improve when particulate matter is removed from the flue gas prior to the scrubbing process.

Pre-treatment of the flue gas is vital for the operation and economics of the process to result in the optimum effectiveness of the carbon capture technology. B&W has many decades of experience in emissions control solutions, pioneering technologies that have helped customers comply with stringent emissions regulations for more than 50 years.

BENEFITS

- Flue gas pre-treatment provides optimum effectiveness of the post-combustion carbon capture technology.
- Wide range of proven pre-treatment technologies to significantly reduce incoming flue gas pollutants, including sulphur oxides, particulates, nitrogen oxides, mercury and other acid gases.
- Experience with more than 2300 installations of various pollutant control technologies

KEY PROJECTS

Higher concentrations of a wide range of inlet pollutants lead to higher solvent make-up rates and higher operating costs. Since solvent is typically much more expensive than other reagents, removal of the pollutants upstream of the CO₂ absorber typically results in a reduction of overall operating costs. Our flue gas treatment installations include these impressive numbers which control a wide range of pollutants from diverse industrial segments:

- Wet flue gas desulphurisation (FGD) and wet gas scrubbers: 300+
- Dry scrubber technologies (spray dryer absorbers [SDA] and circulating dry scrubbers [CDS]): 90
- Selective catalytic reduction (SCR): 100+
- Dry sorbent injection (DSI): 35+
- Wet and dry electrostatic precipitators (ESP): 750+
- Fabric filter baghouses: 1000+
- Flue gas condensation: 35+

KEY DATA

TRL	9	Number of Commercial Plants	2,300	Modular (Y/N)	No
Target Industries	Utility Power, Waste/Biomass to Energy, Medium to Heavy Industry such as Oil & Gas, refineries, Iron & Steel, Pulp & Paper, Cement				



BASF

DEOXYGENATION AND DEHYDRATION OF CO₂



SUMMARY

Treatment of CO₂ to remove impurities and water is an integral step in the CCS value chain. Following CO₂ capture and prior to transportation, CO₂ must be treated for impurity removal to meet project specific specifications. Treated CO₂ specifications depend on the transportation method and/or storage requirements. Generally, impurities such as oxygen and water need to be removed to low levels to ensure pipeline integrity.

BASF offers a wide portfolio of catalysts and adsorbents to treat CO₂. Removal of oxygen is achieved with BASF DeOxo products and removal of water is achieved with BASF Sorbead® line of products. BASF relies on proprietary design tools and technology manager expertise to design optimised units with long lifetime, leading to lower CapEx and OpEx compared to other offerings. BASF also has an extensive reference list for CO₂ conditioning, as well as operational experience in our own plants.

BENEFITS

- BASF's broad portfolio of catalysts and adsorbents provides solutions to a wide range of CO₂ treatment requirements.
- BASF DeOxo and Sorbead® products are proven in the industry.
- BASF experienced technology managers provide designs that optimise CapEx and OpEx. Highly efficient DeOxo catalyst provides smaller vessels. Sorbead® adsorbent has lower regeneration temperature compared to other adsorbents, leading to lower energy requirement.
- BASF provides technical support and global logistics to deliver products on time.

KEY PROJECTS

BASF DeOxo products have been employed to treat CO₂ in BASF Urea Safety reactors as well as CCS projects, providing experience, knowledge, and operational data on the catalysts.

BASF Sorbead® has been used to treat high CO₂ gas streams for enhanced oil recovery and membrane protection applications for over three decades.

BASF DeOxo and Sorbead® products have also been qualified by major oil and gas companies and engineering and procurement companies globally.

- Project 1 DeOxo: Italy CCS (1.7 MMSCFD)
- Project 2 DeOxo: Texas CCS (126 MMSCFD)
- Project 3 Dehy: Louisiana CCS (41 MMSCFD)
- Project 4 Dehy: Netherlands CCS (46 MMSCFD)

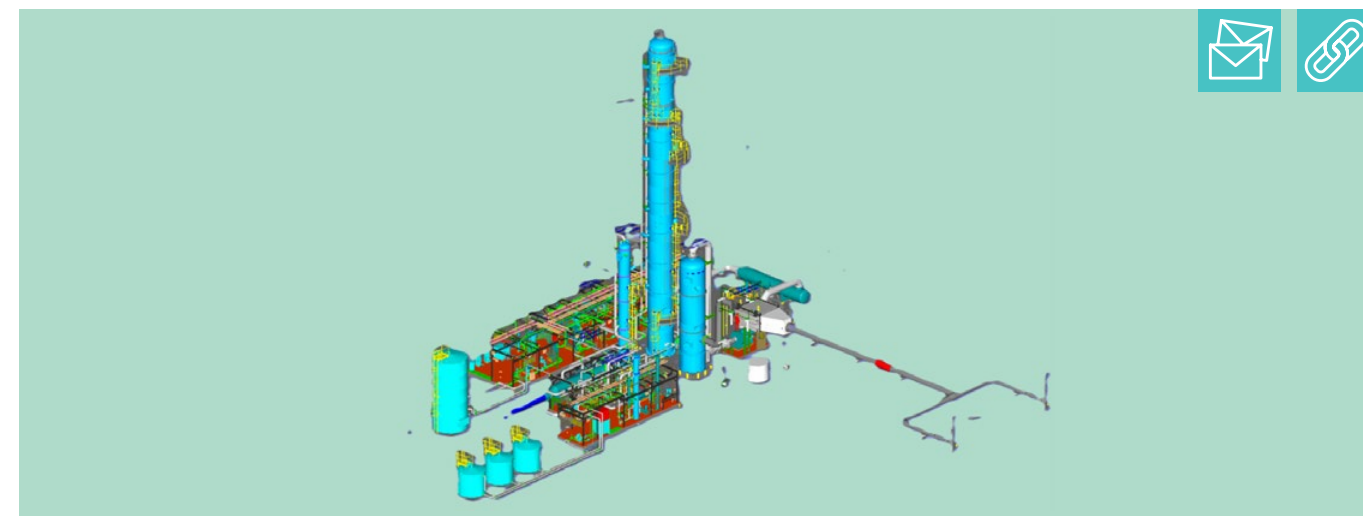
KEY DATA

TRL	9	Number of Commercial Plants	>50	Years of Experience	>50
DeOxo Operating Temp (C)	>30	DeOxo lifetime (years)	3 - 10	DeOxo O ₂ spec (ppmv)	<10
Sorbead® Regeneration Temp (C)	180	Sorbead® lifetime (years)	5	Sorbead® water spec (ppmv)	<10
Target Industries	Treatment downstream of capture technology				



DELTA CLEANTECH

PURERX SOLVENT PURIFICATION AND RECYCLING SYSTEM



SUMMARY

Delta CleanTech Ltd. has offered carbon capture solutions since 2004, including PureRX, a patented proprietary vacuum reclaimer system that purifies and recycles solvents to cut costs and boost efficiency in solvent-based operations. PureRX tackles solvent degradation, a major issue that raises expenses and lowers performance. PureRX employs thermal reclamation and advanced separation techniques to remove heat-stable salts, degradation products, and contaminants from carbon capture solvents and glycol systems. The system significantly extends solvent life, reduces fresh solvent make-up requirements, minimises waste disposal costs, and maintains optimal capture performance. Integrated with Delta's CarbX capture technology or available as a standalone solution for existing facilities. PureRX is commercially proven with multiple installations. Following Scovan Group's acquisition of Delta in January 2025, the company now offers enhanced engineering capabilities and full EPCF services for solvent management solutions. Delta is headquartered in Calgary, Alberta, Canada.

BENEFITS

- **Lower Operating Costs:** Reduces solvent make-up and waste disposal costs.
- **Extended Solvent Life:** Removes heat-stable salts and degradation products, extending solvent life by 300–500%.
- **Optimised Performance:** Maintains solvent quality for consistent CO₂ capture efficiency.
- **Environmental Impact:** Reduces waste generation and supports regulatory compliance.
- **Flexible Deployment:** Available with CarbX systems or as a retrofit for existing facilities.
- **Commercially Proven:** Technology Readiness Level (TRL) 9 technology with multiple commercial installations.
- **Technical Support:** Comprehensive solvent analysis, optimization, and troubleshooting services.
- **Rapid ROI:** Typical return on investment within 1–2 years.

KEY PROJECTS REFERENCES

- Multiple commercial installations have been operating successfully across diverse industrial applications since 2004.
- Retrofit installations at existing carbon capture facilities showing immediate improvements in solvent quality and operational costs.
- Continuous operation spanning thousands of hours across multiple facilities, validating system reliability and performance.
- Case studies demonstrate substantial reduction in fresh solvent make-up requirements and corresponding waste reduction.
- Long-term monitoring data confirming sustained solvent quality improvement and capture system performance maintenance.
- Successfully processed various amine-based solvents including MEA, DEA, MDEA, and proprietary formulations and glycols across temperature and concentration ranges.

KEY DATA

TRL	9	Processing Capacity Range	5 - 15% of inventory*	Heat-Stable Salt Removal	>95%
Reclamation Efficiency	>90%	Fresh Solvent Reduction	60 - 80%	Operating Temperatures	120 - 160°C
Applicable Solvents	MEA, DEA, MDEA, and other amines	Number of Pilot/Demos	2	Modular (Y/N)	Yes
Target Industries	All amine-based facilities requiring solvent management, including oil and gas, power generation, cement, steel, refining, chemicals, bioenergy, and industrial facilities				

*Total solvent inventory, customisable to host facility requirements.



ELESSENT CLEAN TECHNOLOGIES BELCO® GAS CLEANING



SUMMARY

ELESSENT CLEAN TECHNOLOGIES - PIONEERING GAS CLEANING SOLUTIONS FOR CARBON CAPTURE

In the pursuit of environmental sustainability, Elessent Clean Technologies stands as a catalyst for change, driving innovation in gas cleaning solutions for carbon capture technologies. Specialising in wet gas cleaning systems, Elessent offers state-of-the-art solutions for pre-cleaning and cooling hot dirty flue gas streams, essential steps preceding carbon capture units (CCUs) aimed at CO₂ reduction. By offering proven scrubbing performance, compact design, and minimal environmental impact, Elessent continues to shape the landscape of emissions reduction, paving the way for a greener, more sustainable future.

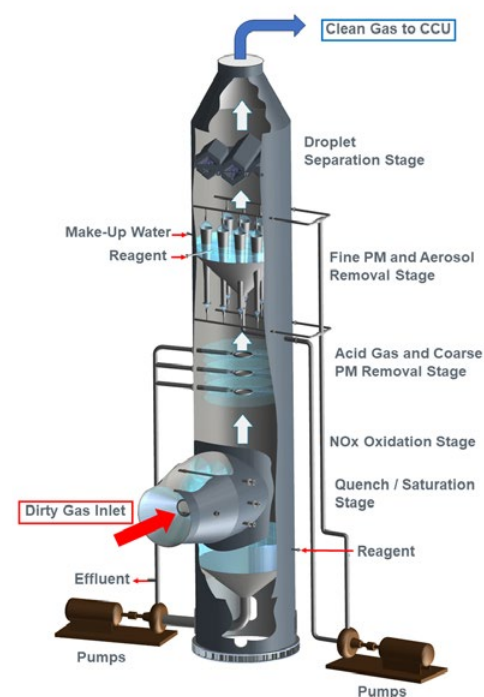
BENEFITS

- Proven scrubbing performance for severe service hot dirty flue gas applications
- Unique single up-flow design allows plot space requirements
- 160+ licensed units globally
- Applications in refinery fluid catalytic cracking units (FCCUs), boilers, heaters, and fluid cokers
- Installed in various industries including metallurgical plants, oil refining processes, Sulphuric acid plants, cement kilns, power plants, and incinerators
- Capable of meeting extremely low particulate matter (PM), SO_x and NO_x concentrations
- Robust non-plugging scrubbing designs using open towers
- Energy efficient and optimised for site water usage requirements

KEY DATA

TRL	9	Number of Commercial Plants	160
Target Industries	Refining, Petrochemical, Steel, and Industrial Application		

TYPICAL BELCO® WET SCRUBBER



ELESSENT CLEAN TECHNOLOGIES MECS® BRINK® FIBER BEDS



SUMMARY

Elessent Clean Technology's MECS® Brink® fiber bed mist eliminators have a long history of nearly 70 years in industrial applications. Over the decades, these devices have become well-known for providing an energy-efficient method for product capture, protection of downstream equipment, and protection of the environment. Used in industries such as Sulphuric acid, chlorine, fertiliser production, specialty chemical production, organic synthesis and many others, these devices have become a mainstay of industrial gas handling. This article addresses how these devices operate and how their use can be of great benefit in CO₂ capture and amine recovery operations. The use of fiber bed technology offers a cleaner, more economical operation for this industry while allowing these facilities to operate more reliably in compliance with government-mandated emissions regulations.

BENEFITS

- **Reliable Operation:** Brink® fiber bed mist eliminators have a 70-year history in industry with proven, reliable operation with no need for continual maintenance and upkeep.
- **Efficient Operation:** When operated as designed, rated efficiency can be achieved and there is infinite turn-down with Brink® technology.
- **Low Energy Consumption:** There is no application of direct energy for operation. Energy consumed is provided by pressure drop required to push process gas through the devices (3 kPa pressure drop typical).
- **Effective Recycle of Drainage:** Liquid draining from fiber beds can be recycled back to the process directly (when appropriate) offering savings in raw material cost to the client.

KEY DATA

TRL	9	Aerosol Capture Efficiency (%)	95 - 99.5%
Number of Commercial Plants	>5,000	Number of Pilot Plants	1
Target Industries	Various Sulphuric, Phosphoric, Chloro-Alki, etc. Applications		





EMERSON AUTOMATION SOLUTIONS

AMS RELIABILITY | MACHINERY HEALTH MANAGEMENT



SUMMARY

Carbon capture, utilisation, and storage are essential for reducing emissions and achieving sustainability goals. Efficient operations require an end-to-end solution that optimises automation processes. However, fragmented data from technology stacks across departments can hinder integration and use.

Emerson's AMS Reliability portfolio addresses these challenges by offering a unified software platform that includes route-based portable devices, wireless sensing, edge AI analytics, and online prediction-plus-protection systems. The AMS Asset Monitor, an award-winning edge AI analytics device, uses CHARMS-based technology to collect vibration and process data, providing critical insights and maintaining optimal performance. Integrated vibration condition monitoring, enhanced by Emerson's PeakVue™ and PeakVue Plus technologies, ensures the reliability, efficiency, and safety of CO₂ compression and pumping stations.

BENEFITS

Emerson's AMS Asset Monitor collects vibration and process data, applying embedded auto analytics to alert personnel to common faults. This advanced monitoring system, featuring PeakVue™ and PeakVue Plus technologies, offers significant benefits:

- 60-90% Downtime Reduction
- 10-20% Availability Improvement
- 30-50% PM Workload Reduction
- 25-50% Calibration Workload Reduction
- 25-50% Scrap and Rework Reduction
- 15-50% Cost of Failure Reduction
- 5-15% Asset Lifecycle Extension
- 20-30% MRO Inventory Reduction

Additionally, the AMS Asset Monitor can be paired with AMS Machine Works software for real-time updates, deeper analysis, and scalable cloud deployment, further enhancing asset management and operational efficiency.



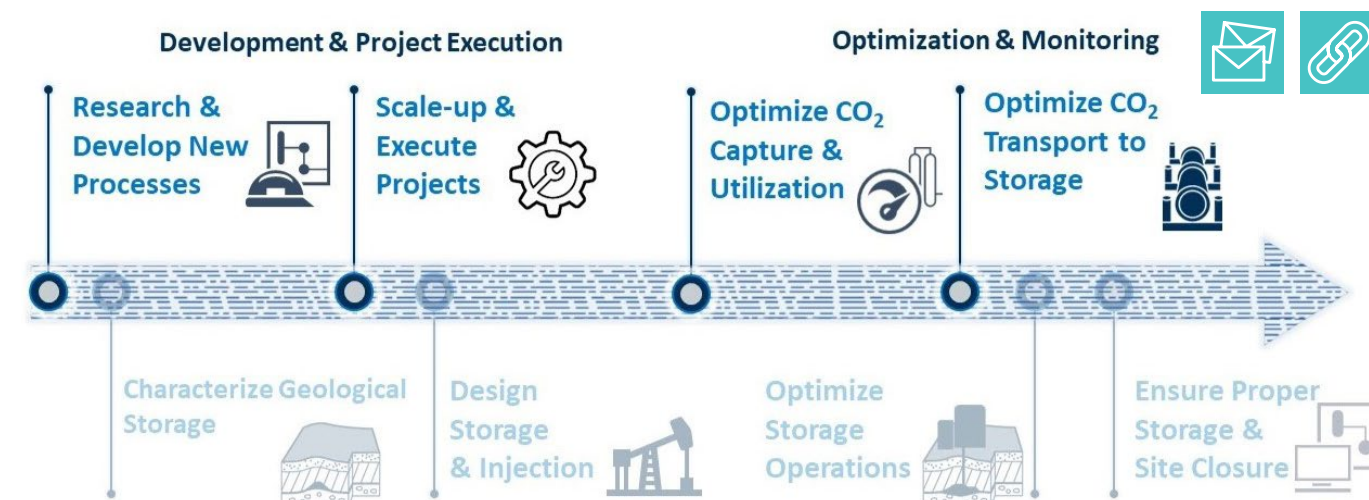
KEY DATA

TRL	9
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EMERSON AUTOMATION SOLUTIONS

ASPENTECH CARBON CAPTURE PATHWAY



SUMMARY

Emerson's Aspen Technology business is an industrial software company with over 40 years of history in innovation, and a digital portfolio that provides a comprehensive, holistic approach to asset optimisation and process decarbonisation across design, operations and maintenance. Throughout the CCUS value chain and across the asset lifecycle, AspenTech combines the power of AI with our domain expertise to support the development of scalable carbon capture and carbon storage solutions, prioritise investment decisions, improve efficiencies and have visibility across all stages of the value chain.

Digital technologies applied to carbon capture and removal, transportation, and storage, enable ongoing innovation, rapid scaling, and increased confidence in geological CO₂ storage. The powerful combination of AspenTech solutions and an Industrial AI approach for process simulation and optimisation, subsurface geophysical and geological modelling and digital grid management, deliver performance breakthroughs at scale—both economically and at an accelerated pace, to meet the requirements of industrial carbon mitigation.

BENEFITS

- Drive innovation in the development of new carbon capture and carbon removal technologies
- Evaluate risk in CCS projects to make informed decisions across the value chain, including capture technologies and processes selection, and prioritising investments
- Assess technical and economic feasibility and reduce capital and operational expenditures in carbon capture processes with rigorous process simulation
- Accelerate cost-effective commercialisation and scale-up of carbon capture processes with optimised process designs
- Maximise energy efficiency and process stability, optimising operations and ensuring safety, with advanced process control and digital guidance for enhanced decision-making
- Improve reliability, safety and efficiency in carbon capture, transport and compression operations

KEY AREAS

- **Techno-Economics:** Well-known process simulators Aspen Plus® and Aspen HYSYS® help to further optimise processes, identifying right trade-offs between capture efficiency and energy use.
- **Investment Certainty:** Dynamic, event-driven modelling with Aspen Fidelis™ guides investment and operational decisions to maximise profits across the lifecycle while identifying uncertainties and bottlenecks to mitigate financial risks.
- **Project Scale-Up And Execution:** Model-based cost estimation provides insights to rapidly define scale, size and economic feasibility. AspenTech's concurrent engineering workflows accelerate project development by improving collaboration between stakeholders.
- **Carbon Capture Operations:** Advanced process control technologies such as Aspen DMC3, improve the process stability and reduce energy use in key unit operations. Design models can be used to train operators and improve operational decisions.

KEY DATA

TRL	9
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EMERSON AUTOMATION SOLUTIONS DELTA V AUTOMATION PLATFORM



SUMMARY

Retrofitting an existing facility with one of the commercially available capture technologies poses many challenges from both a capital expenditure (CAPEX) and operational expenditure (OPEX) perspective. The automation portion makes up <10% of the overall CAPEX, but choosing the right automation platform has severe impacts on the overall project's total install cost, schedule, and risk management. Emerson's DeltaV platform offers valuable technology enablers aimed at addressing these challenges. DeltaV is designed to be a fit for purpose platform that can accommodate small systems, such as equipment skids, to large scale >30,000 IO systems.

The DeltaV automation platform provides the infrastructure for users to develop a "Born Digital" automation layer that is easily integrated into a centralised data-management system. Adding carbon capture reduces efficiency of the production facility and increases power and water usage. Getting contextualised data to advanced applications is key to performing first-principles and data-driven analysis for energy optimisation.

BENEFITS

- Electronic Marshalling and Standard Smart Junction Boxes enables faster deployment of modular units that are de-coupled from one another.
- DeltaV Edge solution delivers a one-way encrypted outbound dataflow that can serve data to an Energy Management Information System to drive reduction in total site energy usage.
- For schedule-driven projects, Smart Commissioning uses embedded features within DeltaV to reduce commissioning time of each device by up to 90%.
- Native integration with AMS Device Manager allows for users to manage all your field devices using a single, integrated application and predict necessary maintenance activities instead of reacting to problems.
- Built on a digital ethernet and fiber backbone, centralised remote operations is possible for disparate remote assets.
- For customers needing a small system with a lower initial investment cost, DeltaV Flex is a subscription package that provides a fully functional DeltaV system with only the features you need.

PROVEN RESULTS

- Since the release of DeltaV Electronic Marshalling CHARMs IO technology in 2011, there has been over 3 million CHARMs deployed and running with a cumulative 200+ billion hours of operating experience.
- A leading cryogenic process technology company is utilising DeltaV for their R&D and pilot system that can be easily scaled up to a full production facility.
- In 2024, one of the largest CCU facilities was put into operation utilising DeltaV technology and is expected to capture 180,000 metric tons of CO₂.
- A cement facility in the Middle East is utilising DeltaV to capture 800,000 tonnes of CO₂ per year from the flue gas and injecting the CO₂ for enhanced oil recovery (EOR).
- DeltaV has been selected to automate a new greenfield blue hydrogen facility in Texas that is expected to sequester 1.7 million metric tons of CO₂ emissions each year.

KEY DATA

TRL	9
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EMERSON AUTOMATION SOLUTIONS INTEGRATED HARDWARE & SOFTWARE LOGISTICS PORTFOLIO FOR MIDSTREAM



SUMMARY

Emerson dedicated measurement and control solutions for liquid and gas products transportation and storage enable accurate flow calculations and historical auditing to secure critical carbon credits. From highly reliable, easy-to-use flow computers and RTUs to modern host systems with integrated software applications, Emerson's comprehensive logistics portfolio addresses key design and operational challenges across the CCS value chain through a highly flexible, scalable environment for programmable control and custody transfer measurement.

Emerson's next-gen FB Automation Platform protects critical infrastructure from cyber-attacks using highly secure, authenticated communications protocols between automation system components. The software suite offers solutions for pipeline network design, prescriptive risk-based maintenance and real-time hydraulic simulation for enhanced operations. To ensure project success, Emerson provides innovative thought leadership, a unique understanding of the entire energy value chain, and extensive project management experience.

BENEFITS

- Emerson's hardware and software solutions ensure accurate flow calculations and historical auditing for securing critical carbon credits.
- The FB Automation Platform, including DeltaV FB3000 RTU, FB1000 and FB2000 Series Flow Computers, and fit-for-purpose software applications, optimise production, transmission, networking, and station control.
- Integrated applications and robust historian from AspenTech OSI monarch SCADA™ platform transfer data from remote pipeline operations and transforms it into visual insights to improve decision-making.
- Data connections are secured to protect critical infrastructure from cyber-attacks
- The IntegrityManager™ software suite provides risk-based maintenance models for gas and liquids pipeline maintenance.
- The PipelineManager™ software suite provides real-time hydraulic simulation for safe operation, leak detection, forecasting, network design and more.

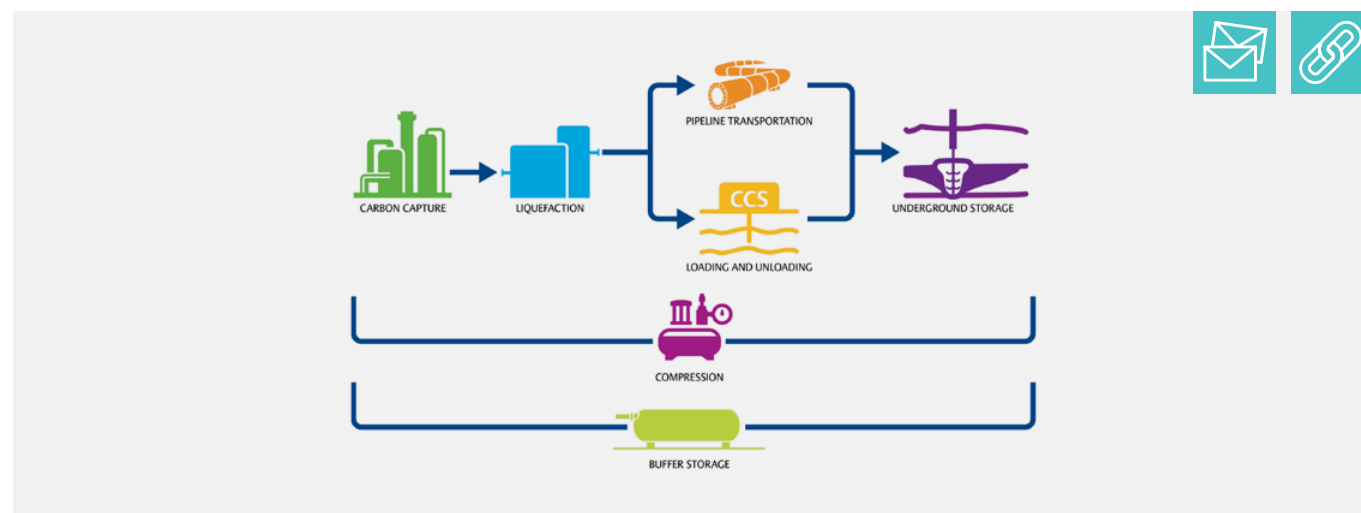


KEY DATA

TRL	9
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EMERSON AUTOMATION SOLUTIONS PRESSURE SAFETY VALVES



SUMMARY

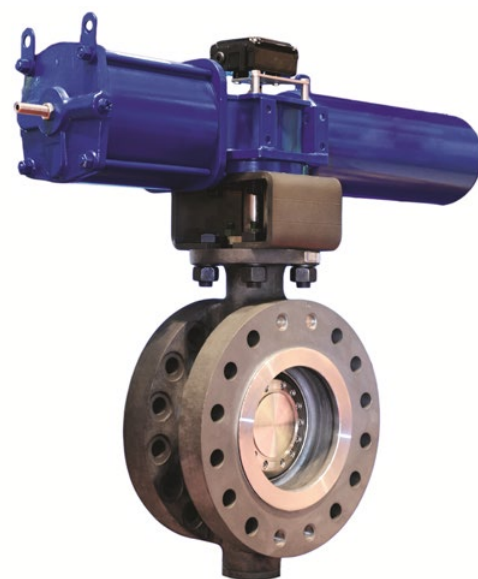
As carbon capture and storage (CCS) gains traction as a means of reducing emissions from large point sources, such as power plants and fuel processing facilities, it is critical for process manufacturers to specify and install equipment that facilitates efficient CCS, along with safe and reliable everyday operations. Valves are required in all stages of the CCS value chain, including post-combustion CO₂ capture, pre-combustion capture, direct air capture, transportation, utilisation, and sequestration.

Pressure safety valves (PSVs) are a common area for operational and emissions inefficiencies. Most conventional PSVs are oversized, releasing too much gas during over-pressure events, which translates to excess releases of CO₂ into the atmosphere. Additionally, leaking valve seats often limit the working pressure of compressors, reducing process efficiency.

Compressor surge is another source of regular process inefficiencies, as well as potential equipment damage. Because surges occur rapidly, traditional control valves often do not react quickly enough.

BENEFITS

- Emerson provides modern valve and accessory solutions, along with recommendations for appropriate selection in each application.
- Anderson Greenwood type 400/800 true modulating PSVs provide overpressure protection, while minimising discharging to the atmosphere. These valves also facilitate maximum compressor efficiency by providing seat tightness up to 98% of setpoint. Additionally, optional spike snubbers dampen the impact of pressure spikes, helping process units operate closer to set pressure for more efficient operation and reduced emissions.
- To protect against compressor surge, Vanessa V30K triple offset valves provide reliable bypass solutions, speeding response time and improving protective safety system operation. Fisher optimised Anti-Surge Control Valves with FIELDVUE positioners ensure safe operations of critical compressor assets.
- Finally, Shafer Emissions Controlled Actuation Technology (ECAT) provides a zero-emission option for pipeline valve actuation. This innovative technology uses accumulators to re-inject pipeline gas that is used to drive the actuator and valve with zero emissions.

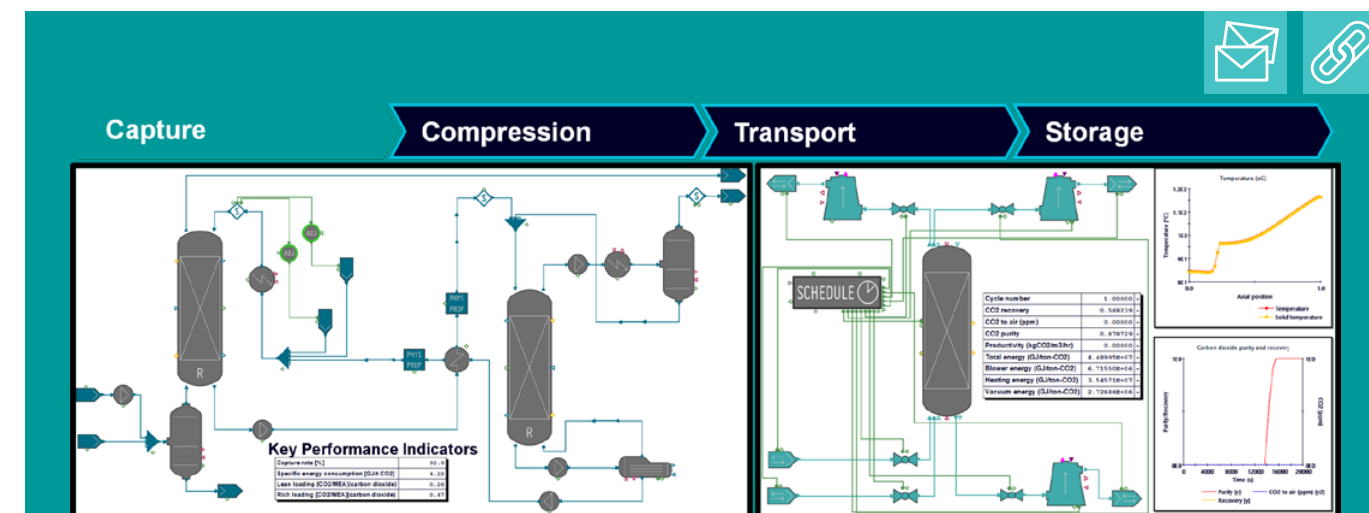


KEY DATA

TRL	9
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SIEMENS INDUSTRY SOFTWARE LIMITED gPROMS PROCESS FOR CARBON CAPTURE



SUMMARY

Siemens' gPROMS platform is a leading modelling environment for digital process design. It is used to map system interactions and predict process responses, also in transient scenarios. The platform enables users to optimise equipment and system designs, predict plant performance, and operate closer to true limitations.

gPROMS uses CCS-specific models, developed in collaboration with industry partners, to cover the entire CO₂ value chain – from the generating processes to capture (encompassing a wide range of technologies), compression, transportation, and storage. By factoring in uncertainty, e.g., gas composition, economic conditions, or equipment availability, gPROMS enables the quantification and management of risk. The platform offers reassurance to stakeholders throughout the entire CCS chain, allowing users to confidently navigate the road to decarbonisation.

BENEFITS

- Accelerate innovation.** Test and improve the performance of a wide variety of technologies.
- One platform for the entire lifecycle.** Model and manage a process from development to operations in a single platform.
- Accurate physical property prediction.** Use thermodynamic packages specifically developed for handling CO₂, amines, and associated ionic species.
- Integrated modelling environment.** One software platform to model different capture technologies and integrate them in the entire CCS value chain.
- Customisable and flexible.** Go beyond conventional technology by easily combining built-in and custom models.
- Design space exploration.** Explore ranges of design and operating parameters using a unique tool within the software.
- Uncertainty analysis.** Quantify the effects of technological uncertainty and manage associated risk.
- Make your process economically viable.** Optimise a single process or an entire chain by maximising efficiency, reduce energy penalty, or minimising costs.



Solvent-based capture:
Model standard solvent CO₂ capture processes for optimal performance



Solvent Regeneration via electrodes:
Simulate advanced regeneration methods to minimize energy use



Adsorption (PSA and TSA):
Optimize adsorption-based CO₂ capture through PSA/TSA cycle simulations



Direct Air Capture:
Model DAC processes to improve efficiency and scalability

KEY DATA

TRL	9
Target Industries	Emitting industries (steel, cement, power generation, etc). Providers of capture technology incl. direct air capture.



VEOLIA

AMINE RECLAIMING



SUMMARY

Carbon Capture solvents are susceptible to several degradation pathways; via oxidation due to contact with O₂ in the flue gas, thermal degradation due to high operating temperatures, and reaction with various contaminants present in the feed/flue gas (e.g. SO_x, NO_x, acids, metal ions). This causes the production of various degradation products, primarily Heat Stable Salts (HSS). Solvent degradation leads to a decrease in plant efficiency and increased emissions so maintaining solvent quality by both minimising degradation and effective solvent reclamation is vital.

Thermal (vacuum & pressurised) Reclaiming and Electrodialysis (ED) Reclaiming have been used extensively in the Oil & Gas industry for decades to reclaim amine solvents and are also the most common technologies used to reclaim amine CC solvents. ED Reclaiming is particularly promising as it has significantly lower CAPEX and solvent losses compared to Thermal Reclaiming for removing the principal degradation products, which are ionic.

BENEFITS

- Solvent degradation leads to a decrease in plant efficiency and increased emissions.
- Amine based solvents degrade due to exposure to heat, oxygen and other contaminants (NO₂, SO₂, HCl, HF...).
- Degradation processes often occur simultaneously producing a wide range of degradation products.
- The rate of degradation product formation increases with increasing temperature.
- Thermal (vacuum & pressurised) and Electrodialysis are employed to maintain plant performance.

KEY PROJECTS

Veolia has extensive operational experience with vacuum/thermal amine reclamation in gas-sweetening applications (30+ references), where high-pressure, low-impurity feeds create stable conditions and well-understood degradation pathways. These long-standing references have shaped industry design practices and performance expectations for vacuum / thermal reclaiming in Carbon Capture applications.

KEY DATA

TRL (Thermal Reclaiming)	9	TRL (ED Reclaiming)	7 - 8*	Overall Amine Recovery with ED	99%
Number of Commercial Plants	30+	Modular (Y/N)	Yes		
Target Industries	All CCUS Applications				

* TRL 9 for Pre-Combustion Applications



VEOLIA

CO₂ DEOXYGENATION AND DEHYDRATION

SUMMARY

To meet the strict quality requirements of transport, utilisation, or long-term storage, captured CO₂ must be conditioned beyond the capture step to ensure the CO₂ stream is clean, stable, and fully compliant with downstream specifications. Deoxygenation systems remove residual oxygen that can cause corrosion, solvent degradation, and operational issues in compression and pipeline networks. Complementing this, dehydration units reduce moisture to extremely low levels, preventing hydrate formation and ensuring safe, reliable handling of high-pressure CO₂.

Backed by decades of expertise in water treatment and gas purification, Veolia delivers compact, standardised purification packages supported by global technical services and digital monitoring. The result is a robust, efficient purification line that seamlessly integrates into your CCUS facility and safeguards the performance of your entire value chain.

BENEFITS

- **Ease of capacity expansion:** modular design enables straightforward scaling through discrete trains.
- **Optimised turndown and rapid ramp-up:** maintains stable performance across wide operating ranges.
- **Minimal CO₂ venting during operation:** ensures high capture efficiency even during transitions.
- **Full compliance with HSE requirements:** robust design aligned with stringent safety and environmental standards.
- **High customisation flexibility:** adaptable configuration to meet site-specific constraints and performance targets.

KEY PROJECTS

With a long track record of successful CO₂ deoxygenation and drying projects, Veolia is internationally recognised for its capabilities in CO₂ conditioning. The company combines proven technologies with extensive field experience, having delivered numerous CO₂ treatment systems across the globe, as for example:

- **Deoxygenation/CATOX:** Australia (1st reference in 2006)
- **Dehydration/TEG:** Canada (Starting-up in 2026)
- **Dehydration/Molecular Sieve:** UAE (In operations since 2015)

KEY DATA

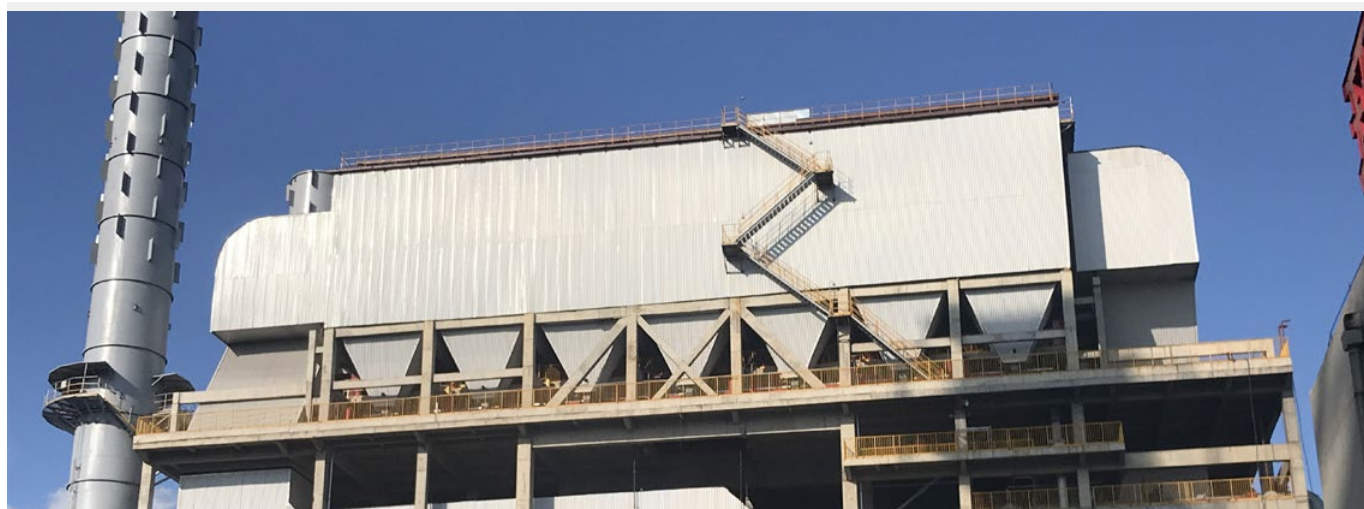
TRL (Deox & Dehy)	9	CO ₂ Inlet Capacity (ktpa)	10 - 5,000	Deox / O ₂ Outlet (ppmv)	< 10
Dehy TSA / H ₂ O outlet (ppmv)	< 1 - 50	Dehy TEG / H ₂ O Outlet (ppmv)	50 - 500	Modular (Y/N)	Yes
Number of Commercial Plants	80+*				
Target Industries	All CCUS Applications				

*including Natural Gas Applications



W. L. GORE & ASSOCIATES

GORE® DENOX CATALYTIC FILTER BAGS



SUMMARY

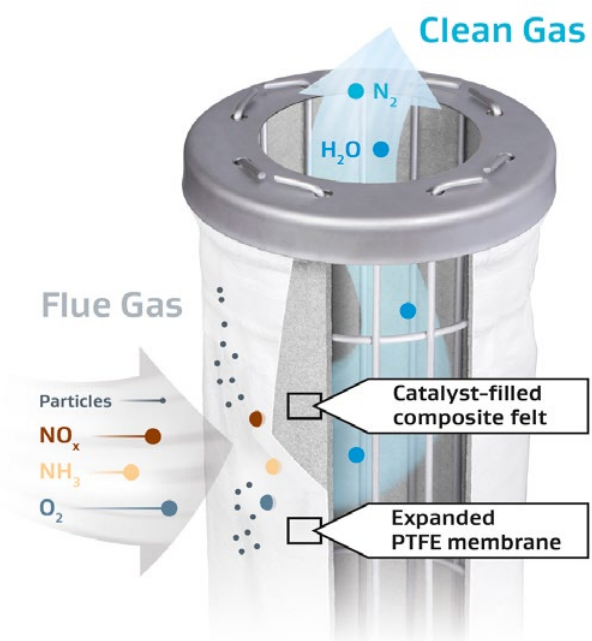
Choosing CCUS Pretreatment can be complex. Flue gas characteristics are different at every industrial plant. Particulate (PM), NO_x and SO_x complicate operation, causing solvent degradation, nitrosamine emissions and equipment corrosion, affecting CCS efficiency and cost. Even trace impurities can make it challenging to meet usage, transportation or sequestration specifications. With over fifty years delivering successful pollution abatement solutions in demanding industrial environments, Gore understands the challenges of flue gas and the pollutants impacting Carbon Capture Systems.

Protect your CCUS investment with simple & proven GORE® DeNO_x Catalytic filters. SCR catalyst is embedded inside a membrane filter bag. Combined with Dry Sorbent Injection (DSI) and Ammonia injection, NO, NO₂, SO₂, SO₃ and PM are removed in a SINGLE, low maintenance, low OPEX baghouse. Our GORE® DeNO_x Catalytic Filter Bags have been proven effective and reliable time and again in Lime, Sinter Steel, Cement and WTE commercial applications.

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BENEFITS

- **Fewer Unit Operations:** One baghouse acts as an FGD, SCR and filter combined, to remove NO_x, SO_x, and PM from the flue gas. With only one unit, CAPEX, OPEX and footprint are minimised.
- **Lower Operating Cost:** More than 95% reduction in NO_x, SO_x and PM can be reliably achieved at a low pressure drop.
- **Low maintenance:** Proven reliable, simple operation in systems over 1,000,000 Nm³/hr. More than 5yr bag life reduces maintenance significantly.
- **Simplification of permitting:** This solution eliminates liquid discharge and avoids the need for wastewater permitting. The bags are disposed of in a standard landfill.



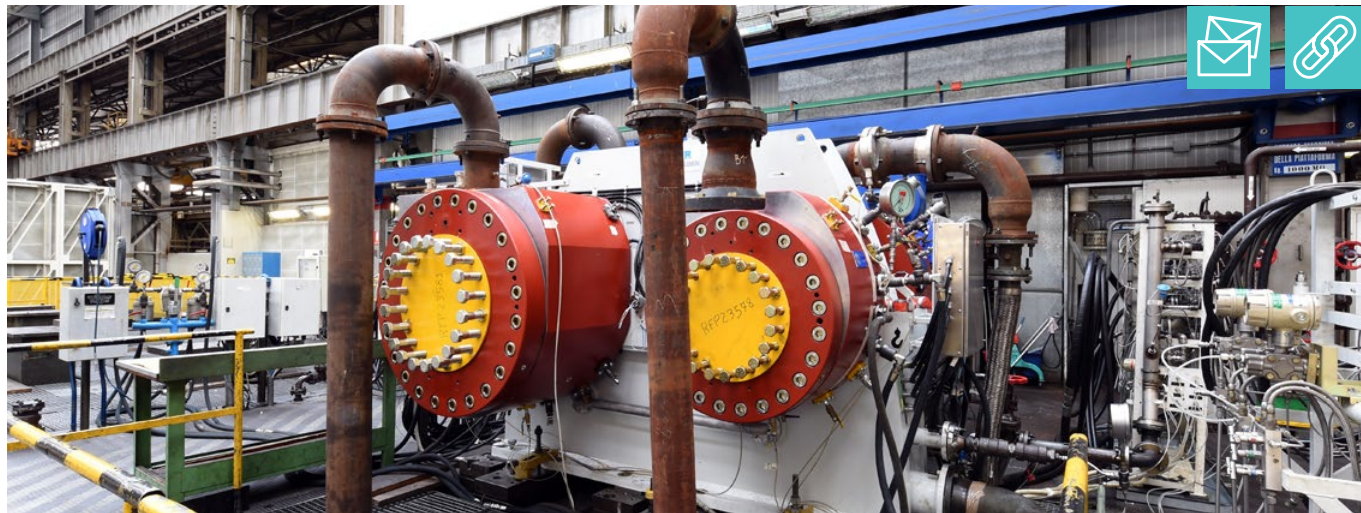
KEY DATA

TRL	9
Target Industries	Cement, Lime, Steel, Waste to Energy (WTE), Chemicals, Coal-fired Boilers

TRANSPORT



Baker Hughes **BAKER HUGHES** **CO₂ COMPRESSION**



SUMMARY

Leveraging its extensive domain expertise in compression and pumping technologies from decades of experience in related areas such as urea, liquefied natural gas and enhanced oil recovery, Baker Hughes has the needed capabilities to make the compression of CO₂ safer, easier and more cost-effective for CCUS applications. Baker Hughes has focused its attention on customising complete compression trains suited for the unique characteristics of CO₂ so that these can operate more efficiently and minimise the overall parasitic power consumption of CCUS processes.

Baker Hughes offers a range of products, including reciprocating, in-line and integrally geared centrifugal compressors, as well as centrifugal CO₂ pumps. These technologies have undergone years of proven in-field performance. Baker Hughes has also continued to develop and optimise these technologies at our global research centers, performing extensive testing in both laboratory and in-field environments before launching these products for our customers' use. In addition to core rotating equipment, Baker Hughes has capability and expertise to provide complete plant solutions that can include CO₂ compression, treatment, liquefaction, and heat recovery.

BENEFITS

- Reduced compression train parasitic power consumption
- Optimised high compression ratio across a wide range of flow rates
- High reliability and easy maintenance
- Automatic capacity control and safety system to reliably match any operating condition
- Reduced lead time through standardised and containerised production, design thinking for simplified logistics, and decreased demand for civil works
- Comprehensive turbomachinery portfolio to transport CO₂ across the CCUS value chain

KEY DATA

TRL	9	Number of Commercial Plants	~	Number of Pilot Plants	~
Target Industries	~				

TECHNOLOGY DESCRIPTION

The operating envelope of CO₂ as it is transported from capture up to utilisation and storage is very broad in terms of volumetric flow and delivery pressure. It ranges from several thousand m³/h at relatively low pressures, up to a few hundred m³/h at extremely high pressures (700-800 bar). Different technologies are required to manage such wide variations and Baker Hughes has a comprehensive portfolio that can match specific applications. The table below shows which type of technology can be employed in increasing the pressure of a certain CO₂ stream.

Pressure	Configuration
< 200 bar	Inline compressor, integrally geared compressor, reciprocating compressor, centrifugal pump
> 200 bar	Inline compressor, reciprocating compressor, centrifugal pump

By manufacturing both CO₂ compressors and pumps, Baker Hughes is able to identify the optimum configuration between technologies, eventually fine tuning the interstage pressures and review the overall operability and control scheme with the goal of minimising the total power consumption at different operating scenarios.

INTEGRALLY GEARED COMPRESSORS

Integrally geared centrifugal compressors can deliver a pressure ratio up to 200, with multiple intercooling steps between stages, which is a typical requirement for CO₂ compressors. Baker Hughes' design features a bull gear and from one to four high-speed pinions, with one or two impellers mounted on each pinion shaft. Stand-alone stages optimise impeller speed and allow impellers to operate at higher peripheral speed and optimum flow coefficient. Variable inlet guide vanes are used for part load operation. The net result is a highly efficient, compact compressor solution.

IN-LINE CENTRIFUGAL COMPRESSORS

Baker Hughes has a strong operating track record in supplying inline centrifugal compressors also for the toughest applications. Inline compressors are high efficiency machines with superior reliability and can be applied across the whole CCUS value chain, completing the portfolio in applications where integrally geared compressors are less present such as ultra-high pressure or extremely toxic gases. BH has experience in compressing and injecting CO₂ for enhanced oil recovery at pressures as high as 550 bar. Multiple train configuration with one, two or even three casings in the same shaft line and different drivers such as electric motor, steam turbine or even hot gas expander.

PUMPS

Baker Hughes' development of its high-pressure CO₂ injection pumps rely on the experience of delivering over 1,000 multi-stage centrifugal pumps for liquefied gas applications. Our multi-stage barrel pump is a good fit for CO₂ applications, especially in supercritical and high pressure services for which, since 2009, Baker Hughes designed the pioneering BB5 pump for EOR service with a design pressure of 670 barg.

In terms of cost expended per unit of mass of re-injected CO₂, the use of centrifugal pumps in the overall compression process, combined with various forms of heat recovery, is the most favourable solution for CCUS applications and is now a proven technology ready for a various types of injection wells.

PLANT DESIGN CAPABILITY

Baker Hughes has experience in delivering complex projects, from modular solutions to entire process plants. CO₂ transportation can involve different processes such as dehydration, treatment, liquefaction and heat recovery, and in all of them turbomachinery represents a critical equipment. By designing and providing the complete plant, Baker Hughes can evaluate opportunities for improving system performance, as well as maximising mechanical integration at factory thus minimising footprint and field activities and at the same time mitigating delivery risks by having a single supplier that covers the complete scope.

Baker Hughes BAKER HUGHES CO₂ PUMPING SOLUTIONS



SUMMARY

Baker Hughes can deliver technological pumping solutions that accomplish the end users' stringent requirements and best fit variable operating conditions which characterise the entire CCUS Industry.

Baker Hughes pump technologies cover services that operate with CO₂ as the process fluid across multiple inlet conditions and discharge pressures ranging from 15 to 50 MPa and above, depending on specific applications. Such applications range from transportation to storage and injection of CO₂ or even power cycles (e.g. supercritical CO₂ power cycles) that use carbon dioxide as process fluid. Moreover, high flow circulation pumps cover CO₂ removal services through appropriate organic or inorganic water solutions.

Driven by API610/ISO13709 criteria, Baker Hughes' specific pump design and selection can provide the correct response to the mentioned needs, taking into account specific features that differentiate the CO₂ service from other services.

BENEFITS

- Accuracy of rotordynamic analysis (leveraging Baker Hughes know-how on API 617 compressors) for high rotor stability
- Impellers arrangement to accommodate the CO₂ high compressibility
- Proper Equations of state selection based on different CO₂ mixtures for accurate pump selection and performances assessment
- Check of acoustic resonance in hydraulic channels through accurate thermodynamic properties
- Optimised seals technology selection (wet and dry gas)
- Validated Water vs. CO₂ correlation laws

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

The selection of pumps for CO₂ applications needs to take care of several differences between conventional incompressible fluids and supercritical CO₂. Supercritical CO₂ is a compressible fluid characterised by high density and low viscosity. Traditionally, supercritical CO₂ has been used for crude oil recovery due to its high diffusivity and liquid solubility, while also being soluble in crude oil increasing the mixture's fluidity.

Pump selection must consider the high compressibility of supercritical CO₂ and use a suitable thermodynamic model to predict the behavior of different CO₂ mixtures. An iterative calculation is used to calculate the polytropic head and efficiency with validated correlations between CO₂ and water, reaching convergence at the pump discharge temperature when the polytropic head is equal to the pump differential head. The right pump, acting as a "quasi-compressor" is then selected. The equations of state available to calculate CO₂ mixtures physical properties are different and applied based on pressure, temperature, and chemical components.

A reliable pump selection tool that uses Equations of State has been extensively validated over multiple test campaigns in the last ten years. This enables the selection of optimal stand-alone or pre-defined integrated solutions, maximizing energy savings (up to 10-15% in supercritical condition and up to 30% in subcooled condition) and minimizing the pump's operational carbon footprint.

Baker Hughes has developed experimental correction factors based on extensive test campaigns where characteristics such as density, specific heat, and speed of sound were measured for various CO₂ mixtures with up to 23 mol% of hydrocarbons and/or inert gases.

Additional consideration must be given with respect to the low viscosity of supercritical CO₂. This has a big impact on pump rotor-dynamics due to the low damping effect provided by the fluid across annular seals. Clearances thus must be carefully calculated, while wear rings need to be made from non-conventional materials. Additionally, the maximum number of stages pump stages can be limited by rotor stability.

Supercritical CO₂ characteristics also influence mechanical seal technology and selection. Based on fluid thermodynamic properties and seal chamber pressure, two different technologies can be applied to CO₂ pumps. These are:

- Engineered double or triple mechanical wet seals (API 682 compliant)
- Dry gas seals (API 692 compliant)

While double or triple mechanical wet seals with pressurised barrier fluid tend to be more reliable, they typically have a larger footprint and consume more power consumption. Dry gas seals, on the other hand, are a well proven technology and Baker Hughes can leverage the extensive experience acquired in these seals from centrifugal compressor applications. Dry gas seals require a smaller space for installation while also absorbing less power, but these need to be installed with a reliable control panel equipped with heater and gas booster to avoid CO₂ freezing during transient operating conditions.

CO₂ PUMPS FOR OFFSHORE INJECTION

Since there is no established infrastructure for pipeline transport of CO₂, many CCUS projects consider using concepts where ships are used as the mode of transport of liquefied CO₂ from collection to storage, and an injection using an offshore injection concept.

Through a partnership with Carbon Collectors and collaborations with various offshore operators, Baker Hughes is participating in a collaborative effort dedicated to addressing the challenges posed by offshore injection of CO₂. The aim is to establish a common understanding of strengths and weaknesses of different CO₂ offshore injection concepts, which are mainly:

1. **Direct Injection:** injection directly from a CO₂ carrier equipped with an onboard treatment system.
2. **Floating Storage Injection Unit (FSIU):** CO₂ carriers offloading to FSIU which injects into the well.
3. **Offshore Injection Unit (OIU):** floating or fixed structure with necessary conditioning and injection systems. The unit may be equipped with buffer storage or allows the connection to more than one ship to facilitate to facilitate the continuous injection.

Baker Hughes is leveraging the experience in both pumping solutions for offshore oil and gas production and CO₂ pump designs to develop cutting-edge solutions to help operators meet the stringent requirements of offshore CO₂ injection. Baker Hughes is particularly focused in developing pumps to handle different CO₂ mixtures, withstand extreme pressures and highly corrosive environments, while also ensuring high reliability, efficiency and durability. Finally, with a growing package of digital solutions for remote monitoring and predictive maintenance, Baker Hughes pumps will ensure offshore operations are conducted in a safe and timely, while minimizing the need for human intervention.

Baker Hughes **BAKER HUGHES** **OFFSHORE FLEXIBLE PIPES**



SUMMARY

Subsea CCS projects require pipelines for transportation of CO₂ to the reservoir. Key requirements of these pipelines include technical capability, cost-effectiveness and risk reduction. Baker Hughes unbonded flexible pipes have a proven track record in CO₂-rich applications that address these technical requirements. Baker Hughes' flexible pipe product has the potential to offer significant cost and risk benefits to a CCS project compared to alternative options such as rigid pipes.

BENEFITS

- Proven capability for high-pressure CO₂ transportation using standard materials and product design
- Project schedule is hugely benefited when compared to rigid alternatives
- Enabling technology for shallow-water dynamic CO₂ risers

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

Baker Hughes has been supplying unbonded flexible pipe to the offshore oil & gas industry for more than 30 years, supporting the development of such projects that face some of the harshest conditions in the world. An unbonded flexible pipe is made up of a series of polymer and metallic layers that are uniquely configured to suit each project's specific requirements.

The traditional oil & gas industry is witnessing a remarkable surge in demand for CO₂-compatible pipelines, primarily fueled by the unique challenges posed by CO₂-rich pre-salt reservoirs in Brazil. In these projects, CO₂ stripped from the pre-salt fields' production fluids is reinjected into the reservoirs at high pressures.

Baker Hughes has undertaken significant research and development over more than five years to support the use of its conventional flexible pipe products in CO₂-rich applications. This research, which includes small-, mid- and full-scale tests, has led to a detailed understanding of the critical design parameters for transporting CO₂. A review by an Independent Verifying Authority has led to an approved 'safe envelope' of operating conditions under which no failure modes, including stress corrosion cracking, will occur.

Baker Hughes' proven expertise in CO₂-rich applications has positioned the company as a leading supplier of flexible pipes, with more than 70 km of such pipes already installed. These CO₂-compatible products leverage the same set of standard materials and manufacturing techniques employed in more traditional applications, ensuring consistent quality and performance across the board.

Based on the product's capability and track record, Baker Hughes' flexible pipes are equally suitable for use in CCS applications and there are clear value propositions for this product. For example, shallow water CCS dynamic applications necessitate a technology that can withstand CO₂ and a high-fatigue environment. Only an unbonded flexible pipe has a proven track record in both.

When used as infield flowlines, flexible pipes can lead to a lower total-installed cost than rigid pipes. Furthermore, flexibles remove the need for rigid jumpers, which require metrology and fabrication before installation. This hugely benefits the schedule at the most critical time – shortly before start-up.

Baker Hughes remains committed to providing cutting-edge, reliable solutions for the offshore oil & gas industry, while simultaneously addressing the growing need for CO₂-compatible pipelines in CCS applications. By consistently delivering high-quality, innovative products, Baker Hughes cements its position as a trusted partner, helping to shape a sustainable future for the energy sector.

CO₂ COMPRESSION SOLUTIONS

SUMMARY

Everllence's CO₂ Compression Solution gives project owners a fast, low-risk path from capture to transport and injection. The heart of the offer is a modular, integrally geared compressor (IGC) platform that is shipped as pre-engineered packages and installed quickly on site. It includes the compressor, driver, coolers, lube and seal systems, prefabricated piping, steel structures, and controls, all designed to work together from day one. The standardised approach typically shortens lead time by up to 30 percent, lowers price by around 15 percent, and reduces erection time by about a month versus stick-build. Our compression solutions fits very well to every capture route and is the perfect match to supply every pressure condition like for pipeline transport, liquefaction or injection purpose. Optional heat and power recovery can cut capture energy cost significantly. The solution builds on decades of CO₂ projects and more than one million operating hours in CO₂ compression.

BENEFITS

- **Package modularization:** Everllence offers modularised systems with standardised components that reduce cost, complexity, maintenance and lead time.
- **Technical certainty:** Validated operating maps for wet/dry CO₂ and discharge to injection or liquefaction pressure, with fewer stages/casings than inline alternatives and demonstrable power advantages.
- **Own gear engineering and production**
- **Faster schedules:** design-to-delivery by modularization
- **Lower total cost:** CAPEX reductions from standard modules and supply-chain leverage; OPEX gains from higher efficiency and integrated heat/power recovery
- **Operational resilience:** digital monitoring and proactive service to stabilise uptime over the asset life
- **Decades of CO₂ compression experience** with over 1 million operating hours and 200 million tons compressed.

KEY PROJECTS

- **Standardised CO₂ compression:** The modular package for our clients accelerates delivery, simplifies interfaces, and reduces onsite risk - creating a replicable path from capture to dense-phase transport for industrial emitters.
- **BECCS project in Sweden:** Everllence supplies a MAX1 axial compressor and expander for high-volume flue gas, enabling 800,000 t/y biogenic CO₂ removal with permanent North Sea storage, delivered as a single-source turbomachinery train package
- **Cement industry project in Norway:** Everllence provides CO₂ compression with heat recovery, enabling liquefaction and ship transport to storage.
- **Range of compression solutions in UK:** Everllence supplies two IGC for wet low-pressure boosting and three inline compressor trains for dry CO₂ high-pressure export. The single-source delivery ensures seamless integration, fewer interfaces, and dependable performance overall.

KEY DATA

TRL	9	Flow Rate	up to 600,000 m ³ /h	Efficiency	>88%
Max. Discharge Pressure	250 bar	Power Range	up to 75 MW		
Target Industries	All CO ₂ emitting industries, transport facilities, plants with use of CO ₂				

TECHNOLOGY DESCRIPTION

EVERLLENCE CO₂ COMPRESSION SOLUTION

Everllence provides high-efficiency, integrally geared centrifugal compressor (IGC) trains engineered

specifically for CO₂ service, both dry and wet, covering compression at the capture site (pre-transport), pipeline booster duties, and injection-side duties. The solution is available as modularised, pre-engineered packages (RG 63/71/80/90 platform) and as engineered-to-order (ETO) configurations for exceptional pressures/flows and specific customer preferences. The modular system with standardised components reduces site work, accelerates delivery, and standardises critical subsystems without sacrificing process fit.



Our modular RG platform covers

- suction pressures ~1.02–1.8 bara
- discharge pressures up to 180 bara
- with volume flows of ~38,000–115,000 m³/h
- mass flows of ~0.55–2.75 Mtpa
- Typical driver powers span ~9–32.5 MW (50/60 Hz).
- Inlet temperatures up to ~58 °C and outlet temperatures up to ~185 °C are supported
- both wet and dry CO₂ can be handled

For projects requiring higher discharge pressures or much larger flows (e.g., dense-phase transport or urea synthesis), Everllence delivers ETO IGC solutions up to ~250 bara and up to ~600,000 Nm³/h, maintaining API compliance and CO₂-specific aerodynamics and materials selection. Packages include the integrally geared compressor core, electric driver and coupling, lube-oil system, dry-gas seal system, inter/after-coolers, process and auxiliary piping, steel structures, instrumentation with wiring and junction boxes, and a control/protection system. Modules are designed for workshop assembly and shipment as skids for rapid re-assembly on site.

CORE TECHNOLOGY

Everllence adopts overhung impeller stages on an integral gearbox, enabling high tip speeds, high flow coefficients, and efficient multi-stage compression to dense-phase conditions with fewer stages than inline alternatives.

Head control is achieved via modular inlet guide vanes (IGV), providing a wide operating range without expensive variable-speed drives in many cases; anti-surge control loops are integrated. The solution interfaces seamlessly with capture technologies (amine, membrane, adsorption, cryogenic) and downstream pathways.

- Pipeline transport: 7–8-stage compression to >130 bara for efficient long-distance transport.
- Liquefaction and shipping: compression to supercritical region followed by refrigeration/liquefaction; pump-out at destination for injection or utilization.
- Injection/Utilization sites: post-transport booster or injection service as needed by reservoir or process specifications.

ENERGY INTEGRATION OPTIONS

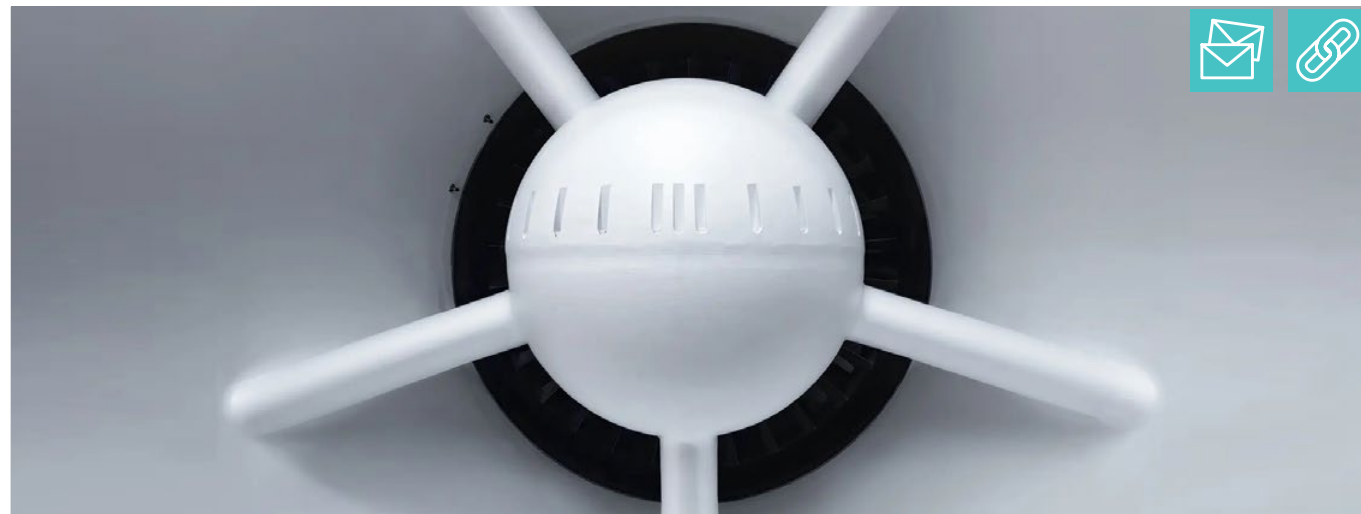
Everllence's packages are engineered for heat recovery between stages (hot water/steam, hot oil, ORC), enabling ~30–50% heat-energy savings for capture plants when integrated correctly; in a cement reference case, ~33% savings were achieved. For concepts combining PSA + cryogenic polishing, compander arrangements with power and heat recovery can deliver ~30% energy savings on that sub-process.



PROVEN IN PRACTICE

Everllence has 30+ years of CO₂ compression experience with >1,000,000 operating hours and a large installed base up to ~200 bara discharge. Recent and ongoing projects demonstrate the breadth of our scope. From point-source compression with heat recovery in cement, to multi-train solutions coupling low-pressure wet boosting and high-pressure pipeline compression for power and chemical clusters, to long-distance supercritical pipeline service.

FLUE GAS COMPRESSION SOLUTIONS



SUMMARY

Everllence's Flue Gas CCUS Solution combines leading high-capacity AG-MAX1 axial compressor technology with modern post-combustion capture to separate CO₂ efficiently from very large, dilute flue-gas streams. Built on the robust MAX1 axial compressor blading, it conditions flue gas to the pressure and temperature levels required by hot potassium carbonate and cryogenic capture processes, providing the volume flow, reliability, and efficiency needed for a large-scale front-end process. By delivering the required pressure rise at high flows and a minimised power consumption, it enables viable capture in waste-to-energy, cement, pulp & paper, and refinery plants and supports long term reliable operation across a wide operation range. An axial expander can be integrated for power recovery if applicable. For lower flows we use our compressor-expander (compander) configuration including expanders stages within the compressor casing, reducing net electrical demand.

BENEFITS

- AG-MAX1 suitable for flue-gas compression of large volume flows – up to 1.000.000 m³/h
- Outstanding compactness due to increased power density with MAX1 blading
- Outstanding robustness due to most robust MAX1 blading design
- Outstanding power consumption due to CFD optimised profiles, stage matching and reduced inlet and outlet losses
- Proven axial compressor technology since 1933 (>30 axial-gas-compressor references and in total >1.000 axial compressor references)
- Everllence latest CCUS experience BECCS 2025
- Well Standardised modular system in fixed frame sizes
- Following API Standard 617, chapter 2

KEY PROJECTS

- BECCS: Everllence supplies a MAX1 axial compressor and expander for flue gas CCUS application, enabling 800,000 t/y biogenic CO₂ removal with permanent North Sea storage, delivered as a single-source turbomachinery train package
- References in traditional industry applications
 - Nitric-Acid NO-compression
 - PDH-REC Propylene compression
 - LNG – Natural gas compression
 - Blast Furnace - tail-gas-compression
 - FCC – Main air compression
 - Nitric-Acid Main Air Compression
 - Blast Furnace Main Air Blower
 - ASU – Main Air Compression

KEY DATA

TRL	9	Pressure ratio	1.5 - 15 bar
Max. volume flow	1,000,000 m ³ /h	Power	Up to 120 MW
Target Industries	Energy / Biomass, Cement, Refinery / Pulp & Paper		

TECHNOLOGY DESCRIPTION

EVERLLENCE FLUE GAS COMPRESSION SOLUTION

Everllence's Flue Gas CCUS Solution combines leading high-capacity AG-MAX1 axial compressors with modern post-combustion capture to separate CO₂ efficiently from very large, dilute flue-gas streams.

The proven AG-MAX1 axial compressor technology offers an excellent solution with its well standardised modular system, purpose-built for large volume flows and continuous reliable operation under industrial conditions. By conditioning the flue gas to the pressure and temperature levels required by hot potassium carbonate (HPC) and cryogenic processes, AG-MAX1 provides the volume flow, reliability, and efficiency needed for a large-scale front-end process.

Industrial flue gas typically exhibits very high mass flows, low static pressure, low CO₂ concentration, and—in waste-to-energy and biomass applications—aggressive components. Compression is therefore the decisive enabling step for capture system performance and economics. MAX1 delivers the required pressure rise at very high flow, minimizing power consumption and safeguarding reliable operation across a wide operating range. This makes post-combustion capture viable at scale for waste-to-energy, cement, pulp & paper, and refinery plants

INTEGRATION WITH CAPTURE TECHNOLOGIES

MAX1 is explicitly positioned for flue gas capture processes, with benefits from very high, reliable flue-gas flows. In HPC systems, compression supports absorber/stripper hydraulics and solvent circulation at industrial scale. In cryogenic systems, compression stabilises upstream conditions for refrigeration and separation. The Flue Gas CCUS Solution's envelope and controls are tuned to these integration needs, reducing project interface risk and shortening time-to-operation.

Applications include:

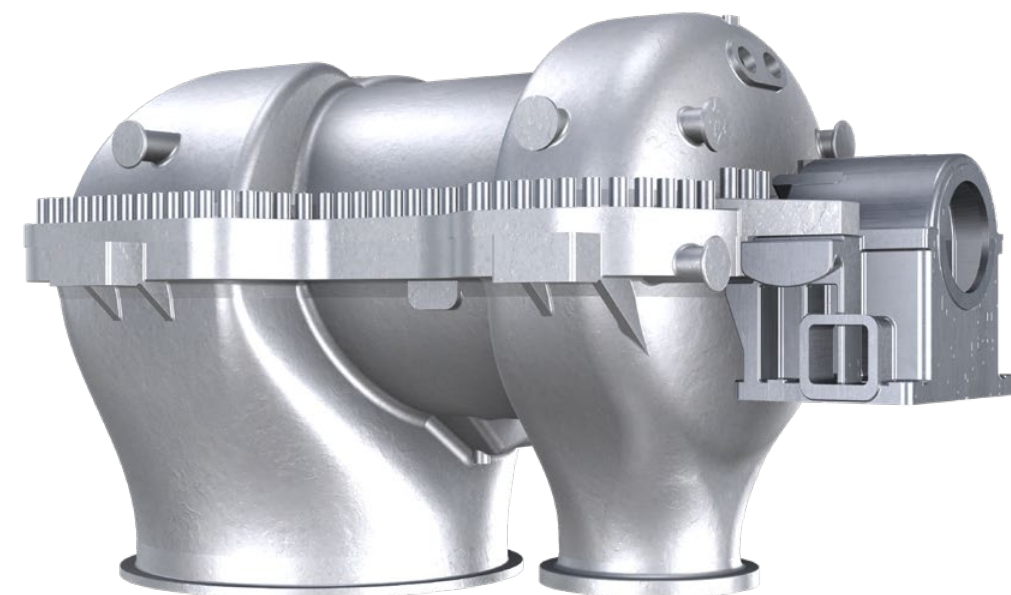
- Waste-to-Energy / Biomass
- Cement
- Refinery & Pulp & Paper

EVIDENCE FROM DEPLOYMENTS

Everllence axial turbomachinery for high-volume flue-gas handling has been selected in high-visibility carbon capture projects. A Stockholm BECCS configuration, for example, deploys an electrically driven axial compressor with an axial expander for power recovery—illustrating how the compression/expansion front-end can de-risk scale-up and contribute to the capture plant's overall energy balance.

ENERGY-EFFICIENCY AND POWER-RECOVERY OPTIONS

Everllence can integrate an axial expander for power recovery (compander configuration) to reduce net electrical demand of the flue-gas handling train. This architecture has been selected in large BECCS configurations to support high-throughput operation with improved overall energy performance.





GAS VESSEL PRODUCTION - GVP

TANKS FOR COMPRESSED CO₂ TRANSPORT

SUMMARY

GVP Italy is an engineering company founded in 2021 as a spin-off of the EU-funded GASVESSEL project. Leveraging decades of experience in pressurised gas technologies, GVP has developed and patented the world's largest lightweight pressure tanks, designed for high working pressures (100–300+ bar). Our solution sets a new benchmark for the CCS industry, enabling scalable, cost-effective CO₂ transport between capture sites and storage or end-use locations—without the need for liquefaction and with reduced purification requirements.

Fully tested, certified, and approved for shore-based and ship-fixed applications, GVP's tanks are now in the final stage of ADR/RID and IMDG certification, enabling safe and flexible multimodal transport by road, rail, and sea. This makes GVP the most cost-efficient CO₂ transport solution available today—unlocking the economics of CCS projects and accelerating decarbonisation.

BENEFITS

- **No Liquefaction or Regasification:** CO₂ is transported in dense gas phase, avoiding energy-intensive cryogenic processes and reducing OPEX.
- **Corrosion-Resistant Design:** Unlike carbon steel LCO₂ tanks, GVP's stainless steel liner lowers corrosion risk and allows for more relaxed CO₂ purity specs—cutting both CAPEX and OPEX for purification.
- **No Dry Ice Formation:** High-pressure tanks keep CO₂ in stable dense gas form, eliminating operational risks linked to dry ice.
- **Cost-Effective & Scalable:** GVP's carriers transport similar CO₂ mass at significantly lower cost than LCO₂ ships—delivering a more efficient and scalable solution for CCS logistics.



KEY DATA

TRL	9	30FT ISO Container Carbon Fiber (CO ₂ Payload, kg)	21,475	Years of Experience	>50
Nominal Loading Pressure (bar)	60	30FT ISO Container Glass Fiber (CO ₂ Payload, kg)	21,150		
Loading Temperature (°C)	20	40FT ISO Container Glass Fiber (CO ₂ Payload, kg)	30,750		
Target Industries	~				

TECHNOLOGY DESCRIPTION



GVP'S INNOVATION

World's largest high Pressure tanks

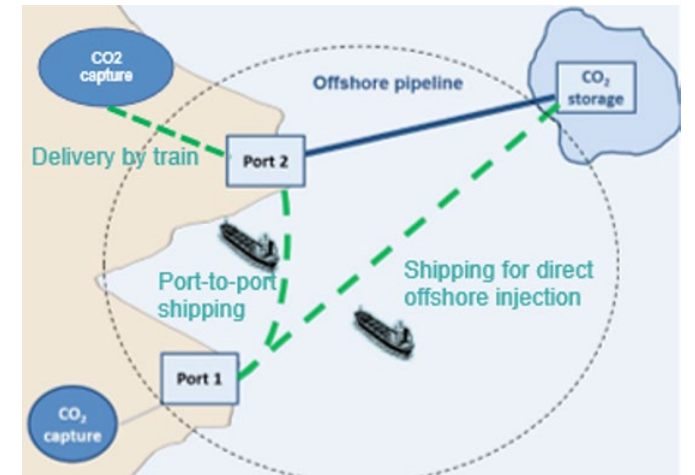
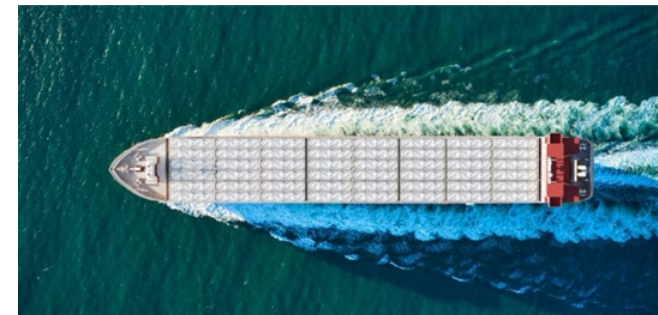
Our innovation begins with the fabrication of a non-load-sharing stainless steel liner, engineered for high pressure conditions and long-term durability. Using high-precision manufacturing and welding techniques, we ensure gas-tightness even after tens of thousands of fatigue cycles.

Under the EU-funded GASVESSEL project, we performed hundreds of material tests and full-scale prototype trials. During this time, we also developed unique equipment for our pilot production line—the unique system capable of wrapping composite cylindrical tanks with a 2.4 m diameter. Extensive HAZID/HAZOP and FMECA risk assessments were conducted, leading to optimised processes and full hazard mitigation.

We also ran rigorous hydrogen embrittlement tests, confirming that our chosen liner material, AISI 304L, is fully compatible with hydrogen environments.

After welding, each liner undergoes hydroforming—a patented process that improves the stainless steel's mechanical properties and guarantees dimensional accuracy. This enables optimal composite fiber wrapping, allowing for thinner liners and enhanced tank performance.

Finally, the hydroformed liner is transferred to our custom-built composite winding machine—the only one of its kind for this tank size—ensuring exceptional quality and consistency in every wrap.



After winding and curing, the tank undergoes autofrettage—a critical step in which it is pressurised beyond the maximum expected operating pressure defined by industry standards. This process ensures the liner stays within its elastic stress region under all normal and emergency conditions, significantly extending the tank's lifespan and ensuring safe operation.

Through years of rigorous testing, we have validated the mechanical strength, fatigue resistance, and hydrogen compatibility of our tanks—giving the full confidence in their long-term performance.

For certification, we have followed the ISO 17519 standard and the ABS rules for the pressure vessels, along with ADR/RID, CSC, and IMDG code regulations for the complete freight tank container solution.

With our full prototype testing program now complete, our technology has been approved for shore-based and ship-fixed storage applications. We are currently in the final stages of obtaining certification for multimodal freight transport under the oversight of the Italian Ministry of Transport.

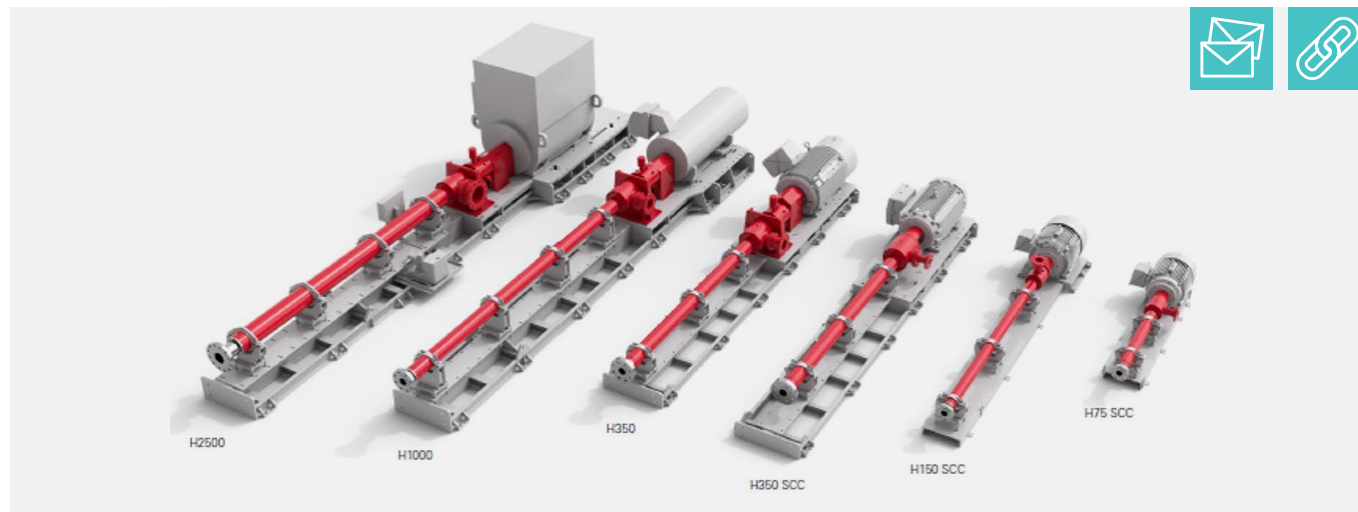
WHAT MAKES GVP'S TANKS SO DIFFERENT?

GVP's innovative technology unlocks CCS and CCU supply chains—particularly for smaller, decentralised, and widespread emitters where CO₂ purification and liquefaction render projects economically inefficient or technically unfeasible.

By transporting CO₂ in dense phase, GVP's solution reduces energy demand by 30–35% compared to liquefaction. The use of a stainless steel liner also relaxes CO₂ purity requirements, shifting the burden of purification from the emitter to the storage or hub side—when needed. GVP's virtual pipeline concept accelerates the development of CCUS networks and supports the growth of a flexible, scalable CO₂ market.

As part of the EU-funded COREu project, GVP will demonstrate a full CCS value chain—from CO₂ capture to permanent geological storage. The demonstration project is scheduled for the second half of 2026.

HALLIBURTON HALLIBURTON HERCULES™ HORIZONTAL PUMPING SYSTEMS



SUMMARY

Summit ESP® – A Halliburton Service offers a horizontal surface pumping system as an efficient alternative to positive-displacement, split-case, and other surface pumping options. The system design is based on our proven electric submersible pump (ESP) systems already in use in thousands of downhole applications. The multistage centrifugal pump is mounted securely on a modular skid, powered by a two-pole motor, and protected by a robust thrust chamber.

Using proprietary web-based applications engineering software, our engineers mathematically model operating conditions of downhole equipment and the inflow characteristics unique to each well, allowing them to fine-tune operating conditions. Our well surveillance monitoring service also allows the customer to avoid nuisance trips to the site by remotely starting and stopping the unit and adjusting setup points such as intake pressure, discharge pressure, and speed of the unit.

BENEFITS

- Lower initial operating and maintenance costs
- Modular design with short lead times on new and replacement equipment
- Flexible designs from 35 BPD to 100,000 BPD (1 USgpm to 2,916 USgpm)
- Back pull-out thrust chamber
- A single low-pressure mechanical seal
- Minimal noise and vibration; pulse-free flow
- Health, safety, and environment (HSE) friendly



EOR CO₂ booster (800 hp / 35,000 bpd / 2,000 psi)

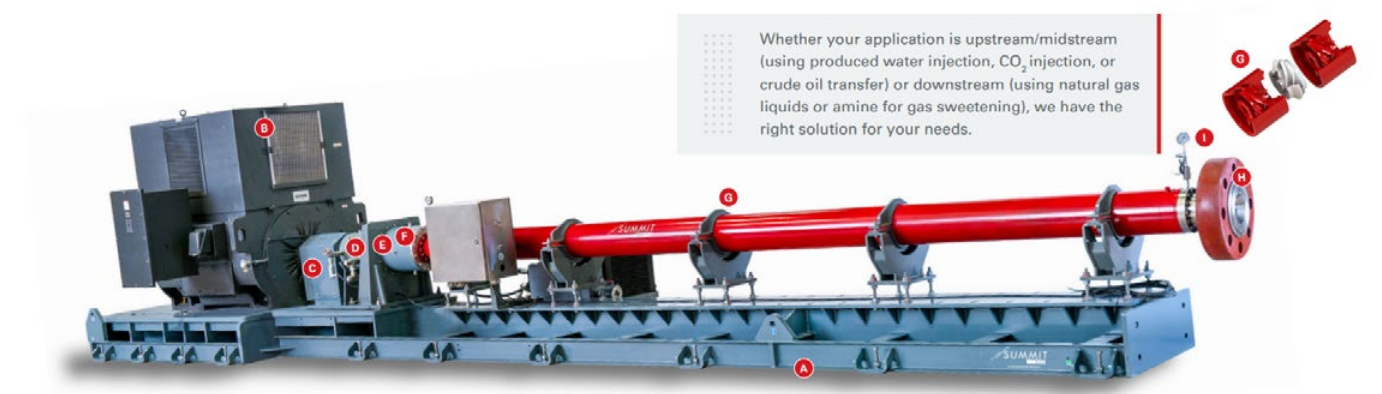


Produced Salt Water Disposal (400 hp / 12,000 bpd / 1,250 psi)

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION



A. HEAVY-DUTY SKID

- Modular skid, designed using extensive finite element
- Hoist mounting points to simplify installation

B. MOTOR

- Power units available from 20 hp to 2,500 hp (15 kW to 2,000 kW)
- Electric motor options include TEFC, WPII, TEAAC, with area classification Class I Div II; other options available
- Diesel, natural gas engine, steam or gas turbine

C. BALANCED SPACER COUPLING

- Maintenance free and helps reduce vibration
- Facilitates quick mechanical seal replacement without breaking pump or piping connections

D. THRUST CHAMBER

- Designed for increased reliability, seal support, and access
- Back pull-out for quick seal changeout
- Seal failure will not contaminate thrust chamber
- Minimal routine maintenance required

E. MECHANICAL SEAL

- Single seal assembly, exposed only to intake pressure
- Available in component or various cartridge seal designs
- API 682 and all applicable API flush and quench plans to meet customer and application requirements

F. INTAKE AND SUCTION FLANGE

- 316SS ANSI raised face flange is standard; other materials and types are available up to 3,000 psi (207 bar)
- Intake can be rotated in 90° increments to accommodate suction pipework

G. PUMP

- Flow range of pumps covers 35 BPD to 100,000 BPD (1 USgpm to 2,916 USgpm)
- Discharge pressures up to 7,100 psi (500 bar)
- Mixed-flow stage design for reduced abrasive wear, optimal efficiency, and head per stage
- Ni-Resist iron is standard stage material; other materials available upon request
- Tungsten carbide or GRAPHALLOY® bearings are available for wear resistance or low-lubricity fluids, respectively
- Tiger Shark® pump option to reduce pump thrust

H. DISCHARGE FLANGE

- Lap-joint type, comprising 316SS wetted parts and CS flange, meets ANSI flange standards
- Available in raised face or RTJ classes up to 5,500 psi (380 bar)
- API flange options available for higher pressures

I. INSTRUMENTATION

- Standard offering is intake and discharge pressure transmitter and vibration switch
- Skid-mounted junction box is available to provide single-point wiring
- Available in standard and explosion-proof enclosures, and customizable to suit customer or application requirements

MODEL	SIZE (OD)	CAPACITY (BPD)
SF	4"	35 to 7,500 (1-218 GPM)
SJ	5.38" / 5.62" / 6.00"	500 to 13,000 (15-380 GPM)
SH	6.75" / 7.25" / 7.50"	1,980 to 46,400 (57-1353 GPM)
SM	8.75" / 9.13"	8,100 to 58,200 (236-1697 GPM)
SN	9.50" / 10.0"	12,400 to 100,000 (361-2916 GPM)
ST	13"	50,000 to 100,000 (1458-2916 GPM)

LCO₂-EP (ELEVATED PRESSURE) AND OPTIMISATION OF THE CCS VALUE CHAIN



SUMMARY

Knutzen NYK Carbon Carriers AS ("KNCC") is a joint venture company between Knutzen of Norway and NYK of Japan. The objective for the company is to offer all LCO₂ transportation modes; low pressure ("LP"), medium pressure ("MP"), and elevated pressure ("EP," working range 0-10°C / 34-45 barG), catering to the CCS market under rapid development. In this compendium, we will focus on the features of LCO₂-EP and the specially designed containment system, the Cargo Tank Cylinders (CTC). In addition to introducing and marketing EP for marine transportation of LCO₂, KNCC is actively engaged in the entire CCS value chain to identify cost reductions. In the following, we present two of our studies conducted in collaboration with Chiyoda Corporation ("Chiyoda") on the "Quantitative Comparison of CO₂ Liquefaction, Temporary Storage, and Transportation," as well as with ENEOS Xplora Inc. ("Xplora") on the "Optimisation of CO₂ Liquefaction and Storage Process."

BENEFITS

- Less energy requirements for liquefaction, and less heat and pressurisation prior to injection into the reservoir, resulting in lower overall OPEX.
- Suitable for the concept of both Terminal To Terminal ("TTT") and Direct Injection Offshore ("DIO"), which eliminates the need for onshore terminal facilities and pipeline to the reservoir.
- Ambient/non-cryogenic requirements, with a working temperature of 0°C, facilitating for the application of lower-grade steel and corresponding low CAPEX.
- LCO₂-EP utilises the CTC which is planned to be produced through an automated series production by a dedicated factory. This will result in a significant shorter tank manufacturing period, particularly for onshore tanks which will contribute to shorter overall project timelines.
- The EP working pressure, 34-45 barG, allows for greater tolerance towards CO₂ impurities without requiring special design or special operational procedures
- EP, with a lower energy requirements for the liquefaction process, has also the potential to reduce the required land space and tank volume across the value chain.

KEY DATA

TRL	6	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Marine transportation, onshore tank and liquefaction if EP apply to the CCS value chain				

KEY PROJECTS

- **Project One:** CO₂ marine transportation. Especially CO₂ direct injection offshore projects in any region (Europe and Asia Pacific).
- **Project Two:** Opportunities for reservoir and well testing of amongst others injectivity
- **Project Three:** Projects fit the aim of the study with Xplora. It is to enable onshore carbon capture projects that intend to load the LCO₂ to a vessel with minimised CAPEX/OPEX and minimised required land space.

TECHNOLOGY DESCRIPTION

Figure 1 illustrates the CCS value chain with the three CO₂ transportation modes: LP, MP, and EP, represented by their respective temperature and pressure. CO₂ transport, with the objective of injection into CCS wells, typically requires pressure ranging from 50 bar to 300 barG, although specific requirements may vary from project to project.

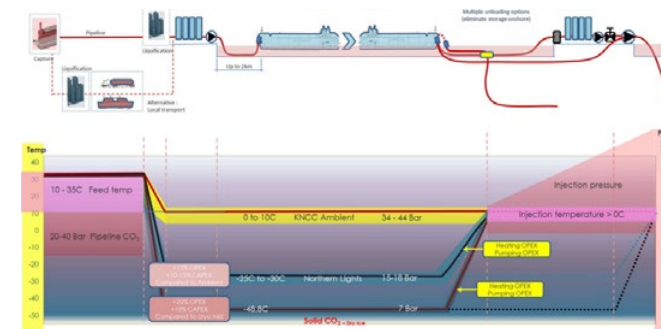


Figure 1: Energy conditions of LP/MP/EP through CCS value Chain

CO₂ needs to be pre-conditioned above 0°C before injection into CCS wells regardless of LP/MP/EP. EP is unique to CO₂ in the CCS industry and contributes to the concept of lower OPEX and CAPEX. Additionally, in the case of DIO, this feature reduces the need for additional equipment, providing advantages in terms of space availability and CAPEX/OPEX reduction. EP further optimises for the DIO concept, due to the elimination of the requirement for onshore terminal facilities. To realise this concept, the CTC has been developed as a storage tank in accordance with the IGC code and CNG principles. Carbon steel is used considering the working temperature of 0°C, in order to minimise the steel costs, also taking into account that the total weight of steel is higher compared to other modes.

The CTC will be fabricated using an automated series production approach. This method reduces the need for manual labour, leading to shorter lead times and requiring fewer workers. This is particularly advantageous for the CCS market, which often involves large-scale infrastructure and significant workloads.

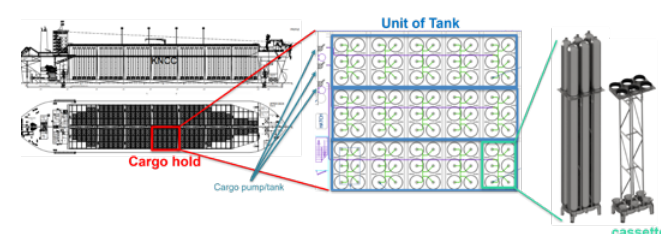


Figure 2: CTC arrangement sample for a LCO₂-EP

CO₂ IMPURITY

The CCS industry considers CO₂ impurities to be a significant issue. The type and variety of CO₂ impurities can vary depending on the emitter plant, and even impurities in the ppm range can cause changes in the CO₂ phase diagram. The main reason for liquid phase transportation of CO₂ is to achieve volume efficiency, allowing for 500 – 800 times higher volume compared with CO₂ in gas phase.

Figure 3 illustrates a sample phase diagram change in terms of pressure-enthalpy. The left side represents the case of pure CO₂, while the right side represents a case with 99.0% CO₂, 0.5% H₂, and 0.5% N₂. In this particular

case, liquid transportation requires a minimum pressure of 30 bar G; otherwise, transportation would be conducted in the gas phase. The CO₂ impurities has implications throughout the entire cargo handling process, requiring careful consideration of mechanical, operational, health, safety, and environmental (HSE), as well as reservoir storage aspects.

CCS VALUE CHAIN APPROACH

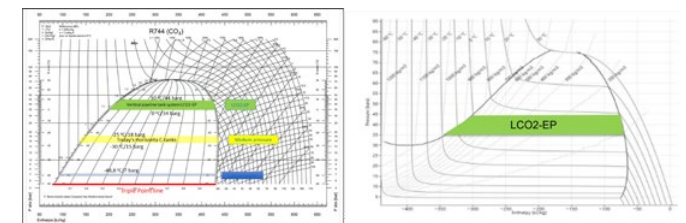


Figure 3: Phase diagram (pure CO₂, 99%CO₂/0.5%H₂/0.5%N₂)

The CCS industry is still in its early stages, and there are a huge potential for further optimisation. Collaboration with experts from different fields is the key to push CCS optimisation and simplification aiming for lower costs. Below we present two case studies highlighting the importance of collaboration in achieving CCS materialisation and optimisation.

1. Evaluation of the CCS value chain with Chiyoda

The base assumptions are, a CO₂ emitter in Japan handling 2 Mtpa and evaluating terminal to terminal transportation, the following key points were highlighted.

- The comparison between EP, MP, and LP liquefaction and transport in Japan showed that CAPEX is similar for LP and EP, but relatively higher for MP due to the large number of tanks required. In terms of OPEX, EP is lower through liquefaction and injection compared to MP/LP.
- Long haul case, LP had an advantage in terms of marine transport costs. However, EP was confirmed to have an advantage across the entire CCS value chain.
- Challenges: The study identified temporary onshore storage as the most challenging aspect of the value chain due to the prolonged construction period.

Global CCS Institute presentation material on 2024/3/4

Quantitative Comparison of CCS Value Chain with LCO₂ three modes (LP/MP/EP)

2. Joint Study on Optimisation of CO₂ Liquefaction and storage Process with Xplora

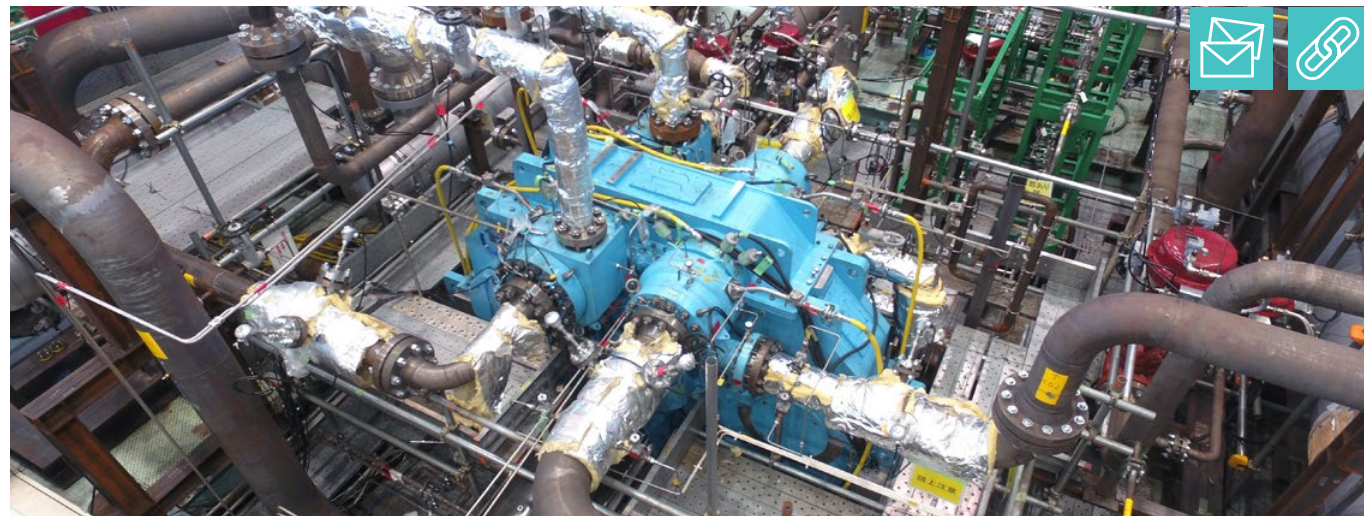
This study aims to optimise the CO₂ transportation system by leveraging the unique characteristics of the EP method. The objective is to address challenges in the CCUS value chain, including capital investment, energy consumption, and environmental impact. To verify these aspects, the study will utilise KNCC's CTC demonstration facility test rig located in Haugesund, Norway. Based on the results of this verification, ENEOS Xplora Inc., NYK and KNCC developed the initial LCO₂-EP Floating Liquefaction and Storage Unit design and obtained AiP from ClassNK.

Press Release NYK (2025/3/27) AiPs Obtained for Liquefied CO₂ Carrier Design and Floating Liquefied Storage Facility



KOBE STEEL, LTD.

HIGH PRESSURE INTEGRALLY GEARED CENTRIFUGAL COMPRESSOR



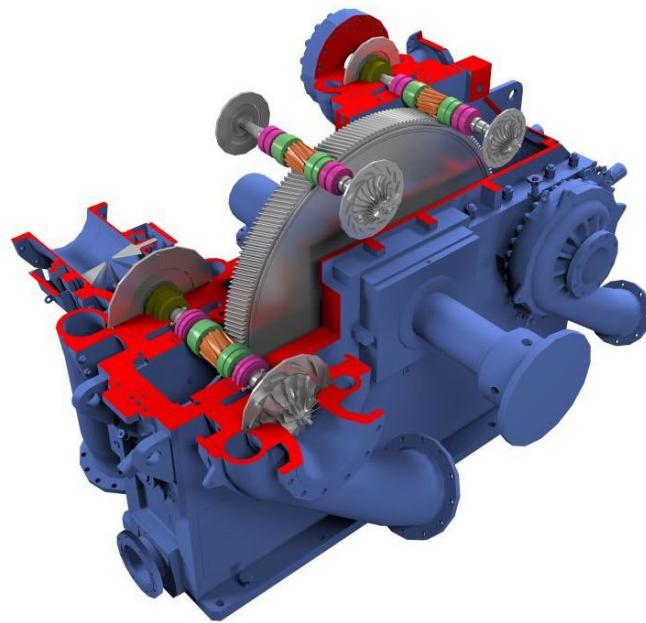
SUMMARY

Energy savings have become a prevailing trend in industrial machinery as a response to the global warming issue. KOBELCO compressors, utilised in various manufacturing plants and facilities, now face a heightened demand for energy efficiency, particularly in power reduction. The utilisation of high-pressure CO₂ centrifugal compressors in carbon capture and storage (CCS) applications has increased remarkably, facilitated by significant technological advancements. Integrally geared centrifugal compressors, benefiting from optimised rotating speeds for each stage and the ease of intercooler integration, have been adopted as a solution for reducing power consumption. Consequently, the development of high-pressure CO₂ centrifugal compressors aligns with the imperative of energy conservation.

BENEFITS

High Efficiency & Compact Arrangement:

- Optimised Rotating Speeds: Integrally geared centrifugal compressors enable the customisation of rotating speeds for each stage, thereby achieving high efficiency.
- Cooler Arrangement: The straightforward insertion of intercoolers between stages facilitates the reduction of compression power by lowering suction temperatures at each stage, resulting in decreased power consumption.



KEY DATA

TRL	9	Number of Commercial Plants	4	Number of Pilot Plants	1
Target Industries	~				

TECHNOLOGY DESCRIPTION

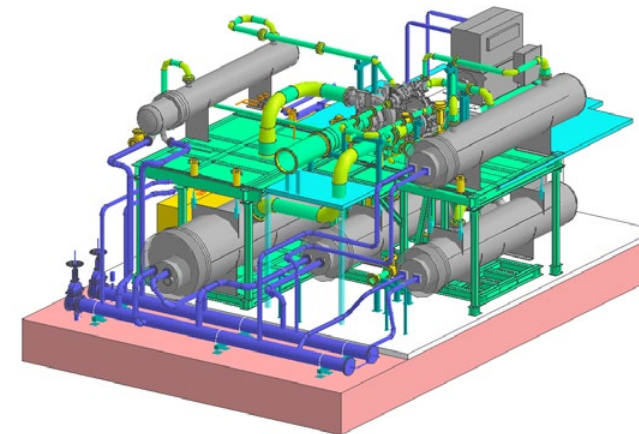
KOBELCO is one of the leading steel manufacturers in Japan, as well as a major supplier of aluminium and copper products. Other business segments include machinery, construction machinery, power supply, and others.

In the machinery business, KOBELCO is a unique company capable of supplying all three types of compressors - screw, centrifugal, and reciprocating compressors since 1915. Each type of compressor possesses its own strengths and characteristics, such as capacity, pressure range, and the gases they handle.

Centrifugal compressors are broadly classified into in-line compressors and integrally geared centrifugal compressors. However, integrally geared centrifugal compressors have expanded their fields due to their excellent qualities.

In an integrally geared centrifugal compressor, pinion shafts with different rotational speeds are generally arranged on both sides of a large gear driven by a low-speed driving machine. Since each impeller is mounted on both sides of the pinion shaft, the impeller diameter of each stage and the rotating speed of each shaft can be easily selected according to the specifications. This allows for a high pressure ratio per single stage and a high compression ratio to be realised. Additionally, the application of the open backward type impeller and the optimal selection of the flow coefficient ensure high efficiency and performance. Furthermore, in terms of package arrangement, intercoolers can be easily arranged between each stage to realise a compact package design and a highly efficient compressor, thereby reducing power consumption.

KOBELCO has been manufacturing integrally geared centrifugal compressors for process gas applications, such as air, nitrogen, hydrocarbons, toxic, and flammable gases.



INTEGRALLY GEARED COMPRESSOR FOR HIGH PRESSURE APPLICATION

To address the global warming problem, energy-saving and decarbonisation have become trends in the industrial machinery industry. Specifically, the response to CCS applications, which are recognised as part of decarbonisation efforts, is required. KOBELCO has developed a compressor with a discharge pressure of 20 MPaG to apply it to high-pressure applications. The key requirements for such a compressor include designing it to withstand high-pressure CO₂, ensuring rotor stability, and verifying performance. Stress analysis using the finite element method (FEM) was conducted during trial manufacturing to design the compressor casing to withstand high-pressure CO₂ gas. Strain measurements of the casing during the pressure resistance test were carried out to verify the analysis results, confirming the validity of the pressure resistance design.

In a high-pressure compressor, the high density of the fluid causes an exciting force to act on the impeller and the seal, necessitating vibration stability against unstable vibration. Stability evaluation was conducted by exciting the rotor system from the outside using electromagnet technology designed specifically for this purpose. After verifying each element, a demonstration test was conducted with the pressure increased to 20 MPaG. Mechanical stability and performance were verified, confirming successful operation.

KOBELCO's integrally geared centrifugal compressor will contribute to future environmental issues.

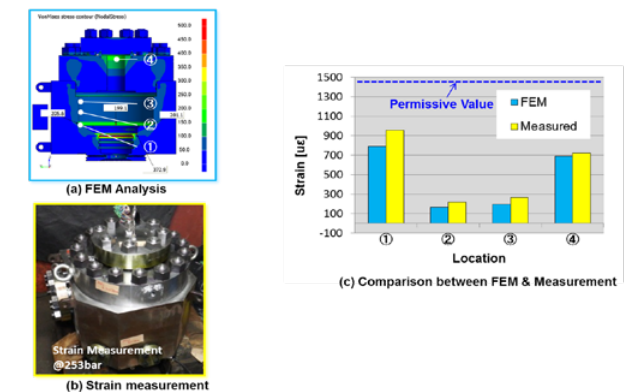


Figure 1: FEM Analysis and Strain Measurement Results of Compressor Casing



LINDE HITREAT™ CO₂ COMPRESSION & DEHYDRATION



SUMMARY

CO₂ compression and dehydration are the most common process units in all CO₂ plants. If the CO₂ purity already meets specification requirements after the CO₂ capture process, the downstream CO₂ treatment usually involves compression and dehydration. It is also a typical process unit for a CO₂ Processing Unit (CPU) and CO₂ liquefaction plants.

Depending on the plant capacity, different types of compressors can be used, such as piston, screw, and turbo compressors. Depending on local costs for utilities, electrical or steam-driven compressors can be employed.

The targeted CO₂ product pressure is defined by the downstream application or distribution concept. Pressures of up to a maximum of 215 bar have been realised.

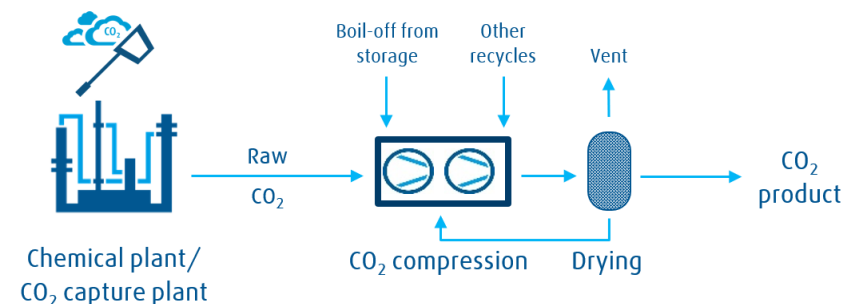
Compressor stations not only compress the main CO₂ feed gas stream, but can also be used to integrate and compress boil-off gases from storage tanks and other CO₂-rich vents from the plant.

BENEFITS

- Mature and robust technology
- Various options for compressor type
- Multiple references for different scales worldwide

KEY PROJECTS

- Linde as a CO₂ network owner and major supplier of CO₂ to greenhouses ensures access to the CCS network in the Netherlands for several emitters.



CO₂ compression and drying process design

KEY DATA

TRL

9



LINDE HITREAT™ CO₂ HUB

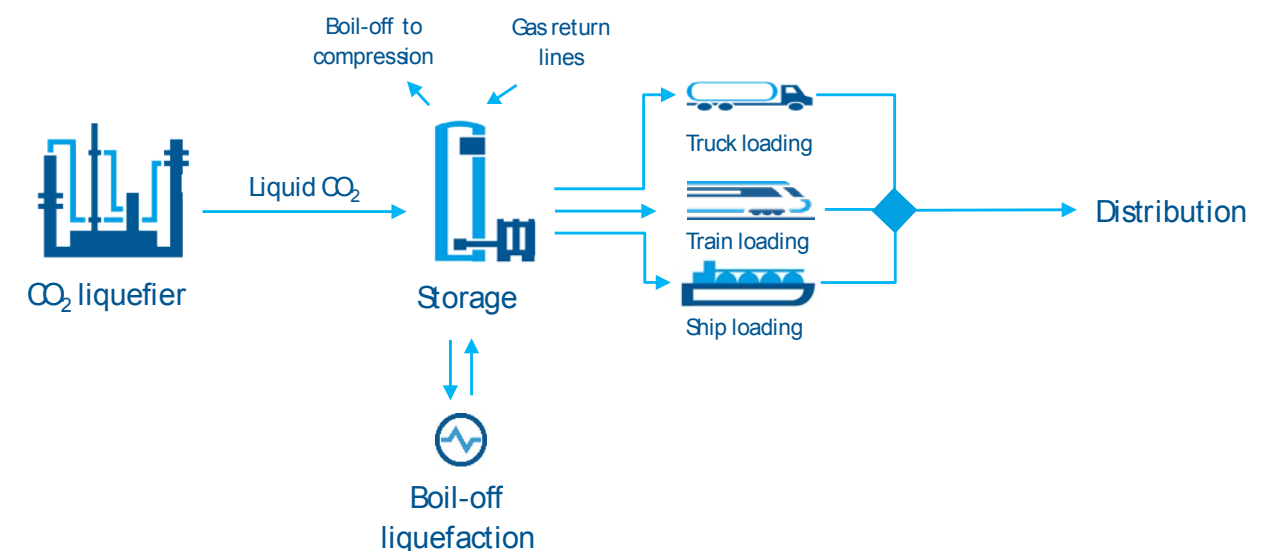


SUMMARY

Linde offers state-of-the-art tank farms to store liquid CO₂. A range of configurations are available. For example, the storage tanks can be spherical or cylindrical (vertical or horizontal). Tank farms can be equipped with boil-off gas re-liquefaction as well as integration of gas return lines. Moreover, an essential component of a tank farm is a loading station. While most tank farms feature trailer loading stations, Linde has also built train and ship loading stations to cover the whole range of potential distribution concepts.

HIGHLIGHTS

- Extended reference list at various product capacities
- High degree of standardization and skidded packages to reduce CAPEX
- Advanced sampling and loading system



KEY DATA

TRL

9

NOV – CO₂ TRANSPORTCOMPOSITE SOLUTIONS FOR CO₂ TRANSPORT

SUMMARY

The transition to lower-carbon energy, coupled with the growth in decarbonisation methods, is only possible with a robust transportation network. However, the efficient and safe transportation of large volumes of carbon dioxide from industrial sources to storage or utilisation sites presents several significant challenges. Developing, maintaining, and ensuring the integrity and safety of such infrastructure involves considerable investment, particularly in corrosion control.

As the leading worldwide manufacturer of fiberglass-reinforced epoxy (GRE) products, NOV's Fiber Glass Systems (FGS) business unit provides proven corrosion-resistant composite solutions for onshore and offshore applications in a variety of low- to high-pressure services. In fact, composite pipe from FGS has been used in CO₂ injection lines, high- and low-pressure pipelines, water alternating gas (WAG) systems, and other challenging transportation applications for more than 50 years. FGS brings a comprehensive suite of benefits to CO₂ transport, leveraging the properties of composite technology to enhance reliability and sustainability.

BENEFITS

- Whether it is 100% wet, dry, or even supercritical CO₂, our high-pressure fiberglass piping systems eliminate the challenges and concerns of carbonic acid.
- GRE piping systems can be installed as new above- or below-ground pipelines or inserted into an existing pipeline with pull sections up to 1.8 km long.
- In any scenario, our composite solutions bring superior corrosion resistance and ease of installation without the additional cost of coatings, cathodic protection, or expensive alloys.
- GRE has a reduced embodied carbon footprint compared to steel piping systems. On a per kilometer basis, GRE piping systems require 31% less energy to produce and can deliver 65% energy savings throughout a 20-year life cycle due to a smoother inner pipe surface. The lightweight nature of GRE pipes can greatly reduce the emissions caused by travel. Shipping GRE pipe via semi-trucks can reduce CO₂ emissions by up to 77%.

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

FGS specialises in designing and manufacturing highquality fiberglass pipes and systems renowned for their excellent corrosion resistance, durability, and reliability. We are proud to offer a family of industry-leading line pipe products that combine strength, durability, and corrosion resistance. These products are an ideal choice for the demanding environments inherent in carbon capture and CO₂ transportation systems.

Our Fiberspar™ spoolable line pipe consists of an inner thermoplastic pressure barrier reinforced by high-strength glass fibres embedded in an epoxy matrix. It is intended for corrosive gathering and injection applications, including general and sour-produced fluids and gases. Fiberspar is available with high-density polyethylene or high-temperature polyethylene pressure barriers with temperature ratings of 150°F (65°C), 180°F (82°C), and 203°F (95°C). This high-pressure pipe is available in continuous lengths of up to 9,000 ft (2,743 m) and is immune to corrosion. Our products are designed with service factors for water, oil, and gas in full compliance with API RP 15S, API 15HR, and CSA Z662.



Fiberspar Spoolable Fiberglass Pipe

Our proven family of jointed line pipe, such as Star and Star Super Seal HP, is manufactured in sizes ranging from 1½-in. to 42-in. (40-mm to 1,050-mm) diameters. Depending on size, these products will handle pressures from 150 psi (1.0 MPa) to 3,500 psi (24.1 Mpa) and temperatures up to 212°F (100°C).

Our high-pressure products are commonly used to transport highly corrosive produced water and CO₂ gas from an oil field's central station to injection wells and have

a proven track record in handling CO₂. The epoxy resin systems we offer include aliphatic amine, aromatic amine, and anhydride curing agents, each providing slightly different chemical and temperature resistance. Our line pipe is manufactured to a minimum design life of 20 years at rated temperature and pressure in accordance with ASTM D2992 Procedure B and industry standards such as API 15HR and 15LR.

The latest development in our high-pressure, large-diameter product offering is the patented Star Super Seal Key-Lock (SSKL), which achieves the fastest and easiest installation with jointed fiberglass pipe. With sizes spanning 8 in. to 40 in., SSKL can withstand pressures of 300 to 3,000 psi and with temperatures of 150°F (65°C), 200°F (93°C), and 212°F (100°C) designs available. Our high-pressure designs are laminate designed using API 15HR and ISO 14692 procedures, making them reliable and trusted products in our portfolio.



Star Super Seal Key-Lock

Its unique joining system specialises in the key-lock method of a self-restrained joint, offering quick assembly in minutes by utilising ductile locking keys for mechanical restraint. The joint is directly inserted with no rotation and is available with one or up to 10 locking keys, depending on diameter and pressure requirements. A hydrostatic seal is made by means of an elastomeric O-ring.

Field support during installation is an integral part to ensure the reliability and long-term, worry-free performance of your piping system. FGS offers complete training and inspection services for all products throughout the world.



NOV – CO₂ TRANSPORT
HOSS HORIZONTAL PUMPING SYSTEM



SUMMARY

The NOV’s HOSS Horizontal Pump System is the industry-leading solution for efficient and reliable CO₂ pumping. Whether for CO₂ pumping or injection processes, this system is designed to handle the unique challenges of CO₂ transportation, even when combined with H₂S "sour gas".

BENEFITS

Superior Performance & Efficiency:

- High-pressure capabilities for enhanced injection efficiency
- Optimised hydraulic design for maximum flow rates
- Low energy consumption compared to traditional methods

Reliability in Harsh Conditions:

- Designed to handle CO₂ in both supercritical and dense-phase states
- Proven performance in challenging environments, including H₂S-laden sour gas applications
- Robust construction with corrosion-resistant materials
- API Seal and corresponding Seal Plans

BENEFITS

Cost-Effective & Low Maintenance:

- Longer operational life with reduced downtime
- Easy maintenance with modular design and readily available components
- Lower overall cost of ownership compared to alternative pumping solutions

Industry-Proven Solution:

- Successfully deployed in multiple carbon capture and enhanced oil recovery (EOR) projects
- Trusted by industry leaders for high-reliability CO₂ and sour gas pumping

Why Choose NOV Hoss Pumping Systems?

With extensive expertise and a strong track record in CO₂ injection and sour gas handling, NOV/HOSS continues to lead the way in innovative pumping solutions. Our Horizontal Pump System is the ideal choice for industries looking to optimise CO₂ transportation while ensuring safety, efficiency, and cost savings.

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KEY DATA

TRL	9	Flowrates (GPM)	50 - 600	Pressures (PSIG)	>95%
Number of Commercial Plants	10+	Size range	Custom units to suit customer compatibility		
Target Industries	Supercritical or dense phase CO ₂				



SLB

OLGA DYNAMIC MULTIPHASE FLOW SIMULATOR



SUMMARY

Transport and injection are critical components of the CCS value chain, and safe and optimised design and operation of the transport system is essential to the economic viability of CCS projects. There are numerous challenges associated with CO₂ transport, and it is important to better understand different complexities and increase insight into operational aspects. Although most CCS systems are designed for dense (single) phase CO₂, there are many operational scenarios where multiphase conditions will be applicable. Moreover multiphase represents a future potential option for lower cost transport and injection systems. The Olga™ dynamic multiphase flow simulator, part of the Sequestri™ digital ecosystem, has been the de-facto industry standard for oil and gas flow simulation for four decades. In the last few years, Olga simulator has been repurposed to include CO₂ flow simulation, and it has become a leading simulator for CCS transport and injection simulations.

BENEFITS

- The flow algorithms in Olga have been validated through comparisons with the most diverse flow data base in the world through the Olga Verification and Improvement Project, which has been running continuously since 1996.
- The Olga simulator's new solver for CCS provides robust, accurate, and fast flow simulation results for fluids relevant for CCS.
- Olga simulator's open integration protocol allows for integration with other simulators, such as process simulators.
- Multiphase flow unlocks lower pressure and lower cost CCS alternatives for the future.



KEY DATA

TRL

9

TECHNOLOGY DESCRIPTION

OLGA SIMULATOR

The Olga simulator is the de-facto industry standard for multiphase, transient flow simulation, a position it has held since it was introduced more than 40 years ago. It has a mechanistic flow model built on first principle physics equations. The simulator has helped unlock hundreds of billions of dollars in value by enabling multiphase subsea oil and gas production. It has a global footprint, and has been used in planning, development and operations of all major subsea projects over the last 30 years. Development has been sponsored by many of the oil and gas majors, and through the Olga Verification and Improvement Project (OVIP), which has been running continuously for 30 years. The simulator has been validated against the most diverse field flow data base in the world. This database consists of field data contributions from dozens of operating companies, who have been members of the project.

CO₂ TRANSPORT JOINT INDUSTRY PROJECTS (JIP)

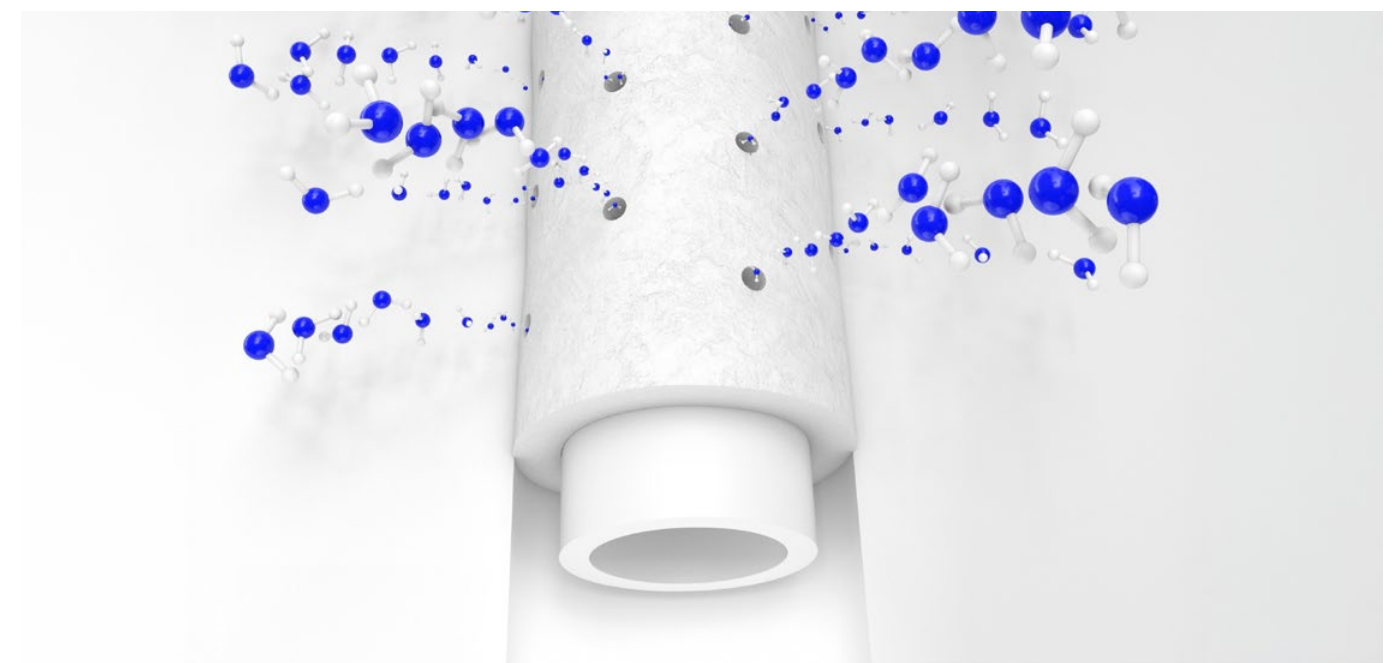
From 2018 to 2021, the CO₂ Flow Assurance for Cost-effective Transport (FACT) Joint Industry Project (JIT) focused on generating data for validation of multiphase CO₂ flow simulators. FACT was supported by several industry partners and the Norwegian Research Council through Gassnova, with the aim of securing accurate simulation results for CCS projects. This validation process resulted in a series of improvements which founded the basis for a new JIP called Olga CO₂ REACH, where REACH is an acronym for Robust Enhanced and Accurate CO₂ Handling. The project has focused on improving the robustness of the numerical solver, enhancing the thermodynamic functionality, qualifying process equipment models, and updating the flow model of the simulator for CCS applications. In parallel, a second JIP called Olga CO₂ TIDE (Transport and Inter-domain Extensions) has been launched focusing on simulating effects of injection in the near wellbore region.

NEW SOLVER FOR CCS

As the first direct result of the REACH JIP, a new numerical solver for CCS was released in 2024. This solver provides robust, accurate, and fast simulation results for both single and multiphase flow. Multiphase flow is typically present during certain transient operations of CO₂ with impurities, such as depressurizations, and it also enables future low-pressure and low-cost CCS operations. The new solver is offered as an integral part of the Olga simulator and provides a superior alternative to traditional solvers.

NEAR-WELLBORE CHALLENGES

CO₂ is typically injected into either depleted gas reservoirs or saline aquifers for carbon storage. Both types of reservoirs pose their own set of challenges for operators. For instance, Joule-Thompson (JT) cooling, caused by sudden pressure drop during injection into depleted reservoirs, can lead to liquid drop-out, ice formations, and salt precipitation in the near-wellbore zone of the reservoir. Additionally, backflow during shut in conditions from a saline aquifer to an injection well can lead to critical material integrity issues in the form of corrosion, and cause issues related to gas hydrates. Through the Olga CO₂ TIDE JIP, the simulator has been integrated with a near-wellbore reservoir simulator, allowing for a full thermal and mass balance coupling of the reservoir and the entire well interface. This functionality provides increased insights into JT-cooling effects, better control of short-term injection transients, improved understanding of backflow during shut-down, and accurate modeling of temperature and pressure gradients across the well-reservoir interface.



ALLEIMA **CRA TUBULARS FOR DOWNHOLE CO₂ INJECTION**



SUMMARY

Alleima is a world-leading developer, manufacturer and supplier of tubular products in advanced stainless steels and special alloys. An integrated steel production facility based in Sandviken, Sweden assures that the tubing meets and exceeds the industry specifications and ensures complete traceability. Alleima has a strong culture of R&D and works closely with academia and industry to constantly push the boundaries of metallurgy and knowledge of corrosion mechanisms.

With the global transition to cleaner energy systems, Alleima's advanced alloys help in operations in extreme conditions. Geological CCS injection (OCTG Tube) has unique challenges that requires materials to perform at low temperatures and corrosive conditions. Geological CO₂ storage also has stringent requirements on safety and well monitoring. The use of CRA alloys are essential to maintain well integrity. Alleima has an extensive range of OCTG CRA casing & tubing compliant to API 5CRA (ISO 13680) and API Q1.

BENEFITS

- Comprehensive range of CRA tubing grades including Super Duplex – SAF™2507 and high nickel alloys like Sanicro®28 and Sanicro®29 that can offer an extended service life in downhole injection conditions.
- API Q1 manufacturing facility with an integrated production route ensures high quality and material traceability (Tubes marked with API Monogram).
- Extensive track record of supply of downhole OCTG tubing across the globe with major national and international operators.
- Extensive Research and Development with the possibility for supplying samples for material / metallurgical testing. Alleima also has state of the art laboratories that can conduct corrosion / material / failure analysis.

KEY PROJECTS

- Alleima has a long tradition of delivering downhole OCTG for CO₂ injection. The first CCS project – Sleipner (Norway – 1996) use super duplex (SAF™2507) from Alleima.
- Alleima has supplied downhole OCTG CRA tubing and casing for CO₂ injection at a major project in Australia, where CO₂, separated from offshore natural gas production, is re-injected into the saline aquifer approx. 2 km deep for permanent geological storage
- Alleima has also successfully supplied downhole OCTG tubing for a European flagship project where CO₂ is injected into depleted offshore gas formations (3-4 km deep) through converting old production wells into CO₂ injection wells. Project is expected to be operational in 2026.

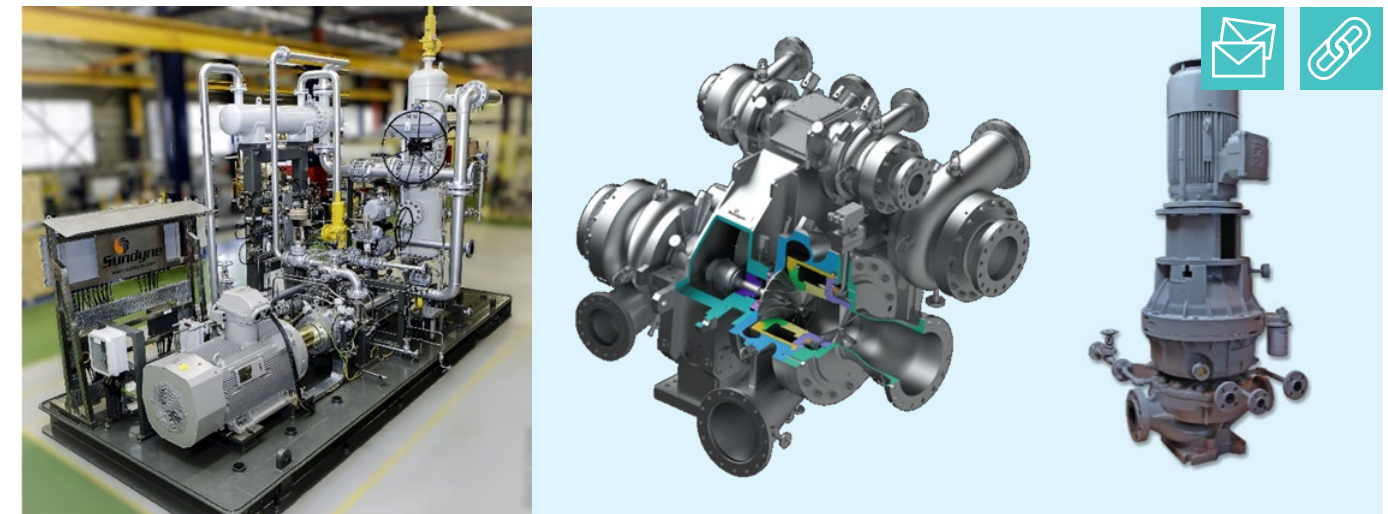
KEY DATA

TRL	9	
Target Industries	CO ₂ injection sites (incl. CCUS injection hubs), EOR wells, Well design companies	



HONEYWELL SUNDYNE

INTEGRALLY GEARED MULTISTAGE CO₂ AND sCO₂ COMPRESSOR



SUMMARY

Honeywell Sundyne is a global manufacturer of precision-engineered integrally geared centrifugal pumps and compressors, leakage-free magnetic drive centrifugal pumps, and diaphragm compressors for use in energy, chemical, and industrial applications. Building on over 75 years of experience in supplying highly reliable, safe, and efficient packages, Sundyne is now focused on delivering the rotating equipment needed for carbon capture, utilisation, or storage projects.

Honeywell Sundyne offers a fit-for-purpose CO₂ compressor package designed to meet the techno-economic needs of the carbon capture market. Our centrifugal compressor design includes all process & auxiliary systems. Sundyne offers this package in modules shipped ready for operation, or the package can be engineered-to-order to meet any site-specific needs.

BENEFITS

- **Centrifugal Design:** Range from 100 to 22,000 m³/h combining 99.7% reliability and minimum emissions down to zero leakage
- **High Efficiency:** Customised rotating speed for each impeller, intercooling between each stage, and variable inlet guide vane (IGV) control
- **Compact Footprint:** High-speed technology and modularised arrangement of compression package
- **Lead Time and Installation:** Standardised product offering specific to CO₂ to reduce lead time, site works, and enable repeated success
- **Demonstrated Performance:** Dedicated test bench for supercritical CO₂ at Sundyne's factory
- **Comprehensive OEM:** Sundyne's product portfolio offers the unique capability to meet all rotating equipment needs for CCUS projects by providing both pumps and compressors

BENEFITS

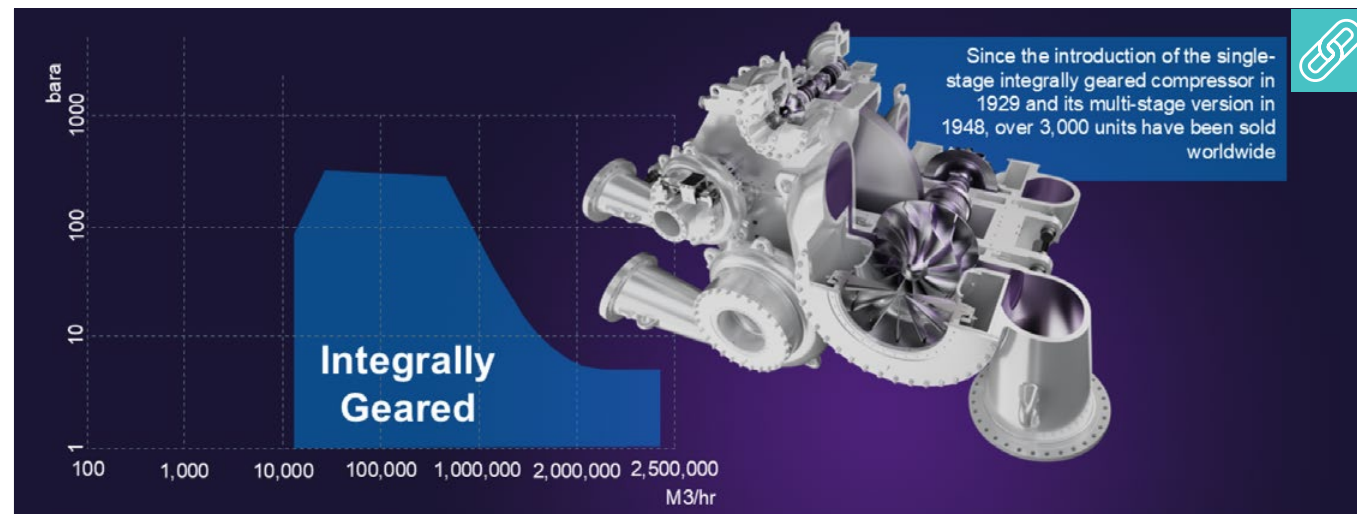
- **CO₂ compressor running since 2009** in Asia, large MEG unit in Petrochemical complex



- **1300 KTPA CO₂ HP Flash Gas Compressor** in Middle East, Blue Ammonia Production
- **Net-Zero Teesside Power CO₂ Compression for Power Plant carbon capture & storage**

KEY DATA

TRL	8 - 9	Flow Rate Range (tpd)	0 - 1,200	Working Pressure (bar)	250
Maximum Power (kW)	7,500	Maximum Flow (m ³ /h)	22,000	Reliability	API 617 Part 3
Number of Commercial Plants	19	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Refining & Chemicals, Natural Gas Processing, Hydrogen, Power-to-X, Power Generation, Waste-to-Energy				



SUMMARY

Siemens Energy integrally geared compressors provide a highly efficient and flexible solution for CCS CO₂ transport applications, particularly in multi-source pipeline networks. The integrally geared architecture enables multiple impellers operating at individually optimised speeds, delivering high aerodynamic efficiency across a wider operating range and accommodating variable flow conditions typical of CO₂ transport systems. The compact, multi-stage configuration significantly reduces footprint compared to conventional arrangements, making it well suited for constrained onshore transport stations and industrial hubs. High part-load efficiency supports dynamic pipeline balancing between capture sites and storage locations while maintaining stable discharge pressures required to sustain dense or supercritical CO₂.

BENEFITS

IGCs provide multiple impellers operating at optimised speeds, delivering high efficiency across a broad operating envelope, which is ideal for CCS transport.

Compact footprint for onshore transport stations:

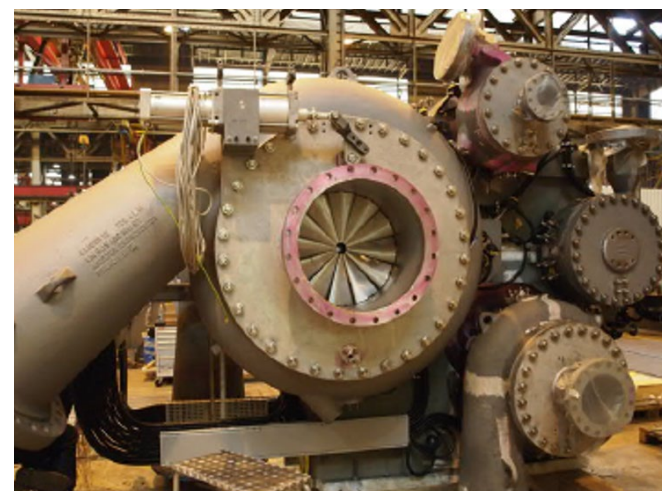
- Integrally geared design reduces overall equipment footprint.

Reduced lifecycle cost for CCS compression:

- High efficiency reduces energy costs
- Constant-speed operation streamlines system design by reducing overall equipment count, complexity, and lifecycle costs.
- Reducing the number of compressor casings minimises spare parts inventory and simplifies maintenance complexity.

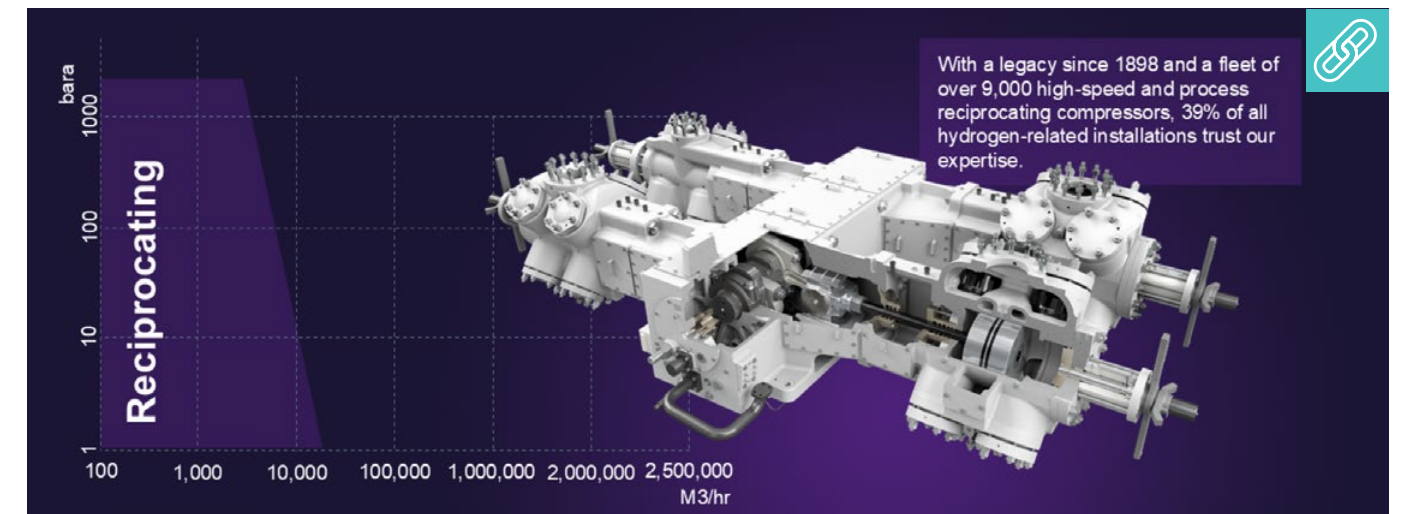
KEY PROJECT

- Deployed in capture service including Direct Air Capture (DAC), Blue H₂, Steel, Ethanol, Gasification.
- Over 25 units operating in CO₂ applications
- Discharge pressure up to 250 bar (3,675 psi)
- Available with electric motor, steam turbine, and gas turbine drivers



KEY DATA

TRL	9				
Target Industries	Oil and Gas; process industry's; CCUS for all industries				



SUMMARY

Siemens Energy's reciprocating compressors deliver high performance, efficiency, reliability, and low maintenance for challenging applications, including high-pressure CO₂. Designed to meet ISO 13631, with options for ISO 13707 or API 618 specifications, these compressors feature horsepower up to 7,800 HP (5,816 kW), rod loads up to 75,000 PSI (333 kN), speeds up to 1,500 RPM, and pressures up to 10,000 PSIG. The comprehensive Siemens Energy portfolio includes slow-speed process compressors and medium- to high-speed separable units, catering to both process industries and the growing decarbonization sector.

BENEFITS

High-efficiency for dense, high-pressure CO₂ service:

Siemens Energy reciprocating compressors are well-suited for CO₂ because they handle high molecular weight and dense phase gases efficiently, especially at elevated pressures used in:

- CO₂ pipeline transport
- Carbon capture and storage (CCUS) injection
- Enhanced Oil Recovery (EOR)

Lower lifecycle cost through efficiency and serviceability:

Benefits include:

- Reduced operating cost through efficient staging and compression control
- Long maintenance intervals and service programs
- Lifecycle optimization for large CO₂ infrastructure projects

Flexible, modular, application-specific design:

- Each reciprocating compressor system is:
- Custom-engineered per application
- Configured for specific CO₂ composition and pressure stages
- Available in process and high-speed configurations

KEY PROJECT

- Used in Capture, EOR, and Pipeline services
- Over 130 units operating in CO₂ applications
- Discharge pressure above 200 bar (2,900 psi)
- Over 450,000 HP of CO₂ total installed base
- Available with electric motor and gas engine drivers



KEY DATA

TRL	9				
Target Industries	Oil and Gas; process industry's; CCUS for all industries				



SUMMARY

Siemens Energy single-shaft centrifugal compressor technology for CCS storage is designed as an engineered solution that directly addresses the mechanical challenges of dense phase CO₂ compression, including high fluid densities, gas and dense phase behavior, and associated rotor dynamic stability requirements. The high-stiffness rotor system and advanced casing design ensure robust performance under demanding operating conditions, maintaining stability even under supercritical conditions. This solution is especially well suited for high-volume, high-pressure injection service in space constrained CCS hubs, where footprint efficiency and simplification are critical. With proven operation experience at pressures above 550 bar, the platform delivers the reliability and technical maturity required for large scale carbon storage networks. This includes multi-source carbon hubs and deep well injection projects, where financial risk reduction, long-term operability and continuous injection integrity are essential to project viability and regulatory compliance.

BENEFITS

High-pressure capability for reservoir injection

Optimised for large-scale, continuous CO₂ storage operations:

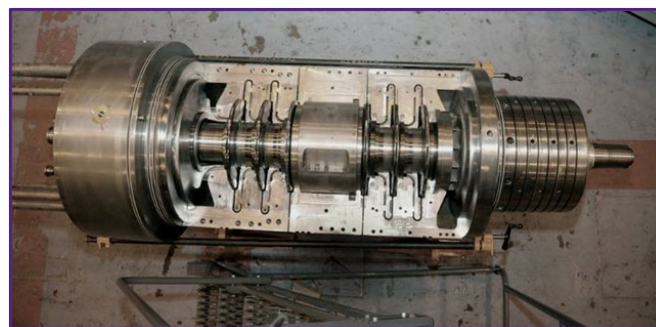
- Centrifugal compressors are designed for continuous duty and high throughput
- Single-shaft configurations are particularly strong for large baseload CCS injection trains.
- Long maintenance intervals and service programs
- Lifecycle optimization for large CO₂ infrastructure projects

Reduced footprint for storage hub integration:

- Provide compact train configuration
- Fewer major rotating elements
- Easier integration

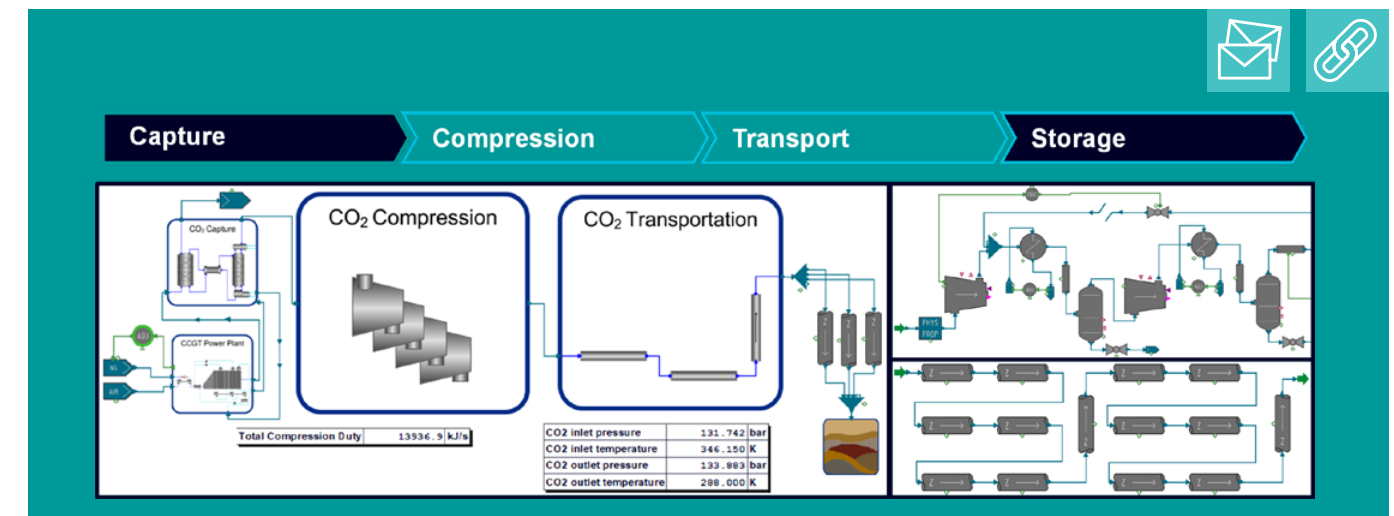
KEY PROJECT

- Used in capture and injection services
- Over 60 units operating in CO₂ applications
- Discharge pressure above 550 bar (8,000 psi)
- Available with electric motor, steam turbine, and gas turbine drivers
- On-shore and off-shore



KEY DATA

TRL	9				
Target Industries	Oil and Gas; process industry's; CCUS for all industries				



SUMMARY

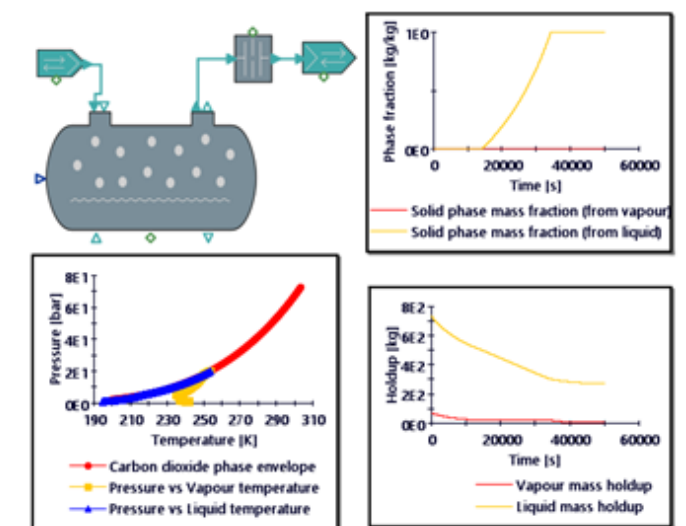
Siemens' gPROMS platform is a leading modelling environment for digital process design. It is used to map system interactions and predict process responses, also in transient scenarios. The platform enables users to optimise equipment and system designs, predict plant performance, and operate closer to true limitations.

gPROMS uses CCS-specific models, developed in collaboration with industry partners, to cover the entire CO₂ value chain – from the generating processes to capture (encompassing a wide range of technologies), compression, transportation, and storage. By factoring in uncertainty, e.g., gas composition, economic conditions, or equipment availability, gPROMS enables the quantification and management of risk. The platform offers reassurance to stakeholders throughout the entire CCS chain, allowing users to confidently navigate the road to decarbonisation.

BENEFITS

- Accurate physical property prediction.** Use thermodynamic packages specifically developed for handling CO₂ in vapour, liquid, solid, or dense phase
- Safety studies.** Monitor temperature and solid or acid formation in tanks and pipelines during compression, transportation, or depressurisation.
- Impurity detection.** Model the effect of impurities such as water, H₂S, or NO_x on acid formation.
- Routing analysis.** Decide the most efficient way of distributing CO₂ across a complex piping network.
- Integrated modelling environment.** One software platform to model different capture technologies and integrate them in the entire CCS value chain.
- Uncertainty analysis.** Quantify the effects of technological uncertainty and manage associated risk.
- Make your process economically viable.** Optimise a single process or an entire chain by maximising efficiency, reduce energy penalty, or minimising costs.

KEY APPLICATIONS



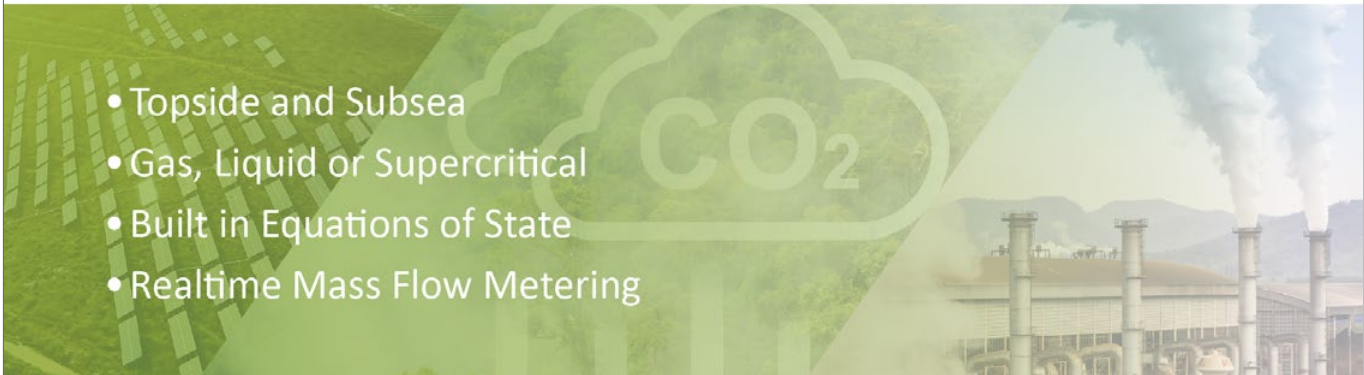
KEY DATA

TRL	9				
Target Industries	CCS hubs, technology providers, compression & transportation operators.				




CARBONSTREAM™

Flow Meters for Transmission and Storage of Carbon Dioxide



- Topside and Subsea
- Gas, Liquid or Supercritical
- Built in Equations of State
- Realtime Mass Flow Metering

SUMMARY

Solartron ISA is the leading supplier of wellhead flow meters to provide life of field solutions for the Oil & Gas Industry. From our headquarters in Shildon, Co. Durham, UK, we design, manufacture and support equipment used for flow measurement applications across the globe. Key applications include multiphase measurement of wet gas in conventional and unconventional fields as well as injection measurement for gas lift or water/inhibitor injection for subsea oil or gas developments. Most recently, Solartron ISA has introduced its range of Carbonstream CO₂ flow meters, operating in either gas or liquid single phase, or supercritical flow regimes. Carbonstream flow meters provide high accuracy and reliable flow measurement data within the harshest of remote, offshore and subsea environments. Carbonstream is supplied with differential pressure and temperature sensors and an onboard flow computer (with pre-programmed equations of state), providing a low-maintenance, flexible and space-saving solution for CO₂ measurement.

BENEFITS

TOPSIDE METER

- Plug and play with Hazardous Area Flow Computer or FloCalculator (ATEX or IECEx approved). Ultra-low power consumption – ideal for remote locations. Perfectly suited for unmanned facilities or solar powered applications with Ethernet and RS485 communication options.
- High accuracy, real time mass flow, differential pressure, pressure and temperature outputs. Low maintenance with no requirement for in line or product removal calibrations (Venturi DP technology with high performance instrumentation).



SUBSEA METER

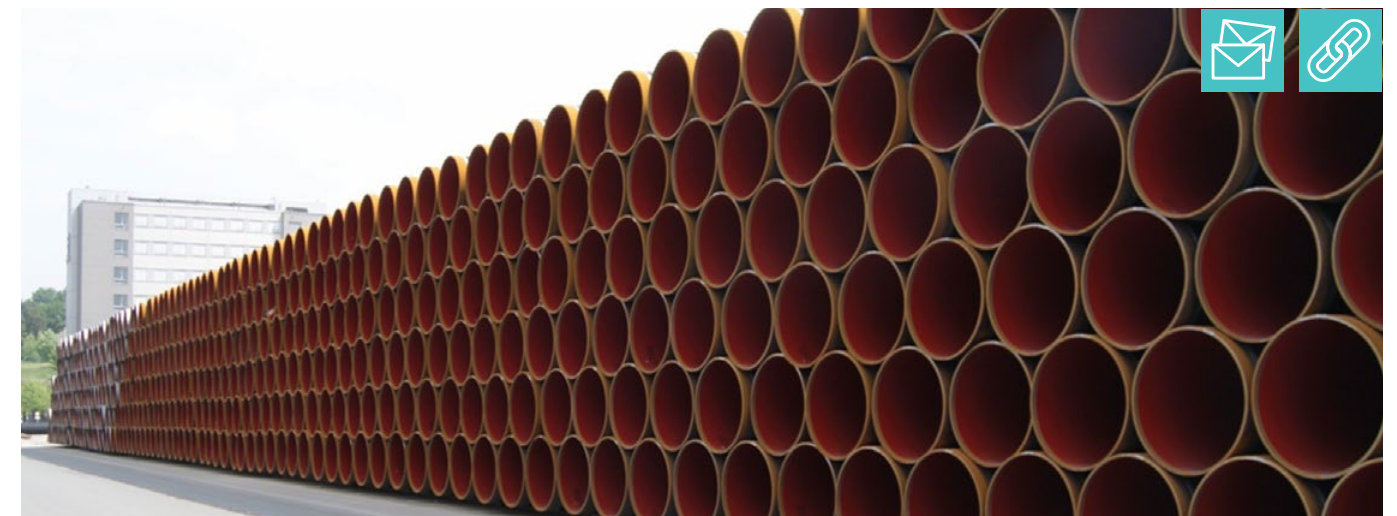
- Highly reliable flow meter designed for installation depths up to 3,000m. Carbonstream Subsea has fully redundant DP, P&T sensors and electronics providing a minimum design lifespan of over 25 years.
- The flow meter comes with built in equations of state which can be remotely updated during operational life as process conditions change. With low power requirements, the flow meter utilises SIFS Level 2 Canbus and Modbus (485) communication outputs.



KEY DATA

TRL	5	Material of Construction	Duplex or better	Design Life	>25 years
Typical Uncertainty (95% confidence)	Better than ± 2%	Turndown Typical	>8:1	Measurement Phases	Gas, liquid, supercritical
Target Industries	CO ₂ Transport and Storage – both gas and dense phase measurement				

CO₂-RESISTANT INTERNAL FLOW COATING FOR CCS PIPELINE TRANSPORT



SUMMARY

As Carbon Capture and Storage (CCS) projects scale globally, the reliable transport of captured CO₂ becomes a critical element of the emerging infrastructure. CO₂ pipelines operate under demanding conditions, including high pressure, varying temperatures, multi-phase CO₂ states, and the presence of impurities. Teknos has developed an internal epoxy flow coating technology designed to support the safe and efficient transport of CO₂ in pipeline systems. The coating provides a smooth internal surface that reduces hydraulic friction while maintaining chemical and mechanical stability under CCS-relevant conditions. The technology has been evaluated through systematic testing under gaseous, liquid, and supercritical CO₂ environments, including long-term exposure and operational stress scenarios. The results demonstrate stable coating performance, supporting qualification approaches for future CO₂ transport pipelines and contributing to reliable CCS infrastructure deployment.

BENEFITS

- **Enhanced durability under CO₂ transport conditions:** Designed to withstand demanding CO₂ environments, including multiple CO₂ phases and potential impurity exposure.
- **Improved flow efficiency:** The smooth internal coating surface reduces friction losses, supporting efficient CO₂ transport and improved hydraulic performance.
- **Potential pipeline design optimisation:** Reduced internal roughness can enable optimisation of pipeline design parameters, such as pipe diameter and wall thickness, while maintaining transport capacity.
- **Supporting reliable CCS infrastructure:** By combining chemical resistance, mechanical durability, and flow efficiency, the technology contributes to the safe and long-term operation of CO₂ transport pipelines.

KEY PROJECTS

- The technology has been evaluated through a structured technical investigation focusing on coating performance in CCS-relevant environments. Testing included exposure to gaseous, liquid, and supercritical CO₂ conditions, as well as operational stress scenarios representative of pipeline transport systems.
- The investigation assessed chemical resistance, mechanical stability, and coating integrity during long-term exposure and pressure-temperature variations. The results demonstrate stable coating behaviour and support qualification strategies for internal pipeline coatings in CO₂ transport infrastructure.
- These findings provide valuable technical data for pipeline developers, operators, and engineering companies involved in the design and deployment of CCS transport systems.

KEY DATA

TRL	8				
Target Industries	CO ₂ transport infrastructure, CCS / CCUS projects, Energy infrastructure, Industrial decarbonisation projects				

STORAGE



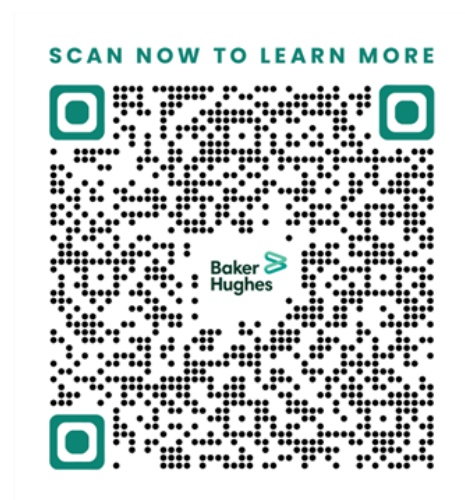


SUMMARY

CarbonEdge™ is Baker Hughes' risk-based digital platform for CCUS operations, connecting capture, compression, transport, injection and storage in a single, traceable system of record. It ingests real-time sensor and historian data and aligns it with engineering models to define operating envelopes and deliver exception-based alerts. A dynamic risk catalogue and audit trails support proactive integrity management and measurement, monitoring and verification (MMV). Modular deployment and open integration let projects start at pilot scale and expand across portfolios without vendor lock-in. Automated, audit-ready reporting packages streamline regulatory, tax and carbon credit submissions, reducing manual effort while improving confidence in CO₂ accounting. CarbonEdge helps operators de-risk performance, strengthen compliance, and accelerate decisions across the full CCUS lifecycle.

BENEFITS

- **Scalable and flexible deployment:** Modular, interoperable, and vendor-agnostic architecture that scales with project maturity and portfolio growth.
- **Accelerated carbon credit realization:** Automated workflows and audit-ready documentation reduce manual effort and help expedite verification and submission processes.
- **Improved safety and reliability:** Continuous monitoring, predictive analytics, and integrated safety protocols support safer operations and reduced unplanned downtime.
- **Lower operating cost:** Automation and edge-to-enterprise processing improve productivity and reduce total cost of ownership.



KEY DATA

TRL	7
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TECHNOLOGY DESCRIPTION

RISK-BASED DIGITAL PLATFORM FOR END-TO-END CCUS MMV

CarbonEdge™ is a modular, risk-based digital platform designed to support reliable measurement, monitoring, and verification (MMV) across the CCUS lifecycle. It connects surface systems (capture plants, compression, pipelines, and facilities) with subsurface storage monitoring and engineering models to create a unified, traceable view of operations. By combining real-time data ingestion with contextualization and analytics, the platform helps define and continuously monitor operating envelopes, identify deviations early, and guide response actions through exception-based workflows.

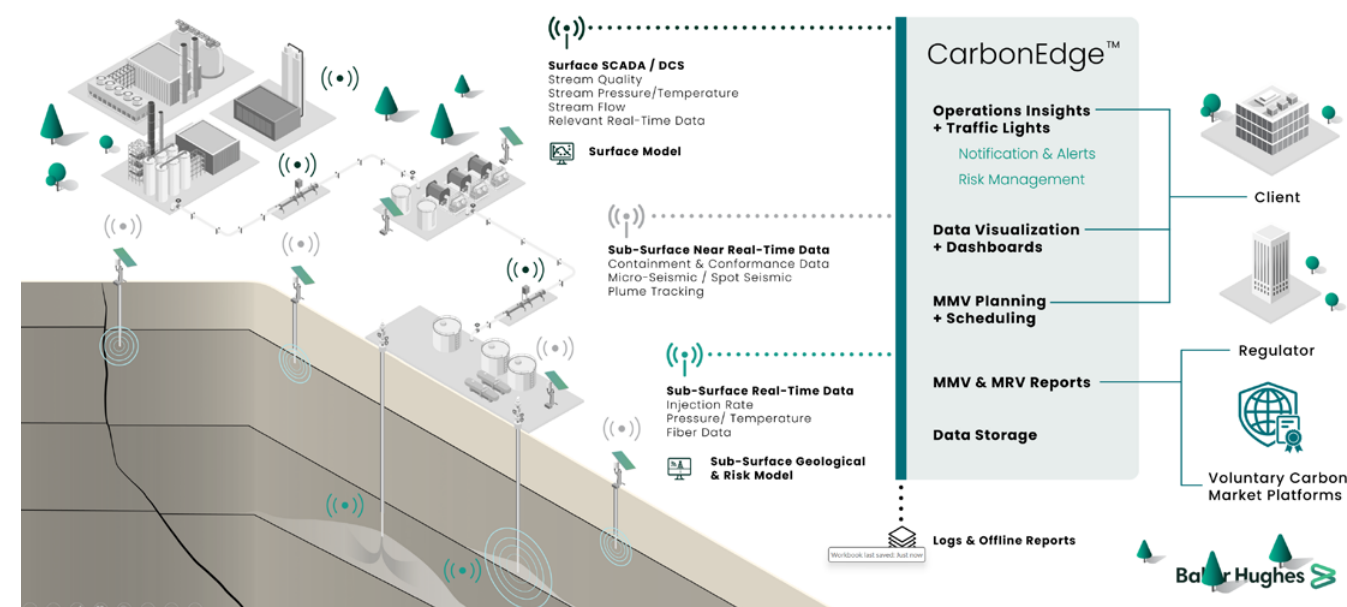
Data integration is delivered through an edge-to-enterprise approach. Data can be processed close to the asset for responsiveness and resiliency, while centralised services enable portfolio-wide governance, reporting, and analytics. CarbonEdge is designed to work with heterogeneous environments by integrating sensor streams, historian/SCADA data, engineering applications, and operational workflows. Persona-based dashboards translate this information into actionable insights for operators, integrity teams, and compliance stakeholders.

RISK-DRIVEN MMV EXECUTION AND SCALABLE COMPLIANCE ACROSS THE CCUS VALUE CHAIN

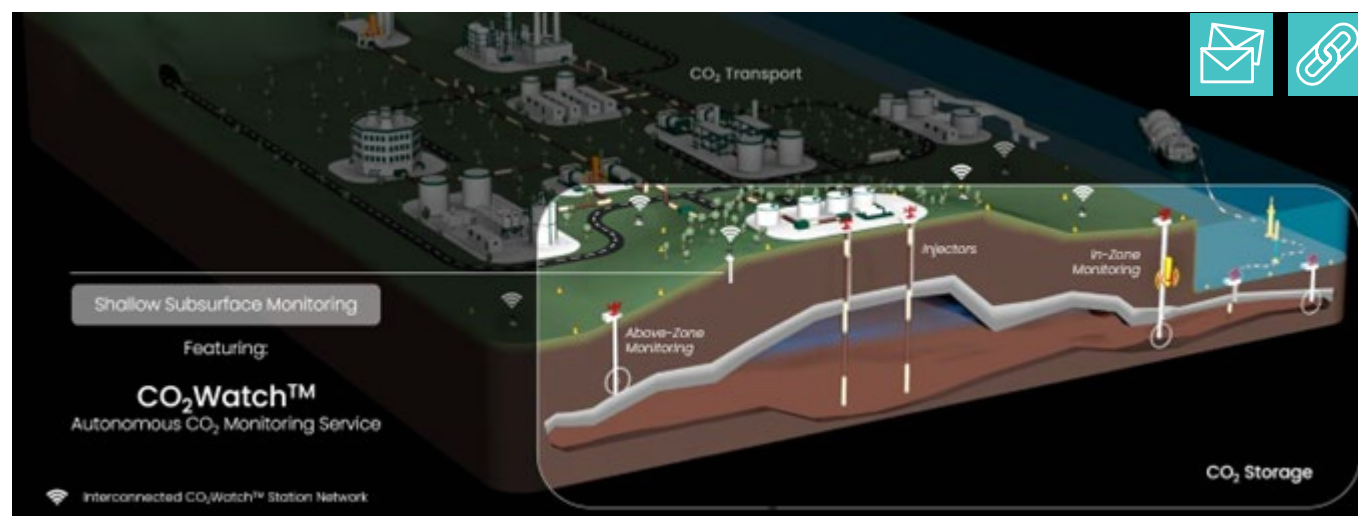
Risk management is supported through a dynamic risk catalogue that can be configured to align with project hazards, integrity threats, and compliance obligations. Users can set alarms and thresholds, link events to evidence, and maintain audit trails for key decisions. Predictive analytics and condition-based monitoring help reduce downtime and extend asset life by enabling proactive interventions.

For MMV planning and execution, CarbonEdge focuses on three operational objectives: capacity, injectivity, and containment. The platform supports continuous tracking of CO₂ movement and operational performance, providing traceability from capture through transport to injection and storage. Automated workflows and audit-ready documentation reduce manual effort, improve consistency, and help streamline regulatory, tax, and carbon credit reporting. The result is a scalable foundation that can start with pilots and expand to full deployments and multi-site portfolios, while maintaining secure access to trusted, high-quality data and clear accountability for reporting.

CarbonEdge: end-to-end digital solution for CCUS operations



- **Value chain coverage:** Capture • Compression • Transport • Injection • Storage (end-to-end)
- **Integration model:** Edge-to-enterprise; surface-to-subsurface "single pane of glass"
- **Data inputs:** Sensors, historian/SCADA, engineering models, operational workflows
- **Risk management:** Dynamic risk catalogue, configurable alarms, integrity/compliance monitoring
- **MMV enablement:** Automated CO₂ tracking, audit trails, evidence packs for reporting
- **Decision support:** Predictive analytics, operating envelopes, exception-based workflows
- **Deployment approach:** Modular, interoperable, vendor-agnostic integration
- **Reporting outputs:** Audit-ready regulatory, tax, and carbon credit documentation



SUMMARY

CO₂Watch™ is an autonomous, integrated CO₂ monitoring service designed to close the visibility gap between conventional 3D seismic surveys across the entire CCUS project lifecycle. It provides continuous plume mapping, targeted high-fidelity calibration points, microseismic monitoring, and shallow-subsurface environmental surveillance. The system deploys a network of onshore or offshore stations equipped with multi-physics sensing capability, delivering near-real-time CO₂ conformance and containment assurance. By combining ambient noise interferometry, focused seismic, and multi-layer data integration from reservoir to biosphere, CO₂Watch delivers early anomaly detection, operational decision support, and regulatory-compliant datasets. The technology reduces OPEX, accelerates model validation, enhances stakeholder transparency, and strengthens risk mitigation across injection and post-injection phases. Its autonomous operation and modular deployment make it suitable for large-scale storage projects seeking a cost-efficient, high-frequency monitoring solution.

BENEFITS

- **Continuous, Integrated Monitoring:** CO₂Watch provides 24/7 plume tracking, microseismicity, and environmental signals across the reservoir, subsurface, and near-surface layers, removing the temporal blind spots of conventional periodic 3D seismic.
- **Lower OPEX and Faster Insights:** Autonomous stations reduce mobilization costs and shorten the time between acquisition and interpretation, enabling more cost effective MMV execution.
- **Conformance & Containment Verification:** High fidelity focused seismic anomaly detection, and multi physics integration provide early warning of deviations from reservoir simulation forecasts.
- **Regulatory & Stakeholder Confidence:** Integrated datasets, transparency, and continuous monitoring indicators support Class VI compliance, community reassurance, and investor risk reduction.

KEY DATA

TRL	7 - 8
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BENEFITS

- **Project One:** Onshore CCUS monitoring in Australia. This project focuses on the passive seismic monitoring component of the CO₂Watch™ solution. Deployed in 2018 and expanded since, this project consists in 25 stations spread around the field to monitor the containment of the injected CO₂.
- **Project Two:** 2 onshore CCUS sites to be monitored. Currently in early stage (Baseline), the surveillance would focus both on the CO₂ containment and conformance with an advanced set of equipment (atmospheric, subsurface seismic sensors).

TECHNOLOGY DESCRIPTION

CO₂Watch™ is an autonomous, multi-physics monitoring system designed to support robust MMV (Measurement, Monitoring, and Verification) programs for CO₂ storage projects. Traditional plume-tracking approaches (particularly repeated 3D seismic) are constrained by high mobilization cost, long cycle times, delayed results, and limited temporal resolution. CO₂Watch addresses these gaps by providing continuous mapping, shallow-subsurface surveillance, and targeted seismic verification using a network of permanent or semi-permanent monitoring stations.

SYSTEM ARCHITECTURE AND OPERATING PRINCIPLE

At the core of CO₂Watch™ is a distributed network of shallow-borehole stations, each equipped with sensors spanning multiple depth intervals, from the surface (or seabed) to 70-200 meters. The wells are PVC-lined rather than steel-cased to ensure low-cost installation, minimal environmental footprint as well as improved seismic sensitivity. Each station autonomously digitises and transmits data over 4G networks with full uplink and downlink capability. Onshore systems rely on solar-powered units, while offshore networks incorporate buoy-mounted communication modules and seabed sensor packages.

This customizable system can collect and integrate data from several “physics domains,” including seismic ambient noise, microseismic events, soil gas, groundwater quality, seabed flux (for offshore), and atmospheric CO₂. This enables a holistic view spanning the entire zone of interest from the injection reservoir (via indirect seismic inference) to the near-surface environment where CO₂ containment concerns typically focus.

CONFORMANCE MONITORING

CO₂Watch™ delivers continuous, low-resolution plume mapping using ambient noise interferometry, a passive seismic technique that reconstructs seismic wavefields from natural and industrial background noise. This allows ongoing detection of changes in seismic velocity and attenuation, which are properties directly affected by CO₂ saturation and pressure variations. These continuous maps serve as the “always-on” monitoring layer in between larger-scale seismic surveys.

To reinforce and calibrate these continuous outputs, CO₂Watch incorporates high-fidelity measurements acquired on demand using advanced seismic methods such as focused active-source surveys. These verification points are compared against reservoir simulation forecasts. If deviations occur, CO₂Watch automatically flags potential conformance issues and triggers model reassessment. The combination of continuous mapping plus periodic high-resolution checks offers a scalable, risk-driven monitoring methodology.

CONTAINMENT MONITORING

Containment assurance is supported through microseismic monitoring and, in offshore contexts, seabed CO₂ flux channels. Each station captures microseismicity that may relate to pressure buildup, fault activation, or wellbore/caprock integrity issues. Abnormal seismic patterns or anomalous readings trigger alerts, enabling operators to act before any containment loss evolves into a material incident.

Offshore sites further benefit from coupling CO₂Watch with seabed CO₂ detection (e.g., Sentinel systems), enabling simultaneous monitoring of plume migration and potential leakage pathways. This union provides full depth environmental coverage, reinforcing containment verification from reservoir to seafloor.

ADVANCED SEISMIC TECHNOLOGIES WITHIN CO₂WATCH

The system leverages several novel seismic technologies:

- **Ambient-Noise Seismic Interferometry (ANSI)** –Extracts seismic attributes from ambient noise without the need of a seismic source to track CO₂ induced changes in velocity and attenuation. Surface waves captured by ANSI are sensitive to saturation changes and sample broad areas of the reservoir region.
- **Targeted CO₂ Detection** – A cost efficient “CO₂ detector” for precise locations in the subsurface using only one active seismic source and one receiver.

These seismic capabilities enhance both conformance and containment, delivering multi resolution insights without the cost of frequent full-field active seismic campaigns.

LIFECYCLE INTEGRATION AND REGULATORY ALIGNMENT

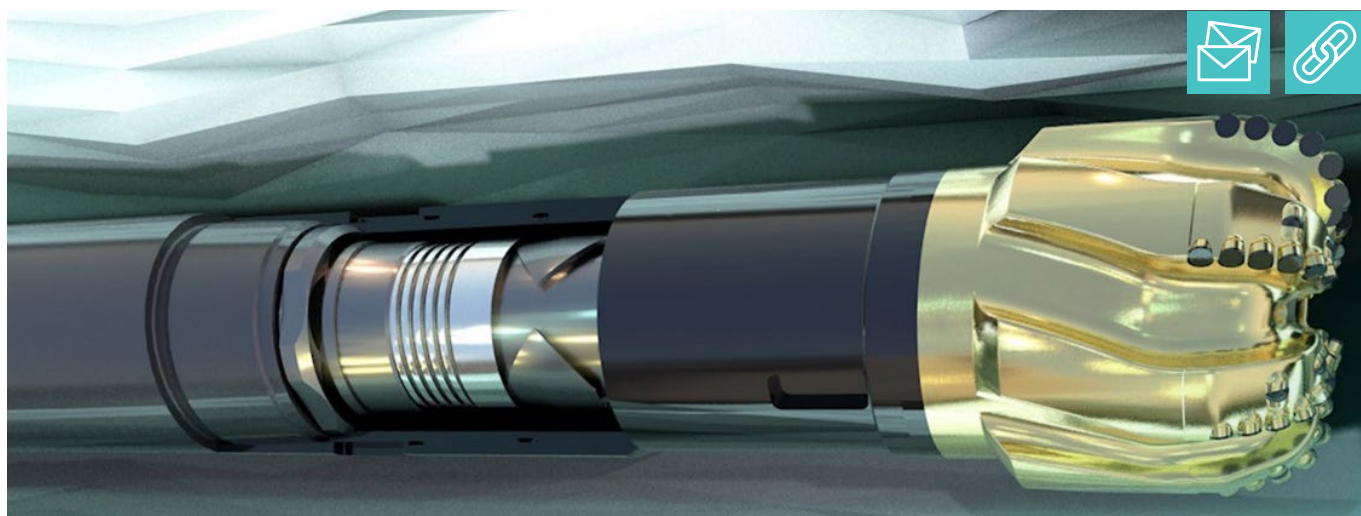
CO₂Watch covers the full CCUS project lifecycle, from baseline acquisition to injection, closure, and post injection site care. It provides repeatable time lapse datasets suitable for regulatory reporting and risk management frameworks.

The system’s ability to integrate data across depth horizons ensures compliance with expectations for multi domain surveillance, while its autonomous nature reduces human presence and helps maintain consistent data quality across decades-long monitoring periods.

OPERATIONAL AND ECONOMIC ADVANTAGES

Compared to traditional monitoring technologies, CO₂Watch reduces mobilization needs, offers faster turnaround times, and lowers overall OPEX. Its modular design allows operators to scale the monitoring network according to project size and risk distribution. The continuous data feed enables predictive, rather than reactive, reservoir management, supporting early intervention and more informed operational decisions.

Baker Hughes **BAKER HUGHES** **CORTIVA™ CORING SYSTEM**



SUMMARY

Seal integrity is key to the success of any geological sequestration project. Along with the logging and measurement technology, taking physical cores is one of the best ways to characterise these structures. Core samples retrieved with traditional coring systems can often break and become jammed or lost in a hole. Jams and poor core quality can lead to re-runs that incur significant additional cost. The CORTIVA™ coring system improves efficiency and de-risks core recovery through the use of a fully-closed and jam-mitigating core barrel. By combining these key features, CORTIVA™ shortens the time and costs required to cut and retrieve a core sample by ensuring the whole core section is retrieved safely in a single trip.

BENEFITS

- Core longer even in fractured or other jam-prone formations by neutralising up to two jamming events
- Full-closure catcher completely seals inner tube to prevent loss even when the core is unconsolidated
- The HT30™ Max core barrel system delivers larger, longer samples than other systems
- Unobstructed ‘slick’ entry eliminates risk of jam at core’s centre

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

Core jamming during coring operations and/or loss of friable core material during trip-outs leads to additional coring runs, resulting in increased rig time and cost. Jams that occur inside the inner tube of a core barrel can often be mitigated by certain jam-mitigation techniques, allowing coring to continue. However, jams that occur in the core catcher, provoked by the mechanical interaction of the core with the catcher mechanism, would not be mitigated by such anti-jamming technologies. These typically occur in formations that are a mixture of fractured (jamming-prone) and friable rock. This type of complex, coring application demands technologies beyond what is currently available in the market. Competitors have either standalone jam mitigation systems for jam-prone formations, or full-closure catcher systems for unconsolidated/friable rock.

Baker Hughes combines the benefits of various technologies to improve the efficiency of coring operations in complex formations. With its CORTIVA™ full-closure system with jam mitigation technology, Baker Hughes combines the JamBuster™ jam mitigation coring system

and the HydroLift™ full-closure catcher system—industry standards for jam mitigation and recovery of friable rock to improve the efficiency and recovery of high-quality core in complex fractured and friable formations.

The Baker Hughes patented JamBuster™ system neutralises jams inside the inner tube through concentric inner core barrel sleeves that automatically telescope if a core becomes jammed in the core barrel, allowing coring to continue without interruption. The HydroLift™ system efficiently recovers high-quality, intact core samples collected in soft, or unconsolidated formations. The system’s slick, unobstructed entry eliminates the risk of jamming at the core catcher for the incoming core, while the full closure mechanism secures the core, thus preventing loss of friable/loose formation during trip-out.

The CORTIVA™ full-closure system with jam mitigation technology is also integrated with HT30™ Max core barrel system to deliver an unmatched core size. It also reduces core acquisition costs by acquiring longer, high-quality core samples per run, even in harsh environments.



Baker Hughes **BAKER HUGHES** **HEAVY METAL™ SWARF-FREE SECTION MILLING**



SUMMARY

Many of the world's most promising geological targets for large scale CO₂ storage exist in and above late-life and depleted hydrocarbon plays. Late-life fields often have many existing wells that penetrate the target storage geology and can pose seal integrity risks. Baker Hughes offers advanced plug and abandonment solutions to ensure that the integrity of aging infrastructure is not compromised for the life of the sequestration project. During plug and abandonment operations, it is sometimes required to remove a section of the casing and adjacent cement sheath to expose the formation. This process is called section milling. Section milling operations provide an effective downhole seal during plug and abandonment by setting a cement plug directly across the geologic seal - removing metal tubulars and potentially failed cement. However, section milling operations can be challenging, which makes its large scale use less appealing. Additionally, conventional section milling requires specialised equipment to handle the cuttings or 'swarf' that are brought to surface during milling operations. HEAVY METAL™ swarf-free section milling system increases the efficiency while decreasing the cost and carbon footprint of section milling operations. By improving the performance and economics of section milling operations, wells can be plugged more effectively and with less long-term risk of seal integrity issues.

BENEFITS

- Provides a robust rock-to-rock barrier
- Reduces cost and time associated with section milling
- Decreased health, safety & environment (HSE) risk for personnel on site
- Reduces requirements for rig capability, swarf handling, and other specialised equipment
- Eliminates the need for swarf cleaning, transport, and disposal

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

Section milling is a conventional method for casing removal during plug and abandonment (P&A) operations where annular well integrity is compromised or questioned. The removal of casing by milling a window provides full access to the virgin formation, enabling placement of a rock-to-rock barrier. Swarf is an unavoidable by-product of section milling, generating thousands of pounds of these sharp metal cuttings that have to be removed from the well.

Retrieving and handling the swarf is a time-consuming and costly process that poses additional health, safety, and environmental (HSE) risks, and oftentimes operators will opt for less reliable options, such as perf-and-wash, just to avoid swarf. Baker Hughes offers the HEAVY METAL™ swarf-free section milling service to provide a reliable solution without the negative side effects of swarf. It eliminates swarf to surface through a unique upwards milling process, depositing swarf deep in the rathole, while still enabling a secure rock-to-rock barrier. This unique service reduces time and costs in half, eliminating the need for swarf removal and the risks that swarf presents to people, equipment, and the environment. The bottomhole assembly (BHA) consists of multiple tools providing different functions to enable upwards section milling using normal right hand drill pipe connections without any rotation at surface. A torque isolator allows uninterrupted

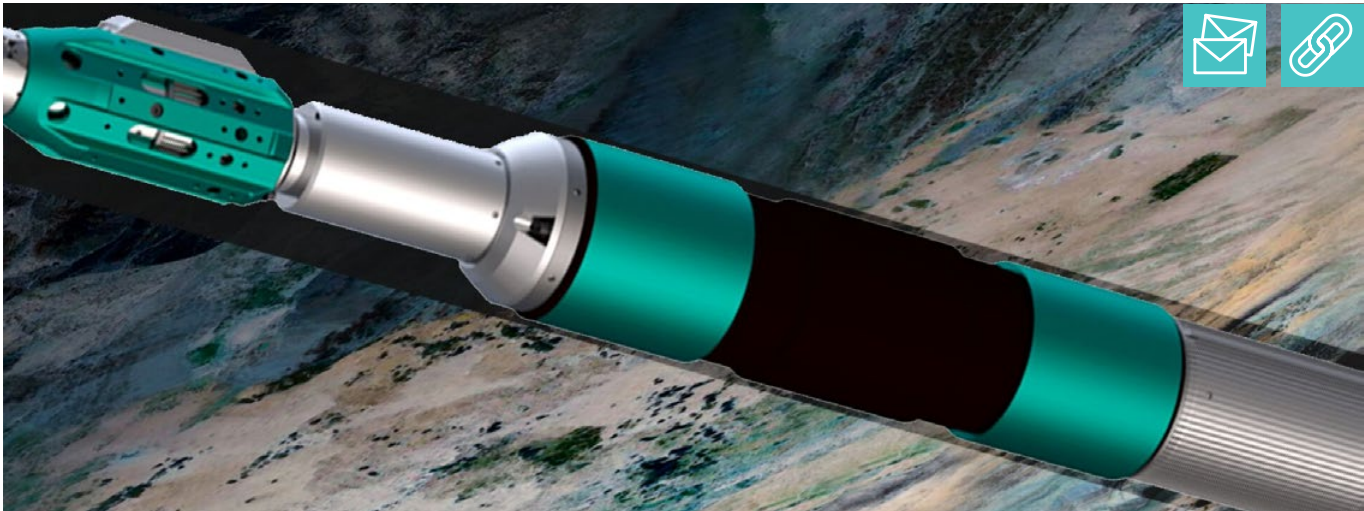
axial movement and continuously isolates reactive torque of the left-hand mud motor, while milling upwards. The mud motor requires circulation from surface and provides downhole left-hand rotation and torque to the section mill and auger. The system's section mill features upward-facing knives that utilise METAL MUNCHER™ advanced milling technology (AMT) carbide cutting structures and allow upward milling and reaming in one run—even in long laterals. The section mill cuts through the casing at the bottom of the window, mills upwards to the desired distance, and then reliably retracts its knives at the top of the window.

The auger continuously transports any swarf created from the window to the bottom of the rathole, leaving it all in the well, while providing a window free of swarf. Because the swarf does not have to be circulated to surface, there is no need to change over to a high viscosity milling fluid, saving additional cost and logistics.

A Baker Hughes dedicated project management team can oversee the entire P&A project—from planning phase through final abandonment— all with a strong focus on safety and efficiency. With a single point of contact, customers achieve a simplified, streamlined process that helps reduce time and minimise risk.

BAKER HUGHES

MAXIMA FRAC STRADDLE PACKER



SUMMARY

The Maxima™ Frac straddle packer pushes reservoir testing further than ever, delivering high-confidence sampling and micro-frac performance in ultralow-mobility and extremely hard rock formations. Its dual inflatable elements isolate a precise 1-meter interval, while industry-leading pressure capability—up to 10,000 psi—opens access to reservoirs unreachable with conventional tools. Fully compatible with the RCX™ platform, Maxima Frac enables high-pressure injection for fracture propagation studies, deep transient analysis up to three times farther from the wellbore, and reliable sampling in tight formations. With proven results in CCUS caprock integrity and seal verification, its active hydraulic retraction system ensures safe retrieval and dependable performance in the most challenging environments.

BENEFITS

- Combines fully and easily with all RCX service modules
- Achieves objectives in challenging high-solids and LCM mud thanks to full-area filters
- Accurately monitors flowing temperature of the fluid with in-line temperature probe
- Enhances formation pressure accuracy with an in-line quartz pressure crystal and zero depth offset
- Provides high deployment versatility with standard elements that cover both water- and oil-based mud systems

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

The Maxima™ Frac straddle packer module is the latest addition to the Baker Hughes fluid characterization and testing portfolio. Featuring two custom-designed inflatable packer elements, the packer isolates a 1-meter zone of the borehole, enabling reliable testing and sampling in ultralow mobility and micro-frac in extremely hard rock formations.

Fully compatible and combinable with all service modules in the Reservoir Characterization eXplorer™ (RCX™) service platform and with a market- leading 10,000-psi differential pressure working limit in 8 1/2-in. hole sizes and 6,000 psi in 12 1/4-in. hole, the Maxima Frac straddle packer expands the range of testing in reservoirs that were previously inaccessible to conventional testing tools. The active hydraulic retract mechanism ensures the elements are retracted fully, ensuring safe pull out of hole even after losing communication to the tool.

FORMATION FLUID SAMPLING IN LOW-MOBILITY ROCKS.

The straddle packer’s highly durable mandrel assembly reliably handles high differential pressures, allowing it to collect formation fluid samples from low-mobility rocks.

PROPAGATION STUDIES OF INDUCED FRACTURES IN HARD ROCK.

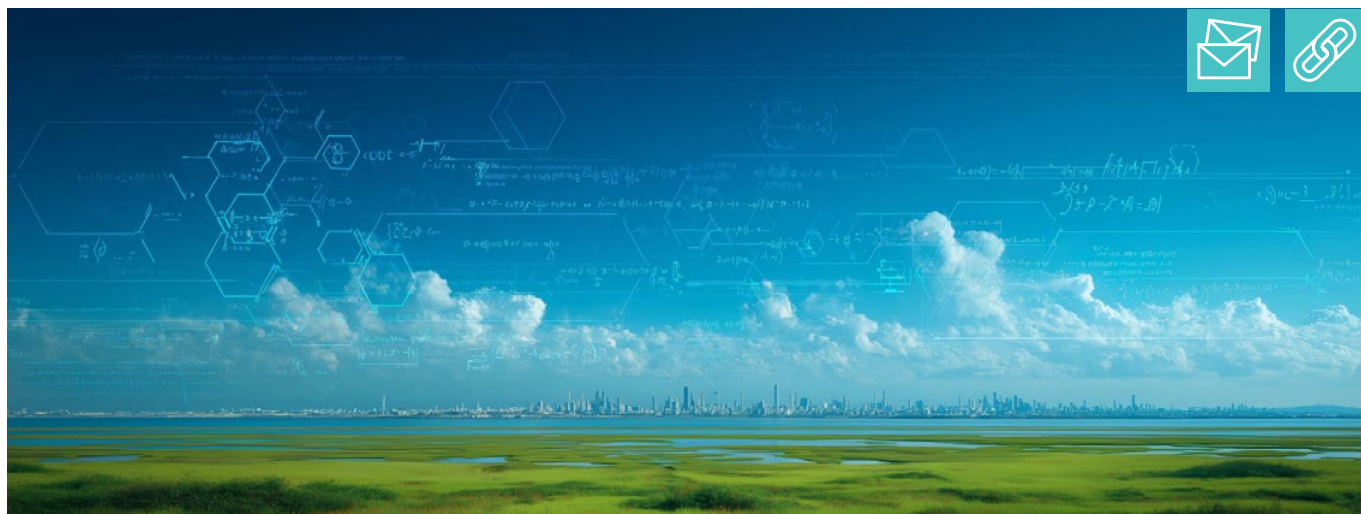
The Maxima Frac straddle packer allows injection pressures of 10,000 psi over the hydrostatic pressure in 8 1/2-in. hole sizes and 5,700 psi in 12 1/4-in. hole. As a result, it allows fracturing of much harder rock formations during micro-frac testing than previous generations of tools. Operators can confidently determine yield strengths and track fracture growth in extremely hard rock reservoirs.

DEEP TRANSIENT ANALYSIS FARTHER FROM THE WELLBORE.

The Maxima Frac straddle packer’s ability to handle high pressure differentials helps ensure higher flow rates for deep transient analysis. Combining the straddle packer with high-rate pumps increases the depth of investigation for deep transient analysis by up to three times compared to conventional analysis tools.

With successful application on caprock integrity evaluation to ensure long- term CO₂ containment as well as seal verification and fracture propagation studies in CCUS projects Maxima Frac delivers results where others fall short.

Baker Hughes BAKER HUGHES MICROSEISMIC MONITORING



SUMMARY

Microseismic monitoring plays a key role for safe and efficient Carbon Capture and Storage (CCS), by providing continuous insight into subsurface integrity during and after CO₂ injection. By detecting very small seismic events, it helps to track stress changes, identify fault reactivation, and highlight deformation that could create potential pathways for CO₂ or fluid migration. Seismic activity in the caprock is an essential indicator of containment performance, while events at reservoir scale can reveal how injection operations interact with existing geological structures. CCS-focused microseismic solutions typically combine tailored network design, surface and borehole sensors, autonomous long-term operation, and daily data processing. Advanced visualization, correlation with injection pressure and flow rates, and automated alert systems enable operators to proactively manage seismic risk, support regulatory compliance, and safely maximise storage capacity over the asset lifetime.

BENEFITS

- **Caprock integrity assurance:** Detects micro-events within the caprock that may indicate evolving stress conditions or early signs of containment loss, supporting long-term CO₂ confinement.
- **Fault and fracture monitoring:** Identifies fault reactivation or fracture growth induced by CO₂ injection, helping assess leakage risk and subsurface integrity in near-real time.
- **Proactive risk management:** Enables early detection of increasing seismic trends, allowing operators to adjust injection rates and pressures before seismicity escalates.
- **Regulatory compliance and storage optimization:** Supports permitting and public confidence while helping safely maximise injection pressure and storage capacity within defined safety limits.

KEY PROJECTS

- **Microseismic feasibility assessment:** Effective network design and appropriate technology selection are critical to building a fit-for-purpose monitoring solution. Several studies have been conducted across Europe, including detailed benchmarking of available technologies and optimised sensor-placement strategies to ensure reliable detection and overall performance.
- **CCUS monitoring in APAC:** Monitoring for this site was developed and progressively optimised in response to evolving challenges. Initially based on surface sensors, the network gradually expanded into an integrated, multi-scale system combining surface, borehole, and shallow sensors, complemented by fiber-optic technologies.
- **Advanced monitoring solutions:** To support holistic subsurface surveillance, Baker Hughes has developed an integrated approach combining multiple services, from passive seismic monitoring (microseismic) to atmospheric sensing, with provisions for advanced capabilities such as active seismic surveys and groundwater monitoring.

KEY DATA

TRL	9	Number of Pilot Plants	0
Number of Commercial Plants	28	Modular (Y/N)	Yes
Target Industries	CO ₂ Storage Site Operators and Developers		

TECHNOLOGY DESCRIPTION

Microseismic monitoring is a proven geophysical technology that provides continuous, high-resolution insight into subsurface behavior during CO₂ storage and Underground Gas Storage (UGS) operations. By detecting and analyzing very small seismic events that are not felt at the surface, it enables operators to assess reservoir response to injection and withdrawal, verify containment, and manage both physical and reputational risk over the full lifecycle of the asset.

In CO₂ storage applications, microseismic monitoring plays a critical role in verifying the integrity of the storage complex. Seismicity within the reservoir or caprock can indicate stress changes linked to pressure buildup, fault reactivation, or fracture growth. Early detection of these signals helps determine whether injected CO₂ remains securely contained or if preferential migration pathways may be developing. Event locations and temporal trends also provide insight into how injection pressures interact with faults and structural features, supporting safe operating limits and long-term storage assurance.

A complete microseismic monitoring solution typically consists of three integrated stages: network design, installation and maintenance, and data processing and reporting. During the network design phase, regulatory requirements, geological conditions, operational objectives, and logistical constraints are evaluated. Advanced modeling is used to design a cost-effective network capable of meeting sensitivity and location accuracy requirements. Depending on monitoring objectives - fault detection, cap-rock integrity assessment, or reservoir-scale surveillance - networks may include surface sensors, shallow buried sensors, borehole geophones, or hybrid configurations.

Installation and maintenance focus on deploying robust instrumentation, designed for long-term, continuous operation. Systems are typically autonomous, powered by solar energy, and connected via cellular or satellite communications, minimizing site visits. Hardware is selected for high reliability and low maintenance, allowing multi-year monitoring with minimal operational burden. maintenance, allowing multi-year monitoring with minimal operational burden.

Microseismic data are processed continuously by dedicated expert teams and delivered through secure web-based platforms. Microseismic data are processed continuously

by dedicated expert teams and delivered through secure web-based platforms. Operators can visualise seismicity in 2D and 3D alongside well trajectories, formation boundaries, and infrastructure. Seismic event trends can be correlated with injection pressures, flow rates, and operating schedules to identify causal relationships. Statistical analysis tools support the interpretation of seismic patterns, while automated system-health checks ensure data quality and network performance. Statistical analysis tools support the interpretation of seismic patterns, while automated system-health checks ensure data quality and network performance.

Automation can strengthen monitoring through 24/7 alerting systems, such as traffic-light protocols, which notify operators when predefined seismic thresholds are exceeded. Automation can strengthen monitoring through 24/7 alerting systems, such as traffic-light protocols, which notify operators when predefined seismic thresholds are exceeded. Machine-learning-based forecasting tools can also be applied to assess short-term seismic risk, supporting proactive decision-making during sensitive operational periods. Machine-learning-based forecasting tools can also be applied to assess short-term seismic risk, supporting proactive decision-making during sensitive operational periods.

Beyond technical assurance, microseismic monitoring offers significant commercial and regulatory value. Regulators increasingly require site-specific seismic monitoring for CO₂ storage and UGS projects, and proactive deployment can facilitate permitting and approval processes. Long-term seismic records help differentiate induced seismicity from natural background events, protecting operators from unjustified claims and public concern. Over time, demonstrated low seismic response can support arguments for higher injection pressures or expanded storage capacity, delivering value that far exceeds the cost of monitoring.

Microseismic monitoring is a fundamental component of safe, compliant, and optimised CO₂ and underground gas storage operations. Microseismic monitoring is a fundamental component of safe, compliant, and optimised CO₂ and underground gas storage operations. It provides early warning of subsurface risks, supports containment assurance, strengthens stakeholder confidence, and helps operators maximise asset value while maintaining the highest standards of subsurface integrity.

Baker Hughes **BAKER HUGHES** **PERMASET ULTRA™ CEMENT SYSTEM**



SUMMARY

Drilling exposes different geologic features and zones of the reservoir. During well construction, casings and liners are cemented in place to create a barrier between the wellbore and formation, allowing the operator to isolate a specific zone of the reservoir for production or injection.

The PermaSet Ultra slurries are fit-for-purpose, corrosion-resistant cement systems designed primarily for carbon dioxide (CO₂) and hydrogen sulfide (H₂S) environments. They are used in primary and remedial cementing operations. They are compatible with most Baker Hughes additives and can be designed for use in virtually any well condition anywhere in the world. PermaSet Ultra cement slurries are part of the Baker Hughes Set for Life family of cement systems that isolate and protect the targeted zone for the life of the well. These slurries can be blended with other systems in this family to help ensure long-term zonal isolation. Baker Hughes solves cementing problems at the wellhead by taking CO₂- and H₂S-resistant cement systems out of the laboratory and into the real world.

BENEFITS

- Improves the cement's resistance to attacks from CO₂, H₂S, magnesium, and sulfate
- Zero portlandite content eliminates weak points and reduces carbonation.
- Delivers cement with lower permeability than conventional systems.
- Lower heat evolution during setting (less shrinkage and cracking)
- Provides minimal permeability and improved mechanical properties.
- Uses real-time well conditions to determine the final slurry composition.

APPLICATIONS

- Conventional primary and remedial cementing operations in CO₂ and H₂S environments
- Ideally suited to Carbon Capture and Storage Wells (CCS)
- Compatible with virtually all API and ASTM cements and most cement additives

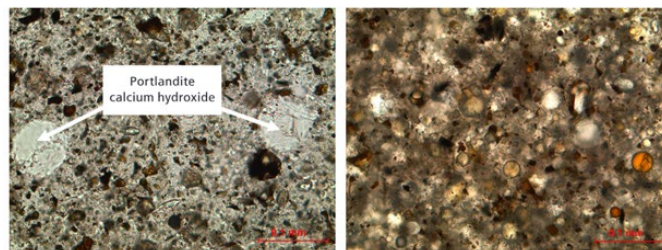


Fig.1: Thin sections of set samples at 15.8 ppg (1893 kg/m³) under a light microscope indicating absence of portlandite in PermaSet Ultra

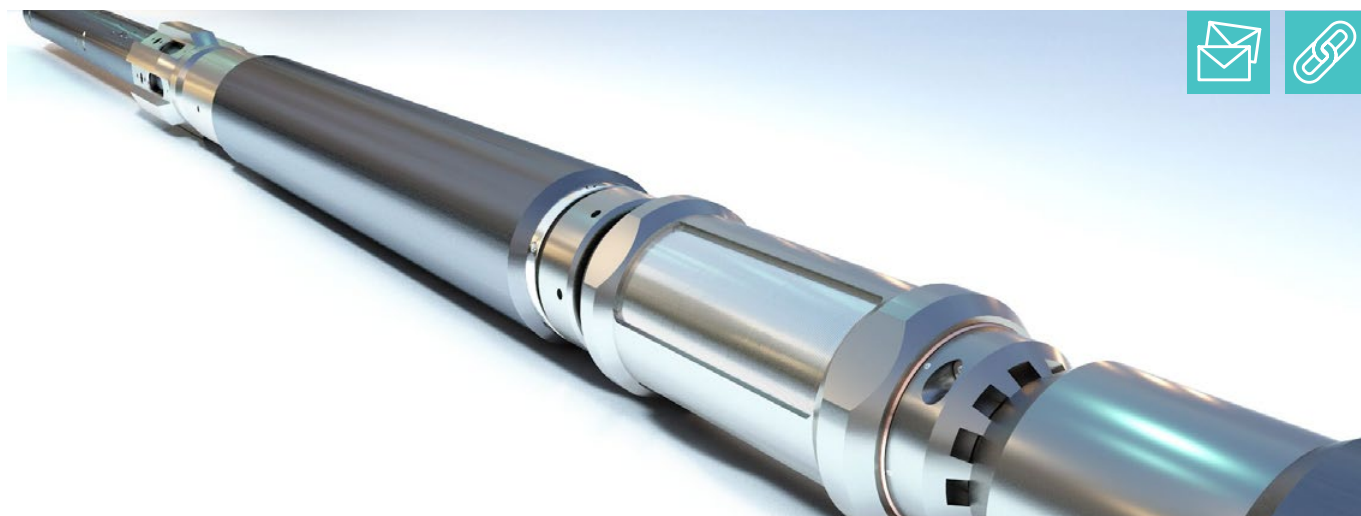
Achieving zonal isolation is important as not only can it be expensive to repair, but it can also lead to the uncontrolled release of CO₂ to other formations and/or the atmosphere. Additionally, lack of zonal isolation may cause well operational problems, such as sub-optimal injection, due to CO₂ migration into unintended formation intervals. In CO₂ injection wells, zonal isolation can be especially difficult to achieve and maintain due to the high pressure and corrosive nature of supercritical CO₂, which poses additional risks to cement integrity.

KEY DATA

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Baker Hughes **BAKER HUGHES** **RCX™ CHITON STRADDLE PACKER**



SUMMARY

The RCX™ CHITON straddle packer expands what's possible in challenging reservoirs, delivering safer, more reliable sampling and testing. Its active hydraulic retraction system and contra-wound elements prevent plastic deformation and sticking, ensuring smooth deployment. CHITON enables faster sampling in high-overbalance and ultra-low mobility environments and supports advanced diagnostics such as mini-DST and vertical interference testing. Higher injection pressure strengthens micro-frac performance in high-strength formations, unlocking a wider reservoir range. Fully compatible with the proven RCX platform, it adds flexibility with inline temperature and pressure sensors for accurate formation evaluation.

BENEFITS

- **Reduced deployment risk:** Active hydraulic mechanism, superior retraction capability, minimises plastic deformation, minimal inflation and deflation times, multiple settings in a single descent.
- **Enhanced drawdown capability:** Delivers faster sampling, operates in high-overbalanced environments, conducts Mini-DST and VIT testing.
- **Increased injection pressure:** Enhances Micro-FRAC testing capability, extends the range of formations that can be investigated
- **Improved flexibility and versatility:** Fully compatible with the RCX platform, inline temperature and pressure sensors

KEY PROJECTS

- **Onshore MENATI, EOR:** SPE-202600-MS: Five pilot wells in onshore Abu Dhabi were drilled to gather formation evaluation data and in-situ stress measurements to calibrate fracture gradients in reservoirs under water and CO₂ injection for enhanced recovery. Microfrac testing defined the injection-pressure limits for each flow unit and provided multi-well insights on maximum CO₂ injection pressures across different reservoir compartments.
- **KSA CCS:** IPTC-24673-MS/SPE-226994-MS/ IPTC-23877-MS/ARMA-19-1637. Downhole Microfrac measurements in carbonate and clastic reservoirs across the Middle East and North America provide in-situ calibration of maximum CO₂ injection pressure for CCUS. Comprehensive case study of 31 Microfrac stations assessing CO₂ caprock integrity across multiple flow units in a Saudi Arabia pilot well.

KEY DATA

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TECHNOLOGY DESCRIPTION

The RCX™ CHITON straddle packer expands the operating envelope of sampling and testing in challenging reservoirs and delivers a safer and more efficient deployment.

When sampling and testing within extremely complex reservoirs, there is always concern about deploying inflatable packers. Multiple settings can cause permanent deformations that lead to swabbing on the trip out of the well, while also increasing the risk of becoming stuck.

ENSURE SAFE AND EFFICIENT DEPLOYMENT

The RCX CHITON straddle packer includes an active hydraulic mechanism that enhances the elements retraction in addition to natural deflation. Additionally, the new design includes contra-wound elements delivering superior retraction properties with minimal plastic deformation. These features prevent any sticking or deployment risks.

ENHANCED DRAWDOWN CAPABILITY

The RCX CHITON enables faster sampling in high-overbalance and ultra-low mobility reservoirs within challenging wells due to its enhanced differential pressure capability. The advanced applications of mini-DST testing and vertical interference testing (VIT) allows for a better understanding of the reservoirs.

INCREASED INJECTION PRESSURE

The increased injection pressure enhances the micro-frac testing capabilities in high-strength formations. As a result, the ability to investigate an extended range of formations is possible—overcoming testing limitations in formations that can be incredibly difficult to fracture.

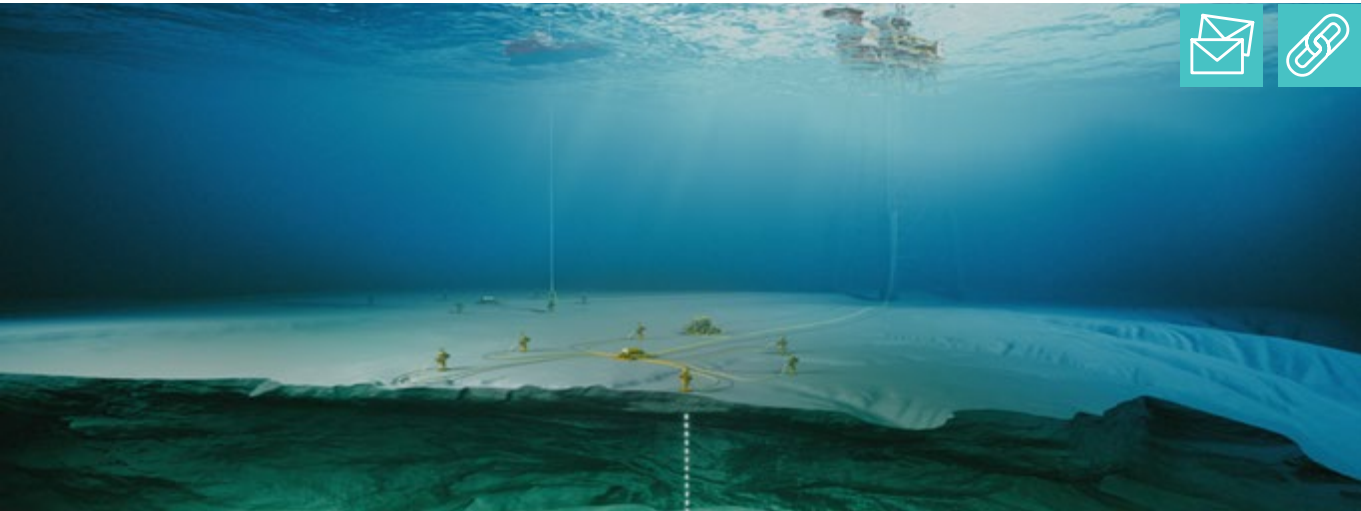
IMPROVED FLEXIBILITY AND VERSATILITY

The RCX CHITON can be combined with RCX platform, which has proven track record of reliable operations in hostile and challenging environments. Inline temperature and pressure sensors monitor the flowing temperature of the fluid and determine formation pressure with zero offset respectively.

Baker Hughes

BAKER HUGHES

SUBSEA CCS INJECTION SYSTEM



SUMMARY

Baker Hughes has over 60 years of subsea technology experience, with over 1600 subsea Trees installed worldwide. Baker Hughes first subsea CCS injection system was installed in 2007 on the Snohvit Field to dispose of CO₂ from the Snohvit LNG plant and is still injecting today. With the rise of global demand for CCS solutions, Baker Hughes has designed the CCS Subsea Injection System to meet the demand for disposing of post-combustion emissions safely and reliably.

Baker Hughes CO₂ subsea injection system leverages our wide portfolio of CCS transport and storage integrated system solutions. Compression and pumping; Flowlines and Risers; Manifold/Template structures, and the Subsea Tree and Wellhead. All designed for the full project life cycle, including post-injection monitoring and MMV support.

Anticipating new operating models for CCS, including extended field life over many decades, batch injection modes, comingling CO₂ sources, uncertainty over fluids composition, low temperatures and multi-phase flow streams; Baker Hughes fornt end field architecture solution development utilising in-house expertise reduces traditional concept development timescales to reach FID efficiently.

BENEFITS

- **Benefit One:** Fit-for-purpose CCS functionality solutions minimise CAPEX with structured product portfolio capable of faster delivery and maintaining time to first-injection to the minimum.
- **Benefit Two:** Direct involvement in developing subsea CCS industry standards and guidlines.
- **Benefit Three:** Inovative subsea architectures to optimise field layouts and minimise the hardware required to achieve injection targets.
- **Benefit Four:** Technology that builds upon field proven designs and a history of safe, reliable CCS subsea injection track record.
- **Benefit Five:** Innovative concepts designed specifically for optimum CCS operations and system integrity.

KEY PROJECTS

- **Project One:** Snohvit LNG plant CO₂ disposal. 260km tie-back to shore. Two tamplate mounted wells, injecting reliably for a total of 19 years.
- **Project Two:** Over 300km of flexible pipe installed in South American pre-salt fields with over 85% CO₂ content and pressures up to 620 Bar.
- **Project Three:** Extensive early phase engineering consultancy in concept selection and definition.
 - Horisont Polaris
 - Horisont Errai
- **Project Four:** Extensive commercial and strategic analyses for state and operator entities globally. Kowledge extending to reservoir technical due diligence, license applications, funding applications, commercial structures, site certification, etc.

KEY DATA

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TECHNOLOGY DESCRIPTION

SYSTEM INTEGRATION

Baker Hughes views CCS as a genuine opportunity to realise standardised system components assembled in to an optimised CCS injection system. Our full value chain experience enables us to integrate all the key system components from the injection pump, to the reservoir, not just the subsea infrastructure.

Well established interface definitions reduce project uncertainties and risks when infield construction begins.

How does this integrated approach benefit our clients?

Greater pre-FID efficiency, reduced client administration through a vendor-led solution development, following the rigorous Baker Hughes Governance processes, stock-purchase and Quality Planning, leading to faster equipment delivery.

CCS TAILORED SOLUTIONS

Our structured products provide an assembly designed for simple reconfiguration for the CCS applications. This results in products such as the Subsea Tree when configured for CCS, excludes the additional components required by Oil & Gas developments. No additional component development and qualification is required.

All-Electric control systems allow for greater flexibility in design, reduction of OPEX requirements, increased diagnostics and better reliability over hydraulic systems.

Demand for CCS reservoir moitoring both during and post-injection activities considers the application of in-well fibre-optic sensors for DAS and DTS interpretation, requiring a fibre-optic feed-through connection between the Tubing Hanger and subsea Tree. Our vertical CCS Trees employ a qualified vertical feed-through device for the in-well fibre-optic MMV applications.

For infield injection distribution and tie-back to the injection faciltiy using our versatile CCS flexible pipe systems allow for faster installation and TOTEX savings.

Distribution templates and manifolds for CCS fields where operational pressures and temperatures are typically much lower than O&G fields, allow for lighter structures and lower cost large-bore isolation valves. Connections employ Baker Hughes' ROV horizontal and vertical connection systems or diver/ROV assembly of traditional flange connection.

Baker Hughes experienced CCS Flow Assurance experts contribute to system optimization from the injection pump to the well bottom-hole conditions, including steady state and transient events to support field operational procedures and maximise injection rates.

KEY SUBSEA EQUIPMENT

The Aptara-L VXT can support 5" or 7" completions, set on 18-3/4" or 13-5/8" Wellheads. HH-EE trim and all metal-to-metal primary seals.



The Aptara-S shallow water VXT provides a 5" bore on a 13-5/8" wellhead. HH-EE trim and metal-to-metal primary seals.



CCS satellite, manifold and template structures to suit any field architecture.



Baker Hughes

BAKER HUGHES

SURESENS™ QPT ELITE PDHG



SUMMARY

Well-known pressure and temperature are key to proper functioning throughout a CO₂ storage system. For most applications, the best way to monitor these parameters is with permanent downhole gauges (PDHGs). These gauges can be used as a standalone means of measurement or as calibration for a fibre optic-based or other extensive measurement system. Baker Hughes leverages the quality and performance of the SureSENS™ line to execute integrated monitoring solutions that combine point gauges, fibre optics, along with periodic means of measurement such as wireline logging data.

BENEFITS

- Provides superior reliability in long-life and/or demanding (high-pressure and high-temperature) applications
- Derives finest pressure/temperature measurement resolution attainable
- Deploys multiple gauge combinations on a single standardised carrier
- Eliminates the need for additional splices, increases reliability, and reduces installation time through unique construction configurations with fewer connections
- Deploys multiple gauges, flowmeters, and valve positions to provide redundant readings
- Serves as platform for future developments

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

The SureSENS™ QPT ELITE gauge for permanent downhole installations measures static and dynamic pressures and temperatures while introducing a step change in reliability and accuracy. The gauge is qualified for operation at pressures up to 30,000 psi and temperatures up to 225 °C (437 °F). The static and dynamic pressure information obtained can be used to determine the effects of injection and plume growth on monitoring wells, monitor injection characteristics, and provide input or validation to reservoir models. The SureSENS™ QPT ELITE gauge includes the new ELITE electronics package, built upon Baker Hughes’ industry-leading STAR hybrid electronic package design. The ELITE electronics package incorporates an application-specific integrated circuit (ASIC), providing a new level of reliability to the industry. Baker Hughes provides three configuration options—single, dual, and triple gauge. The single-gauge configuration is an economical option that will also permit the smallest possible running diameter for a streamlined, slim-hole gauge carrier. A dual-gauge configuration provides isolated operational redundancy of electronics and transducer at any given installation point. Each gauge in a dual package operates individually, providing independent measurements for data redundancy and integrity verification. The triple gauge option can offer

redundancy or be ported to record three independent pressure measurements. The shorter carrier for a side-by-side triple-gauge assembly also retains a slim hole running outside diameter.

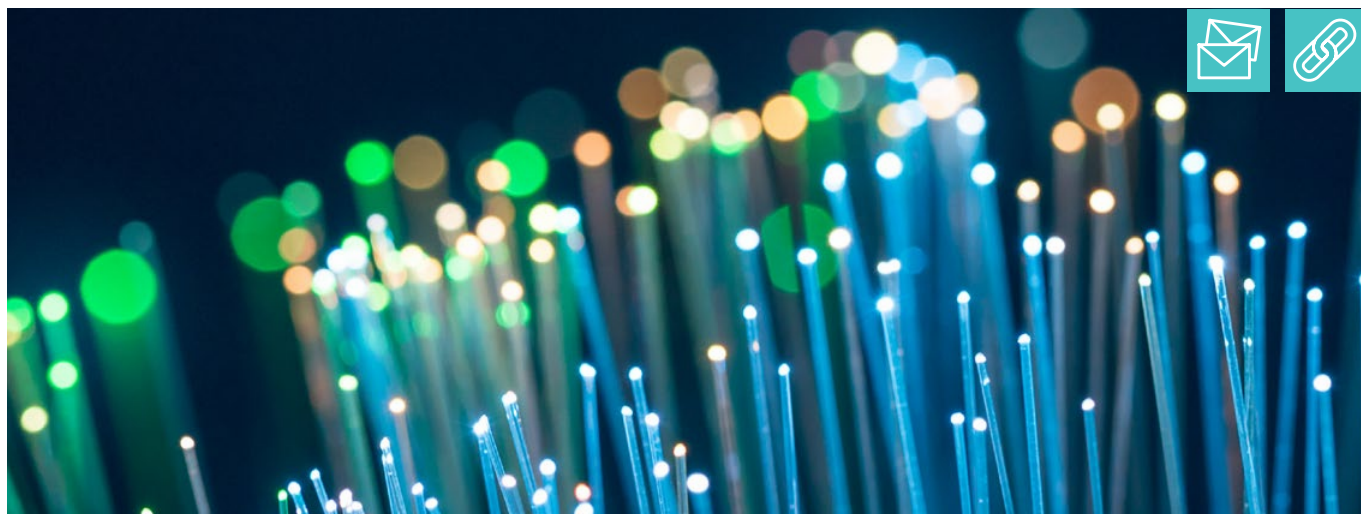
For applications requiring long active life and high data accuracy, even in demanding high-pressure/high-temperature type environments, the SureSENS™ QPT ELITE gauge system provides a flexible and reliable solution.

Being highly robust, the SureSENS™ QPT ELITE gauge maintains mechanical integrity by deep-penetration and high vacuum, electron-beam fusion welds, without the need for filler material. The gauge pressure interface connection to the carrier is dual metal-to-metal gas tight seal that can be externally tested in the direction in which it will experience pressure, eliminating the need for an internal pressure test tool. The TEC’s primary seal is a dual metal-to-metal pressure-testable interface. The mechanical package is completely integrated into the gauge assembly, which eliminates the requirement for external Y-block components.



Gauge Carrier configured with QPT ELITE permanent downhole gauge

Baker Hughes **BAKER HUGHES** **SUREVIEW™ WITH COREBRIGHT™ OPTICAL FIBRE**



SUMMARY

Reliable downhole measurement of well and reservoir parameters is imperative to the success of geological sequestration projects. Baker Hughes is uniquely positioned to holistically address the monitoring challenges. Baker Hughes leverages a broad portfolio of technology and experience across permanent downhole gauges, microseismic monitoring, wireline monitoring, and fibre optic solutions. Specifically, fibre optic monitoring is an effective solution to gather a range of real-time data downhole. These systems can provide distributed temperature, acoustic & strain measurements, transmit point gauge data, and capture seismic measurements for use in vertical seismic profiling. The majority of traditional downhole fibre optic installations are intended for 10-20 years of hydrocarbon production life. However, the geological sequestration projects can require much longer service life. SureVIEW fiber optic cable utilises proprietary CoreBRIGHT fiber formulated specifically for long-life downhole applications and has unique resistance to common hydrogen darkening failure.

BENEFITS

- Collect multiple measurements with a single cable including distributed fibre optic sensing, pressure/temperature gauges for well integrity, compaction monitoring, and seismic data.
- Utilises CoreBright™ hydrogen resistant fibres to limit the effects of hydrogen darkening
- Cable is clad with robust Inconel 825 corrosion-resistant nickel alloy for maximum protection against chemicals, abrasion, crimping and crush.
- Continuous cable with no orbital welds
- Fibre In Metal Tube (FIMT) utilises continuous (splice-free) fibres throughout
- Equipped with excess fibre to ensure that no strain is transferred to the optical fibre core during deployment or operation. Excess fibre compensates for thermal expansion, as well as tubing stretch.

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

SureVIEW™ downhole cable by Baker Hughes uses CoreBright™ optical fibre, which leads the industry in hydrogen darkening resistance, a leading cause of failure for fibre optic systems over time. CoreBright™ fibre is constructed from pure silica that minimises hydrogen darkening. The cable also includes a layer of hydrogen-absorbing gel. This combination provides the industry's best protection against hydrogen darkening.

Fabricating a downhole optical cable with the performance and reliability demanded by our industry requires a sophisticated understanding of fibre design, fibre coatings, cable manufacturing processes, and cable construction.

Fibres are typically coated, often with carbon, to prevent this hydrogen darkening. However, over time, this coating can break down or suffer from uneven application during manufacturing. A well applied coating will likely break down in about 20 years, particularly at higher temperatures (above 150 °C). CoreBright™ fibre offers its extended lifetime through a simple principle: instead of attempting to avoid hydrogen damage by trying to block hydrogen, CoreBright™ optical fibre avoids the hydrogen damage by preventing the reaction between the SiO₂ structure of the optical fibre and the hydrogen. In addition, Baker Hughes' fibre optic cables are fitted with hydrogen scavenging gels to further reduce darkening risk.

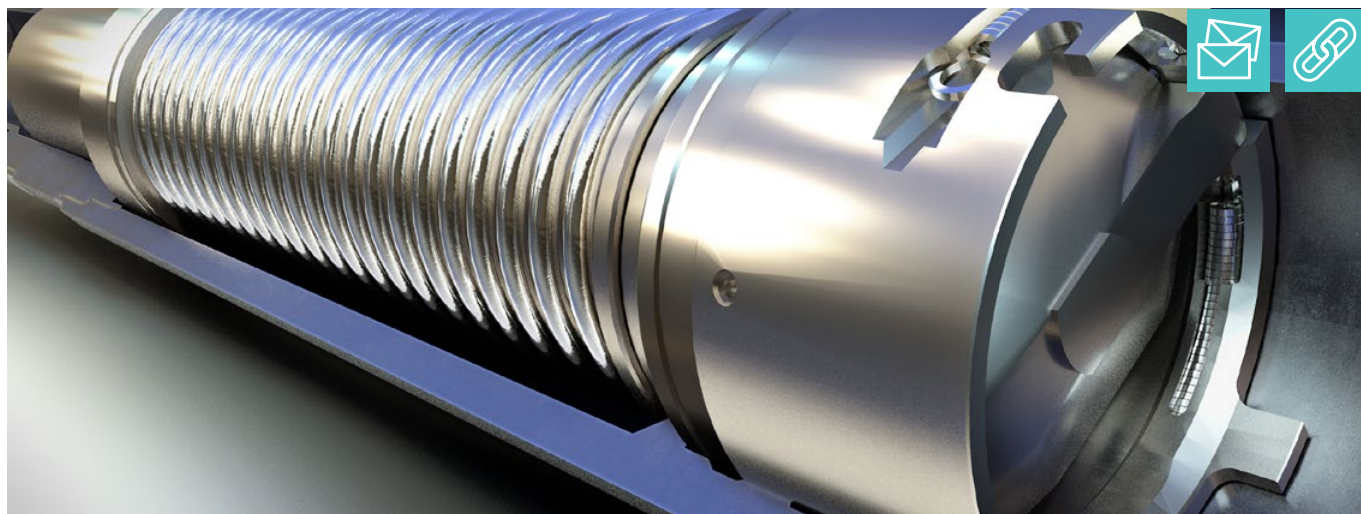
In this way, Baker Hughes' solution is unique: the fibre will not darken, and reliable readings over the full life of the installation are assured. Independent testing has concluded that CoreBright™ optical fibre is the only fibre in the industry that is suitable for harsh downhole environments over a long duration. It is the only known fibre that was designed for, and has demonstrated, long-term immunity to first and second-order hydrogen darkening effects.

SureVIEW™ fibre optic cables, powered by CoreBright™ fibre, have been installed in over hundreds of wells worldwide. As of today, there are no instances of hydrogen darkening ever reported.

High reliability and longevity enable the use of fibre optic measurement in more applications particularly behind the casing where workover is likely impossible. Baker Hughes' SureVIEW™ downhole cable is expected to improve data quality and facilitate better decision-making in geological sequestration today.



Baker Hughes **BAKER HUGHES** **THUNDER TUBING RETRIEVABLE SAFETY VALVE FOR CCS**



SUMMARY

The Thunder™ subsurface safety valve brings CCS-ready reliability to our tubing-retrievable valve portfolio. Fully qualified to API 14A Annex P, Thunder excels in extreme CCS conditions, including low-temperature testing down to -35°C and survivability to -80°C for Joule-Thomson cooling during CO₂ venting. Built for 5,000-psi, 9,000-ft service, it uses metal-to-metal sealing for unmatched reliability. A non-elastomeric seal assembly ensures stability under gas-decompression and thermal cycling. With a flapper proven against wireline damage and high-flow slam closure, Thunder delivers long-term performance for demanding CCS applications.

BENEFITS

- Provides high-integrity sealing and simple intervention operations without conventional failure modes associated with sliding sleeve type communication features
- Resists high impact loads even in extreme high-flow-rate applications through robust flapper closure mechanism
- Maximises the internal diameter of the valve while providing gas-tight sealing and high tensile ratings
- Minimises the risk of thermal degradation and rapid gas decompression with non-elastomeric dynamic seals

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

Baker Hughes's Thunder™ subsurface safety valve completes our portfolio of reliable tubing-retrievable safety valves (TRSVs). Leveraging more than 30 years of experience, supplying over 50,000 valves to operators throughout the world, the Thunder valve offers fail-safe operation in a broad range of applications.

Our CCS Qualified Thunder safety valves were tested in accordance with API 14A Annex P, Requirements for CCS Environments, December 2025, which includes operating temperatures from -35°C to 80°C (-31°F to 176°F) and survivability down to -80°C (-112°F) due to Joule-Thomson cooling during CO₂ venting. Our Thunder safety valves accommodate working pressures up to 5,000 psi, and maintains fail-safe operation at depths of up to 9,000 ft. The valve features metal-to-metal containment of wellbore fluids in the closed position.

The Thunder also incorporates a non-elastomeric dynamic seal assembly to avoid rapid gas decompression and thermal degradation associated with some elastomeric seal designs. Every Thunder safety valve utilises Baker Hughes's proprietary RBT metal-to-metal sealing thread technology for high tensile ratings and gas-tight sealing. Each thread is analyzed for combined stress and completes a combined load test as part of our standard prototype test program.

During wireline operations, a flapper can be inadvertently damaged if it is not held in the fully open position. The Thunder valve's flapper design recesses the sealing surface away from the edge of the flapper, protecting it from damage when wireline cable drags across the edge. High-flow-rate wells also generate tremendous energy that can cause damage to a flapper during an uncontrolled slam closure. The Thunder flapper design is also proven through high-flow-rate gas testing to ensure reliable sealing, even after slam closure.

Finite element analysis, rigorous testing, and decades of experience have produced a valve that offers an ultra-strong flapper closure mechanism that is designed to ensure reliable, long-term operation in a broad range of completions.



SUMMARY

The Carbfix process captures CO₂ and turns it into stone underground in under two years through technology that imitates and accelerates natural processes, providing a permanent carbon storage solution. Carbfix is the world's first organization dedicated to facilitating and implementing carbon capture and mineral storage (CCMS) worldwide. Robust research and innovation based on subsurface geochemical processes laid the foundation for injection of dissolved CO₂ into reactive rock formations for efficient CO₂ mineralization. To date, such approach is the safest and fastest carbon capture and storage (CCS) method applicable at industrial scale. Carbfix can adapt its well-established technology to a range of pure and impure emission streams as well as direct air capture technologies with a portfolio of patented solutions. Carbfix is also pioneering mineral storage in large scale hubs that can inject and store CO₂ transported via ship or pipeline.

BENEFITS

- **Safe:** The risks related to the leakage is eliminated by dissolving CO₂ in water for instant solubility trapping.
- **Low cost:** Cheaper than alternative geological storage solutions with lower up-front capital costs and lower operational risks using a network of shallow onshore wells.
- **Permanent:** Robust MRV campaign verifies mineralization which are stable for thousands of years limiting the need for long term monitoring.
- **Natural:** The process imitates and accelerates nature's way of storing CO₂ in rocks with no chemicals other than water.
- **Experience:** With over a decade of commercial operations, Carbfix has developed and optimised storage in reactive rocks and offers various tested solutions.

KEY PROJECTS

- **Coda Terminal:** A scalable cross border carbon transport and mineral storage hub in Iceland, Coda will receive CO₂ captured from industrial sites in Europe in a liquified state before conditioning and injecting in aqueous state into a network of injection wells. The target capacity is to sequester 3 Mtpa CO₂ by 2030-2034.
- **Mammoth:** Permanent storage of CO₂ from the world's largest direct air capture facility in collaboration with Climeworks, capturing 36 000 t/yr. Operational since 2024.
- **Seastone:** The world's first demonstration of seawater-dissolved CO₂ injection into reactive rocks. In addition to seawater, the test facility hosts a range of R&D activities related to mineral storage in basalts. Operational since 2022.
- **Silverstone:** Full scale capture and mineral storage of geothermal CO₂ and H₂S from the Hellisheidi power plant of 36 000 tCO₂/yr. Operational in 2025. First EU IF project within the Industrial Carbon Management portfolio to enter into operation.

KEY DATA

TRL	9	Mineralisation Time Scale (yr)	0.5 - 10	Capture Efficiency (%)	100
Source CO ₂ Purity Range	40 - 100%	System Energy (kWh/tCO ₂)	25 - 350	Water/seawater demand (t/tCO ₂)	25 - 55
Number of Commercial Plants	3	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Hard-to-abate Industries (Cement, Steel, Aluminium, Chemicals), Geothermal, BECCS and DAC*				

TECHNOLOGY DESCRIPTION

CO₂ mineral storage occurs when CO₂ and water are co-injected into suitable rock formations (mafic or ultramafic rocks), containing high concentrations of divalent cations. The CO₂ is fully dissolved in the injection well resulting in acidic carbonated water which dissolves the host rock reservoir, causing it to release its cations into the fluid. These cations react with the dissolved CO₂ to form stable carbonate minerals in the pore spaces and fractures of the host rock.

Alternatively, impure gas streams can be compressed into an absorption column where CO₂ and other soluble gases are selectively dissolved in water while non soluble gases such as N₂ and O₂ are vented from the process. The gas charged water is then diverted to an injection well that extends into the storage reservoir. Only electricity and water are needed for this capture method. This patented solution is ideal for emitters or DAC operators that deliver impure streams, eliminating the need for a liquefaction or purification step prior to injection.

OFFERINGS

Carbfix offers point source storage solutions to emitters located at, or near, favorable geological areas (example Silverstone, Mammoth) and point to point storage solutions to emitters located in areas where geological conditions are not favorable for point source injections (example: Coda Terminal).



Feasibility Studies - Carbfix proceeds to derisk prospective storage sites in dedicated Level 1 – Level 3 feasibility studies. With over a decade of commercial operations, Carbfix has developed a step-by-step process to evaluate potential mineral storage sites across the globe, to maximise its potential impact. This process, mitigates risks, increases value and provides the preliminary storage capacity of the reservoir.

Mobile Injection Unit (MIU) – Carbfix offers tailor-made mobile injection unit to complete an injection demonstration with an injection capacity of up to 5,000 tons per year. MIU arrives as a 40-foot container and is connected to necessary utilities (water, electricity and CO₂) as well as with an injection well enabling quantifiable and validated injection operations. The MIU can be rented or tailor-made based on customer needs.

Reservoir Monitoring Unit (RMU) – Carbfix offers a reservoir monitoring unit that enables the remote operation of series of reservoir characterization and monitoring solutions. The unit is deployed prior to injection operations.

Mobile Capture Unit (MCU) – Product aimed to demonstrate CO₂ capture from impure gas streams (>40 vol% CO₂) and dissolve in water for injection in a single step.

Drilling consultancy and well-design – Carbfix uses integrated well and injection systems ensuring seamless operation and robust MRV campaigns. Carbfix offers consultancy on drilling and completion activities.





CARBON GEOCAPTURE

COAL-ASSISTED CARBON CAPTURE AND STORAGE TECHNOLOGY



SUMMARY

Carbon GeoCapture (CGC) is a carbon capture and storage company that permanently buries carbon dioxide in unmineable coal seams through a safe, cost-effective, and scalable process. By revitalizing and refining a proven approach, we enable large-scale carbon sequestration at lower costs, helping industries and power producers meet their economic and environmental goals safely and efficiently. Coals act as a carbon filter, preferentially absorbing CO₂ and thereby greatly reducing the need and cost of cleaning up flue gas to the 99% purity required by conventional CCS. Our coal-assisted CCS technology meets growing baseload energy demand from data centers without sacrificing reliability or economic growth, ensuring our grid stays strong while simultaneously reducing CO₂ emissions. Unmineable coal seams are an abundant, proven, geologically stable option for permanent CO₂ storage. Coals provide a scalable, cost-effective solution. By using these existing natural formations, we ensure safe, scalable, cost effective, and permanent carbon removal.

BENEFITS

- Suitable for use anywhere in the world where coal occurs, commercially deployable at scale today.
- Burying CO₂ in unmineable coal seams poses lower geological and liability risk. These shallower, underpressurised, nanoporous formations securely store CO₂ for millennia.
- CO₂ sequestration monitored and controlled using proprietary patented in situ sensing technology.
- Our approach significantly reduces the CO₂ purity required for sequestration, eliminating the need for costly purification and compression of captured flue gas.
- By using existing coal beds, we reduce or eliminate the high transportation costs and project lead times required for conventional CCS. CGC's technique is 70% cheaper end-to-end than conventional CCS.
- Capable of use in US Class II or VI wells. Class II offers speed to market of months as opposed to years.
- Closed loop to preserve water and energy and protect aquifers; safe, easily monitored, and controlled.

KEY PROJECTS

- Developing our approach entailed more than 25 years of R&D and field work and significant investment.
- Worldwide applicability – we currently have a pipeline of commercially viable projects under development across North America, Europe, and Asia.
- CGC and Black Hills Energy (BHE) are partnering to demonstrate how Wyoming coal- and natural-gas-fired power plants can deliver low-cost, dispatchable energy while managing carbon emissions by using unmineable coal seams to store CO₂ from flue gases naturally.
- The project will establish a test bed at the Neil Simpson Complex in Gillette, Wyoming, to support future full-scale deployment, unlock significant carbon storage capacity, and help protect reliable baseload power generation as energy demand grows.

TECHNOLOGY DESCRIPTION

CGC's coal-assisted carbon capture and storage technology permanently buries carbon dioxide in unmineable coal seams through a safe and efficient process. Sequestering carbon in coal can occur at a cost that allows us to help meet the world's climate goals. Those cost savings can accrue significantly over time, allowing us to do more with less. Burying carbon dioxide in coal, instead of in deep sandstones and salt domes, also poses a lower geological risk, as these shallower, lower pressure, nanoporous formations are underpressurised and therefore safer.

Coals act like carbon filters, preferentially absorbing and storing carbon dioxide at lower cost than storing it deep underground with conventional carbon capture and storage. Our approach repurposes existing oil and gas industry participants and creates new opportunities for workers and communities historically reliant on fossil fuels. This means good-paying jobs, stronger local economies, and a competitive edge in the global energy transition. This lowers costs while providing high-quality jobs in the emerging carbon management sector, ensuring that the transition to a low-carbon economy is inclusive and economically viable.

Our active CCS projects span diverse sectors, including coal-fired power, natural gas-fired power, chemical production, cement production, and natural gas processing. Our coal-assisted CCS technology allows countries to meet growing energy demand without sacrificing reliability or economic growth, ensuring power grids stay strong while simultaneously reducing CO₂ emissions. Unmineable coal seams are a proven, geologically stable option for permanent CO₂ storage. They provide a scalable, cost-effective solution. By using these existing natural formations, we ensure safe, permanent carbon removal.

To successfully bury CO₂ in unmineable coal seams at scale, CGC has developed a modern approach to avoid geological damage and ensure these formations are utilizing their full potential to store carbon dioxide. Commercializing this approach entailed more than 25 years of R&D and field work and significant investment. Currently, we have a pipeline of commercially viable projects under development across North America, Europe, and Asia.

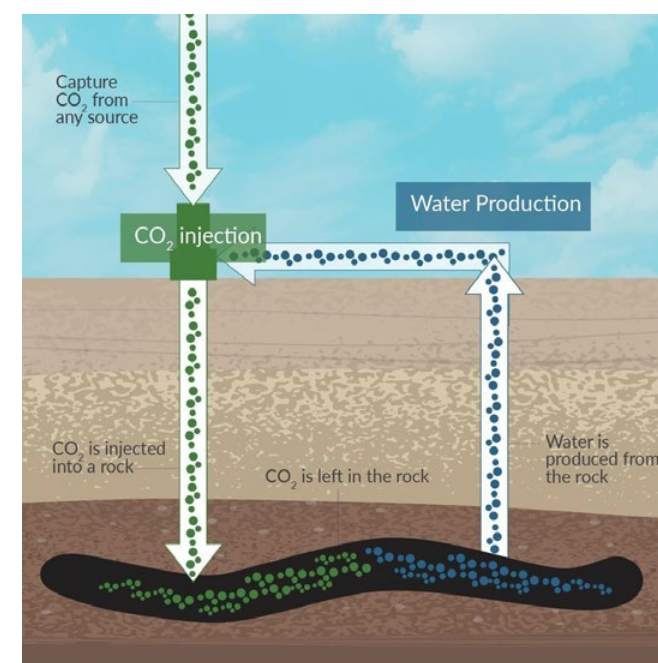
CGC's unique process was designed to be resilient, flexible and modular to work with various carbon dioxide volumes, sources, capture technologies, power sources, and rock formation types. Our approach captures and stores carbon dioxide from a variety of emission sources, including power plants, and industries like chemicals, cement and paper, and can work with any variety of capture (membranes, amines, DAC technology) whereby CGC can store the captured carbon dioxide.

MONITORING AND SAFETY ATTRIBUTES

In partnership with our sister company, WellDog, our downhole systems have been used in thousands of locations around the world over the last two decades to directly measure and monitor key geophysical and geochemical data in the subsurface.

Our unique proprietary downhole Raman and pressure sensors and database are based on decades of knowing how coal seams absorb CO₂, both in the field and in the lab. Our sensing systems operate on a 24/7 basis; therefore, any detection of any potential type of leak is identified in real time. These sensors take an agnostic approach to technology selection and deliver engineered fit-for-purpose subsurface monitoring solutions. These solutions take into consideration pressure sensor types, covering a variety of pressure ranges, that are available with different temperature ratings, and capable of either analogue or digital transmission of data.

WellDog has also pioneered a number of different gauge architectures and deployment methods that allow one or more gauges of the same or different type, to be installed in the same well, either on tubing, coil, and/or behind casing. This high degree of flexibility enables permanent downhole monitoring systems to be configured to exactly suit well and reservoir conditions, and data needs.



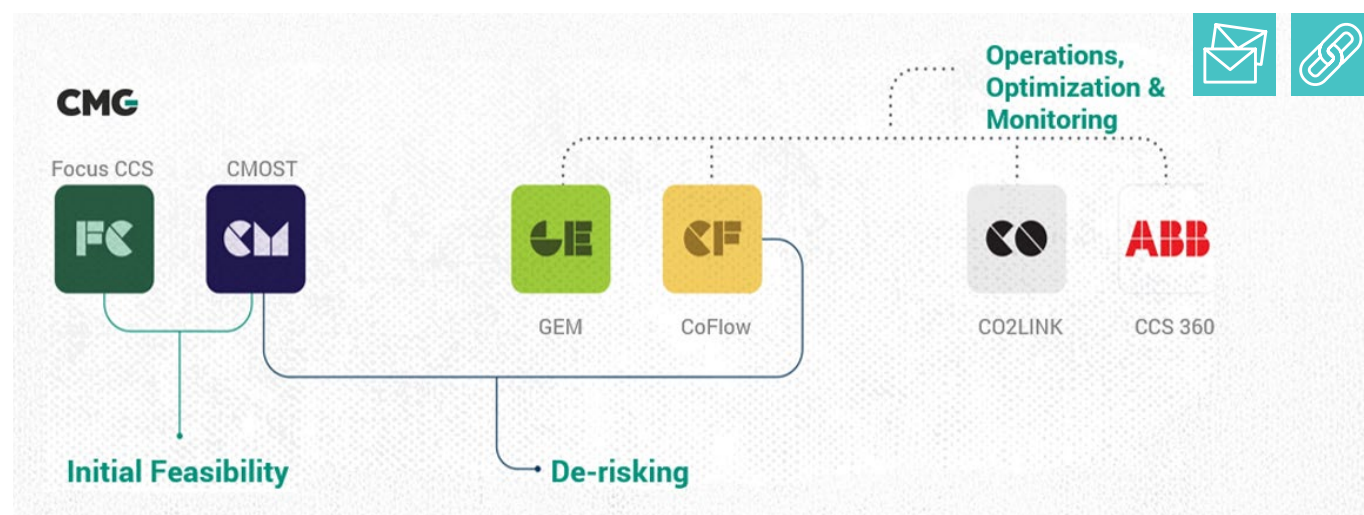
KEY DATA

TRL	8	Capture Rate Range (tpd)	1 - 200 (per injection well) To 50,000 (project)	Capture Efficiency (%)	90%+
Source CO ₂ Purity Range	4 - 100%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Power, cement, chemical, steel, natural gas processing, fuel, pulp/paper				



CMG

INTEGRATED CCS SOLUTION



SUMMARY

Computer Modelling Group (CMG) is a global software and consulting company that combines science and technology with deep industry expertise to solve complex subsurface and surface challenges for the new energy industry. As the world's leading independent supplier of Carbon Capture and Storage (CCS) simulation solutions, CMG provides an integrated approach that combines advanced CO₂ storage physics modeling, history matching, subsurface-to-surface integration, and multi-objective optimization to de-risk projects, ensure regulatory compliance, and maximise economic value.

BENEFITS

- **De-Risk Energy Transition Projects:** Comprehensive modeling for CO₂ storage (also other energy transition processes like H₂ storage, geothermal) process to ensure long-term injectivity, operational stability and containment.
- **Integrated Workflow:** End-to-end solutions coupling subsurface reservoir models with wells and surface facilities to optimise the entire injection chain – from transient well start-up and injection ramp-up/down to long-term steady-state system optimization.
- **Decision-Ready Insights:** Use of AI and machine learning to quantify uncertainties and run thousands of scenarios for optimal multi-objective configurations.
- **Regulatory & Monitoring Support:** Delineation of Area of Review (AoR) and support for Monitoring, Measurement, and Verification (MMV) strategy design to satisfy global regulators.

KEY PROJECTS

Innovation at CMG is driven by extensive research, world-class partnerships with multiple technology leaders in complementary fields, collaborations with leading research groups and joint industry projects (JIPs). Some of the past collaborations include:

- **Kongsberg:** A JIP of +10 industry partners to focus on modeling safe start-up and shutdown of injection operations.
- **Japan's Research Institute of Innovative Technology for the Earth (RITE) & Japan Oil Engineering:** A long-standing research consortium (since c.1998) that was world's flagship initiative to provide predictive modeling capabilities for CO₂ storage in deep saline aquifers.
- **ABB:** Integrated CO₂ injection management by integrating control systems engineering with on-demand reservoir simulation.

KEY DATA

TRL	9	Regions	Global
Saline aquifers or depleted fields	Both	No. of applications / projects	+25
Operational synergies	Yes	Regulatory body recognition	Yes
Target Industries	Oil and Gas, hard to abate industries like cement, power generation and steel, regulators, lenders, insurers		

TECHNOLOGY DESCRIPTION

THE PHYSICS OF CARBON STORAGE

CMG's flagship reservoir simulator, GEM, provides the physical mechanisms required to capture how CO₂ behaves in complex underground environments. The physics modeled include:

- **CO₂ Phase Behavior, Phase Transition & More:** GEM allows for detailed phase behaviour of pure and impure CO₂ at all pressures and temperatures, accurate solubility calculations for CO₂ in subsurface fluids, and molecular dispersion and diffusion models.
- **Geochemical Reactions:** GEM's geochemistry capabilities capture chemical interactions between injected CO₂, reservoir fluids, and minerals in the aquifer rock to predict long-term mineral trapping and potential mineral dissolution, as well as model near-wellbore salt precipitation that affects injectivity.
- **Geomechanics & Integrity:** GEM features a two-way coupling between geomechanics and flow to evaluate the mechanical response of reservoirs and caprock. This quantifies risks such as caprock integrity, fault reactivation, and surface uplift, as well as captures effects such as thermal fracturing.
- **Thermal & Seasonal Effects:** GEM allows for analysis of rapid cooling (Joule-Thomson effects) around injection wells and the impact of thermal gradients and seasonal variations on well integrity and injectivity.

INTEGRATED SOFTWARE SOLUTIONS

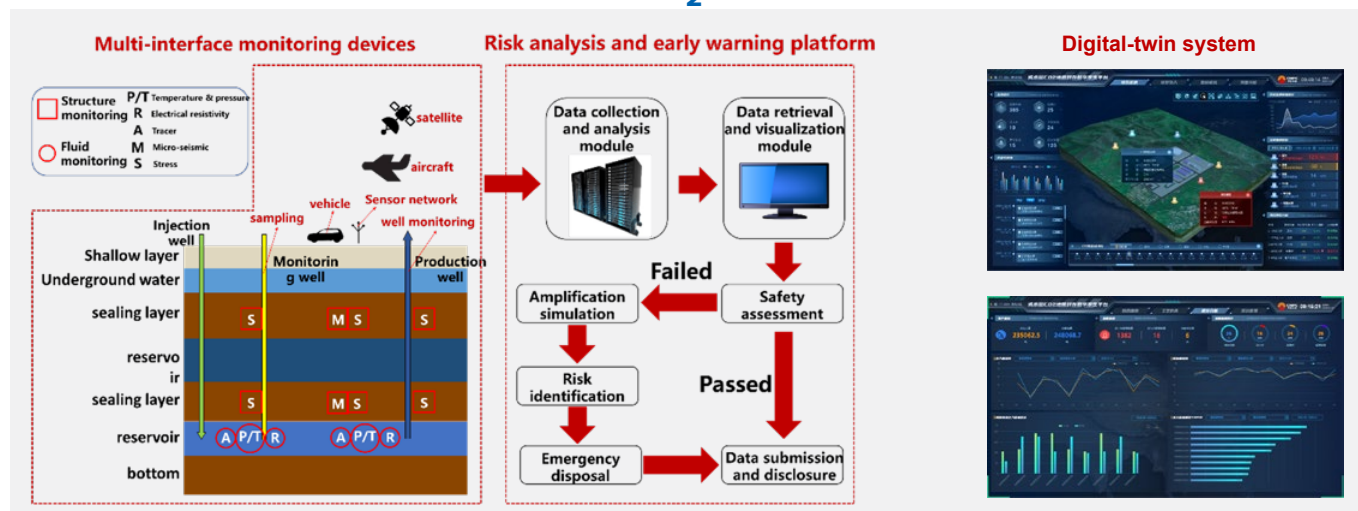
CMG offers the industry's first end-to-end integration across the entire CCS lifecycle to move from early scoping to injection, monitoring, and optimization. The workflow is powered by:

- **GEM:** The industry standard for compositional and unconventional reservoir simulation, enhanced specifically for CO₂ storage modeling.
- **CoFlow:** An integrated reservoir and surface facility system modeling environment that allows for the detailed long-term analysis of well and pipeline systems feeding CO₂ into the subsurface.
- **CO₂LINK:** Links transient wellbore modeling with reservoir simulation to accurately capture CO₂ behavior during critical phases such as well start-up and shut-down.
- **CMOST:** An intelligent optimization and analysis tool that uses advanced algorithms (e.g., particle swarm optimization) for history matching, sensitivity analysis, and uncertainty quantification.
- **FOCUS CCS:** Rapid feasibility and storage validation in minutes, even for non-specialists

CMG is more than a technology provider; it is a trusted partner empowering project executors to navigate complexity and mitigate risk – all the way from screening to project development, MMV, and operations. With detailed physics modeling for CO₂ transportation, injection and storage, CMG solutions accelerate decision making and enable better decisions for site-selection, concept selection, operational design and planning, injection forecasting, plume and Area-of-Review predictions and MMV planning.



CHINA NATIONAL PETROLEUM CORPORATION

REAL-TIME MONITORING AND DIGITAL-TWIN SYSTEM FOR CO₂ GEOLOGICAL STORAGE

SUMMARY

To address potential leakage risks in CO₂ geological storage, CNPC developed a real-time monitoring and digital-twin system integrating microgravity instruments, multi-parameter sensors, IoT devices, and dynamic inversion models. Operating at 0.2 Hz, the system continuously acquires ppm-level field data and synchronizes monitoring, data aggregation, hydrodynamic inversion, and virtual reservoir updates. It supports deep-fluid tracking, shallow and near-surface environmental surveillance, and dynamic prediction of CO₂ migration, accumulation, and multiphase fluid distribution within geological formations. The technology has been applied to saline aquifer storage, depleted reservoir storage, and CO₂-EOR projects, providing support for leakage risk prevention, environmental integrity management, safer operational optimization, and quantitative verification of carbon emission reductions throughout the full project lifecycle.

BENEFITS

- **Comprehensive Coverage:** Encompasses deep, shallow, and near-surface interfaces to achieve three-dimensional monitoring of leakage risks in CO₂ geological storage projects.
- **All-Element Monitoring:** Covers all essential parameters required for on-site environmental integrity management, including groundwater quality, atmospheric CO₂ concentration, surface deformation.
- **All-time Operation:** Integrates monitoring sensors and IoT technology to enable real-time, continuous monitoring of most on-site parameters under all weather conditions.
- **Life-Cycle Monitoring:** Extends across the entire lifecycle of CO₂ injection, covering pre-injection, injection, and post-injection site maintenance.

KEY PROJECTS

- **CNPC Hainan Onshore Saline Aquifer Carbon Sequestration Project:** Successfully implemented full life-cycle monitoring, covering pre-injection, injection, and post-injection phases.
- **CNPC Jilin Oilfield CO₂-EOR Project:** Completed long-term continuous monitoring and multiphase (oil, water, and gas) fluid distribution prediction, achieving high consistency with geophysical survey and numerical simulation results.
- **National Energy Group Yulin Multi-layer CO₂ Geological Storage Project:** Achieved coordinated monitoring across multiple formations—including saline aquifers and coal seams—and concurrently predicted the vertical and horizontal distribution of CO₂ within the strata.

KEY DATA

TRL	9	Monitoring Range (m)	Above ground: 0–3 meters, Below ground: 0–3,000 meters
Function	Safety and effectiveness monitoring of CO ₂ geological storage to identifying CO ₂ leakage from multi-interfaces and predicting CO ₂ migration in the subterranean space.		
Performance Indicators	Surface Elevation: Millimeter-level, Microgravity: Microgal-level, Temperature: 0.1°C, Pressure: 0.01 MPa, ORP: 1 mV, Water Level: Millimeter-level, Geostress: 0.01 MPa, Formation Dip Angle: 0.1°, Frequency: 0.2 Hz.		
Target Industries	CO ₂ geological storage in saline water layer or depleted oil and gas reservoirs, CO ₂ -EOR		

TECHNOLOGY DESCRIPTION

INTEGRATED MONITORING AND DIGITAL-TWIN FRAMEWORK

The Real-time Monitoring and Digital-twin System for CO₂ Geological Storage is an integrated technology platform developed to improve the safety, effectiveness, and manageability of CCS projects. The system combines multi-interface monitoring hardware with real-time data transmission, dynamic inversion, and digital-twin modelling to maintain a continuous link between the physical storage site and its virtual representation. By integrating microgravity measurements, groundwater and atmospheric monitoring, surface deformation observations, formation pressure and temperature data, and other site parameters, it provides a unified basis for tracking CO₂ behaviour from the deep reservoir to the near-surface environment. Operating at 0.2 Hz, the platform continuously acquires ppm-level and engineering-scale data and feeds them into a real-time computational workflow for aggregation, quality control, inversion, and interpretation. This enables operators not only to observe current site conditions, but also to update subsurface understanding and assess whether monitored responses remain consistent with expected migration patterns and storage performance. The digital twin functions as a living model of the storage system. It couples geological structure, reservoir properties, operational parameters, and monitoring observations to reconstruct site conditions during pre-injection, injection, and post-injection phases. In practical use, the twin supports hydrodynamic inversion, multiphase fluid distribution prediction, and dynamic visualization of CO₂ movement in the reservoir. It also links deep, shallow, and near-surface observations within one digital environment, helping operators compare signals from different interfaces and identify whether anomalies reflect normal reservoir evolution or emerging leakage risks. Because the same platform combines monitoring, inversion, visualization, and model correction, it supports more coherent interpretation than isolated datasets or disconnected software tools. When field measurements depart from expected trends, the model can be recalibrated with new observations, improving interpretation reliability and supporting timely operational decisions. This combination of sensing and modelling moves the system beyond static monitoring toward closed-loop site management. It therefore provides a practical foundation for integrating measurement, model updating, and decision support across the full project lifecycle, rather than treating monitoring, interpretation, and risk management as separate tasks. This improves consistency for operators.

FIELD APPLICATION, PRECISION, AND OPERATIONAL VALUE

Field deployment has demonstrated applicability across different storage settings. In the CNPC Hainan Onshore Saline Aquifer Carbon Sequestration Project, the system supported full life-cycle monitoring and provided a digital basis for evaluating environmental integrity before, during, and after injection. In the CNPC Jilin Oilfield CO₂-EOR Project, long-term monitoring data were integrated with digital-twin prediction of oil, water, and gas distributions, and the results showed high consistency with geophysical survey and numerical simulation outputs. In the National Energy Group Yulin Multi-layer CO₂ Geological Storage Project, the system coordinated monitoring across saline aquifers and coal seams and simultaneously predicted the vertical and horizontal distribution of CO₂ within multiple formations. From a technical perspective, the platform integrates high-precision sensing with dynamic model updating. Surface elevation measurements achieve millimeter-level accuracy, microgravity monitoring reaches microgal-level sensitivity, temperature accuracy is 0.1°C, pressure accuracy is 0.01 MPa, oxidation-reduction potential accuracy is 1 mV, and water level monitoring remains at millimeter level. Geostress and formation dip measurements reach 0.01 MPa and 0.1°, respectively, providing a high-resolution basis for calibration and anomaly recognition. Because these datasets are collected continuously and transmitted in near real time, the digital twin can be refreshed with new site evidence rather than periodic reinterpretation alone. This strengthens early warning capability, supports optimization of injection and monitoring strategies, and improves the transparency of storage performance assessment for project managers and stakeholders. The modular architecture also allows the platform to adapt to different geological settings and project scales as new sensors or algorithms are introduced. Overall, the technology advances conventional monitoring toward intelligent storage management by combining all-time data acquisition, multi-interface environmental observation, and continuously updated digital-twin simulation for risk prevention, environmental integrity management, and carbon reduction verification. By turning continuous monitoring results into a traceable virtual replica of the storage system, the platform improves confidence in leakage risk prevention, environmental integrity management, and carbon emission reductions. It supports stewardship over time.



CVICTUS INC

CARBON STORAGE IN DEEP COAL



SUMMARY

Deep, unmineable coal seams are an ideal target for CO₂ storage because of the vast global distribution of coal resources and the high storage permanence. The primary gas storage mechanism in coal is adsorption, where CO₂ is adsorbed more strongly than other coal seam fluids, providing a very secure method for sequestration. Cvictus has leveraged proven coalbed methane technologies and the past CO₂ injection and has successfully demonstrated that large quantities of CO₂ can be injected into deep coal seams, paving the way for a larger, more stable sink for CO₂, at a lower cost than currently required. Cvictus's method for CCS in deep coal is cheap and secure, and can be further improved by integration in their Enhanced Hydrogen Recovery™ (EHR™) technology.

BENEFITS

- Injected CO₂ is physically adsorbed onto the coal matrix for proven, permanent, and stable geological sequestration.
- Each tonne of deep coal can physically adsorb over 100 kg of CO₂, at a cost of <\$10/t of CO₂ sequestered.
- This technology requires resources that are not considered recoverable by surface / underground coal mining, or functional for coalbed methane. There are 30-50 trillion tonnes of suitable resource for CCS around the world, providing value to a stranded, forgotten resource.
- Previous tests (Fenn Big Valley; Allison Unit) demonstrated that large scale sequestration in deep coal is possible, although not economical for its intended purpose of ECBM.
- Huge amounts of the most suitable resources for deep coal CCS are in China, India, Indonesia, and other emerging economies with massive, growing carbon emissions. Cvictus's technology a cost-effective way to decarbonise coal dependent countries that are driving future climate change.

KEY PROJECTS

Cvictus and a team of experts including those from the University of Calgary injected a total of 1,512 tonnes of CO₂ into the 1,500-meter deep Mannville coal seam at Cvictus's site near Red Deer, Alberta. Relatively low injection pressures and energy requirements confirm the commercial viability of Cvictus's patented process for carbon sequestration and EHR™.

A [recent peer reviewed paper](#) in the International Journal of Coal Geology summarises analysis and results from the program and outlines the potential for deep coal as a sink for CO₂ sequestration.

This work confirms key components for Cvictus's technology and increases the scientific understanding of the role unmineable coals could play in global decarbonisation.

Cvictus's first 'small' commercial plant in Alberta, Canada – producing 2,500 tonnes a year of clean hydrogen while sequestering all produced CO₂ onsite – will demonstrate the commerciality of this technology.

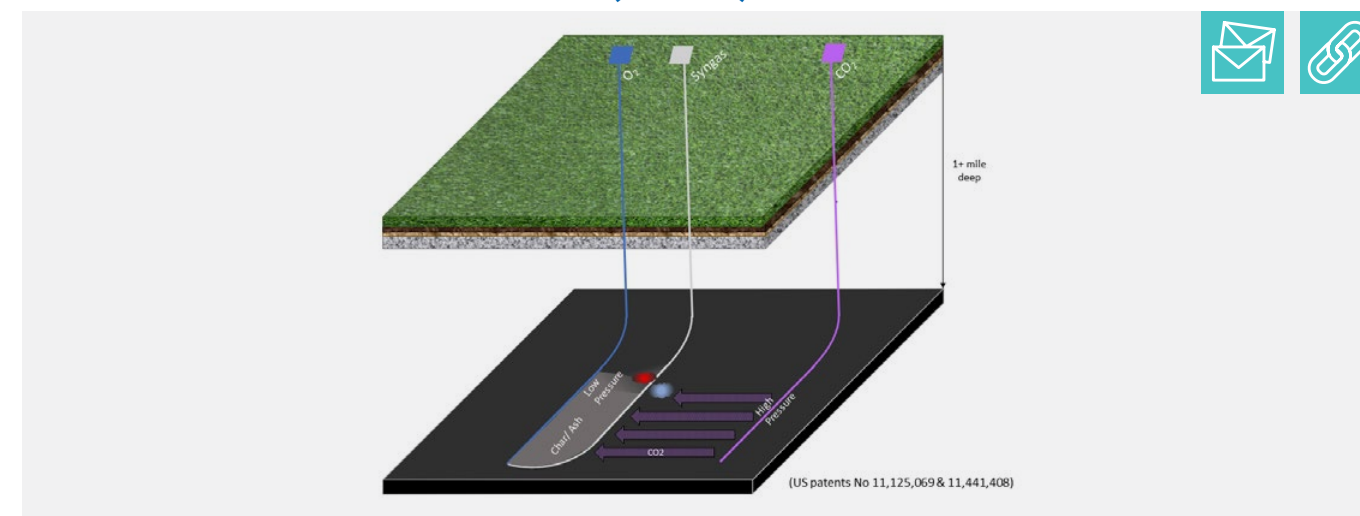
KEY DATA

TRL	5	Number of Commercial Plants	1	Number of Pilot Plants	~
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DESCRIPTION INC

CCUS THROUGH ENHANCED HYDROGEN RECOVERY™ (EHR™)



Coal has huge, largely unrecognised, potential for carbon sequestration. The key is to co-produce syngas from deep coal symbiotically with carbon capture, use, and sequestration (CCUS) to create the space needed to sequester CO₂ on site and fuel the low-cost energy required for CO₂ capture and compression. Cvictus's patented Enhanced Hydrogen Recovery™ (EHR™) technology mobilises brine and beneficial gases from the coal matrix by injecting CO₂, while extracting hydrogen-rich syngas. CO₂ is preferentially adsorbed onto the coal matrix. Cvictus has successfully demonstrated that large quantities of CO₂ can be injected into deep coal seams for permanent geological sequestration, opening up a vast new geologic sink for CO₂ at <\$0.10/t of CO₂ sequestered and turning coal 'from a source to a sink' of CO₂.

BENEFITS

- EHR™ is an integrated system, creating all the power needed for capture and compression, and geological space for sequestration onsite – eliminating the need for costly transportation and carbon intensive processing.
- Injected CO₂ is physically adsorbed onto the carbon char in the depleted underground zone and in the adjacent virgin coal for proven, permanent, and stable geological sequestration.
- The injection of CO₂ additionally pushes saline formation water into the gasification panel, increasing hydrogen recovery.
- EHR™ requires deep coal resources that are not considered recoverable by surface / underground coal mining, or functional for coal bed methane. There are 30-50 trillion tonnes of suitable resource around the world, providing value to a stranded, neglected resource.
- Huge amounts of the most suitable resources for EHR™ are in China, India, Indonesia, and other emerging economies with massive, growing emissions. EHR™ is the most realistic, cost-effective way to decarbonise these coal-dependent countries.

KEY PROJECTS

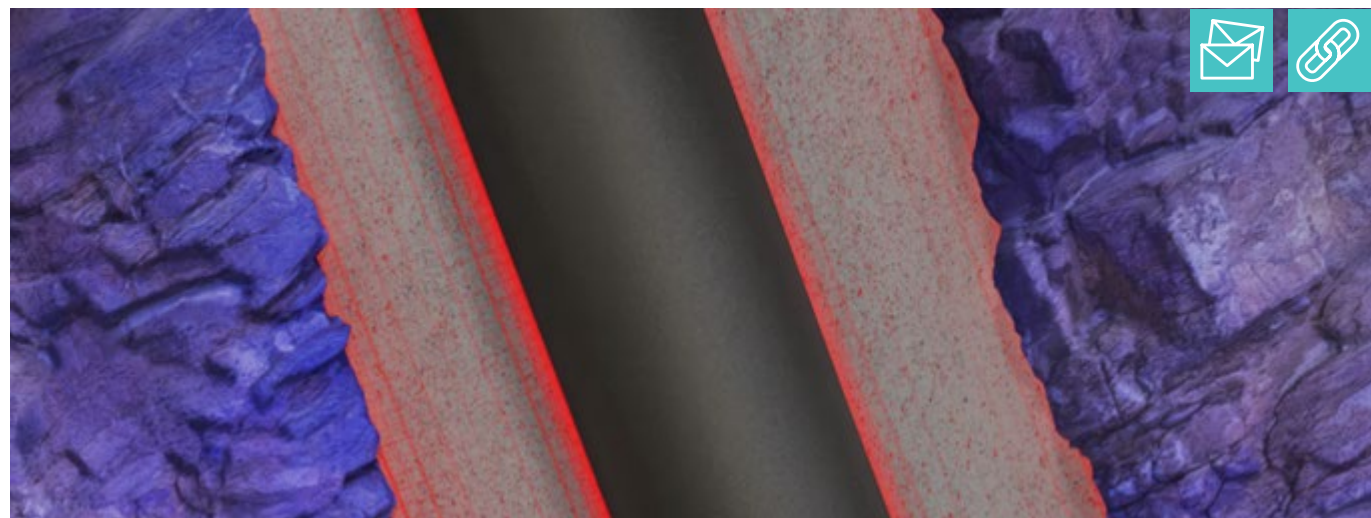
- Cvictus is building their first 'small' commercial plant in Alberta, Canada that will produce 2,500 tonnes a year of clean hydrogen while sequestering all produced CO₂ onsite – proving their patented EHR™ and CCS technology for commercialisation.
- The commercial facility will be located at the same site Cvictus and a team of experts injected a total of 1,512 tonnes of CO₂ into a 1,500-meter deep single coal seam in Alberta in 2022.
- EHR™ combines two proven technologies – Underground Coal Gasification (UCG) and CCS to produce the lowest cost, lowest carbon intensity chemical feedstocks.
- UCG has a 60+ year history of successful operations with Cvictus founders leading recent successful demonstrations in New Zealand, Australia, and South Africa.
- A [recent peer reviewed paper](#) in the International Journal of Coal Geology summarises analysis and results from the 2022 CO₂ injection program and the potential for deep coal as a sink for CO₂ sequestration.

KEY DATA

TRL	5	Number of Commercial Plants	0	Number of Pilot Plants	1
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HALLIBURTON HALLIBURTON

CORROSALOCK™ CEMENT SYSTEM



SUMMARY

Cementing wells for carbon capture, utilization, and storage (CCUS) presents unique challenges for maintaining barrier integrity and long-term stored CO₂ containment. CCUS projects aim for permanent underground CO₂ storage, which requires long-term cement sheath chemical and mechanical stability. Factors like temperature and pressure cycles and chemical interactions can impact the cement integrity over time. CO₂ produces carbonic acid in the presence of water, which can degrade conventional Portland cement. Cement used with CCUS applications must be resistant to CO₂ exposure.

CCUS operations inject CO₂ deep into subsurface formations, typically at elevated pressures. For this reason, cement slurry design and placement techniques must help ensure proper bonding of cement to the wellbore and formation to provide a reliable and impermeable seal. Halliburton has decades of experience in annular barrier design for corrosive environments and applies proven material selection and best practices to support long-term CO₂ storage. The CorrosaLock™ cement system, part of the Halliburton's CCUS solutions portfolio, delivers improved chemical resistance to CO₂ and is tailored with mechanical properties that minimise the impact of cyclic loading on the mechanical integrity of the cement barrier.

BENEFITS

- Resistant to chemical alteration caused by carbonation and other corrosion reactions
- Combats the effects of stress induced by downhole conditions and injection operations
- Provides improved bonding between the formation, cement, and casing

FEATURES

- Significantly reduces permeability compared to conventional Portland cement slurry designs
- Delivers improved elasticity and shear bond strength

KEY DATA

TRL	9
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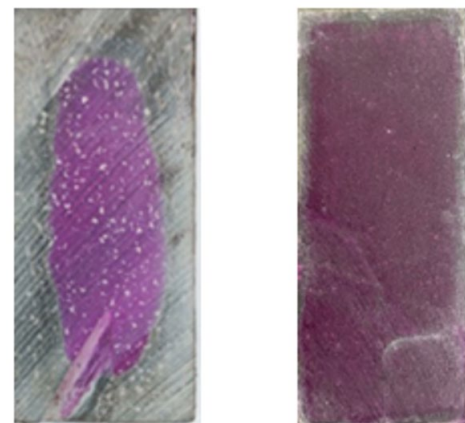
TECHNOLOGY DESCRIPTION

The Halliburton CCUS solutions portfolio includes non-Portland, modified Portland, and reduced Portland products. These solutions use tailored chemistries, pure resin, cement and resin composites, and additives to improve mechanical properties. They also reduce the set cement permeability and help deliver an improved CO₂-resistant barrier with long-term integrity.

REDUCED PORTLAND SOLUTION

CorrosaCem™ cement system

CorrosaCem™ cement system is designed to minimise components that readily react with CO₂. Supplementary cementitious materials (SCMs), that reduce reactivity with CO₂, replace a portion of the Portland cement in the system. This feature improves the CO₂ corrosion resistance of the system. The modification of the blend with other additives lowers the permeability of the system, which mitigates the potential for CO₂ to penetrate the cement matrix. Elastomers and fibers enhance the system's elasticity to provide a more elastic barrier. This provides a more crack-resistant system to help withstand downhole forces during cyclic injection compared to conventional Portland systems.



(left - Portland cement; right - CorrosaCem™ cement)
Phenolphthalein, a pH stain, provides visual clues of carbonation. Purple represents unaltered cement. The results of CorrosaCem cement after one month of static supercritical CO₂ exposure at 100°F show improved resistance to CO₂, chemical alteration compared to conventional Portland cement.

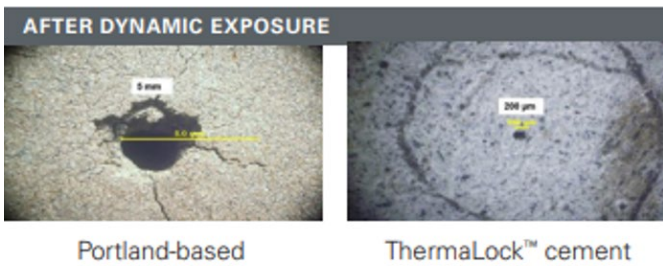
NON-PORTLAND SOLUTIONS

WellLock® resin system

WellLock® resin is a non-Portland system that does not chemically react with CO₂ and has ultralow permeability. Those two features help the system provide outstanding CO₂ corrosion resistance. WellLock® resin also provides superior mechanical properties to deliver improved performance. The high elasticity of the system compared to conventional cement barriers helps the system better withstand the stresses induced by the cyclic load of injection operations, which helps prevent mechanical failure of the barrier. WellLock® resin also provides improved shear bond strength, which helps the system better anchor to the casing and formation. This can significantly minimise debonding, which can create pathways for CO₂ flow up to the surface.

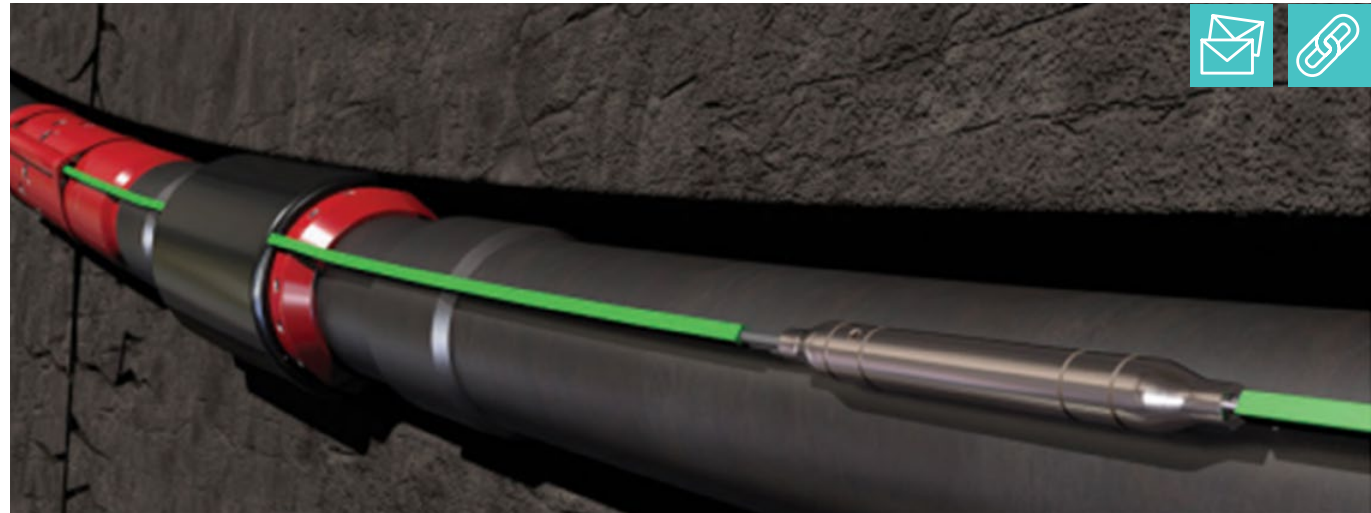
THERMALOCK™ CEMENT SYSTEMS

ThermaLock™ cement system, a specially formulated calcium aluminate phosphate cement, resists both CO₂ and acid corrosion. Developed for high-temperature geothermal wells and CO₂ environments, it offers superior thermal and chemical stability under ultrahigh-temperature and corrosive environments with a lower permeability than Portland-based designs. Mechanical properties modifiers are added to improve the elasticity of the system and help make the cement barrier more resilient to the cyclic loading imposed by CO₂ injection and storage operations.



After dynamic, supercritical CO₂ exposure at 180°F for 12 weeks, ThermaLock™ cement system exhibits no change compared to Portland cement where the CO₂ flow path expands from 200 Micron to 5 mm.

DATASPHERE® CS PERMANENT DOWNHOLE MONITORING SYSTEMS

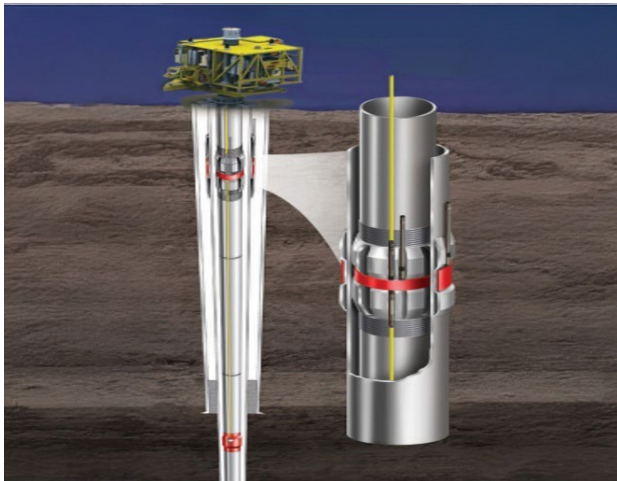


SUMMARY

Halliburton’s robust CO₂ well design portfolio includes in-well sensing technology and continuous parameter collection. A combination of electronic gauges and fiber optic technology can address conformance and containment risks as well as mitigating CO₂ injection uncertainties and ensure regulatory compliance. The devices can provide reliable in wellbore and behind casing, real-time, long-term data for reservoir characterization. Fully customizable, the sensors are essential to monitor injection and help verify CO₂ containment.

BENEFITS

- Continuous and reliable pressure and temperature data without the need for well intervention
- Enhanced reservoir management – Pressure, Temperature, DTS, DAS, DSS, VSP, MSM, MIT
- Increased system reliability using stable pressure/temperature measurements
- Quartz-based sensor for high accuracy, low drift
- Regulatory compliance
- Operational efficiency
- Integrated data visualization via Clariti® platform and Visum® service



KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

FEATURES

- Flexible electronic and fiber solutions – hybrid or standalone
- Designed to monitor in harsh environments down to -35°C with survivability down to -80°C
- Demonstrated downhole gauge reliability 10 years at 185°C
- Onboard intelligent quartz gauge diagnostics
- Simplified systems with multiple sensor options
- Field-testable dual metal-to-metal (MTM) seal
- Fault-tolerance features for maximum reliability

DOWNHOLE GAUGES

Opsis® CS

Opsis gauges can be used for single or multi-zone monitoring applications. These gauges may be ported to tubing, annulus, or control line. The addition of feed-through or splitter block assemblies enables the monitoring of multiple zones. Using industry-proven resonating quartz crystal sensors, these systems use the latest generation of ASIC electronics to provide highly accurate pressure and temperature data calibrated down to -35°C and proven survivability to -80°C.

Array CS

Using the same sensor and electronics technology, the Array CS system provides a slimline electronic gauge design for distributed pressure and temperature sensing. Sensors are embedded into the TEC during manufacturing to provide the customer with a seamless and customizable solution.

LinX®

Wireless inductive coupling technology that captures accurate real-time reservoir data without halting production. The system is ideal for caprock and annulus monitoring.



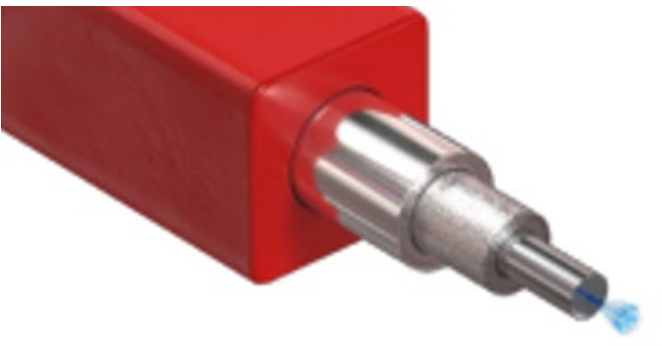
Opsis® permanent downhole single sensor gauge.

APPLICATIONS

- Riser/umbilical monitoring
- VSP
- MSM
- Caprock integrity
- Out of zone injection
- Well monitoring
- Stimulation operation monitoring
- Cement evaluation (MIT)
- Subsidence monitoring

FIBER OPTIC

Fiber-optic monitoring allows vertical seismic profiling (VSP), micro-seismic monitoring (MSM), and the assessment of external and internal mechanical integrity testing (MIT) of wellbores. Trigger events that indicate containment risk are derived in real time from distributed acoustic sensing (DAS), distributed temperature sensing (DTS), and distributed strain sensing (DSS).



DataSphere® CS permanent monitoring system with fiber-optic cable detail.

Opsis® CS and Array CS temperature performance

Accuracy (°C)	0.5
Typical accuracy (°C)	0.15
Achievable resolution (°C/sec)	<0.005
Repeatability (°C)	<0.01
Drift at 177°C (°C/year)	<0.1
Survivability (°C)	-80
Calibrated operating range (°C)	-35 to 150

Opsis® CS and Array CS pressure performance

PRESSURE RANGE PSI/BAR	ACCURACY* PSI	TYPICAL ACCURACY* PSI	ACHIEVABLE RESOLUTION PSI/SEC	DRIFT AT 14 PSI AND 25°C*	MAXIMUM DRIFT AT MAXIMUM PRESSURE AND TEMPERATURE** PSI
200 to 10,000 13.8 to 690	0.015 (1.5)	0.012 (1.2)	<0.006	Negligible	0.02 (2.0)

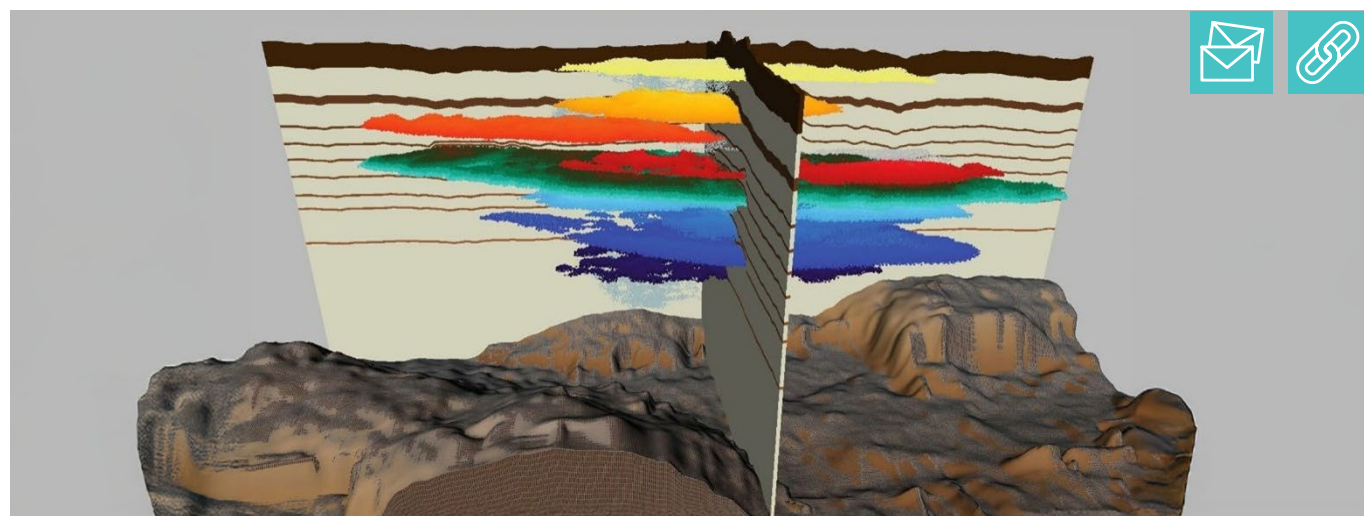
*% FS, ** %FS/Year

Fiber performance

PRESSURE RATING PSI/BAR	NUMBER OF FIBERS	MINIMUM OPERATING TEMPERATURE (°C)	MAXIMUM OPERATING TEMPERATURE (°C)	PARAMETERS AVAILABLE	ANSWER PRODUCTS
20,000	Up to 10	-82	150	DAS/DTS/DSS	MSM/VSP/ MIT

HALLIBURTON HALLIBURTON

DECISIONSPACE® 365 CO₂ STORAGE SOLUTION



SUMMARY

CO₂ Storage Solution provides flexible, integrated workflows for subsurface characterization, well integrity evaluation, and comprehensive risk assessment. It supports the CCS lifecycle—from early site screening through CO₂ storage modeling and permitting—helping reduce uncertainty and predict long term site performance. Within CO₂ Storage Suite, advanced geoscience modeling capabilities enable operators to mitigate risk, optimise injection strategies, and ensure secure, durable CO₂ storage.

The entire suite is delivered on the cloud and enables a flexible approach to accessing and using these tools to optimise interpretation and modeling at each critical stage of the CO₂ storage lifecycle (Figure 1). It's empowered with industry-validated tools, enabling efficient, cost-effective CCS projects through on-demand storage capacity insights, scenario modeling for plume capacity and containment, pressure and brine displacement modeling, and injectivity planning. The solution also facilitates specific workflows designed between applications to optimise modeling and create a greater efficiency for more timely results and decisions.

BENEFITS

Building confidence from screening to concept selection: Provides a suite of industry validated tools that streamline the early stages of the CO₂ storage lifecycle, from site screening in the Initiate phase to feasibility assessment in the Assess phase and focused concept development in the Select phase (Figure 1).

- **Capability optimization:** Helps build and optimise carbon storage capabilities with an open and cost-effective software solution.
- **Lower CAPEX:** Open software architecture allows easy integration with existing software investments.
- **Collaborative:** A multi-user environment supports effective teamwork, and knowledge transfer.

Performance optimization: Accelerates the time to Final Investment Decision (FID) with automated CO₂ specific workflows.

- **Automated workflows:** Automated feasibility characterization and pre-FEED workflows help optimise lifecycle efficiency.
- **CO₂ specific:** Industry-validated tools and workflows designed specifically for CCS projects to provide accurate insights (Figure 2).

KEY DATA

TRL

9

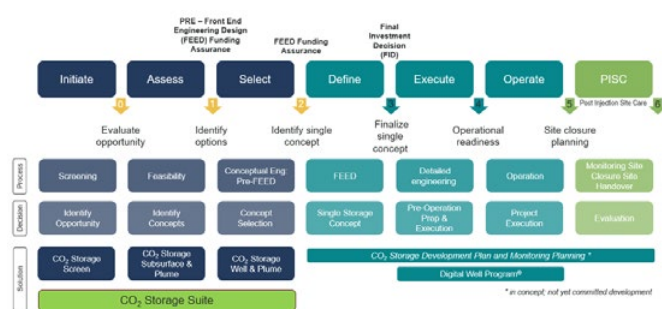


Figure 1: CO₂ storage lifecycle and different stage-gate processes

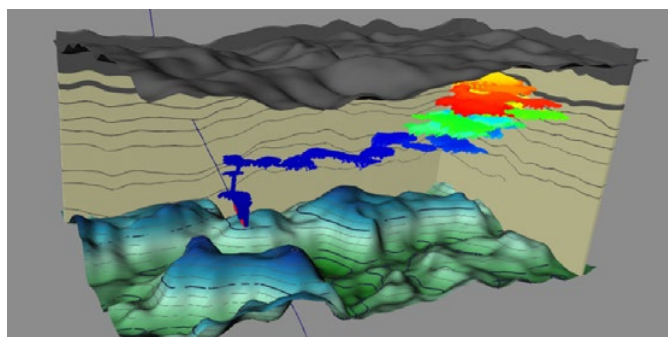


Figure 2: CO₂ Plume Migration modeled using CO₂ Storage Plume powered by Permedia® Simulator service

TECHNOLOGY DESCRIPTION

BASIN SCREENING

Evaluate large scale storage potential in any basin with ease

CO₂ Storage Screen provides automated workflows to rapidly identify and evaluate potential for storing CO₂ in saline aquifers in any basin in the world, leveraging a geologically consistent subsurface knowledge base. This tool helps to dramatically reduce time to first assessment of a region, accelerate the process of identifying sweet spot for future storage potential, and allows teams to focus attention on highly prospective areas (Figure 3).

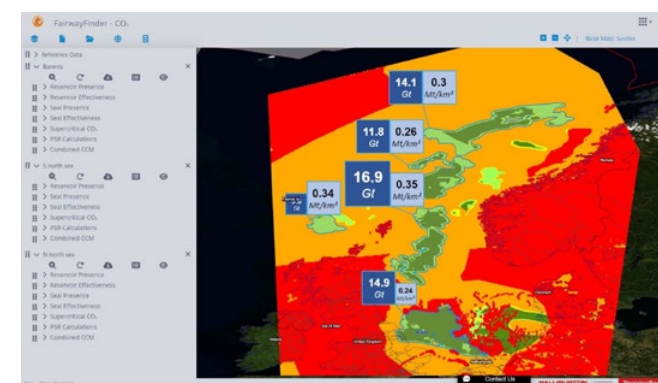


Figure 3: Site screening performed by CO₂ storage screen highlighting prospective fairways identified in the North Sea. Prospective storage resources are visualised for quick comparison and rank different fairways.

GEOSCIENCE SUITE

Reduce your subsurface uncertainty

The Geosciences Suite combines innovative technology and a tightly integrated, end-to-end suite of cross-domain workflows to increase subsurface understanding, reduce uncertainty in CO₂ projects, and help to tackle future energy challenges.

PLUME MIGRATION MODELING

Understand the capacity and containment of the long-term fate on injected CO₂

Integrated suite of high-resolution modeling tools for CO₂ storage capacity and containment assessment. The software addresses key aspects of CO₂ Storage workflows outlined below:

CO₂ migration: A CO₂-adapted modified invasion percolation simulator for multi-phase plume modeling. Built on the Permedia CO₂ Toolkit, it delivers extremely high-resolution models of gravity-segregated plume distributions in variably heterogeneous reservoir settings (Figure 2). This is particularly helpful for understanding long-term CO₂ plume behavior and assessing site feasibility for containment assurance.

CO₂ flow: A high-resolution hydrodynamic solver for modeling CO₂ storage-related pressure changes.

CO₂ flow simulates regional scale pressure changes from brine displacement using a high resolution heterogeneous model, providing insight into pressure dissipation and enhancing the safety and long term integrity of CO₂ storage operations.

CO₂ dashboard: A CO₂-specific equation-of-state and PVT wizard for initializing simulations with accurate CO₂ and brine properties. Validated against published theoretical and experimental data, it enables seamless transfer of initial conditions to CO₂ simulators, ensuring accurate subsurface characterization and reliable plume and trapping predictions.

CO₂ BOS: A fast multi-threaded black oil simulator that leverages Darcy flow physics to model CO₂ storage and solubility trapping. Specially adapted for two-phase (i.e. CO₂ and brine) modeling, CO₂ BOS is built on the Permedia® CO₂ Toolkit service and addresses reservoir engineering workflows for CO₂ modeling in storage site settings. Specifically tuned to run CO₂ injection out-of-the-box, CO₂ BOS is fast, with built-in CO₂ injection scheduling, PVT, and solubility handling.

STORAGE RESOURCE CHARACTERIZATION

Understand and characterise storage resources for long-term CO₂ storage characterise storage resource formations and sites to understand storage resource characteristics to help provide for safe, long-term containment of injected CO₂. Interpret and manage geological data with predictive tools that provide insight into storage resource characteristics from data-sparse saline basins to data-rich oil and gas assets designated for CO₂ storage.

WELLBORE AND COMPLETION SIMULATION FOR CO₂

Evaluate large scale storage potential in any basin with ease

Design highly detailed wellbore and completion simulations for CO₂ storage sites (Figure 4). Address all phases of injectivity planning and operations from injection well design to execution control.

Figure 4: NETool® Completions and CO₂ Phase Analysis



HALLIBURTON HALLIBURTON

NEOSTAR™ CS TUBING-RETRIEVABLE SAFETY VALVE



SUMMARY

The Halliburton NeoStar™ CS tubing retrieveable safety valve (TRSV) single rod-piston non-elastomer flapper valve is designed for hostile environments and extended life applications where ultimate reliability is required. Halliburton based the NeoStar CS TRSV on the industry-proven SP™ platform to be a robust solution for carbon capture, utilization, and storage (CCUS) applications.

The NeoStar CS TRSV builds upon all the key features of the legacy SP safety valve by being equipped to handle ultralow temperature operation and survival scenarios required for CCUS applications. The “CS” designation was earned through qualification to CCUS industry test protocols where operability and survivability were proven at temperatures down to -35°C and -78.5°C. Having been validated in the vertical position ensures optimal performance in CCUS applications

BENEFITS

- Low-temperature, non-elastomer dynamic piston seals
- API validated
- Non-equalizing for CCUS environments
- MTM static seal at upper and lower piston positions with MTM body joints

FEATURES

- Reliability of hydraulic actuator; dynamic and static seals independently verified gas-tight
- Control line isolated from well fluid by MTM seal with valve in closed position
- Hydraulic system isolated from well pressure by MTM seal with valve in open position
- MTM thread sealing and self-locking capability

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

TUBING SIZE (IN.)	PRESSURE RATING (PSI/BAR)	TEMPERATURE RATING	MAX. OD (IN.)
3.5	10,000 (689)	"Survival: -78.5C (-109F) Operating: -35C to +177C (-31F to +350F)"	5.86
4.5	10,000 (689)	"Survival: -78.5C (-109F) Operating: -35C to +177C (-31F to +350F)"	7.35
5.5	10,000 (689)	"Survival: -78.5C (-109F) Operating: -35C to +177C (-31F to +350F)"	7.69
7	7,500 (517)	"Survival: -78.5C (-109F) Operating: -35C to +177C (-31F to +350F)"	8.9

OPERATIONAL RELIABILITY AND SURVIVABILITY FOR CCUS APPLICATIONS

The NeoStar™ CS TRSV can minimise potential leak paths within the valve attributed to its single rod-piston design. The piston achieves a metal-to-metal (MTM) seal at its uppermost and lowermost positions to seal well pressure from the control system.

The low-temperature rod-piston design in the Halliburton NeoStar™ CS TRSV has been qualified as gas tight throughout all operating and survival conditions, thus providing higher reliability across CCUS temperature ranges.

A safety valve that can dynamically operate effectively at extreme temperatures under transient conditions and seal during a survival scenario in the most extreme temperatures is vital to well integrity.

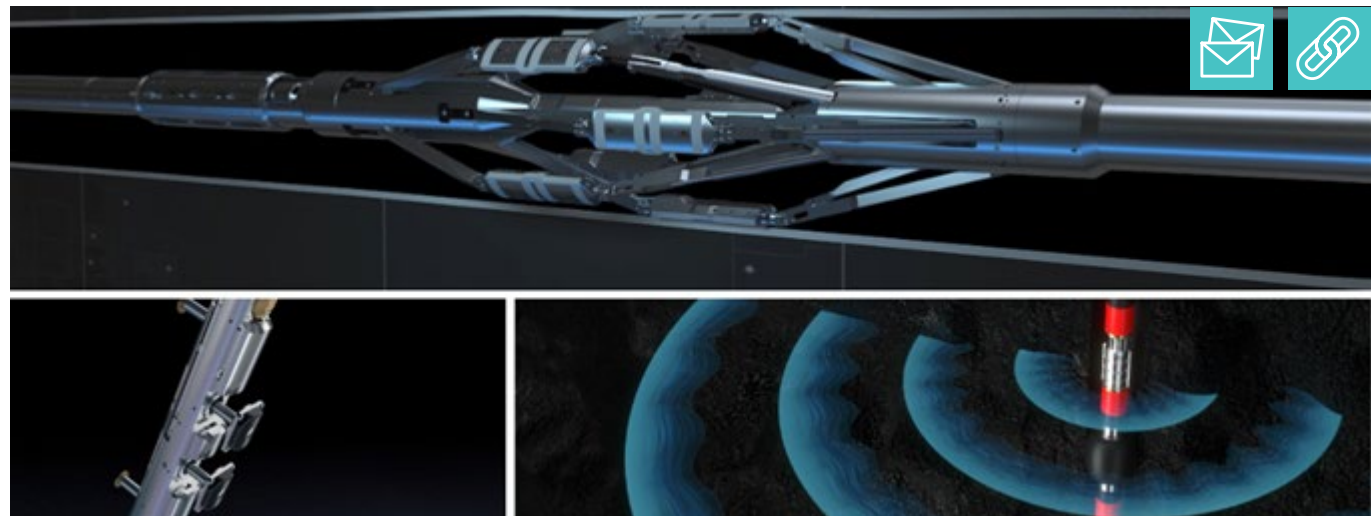
Halliburton offers a diverse range of API qualified non-elastomeric safety valve designs in the sizes demanded by the CCUS industry, which helps provide full MTM containment in both open and closed positions. For permanent CCUS monitoring operations, slim OD solutions are available that allow the passage of gauge, fiber-optic, and hydraulic lines. These designs can be customised to suit shallow or deep-set applications.

The Halliburton in-house Material Science Center of Excellence located in Singapore is heavily invested in testing metallic and non-metallic materials in simulated CCUS environments to gain the appropriate knowledge to help select suitable materials for both environmental compatibility and cost effectiveness. These facilities are equipped to perform low-temperature testing on full-scale completion technology at temperatures down to -80°C as part of the ongoing CCUS safety valve operating life test program for industry demanded safety valve sizes.



HALLIBURTON HALLIBURTON

XAMINER® RESERVOIR CHARACTERIZATION SERVICE



SUMMARY

Turn subsurface uncertainty into early, decision ready insight to move faster with less compromise. Reduce rig time through efficient, single run data acquisition that directly supports injection planning and long term storage decisions. Reduce uncertainty in capacity, injectivity, and containment—the critical factors that determine whether CO₂ can be safely stored and remain confined over time.

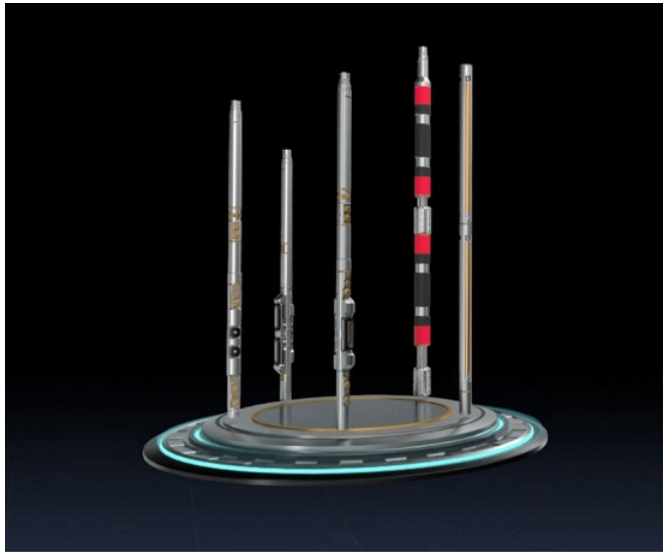
Xaminer reservoir characterization service strengthens confidence in subsurface models by quantifying heterogeneity, anisotropy, fractures, and stress drivers. It integrates formation pressure gradients, representative fluid properties, and dynamic reservoir behavior to evaluate not only the storage reservoir, but also upper and lower confining layers and dissipation zones, helping verify containment integrity and protect underground sources of drinking water.

BENEFITS

- Reduce subsurface uncertainty with early, decision-ready insight
- Move faster with fewer compromises across completion and development planning
- Strengthen confidence in reservoir models to focus time and capital on the most productive intervals

Features

- Single run acquisition of pressure, fluid, and dynamic reservoir data
- Quantification of heterogeneity, anisotropy, fractures, and stress drivers
- Integrated pressure gradients, fluid properties, and reservoir behavior



KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

Make faster, more confident reservoir decisions with next generation subsurface insight. The Xaminer® reservoir characterization suite delivers vital petrophysical and fluid data for exploration, production, and injection.

XAMINER® SONIC IMAGER (XSI)

Reduce uncertainty in geomechanics and seismic interpretation with high-fidelity sonic insight that reveals true formation properties beyond the altered zone. Gain insight into rock physics inputs, stress tensors for geomechanics model, stress anisotropy.



STRATAXAMINER™ BOREHOLE IMAGING SERVICE (STX)

Reduce subsurface uncertainty with high resolution borehole images in oil and synthetic based mud that deliver stress orientation and tensile fractures, identify faults, and reveal how laminations and heterogeneity can impact injectivity and reservoir conformance.

RESERVOIR XAMINER™ FORMATION TESTING SERVICE

Reduce subsurface uncertainty with in-situ stress tests for direct calibration of the geomechanics model, pressure, and fluid insight that enables confident reservoir decisions, injectivity and containment evaluation, and effective DST screening in complex formations.

XAMINER® MAGNETIC RESONANCE (XMR™)

Reveal true reservoir quality with high resolution magnetic resonance insight that characterises pore size, permeability, and free versus bound fluids, clarifying how much pore space is truly available for CO₂ storage in a single, efficient logging run.



X-TENDED RANGE MICRO IMAGING (XRMI™)

See fine scale reservoir detail with high resolution borehole images that reveal bedding, fractures, and rock texture even in highly resistive formations.



XAMINER® CORING TOOL

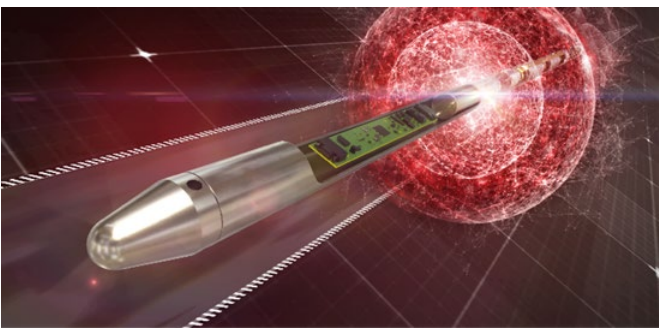
Capture high quality, undisturbed core in hard and soft rock formations to assess preexisting formation damage, adjust operations in real time, and optimise recovery in challenging reservoirs.

GEM™ ELEMENTAL ANALYSIS TOOL

Deliver quick, precise elemental evaluation to strengthen integrated petrophysical analysis, estimate mineral fractions and matrix density, and improve key property calculations even in challenging conditions.

INTELLISAT™ PULSED NEUTRON LOGGING SERVICE

Increase production confidence with accurate oil, water, and gas saturation insight through tubing in any well condition, delivered faster with a single pass pulsed neutron solution.

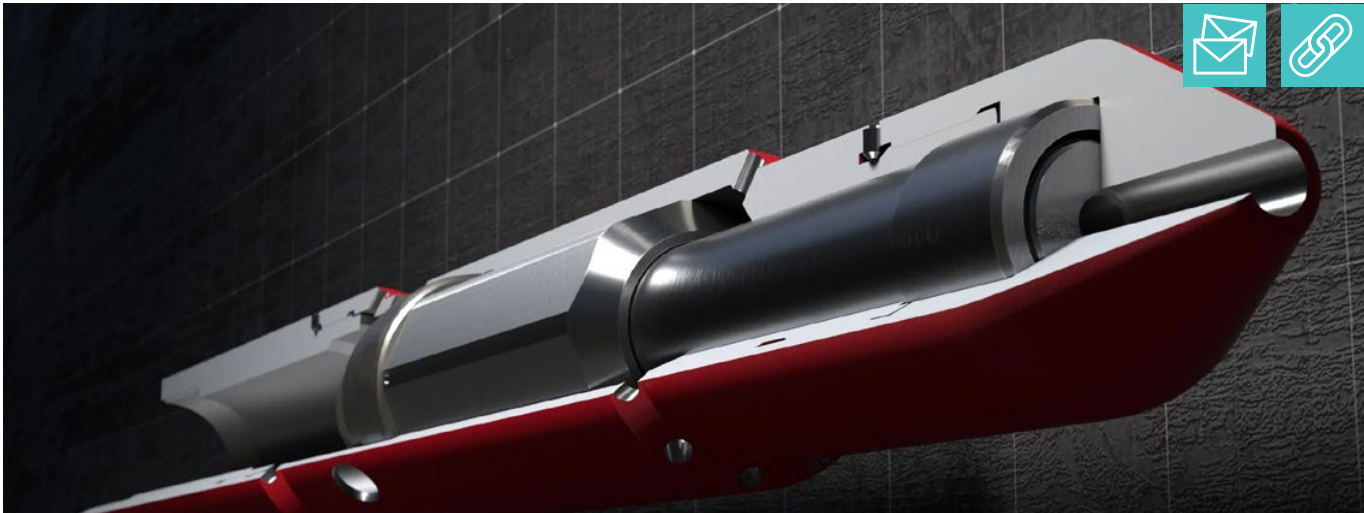


DIGITAL ROCK ANALYSIS

Gain faster, more reliable reservoir insight by integrating digital and physical core analysis into a single, transparent workflow that supports better decisions at every stage.

HALLIBURTON HALLIBURTON

XTR™ CS INJECTION VALVE



SUMMARY

The XTR™ CS injection valve is a compact, spring-loaded, full metal-to-metal design engineered for CO₂ injection and CCUS wells where reliability, high injection rates, and low-pressure drops are critical.

Qualified for extreme temperature environments, the valve is deployed as part of the XTR™ CS injection system, which includes a non-elastomeric lock mandrel/ landing nipple. The valve remains closed via a spring-loaded metal-to-metal poppet and seat mechanism. Upon injection, the poppet is easily displaced to allow smooth flow. As flow increases, a proprietary anti-throttling mechanism helps ensure the valve stays fully open to minimise chatter and extend service life. When injection stops, the spring returns the poppet to its seat to help prevent backflow.

BENEFITS

- Simplifies inventory and planning; installable at any depth
- High injection rates with smooth flow profile, minimal pressure drop
- Bypass ports reduce debris buildup
- Longevity and erosion protection
- Opens with minimal flow and optimal sealing when closed
- Patented anti-throttling keeps valve open, reduces wear
- Easy installation, repositioning, and retrieval

FEATURES

- Depth insensitive
- Minimised leak paths
- Large flow area
- Self-cleaning design
- Full metal-to-metal body
- Metal-to-metal poppet sealing
- Low opening pressure
- Anti-chatter
- Wireline deployment

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

The XTR™ CS injection system offers a robust solution for ultralow-temperature CO₂ injection, serving as a primary non-return valve, contingency insert valve, or deep-set flowback prevention device. The valve's depth-insensitive design allows installation at any point in the wellbore without adjustment to simplify planning and logistics, while also eliminating concerns about hydraulic fluid mobility at CCUS temperatures, which can impact the functionality of surface controlled wireline deployed options.

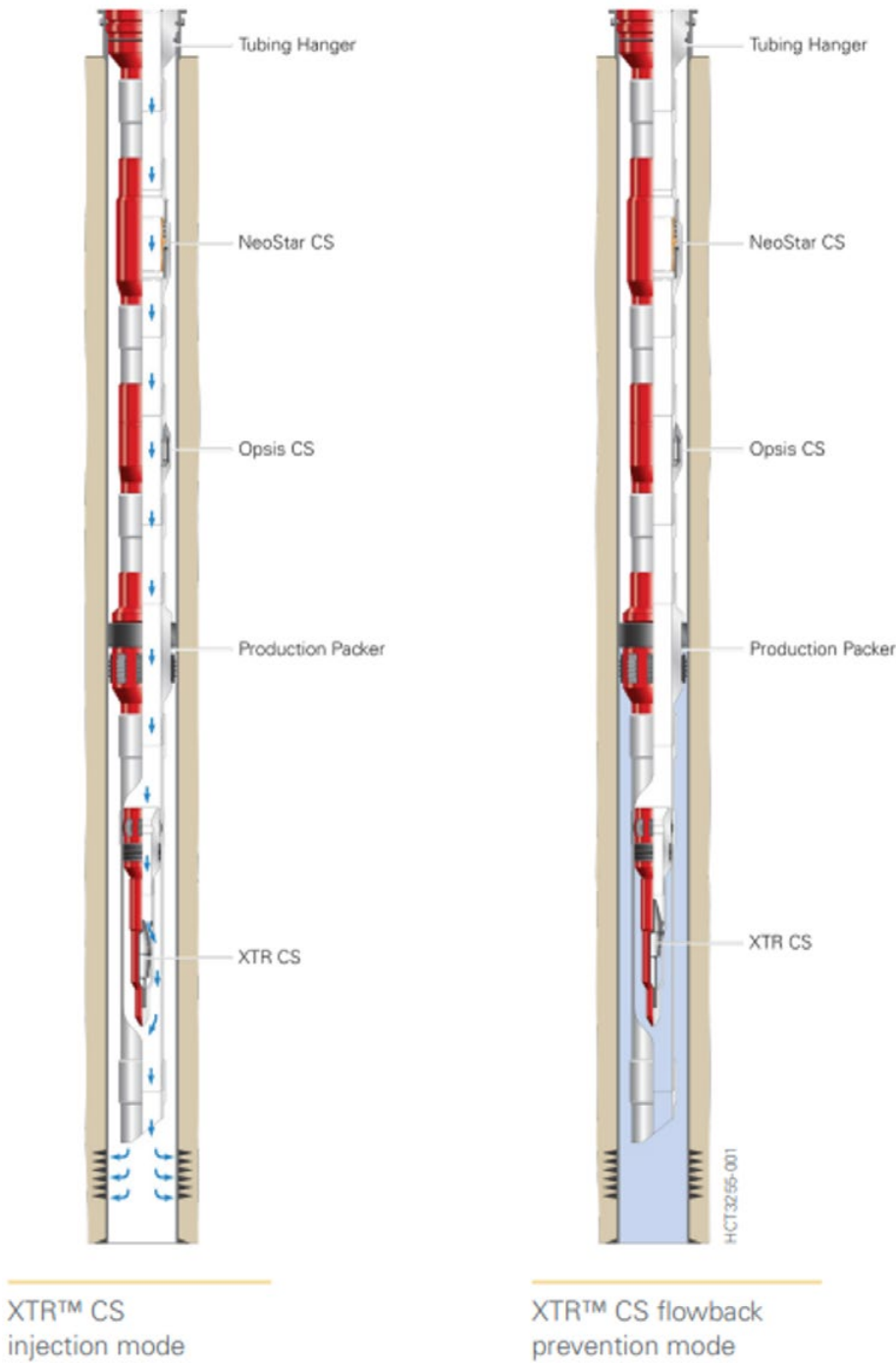
DEBRIS AND FLOW

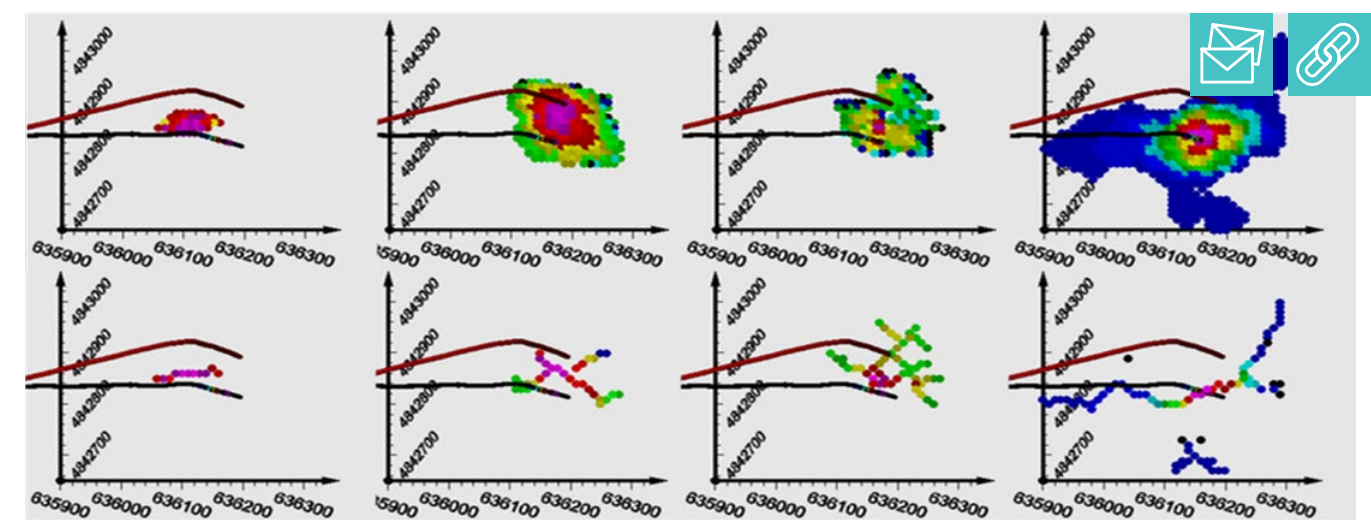
Poor injection medium cleanliness is a leading cause of injection valve failure. To combat this, the XTR™ CS injection valve incorporates cleanout jetting ports in its main body to

minimise debris buildup. Additionally, specialised materials protect key components exposed to flow, which safeguards sealing surfaces from erosional damage—especially in high-debris environments. The poppet geometry is also optimised to deflect solids away from the seal face to provide further erosion resistance during injection.

SPECIFICATIONS

- Operating temperature range: -31 to 350°F
- Survivability temperature rating: -109°F
- Pressure rating: up to 10,000 psi
- Flow rating: up to 2.5 MTPA
- API 14A validation grade: V3-R





SUMMARY

PFI™ (Permeable Fracture Imaging) is a passive seismic technology that directly maps the subsurface permeability field including the fluid-filled fractures, joints, faults, and fault zones that form connected pathways governing fluid migration in rock. PFI deploys hundreds to thousands of time-synchronised surface seismic receivers to passively detect seismic emissions generated by stress-driven fluid-rock interactions within these structures. The signals are processed into high-resolution three-dimensional volumes, achieving detail one to two orders of magnitude finer than magnetotelluric methods. No controlled seismic source or downhole instrumentation is required. For CO₂ storage, PFI de-risks site selection and operations by characterising the fracture connectivity that controls reservoir injectivity, caprock sealing integrity, and potential leakage pathways. PFI is fundamentally different from microseismic monitoring, which requires microearthquakes. A passive technique, PFI directly maps permeability structures continuously, which enables pre-injection site characterisation, ongoing plume migration monitoring, and storage conformance verification throughout a CCS project's operational life.

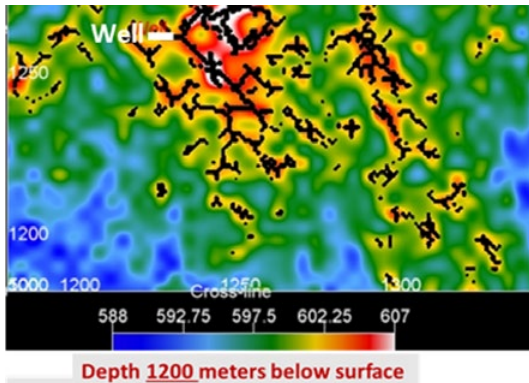
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BENEFITS

- **Pre-injection Characterisation:** PFI maps the subsurface fracture network before CO₂ injections begin, characterising connected permeability pathways, caprock integrity, and potential leakage sites to inform site selection and well placement.
- **Ongoing Storage Monitoring:** During injection and post-closure, PFI tracks changes in fracture connectivity driven by fluid migration.
- **Passive:** PFI requires no active seismic sources or downhole instrumentation. By imaging fracture emissions directly, permeability structures are predictive rather than reactively mapping failure events after they occur.
- **Non-invasive:** Surface nodal arrays have minimal operational disruption and high repeatability.

KEY PROJECTS

Newberry Volcano, Oregon (2023 & 25): Deployed up to 1325 seismic receivers across 37 km² to map permeable fracture architecture surrounding a 3 km deep well. PFI resolved NNW-trending normal faults, correlated with well log density and lithology, and identified a low-permeability clay cap validated against magnetotelluric resistivity data. Mapped fluid flow between a well doublet during active injection, and plume tracking.



KEY DATA

TRL	8	Target Depth Range (km)	0.5 - 4.5+	Spatial Resolution (m)	Up to 8 m
Node count	1000+	Field Recording Time (weeks)	~1	Source Requirements	None
Target Industries	CCS characterisation and monitoring; Geothermal; O&G; Wastewater; Fracture detection in mining				



INNOVEX

CARBON INJECTION AND MONITORING WELLHEADS



SUMMARY

An essential component of CCS is injecting and permanently storing CO₂ into underground reservoirs. As a result of the merger with Dril-Quip, Innovex specialises in equipment that facilitates the well construction, injection, and post-injection monitoring of CO₂. This equipment is colloquially known as a wellhead. Whether your injection location is onshore, offshore, or subsea, Innovex provides wellhead products specifically designed for the unique requirements of CCS.

Innovex's CCS wellheads are tailor-made for CCS applications by addressing the unique risks of CO₂ injection that are not always present in traditional wellhead use cases. Two particular risks are the corrosiveness of CO₂ when water is introduced, and the cryogenic effects when a pressure drop in CO₂ occurs across an orifice. Innovex is conducting materials testing through third party laboratories and seal testing in-house, specific to CO₂ injection requirements to ensure our products are suitable for these scenarios.

BENEFITS

- Track record from early mover projects
- Bespoke products designed specifically for CCS
- Engineered to tolerate low purity CO₂ and Carbonic Acid
- Low-Temperature Seals and Materials Compatible with Joule-Thomson cooling effects
- Equipment provisions for CO₂ monitoring and pressure management, including fiber optics behind the injection casing.
- Up to 7-1/16" valves for faster injection rates.

KEY PROJECTS

- **Greensands:** First injection in March 2023 via Offshore Platform Wellhead
- **Alberta Carbon Grid:** Equipment for 3 CCUS appraisal wells, 2023
- **Heartland Carbon Project:** 4 Wellheads ordered, 2023
- **Subsea CCS Exploration Well:** 1 Wellhead ordered in 2024
- **Enbridge:** 15+ years providing engineered wellhead systems included +200 cavern and monitoring wells

KEY DATA

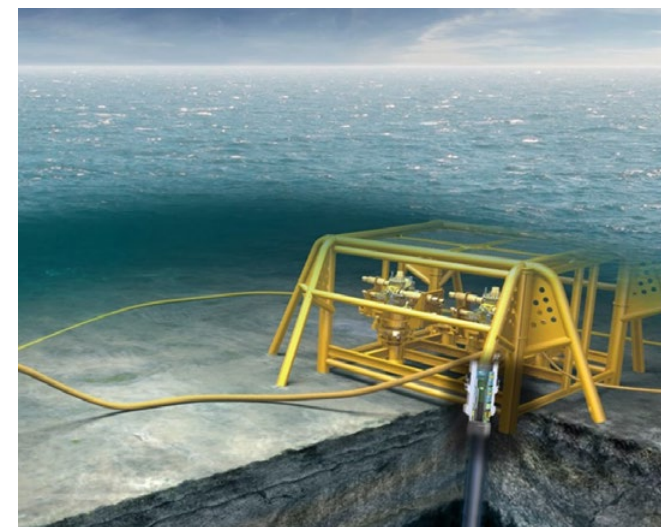
TRL	7 - 9	Source CO ₂ Purity Range	No Limit	Temperature Range	-75°F to 250°F (-60°C to 121°C)
Injection Pressure Rating	Up to 15 kpsi (104 Mpa)				
Target Industries	~				

TECHNOLOGY DESCRIPTION

Innovex has three types of injection wellheads, each unique to the injection location: onshore, offshore-from-a-platform, and subsea. Each product's design has been re-engineered for CO₂ injection purposes.

ONSHORE

Innovex has an extensive track record in gas storage and CO₂ injection for EOR (enhanced oil recovery) purposes. This experience lends itself to supporting your CO₂ injection projects including permitting applications. Onshore wellhead products can easily facilitate the installation of fiber optic cables behind the casing string to support monitoring, measurement, and verification (MMV) plans.



OFFSHORE

Innovex has a long history of serving the offshore industry. Offshore storage wells have the unique advantage of being located away from communities and in remote locations. Innovex's offshore wellhead products can be subdivided into two categories: Platform Wellheads and Subsea Wellheads.

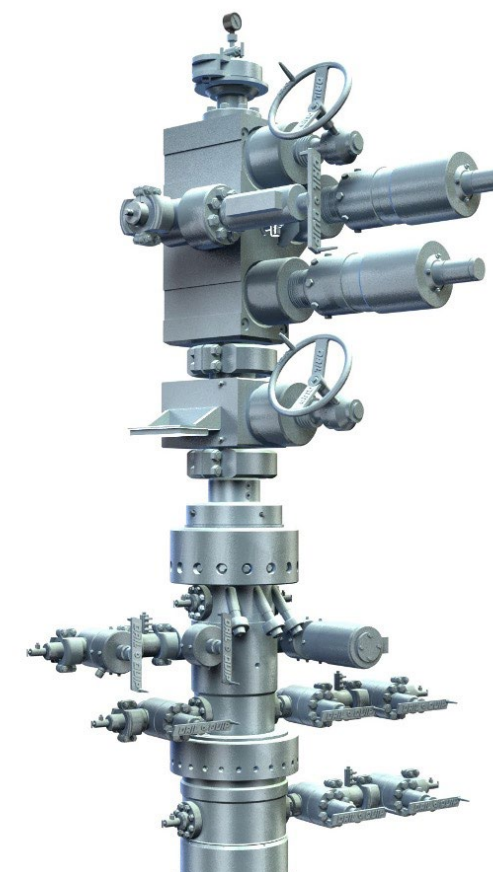
Platform Wellheads

Innovex's Platform Wellheads reside on semi-permanent platform structures, providing offshore access to CO₂ storage reservoirs beneath the seabed. Because these wellheads remain above the ocean surface, they provide similar MMV advantages to onshore wellheads, but can be located in remote offshore locations. These wellheads operate safely and efficiently within the unique constraints of an offshore environment.



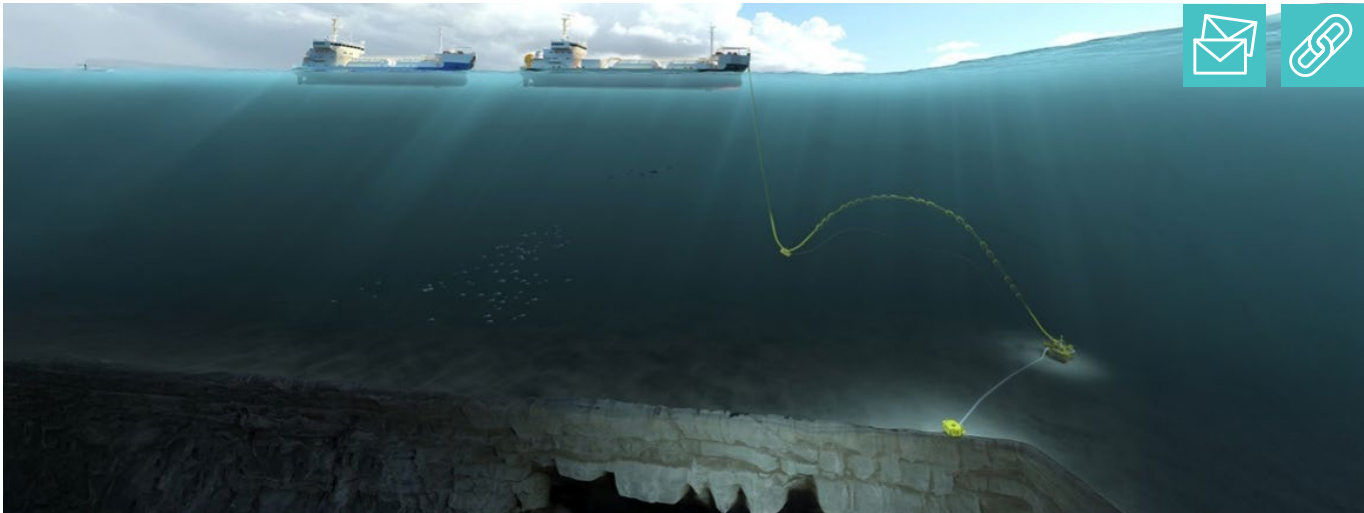
Subsea Wellheads

When water depths are too deep for offshore platforms to be economically constructed or when injection wells are to be spread far apart, Innovex's Subsea Wellheads are used to facilitate access and pressure control of subsea storage sites. Due to its ease of use and minimised carbon footprint, Innovex's Subsea Wellhead product line is the industry's preferred solution for subsea projects. Innovex has invested heavily in product engineering and design to make its subsea products the most economical and environmentally friendly on the planet.





NOV – CO₂ CAPTURE AND CONDITIONING
OFFSHORE CO₂ INJECTION

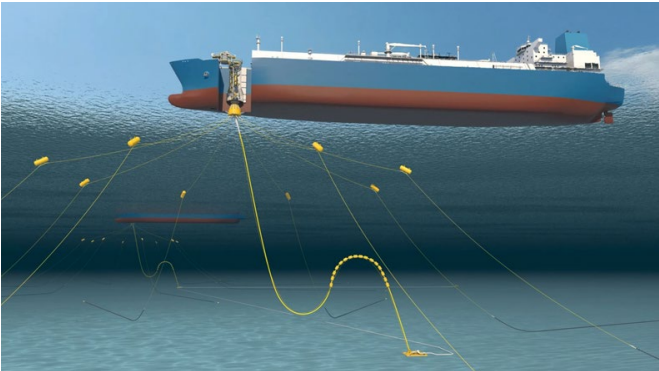


SUMMARY

Offshore CO₂ storage excels in scalability, adaptability, and timing over onshore storage options. The two NOV groups; APL and Subsea Production Systems (SPS) provide a combined offshore solution for safe CO₂ transfer and injection into the storage reservoir. Our advanced turret mooring and offloading systems enable direct CO₂ injection from the CO₂ carrier. The unbonded flexible pipes designed and certified for corrosive environments and dynamic conditions emerge as the preferred conduit for the injection and subsea distribution of non-cryogenic CO₂ into reservoirs. The CO₂ offloading and injection system is easy to scale and adapt to both batch-wise and continuous operation in all weather conditions.

BENEFITS

- High flexibility and fast capacity expansions: The APL/ SPS CO₂ injection system enables CO₂ to be delivered from anywhere directly to the storage site without need for land-based interim storage and long trunklines. It is easy and fast to add capacity when needed.
- Adaptable injection systems to suit different storage locations: The Single Anchor Loading (SAL) and Submerged Turret Loading (STL) has both its key benefits. The SAL system being a light and fast system to deploy and are well suited from shallow to moderate water depths.
- The STL system delivers safe passive mooring and can ensure continuous injection even in harsh conditions and fits moderate to deeper water depths. Each system can do batchwise injection or continuous injection in a dual configuration.
- Certified CO₂-resistant flexible pipes ensure safe CO₂ transport from topside to well. SPS' flexible pipes have a proven track record with high CO₂ content, and new materials are certified for CCS applications.



STL - Submerged Turret Loading System



Flexible pipe cross section

KEY DATA

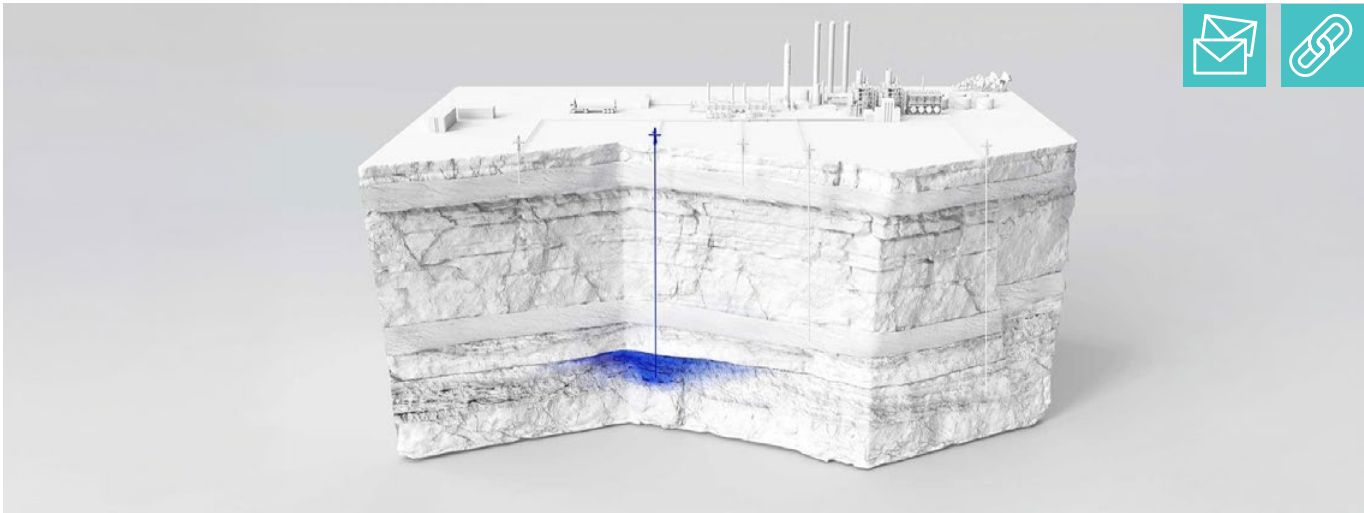
TRL	7+	Design Pressure (bar)	0 - 345	Design Temperature (°C)	-20 - +60
Size	4" to 12"	Continuous and batchwise loading			
Target Industries	CCS Transportation and Storage - Project Developers, shipowners				

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SLB

CAMERON CARBON STORAGE WELLHEAD SYSTEM

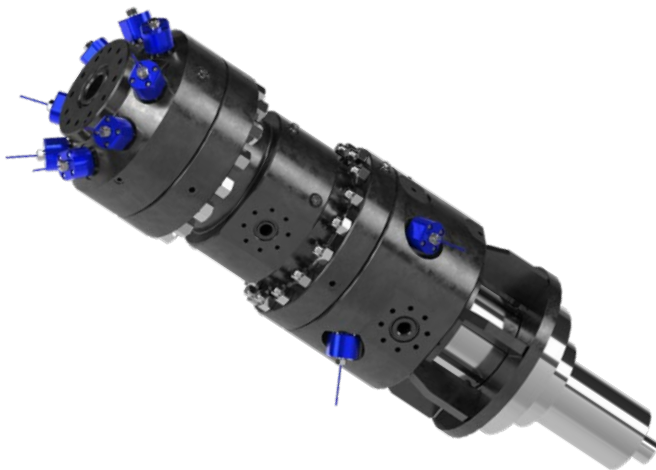


SUMMARY

SLB's carbon storage wellhead system is a purpose built solution engineered to ensure safe, reliable, and long term CO₂ injection and storage. Designed to withstand extreme low temperatures caused by the Joule Thomson effect, it incorporates advanced non-metallic sealing technologies qualified down to -112 degF for containment assurance. The system provides corrosion resistant, high integrity performance throughout decades of injection and monitoring. A unique feature is integrated fiber optic control line termination through the casing annuli, enabling continuous plume and pressure monitoring to meet US EPA Class VI regulations without adding height or complexity. Mandrel hangers, compact modular architecture, and no specialised tooling installation reduce rig time, simplify operations, and lower total cost. Available in tiered configurations, the carbon storage wellhead adapts to both injection and monitoring wells, offering a scalable, cost effective path for operators developing carbon storage projects.

BENEFITS

- **Reliable sealing** in CO₂ service.
- **Lower total cost of ownership** with a CCS-specific design that reduces capex and opex.
- **Support for long-term storage integrity** with a design philosophy aligned with the permanence requirements of Class VI storage.
- **Simplified field operations and reduced human intervention** due to streamlined seal installation and removal, fewer specialised components, lower maintenance requirements, and integrated monitoring capabilities.
- **Future-proof platform** for digital and monitoring upgrades at surface, enabling compliance with evolving standards without costly redesigns.



KEY DATA

TRL	7	Wellhead Size (in)	11 & 13-5/8	Maximum Pressure (psi)	10,000
Low Temperature Sealing (degF)	-112	High Temperature Sealing (degF)	250	Wellhead Qualification	API
CO ₂ Compatibility	>95%	Suitable for Injection Wells	Yes	Suitable for Monitoring Wells	Yes
Target Industries	CCS project developers & operators; Industrial emitters directly investing in CCS; Energy companies				

TECHNOLOGY DESCRIPTION

HOW IT IMPROVES PERFORMANCE

The Cameron carbon storage wellhead system is part of our Sequestri™ carbon storage solutions portfolio. It improves performance by delivering significantly higher barrier integrity and life cycle durability under the demanding conditions of CO₂ injection compared with traditional O&G wellhead systems. Its sealing system is engineered to maintain full functionality across extreme temperature swings, from -112 to 250 degF, preventing loss of integrity during Joule–Thomson cooling events that commonly compromise standard wellhead sealing. The nonmetallic seals eliminate galling, corrosion, and degradation in CO₂ streams, resulting in more consistent long-term sealing performance and fewer interventions.

Compact, modular architecture reduces installation complexity, improves uptime, and supports seamless integration of fiber-optic lines (for monitoring pressure, temperature, and wellbore movement) without additional termination hardware, facilitating continuous measurement and verification aligned with Class VI requirements. Together, this wellhead system's capabilities enhance operational efficiency, reduce NPT, minimise long-term maintenance, and ensure superior wellbore integrity over the multidecade life cycle expected in CCS projects.

HOW IT WORKS

The system works by providing a built-for-purpose pressure-containment and monitoring interface between the surface facility and the CO₂ injection wellbore, using materials, sealing systems, and architecture specifically engineered for the thermodynamic and chemical demands of CO₂ injection and sequestration. Seals are installed without Specialised tooling and energise against the wellhead housing and casing to create reliable primary and secondary barriers.

The compact, modular design enables assembling components in a streamlined sequence that reduces rig time and simplifies installation. During operation, the wellhead maintains constant pressure containment. Over the life of the well, the system enables continuous monitoring, stable sealing performance, and easy replacement or upgrade of components, ensuring long-term CO₂ containment.

WHAT IT REPLACES

Our carbon storage wellhead system replaces traditional O&G wellheads that have been adapted for CO₂ injection and long-term sequestration service. Traditional wellheads are designed for hydrocarbon production, not for the extreme low-temperature, high-purity CO₂ and acid-gas conditions found in CCS operations. For most CCS projects on land, operators in the US currently rely on standard API Spec 6A wellheads with potentially inadequate seals, add-on corrosion-resistant components, and external fiber-optic termination spools to support monitoring. These configurations are expensive, operationally inefficient, and not engineered for the inherent challenges associated with CO₂ storage.

In contrast, our built-for-purpose solution eliminates the need for

- multiple retrofit components
- modified O&G wellheads with insufficient low-temperature qualification
- sealing systems requiring specialised tooling and technical expertise for installation
- external fiber-optic termination spools that increase stack height and installation time

In essence, it replaces a patchwork of modified O&G hardware with a single, integrated, application-specific CCS wellhead system optimised for reliability, monitoring, and long-term containment.

WELLHEAD & SEAL QUALIFICATION

Wellhead sealing technologies were subject to a multi-stage qualification program aligned with API 6A PR2F requirements and expanded CCS-specific stress tests. The test included dynamic cycling across minimum and maximum temperature limits whilst applying differential pressure to stress test seals and mechanical components of the wellhead.

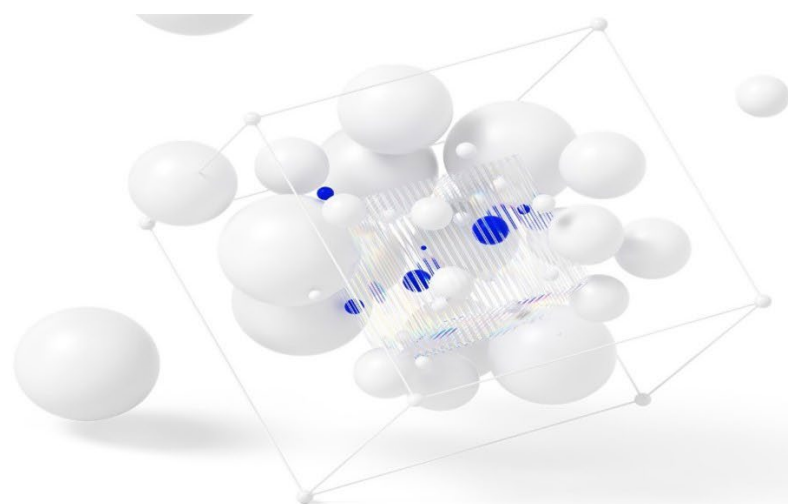
Seals are validated across -75 degF to 250 degF at 10,000 psi with extended survival tests to -112 degF to simulate Joule-Thomson effect-induced cooling (beyond API limits).

The wellhead technology is tailored specifically for the extreme thermal, chemical, and operational demands of carbon storage injection wells.



SLB

CARBON STORAGE RANKING



SUMMARY

Site screening is the critical first step in selecting the most suitable location for your carbon storage project. Our digital site screening solution—carbon storage ranking, part of the Sequestri™ digital ecosystem—empowers you to efficiently evaluate and prioritise potential CO₂ storage sites using a robust, science-backed methodology. By integrating geological, environmental, economic, and infrastructure data, the tool delivers a comprehensive, multidisciplinary analysis of site viability. It enables early insights into storage capacity, injectivity, containment, long-term performance, and economic feasibility—helping you confidently benchmark project potential. With structured, data-driven screening and ranking, you can make informed decisions on where to focus resources for detailed characterization and engineering, reducing uncertainty and accelerating your path to a successful CCS project.

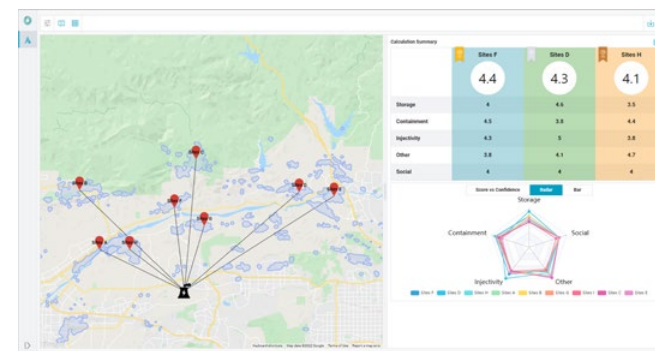
BENEFITS

- **Regional site prioritization:** Rapidly assess and rank storage capacity, injectivity, containment, and risk across many candidate sites within a region, enabling efficient prioritization for further feasibility and characterization studies.
- **Informed decision making:** Apply multi-criteria decision-making algorithms, like the Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), to systematically identify the most promising storage sites.
- **Comprehensive evaluation framework:** Assess both technical (capacity, injectivity, containment) and non-technical (regulations, monitoring, infrastructure, and socio-economic factors) criteria in a consistent, auditable process.
- **Accelerated project timelines:** Leverage integrated digital solutions to fast-track CCS site screening and ranking, enabling quicker progression from early screening to detailed evaluation.

CASE STUDIES

- **Shell, EGAS, University of Aberdeen, Egypt:** SLB led the first offshore CCUS screening of the Nile Delta, identifying 16 viable sites with a potential storage capacity of 622 million metric tons. Source: [Link 1](#)
- **Geoscience Australia, Australia:** SLB delivered a regional CCS screening study for the Barrow and Dampier sub-basins. The project included reprocessing 31 3D seismic surveys (~26,000 km²), ranking over 1,600 wells, and subsurface interpretation to assess CO₂ storage potential and create a publicly available storage atlas to accelerate CCS development. Sources: D. Barlass et. al. DOI: [Link 2](#), A. Parent et. al., DOI: [Link 3](#).
- **Trinidad and Tobago:** This study involved the screening of three offshore blocks using 67 technical and non-technical criteria, identifying the most viable sites—benchmarked against Norway's Utsira Formation and the US's Illinois Basin sites.

TECHNOLOGY DESCRIPTION



CARBON STORAGE RANKING

Carbon storage ranking is a dedicated application for screening CCS storage sites. It enables users to screen and rank potential CO₂ storage sites using a set of criteria weighted through the AHP. The user can select from a preexisting criteria template consisting of 140 criteria or create their own template. It supports the integration of early-phase technical screening work, benchmarking against geological analogues, and quantification of uncertainty ranges for key ranking criteria.

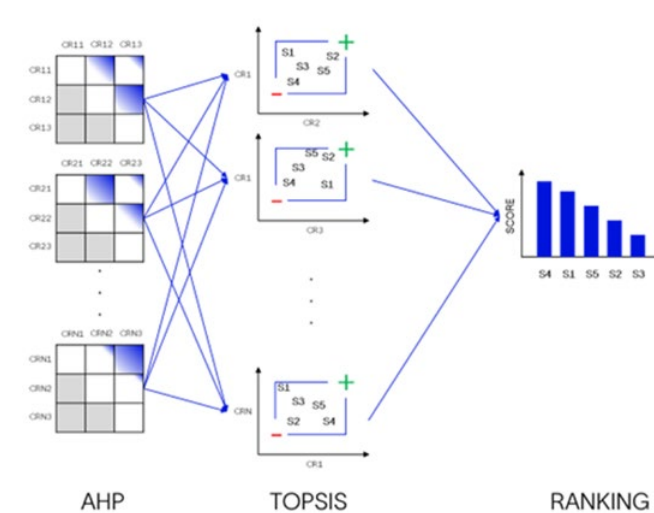
CRITERIA SELECTION AND WEIGHTING

Robust screening and ranking of carbon storage sites requires a thorough evaluation of both technical and non-technical criteria.

Technical criteria are categorised into capacity, injectivity, and containment. These criteria are often interdependent. For example, reducing containment risk often means lowering injectivity and capacity, highlighting the need for holistic evaluation. Non-technical criteria—including legal, environmental, economic, and societal considerations—further influence project feasibility and vary by region.

Carbon storage ranking integrates technical and non-technical criteria into a defined hierarchy, built on experience from previous SLB global CCS projects. Each criterion is assigned a default weight based on best practices, which can be customised to reflect specific project goals.

Users can input criterion values manually as single points or as probability ranges, depending on data availability. Quantitative inputs (e.g., reservoir depth) are numerical, while qualitative ones (e.g., seal quality) use dropdown scales (e.g., very poor to very good). Additionally, many values can be auto populated from other SLB subsurface tools such as PetroMod™ basin modeling software, ensuring efficiency and consistency across evaluations.



PROPOSED RANKING METHODOLOGY

AHP is used to define the relative importance of each criterion and sub-criterion in the evaluation hierarchy. By leveraging structured pairwise comparisons, AHP enables the balanced weighting of a wide range of factors—both quantitative and qualitative—ensuring that final weights reflect expert insights, project learnings, and stakeholder priorities.

Once weights are established, the site evaluation process begins. Every selected criterion must be populated for each candidate site. Inputs can be provided as either single-point values or ranges defined by probability distributions, supporting both deterministic and probabilistic assessments. Quantitative data (such as net reservoir thickness) is entered numerically, while qualitative criteria (such as seal integrity or regulatory alignment) are scored using predefined ordinal scales (e.g., very poor to very good). Many criteria can also be auto filled using SLB subsurface tools like PetroMod software.

When all data is in place, carbon storage ranking applies the TOPSIS method to rank the sites. TOPSIS measures each site's relative proximity to an ideal scenario, considering all weighted criteria. It simultaneously accounts for the distance from a negative or worst-case scenario. This approach results in a normalised score for each site, enabling transparent, consistent, and scalable comparison across multiple locations, including benchmarking against analogues.

Overall, the methodology applied in carbon storage ranking ensures that every dimension of site suitability—from subsurface containment potential to surface-level socio-environmental factors—is evaluated in a structured and consistent manner. By combining proven algorithms, flexible data entry, and a comprehensive, customizable criteria hierarchy, carbon storage ranking offers a robust, defensible framework for identifying and prioritizing the most promising CO₂ storage sites.

To learn more, visit www.slb.com/sequestri

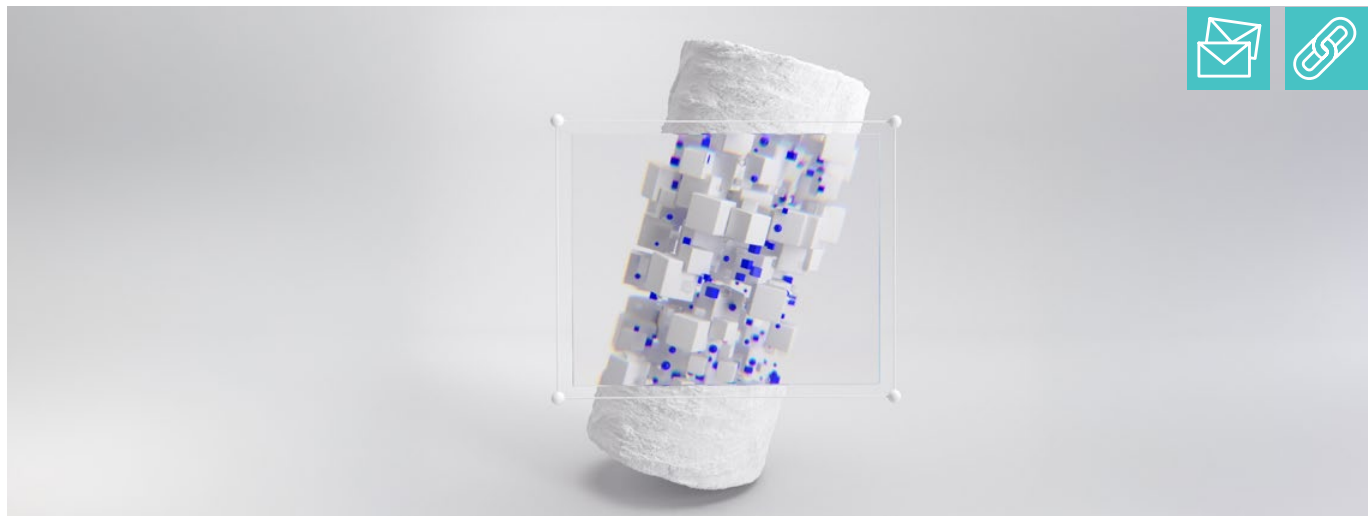
KEY DATA

TRL	9
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SLB RESERVOIR LABS

CCS FLOW GEOMECHANICS



SUMMARY

Derisking CCUS operations requires geomechanics laboratory measurements where validation of injection processes can only be captured with physical reference data. To ensure reservoir stability and seal containment requirements are met, laboratory measurements must be performed at the right conditions to accurately model both reservoir and seal integrity vs time. During injection, the plume will progress through the reservoir and move towards the caprock where temperature and pressure sensitive geochemical processes can alter rock strength, storage volume and flow performance. These active field processes require matching laboratory methods where dynamic fluid flow applications must be adopted to truly simulate CCS injectivity, and robust assessment of reservoir and seal integrity. To meet all these requirements, SLB Reservoir Labs (SRL) has developed a CCS Flow Geomechanics lab workflow, part of the Sequestri™ carbon storage solutions portfolio, that adopts TerraTek stress frames and technology. Newly developed capabilities include dynamic treatment/injection of CO₂/brine or supercritical CO₂ combinations to rock samples all under in-situ stress and temperature conditions with measurements of rock deformation.

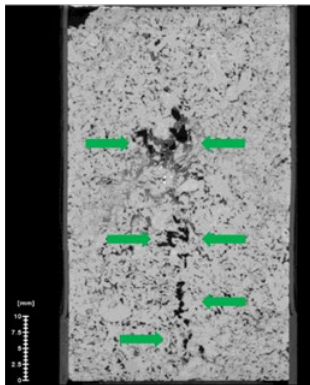
BENEFITS

- Geomechanics testing combined with dynamic CO₂-brine or supercritical CO₂ brine flooding. Allows direct comparison of realistic treatment conditions with pristine samples.
- MicroCT imaging of geomechanics test samples before and after treatment for evaluation of dissolution or precipitation processes. Determine if channeling occurs from flow-through tests.
- Collection of effluent versus time during CCS Flow Geomechanics for fluid composition analysis. Assess reactivity of rock during treatment.
- Application of treatment fluids at actual reservoir conditions of stress and temperature. Including static and dynamic elastic properties measured concurrently.

KEY PROJECTS

Triaxial compression results showing stress-strain response at left and rock stiffness changes (i.e., Young's modulus). There is a clear strength and modulus reduction from CO₂ treatment with the largest changes occurring following pressurised flow-through (i.e., dynamic treatment-Green).

The development of a channel is clearly evident (arrows) resulting from CO₂-brine dissolution processes taken from post-test microCT.



KEY DATA

TRL	9
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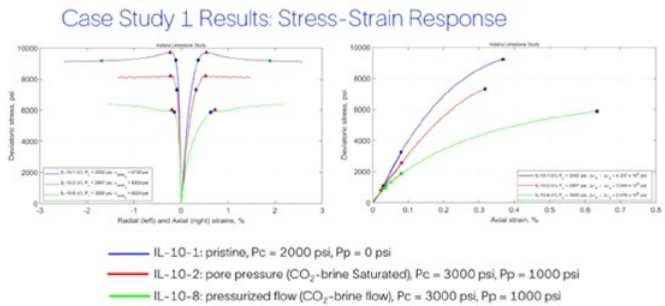
TECHNOLOGY DESCRIPTION

CCS FLOW GEOMECHANICS SYSTEM

SLB has built a geomechanics system allowing control of pore pressure using brine, CO₂-brine, supercritical CO₂, or any combination of these all under reservoir conditions of stress and temperature. CO₂ treatment is performed statically (constant pore pressure) or dynamically consisting of flow-through CO₂/brine or supercritical CO₂. The workflow using these treatment conditions, sample deformation, ultrasonic velocities, flow-through properties (permeability), static/dynamic elastic properties, rock strength and collection of effluent with compositional analysis versus exposure time is available. The unique capabilities include core flooding with representative formation brine synthesised under reservoir conditions and applied to sample under the same conditions. The workflow also includes high resolution imaging (10 to 20 μm) of the pore network using microCT. This process allows 3D reconstruction of the entire test sample prior to testing highlighting pore morphologies and grain/texture relationships. The sample is then reimaged post CO₂ treatment to compare with initial rock framework and determination of dissolution processes and development of channels through the test plug.

The CCS Flow Geomechanics system consists of in-vessel instrumentation to capture continuous temperature and sample deformation (radial and axial) during testing. The system has high resolution pore pressure transducers located at the upstream and downstream connections to the endcaps with a differential pressure transducer. Corrosion resistant flow-volume accumulators are attached at both upstream and downstream ends to measure fluid-flow. Homogenization of the CO₂-brine solution is achieved from thorough mixing using a rocking system prior to introduction to the CCS Flow Geomechanics system. A series of pumps located at both the upstream & downstream ends provide continuous pressure and flow-through capabilities for extended periods of time. It operates at pressures up to 7500 psi and flow rates ranging from 0.001 to 70 ml/min. This capability also allows monitoring permeability change at in-situ stress conditions where dissolution/precipitation processes due to CO₂ exposure impact flow conditions, which is directly applicable for injectivity monitoring.

Based on the in-situ fluid composition of the project, SRL replicates it, then mix with pressurised CO₂ and condition to be homogenous. The pressure is then reduced to 2500 psi and excess CO₂ is removed. The initial brine-CO₂ composition is sampled and pH measured at in-situ stress conditions, which is a key parameter for reactivity modeling.



TESTING CONSIDERATIONS AND EXAMPLE RESULTS

Testing requirements dictate the samples are saturated with existing fluids prior to testing. Once saturated, CO₂, CO₂-brine or supercritical CO₂ is introduced to the rock. The test can include simple initial application of these fluids with a hold period for an extended period (e.g., days). This would be equivalent to static aging. After the required period, rock strength/elastic properties can be measured. More sophisticated testing would involve the flow-through (dynamic aging), for an extended period. In these tests, supercritical CO₂ is introduced to the brine saturated rock simulating true injection, where the reservoir will be at warmer temperatures than the injecting fluid. The CCS Flow Geomechanics system allows for all these testing scenarios (static pressure control and various flow-through applications), ultimately providing in-situ dynamic rock deformation measurements. Flow-through tests are typically complemented with microCT imaging characterizing pore morphology changes from CO₂-brine (de)mineralization processes.

To evaluate this novel approach, a series of tests were conducted on Indiana limestone using the new CCS Flow Geomechanics system. Triaxial testing was conducted under standard conditions (dry and brine saturation), in-situ static aging (CO₂-brine), and dynamic flow-through (CO₂-brine continuous flow). The comparison pristine vs static aging, vs dynamic CO₂ treated triaxial compression tests is shown below, where we can see a clear strength and modulus reduction from CO₂ treatment with the largest changes occurring on pressurised flow-through (i.e., dynamic treatment) sample

The controlled pore pressure test represents static aging process where all pore volume is in contact with the treatment fluid. The static aging test shows a drop in compressive strength of 20% and a reduction in Young's modulus of 30% compared to the pristine rock.

Property	IL-10-1 (pristine)	IL-10-2 (CO ₂ -brine pore pressure)	IL-10-8 (CO ₂ -brine, pressurized flow)
Bulk Density (dry), g/cc	2.299	2.271	2.249
Young's Modulus*	4.3 Mpsi	3.0 Mpsi (30% ↓)	2.1 Mpsi (51% ↓)
Poisson's Ratio*	0.25	0.19	0.15
Yield Strength	11227 psi	9504 psi	7869 psi
Compressive Strength	11726 psi	10402 psi (11% ↓)	8006 psi (32% ↓)
Dynamic Young's Modulus	5.48 Mpsi	5.0 Mpsi (9% ↓)	--

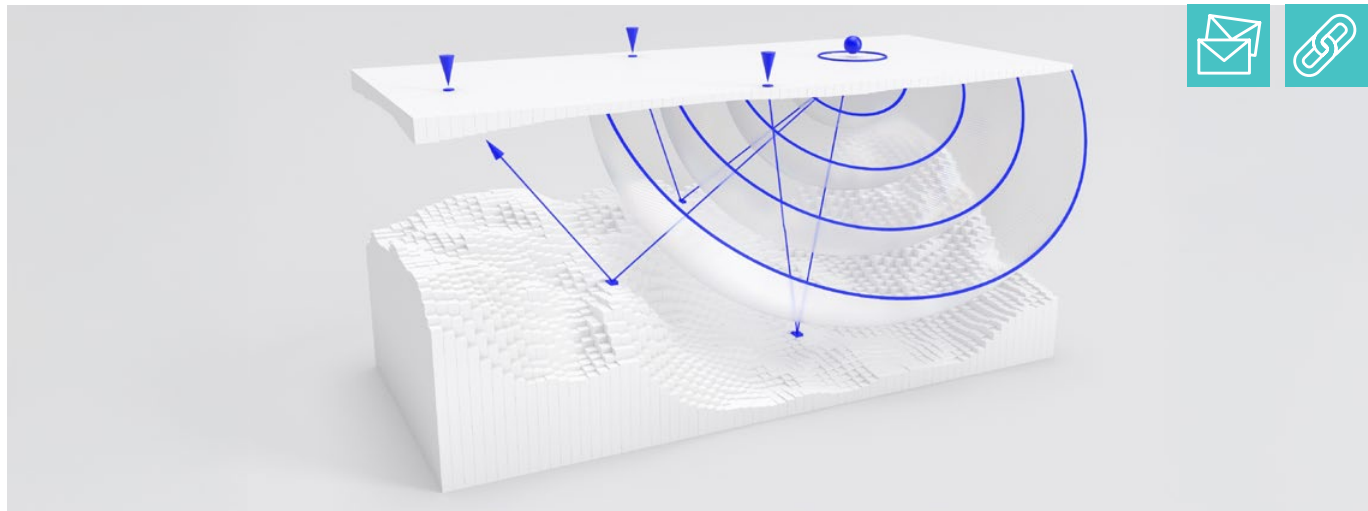
*Elastic properties evaluated over similar axial strain ranges for comparison.

To learn more, visit www.slb.com/sequestri



SLB

CCS REAL-TIME INDUCED SEISMICITY MONITORING



SUMMARY

Induced seismicity refers to the occurrence of tremors resulting from mechanical stress that causes shifts in subsurface layers. Large-scale fluid injections, such as those used in carbon capture and sequestration (CCS), underground natural gas storage, saltwater disposal, stimulation, and geothermal injection, have the potential to trigger induced seismic events. The CCS real-time induced seismicity monitoring (RT-ISM), part of the Sequestri™ carbon storage solutions portfolio, is the one of the first automated microseismic monitoring system designed to detect seismic events and provide users with real-time information regarding the magnitude and location of these occurrences. ISM continuously acquires distributed acoustic sensing (DAS) data and utilises edge computing to perform all necessary processing and computations on site, thereby enabling a light data stream transmission. ISM operates autonomously without requiring human interaction in situ and is conveyance agnostic, functioning seamlessly with permanent fiber installations, temporary intervention fibers, as well as geophone arrays.

BENEFITS

- Real-time fully automated events detection requiring no human presence
- Event location display and magnitude quantification
- In-situ edge processing and computing
- Light data streaming with cloud visualization and reporting system
- Conveyance-agnostic solution which can be provided with permanent and/or temporarily deployed fiber optic
- Integration with geophone(s)
- Advanced processing and geophysical interpretation available through SLB support team

APPLICATIONS

- Regulatory induced-seismicity monitoring, reservoir monitoring, and stimulation monitoring
- Saltwater disposal injection, geothermal injection, enhanced geothermal systems (EGS)
- Carbon capture and sequestration (CCS) projects
- Underground natural gas injection and storage (UGS)
- Seismic data acquisition (internal or external data sources)

KEY DATA

TRL	9
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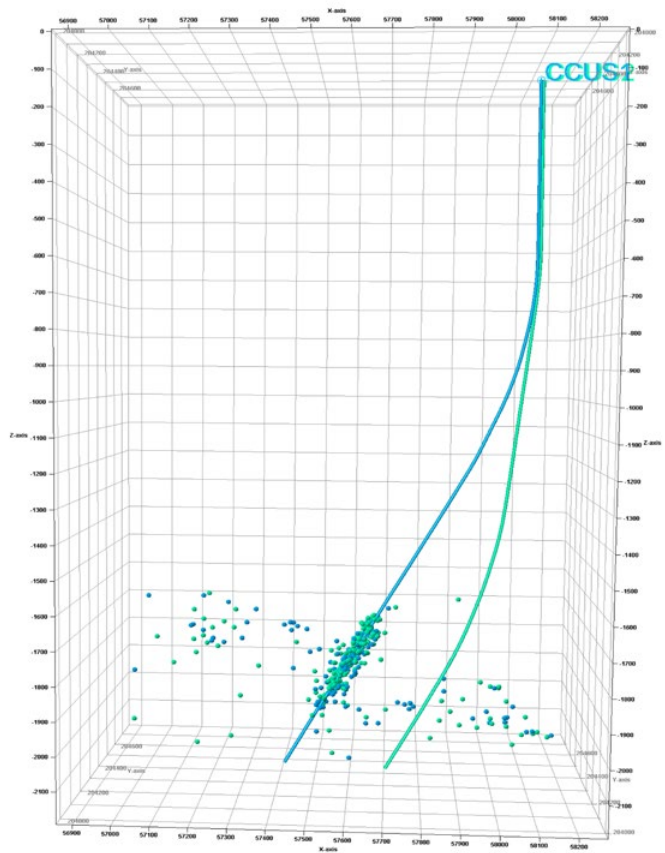
TECHNOLOGY DESCRIPTION

CASE STUDY

The success of a carbon capture and sequestration (CCS) project hinges on precise measurement, monitoring, and verification (MMV) of injected and stored CO₂ to ensure long-term containment and environmental safety. Traditional MMV approaches often face challenges in terms of cost, precision, and coverage, necessitating innovative solutions to optimise CCS operations.

The Minami-aga pilot project, conducted by INPEX Corporation and Japan Organization for Metals and Energy Security, aimed to demonstrate the effectiveness of DAS technology in enhancing MMV practices. By leveraging fiber-optic cables as sensors, the project sought to provide real-time, high-resolution subsurface data, thereby improving operational efficiency and ensuring the integrity of the storage complex.

The Minami-aga pilot project successfully integrated DAS technology into various aspects of CCS operations, showcasing its transformative potential. One of the key applications was continuous microseismic monitoring, in addition to vertical seismic profiling (VSP), crosswell seismic acquisition, and injection profiling.



Nakayama, S., Yamada, Y., Mouri, T., Bettinelli, P., Mizuno, T., Chen, J., Armstrong, P., and Maehara, Y., (2024) Continuous DAS measurements during CCUS operations onshore Japan, 4th International Meeting for Applied Geoscience & Energy, Expanded Abstracts

1. Vertical seismic profiling (VSP): DAS technology was employed to acquire zero-offset VSP and walkaway VSP data sets simultaneously from two wells. This hybrid acquisition strategy, utilizing both land-based vibrator sources and river-deployed mud gun systems, ensured comprehensive subsurface coverage. The recorded data sets were processed using advanced imaging techniques, resulting in high-resolution subsurface images that provided detailed insights into the structural and stratigraphic definition of the area.
2. Crosswell seismic acquisition: The project marked the first worldwide implementation of DAS in crosswell seismic data acquisition. By using a borehole vibrator source, the initiative achieved enhanced resolution in subsurface imaging and reservoir characterization. This innovative approach demonstrated the potential of DAS technology in pushing the boundaries of seismic imaging techniques.
3. Microseismic monitoring: Continuous DAS measurements were conducted across two wells with the induced seismicity monitoring (ISM), focusing on microseismic monitoring during CCUS operations. Automated event detection algorithms enabled real-time identification and extraction of seismic events, which were then transmitted to processing centers for immediate analysis. This integrated approach validated the accuracy of presurvey modeling predictions and optimised resource utilisation.
4. Injection profiling: DAS technology facilitated precise monitoring of CO₂ injection processes by providing real-time temperature sensing along the borehole. This capability allowed operators to assess reservoir integrity, optimise injection rates, and mitigate risks associated with CO₂ migration. The use of low-frequency DAS data further enhanced reservoir characterization efforts, aiding in the selection of suitable injection sites and validation of storage capacity.

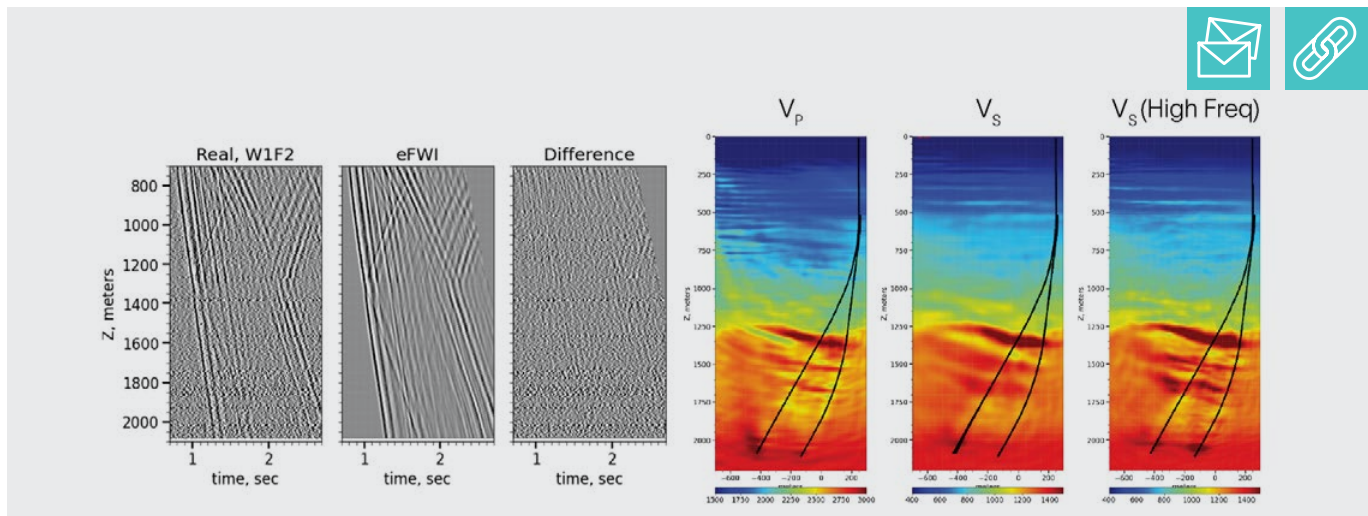
Overall, the Minami-aga pilot project demonstrated that DAS technology offers a cost-effective, scalable solution for comprehensive subsurface monitoring in CCS projects. By revolutionizing traditional MMV approaches, our induced seismicity monitoring (ISM) together with our full offering of DAS technology contributes to optimising operational efficiency, ensuring environmental safety, and supporting informed decision-making in the pursuit of sustainable climate mitigation strategies.

To learn more, visit www.slb.com/sequestri



SLB

ELASTIC FULL WAVEFORM INVERSION



SUMMARY

Elastic Full-Waveform Inversion (eFWI) is a method for deriving detailed elastic properties of the subsurface from seismic data, specifically using Distributed Acoustic Sensing (DAS) technology. DAS measures strain along a fiber optic cable in a well, capturing seismic wave propagation. eFWI minimises the difference between observed and synthetic seismic data by solving elastic wave equations, allowing for accurate characterization of subsurface formations, including compressional (P-wave) and shear (S-wave) velocities. The process involves a multi-scale inversion strategy, starting with low-frequency data and progressively including higher frequencies. A 2D algorithm is developed for multi-offset and walkaway VSP acquisitions, accounting for 3D well deviation effects. This method has proven effective in real data applications, demonstrating its feasibility and accuracy in updating medium properties without requiring DAS data transformation to velocities. Integrating eFWI with carbon capture and sequestration (CCS) projects enhances the storage complex evaluation, monitoring and verification of CO₂ plume migration, ensuring the long-term stability and safety of geological sequestration sites.

BENEFITS

- **High-Resolution Imaging:** eFWI provides detailed elastic properties of the subsurface, including compressional (P-wave) and shear (S-wave) velocities, leading to high-resolution imaging and accurate characterization of geological formations. This is crucial for identifying suitable CO₂ storage sites in CCS projects.
- **Enhanced Data Utilisation:** By using Distributed Acoustic Sensing (DAS) data, eFWI leverages strain measurements along fiber optic cables, capturing comprehensive seismic wave propagation information without the need for data conversion to velocities. This enhances the monitoring of CO₂ injection and storage in CCS projects.
- **Adaptability to Complex Geometries:** The method effectively handles data from deviated wells and complex well trajectories, accounting for 3D well deviation effects and ensuring accurate subsurface modeling. This adaptability is essential for accurately modeling CO₂ plume migration in CCS projects.

KEY PROJECTS

- **Walkaway DAS VSP for CCS Projects:** eFWI was performed for a Carbon Capture and Storage (CCS) project using walkaway DAS VSP data from two fibers permanently installed and cemented behind casing. The data quality was excellent, enabling precise subsurface characterization and effective monitoring of the CCS site.
- **Multi-Offset DAS VSP Data:** eFWI was applied to multi-offset Vertical Seismic Profiling (VSP) data acquired in deviated wells. The inversion successfully reproduced field data, including significant variations in waveform amplitudes due to well deviation, and the obtained compressional and shear velocities agreed with reference models.
- **Joint Fiber and Conventional Data Inversion:** Simultaneous inversion of fiber optic DAS data and conventional sensor data was performed. This approach improved the deep part of the model, covered better with conventional sensors.

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

ELASTIC FULL-WAVEFORM INVERSION (EFWI) OVERVIEW

Elastic Full-Waveform Inversion (eFWI) is a sophisticated technique used to extract detailed elastic properties of the subsurface from seismic data. It involves minimizing the difference between observed seismic data and synthetic data generated by solving the elastic wave equations. This process allows for the accurate characterization of subsurface formations, including both compressional (P-wave) and shear (S-wave) velocities.

KEY COMPONENTS OF EFWI FOR DAS DATA

Modeling DAS Data:

- DAS measures the strain along a fiber optic cable deployed in a well, capturing seismic wave propagation.
- The strain is modeled by solving elastic wave equations, assuming perfect coupling and ignoring borehole effects.
- The strain along the fiber is integrated over the gauge length, which can be hardware-fixed or adjusted during data processing.

Inversion Formulation:

- The inversion process aims to minimise a weighted least-squares data misfit functional over model parameters and source wavelets.
- The gradient of the cost function is computed using the adjoint method, which involves cross-correlation in time of the forward-propagated wavefield and backward-propagated residuals.
- For DAS measurements, residuals are injected as moment tensor sources with radiation patterns determined by the well deviation.

Data Preparation and Workflow:

- A multi-scale inversion strategy is employed, starting with low-frequency data and progressively including higher frequencies.
- The initial model is constructed based on available information, such as surface seismic data, sonic logs, and velocity models.
- Measurements are adjusted to comply with the mathematical formulation, and weights are applied to data points and model parameters to ensure accurate inversion.

2D Axial Symmetric Algorithm for Deviated Wells

- For multi-offset and walkaway VSP acquisitions, a 2D algorithm is developed to invert for a 2D distribution of elastic medium properties, including 3D well deviation effects.
- The algorithm assumes waves propagate mostly in-plane and is suitable for geology with gentle property variations in horizontal directions.
- The axial symmetric approach models correct 3D geometrical spreading from the point source and gives true solutions for horizontally stratified media.

REAL DATA APPLICATIONS OF EFWI

Walkaway DAS VSP for CCS Project:

- eFWI was performed for a CCS project using walkaway DAS VSP data from two fibers permanently installed behind casing with cement.
- The data quality was excellent, enabling precise subsurface characterization and effective monitoring of the CCS site.

Multi-Offset DAS VSP Data, Alberta, Canada:

- The eFWI algorithm was applied to multi-offset VSP data acquired in a deviated well.
- The inversion successfully reproduced field data, including significant variations in waveform amplitudes due to well deviation.
- The obtained compressional and shear velocities agreed with the reference model based on sonic and VSP times data.

Joint Fiber and Conventional Data Inversion:

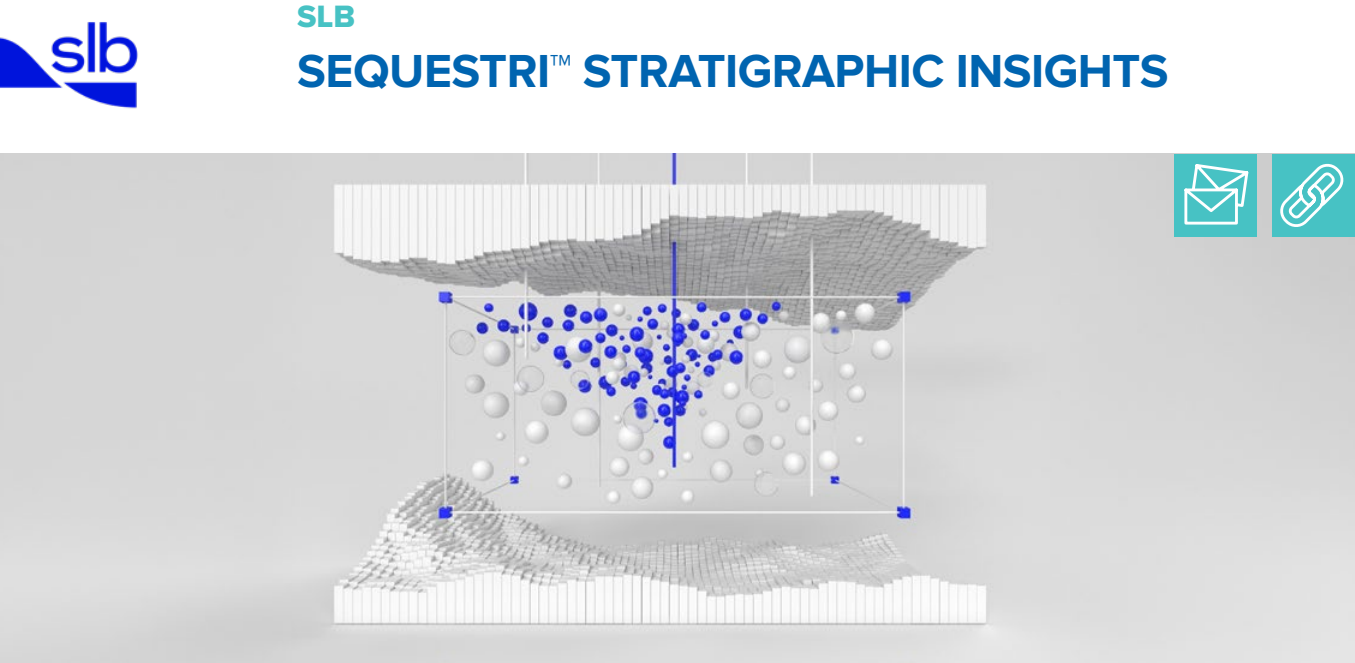
- Simultaneous inversion of fiber and conventional sensor data was performed.
- The deep part of the model, covered better with conventional sensors, was better updated.
- Further improvements are needed for simultaneous DAS and conventional data inversion due to some artifacts caused by inaccurate scaling between the two data types.

Multi-Offset Walk-Above DAS VSP Data, Mediterranean Sea:

- The eFWI algorithm was applied to multi-offset walk-above VSP data in a deviated well.
- The inversion process started with low-frequency data to improve the compressional velocity model and progressively included higher frequencies.
- The final inversion results reproduced most of the events in the data with high accuracy, although further analysis is needed to understand resolution properties and near-well artifacts.

CONCLUSION

eFWI is highly effective in accurately characterizing subsurface formations using DAS data from deviated wells. The proposed formulation does not require DAS data transformation to velocities and can be easily implemented into existing FWI codes for conventional measurements. The real data applications demonstrate the feasibility and effectiveness of the algorithm in reproducing field data and updating medium properties. For CCS projects, eFWI significantly improves the turnaround time by providing rapid and accurate subsurface characterization, which accelerates decision-making processes and reduces project delays.



SUMMARY

Sequestri™ Stratigraphic Insights is a digital interpretation product fully leveraging rich datasets gathered from stratigraphic test wells or site appraisal wells, targeting geological sequestration of CO₂ in saline aquifers. It is used to rapidly quantify and summarise the storage capacity, injectivity, and containment potential of each formation in the stratigraphic column. The results complement field-scale static geologic models and dynamic simulations with fast interpretation based on hard data measured in-situ or in the laboratory. The data are initially available within just hours of logging and are later refined as more specific test results become available. Standard and advanced well logs, formation tests, fluid sample analyses, and routine and special core analysis (RCAL and SCAL) results are integrated in a single platform to narrow the significant residual uncertainties following the regional site screening and selection phase of CCS projects. All results are cumulated by operator-defined zones and summarised in a convenient tabular format.

BENEFITS

- **Simplified zone evaluation and ranking:** Easily compare and rank multiple prospective targets based on key attributes at the well such as salinity, storage capacity, CO₂ injectivity, and safe operating pressure.
- **Rapid decision making:** Make timely decisions on where and how to focus the remaining evaluation program and select the best intervals for testing or completion.
- **Fast reassessment of economics and risk:** Enable rapid estimates of storage capacity, number of injectors required, and containment risks based on hard data observed at the well.
- **Hard data for model updates:** Organise all key wellbore data needed for updating and consolidate static and dynamic models in one place.

KEY DATA

Triple combo & dielectric logs	Primary	Advanced multimode acoustic log	Primary	Fluid samples, stress tests	Calibration
Advanced spectroscopy log	Primary	Image log	Primary	RCAL mineralogy, perm	Calibration
Nuclear magnetic resonance log	Primary	Formation tester pressure & mobility	Calibration	SCAL relative perm, MICP, entry	Calibration
Target Industries	Geologic sequestration projects targeting saline aquifers at the exploration and appraisal phases				

TECHNOLOGY DESCRIPTION

INTEGRATED WELL INTERPRETATION FOR CCS

The geosequestration insight workflow provides rapid, integrated interpretation of well evaluation results via comprehensive analysis of logs, well tests, and core and fluid samples in line with US EPA Class VI data gathering requirements. It produces answers that directly address the key evaluation challenges and risks of geologic sequestration projects.

The first deliverable is available within just hours of acquiring logs. It is later refined as core analysis, fluid analysis, and testing data become available. The graphic layout integrates all data in a composite depth log presentation organised in four logical streams.

EVALUATION FUNDAMENTALS

Basic logs are presented with an interpretation of mineralogy, true and effective porosity, intrinsic permeability, water salinity, and CO₂ density at reservoir conditions. Seven methods of salinity interpretation are supported based on well specifics, aiding the operator in determining the lowest USDW and guiding the fluid sampling program.

STORAGE CAPACITY

Capacity estimates adapt the USDOE method to determine static free-CO₂ capacity per acre for an open system. CO₂ density, effective porosity corrected for mineralogy, and both pore-scale and reservoir-scale efficiency factors are considered. Initial results incorporate standard logs plus advanced measurements such as dielectric, neutron-gamma spectroscopy, and nuclear magnetic resonance (NMR) logs.

INJECTIVITY

First estimates of brine injectivity over a range of injection pressure are based on uncalibrated NMR logs. Subsequent estimates are refined by calibrating NMR permeability with formation tester mobility measurements and RCAL permeability. A proprietary database of nearly 200 dynamic simulations then correlates brine injectivity to supercritical CO₂ injectivity based on delta-P, skin, and relative permeability to CO₂, which will eventually be input from SCAL measurements.

CONTAINMENT

Containment summarises confining zone net seal thickness, permeability, and tectonic integrity (occurrence of natural fractures and faults). A 1D mechanical earth model (MEM) quantifies the hydraulic fracture gradient and safe operating pressure. It is eventually calibrated with core geomechanics and wireline formation stress tests (mini-fracs).

SUMMARY AND REPORT

All computations support operator-defined zones that may represent formations, members, flow units, or prospective completion intervals. A summary table (below) aggregates key attributes of each zone, such as net thickness, net porosity, net permeability, cumulative injectivity, storage capacity, and more. Zones may be rapidly adjusted and results updated accordingly. All interpretation parameters and their data sources are documented. Sources of residual uncertainty affecting the estimates are highlighted, with recommendations for follow-up to further reduce these uncertainties.

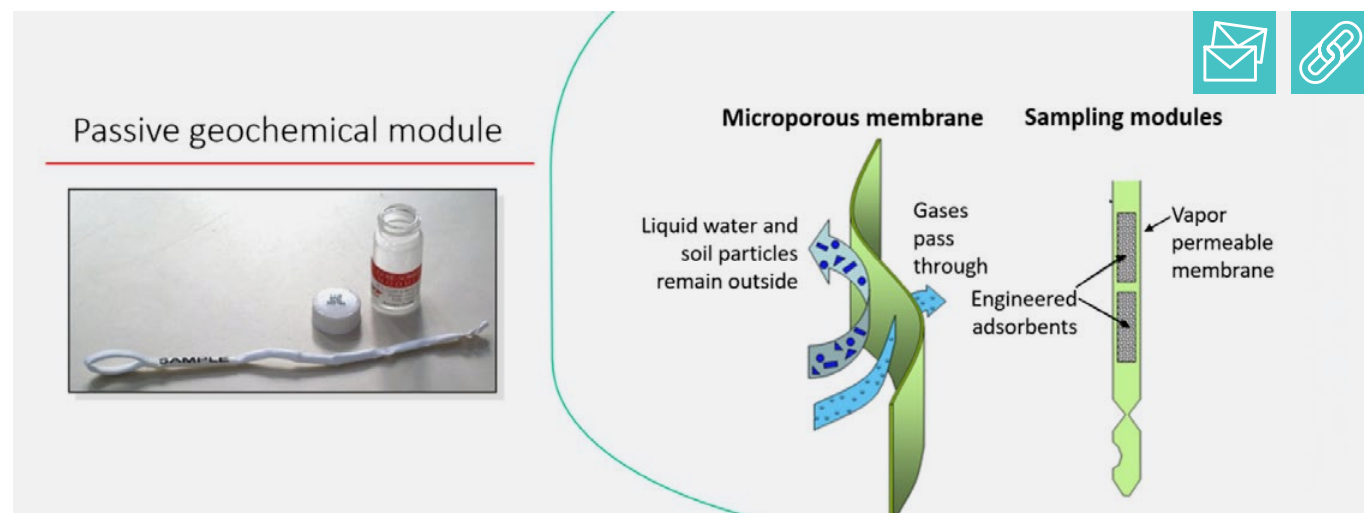
Zone Name	Top Depth	Bottom Depth	Gross Thickness	Net Thickness	Net NaCl Salinity	Net Average Porosity	Average CO2 Accessible Porosity	Net Average Horizontal Permeability	Net Water Injectivity	Net CO2 Injectivity	Static Free CO2 Storage Capacity/Acre
	ft	ft	ft	ft	ppk	ft³/ft³	ft³/ft³	mD	Bbl/day	MTON/day	MTON
Eau Claire	5094	5544.5	450.5	451	101.635	0.072062	-7.26642	1.39301	158.916	67.6689	93.4017
Mt. Simon D	5545	5854	309	309.5	101.072	0.100464	0.0108563	96.3877	15088.3	6349.26	312.938
Mt. Simon C	5854.5	6148.5	294	294.5	102.708	0.0925527	0.00840258	23.3761	3409.12	1447.17	233.345
Mt. Simon B	6149	6409.5	260.5	261	108.865	0.0988768	0.00689304	5.96079	755.274	321.398	171.663
Mt. Simon A	6410	6821.5	411.5	412	134.189	0.179446	0.0275001	68.8161	13235.7	5593.23	1098.44
Pre Mt. Simon	6822	7091	269	269.5	150.958	0.168864	0.0235851	111.863	13384.1	5675.3	624.804

Geosequestration Insight Report



AMPLIFIED GEOCHEMICAL IMAGING, LLC

PASSIVE SOIL GAS IMAGING FOR CO₂ MONITORING



SUMMARY

Passive soil gas imaging (PSGI) is an ultrasensitive surface method for detecting subsurface gases (i.e. CO₂) and hydrocarbons by measuring trace amounts that naturally migrate to the surface. PSGI relies on molecular seepage, for baseline levels and macroseepage conduits in the event of leakage.

These passive collectors (i.e. modules) contain a polymeric adsorbent within a microporous membrane that blocks soil and water but allows vapor molecules to pass through and concentrate on the adsorbent. Deployment involves drilling a ~1-inch hole about 2 ft deep, and inserting the module for ~7 days. During this time, gases diffuse through the membrane and equilibrate with the adsorbent, providing stable CO₂ measurements reflective of subsurface conditions. This stability is critical for generating baseline measurements prior to CO₂ injection for the life of the project. PSGI also provides the benefit of a 250-fold linear range, which is necessary for accurate leakage detection.

BENEFITS

- **High Sensitivity** - Can support early detection of anomalous CO₂ or tracer-gas signals .
- **Expansive Linear Range:** 400 ppm (ambient) to 100,000 ppm (10%).
- **Comprehensive Monitoring** - can monitor CO₂ across a field and CO₂ leakage up the injection well bore, as well as plugged & abandoned wells and orphaned wells, which are the most common sources of leakage.
- **Impurity Detection** - Differentiates industrial CO₂ from ambient CO₂ sources.
- **Versatile Deployment** - Suitable for onshore and offshore environments.
- **EPA Validated** - The technology has been validated by the U.S. EPA's Environmental Technology Verification program.
- **Baseline PSGI surveys** may help detect anomalous near-surface gas signatures that could indicate leakage associated with orphan wells.

KEY PROJECTS

- **Project One:** Used to support reservoir seal-integrity assessment prior to potential CO₂ storage in Oman. The survey identified elevated near-surface hydrocarbon signatures spatially associated with projected fault segments, which AGI interpreted as possible evidence of natural seepage pathways and used to inform storage suitability assessment. **(2012)**.
- **Project 2:** CO₂ was injected in the Krechba Field in Algeria. Seismic data indicated a natural fracture had been opened. The PSGI was used to measure CO₂ and fluorinated tracers. No surface leakage signal was detected by PSGI over the monitoring period **(2015-2020)**.
- **Projects:** Multiple Class II CO₂ monitoring projects have taken place in Texas and New Mexico. Samples were deployed around injection wells and in baseline areas. The results were then statistically compared to evaluate leakage up the well bore **(2023-2026)**.

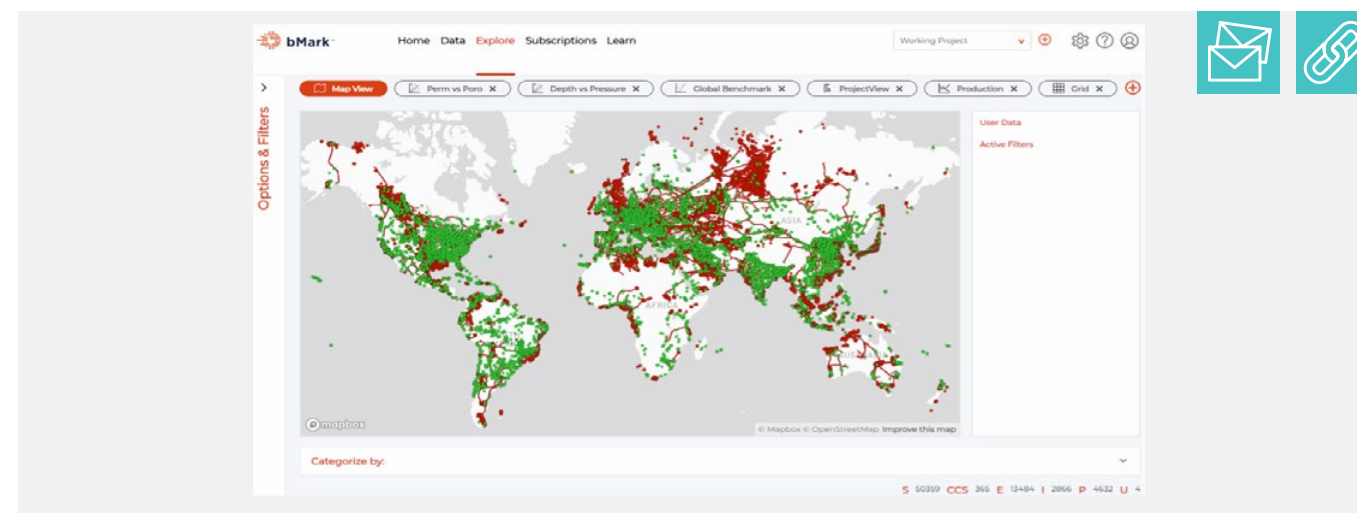
KEY DATA

TRL	9
Target Industries	N/A



BELLTREE

bMark™ bMark™ CCS



SUMMARY

bMark™ CCS offers a robust data-driven approach to screening and benchmarking of Carbon Capture & Storage (CCS) projects.

bMark™ allows users to build a comprehensive CCS project portfolio with access to global subsurface data on potential CO₂ sources, transport & storage sites linked to a dedicated feasibility screening workflow. In addition, key data on existing and proposed projects from around the world is collated allowing users to benchmark their project concepts against the current industry standard.

bMark™ CCS integrates seamlessly with the bMark™ Cloud energy analytics platform enabling teams to collaborate by sharing data and analysis in real-time.

BENEFITS

- **Build CCS Project Portfolios.** Users build custom CCS project concepts leveraging access to a global subsurface dataset of over 51,000 oil & gas fields, a growing suite of potential storage aquifers, nearly 15,000 major CO₂ emissions sites, a global pipeline transport network and their own integrated datasets.
- **Rapidly Assess CCS Feasibility.** Users can design projects, calculate storage capacity and injectivity and align against CO₂ emitter output all within an easy-to-understand dashboard interface.
- **Analyse CCS Risk.** Users rapidly understand the key risk elements within their project concepts using a unique "Storage Quality Index (SQI)" approach. Users can create a detailed risk profile of each project across a multi-parameter domain and rank concepts against each other and existing global projects.

KEY PROJECTS

- **Industrial CCS Screening & Site Evaluation:** Belltree supported an industrial CO₂ emitter in identifying and screening potential carbon storage scenarios, assessing both local hubs and new prospective sites. Using our proprietary bMark™ CCS workflow, we evaluated opportunities at both regional and local scales to ensure optimal site selection.
- **Concept Development & Risk Assessment:** We developed a conceptual CCS project plan and conducted a comprehensive risk assessment across identified storage sites. This included evaluating 15 key parameters such as leakage risk, injectivity constraints, and long-term CO₂ stability within the subsurface, enabling confident decision-making.
- **Portfolio Optimisation:** Leveraged global datasets and subsurface analytics to prioritise viable storage sites and support investment decisions.

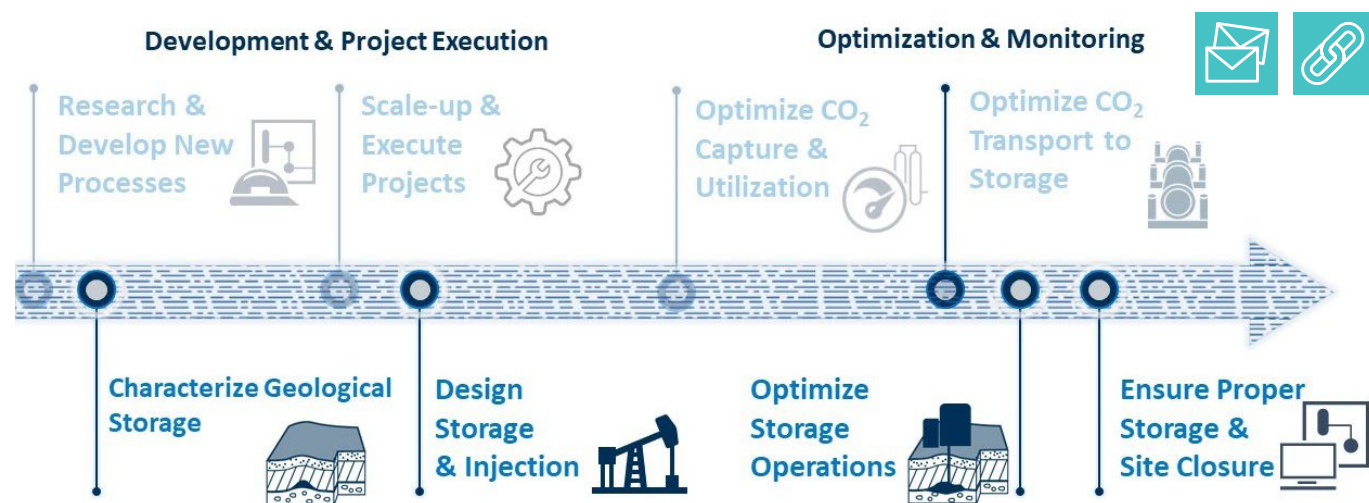
KEY DATA

TRL	9
Target Industries	O&G companies, CO ₂ Emitters, Energy Regulators



EMERSON AUTOMATION SOLUTIONS

ASPENTECH CARBON STORAGE PATHWAY



SUMMARY

Emerson's Aspen Technology business is an industrial software company with over 40 years of history in innovation, and a digital portfolio that provides a comprehensive, holistic approach to asset optimisation and process decarbonisation across design, operations and maintenance. Throughout the CCUS value chain and across the asset lifecycle, AspenTech combines the power of AI with our domain expertise to support the development of scalable carbon capture and carbon storage solutions, prioritise investment decisions, improve efficiencies and have visibility across all stages of the value chain.

Digital technologies applied to carbon capture and removal, transportation, and storage, enable ongoing innovation, rapid scaling, and increased confidence in geological CO₂ storage. The powerful combination of AspenTech solutions and an Industrial AI approach for process simulation and optimisation, subsurface geophysical and geological modelling and digital grid management, deliver performance breakthroughs at scale—both economically and at an accelerated pace, to meet the requirements of industrial carbon mitigation.

BENEFITS

- Streamline the carbon storage site selection process
- Ensure project viability with a thorough evaluation of storage capacity, containment, and site ability for injection and permanent storage
- Reduce geological risk in carbon storage to make informed investment decisions
- Optimise injection conditions to maximise the net present value of CCS projects
- Demonstrate regulatory conformance through efficient CO₂ movements monitoring data analysis, interpretation and integration

KEY AREAS

- **Geologic Characterisation:** AspenTech Subsurface Science & Engineering provides comprehensive solutions from seismic interpretation to geo-modelling, enhancing confidence in carbon storage sites and supporting permit applications. Our suite enables uncertainty propagation for assessing their impact on storage capacity and containment.
- **Carbon Injection And Storage Optimisation:** Optimise CO₂ injection and storage under uncertainties through flow simulation, considering surface and subsurface constraints to make reliable informed decisions and maximise the asset net present value.
- **Long-Term Monitoring Of Geological Storage:** AspenTech Subsurface Science & Engineering provides tools to analyse and interpret monitoring measurements and to efficiently update 3D models and performance prediction through automated workflow for model calibration

KEY DATA

TRL	9
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EXPRO

CATS EMX WIRELESS MONITORING SYSTEM



SUMMARY

For clients working across the entire well life cycle, Expro is a visionary full-cycle energy services expert offering novel, insightful solutions, dependable competency and award-winning safety. Expro's wireless downhole monitoring system uses the world-leading CaTS™ EM technology to transmit high resolution pressure and temperature data from suspended and abandoned wells.

CaTS™ enables suspended and abandoned wells to be converted into high-value long-term monitoring assets, for many years after the rig has left location. Dynamic reservoir pressure responses are monitored during drilling, testing and CO₂ injection in the field to capture cross-field interference and long-term pressure data. The data provides critical information about the connected volumes to characterise the reservoir, validate subsurface models and refine the field development plan. The system can be run on its own or as part of a DST test string and the Duplex functionality allows for optimal battery management, ensuring the right data is delivered at the right time.

BENEFITS

- Doesn't require tubing or completion string in the well.
- Signal is not attenuated by cement or bridge plugs making it ideal where a well is to be abandoned or suspended.
- Uses the industry leading quartz crystal sensor.
- Expanded pressure and temperature operating envelope.
- Uses market leading through seawater communications system.
- Integration with other devices such as acoustic DST SRO system, valves, hangers, surge chamber, TCP and fluid sampling.
- Flexibility to change gauge data transmission rate from surface to align with test objectives.
- Request historical data for periods of interest.
- Request on-demand readings.
- Compatible with third party test strings, completion components and acoustic SRO systems.
- Diagnostic functionality to check tool performance.
- Ability to optimise system performance parameters post-installation.

KEY DATA

TRL	9
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EXPRO

COLLAR LOAD SUPPORT & FLUID GRIP® TONG



SUMMARY

To ensure long-term well integrity assurance in carbon storage wells, a very thorough design review is needed for all aspects of the well architecture to ensure integrity is maintained throughout. Often overlooked, improper handling and installation through lack of knowledge, equipment selection, or technology can lead to well integrity issues in carbon storage wells. To combat the acidic and corrosive downhole environments of carbon storage wells, corrosion resistant alloy (CRA) tubulars are often designed into the well architecture to help ensure well integrity is preserved. These elements must be handled and installed carefully as impressions, marks, and cuts from make-up and handling operations can further accelerate corrosion failures on the tubular, while compromising the integrity of the downhole measuring equipment. Expro provides a line of non-marking tubular handling technologies that were designed to eliminate these risks and enhance the integrity of carbon storage wells.

BENEFITS

Benefits of this system include:

- Eliminating the possibility of slippages due to handling method
- Eliminating iron transfer typically seen with handling systems utilising standard inserts and dies
- Design allows for a large pass-through diameter which can be beneficial for running large OD assemblies and control line clamps
- Ability to run singles, doubles, and stands
- No chance of crushing tubulars as occasionally caused by the radial loads of slip type handling equipment

DESCRIPTION

The design of tubular handling equipment balances the task of supporting the necessary string weight or make-up torques, while minimising the impressions onto the outer surface of the tubular. With the correct handling equipment selection, operators will greatly mitigate risks and maximise the probability of maintained well integrity. The most ideal solution for handling CRA tubulars is to eliminate surface impressions all together using Expro's Collar Load Support (CLSTM) System.

In addition to the CLS™ system, Expro offers a non-marking tong option, which completes the industry's only tubular running package that truly eliminates the risks of corrosion failures due to iron transfer and impressions from die and insert handling systems.

The Fluid Grip® Tong utilises fluid filled bladders and provides a uniform, 360° coverage that conforms to the shape of the tubular outer diameter. This high degree of coverage significantly reduces the stresses imparted to the tubular during make-up and break-out operations, reducing the tendency for distortion and galling.

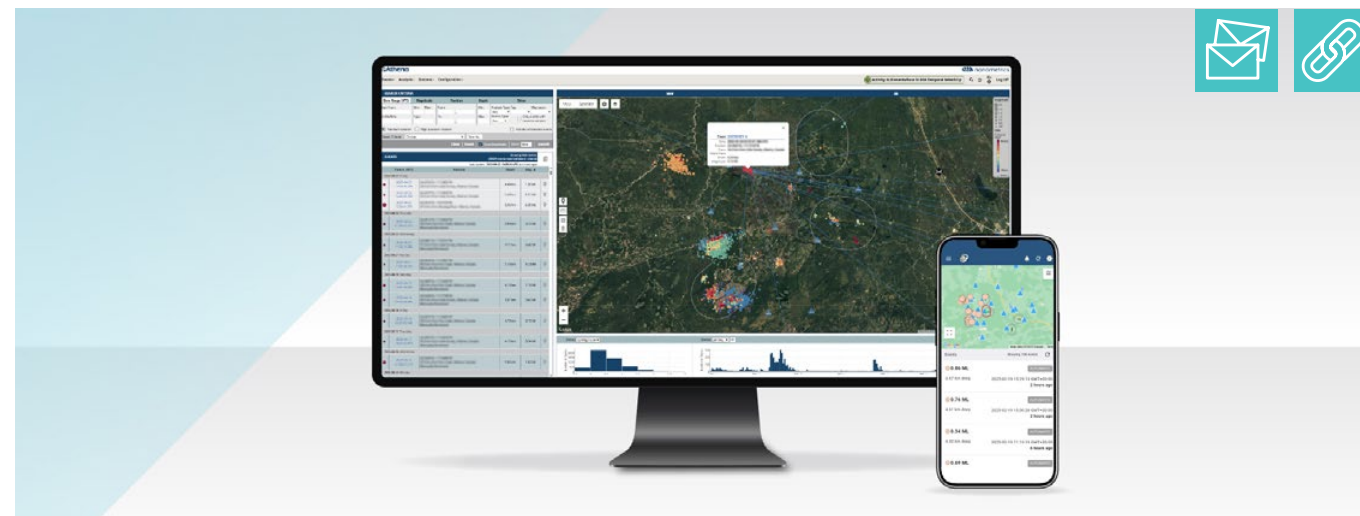
KEY DATA

TRL	9
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NANOMETRICS

REAL-TIME SEISMICITY MONITORING



SUMMARY

In carbon storage operations, induced seismicity can occur due to injection-related pressure and fluid changes shifting stresses in the storage complex and in adjacent underlying and overlying rock formations. In particular, injection and larger injection volumes can expand the area of stress perturbation, which may increase the associated seismicity risk depending on site-specific factors.

To help mitigate these risks, our induced seismicity monitoring technology utilises highly-sensitive seismic stations deployed around operational zones to detect and characterise seismicity in real-time. Compatible with any combination of sensing hardware (including surface seismic arrays, downhole geophone arrays and DAS) across onshore and offshore environments, the system streams raw seismic data to cloud-based infrastructure where it is processed and transformed into meaningful, actionable insights. The Athena and Athena Mobile platforms allow users to visualise and manage their data, configure instant notifications and generate specialised reports for regulators. An API provides a fast, efficient and flexible method to extract and integrate seismic data products into preferred third-party tools, platforms and processes.

BENEFITS

- **Regulatory & Financial Protection:** Avoid costly regulatory shutdowns by utilising defensible, compliant data that meets rigorous oversight standards.
- **Rapid Risk Response:** Enable the immediate triggering of effective Traffic Light Protocol (TLP) responses to manage events as they occur.
- **Operational Precision:** Optimise CO₂ injection schedules in near real-time based on high-resolution microseismic data.
- **Stakeholder Transparency:** Build and maintain public trust by demonstrating a proactive approach to environmental and community safety.
- **Containment Assurance Support:** Support caprock and wellbore integrity assurance by identifying seismicity patterns, seismogenic structures and possible fault activation risks.
- **Scalable, Turnkey Delivery:** Benefit from a fully managed custom solution that evolves with your project.

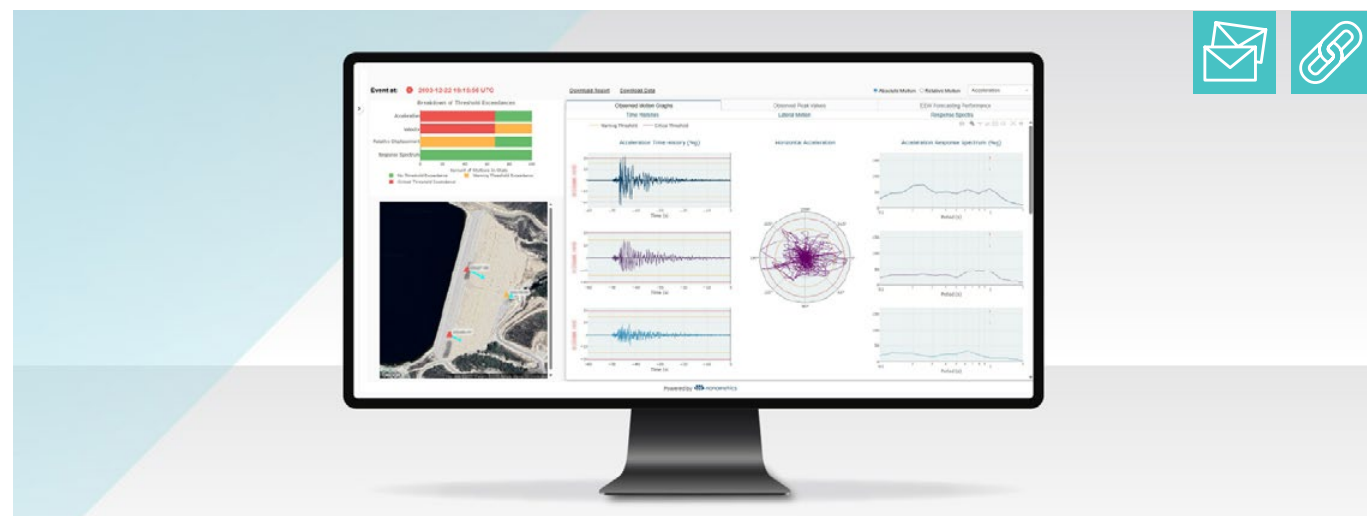
KEY PROJECTS

- **Greensand Future:** Providing advanced data processing for the offshore baseline seismicity surveys conducted by our partner K.U.M. Umwelt- und Meerestechnik Kiel GmbH.
- **Vault 44.01:** Onshore baseline seismicity monitoring project in midwestern USA to detect, locate and quantify seismicity to understand potential ground motion hazards related to CO₂ injection.
- **Gevo:** Onshore CCS project in midwestern USA monitoring seismicity in real-time during long-term CO₂ injection as part of the project's assurance and verification plan.
- **TransAlta:** Long-term seismic monitoring project in western Canada that monitors for induced seismicity in the vicinity of four major hydroelectric dams. Includes 24/7 traffic light protocol system with predefined response thresholds for nearby oil and gas operations.

KEY DATA

TRL	9
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REAL-TIME STRUCTURAL INTEGRITY MONITORING



SUMMARY

Ground motions from seismic events or cumulative industrial activities can affect the structural integrity of critical infrastructure. This is of particular concern for CCS projects located near industrial hubs or population centres, where injection-induced seismicity may raise the potential risks to property and public safety.

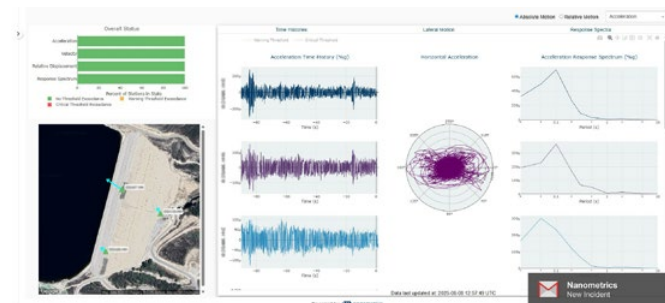
To safeguard these assets, our structural integrity monitoring technology enables operators to detect, respond to, and assess the structural impact of natural and induced seismicity. By deploying ground-motion sensors near and directly on critical infrastructure, the system provides continuous monitoring of the impact of earthquakes and a continuous ground motion record. Raw data streams in real-time to a cloud-based data center, which evaluates waveforms packet-by-packet and delivers analytics via the SiteAlert data management platform. The technology features customizable response thresholds, real-time alerting, and automated post-event data products for rapid engineering assessment. This system seamlessly integrates with our seismicity monitoring technology, providing visibility to seismic events and impact on monitored infrastructure in one-click.

BENEFITS

- **Proactive Risk Management:** Leverage real-time seismic data and automated alerts to maintain operational stability and understand the impact of operations in the surrounding area.
- **Preserve Social Licence:** Demonstrate a commitment to public safety and transparency, fostering community trust in sensitive operational areas.
- **Regulatory Compliance:** Comply with any regulatory requirements to monitor critical infrastructure near CCS operations.
- **Litigation Protection:** Maintain a definitive record of structural health to defend against induced seismicity-related claims or legal disputes.

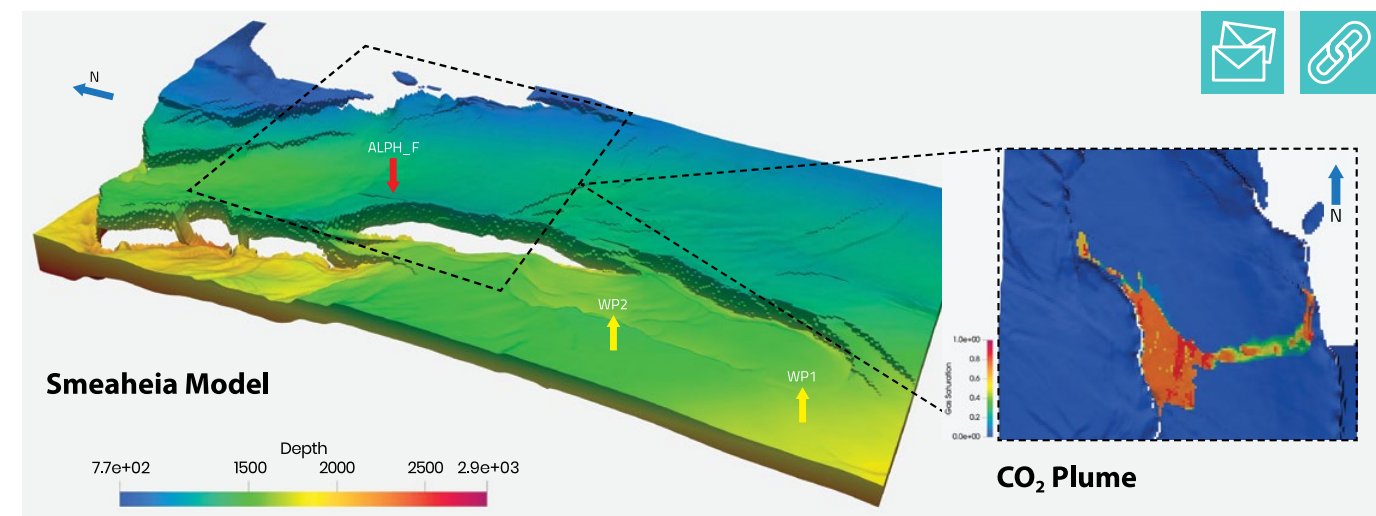
KEY PROJECTS

- **Various Oil & Gas Operators:** Ground Motion Monitoring (GMM) to ensure regulatory compliance in north east British Columbia, Canada.
- **US-based Major Oil Company:** Production facility monitoring in the area of active O&G injection operations to understand potential impact on facilities.
- **North American Power Utility:** Monitoring critical infrastructure in active seismic area to understand impact from natural seismicity.



KEY DATA

TRL	9
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SUMMARY

To plan for and manage a subsurface CO₂ store, plume migration and pressure changes in the reservoir need to be modelled. This is similar to modelling the flow of oil and gas being extracted from a reservoir. However, there are some key differences, such as much larger length and time scales and the need to account for both CO₂ dissolution in brine and temperature effects. Typical oil and gas simulators can be used but must be adapted for this purpose.

Cirrus, previously known as PFLOTTRAN-OGS, is a reservoir simulator dedicated to CCS that can simulate CO₂ storage in both saline aquifers and depleted fields. It is a cost-effective, open-source product that benefits from collaboration with academia for faster development. Thanks to state-of-the-art default modelling options, Cirrus captures the key CCS physics accurately. Recently, an option to compute injection temperature dynamically via a well flow simulator has been added.

BENEFITS

- Integrated modelling of temperature and dissolution effects. This saves time compared to legacy software that requires two separate models to assess the impact of these effects.
- A tailored mathematical model to simulate CO₂ injection into depleted gas fields, faster compared to traditional approaches.
- Simulation of large regional models over long periods in a reasonable time, thanks to scalable parallel computing.
- Easier to set up for new engineers who have no oil and gas experience.

KEY PROJECTS

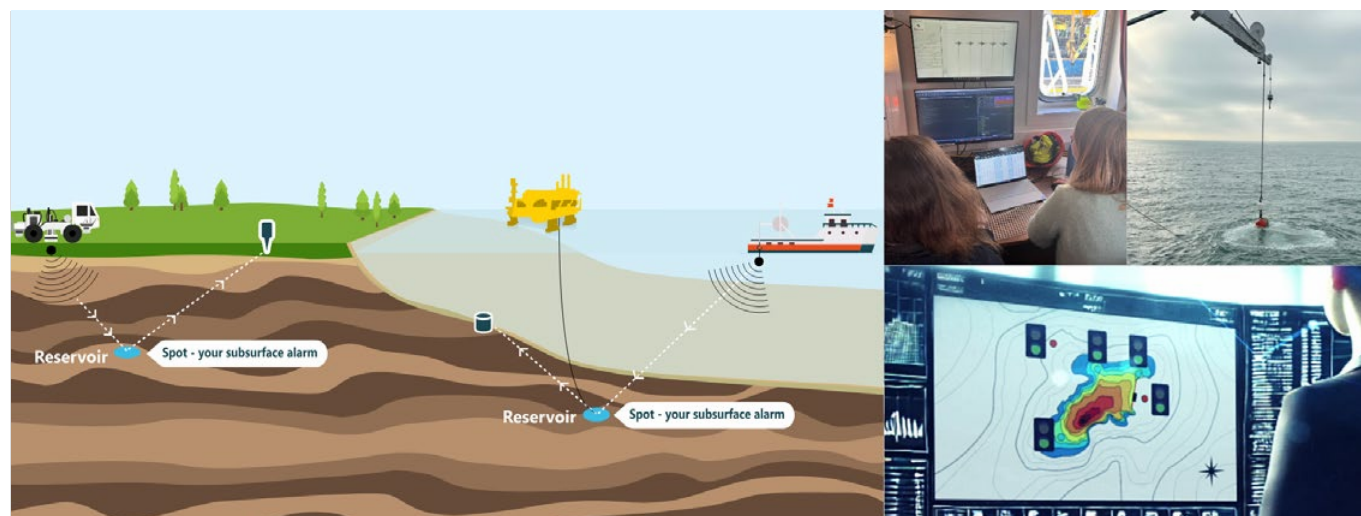
- **Northern Endurance Partnership (UK):** study of pressure interference between multi-store sites and CO₂ plume distribution with a large regional model.
- **Smeaheia (Norway):** modelling the interactions between CO₂ injection and the hydrocarbon production at the nearby Troll field. The CO₂-brine system and hydrocarbon depletion were modelled simultaneously.
- **Ruby (Denmark):** storage capacity assessment in support of license application.
- **Sleipner (Norway):** modelling of the temperature effects on the CO₂ plume movement in the Utsira formation.

KEY DATA

TRL	7	Number of CO ₂ projects supported	>10
Reservoir type	Saline aquifers and depleted fields	Industry workflow compatibility	Yes
Regional model size	~ (100 km x 100 km)	Physical simulation time	>1000 y
Target Industries	Subsurface CO ₂ Storage – site assessment and development		



SPOTLIGHT SPOT SEISMIC



SUMMARY

Spot seismic is an active seismic solution providing frequent, focused detections for the CO₂ reservoir with a minimal acquisition setup: only one source and one or a set of receivers per spot for a total of 20-40 spots per campaign (less than a day of acquisition). This patented, low impact, and cost efficient technology enables higher monitoring frequency (1-3 per year) than other active seismic solutions, allowing early identification of deviations between actual and forecasted CO₂ plume. It supports both conformance (model calibration and verification) and containment (monitoring key risks) requirements. It forms the basis for a strong risk-based and model driven surveillance strategy, providing reservoir subsurface alarms to trigger timely response actions when deviations are detected. By adding frequent focused measurements to their risk-modelling workflows, operators can validate assumptions earlier, reduce technical and financial risk, and support clearer investment decisions and long-term project planning.

BENEFITS

- Increasing site safety with frequent focused active seismic monitoring, evidencing that the CO₂ plume behaves as predicted, supporting regulatory compliance and strengthening permit applications.
- Significantly reducing the environmental impact with minimal offshore or onshore footprint, smaller seismic source, couple of days of acquisition and flexibility to adapt to surface/seabed constraints.
- Cost-effective with a low initial investment, spot seismic enables robust MMV plan using conventional off-the-shelf seismic equipment.
- Frequent focused seismic reduces subsurface and financial uncertainty, stabilizing CAPEX/OPEX exposure and improving insurers' and lenders' risk perception, unlocking better insurance, debt terms, and stronger conditions for FID and long-term project viability.

KEY PROJECTS

- Greensand CCS (Denmark):** Monitoring of the first injection of CO₂ offshore Denmark in a depleted oil reservoir (water leg). Small quantities of CO₂ have been detected after 1 month (2000T) and 3 months of injection (<5000T). The overall acquisition operation lasted few hours, planned swiftly within good weather windows in winter, in the North Sea.
- Weyburn CCUS (Canada):** 4 years of monitoring of the Weyburn field onshore Canada. The 4 years of spot monitoring results have been validated against a 4D seismic.
- Poseidon CCS (UK):** Monitoring of the first CCS project offshore United Kingdom. Spot Detections have been performed during the injection of CO₂ in the Leman depleted gas reservoir.

KEY DATA

TRL	8 - 9	Survey duration	1 day (for 20 - 40 spots)
Reservoir type	Saline aquifers, depleted reservoirs	Survey frequency	1 - 3 per year
Processing duration	1 - 10 days		
Target Industries	Storage, CC(U)S (onshore, offshore)		



SUPERCONDUCTING SENSOR TECHNOLOGY CORPORATION (SUSTEC) SQUID-TEM METHOD AS A COMPETITIVE AND EFFICIENT CCS/CCM MONITORING TOOL



SUMMARY

We provide geophysical exploration services using a transient electromagnetic (TEM) system with 3-axis high-temperature superconducting quantum interference device (HTS-SQUID) magnetic sensors. Our state-of-the-art HTS-SQUID, which is an ultra-highly sensitive magnetometer, has a wide bandwidth and higher durability against external magnetic field and thus allows the system to detect deeper TEM signals. Our SQUID-TEM system combined with a grounded line excitation source and proprietary 3D inversion analysis can provide 3D resistivity mapping with higher spatial resolution at any given depth (few tens meter to 3000-5000 m). Since TEM method is the most sensitive to a change in formation conductance, resistivity change in a reservoir injected with water/CO₂ or CO₂ plume in the reservoir can be detected as a resistivity contrast. Thus, our SQUID-TEM system is a powerful tool for reservoir monitoring of CO₂ storage operation.

BENEFITS

- SQUID-TEM method enables detection of CO₂ plume in a reservoir as a resistivity change in a wide range of CO₂ saturation level.
- SQUID-TEM method enables shallow and deep reservoir monitoring of CO₂ storage operation with a superior spatial resolution than conventional methods.
- SQUID-TEM method is applicable for both onshore and offshore (shallow water application).
- SQUID-TEM's low-cost acquisition makes it an ideal tool for CO₂ plume monitoring and geothermal reservoir exploration/evaluation.
- SQUID-TEM supplements and extends conventional seismic evaluation techniques.

KEY PROJECTS

- Offshore CCS monitoring project: In Tomakomai offshore large-scale CCS verification site (shallow sea region) in Japan, SQUID-TEM method as an effective monitoring tool have been implemented within a framework of Ministry of Environmental project since 2022.
- Onshore CO₂ storage monitoring project: In a Middle Eastern country, SQUID-TEM method has been deployed since 2023 to verify a development of water/CO₂ plume in the reservoir as a time-lapse survey.
- Geothermal exploration projects: In Indonesia and Japan, SQUID-TEM method has been deployed to clarify high-resolution resistivity structure useful for determining drilling points.

KEY DATA

Number of SQUID sensors	3 (x, y, z)	Total weight	20 kg	Continuous operation time	17 h
Typical data acquisition time	1-2 h /point	Exploration depth	0 - 5,000 m	3D inversion analysis	Yes
Exploration/monitoring targets	CCS (onshore, offshore), CCM, EOR, Geothermal resources, Metal resources				

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