



TECHNICAL REPORT

STATE OF THE ART: CCS TECHNOLOGIES 2025



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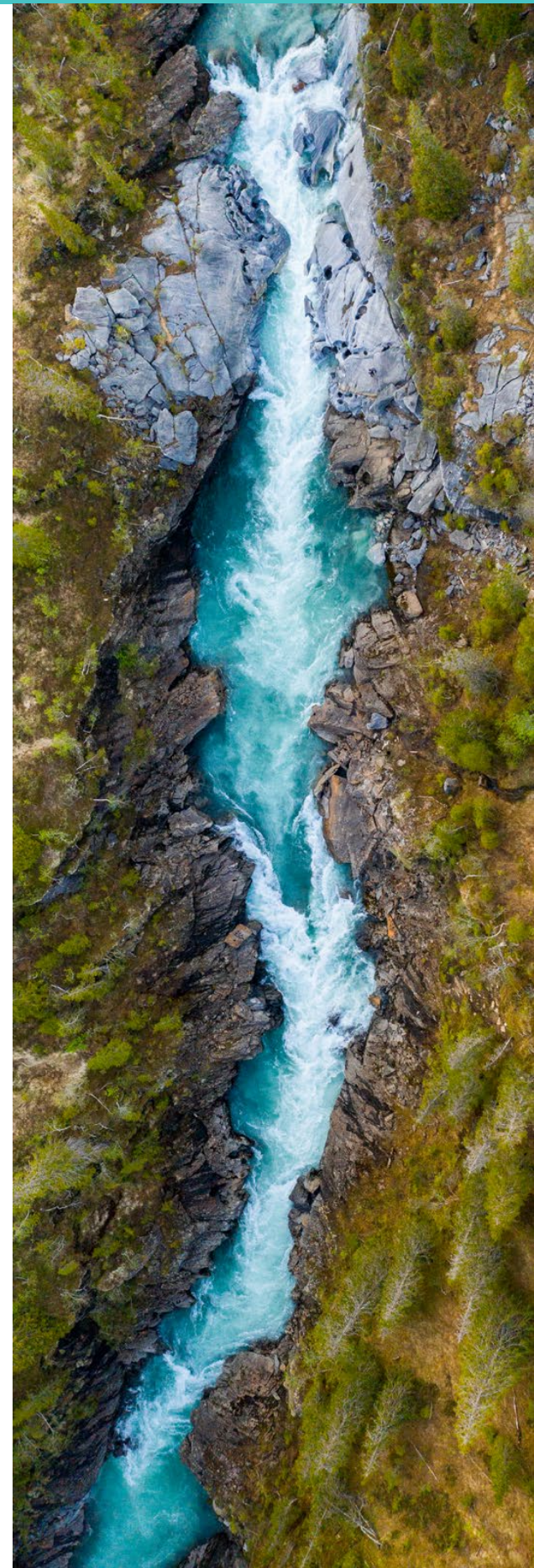
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FOREWORD

Carbon Capture and Storage (CCS) is a crucial tool in addressing global greenhouse gas emissions and tackling climate change. Urgent technological development, deployment, and scale-up of CCS technologies are necessary to meet our net-zero targets across industries such as cement, steel, chemicals, natural gas, and power generation. As we approach 2030, projects will enter critical stages of design and development. It is now that the uptake of CCS technologies must continue to accelerate to address emissions, alongside the deployment of Carbon Dioxide Removal applications to remove CO₂ already present in the atmosphere.

The 2025 “State of the Art: CCS Technologies” Technology Compendium builds upon the momentum of our past editions. Leading technology developers and providers within the CCS landscape are represented, alongside the up-and-coming disruptors seeking to further drive innovation in capture performance, capabilities, energy usage, and, most importantly, cost. The entries in this edition cover a range of methods in capture, transport, and storage to enable the development of the full CCS value chain.

The Technology Compendium showcases the breadth and depth of CCS technology available for deployment today, as well as technologies in the process of reaching full commercial readiness.

The current CCS technological capabilities and upcoming future developments submitted show the strong technical 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.

The Technology Team
Global CCS Institute
July 2025

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](#).

Thank you to Hugh Barlow, Shahrzad Shahi, and Javad Jeddizahed for their invaluable editing and coordination of this report.

Special mentions also go to Aishah Hatta, Bruno Gerrits, Carlo Maccherini, Chris Consoli, Dominic Rassool, Elena Leva, Erin Billeri, Hiroshi Nambo, Honor Iosif, Kamalpreet Kaur, Kazuko Miyashita, Maryem El Farsaoui, Mohammad Abu Zahra, Mojtaba Seyyedi, Ruth Gebremedhin, Sarah Hardman, Spencer Schecht, Wendy Wells, Xiaoliang Yang, Yasuo Murakami, Yi Wu and many more across the Institute for their time, efforts, and care with developing this publication.



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 (CCS), a suite of technologies to tackle climate change and deliver climate neutrality.

The Institute produces the "State of the Art: CCS Technologies" 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 2025 Technology Compendium represent a non-exhaustive picture of the overall landscape of CCS technologies. Where there has been no submission received for the 2025 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 issues.

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

Disclaimer

The Global CCS Institute has endeavoured to ensure the information in this publication is as accurate as possible. However, it does not guarantee that the information in this publication is totally reliable, accurate, or complete. Therefore, the information in this publication should not be relied upon when making an investment or commercial decision or provided to any third party without the written permission of the Global CCS Institute.

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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 2025 Technology Compendium, a Technology must have a TRL of 5 or above.

Table 1: TRL Guidance Provided for 2025 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 Adjacent, 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 that a technology is suitable for deployment on. 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 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 Just Catch™ carbon capture plant at Twence in Hengelo, the Netherlands. Image courtesy of SLB Capturi.

Foreword Image: The Petra Nova Carbon Capture Project in Texas, the United States. Image courtesy of Mitsubishi Heavy Industries.

CAPTURE



Image Credit: Carbon America's FrostCC™ pilot plant at the National Carbon Capture Center. Images are courtesy of Carbon America, National Carbon Capture Center, and Southern Company.



SUMMARY

To meet global climate goals and support the transition to a net zero economy, the world needs clean, affordable, and scalable solutions for producing hydrogen. 8RH₂ is an ultra-low-carbon hydrogen production technology that cost-effectively captures greater than 99.5% of the CO₂ produced during the process. At the heart of 8RH₂ is 8 Rivers' proprietary CO₂ Convective Reformer (CCR), which leverages the company's decades of expertise in oxy-combustion and heat transfer to achieve breakthrough performance.

The 8RH₂ process works by combining the CCR with an Oxy-Combustor, which combusts tail gas and natural gas fuel with synthetic air made up of pure oxygen and CO₂. This results in a high-temperature, high-purity CO₂ stream that provides the necessary heat for steam methane reforming in the CCR. By leveraging the energy in the tail gas, 8RH₂ achieves improved cycle thermal efficiency while avoiding the additional costs associated with back-end carbon capture systems.

BENEFITS

- Our hydrogen production technology has no direct emissions and achieves an ultra-low-carbon intensity that is 15-20% lower than state-of-the-art autothermal reforming with CCS (ATR+CCS).
- The capture of CO₂ is inherently built into the process design, capturing in excess of 99.5%, while avoiding the use of toxic chemicals or energy-intensive processes.
- Combines strengths of commercially proven hydrogen production processes to reliably deliver clean and affordable energy at scale.
- Utilisation of oxy-fired combustion of tail gas to provide heat of reforming and heat integration enables a highly efficient cycle boasting 5-7% thermal efficiency gains versus benchmark ATR+CCS.
- Combined, this results in 8RH₂ having an unrivalled levelised cost compared to all utility-scale hydrogen technology currently on the market.
- Easily integrates with ammonia loop technology to enable production of ultra-low-carbon ammonia, which can be traded as commodity or used for easier H₂ transportation.

KEY DATA

TRL	>5	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	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Hydrogen, Ammonia/Fertiliser, Refining, Transportation Fuels, Coal Fuel Switching, Methanol, Oxo-alcohols				

KEY PROJECTS



In January 2024, 8 Rivers announced Cormorant Clean Energy, located in Port Arthur, Texas, will be the first deployment of the 8RH₂ technology.

Cormorant will produce 880,000 tonnes of ultra-low-carbon ammonia and capture more than 1.4 million tonnes per annum (Mtpa) of CO₂.

The project is expected to bring in over \$1 billion in investment to the region and is expected to reach FID in 2026 with construction commencing shortly thereafter.

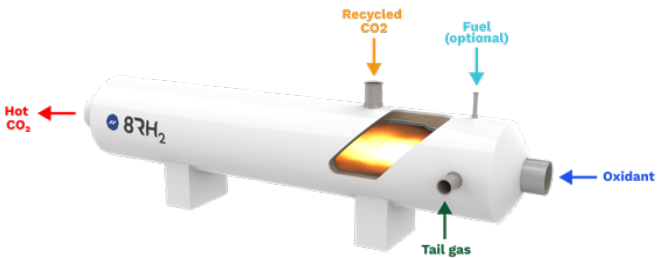
8 Rivers is actively exploring future projects for the 8RH₂ technology to be deployed in the US and abroad.

TECHNOLOGY DESCRIPTION

In May 2023, 8 Rivers announced the development of 8RH₂, an ultra-low-carbon hydrogen production process that cost effectively captures greater than 99.5% of the CO₂ produced. At the heart of the process is 8 Rivers' years of oxy-combustion experience and a proprietary CO₂ Convective Reformer (CCR) that 8 Rivers is jointly developing with Casale SA.

In contrast to conventional steam methane reforming, 8 Rivers technological breakthrough is in the powerful combination of Oxy-Fired Combustion with our proprietary heat exchanger reformer, the CCR.

The Oxy-Combustor is a pressurised combustion heater that combusts tail gas and natural gas fuel with synthetic air made up of pure oxygen and CO₂ diluent. What results is a high temperature CO₂ flue gas stream that has not been contaminated by the impurities in air, namely nitrogen, which complicates back-end CO₂ capture. This hot CO₂ flue gas stream needs water and oxygen removal and is then pipeline ready at high purity.



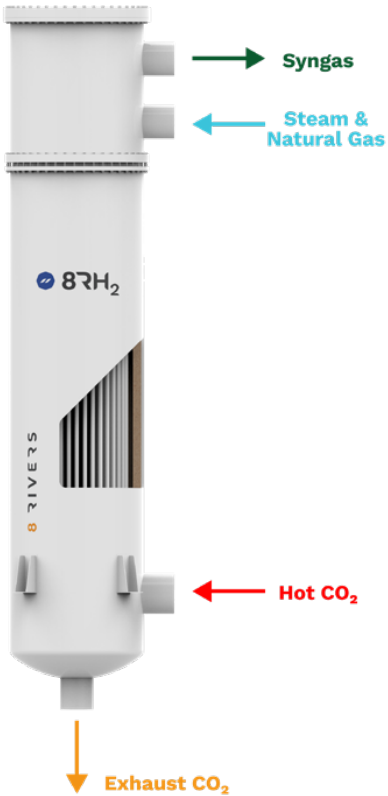
In the 8RH₂ process, the hot CO₂ flue gas stream leaves the Oxy-Combustor and flows through the CCR, providing the heat necessary for steam methane reforming to occur. This allows 8RH₂ to leverage the energy contained in the tail gas fuel for the best purpose – creating more product, while keeping the CO₂ stream separate and pure.

Leveraging this tail gas energy, which is essentially a byproduct of steam methane reforming, in a useful, cost-effective manner and without contributing to emissions is one of the core advantages of 8RH₂ over traditional hydrogen production technologies.

Doing so enables improved cycle thermal efficiency while avoiding the additional costs associated with back-end carbon capture systems such as amine solvents.

After the CO₂ has provided heat to the CCR it will undergo further heat recovery before the Direct Contact Cooler removes water and cools the gas to pipeline ready temperatures. A portion of the CO₂ will be exported for sequestration, while the rest is recycled to act as a diluent in creating synthetic air for the Oxy-Combustor.

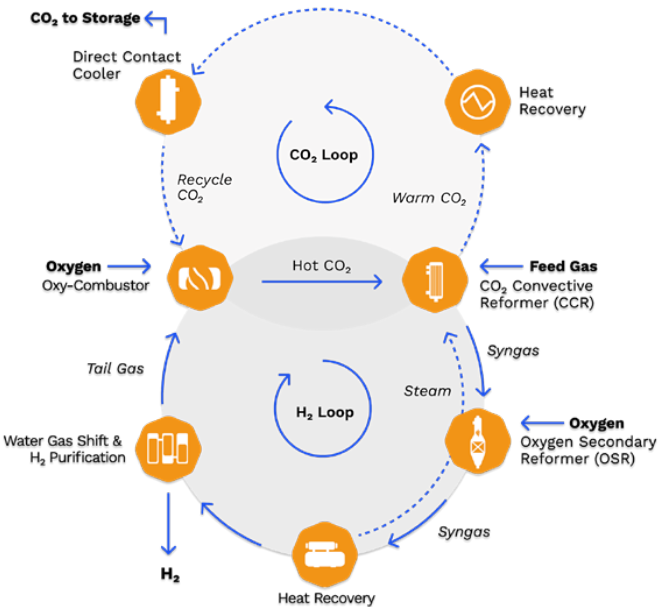
Feed gas leaves the CCR as partially reformed syngas and enters an Oxygen Secondary Reformer (OSR) which completes the reactions. A series of heat recovery, water gas shift reactions, and hydrogen purification operations are carried out, not unlike traditional hydrogen plants.



As its key output, 8RH₂ produces a stream of high-purity hydrogen. The remaining tail gas is separated to be recycled back to the Oxy-Combustor. 8RH₂ was designed to be easily integrated with ammonia loop technology.

8RH₂ technology utilises two distinct loops on each side of the process: hydrogen and CO₂, to unlock greater than 99.5% CO₂ capture without sacrificing cost-effectiveness.

The first commercial deployment of the 8RH₂ technology will be Cormorant Clean Energy in Port Arthur Texas. Cormorant will produce 880,000 tonnes of ultra-low-carbon ammonia and capture more than 1.4 Mtpa of CO₂ annually.





SUMMARY

The success of the energy transition boils down to a single, unavoidable question: how can society source power that is clean, secure, reliable, and affordable? With almost no technology able to meet all these criteria, weighing the tradeoffs can feel like a balancing act at best and a zero-sum game at worst.

Biome and AFC-Carbon (AFC-C) offer a solution, one that can generate reliable, negative-emissions power at affordable prices. As the next-generation of 8 Rivers’ lauded Allam-Fetvedt Cycle (AFC) technology, Biome combusts gasified biomass or municipal solid waste (MSW) while AFC-C combusts gasified coal, petcoke, or heavy distillates, producing a stream of supercritical carbon dioxide (sCO₂). The resulting fluid is used as the working medium in the power cycle, driving a turbine to produce electricity. Featuring inherent carbon capture, steady generation, and strong economics, Biome and AFC-C can help meet today’s surging demand for clean, secure, reliable, and affordable power.

BENEFITS

- Clean
- Oxy-combustion produces pure streams of sCO₂ and H₂O, eliminating virtually all traditional air pollutants
 - Utilisation of CO₂ as the working fluid enables inherent carbon capture
- Secure & Reliable
- Power production from a wide range of feedstocks ensures energy security regardless of location
 - Baseload, dispatchable power production promotes grid stability and pairs well with renewables
- Affordable
- Oxy-combustion with heat recycling boosts performance and cycle efficiency
 - Pure CO₂, CDRs, and other valuable byproducts can reduce power costs far below traditional sources with PCCC
 - Overall plot size is smaller than that of a traditional power block + PCCC

KEY PROJECTS

- In 2024, 8 Rivers entered into an MOU with PacifiCorp, parent of Rocky Mountain Power, to evaluate a potential carbon capture project at one of the utility’s existing power plant sites in Wyoming
- The project will deploy 8 Rivers’ AFC technology and direct-fired supercritical CO₂ turbines being developed with Siemens Energy, who will provide continued support through the Pre-FEED and subsequent FEED
- On March 12, 2025, 8 Rivers awarded Wood an agreement for the project’s preliminary front end engineering design (Pre-FEED)

KEY DATA

TRL	6+	Capture Rate Range (tpd)	~	Capture Efficiency (%)	>97%
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	Power generation				

TECHNOLOGY DESCRIPTION

THE ALLAM-FETVEDT CYCLE

The Allam-Fetvedt Cycle (AFC) is a semi-closed, oxy-fuel power cycle that utilises sCO₂ as the working medium. Being fuel agnostic, the AFC can operate on a wide variety of carbonaceous feedstocks including biomass and MSW (Biome) or coal, petcoke, and heavy distillates (AFC-C). The natural gas version of the cycle was initially developed by 8 Rivers and is now licensed exclusively to NET Power. By leveraging the properties of sCO₂ to drive a turbine, the AFC not only provides efficient power generation but inherent containment and capture of nearly all emissions.

Once the selected fuel has been gasified, the resulting syngas enters the oxy-combustor. An air separation unit (ASU) supplies a pure stream of oxygen which is diluted to safe concentrations with recirculated CO₂. The syngas is combusted, producing a high-pressure exhaust stream of sCO₂ and H₂O. This mixture is then fed into the turbine, specially designed by Siemens Energy to extract energy from the unique working fluid. While the generator converts this work into electricity, the turbine’s outflow is routed through a network of heat exchangers, water separators, and compressors to produce a pure stream of cooled CO₂. A portion of this pipeline-quality gas is exported to sequestration while the remainder is recirculated to the combustor, completing the cycle.

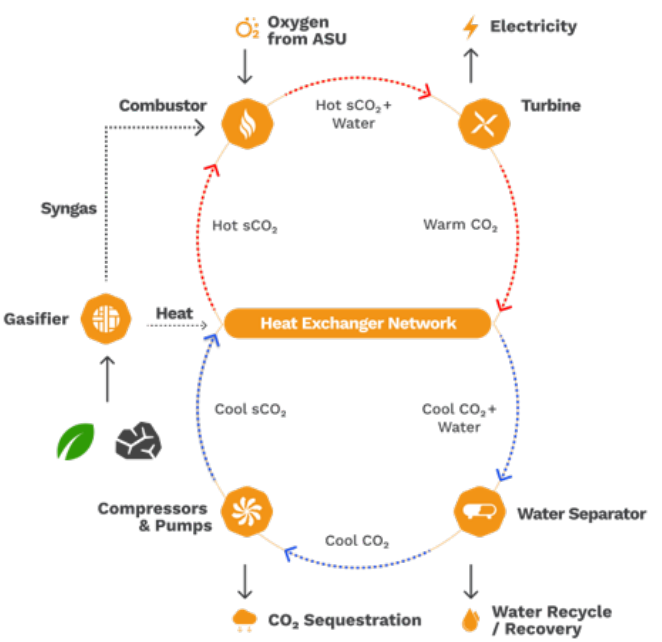
TECHNOLOGY DEVELOPMENT PARTNERSHIP

To support the deployment of this technology, 8 Rivers and Siemens Energy have partnered on the development of a first-of-its-kind, direct-fired sCO₂ turbine. The finished product will be capable of exporting 240-285 MWe, enough to power roughly 210,000 homes each year. Unlike conventional, air-fired power plants that utilise contaminant-rich working fluids, the AFC’s oxy-combustor supplies the turbine with a pure stream of sCO₂ and water, eliminating the need for costly, inefficient post-combustion capture (PCCC) systems. Not only does PCCC cannibalise plant electrical production, but its operational life is also limited to that of its ageing host plant. Siemens Energy’s sCO₂ turbine, on the other hand, will enable Biome and AFC-C facilities to supply zero-to-negative emissions power for 30 years. Critically, this power will be both baseload and dispatchable, providing long-term stability to the grid while addressing the primary obstacle to renewable energy adoption.

THE AFC ADVANTAGE

Beyond inherent carbon capture, the AFC’s revolutionary design offers several key advantages. Due to sCO₂’s high density, the turbomachinery and overall facility plot size are much smaller than typical for large-scale power plants. Supercritical CO₂ also has excellent heat transfer properties which make it ideal for heat integration with the gasification and feedstock preparation steps. Together, these characteristics reduce AFC’s capital and operational expense profiles, strengthening its economic case against competing technologies.

At 8 Rivers, we are developing the infrastructure-scale solutions today to build a cleaner tomorrow. For those looking to achieve their Net Zero goals, Biome and AFC-C technologies are the clear choice for delivering clean, reliable power at an affordable cost.





SUMMARY

As the world confronts climate change, experts agree that emissions reductions must be accompanied by large-scale carbon removal. Calcite, developed by 8 Rivers, uses the calcium cycle to rapidly remove CO₂ from the air. The Calcite carbon removal process works by accelerating the carbonation of calcium, passing ordinary air across calcium hydroxide in a warehouse to absorb CO₂ into calcium carbonate crystals. The calcium carbonate is then cycled into a kiln to regenerate calcium hydroxide and capture CO₂ for permanent sequestration. Calcite's low-cost approach, low technical risk, and hyper scalability make it a promising solution for global carbon removal needs.

8 Rivers and MIT developed Calcite's novel air contactor, which was validated by a prominent US National Laboratory. Calcite was a Milestone winner in the XPRIZE CDR competition, one of the Frontier Climate Fund's first offtakes, won DAC Hubs funding through the US DOE to support its commercial deployment, and was a winner of the DOE CDR Purchase Pilot Prize Phase 1.

BENEFITS

- The Calcite process is simple, leveraging the natural calcium cycle and does not require complicated catalysts or materials.
- Calcite is designed to be extremely scalable by using widely available equipment and existing supply chains as well as limestone, an abundant feedstock, which enables faster scale-up and progression to next-of-a-kind.
- Calcite offers durable carbon removal by permanently sequestering CO₂ geologically through highly regulated, Class VI wells, or through mineralising the CO₂ as limestone, CaCO₃.



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	1	Modular (Y/N)	~
Target Industries	DAC				

TECHNOLOGY DESCRIPTION

THE CALCITE PROCESS

Invented in 2019, Calcite is a cost-effective direct air capture technology to remove CO₂ directly from the ambient atmosphere. The process facilitates carbon removal by relying on the simplicity of the natural calcium cycle.

An oxy-fired kiln combusts fuel and concentrated oxygen to calcine fresh and regenerated calcium carbonate (CaCO₃) to form calcium oxide (CaO), while the effluent CO₂ is captured for sequestration. Oxy-firing replaces the air normally used for fuel combustion with a mixture of high purity oxygen and CO₂. The flue gas from oxy-fired process is almost entirely CO₂ and water, allowing it to be sent through a CO₂ compression and purification unit (CPU) for sequestration. An additional advantage of the oxy-fired kiln is that combusting fuel with carbon capture minimises the requirement for clean electricity for the facility.

Calcium oxide coming out of the kiln is then hydrated, which in turn carbonates with ambient air through air contactor modules. The air contactor is designed to facilitate fast carbonation when CO₂ from the ambient air reacts with the sorbent.

The last major step of the process is to deliver the newly formed calcium carbonate back into the oxy-fired kiln to separate the CO₂ for permanent sequestration. This creates a calcium loop to start a new carbonation cycle.

The technology is designed to facilitate fast carbonation with a high-capacity factor and little downtime. With simple chemistry and engineering, the Calcite process is set up to be a low cost, scalable, and quickly deployable system.

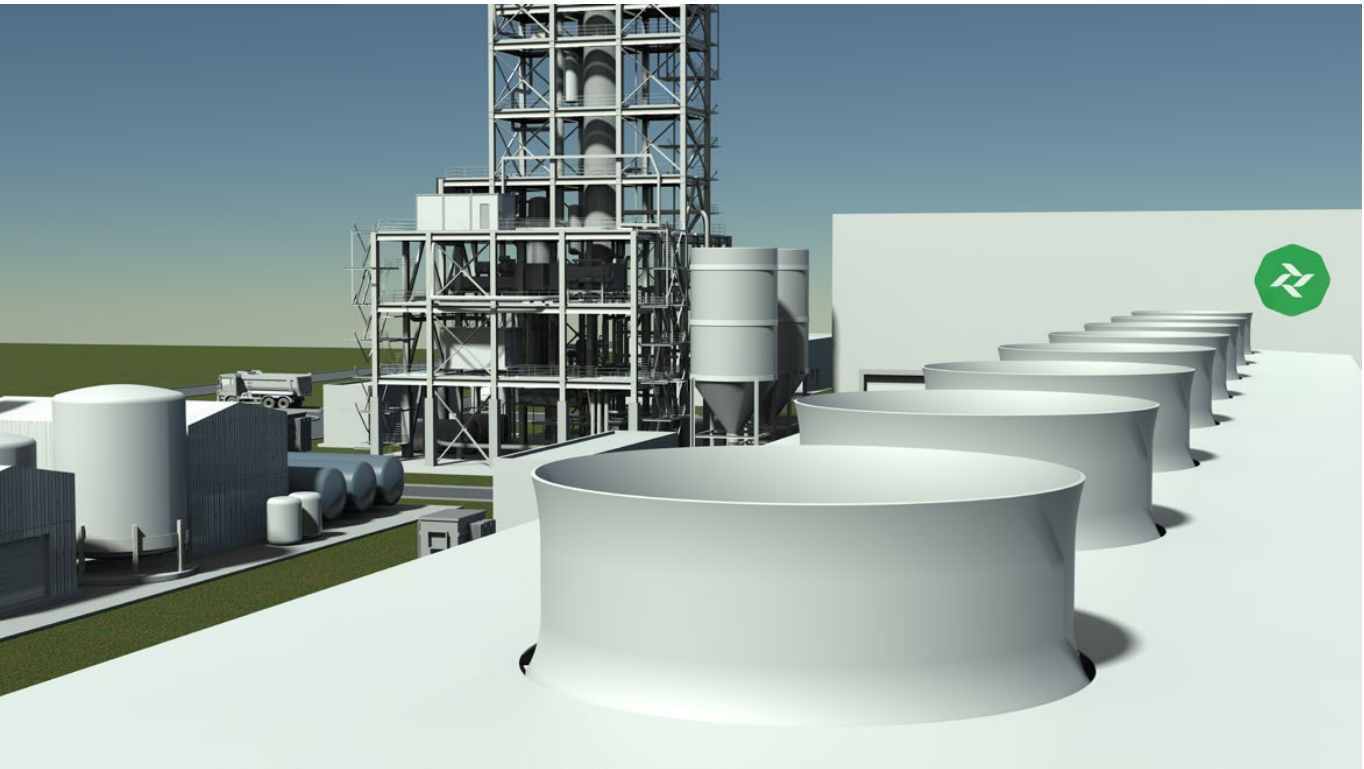
THE CALCITE FACILITY

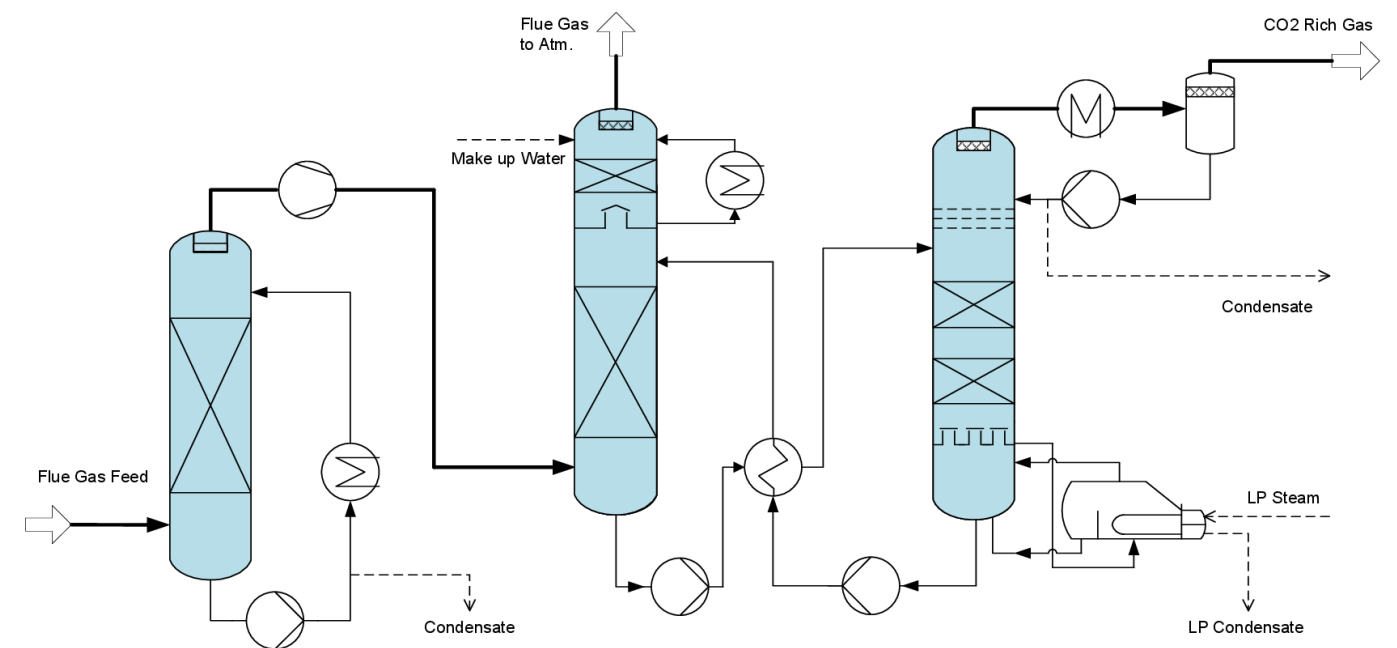
- A Calcite facility will consist of:
- 8 Rivers' novel air contractor where ambient CO₂ is passed over a calcium-based sorbent to form CaCO₃;
 - An oxy-fired calciner which uses thermal heat to decompose CaCO₃ into CO₂ for sequestration and CaO to be hydrated and cycled back to the air contactor;
 - An oxygen production unit to supply oxygen to the oxy-calciner;
 - Limestone storage and equipment to prepare the material to be fed to the oxy-calciner and material to be sent to market;
 - CO₂ purification and compression equipment to prepare the captured CO₂ for pipeline transport.

PROJECT STATUS

Calcite is a member of the Southeast DAC (SEDAC) Hub, a deployment of DAC technologies in northern Mobile County, Alabama. Mobile County is an ideal location to support the initial phases of a DAC hub as it is home to many industrial facilities, large tracts of available land, and appropriate subsurface geology to support the creation of a sustainable CO₂ -based economy. In addition, numerous opportunities exist to employ the region's skilled workforce in pursuit of a variety of CO₂ use cases beyond permanent storage in subsurface reservoirs (e.g., CO₂ to fuels). Because of these attributes, the SEDAC Hub will not only abate local emissions but also lead to the development of a carbon reduction ecosystem in the area and the Gulf South more broadly.

As a recipient of funding under the US Department of Energy's Direct Air Capture (DAC) Hub program, a FEED study will be conducted to support the construction and operation of a 100,000 net tonne per year Calcite carbon removal facility as a part of the SEDAC Hub.







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 8 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%+.

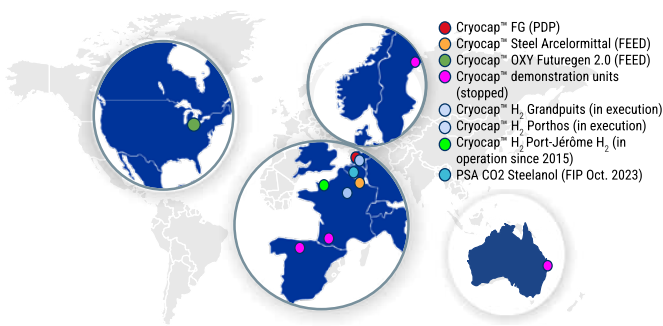
BENEFITS

- 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 - 8	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



TECHNOLOGY DESCRIPTION

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)

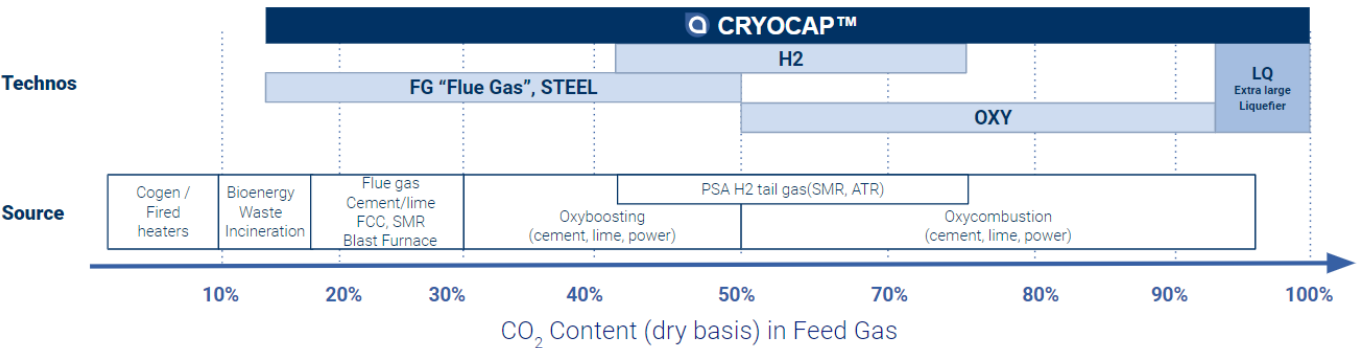
CRYOCAP™ STEEL

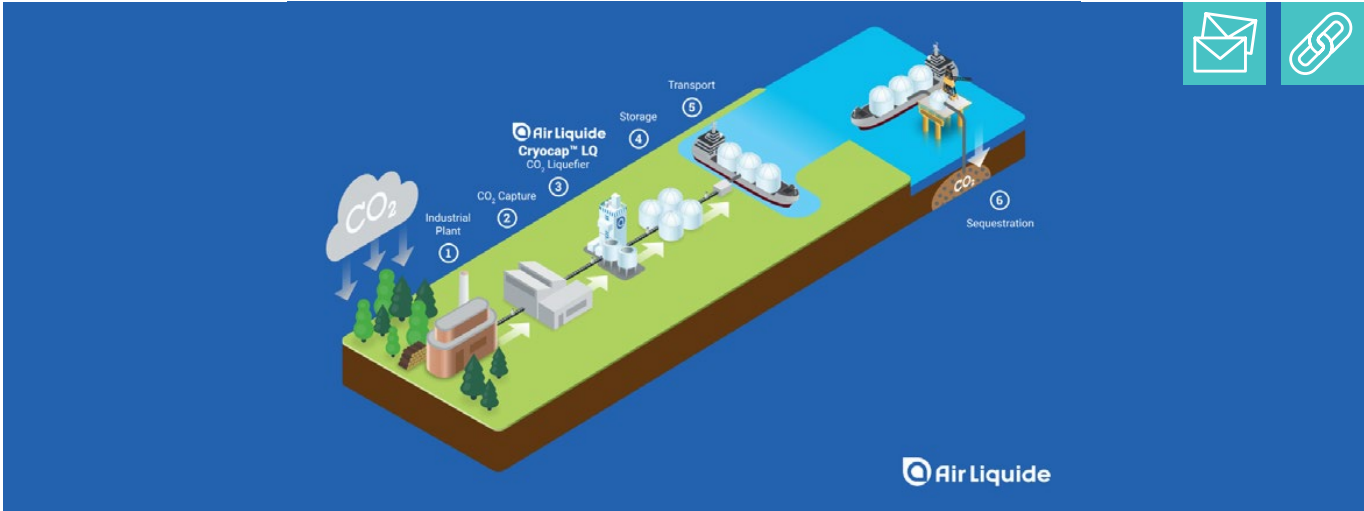
Cryocap™Steel was designed to specifically capture CO₂ from steel making plants with flue gases containing CO₂ in the 20-50% range. The gas is first compressed, dried and sent to a PSA (Pressure Swing Adsorption). The PSA pre-concentrates the CO₂ in the off-gas while producing a CO rich stream. The pre-concentrated 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





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)

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

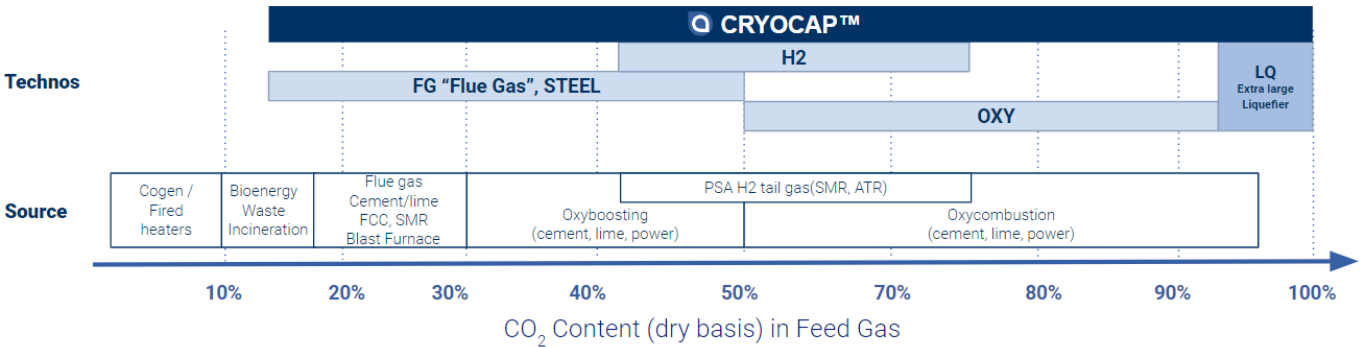
The Cryocap™ LQ process is proposed as an industrial solution to compress, liquefy, and purify the raw CO₂ stream resulting from upstream units. The CO₂ feed gas is compressed in the feed/recycle compressor, dried at an intermediate pressure and then compressed again. The compressed gas is cooled down 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
- Liquefies CO₂ at ambient temperature

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 decarbonized hydrogen and ammonia/urea				

TECHNOLOGY DESCRIPTION

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 suite 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 is demixing under certain conditions of temperature and CO₂ partial pressure in the regeneration section. The DMX™ solvent is regenerable with a much higher capacity than available solvents, whereas only the CO₂-rich phase needs to be regenerated.

The DMX™ Technology has been successfully demonstrated through a large-demonstration plant at ArcelorMittal's steel mill in Dunkirk and 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, composition and flowrate.
- Low energy consumption.
- Thermally stable solvent with low degradation.
- High capture rate (up to 99%) and high purity of produced CO₂ (>99.5%).
- CO₂ produced readily under pressure up to 5 barg for significant compression cost-savings.

KEY DATA

- 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 pilot).
- Support on the full value chain: pre-treatment, capture, conditioning and close collaboration with EPCs and compressor vendors for integrated offer.
- Continuous innovation and testing capabilities at IFPEN facilities.

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	3 - 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				

TECHNOLOGY DESCRIPTION

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 its DMX™ solvent highly tolerant 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.

The regeneration of the CO₂-rich phase is performed under pressure, up to 5 barg, thanks to its thermal stability, enabling the process to achieve significant CO₂ compression-related cost-savings in view of its sequestration or liquefaction.

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™ process has undergone more than 10 years of development from laboratory scale to demonstration level. The Technology has been successfully demonstrated through a large plant at ArcelorMittal steel mill in Dunkirk capturing the CO₂ from a blast furnace gas at a capacity of 0.5t CO₂/h.

DMX™ demonstration unit was built and has been operated with a 24/7 operation between April 2023 and November 2024 within the European H2020 "3D" project bringing together 11 European partners including ArcelorMittal, Axens, IFPEN and TotalEnergies (Grant Agreement N° 838031).

Additional information is available at the following address <https://3d-ccus.com>

3D unit has demonstrated several key aspects of the DMX™ technology, such as process operability, good solvent stability (no degradation observed), low energy consumption and purity of the captured CO₂ for a wide range of CO₂ concentrations.

Based on those results, the DMX™ technology is now ready for commercial deployment.

IFPEN and Axens continue to work on the development of future generations of increasingly efficient DMX™ solvents, as well as other innovative CO₂ capture solutions.

CO₂ CONDITIONING

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

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

Axens offers a complete portfolio based on its own products (catalysts and adsorbents) and technologies to remove contaminants present in the CO₂ and make sure that the specifications are met.

Our wide range of solutions, know-how in process design and our ability to work in close collaboration with compressor suppliers ensure an optimum design of the CO₂ conditioning chain for each project.

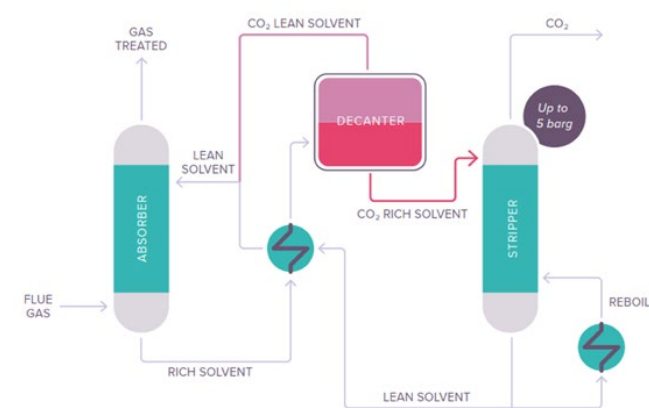


Figure 1: DMX™ Process Concept & PFD

The required reboiler steam consumption is greatly reduced thanks to this feature, associated to the solvent's high capacity.



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				

TECHNOLOGY DESCRIPTION



DEOXO FOR CO₂ DEOXYGENATION

Following the AGRU various impurities may be present in the CO₂ stream that need to be removed prior to dehydration and transportation/storage. These impurities include O₂, CO, and VOCs, among others. BASF's broad portfolio of purification catalysts is used to remove these impurities, either through catalytic oxidation or catalytic deoxygenation by addition of H₂. BASF's DeOxo products R4758 and R4755 have a long history of catalytic DeOxo in the urea process and enables CO₂ projects to meet the required O₂ specifications for the pipeline.

Platinum (Pt) and/or Palladium (Pd) catalysts with metal content ranging from 0.1%-1% are predominantly deployed for use in such deoxygenation applications. These catalysts are typically impregnated spheres or tablets, or sometimes monolith honeycomb type catalysts for low pressure off-gas applications. The catalyst works by converting the O₂ to water using a reactant, most typically H₂, due to its low light off temperature and high conversion efficiency.

Designing and operating an effective DeOxo unit is required to meet the pipeline or feedstock specification of oxygen. However, one must also design carefully to ensure the best economics for the plant. While relatively cheap H₂ may be available in large volumes at certain sites such as refineries or petrochemical plants, other plants looking to deploy CCUS technology such as powerplants or cement plants may not have H₂ available. Therefore, it is imperative that the required H₂ dosing is minimized to avoid costly deliveries of H₂ from offsite, or otherwise costly CapEx to build a H₂ plant to supply the needs.

It is key to select an experienced catalyst supplier that has decades of experience and has generated the knowledge to not only manufacture the catalysts but design these "DeOxo" units economically with optimal performance and lifetime in view of the very dynamic contaminant profiles.



SORBEAD® FOR CO₂ DEHYDRATION

Following the DeOxo unit, the gas needs to be dehydrated to <50ppmv to meet pipeline transportation specifications. TEG is not suitable for CO₂ dehydration because glycol carry over into the treated gas can cause pipeline corrosion, leading to pipeline integrity issues. Most pipeline specifications have a low tolerance for glycol at <50 ppbv and will require using a sacrificial bed, which adds complexity to the project. Therefore, Temperature Swing Adsorption (TSA) is recommended and provides significant benefits, including low water concentration in the treated gas, reliable operation, no maintenance between changeouts, remote operation, zero emission, and quick shutdown/start up times.

TSA process utilises solid adsorbents in a fixed bed. BASF has silica gel, activated alumina, and molecular sieves in our portfolio. Wet CO₂ is an acid gas; CO₂ and water form carbonic acid and can neutralise some adsorbents that have basic sites. Of the three options, silica gels are the only acid-resistant material, which is extremely important for long bed life in CO₂ service. BASF produces Sorbead®, a specialty aluminosilicate gel, for CO₂ dehydration applications. Sorbead® has a low regeneration temperature (160-180°C) leading to lower OpEx and lower energy requirements compared to activated alumina regeneration temperature 220-230°C (Thompson et al., 2022) and molecular sieves (regeneration temperature 230-280°C). The lower regeneration temperature, higher water capacity, and acid resistance of Sorbead® makes Sorbead® the recommended material for CO₂ dehydration.

To learn more about the economic evaluation between TEG, TSA using Sorbead®, and TSA using molecular sieves, see published paper from the Offshore Technology Conference (Müller et al., 2023).



SUMMARY

At BASF, we create chemistry for a sustainable future. With more than 50 years of experience, BASF offers its customers amine-based gas treating solutions under the OASE® brand name for a variety of applications, such as synthesis gas (OASE® white), natural gas (OASE® purple), flue gas (OASE® blue), biogas (OASE® green) and Sulphur selective treatment (OASE® yellow). With recent developments in the OASE® white and OASE® blue technologies, BASF continues to enhance CAPEX and OPEX optimised designs tailored to site specific boundary conditions.

About 70% of the global ammonia production is based on the reforming of natural gas feedstock. A majority of these ammonia plants utilise OASE® white technology for energy efficient two-stage CO₂ removal process. BASF's latest innovation with advanced low-low pressure flash configuration further reduces the specific energy consumption.

OASE® white technology can also be applied to hydrogen production via gasification, reforming, partial oxidation and direct reduction iron processes. In combination with OASE® blue post-combustion CO₂ capture technology, BASF offers deep decarbonisation solutions for ammonia and hydrogen production.

BENEFITS

- OASE® provides to business partners:
- Know-how derived from over 500 references and BASF's expertise in chemistry
 - Long track record and expertise in design and operation of large scale CO₂ capture units
 - Non-exclusive access to OASE® technology for customers and engineering companies
 - Unique licensing model integrated with OASE® solvents sales produced and supplied by BASF
 - Process performance warranties
 - Customised design, operating and analytical manuals
 - OASE® connect digital platform
 - OASE® digilab with the capability to analyse the composition of OASE® solvents in near real time

KEY PROJECTS

- **Tomakomai CCS Demonstration Project, Japan:** In this project, an energy-efficient OASE® process configuration was implemented to capture CO₂ containing tail gas stream from Pressure Swing Adsorption (PSA) of a Hydrogen Production Unit. The captured CO₂ was transported for offshore sequestration.
- **HyNet Low Carbon Hydrogen Production Plant (HPP1), UK:** Syngas stream with CO₂ generated by autothermal reforming process. Highlighted in the Phase 2 Hydrogen Supply Competition Report for UK BEIS, BASF's OASE® technology fulfills all technical requirements while offering the lowest risk technology and the highest CO₂ removal efficiency.
- **Steel Plant in Abu Dhabi, UAE:** A world-scale operational direct reduction iron plant with an integrated OASE® CO₂ capture unit, constructed by Linde Engineering.

KEY DATA

TRL	9	Capture Rate Range (tpd)	10 - 10,000+	Capture Efficiency (%)	>99%
Source CO ₂ Purity Range	<0.1 - 70%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	0.6 - 6.0
Number of Commercial Plants	>500	Number of Pilot Plants	6	Modular (Y/N)	Yes
Target Industries	Ammonia, Hydrogen, LNG, Floating/OCCS, Refineries, Steel, Cement/Lime, Waste-to-Energy, Power Plants				

TECHNOLOGY DESCRIPTION

OASE® WHITE TECHNOLOGY FOR CO₂ REMOVAL IN AMMONIA AND HYDROGEN APPLICATIONS

BASF's OASE® two-stage absorption process know-how

Proven and operating reliably in world scale ammonia production facilities (3300 MTPD capacity) around the world.

Applying BASF's OASE® know-how in hydrogen application

For Tomakomai CCS Demonstration Project, a two-stage OASE® absorption process, which includes a low-pressure (LP) flash tower, had achieved specific thermal energy consumption comparable to 30-50% of a conventional single-stage absorption process.

Advanced low-low pressure (LLP) flash configuration

The additional flashing stage results in lower CO₂ loading of semi-lean solvent, therefore less reboiler heat duty is required for full solvent regeneration. With that, a further reduction in specific thermal energy consumption up to 25% can be achieved in comparison to already energy efficient two-stage absorption process. A revamp opportunity with LLP flash can also be considered by existing plants to achieve capacity debottlenecking or OPEX optimisation.

OASE® BLUE TECHNOLOGY FOR POST-COMBUSTION CO₂ CAPTURE FROM FLUE GAS OF STEAM METHANE REFORMING (SMR) FACILITY

Key features of OASE® blue technology

- Advanced amine solvent with 10-year continuous testing and 7-year commercial operation in various industries
- High oxidative resistance / Low degradation / Low makeup of amine solvent
- Low regeneration energy and maximize heat integration
- OASE® aerozone patented emission reduction technology

Post-Combustion CO₂ Capture Study for Linde's SMR Hydrogen Plant

- Funded project by US Department of Energy under Award Number DE-FE0031943
- Plant design by Linde Engineering, leveraging the key features of OASE® blue technology
- Designed for 95% CO₂ capture rate and 1.4 mtpa (~4200 tpd) CO₂ capture capacity
- Solvent regeneration with an integrated interstage heater enables more efficient semi-lean solution regeneration, resulting in reduced overall thermal energy consumption

INTEGRATION OF OASE® WHITE AND OASE® BLUE TECHNOLOGIES IN A SMR FACILITY

For a natural gas hydrogen SMR plant, about 60% of the total CO₂ quantity is contained in the process gas (syngas) or PSA tail gas stream. OASE® white technology offers the capability to perform deep CO₂ removal from such streams down to ppm level using an energy efficient process configuration. The remaining 40% of the total CO₂ emission comes from the SMR flue gas. CO₂ from these low pressure streams can be captured with OASE® blue advanced amine solvent, resulting in an energy optimised design for large scale plants.

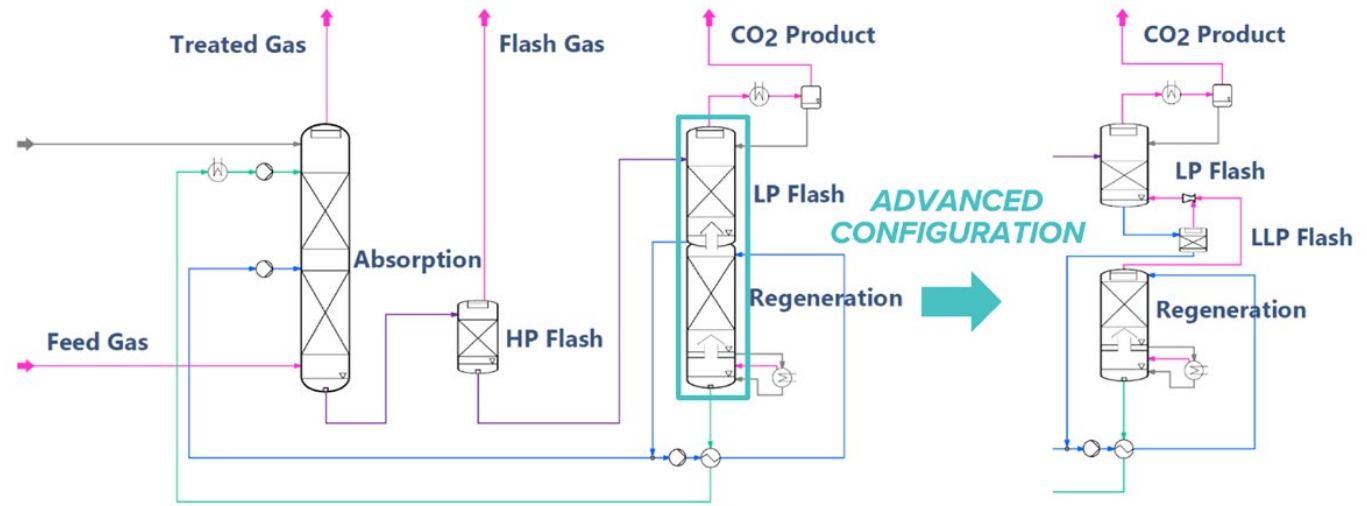


Figure: OASE® technology with two-stage absorption process and advanced LLP flash configuration



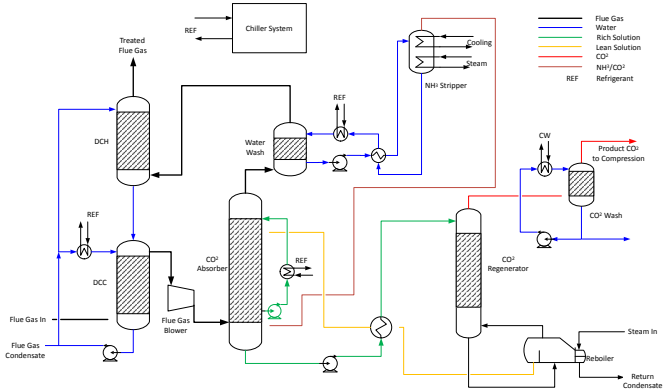
SUMMARY

The Chilled Ammonia Process (CAP) was developed to address the challenges of removing carbon dioxide from low-pressure flue gases, which were generated by fossil-fuel-based power plants and industrial emissions points.

CAP is a post-combustion carbon-capture process that uses a non-proprietary solvent formulation based on ammonia. Ammonia is a low-cost, inorganic commodity chemical, readily available on the global market from multiple sources and not bound to any specific supplier. It is also stable, tolerant to flue gas contaminants and typically exhibits very low and controllable loss in the CAP process. Moreover, green ammonia (produced from green hydrogen) could be used instead of conventional ammonia in the CAP process.

BENEFITS

- Demonstrated low specific thermal energy consumption of 2.6 GJ/ton CO₂
- Uses ammonia, a commodity chemical that is easily procured and not bound to a specific supplier
- Stable reagent. Unlike amine-based solvent systems, it does not suffer from thermal and oxidative degradations
- Flexible for process integration. Allows efficient-direct high temperature waste heat utilisation or direct electrical heating without the degradation of solvent performance
- Tolerant towards oxygen in flue gas and towards contaminants such as SO_x and NO_x
- Produces less harmful emissions and potentially useful by-products
- Regenerates CO₂ at high purity (> 99.5%) at elevated pressure, thus requiring less compression energy for the downstream CO₂ product



KEY DATA

TRL	7	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~	System Energy (GJ/tCO ₂)	2.6	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	~
Target Industries	Fossil Fuel-Based Power Plants, Waste to Energy & Biomass Power Plants, Cement Plants, Refineries and Petrochemical Complexes				

TECHNOLOGY DESCRIPTION

The Chilled Ammonia Process (CAP) uses an ammoniated aqueous carbonate solution to absorb CO₂ from the flue gases at ambient pressure and low temperature. Unlike other technologies, the functionality of the ammonium solution is not affected by oxygen and easily purged of heat stable salts formed by trace acidic components, which may pass dedicated flue gas preconditioning steps. Moreover, since its gaseous emissions and liquid waste streams are non-toxic, no additional treatment facilities are required.

A simplified process flow diagram of the CAP technology is shown in the accompanying figure and the process can be described as follows.

Inlet flue gas first undergoes cooling via a direct contact cooler (DCC) that enables the contact of gas with cooling and chilled water to lower the flue gas temperature to a suitable level (typically below 15 °C), which is needed for the CO₂ absorption process and water balance. Most of the water vapour contained in the flue gas is removed in this step, which reduces the volumetric gas flow and increases the CO₂ concentration. For conventional amine-based solvents, a flue gas pre-treatment step is required, which is typically integrated with the DCC to reduce NO_x, SO_x and other contaminants in the flue gas to very low levels to decrease degradation and formation of heat-stable salts when the flue gas interacts with the solvent. However, for CAP, this pre-treatment step is typically not required as the ammonia-based solvent is able to tolerate these flue gas contaminants. Strong acids such as SO_x react with ammonia and form heat-stable salts, which are withdrawn from the system as an aqueous by-product.

Cooled flue gas from the DCC enters the bottom of the absorber column, where it is washed counter-currently with lean ammonia-based solvent (orange line). CO₂ is selectively removed from the flue gas in a chemical absorption process using the alkaline lean solvent. The lean solvent is a solution comprising ammonia, water and CO₂ where different species (ammonium carbamate, ammonium bicarbonate, ammonium carbonate and a limited amount of free ammonia in an aqueous solution) are in equilibrium. The dissolved ammonia species react with CO₂ from the flue gas in the absorber by shifting the species' equilibria towards bicarbonate. The CO₂-rich solvent (green line) leaves at the bottom of the absorber and is sent to the regenerator section, where it is heated to a temperature high enough for CO₂ to be released from the solvent. A reboiler located at the bottom of the regenerator column provides the heat to the solvent. The heating source is typically steam, although hot oil or heat from a direct-fired or electric heater can also be used due to the absence of thermal degradation.

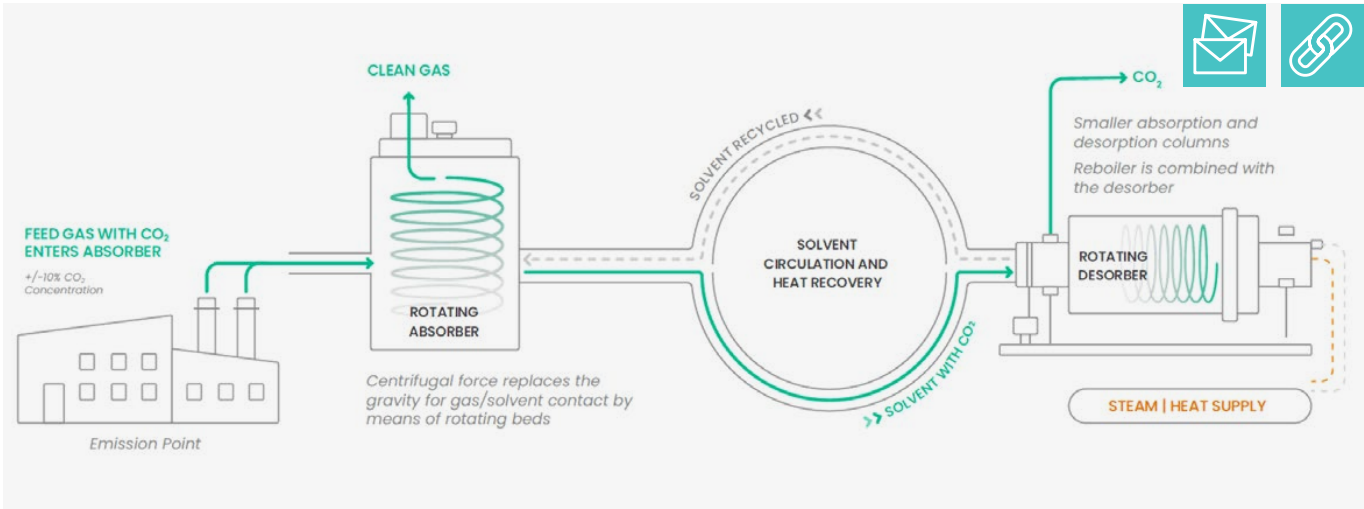
Heat is imparted to the solvent to shift the equilibria to ammonia-rich species releasing the absorbed CO₂, which leaves at the top of the regenerator column. Compared to the amine-based post-combustion technologies that regenerate CO₂ at near atmospheric pressure, CAP regenerates CO₂ at an elevated pressure (14 bar - 25 bar(a)), which reduces the downstream compression power requirements.

Regenerated lean solvent (orange line) is returned to the absorber after undergoing cooling through heat exchange with the cold rich solvent in the lean-rich heat exchanger, which simultaneously heats the rich solvent. This is an important heat integration step that significantly reduces the reboiler heat requirement.

Treated flue gas exiting the top of the absorber column contains residual CO₂ and ammonia, which is recovered with a water wash step to prevent unacceptable emissions of ammonia into the atmosphere. After the water wash step, the flue gas is routed to a flue gas heater. A guard system is integrated with the flue gas heater, which relies on the injection of Sulphuric acid to neutralise any residual ammonia, converting it into ammonium sulphate. The flue gas is reheated with warm water condensed from the DCC, which serves to raise the temperature of the final treated flue gas to a temperature high enough to be released into the stack and to optimise the water balance of the system.

Amine-based solvents have a tendency to degrade as a result of exposure to hot environments (thermal degradation), in the presence of oxygen (oxidative degradation) and in acid gas reactions (such as NO_x). The degradation results in a reduction of performance, solvent loss, equipment corrosion and the generation of volatile degradation compounds that are emitted into the treated flue gas, including nitrosamines, which are known carcinogens. Such degradation phenomena are absent for CAP, as the process uses an ammonia-based solvent, which is inorganic. CAP has the added advantage of being able to regenerate CO₂ at elevated pressure, resulting in reduced energy costs to liquefy or further compress the CO₂ downstream.

CAP has been validated at several test facilities with a design capacity of up to 100 ktpa CO₂, treating flue gases generated by oil boilers, coal boilers and industrial off-gases. A CAP plant designed to capture up to 80 ktpa CO₂ has been operated at Test Centre Mongstad (TCM) in Norway for 2 years, where it demonstrated low specific thermal energy consumption of 2.6 GJ/ton CO₂ on refinery cracker offgas (12.5 - 16.0% CO₂). The testing at TCM also demonstrated CAP's ability for quick start-up, low ammonia emissions, high CO₂ product purity and meeting targeted CO₂ capture rates.



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

- Targeting minimum 95% CO₂ capture rate for a flue gas with 10% CO₂ concentration
- Compared to conventional CO₂ capture plants:
 - Reduction in CAPEX
 - Reduction in equipment size and footprint
 - Less solvent inventory required, reducing operating expenses
- Lower electricity consumption for compression as CO₂ is regenerated at higher pressure
- Reduced lead time through modularized solution design thinking for simplified logistics, and decreased demand for civil works



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 EPC phase to meet TRL 7

TECHNOLOGY DESCRIPTION

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.



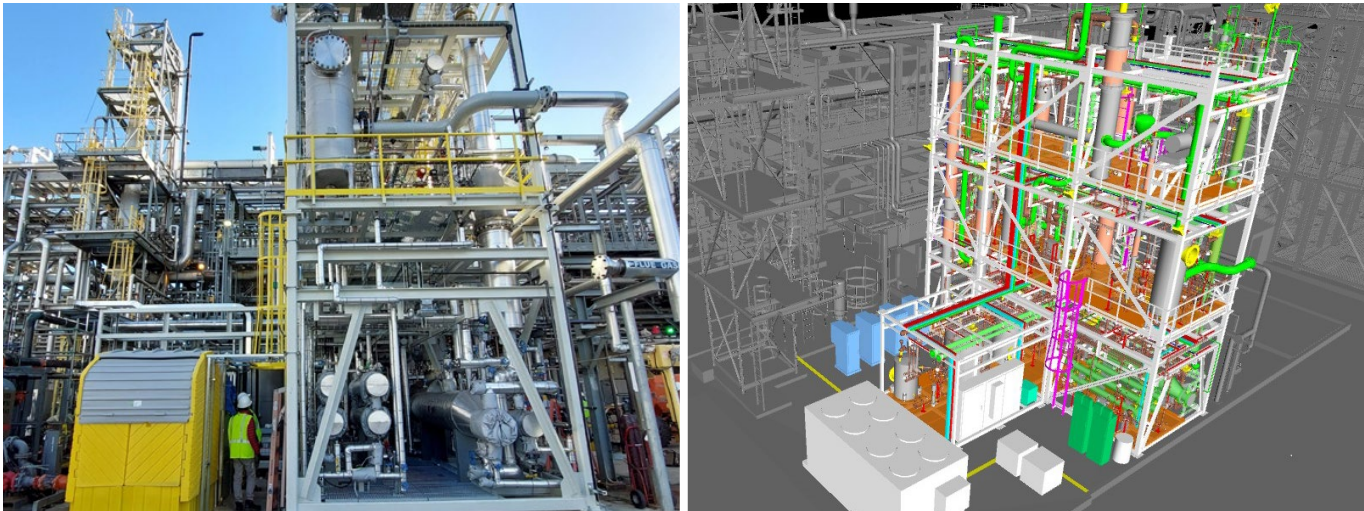
Cross Flow Absorber (CFA)

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 pressurized 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.



Rotating Desorber Wheel (RDW)



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 global market from multiple sources. 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 campus in Menlo Park, USA. MSP’s maturation to TRL: 6 is currently under demonstration using a 10 tpd pilot-scale plant at the National Carbon Capture Center in Alabama.

BENEFITS

- 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 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)	2.0 - 2.3
Number of Commercial Plants	~	Number of Pilot Plants	2**	Modular (Y/N)	~
Target Industries	~				

* Pilot plant (4 ktpa) under construction by SRI.
** Pilot plant and mobile pilot undergoing design by Baker Hughes.

TECHNOLOGY DESCRIPTION

MSP is a post-combustion technology that is applicable to a wide range of flue gases. It uses a blend of ammonium and potassium-based salts to absorb CO₂ from flue gases at ambient pressure and temperature. The stability of the inorganic solvent used by MSP’s ammonium solution is not affected by oxygen and shows high tolerance to acidic trace components present in the incoming flue gas. The process is characterized by very low emissions and produces little-to-no toxic waste.

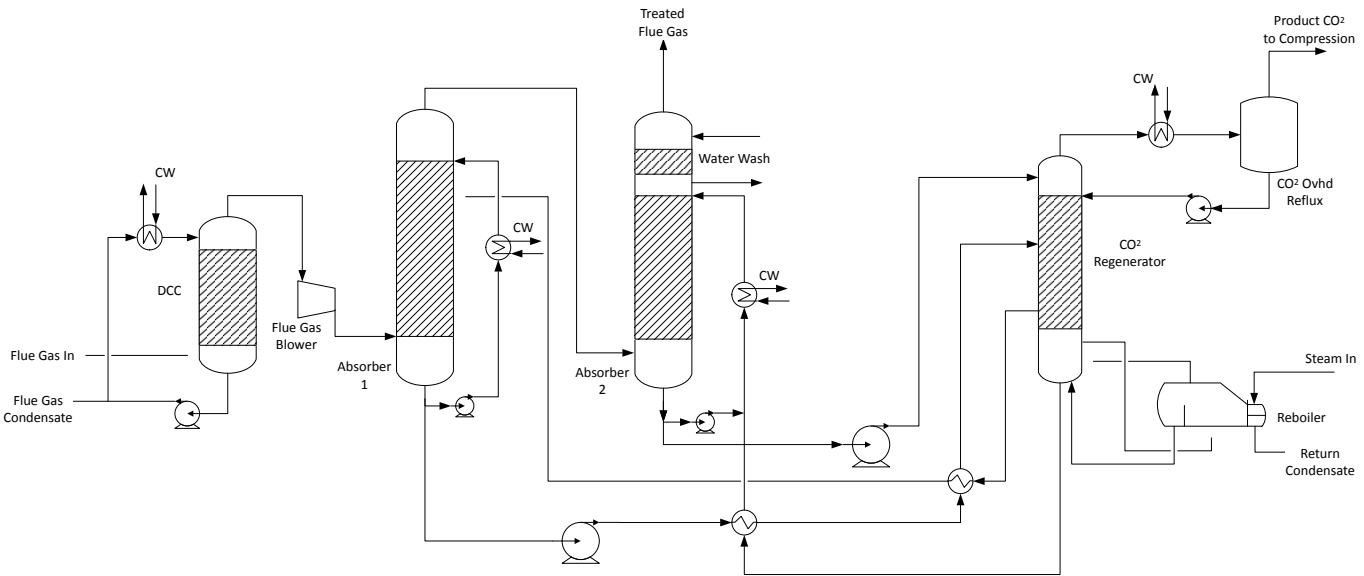
A simplified process flow diagram of the MSP technology is depicted in the accompanying figure and the process can be described as follows.

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. A water wash located at the top of Absorber 2 further reduces the ammonia content in the treated flue gas to ensure that it meets the ammonia emission limits.

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.

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.



A simplified process flow diagram of the MSP technology.



SUMMARY

CapsolEoP® (end-of-pipe) is a full-scale, post-combustion carbon capture technology designed for large industrial emitters in the cement, biomass, EfW (energy-from-waste), lime, pulp and paper, power generation, and process industries. It is a stand-alone, end-of-pipe system that can be retrofitted to existing plants with minimal operational impact.

By utilising its integrated heat recovery, CapsolEoP® requires less energy consumption compared to amine-based solutions. The highly adaptable system offers configurations that generate surplus heat output for district heating applications in bioenergy and energy-from-waste plants.

CapsolEoP® is commercially proven, with almost 19,000 operational hours across Capsol's demonstration units and pilot projects. This positioning makes it a preferred technology for cost-effective carbon capture.

BENEFITS

- Stand-alone unit eases installation and reduces project risk
- Fully electric solution without the need for costly investment in a separate steam boiler
- Inherent heat recovery produces additional heat, improving energy efficiency and reducing opex
- Utilises the safe, non-toxic, readily available HPC (hot potassium carbonate) solvent with a superior HSE profile, making permitting easier

KEY PROJECTS

- The world's first large-scale BECCS (bioenergy with carbon capture and storage) project, deploying Capsol's capture technology, is now moving into construction as Stockholm Exergi has made a final investment decision (FID). The facility is scheduled to begin operations in 2028, permanently removing 800,000 tonnes of CO₂ annually while setting a precedent for negative emissions projects worldwide.
- In addition, Capsol has secured preliminary and frame license agreements and is strengthening its presence in key sectors such as cement, lime, energy-from-waste, biomass, and oil refining. The company has conducted dozens of studies, including feasibility and pre-FEED phases, and completed nine CapsolGo® demonstration campaigns.

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)	~	Specific Regen. Energy (GJ(e)/tCO ₂)	0.7 - 1.5
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.				

TECHNOLOGY DESCRIPTION

Capsol's technology is a carbon capture and heat recovery/generation system in one with an inbuilt heat pump/engine that can generate additional heat and electricity during the capture process. CapsolEoP® has little to no water need, can run on electricity, and requires little integration with the parent plant. The technology is built on decades-proven chemistry and almost 19,000 hours of operating experience verifying the effectiveness of the technology on flue gas streams like cement, energy-from-waste, and biomass. The first successful tests of the technology were performed in 2008 at the Värtaverket power plant in Stockholm, Sweden. Currently, Capsol operates three mobile demonstration units and two liquefaction units at different clients' sites across Europe.

The CapsolEoP® solution is a combination of a Brayton Cycle, an inorganic capture plant (using the safe, environmentally friendly HPC solvent, with lower degradation properties than amine solutions) and mechanical vapor recompression units that recycle hot solvent and condensates, resulting in a highly energy-efficient solution capturing CO₂ with concentrations from 3-30%, capture rates of 95%+ and high CO₂ quality.

HOW IT WORKS

The flue gas is first treated and cooled. It is then compressed without intercooling. The resulting heat is partially used for the capture and expansion processes, where a significant amount of the compression duty is recovered. In the capture section of CapsolEoP®, recycled heat is used towards the desorption process, minimising overall energy use. The mechanical vapor recompression units generate heat internally with a coefficient of

performance (COP) between 7 and 15, resulting in Capsol's energy-efficient performance. Traditional standard, mechanically driven heat pumps are less efficient and more costly.

For some industries, like cement, with CO₂ concentrations of 13-17%, the capture plant can be optimised to increase efficiencies further using compression intercooling towards the coldest available sink or the desorption process. Intercooling reduces the electricity used for compression. Reheating between the expansion stages allows the capture plant to maximise the heat sent to the expander.

CASE STUDY

With Capsol's technology, a 54% reduction in electricity consumption can be achieved for a typical cement case, saving EUR 19 per tonne of CO₂ captured. As for most carbon capture technologies, the central portion of the opex is the cost of energy needed to drive the CO₂ separation process, where energy for the CO₂ separation process can make up 70% of total opex costs. Unlike amine technology, CapsolEoP®'s energy savings increase with higher CO₂ concentrations, making it especially suited for cement.

For example, for an 800,000 tonnes per year capture plant capacity, Capsol's cost advantage could translate into annual energy savings of EUR 15 million.

In addition, HPC offers lower solvent costs, and in many cases, costly modifications are avoided when integrating into the existing plant, which can result in a significant capex advantage.





SUMMARY

CapsolGo® is a mobile carbon capture demonstration unit that allows emitters to test Capsol's technology on-site before committing to full-scale implementation. The all-inclusive rental package covers transport, installation, operation, and reporting, providing customers with valuable real-world performance data on their specific flue gas composition, including liquefaction.

By demonstrating high capture rates, operability, and solvent performance, CapsolGo® helps emitters de-risk their investment decisions and build internal and external stakeholder confidence in carbon capture.

CapsolGo® is a proven tool for accelerating carbon capture adoption. It enables emitters to validate the technology, train personnel, and streamline the path to Final Investment Decision (FID).

BENEFITS

- A fully electric carbon capture demonstration unit used to replicate key aspects of the HPC (hot potassium carbonate) carbon capture process and de-risk the full-scale capture facility
- Easy setup with two 20ft containers supporting a 40ft frame on top
- A powerful tool demonstrating safe carbon capture to various stakeholders
- Additional liquefaction unit available for connection to the CapsolGo® capture unit. Can provide food grade CO₂
- All-inclusive package: transport, installation, operators, equipment, chemicals, rig down, and transport from clients' site
- Typical length of campaigns: six months to one year

KEY PROJECTS

- Capsol's five mobile, containerised carbon capture and liquefaction units have run demonstration campaigns on various heavy-industry flue gases from cement, biomass, and energy-from-waste (EfW) industries. These campaigns prove the suitability of the safe HPC solvent while providing invaluable information on flue gas conditions (CO₂ content and impurities), de-risking the project, and timeline for the full-scale CO₂ capture project.
- Capsol currently operates demonstration campaigns (capture and liquefaction) at plants in Latvia (cement), Germany (cement), and Sweden (energy-from-waste), enabling the clients to get a deeper understanding of carbon capture and verify the technology on their facilities' specific flue gas before committing to a full-scale plant.

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)	~	Specific Regen. Energy (GJ(e)/tCO ₂)	0.7 - 1.5
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				

TECHNOLOGY DESCRIPTION

All emitting facilities are different. However, what comes out of a carbon capture process must be standardised CO₂. Carbon capture is the bridge between point source CO₂ emission and, later, conditioning and transport. As a result, there is a need to demonstrate that the capture and liquefaction solutions can achieve high CO₂ capture rates under various operating conditions for different industries: biomass, energy-from-waste, cement, petrochemicals, and others.

The CapsolGo® demonstration campaigns are used to build valuable knowledge as CCS projects move toward full-scale implementation by answering questions such as:

- What are the actual contaminants and impurities in the flue gas within various operating conditions of the host plant?
- How does the HPC solvent behave with these contaminants and impurities?
- How do varying flue gas and operating conditions impact carbon capture performance?
- Are there any corrosion risks?

In addition, clients typically measure average emission data for reporting reasons. However, there can be seasonal or instantaneous variability. Making sure all cases are covered is important. With CapsolGo®, short-term variations such as peaks, minimums, and maximums are exposed. Experience also shows that the flue gas conditions are often less known to the client than the plant owners initially

thought. This is another advantage of running a CapsolGo® demonstration campaign early in the project, to reduce uncertainties. The early detection of these specificities is one of the keys to a successful project.

The CapsolGo® demonstration units are also often used as a communication tool, to build social acceptance, get public funding, secure internal support, and for training and educational purposes.

R&D CENTER ACCELERATES OUR DEVELOPMENT

The CapsolGo® units are also valuable tools for internal testing of the CapsolEoP® technology. Capsol runs research and development initiatives between client campaigns to develop the technology further. With the demonstration units, Capsol can easily check concepts developed in the lab in their R&D Center in Stavanger, using CapsolGo® as the platform to test the solutions the team has developed.

HIGHLIGHTS

- All-inclusive mobile, small-scale carbon capture demonstration units for cement, biomass, energy-from-waste (EfW), power generation, and large industrial facilities.
- Capture about 0.5-1 tonnes per day, with the option to liquefy CO₂ to assess if Northern Lights standards or food-grade specifications can be met.





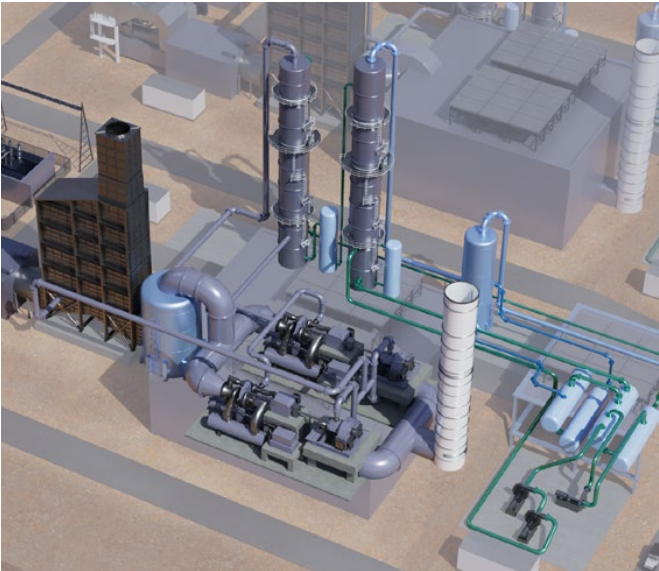
SUMMARY

CapsolGT® captures carbon dioxide directly from the flue gases leaving the gas turbine's exhaust. The solution can be applied to existing simple cycle gas turbines (brownfield) and to low-carbon gas turbine power plants (greenfield), such as those required to meet the growing demand from data centres.

CapsolGT® simplifies the CO₂ capture process by utilising the waste heat from the gas turbine outlet, transferring it into electricity while capturing carbon. It also avoids the need for additional steam, and the costly investment in a separate steam boiler and steam turbine, as would be required for gas turbine power plants with other capture solutions. CapsolGT® for gas turbines enables efficient CO₂ capture with minimal operational impact, helping operators meet decarbonisation targets.

BENEFITS

- Captures 95%+ CO₂ utilising the safe solvent HPC (hot potassium carbonate)
- Utilises gas turbine waste heat to generate additional electricity while capturing CO₂
- Works with aero-derivative and industrial gas turbines (2–120 MW capacity)
- Developed in collaboration with leading gas turbine manufacturers
- Affordable, additional low-carbon electricity for data centres
- Cost-effective decarbonisation of gas turbine power plants



KEY DATA

TRL	>6	Capture Rate Range (tpd)	200 - 1,000 tpd at 95%+	Capture Efficiency (%)	90 - 95%
Source CO ₂ Purity Range	2 - 4 vol%	System Energy (GJ/tCO ₂)	For open cycle gas turbines: 0 GJ/t electric	Specific Regen. Energy (GJ(e)/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	0	Modular (Y/N)	Yes
Target Industries	Gas Turbines, , Low-Carbon Power Plants				

TECHNOLOGY DESCRIPTION

CAPSOLGT® IS TAILORED FOR SIMPLE-CYCLE GAS TURBINES (OFTEN REFERRED TO AS OPEN-CYCLE GAS TURBINES, OCGT).

The CapsolGT® system comprises a gas-to-gas heat exchanger, flue gas handling unit, CO₂ absorption and desorption columns, integrated heat recovery, and a CO₂ compression system. It is designed for full-scale processing of the gas turbine exhaust, capturing 95% of CO₂ and generating additional power for export.

ADVANTAGES OF CAPSOLGT®

Unlike amine-based systems, when integrated with an existing high-temperature flue gas source, CapsolGT® eliminates the need for costly steam cycle implementation. Rather than imposing a parasitic load, the capture island can generate surplus power, even when CO₂ compression duty is accounted for, reducing plant complexity, permitting requirements, and operational costs. The system utilises a widely available, low-cost, non-toxic, and non-volatile solvent with no harmful emissions, ensuring a superior environmental profile compared to conventional carbon capture technologies.

Additionally, overall plant cooling demand is significantly lower than that of other state-of-the-art systems, and the process can be designed to operate without the need for freshwater supply in a steady state.

BROWNFIELD AND GREENFIELD POTENTIAL

Brownfield: By leveraging available infrastructure, CapsolGT® integrates with existing simple cycle gas turbine power plants with minimal modifications, reducing downtime and capital investment while maintaining plant flexibility. CapsolGT® utilises waste heat from the gas turbines to generate additional electricity while capturing 95% of the CO₂.

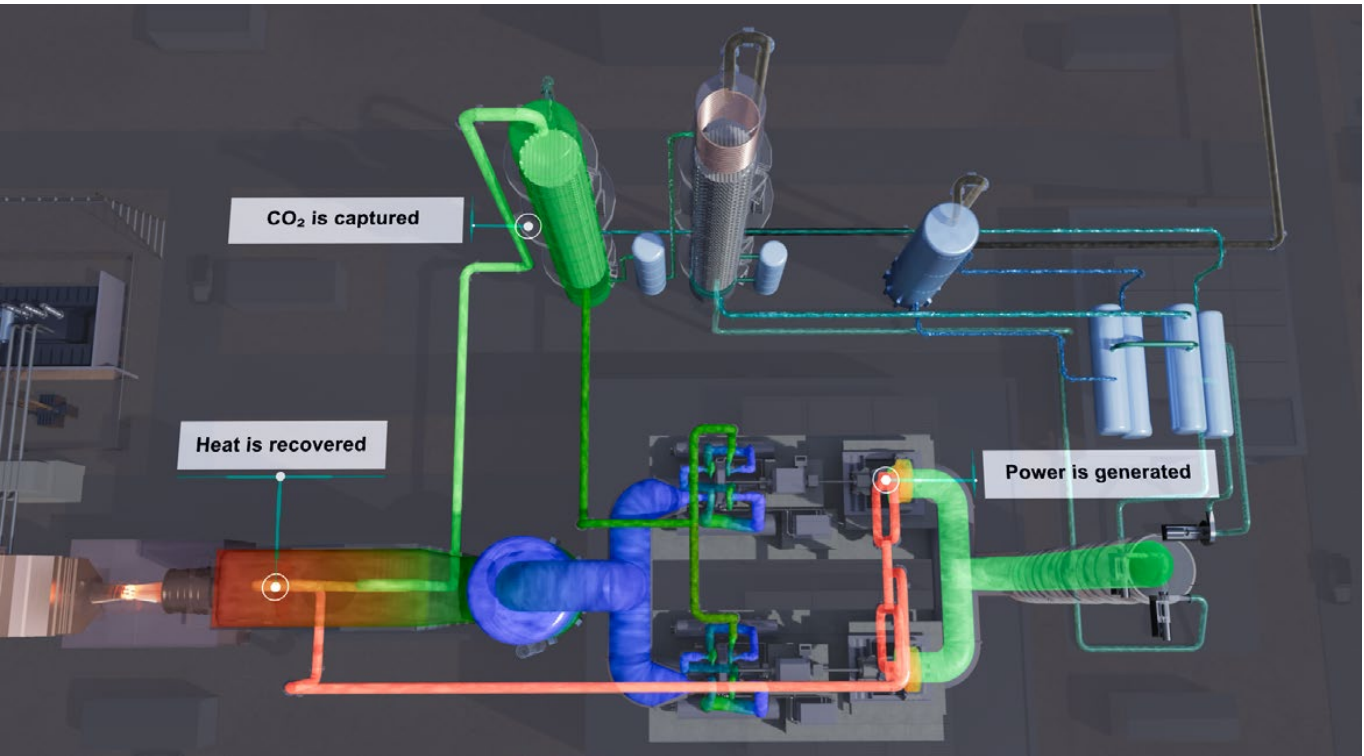
Greenfield: For new power plant projects, CapsolGT® reduces system complexity by eliminating the need for additional steam systems and allowing a more efficient plant layout. This means fewer auxiliary systems, lower capital costs, and simplified operations from day one.

HOW IT WORKS

Highly efficient Simple cycle gas turbines provide low CO₂ concentrated, hot flue gas streams with temperatures typically around 480-600 °C.

Before entering the core of the capture cycle, the flue gas heat is recovered, utilising a pressurised clean gas absorber stream to generate an overall surplus of electricity. Compared with a typical combined cycle gas turbine plant (CCGT), CapsolGT® provides a low-cost, less complex, and high capture rate alternative. The overall cooling demand is also lower, and the capture plant can provide valuable heat at 30-105 °C if required.

The steam required for the capture process is exclusively generated within CapsolGT® using internally sourced electricity. CapsolGT®, therefore, avoids the costly investment into a separate steam boiler and steam turbine, as it would be required for combined cycle gas turbine power plants (CCGT) and other capture solutions. With less equipment, lower external cooling requirements, and water neutrality, CapsolGT® achieves higher overall plant efficiencies and can operate without an ongoing supply of external steam.





SUMMARY

Carbon Clean is a leading expert in point-source carbon capture, helping hard-to-abate industries such as steel, cement, oil & gas, refineries and power to decarbonise for over 15 years. Its CycloneCC technology addresses cost and space challenges, cutting total installed cost and physical footprint by up to 50% compared to conventional systems. In 2024, Carbon Clean launched the CycloneCC C1 series, capable of capturing up to 100,000 tonnes of CO₂ annually, from CO₂ concentrations ranging from 3% to 20%. Rotating packed bed (RPB) technology replaces every column, delivering a height reduction of 70%.

As a standardised, fully modular, cost-effective solution, CycloneCC is poised to accelerate global carbon capture deployment, reshaping the industry landscape. Currently in its penultimate stage of commercialisation at TRL 7, the technology is complemented by Carbon Clean’s semi-modular CaptureX product line, which operates at TRL 9 and has already been deployed at multiple sites globally.

BENEFITS

- CycloneCC’s footprint is up to 50% smaller than conventional carbon capture plants, with its largest equipment sizes reduced by 10x.
- Rotating packed beds (RPBs) replace every column used in a conventional plant, reducing the steel required by 35%, delivering a height reduction of 70%.
- Each unit is prefabricated, skid-mounted and delivered on road truckable modules, cutting the costs associated with transport, logistics, site preparation and installation.
- CycloneCC reduces the total installed cost of carbon capture by up to 50% compared to conventional solutions.
- Carbon Clean’s APBS-CDRMax[®] solvent delivers significant operational savings, lowers energy demand by 10-25%, reduces corrosion by a factor of 20, decreases degradation by a factor of 10, and has a lifespan that is five times longer than conventional solvents.

KEY DATA

TRL	7 - 9*	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, subject to flue gas
Number of Commercial Plants	50	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Energy, industrial power, gas turbines, industrial emitters (cement, steel and energy from waste) and maritime.				

*CycloneCC TRL 7 and CaptureX TRL 9

KEY PROJECTS

In April 2025, Carbon Clean announced the successful completion of the world’s first industrial deployment of CycloneCC. The modular unit has achieved the major milestone of around 4,000 operating hours over a six-month period, moving CycloneCC to Technology Readiness Level 7 (TRL 7).

The mobile CycloneCC unit was installed on site in under a week at Fertiglobe’s nitrogen fertiliser plant in the Al Ruwais Industrial Complex in Abu Dhabi – a record for the carbon capture sector. The CO₂ captured from a reformer flue gas stack has been utilised by Fertiglobe in urea production.

In addition to Fertiglobe, Carbon Clean is working with pioneers and early adopters of CycloneCC, including Aramco, BHP and JSW Steel, CEMEX, and PETRONAS CCS Solutions to validate the technology so that it can be scaled up and commercialised across multiple industries and global markets.

TECHNOLOGY DESCRIPTION

CycloneCC is a cost-effective, space-saving carbon capture solution designed with a modular, plug-and-play, ‘lego-block’ approach, allowing small-to-midsize industrial emitters to scale their decarbonisation investment over time.

CycloneCC intensifies the traditional solvent capture process by combining two proven process intensification technologies:

1. Rotating packed beds (RPBs) process equipment technology
2. Proprietary amine-promoted buffer salt solvent technology

Carbon Clean’s APBS-CDRMax[®] solvent is highly effective at capturing CO₂, while RPBs create an optimal environment for post-combustion CO₂ absorption and solvent regeneration, significantly improving efficiency compared to conventional systems.

ROTATING PACKED BEDS (RPBS)

CycloneCC utilises RPBs for the key column operations in a traditional solvent capture process. RPBs contain a disk of packing material which rotates about their 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. The combination of RPBs and the APBS-CDRMax[®] solvent provides:

- Smaller equipment sizes at equivalent performance – using RPBs in the absorber/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 CycloneCC’s efficiency, ensuring seamless operation with lower energy consumption. Its modular, low-cost 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 formulated to optimise carbon capture performance and is used commercially at both CycloneCC and CaptureX plants globally. Its innovative, patented formulation of amines and salts – amine-promoted buffer salts (APBS) – offers both the high kinetic reactivity of an amine and the low regeneration energy of a buffer salt. The result is a unique, fast-acting, high-capacity solvent that delivers higher performance in any solvent-based carbon capture system.

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 has validated the real-world benefits of APBS-CDRMax[®] including:

- 20x less corrosion and 10x less degradation than conventional solvents.
- A reduction in solvent emissions to parts per billion (ppb) levels, which meets environmental regulatory requirements and facilitates approvals.
- 10% to 25% lower energy demand for the capture and regeneration process.
- 5x longer solvent life and 86% less solvent make-up.

THINKING BIG BUT BUILDING SMALL

The company is working with early adopters of the CycloneCC C1 Series to ensure robust validation and accelerated deployment across global markets. First-mover pioneers of the technology will have the advantage of tangible decarbonisation results whilst benefitting from a staggered approach to capital investment. The commercialisation of Carbon Clean’s CycloneCC technology is revolutionising the sector and reducing CO₂ emissions globally.

With tightening carbon capture regulations and incentives, Carbon Clean expects rapid adoption of its modular and scalable technology, driving global decarbonisation at scale.



AMINE CAPTURE PLANT SYSTEM FOR LARGE SCALE CAPTURE



SUMMARY

To achieve low-cost and long-term operation, great efforts have been taken in the research fields of novel highly-efficient ternary composite amine absorbent, optimised integration between carbon capture and power generation, amine-loss control technology, new packing, intelligent control technology, and optimised design for large-scale equipment. This technology has been applied in the 500 kt/a carbon capture project for Taizhou coal-fired power plant of CHN Energy, currently the largest in Asia and the third-largest coal-fired power plant carbon capture project worldwide. Significant breakthroughs have been achieved, and as a result, the operational indicators demonstrate the superiority of this project, with the carbon capture rate 90.86%, the capture heat consumption 2.35 GJ/tCO₂, and the capture electricity consumption 51.5 kWh/tCO₂, according to the test report by the China National Institute of Metrology.

BENEFITS

- **Social Benefits:** Promote continuous innovation and development in carbon capture technology for industrial appliance. Additionally, actively respond to China's "carbon peak and carbon neutral" strategy, promote the reduction of CO₂ emission in the coal-fired power industry, and effectively address climate change challenges. Furthermore, increase public awareness of environmental protection, advance clean energy technologies and foster sustainable development.
- **Economic Benefits:** By employing efficient energy-saving equipment and optimising processes, construction and operating costs are significantly reduced while the project achieves energy-saving. Based on the local urban planning, this project fully utilises existing resources, scientifically plans layouts, and maximizes the conservation of land, energy, and water, thereby promoting local socio-economic development.
- **Awards:** "Top Ten Scientific and Technological Innovations in the Energy Industry of 2023" by Chinese National Energy Administration; The only case from thermal power generation sector written in "China's Energy Transition" white paper by State Council of China in 2024.

KEY DATA

TRL	7	Capture Rate Range (tpd)	~	Capture Efficiency (%)	>90%
Source CO ₂ Purity Range	~15%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.35
Number of Commercial Plants	1	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Power Generation				

TECHNOLOGY DESCRIPTION

KEY TECHNOLOGICAL INNOVATIONS

Absorbent Research and Development

CO₂ absorbent is the basis for large-scale carbon capture. A novel absorbent with low regeneration energy consumption and minimal losses has been developed through functional group design and solvent matching. Considering the different characteristics (such as absorption capacity, absorption and desorption rate, degradation resistance) of various organic amines, research team take great efforts to select the optimised components and adjust each ratios. Finally, an innovative method has been developed for synthesizing a novel ternary composite amine absorbent with optimal comprehensive performance, possessing independent intellectual property rights, along with mastery of large-scale preparation processes. The superiority of this novel absorbent is demonstrated through comparative results in the laboratory analysis and tests on pilot and industrial-scale carbon capture facilities. The results indicate that the novel absorbent has a circulation load of 41 L/L, and compared to 30wt% MEA, the regeneration heat consumption is reduced by 26.5%, the degradation rate is decreased by 41.2%, and the reduction of unit cost is more than 30%. These features significantly reduce the operational energy consumption and costs of carbon capture systems. According to current operational data, the capture heat consumption is 2.35 GJ/tCO₂, the amine degradation loss rate maintains low levels, and the system has been stably operated for over 3600 consecutive days, therefore greatly reducing capture costs.

Key Equipment Research and Optimisation

This project employs innovative stainless steel small-tooth, high-efficiency packing. The reduction of the top angle of the tooth effectively mitigates liquid phase deviation, lowers cross-flow ratio, and significantly enhances the liquid phase's coverage area and gas-liquid mass transfer flux on the packing surface. Compared to conventional packing, it reduces pressure drop by 30%, increases mass transfer efficiency by 10%, and substantially cuts down investment and energy consumption for the absorption tower. Further advancements include specialized mass transfer separation elements and optimised distributor distribution within the tower. The integrated oil collection tank with beam groove provides ample ventilation area, minimizing resistance, pressure drop, and fan energy consumption while improving absorption efficiency and operational stability for large-scale units, consequently reducing energy consumption and solvent loss.

Moreover, the project introduces a pioneering dry method amine recovery device. Through cooling, condensing, and agglomeration in the dry bed section, followed by water washing and demisting, the amine emissions are effectively controlled, thus addressing issues of excessive amine escape and high operating costs.

Integrated and Large-Scale Production Processes

In terms of process design, to further reduce absorbent loss and operating costs, the operating parameters are optimised, such as liquid-to-gas ratio, the temperature

of inter-stage cooling, and the parameters of diversion desorption process. As a result, the electricity consumption of carbon capture system is significantly decreased, monitored to be reduced to about 51.5 kW/tCO₂. Compared to the typical 90 kW/tCO₂ in general carbon capture systems, this marks a 42.7% decrease in unit capture electricity consumption.

Regarding the integration of thermal system, deep optimisation is conducted between carbon capture and power plant thermal systems. Steam required for desorption reactions is drawn from steam turbine-driven forced draft fans exhaust, and steam condensate is recovered to the unit's low-temperature economizer, achieving full heat recovery and enhancing the economic viability of the coal-fired power plant with carbon capture.

Concerning the carbon capture control system, an intelligent control strategy is established, featuring functions such as APS one-click start-stop and overall control optimisation for single and multiple objectives. This enables intelligent, manpower-saving operation, significantly enhancing device safety.

GENERAL INTRODUCTION OF TAIZHOU CCUS PROJECT

To achieve "carbon peak and carbon neutral" target, the 500 kt/a carbon capture project for Taizhou coal-fired power plant was approved and initiated by CHN Energy in 2021, and was organized by CHN Energy's Jiangsu company, with Taizhou Coal-Fired Power Plant responsible for implementation and New Energy Technology Research Institute managing overall technical work.

Utilizing chemical absorption technology, flue gas undergoes washing, absorption, and regeneration in succession to obtain high-concentration regeneration gas, followed by compressing, drying, liquefying, and purifying to produce liquid CO₂ products. This project is the first to exceed 200 kt/a in China for a coal fired power plant, and the technical R&D team has faced up to the key challenges in preliminary research, process design and equipment development. As a result, technological innovations are achieved throughout the whole chain of large-scale carbon capture system, including novel amine absorbent, key equipment, system integration and intelligent control.

FUTURE OUTLOOK

The CO₂ capture capacity of this project is approximately 1/8 of a 1000 MW unit. To spearhead the development of CCS in thermal power generation, CHN Energy is planning the Taizhou Power Plant's 1000 MW unit integrated carbon capture project with scales of 4 million tons annually. Based on the current technologies, the new project will focus on key technological research and development in absorption techniques, critical equipment, control optimisation, utilisation and storage, as well as demonstration operations, with the purpose of driving the low-carbon transformation of the energy industry and contributing to global climate change mitigation efforts.



CNPC SAFETY AND ENVIRONMENTAL PROTECTION RESEARCH INSTITUTE

HIGH EFFICIENCY CO₂ CAPTURE ABSORBENT



SUMMARY

The New type of compound absorbent developed by CNPC Safety and Environmental Protection Research Institute is an advanced technology for CO₂ capture. This technology uses a proprietary blend of organic amines to achieve high CO₂ absorption rates from flue gases. The process involves the absorption of CO₂ in an amine-based solvent within an absorption column, followed by the release of CO₂ through heating the solvent. The technology is designed to operate at low energy consumption, ensuring cost-effectiveness and high purity of the captured CO₂ (>99%). It is suitable for various industrial applications, including power generation, cement, steel, petrochemical industry, and so on. The technology offers a reliable and efficient solution for CO₂ capture, contributing to the reduction of greenhouse gas emissions.

BENEFITS

- **High CO₂ Capture Efficiency:** Achieves a CO₂ capture rate exceeding 95%, ensuring effective removal of CO₂ from flue gases.
- **Low Energy Consumption:** Operates with minimal energy input, reducing operational costs and enhancing economic viability.
- **High Purity CO₂ Product:** Delivers CO₂ with a purity of over 99%, suitable for applications such as enhanced oil recovery and carbon storage.
- **Robust and Reliable:** Designed for long service life and low maintenance, ensuring stable and consistent performance.
- **Versatile Applications:** Applicable to a wide range of industries, including power generation, cement, steel, and petrochemicals.

ACHIEVEMENTS

- **Coal-fired Power Plant Project:** Applied in a pilot project at a coal-fired power plant in Northern China, achieving a CO₂ capture rate of around 90% and producing high-purity CO₂ for enhanced oil recovery.
- **Natural Gas Processing Plant Project:** Utilised in a natural gas processing plant in Southwest China, effectively capturing CO₂ from the feed gas and contributing to the production of blue hydrogen.
- **Cement Plant Project:** Being tested in a cement plant in East China, demonstrating the technology's versatility and efficiency in capturing CO₂ from different industrial sources.

KEY DATA

TRL	9	Capture Rate Range (tpd)	30 - 300	Capture Efficiency (%)	80 - 90
Source CO ₂ Purity Range	7 - 50%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	1.34 - 2.36
Number of Commercial Plants	2	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Power generation, cement, steel, petrochemicals				

TECHNOLOGY DESCRIPTION

TECHNICAL BACKGROUND AND DEVELOPMENT

Carbon capture and storage (CCS) is a crucial technology for reducing greenhouse gas emissions and mitigating climate change. Among various carbon capture technologies, chemical absorption using organic amine solutions has emerged as one of the most promising approaches due to its high efficiency and maturity. CNPC Safety and Environmental Protection Research Institute has been dedicated to the development of a new type of compound absorbent, aiming to enhance the performance of CO₂ capture and reduce the associated costs.

The new type of compound absorbent developed by CNPC is based on a proprietary blend of organic amines. This blend is designed to optimise the absorption and desorption of CO₂, improving the overall efficiency of the carbon capture process. The technology involves the use of an advanced absorption system where the compound absorbent selectively captures CO₂ from flue gases. The captured CO₂ is then released by heating the absorbent, allowing for its separation and storage.

The process begins with the flue gas containing CO₂ being passed through an absorption column where it comes into contact with the compound absorbent. The absorbent selectively binds with CO₂, removing it from the gas stream. The absorbent, now rich in CO₂, is then transferred to a regeneration unit. Here, the absorbent is heated, causing the CO₂ to be released. The released CO₂ is then compressed and prepared for storage or utilisation. The regenerated absorbent, having released the CO₂, is returned to the absorption column for reuse. This closed-loop system ensures the efficient and continuous operation of the carbon capture process.

The compound absorbent developed by CNPC offers several advantages. Firstly, it achieves a high CO₂ capture rate of around 90%, ensuring that a significant portion of the CO₂ in the flue gas is removed. Secondly, the proprietary blend of organic amines in the absorbent reduces the energy required for CO₂ desorption, leading to lower operational costs. Thirdly, the captured CO₂ has a purity of over 99%, making it suitable for various applications such as enhanced oil recovery (EOR) and carbon storage. Additionally, the compound absorbent is designed to have a long service life, reducing the need for frequent replacement and maintenance. It also minimizes the emission of harmful substances, contributing to a cleaner environment.

TECHNOLOGY APPLICATION AND FUTURE PROSPECTS

The new type of compound absorbent is applicable to a wide range of industrial sectors, including power generation, cement production, steel manufacturing, and the petrochemical industry. In the power generation sector, both coal-fired and natural gas power plants can use this technology to capture CO₂ from their flue gases, reducing emissions. Cement plants can integrate this technology to capture CO₂ from their production processes, contributing to lower carbon footprints. Steel plants can utilise this technology to capture CO₂ from high-temperature flue gases, aiding in their decarbonisation efforts. Petrochemical plants can apply this technology to capture CO₂ from various industrial processes, enhancing their environmental performance. In the power sector, both coal-fired and natural gas power plants can use this technology to capture CO₂ from their flue gases, reducing emissions. Cement plants can integrate this technology to capture CO₂ from their production processes, contributing to lower carbon footprints. Steel plants can utilise this technology to capture CO₂ from high-temperature flue gases, aiding in their decarbonisation efforts. Petrochemical plants can apply this technology to capture CO₂ from various industrial processes, enhancing their environmental performance.

Several key projects have demonstrated the effectiveness of CNPC's compound absorbent. In a pilot project at a coal-fired power plant in Northern China, the compound absorbent achieved a CO₂ capture rate of over 95%. The captured CO₂ was used for enhanced oil recovery, demonstrating the technology's effectiveness and versatility. At a natural gas processing plant in Southwest China, the compound absorbent was used to capture CO₂ from the feed gas. The technology's low energy consumption and high CO₂ purity made it an ideal solution for the plant's needs. In an East China cement plant, the compound absorbent was tested for its ability to capture CO₂ from the production process. The technology's high efficiency and reliability were confirmed, showcasing its potential for wider application in the cement industry. CNPC Safety and Environmental Protection Research Institute is committed to continuous improvement and innovation in the field of carbon capture. Future work will focus on further optimising the compound absorbent's performance, reducing costs, and expanding its application scope. The institute will also explore new methods for solvent recovery and regeneration, aiming to enhance the overall sustainability of the carbon capture process.

In conclusion, the new type of compound absorbent developed by CNPC offers a reliable and efficient solution for CO₂ capture. With its high capture efficiency, low energy consumption, and wide range of applications, this technology has the potential to make significant contributions to global efforts in reducing greenhouse gas emissions and combating climate change.



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% to 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.				

TECHNOLOGY DESCRIPTION

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).

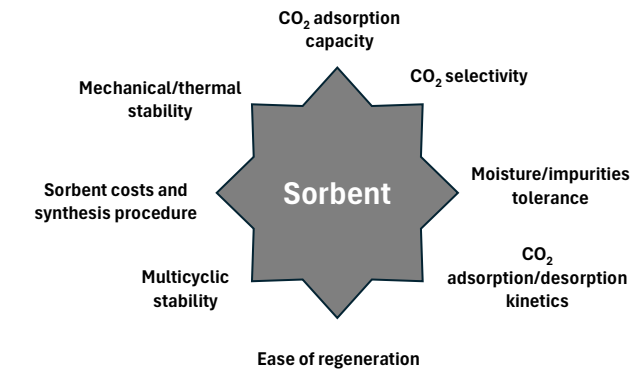


Figure 1

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.

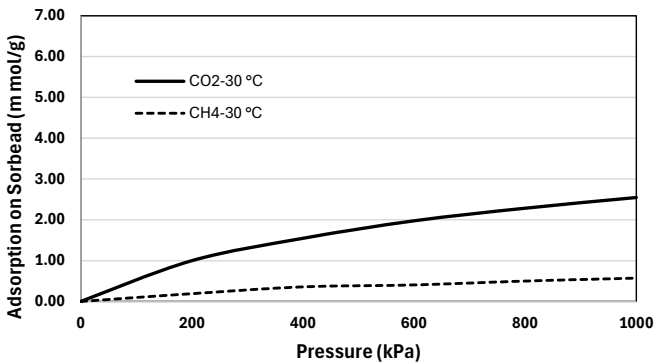


Figure 2

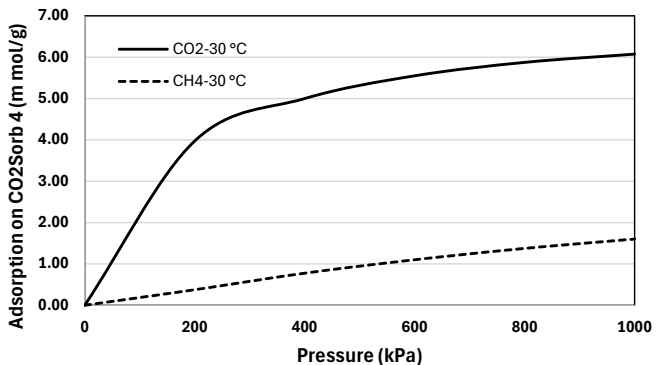
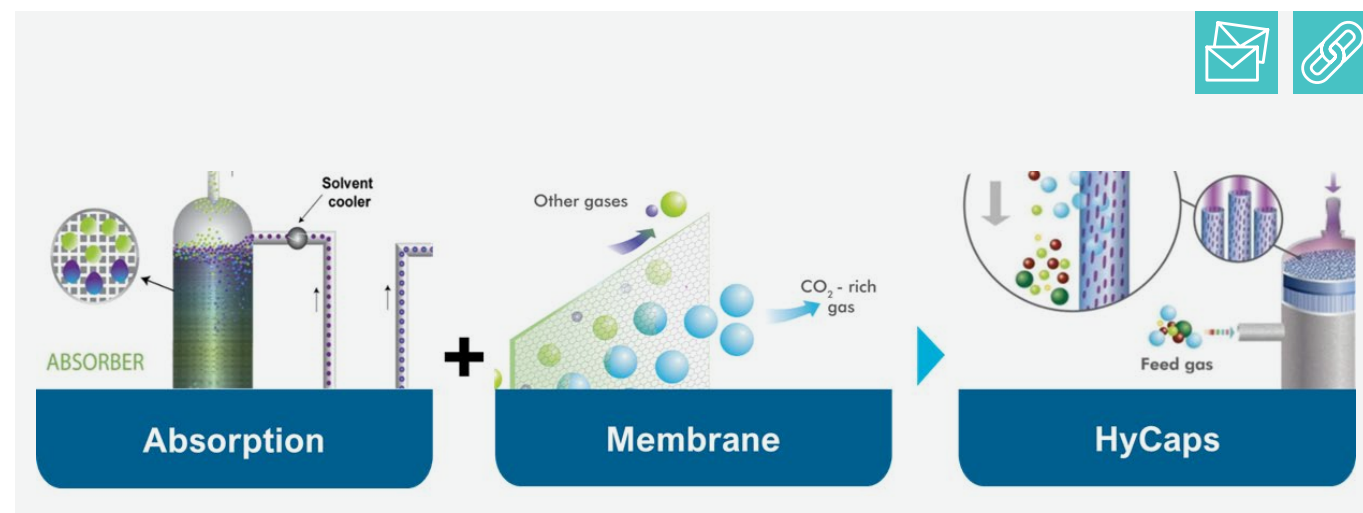


Figure 3



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.)				

TECHNOLOGY DESCRIPTION

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.

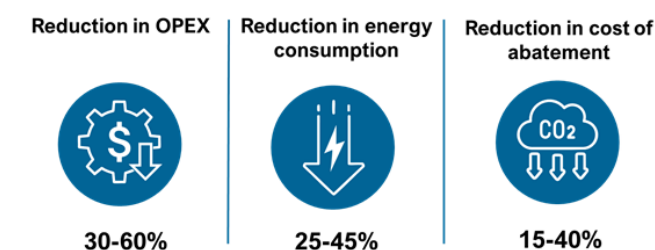
COST EFFECTIVE TECHNOLOGY

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.

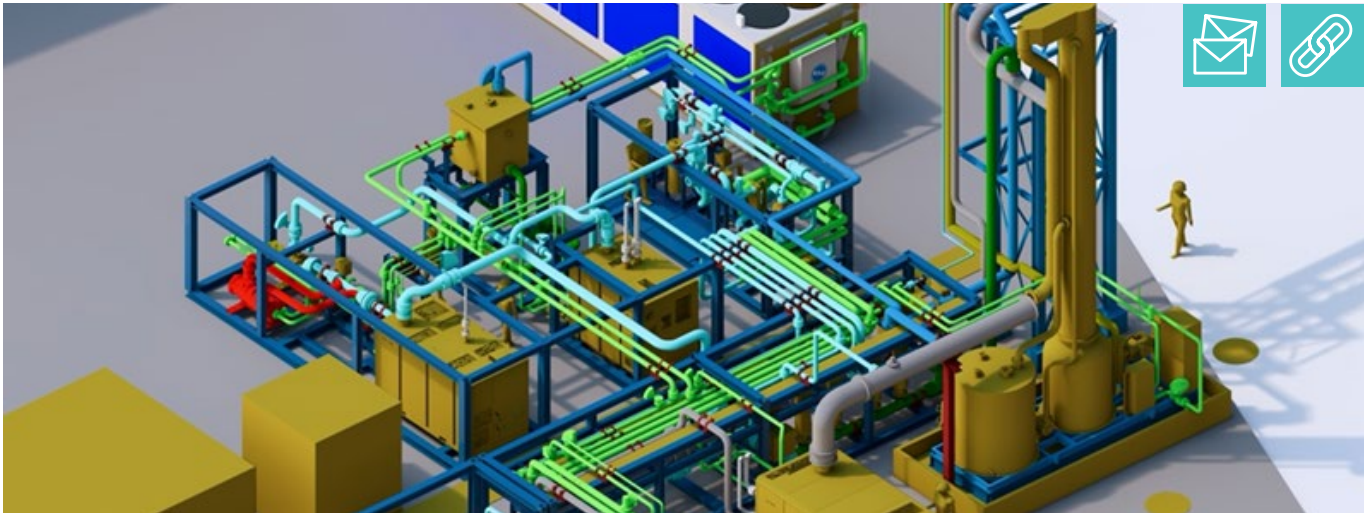
The Hybrid HyCaps is a new approach to carbon capture technology that offers clear advantages in terms of energy requirement and footprint compared to traditional methods. This technology has been demonstrated at three different industrial pilot plants in Australia. It has proven to be deployment-ready 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.



ADVANCED MEMBRANE POST COMBUSTION CARBON CAPTURE TECHNOLOGY



SUMMARY

Cool Planet Technologies is significantly reducing the cost of carbon capture from industrial flue gas emissions offering emitters an easy to install modular, energy efficient membrane-based process ideal for end of pipe retrofits. The compact plant is highly scalable and provides operational flexibility with fast start-up and response times.

Cool Planet is collaborating with Holcim and the Hereon Institute to up-scale the technology building a 10,000 tpa plant at the Höver cement plant, near to Hanover in Germany in 2025 which will be followed by 100,000 tpa and 800,000 tpa plants in 2028 and 2030 respectively.

The investors in Cool Planet are Taranis Investment, Eni Next, Neva SGR, Audacy Ventures, CRH Ventures and BlueScopeX.

BENEFITS

Cool Planet's proprietary 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 requires less energy
- **Highly compact:** The technology has a footprint a fraction of the size of existing solutions and has a low profile. Ideal for retrofitting at small sites.
- **Proven technology:** 15 years of R&D, five industrial pilots and 10+ years of continuous operations.
- **Fully electrical:** Can be powered by renewable electricity.
- **Chemical free:** No harmful emissions.
- **Fast start and response times:** Ideal for intermittent and batch industrial processes.
- **Upgradable:** Easy to benefit from our continued R&D.

KEY DATA

TRL	7	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, Coal-fired Power, Waste to Energy, Paper & Pulp				

KEY PROJECTS

Pilot Testing: Three successful pilots performed at EnBW's Rheinhafen-Dampfkraftwerk coal-fired power plant, followed by a highly positive trial programme completed in 2022 at Holcim's Höver cement plant in Germany. Additional long-term test currently ongoing in Steel. The long-term performance of the membrane has been proven in over 10 years of operations at the world's first bioreactor.

Membrane Module Demonstration: Our 3rd Generation industrial scale membrane module has undergone a highly successful test in the UK in 2025. This demonstration has de-risked the scaling and advanced membrane module design.

Commercial Operations: A 10,000 tpa Commercial Plant is under construction at Holcim's Höver cement plant which will be operational late 2025.

Industry Scaling: The 10,000 tpa Höver plant will be followed by a 100,000 tpa facility in cement in Europe operational 2028 and 800,000 tpa plant at Höver. A 200,000 tpa plant in lime is planned to be operational prior to and 800,000 tpa plant at Höver in 2030..

TECHNOLOGY DESCRIPTION

Collaborating with Hereon, the leading German R&D institute focused on membrane research, Cool Planet has developed a scalable, modular system using the advanced, class leading PolyActive™ membrane and a unique in-house designed compact capture module. This solution can be deployed in a highly scalable manner ranging from a few thousand tonnes per annum (tpa) to installations in excess of 1,000,000 tpa.

PolyActive™ membranes have been systematically developed both in the laboratory and in the field for over 15 years. PolyActive™ is a thin film composite membrane produced as flat sheets and has an excellent optimisation of selectivity and permeability and has been optimised for CO₂ removal. It is a solution diffusion membrane, meaning the transportation of CO₂ through the membrane, occurs via pressure gradient driven diffusion. Consequentially, the PolyActive™ membrane is highly resilient to typical industrial flue gas compositions which include compounds such as NO_x and SO_x. Unlike some other membrane, PolyActive™ is also tolerant to varying operating conditions facilitating its application in a wider variety of industrial settings and locations where operating conditions and seasonal temperature changes significant challenges to alternative technologies. Cool Planet's capture plants have a fast turndown, turnup and response times and can accommodate operational fluctuations including cyclical operations.

Cool Planet and Hereon have an ongoing research and development programme together to further develop their IP and enhance the properties of the PolyActive™ membrane and plant in the capture process.

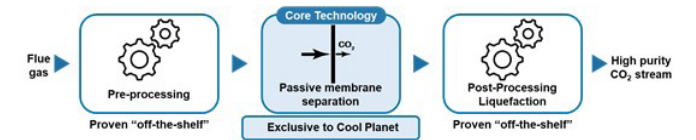
A COMPLETE CAPTURE SOLUTION

Cool Planet works with emitters to provide a highly compact, energy efficient end of pipe carbon capture solution capable of meeting pipeline, sequestration and even food grade specifications. Cool Planet's system is particularly advantaged for flue gases with CO₂ concentrations ranging from close to 10% upwards. Relative to amine-based capture systems it uses up to 60% less energy. Critically, the process does not utilise solvents or effluents in the capture process so there is no disposal or contamination issue. Cool Planet's engineering teams collaborate closely with emitters from first concept to delivering an operational plant to ensure a fit for purpose plant is delivered at a very low unit cost.

Cool Planet can also offer advice to emitters throughout the establishment of the capture, offtake and sequestration /utilisation chain. Finally, Cool Planet can also provide ongoing operational support, membrane management and optimisation services for the project on an ongoing basis.

COOL PLANET CAPTURE PROCESS

The capture process is at its core a simple three step process.



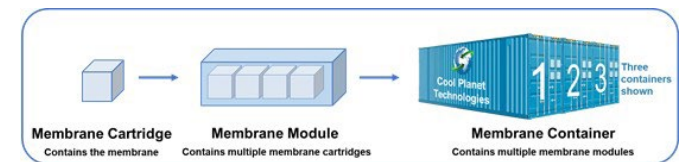
Cool Planet's Carbon Capture Process

Pre-processing

The pre-processing is designed by Cool Planet and is tailored specifically to the characteristics of the emitter's flue gas emissions, utilising proven "off the shelf" technology. The typical pre-treatment unit cools the flue gas and removes the particulates to ensure optimal conditions for input into the membrane separation units.

Separation

The membranes are packed into proprietary high-density, low-cost cartridges and modules jointly developed by Cool Planet and Hereon, which fit into a standard 40ft (12m) ISO container. Capture capacity is scalable and can be readily increased by adding additional membrane containers. These membrane modules can be arranged in series or cascade depending on the operational requirements and project objectives with respect to recovery and product purity. Energy recovery also is integrated into the capture process.



Cool Planet's proprietary membrane cartridge and module technology.

Post processing

The post-processing and purification of the captured CO₂ is designed by Cool Planet and tailored to the emitter's requirements again using proven "off the shelf" designs and technology for the volume of the CO₂ captured and the specification required for onward transportation, sequestration, or utilisation. With no chemicals utilised in the capture process, there are no traces of capture chemicals that require subsequent removal.



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		

TECHNOLOGY DESCRIPTION

ADVANCED TECHNOLOGIES FOR SEVERE SERVICE APPLICATIONS

A flagship scrubbing technology at Elessent, BELCO® gas cleaning has earned widespread acclaim for its unparalleled performance in severe service hot dirty flue gas applications. With over 160 licensed units worldwide, BELCO® technology has become indispensable across a spectrum of industries.

SETTING THE STANDARD

BELCO® wet scrubbing stands as the gold standard in oil refineries, particularly for cleaning flue gas from fluid catalytic cracking Units (FCCUs), fluid cokers, boilers, and process heaters. Utilising a staged cleaning approach, BELCO® technology efficiently removes particulate matter (PM), Sulphur oxides (SO_x), nitrogen oxides (NO_x), and aerosols in a single up-flow tower, ensuring optimal system configurations tailored to specific application needs.

With BELCO® scrubbing, hot, dirty flue gas is quenched/saturated flowing into a horizontal inlet in the lower portion of an up-flow tower. When NO_x control is required, ozone is injected into the scrubber inlet allowing sufficient time to convert oxides of nitrogen to and easily removed nitric acid (HNO₃). Acid gases and coarse PM are removed with buffered water sprays as gas flows up through the vertical tower. Finer PM is removed with a unique particulate growth and buffered water spray filtration stage. Liquid droplets are removed in the final stage at the top of the tower.

AIR POLLUTION CONTROL VS. CARBON CAPTURE: UNDERSTANDING THE DIFFERENCE

While both air pollution control and carbon capture share the common goal of reducing flue gas contaminants, they differ significantly in their requirements, technology complexity, and economic considerations. The flue gas going to a CCU needs to be much cleaner than is typically required to meet regulatory requirements for discharge to the atmosphere.

The requirements for flue gas in air pollution control are less demanding than those for carbon capture, see Table 1 below:

EMISSIONS/ PARAMETERS	TYPICAL STACK EMISSIONS LIMIT	TYPICAL CCU INLET REQUIREMENTS
Particulate matter ¹	<25-100 mg/Nm ³ dry	<25-100 mg/Nm ³ dry
NO _x	< 10–50 ppmvd (NO + NO ₂ as NO ₂)	< 5 ppmvd NO ₂ (NO not typically a concern)
SO ₃	N/A	< 1–5 ppmvd
SO ₂	< 25–150 ppmvd	< 1–5 ppmvd
Temperature	N/A	< 40°–45° C

Table 1. Flue Gas Air Pollution Control Stack Emissions Limits vs Carbon Capture Feed Gas Inlet Requirements

For many carbon capture processes, the clean flue gas must also be cooled well below what would be allowed for discharge to the atmosphere. The below list outlines the relative impacts of flue gas contaminants and temperature with carbon capture.

1. Fine particulate and aerosols can lead to fugitive amine stack emissions.
2. NO_x species may form nitrosamines and nitramines.
3. SO₂ may form heat stable salts which lead to amine degradation.
4. SO₃/HSO₄ may form sub-micron particles which can lead to amine degradation.
5. Lower feed inlet temperatures are required for optimum CO₂ removal.

In some cases, the process design flowsheet necessitates additional unit operations such as a selective catalytic reduction (SCR) unit upstream for NO_x control and/or as a wet electrostatic precipitator (WESP) for lowering particle matter. Elessent Clean Technologies has developed an integrated BELCO® system to meet the more stringent demands required of carbon capture processes. This system is an optimised vessel design to minimise plot space requirements and is backed up by process guarantees.

Below is an analysis of the variances between air pollution control and carbon capture, and why carbon capture can be more demanding:

1. Main Goals:
 - Air pollution control standards minimise the emission to the atmosphere of harmful contaminants like particulate matter and acid gases like SO₂ and NO_x.
 - Carbon capture processes focus on carbon dioxide removal from industrial process gases to reduce climate change impacts. The process of removing CO₂ is an additional layer of complexity given that the flue gas needs to be lower in contaminants that are otherwise emitted into the atmosphere.
2. Regulatory Requirements:
 - Air pollution control standards vary from nation to nation, with further state/provincial variation and site-specific requirements.
 - Carbon capture standards are required by technology licensors to ensure CO₂ capture performance and process guarantees which can be as high as 95% removal efficiency.
3. Technology complexity:
 - Carbon capture processes add a layer of cost to any process comparatively to conventional air pollution control.
 - Carbon capture performance is greatly impacted by flue gas characterisation and its associated contaminant profile.
4. Economic Considerations:
 - The economic feasibility of implementing carbon capture technologies to support greenhouse gas mitigation versus air pollution control requirements plays a significant role in any final investment decision. The cost of carbon dioxide removal technology in addition to cleaning and cooling the flue gas to meet inlet gas stream requirements of these processes is a major factor for project adoption.



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, fertilizer 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		

TECHNOLOGY DESCRIPTION

BACKGROUND

Fiber bed mist eliminators have been a fixture in various industries for nearly 70 years since their introduction in 1958. Developed by Dr. Joseph Brink who worked for Monsanto Central Engineering, the product was invented to solve an emission issue at one of Monsanto's high purity phosphoric acid plants in Trenton, Michigan. After that installation was proven, the product was tested in pilot plant trials in a variety of chemical processes. Today the Brink® mist eliminator is recognised in nearly every chemical production process as the principal liquid and soluble salt removal technology.

THEORY OF OPERATION

The inside of a fiber bed has fibers which are closely packed within the fiber bed volume. The gas and droplets must find a path through the matrix of fibers to pass from the upstream (or dirty side) to the down-stream (or clean side) of the fiber bed. Along the way through the fibers, droplets or solids are captured on the fibers as the gas continues downstream. The liquid coalesces on the fiber surfaces and, by gravity, begins to drain towards the bottom of the fiber bed where it drains from the device. This is shown in Figure 2.

These devices are passive, meaning they have no moving parts and do not require direct application of energy to operate. For the fiber bed to operate, the droplets and any solids must be captured on the fibers in their path, and this is achieved by use of the three capture mechanisms: impaction, interception and Brownian diffusion.

Inertial impaction and direct interception are the primary collection methods for removing larger mists from a gas stream, for instance, in mesh pads. However, if fine mist capture is required i.e., taking sub-micron particles out of a gas stream, the mist eliminator must be designed to take advantage of a third mechanism called Brownian diffusion at velocity of less than 50 feet per minute (0.254 m/s). This velocity varies widely with the fiber diameter used, packing density, desired efficiency at the design velocity and desired pressure drop of the installation. Diffusion fiber bed mist eliminators have infinite turndown, meaning they do not lose efficiency when operating at lower than desired velocity. In fact, the efficiency is inversely proportional to the bed velocity.

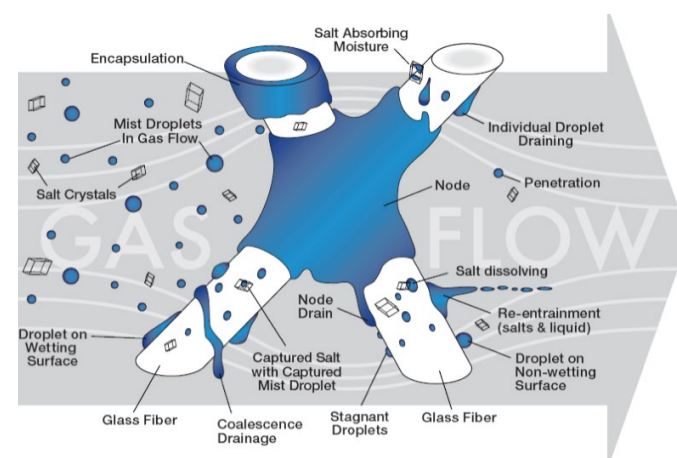


Figure 2.

ADDITIONAL DATA

Turndown Capability	Infinite
Amine Mist Emissions	Lowest ppm Level Possible
Amine Recycle	Yes
Energy Consumption	6-12" w.c. ¹ (can tailor)
Life	Variable

1 – Baseline pressure drop when wetted, but clean and free of any captured insoluble solids.

2 – Varies according to inlet insoluble solids loading. In clean applications we have operated for over a decade.

FIBER BED USE IN CARBON CAPTURE

One of the distinct advantages of fiber beds for the carbon capture industry lies in the capability of this technology to efficiently capture amine laden mist from upstream amine scrubbers and CO₂ stripping operations without altering the chemistry of the amine. The amine rich water solution captured on the mist eliminators after the carbon dioxide scrubbing phase can be recycled back into the process ready-to-use and the same can be said of the amine-rich solution after carbon dioxide stripping. This allows for efficient use of the amine without the need for biological or chemical treatment saving substantially on operating cost. Additionally, since fiber bed mist eliminators have infinite turndown capability, when the plant needs to operate at lower than design criteria for some period due to process limitations, there is no net negative effect on Brink® fiber bed performance offering peace-of-mind during turndown operations, a major advantage over other technologies.

LIMITATIONS

Fiber beds do not remove vapor, so plant designers must minimize amine vapor in the process gas to minimize amine loss. This can be achieved by reducing amine content in the scrubber liquor and maintaining cool process conditions. Additionally, Brink® fiber bed technology is sensitive to insoluble particulate, requiring upstream gas cleaning to remove ash, soot, and other particulates to prevent rapid pressure drop increases. Proper upstream cleaning allows fiber beds to operate for years without replacement. Monitoring pressure drop with differential sensors across the mist eliminator vessel tubesheet is recommended.

A GREENER FUTURE FOR CARBON CAPTURE?

MECS® Brink® fiber beds offer the possibility of operation flexibility, savings on amine expense and reliable adherence to environmental compliance while doing so at a fraction of the energy consumption of other technologies. While there are some limitations, it is worth investigating the possibility of what Brink® can do for the industry as it evolves into a major worldwide industrial effort.



ENTROPY

INTEGRATED CARBON CAPTURE (iCCS™)



SUMMARY

Entropy Inc. is a client-focused global full-service carbon capture and storage (CCS) developer, specialising in innovative solutions to significantly reduce CO₂ emissions from pre and post-combustion sources at third-party sites. Additionally, Entropy offers subsurface expertise in CO₂ sequestration, as demonstrated by decades of experience safely storing acid gas and CO₂ at the Glacier facility. Modular and integrated CCS technology, paired with the proprietary solvent Entropy23™, sets a new standard in efficiency and cost-effectiveness for both retrofit and new CCS installations. Entropy’s strategic partnership with the Clean Energy & Technology Research Institute (CETRI) at the University of Regina comprises a team of internationally renowned experts who develop and test advanced CCS systems. Entropy entered a strategic investment agreement with Brookfield Renewable for \$300 million in addition to a more recent investment agreement with the Canada Growth Fund (CGF) for \$200 million, including a 15-year, \$1 billion fixed-price Carbon Credit Offtake (CCO) agreement for up to 1 million tonnes per annum (tpa) to invest development of CCS facilities at third party emissions sites. (Visit the Entropy website for additional information, www.entropyinc.com).

BENEFITS

- **Proven:** Operating since July 2022, Entropy operates and owns the world’s first and only commercial natural gas post-combustion CCS facility, establishing itself as a leader in cost-efficient, reliable technology.
- **Energy Efficient:** The use of waste heat recovery, heat integration, and a high-performance solvent significantly reduces the energy required for carbon capture, achieving high CO₂ recovery rates with lower electrical energy loads.
- **Advanced Solvent:** The high-performance solvent Entropy23™ offers superior efficiency in CO₂ capture, resulting in lower energy and solvent requirements, enhancing the economic feasibility of CCS projects.
- **Scalable:** Entropy’s iCCS™ technology is designed for scalability, allowing for reduced capital costs, flexible maintenance, and efficient installation across various industrial applications and scales from <100 ktpa to >1Mtpa.

KEY DATA

TRL	9	Capture Rate Range (tpd)	40 - 3,000+	Capture Efficiency (%)	90 - 98%
Source CO ₂ Purity Range	3 - 20%+	System Energy (GJ/tCO ₂)	0	Specific Regen. Energy (GJ/tCO ₂)	2.4 ¹
Number of Commercial Plants	~	Number of Pilot Plants	~	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+

TECHNOLOGY DESCRIPTION

Entropy’s CCS system, utilising advanced solvent-based technology, is currently operational at the Glacier Gas Plant near Grand Prairie, Alberta, Canada, abating CO₂ from the exhaust of two natural gas reciprocating compressor engines. This initiative is part of a larger project to sequester CO₂ from all 11 compressor engines on site, equating to over 41,000 HP of engines collectively. In addition, Entropy has initiated preliminary front-end engineering and design (pre-FEED) and FEED work on several large-scale projects across a broad range of emission sources in both Canada and the United States.

Entropy has focused its carbon capture technology into three standardised designs to optimise post-combustion emissions capture across various industrial applications. The iCCS Thermal™ design targets boilers and steam generators, seamlessly integrating with these systems to curb emissions. For industrial engines, including compressors, the iCCS Recip™ design has been successfully deployed and is currently operating at the Glacier Gas Plant. Lastly, the iCCS Turbine™ design captures emissions from gas-fired turbines with low CO₂ concentrations, applicable worldwide for generating low emissions power generation and compression from turbines.

GLACIER OPERATIONS

Phase 1A - MCCS™

Glacier Phase 1A, the first commercial deployment of Entropy’s MCCS™ technology, abates and stores CO₂ emissions from a 5,000 HP compressor engine. The facility employs heat recovery exchangers, an exhaust gas blower, an absorber tower, solvent and water pumps, a solvent regeneration skid, and compression and dehydration units. By integrating waste heat recovery into the CCS design, the system meets all the heat requirements for amine regeneration, consistently maintaining CO₂ recovery rates between 90% and 98%. The system features a modular design, enabling cost-effective scalability in terms of installation, maintenance, and capital expenditure. The CCS equipment at Glacier is specifically designed for emissions from CAT3616 compressors, 16-cylinder reciprocating engines fuelled by natural gas, which are commonly used in natural gas transportation across North America. This phase sets a new performance benchmark for carbon capture technology, demonstrating its potential in reducing greenhouse gas emissions from existing industrial facilities and contributing to global decarbonisation efforts.

Phase 1B - iCCS™

The Glacier 1B project represents a milestone in the commercial application of Entropy’s CCS technology. As an extension of Phase 1, 1B incorporates Entropy’s integrated carbon capture solution (iCCS™) designed to capture carbon emissions from an additional 3616 unit. This phase leverages a newly installed 5,000 HP gas-fired compressor package equipped with built-in CCS technology, reducing the total installed cost and energy intensity compared to retrofit installations. Successfully installed in the fourth quarter of 2023, Phase 1B is now fully operational, showcasing substantial advancements in design and cost efficiency.

Glacier Phase 2 - iCCS Turbine™ clean power:

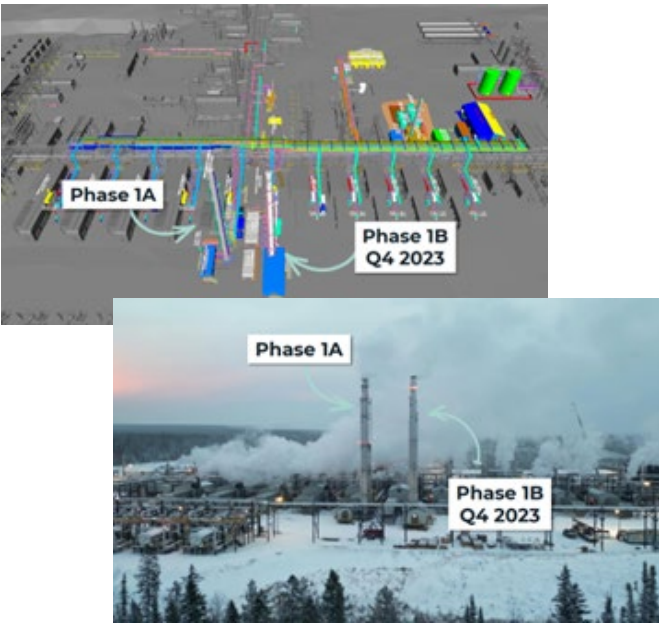
Entropy has reached final investment decision (FID) for Glacier Phase 2, which is planned to come onstream in Q2 of 2026. This phase will capture the emissions from the remaining nine natural gas reciprocating engines at Glacier facility, targeting over 90% efficiency. Additionally, Entropy will install a 15MW gas-fired turbine to provide clean, reliable power and heat for both the Glacier gas plant and Entropy CCS equipment. Entropy will install one iCCS Turbine™ module on the gas turbine, capturing 90% of the CO₂ exhaust emissions (3.5 mol% CO₂ concentration). Total CO₂ capture capacity for Phase 2 is 160,000 TPA, which will be available for permanent geological sequestration in addition to the existing Phase 1 capacity of 32,000 TPA. This project will be contractually underpinned by the 15-year CCO agreement with CGF, as well as a 15-year Power Purchase Agreement (PPA) with Advantage Energy Ltd (Glacier Gas Plant operator). Glacier Phase 2 integrates multiple industry-first innovations developed since 2022 while operating Glacier Phase 1 including design refinements, standardized procedures, enhanced operational strategies identified using EntropyIQ™ data analysis, solvent enhancements, and customised original equipment facilitated by manufacturers.

ENTROPYIQ™

EntropyIQ™ represents the digital innovation arm of Entropy’s CCS technology and enables precise, real-time monitoring and optimisation of carbon capture processes. This digital data gathering and processing engine plays a crucial role in achieving operational efficiencies, as evidenced by the optimisation protocols conducted at the Glacier CCS project. EntropyIQ™ ensures optimal capture rates and energy utilisation, facilitating the continuous improvement of CCS operations. In addition, EntropyIQ™ is instrumental in the monitoring, measurement, and verification of data for third-party verification, reporting, and compliance purposes. This capability is essential for meeting regulatory standards, securing carbon credits, and providing transparency to stakeholders.

ADVANCING CCS DEPLOYMENT

As of the time of this publication, Entropy has entered into a definitive agreement to acquire a strategic interest in three carbon storage hubs. This includes the Belle Plaine and North Battleford hubs in Saskatchewan, Canada and a 50% interest in the Rolling Hills hub in Alberta, Canada. The portfolio includes critical subsurface storage rights, commercial agreements, and intellectual property, providing a foundation for future CCS development in both provinces.





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				

TECHNOLOGY DESCRIPTION

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.

Federated Co-Operatives Renewable Diesel Complex (Canada). Fluor has completed FEED for a greenfield renewable diesel facility that included post-combustion carbon capture from flue gases produced by a steam methane reformer, auxiliary boiler, and a fired heater.

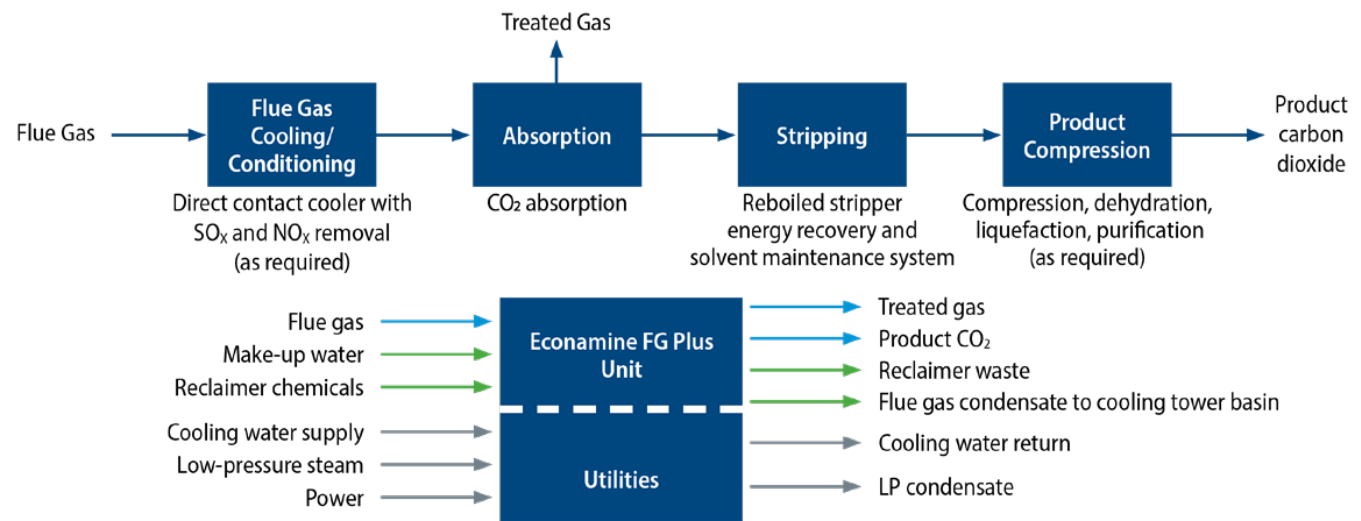


Figure: A typical EFG+ block flow diagram of the process is shown below.



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				

TECHNOLOGY DESCRIPTION

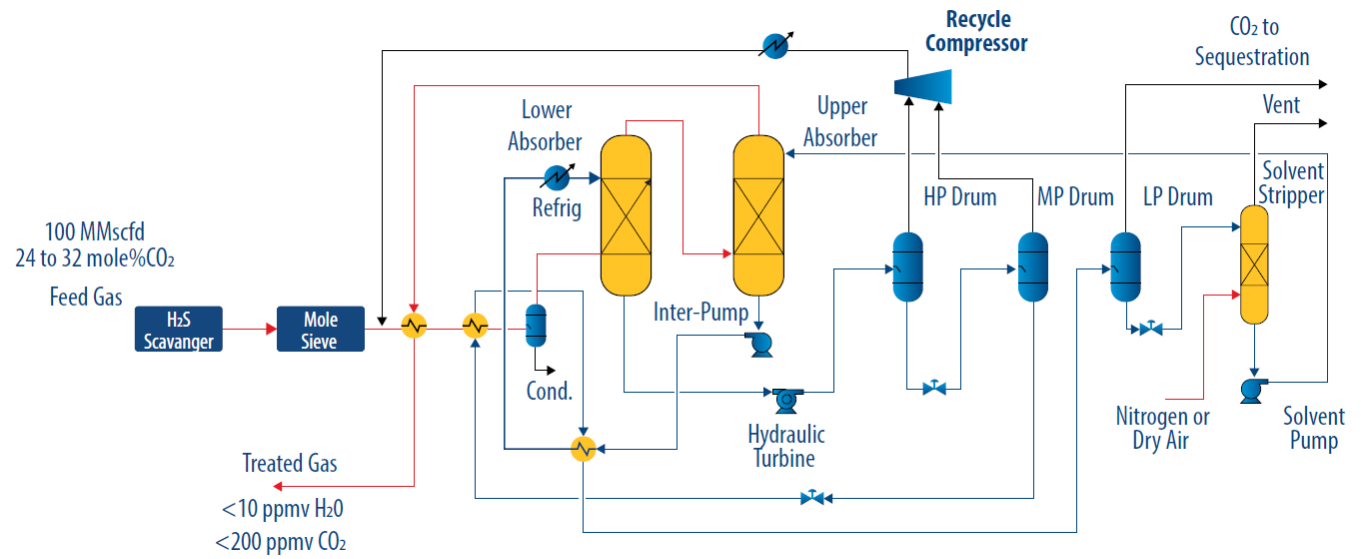


Figure 1: Fluor Solvent's Improved Process

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.

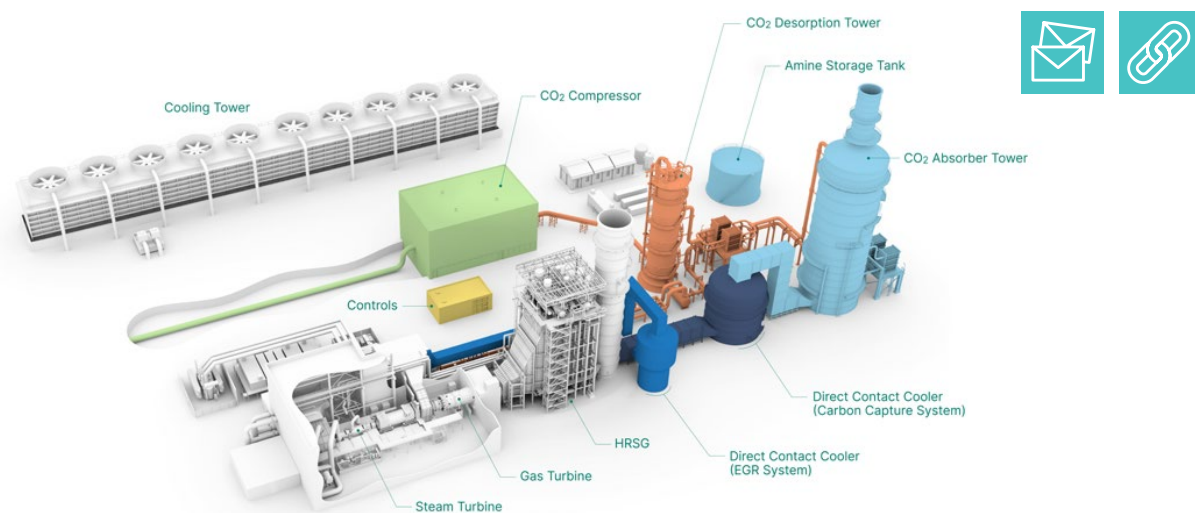
- Two absorber design: the upper absorber produces a semi-lean solvent to be cooled and re-used in the lower absorber.
- Refrigeration generated from flash solvent cools the feed gas and the semi-lean solvent, which helps with regeneration.
- Hydraulic turbine recovers power from the pressure letdown 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.

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SUMMARY

GE Vernova (GEV) is a key player in the power industry, providing a wide range of complementary renewable, gas-fired, nuclear, grid, and digital technologies. GEV is committed to deploying diverse technologies to reduce emissions while laying the groundwork for long-term innovation aiming to deliver decarbonised electric power. GEV has the knowledge and expertise to provide innovative and competitive solutions for integrating carbon capture systems with generating assets. GE Vernova has developed various technologies aimed at enhancing performance and reducing costs in carbon capture plants (CCP). These innovations include exhaust gas recirculation (EGR), the elimination of CCP blowers, steam integration, and upgrade options for gas turbines (GT), steam turbines (ST), heat recovery steam generators (HRSG), control systems and digital monitoring reporting & verification.

BENEFITS

- **Reduced CapEx:** By reducing exhaust flue 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.
- **Enhanced capture:** EGR increases CO₂ concentration in flue gas, which boosts capture efficiency and reduces specific energy requirements.

KEY PROJECTS

- **Net Zero Teesside Power (NZT Power):** NZT Power aims to be the world's first commercial gas-fired power station integrated with full scale carbon capture and storage (CCS), capable of generating more than 740 MW of flexible, dispatchable and low-carbon power, capturing up to two million tonnes of CO₂ per year that will be transported and stored by the Northern Endurance Partnership (NEP) infrastructure. NZT power will demonstrate the first commercial use of GEV's EGR system and CCP blower elimination which will help in boosting the plant performance, reliability and availability, while reducing the costs.
- **DOE FEED study ft. Southern Company's James M. Barry power plant:** GE Vernova led a FEED study demonstrating EGR capability in retrofitting the James M. Barry Electric Generating Plant to capture up to 95% of CO₂ emissions. In this study, the integration reduced the carbon capture facility's total cost by around 3% to 4% and improved the plant output and efficiency. Integration also reduced OpEx due to reduced solvent degradation rate.

KEY DATA

TRL	5 - 7*
Target Industries	Utility Power generation, Industrial Power Generation, Data Center Power Generation

* TRL can differ based on the GT frame and project

TECHNOLOGY DESCRIPTION

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 flue 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, 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.

The gas turbine inlet mixer is engineered to achieve uniform mixing of the ambient inlet air and the recirculating EGR flow. In summary, EGR increases the concentration of CO₂ in the flue 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 flue gas to CCP. This results in less steam extraction and improved NGCC output.

Furthermore, the EGR lowers the oxygen levels in the flue gas, which helps in the reduction of oxidative amine degradation. The reduction in amine degradation is particularly beneficial because it reduces the need for solvent replacement, lowering operational costs.

GE Vernova's confidence in EGR is supported by extensive development work, including testing on commercial combustors.

ELIMINATION OF CCP BLOWER

Operating GT and HRSG at higher backpressure eliminates the need for blowers to move flue gas through the CCP and EGR systems. This simplifies the control system, reduces the CapEx, and improves performance.

STEAM INTEGRATION

The CCP reboiler requires a significant amount of steam to desorb CO₂ from the solvent. Steam can be generated by an additional installed auxiliary boiler known as a bolt-on solution, or by steam extraction from the steam bottoming cycle steam turbine.

A bolt-on solution entails the installation of an additional external auxiliary boiler to supply steam to the CCP, resulting in an increase in the size of the CCP and overall site fuel consumption and increased emissions along with reduced site efficiency.

Steam integration, on the other hand, extracts the steam necessary from the steam bottoming cycle. Steam extraction sources selected for compatibility with CCP reboiler conditions among others include low-pressure superheat and intermediate pressure (IP)/low pressure (LP) crossover. By analyzing each steam source, GE Vernova identifies efficient steam supply ways to reduce the impact on existing NGCC operations while enhancing 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 HRSG 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.

CONTROL SYSTEM UPGRADE

Control capabilities must be seamlessly integrated to enhance overall plant operations. The base offering involves modifying existing control systems to include control I/O, logic, and human-machine interface graphics for all GE Vernova equipment. Advanced options include the Mark VIe control system, which provide an interface with existing plant distributed control systems (DCS) using standard bus protocols.

These systems offer a unified control interface that enhances plant operability, facilitates faster startup times, and enables high fidelity dynamic plant simulations.

DIGITAL MONITORING REPORTING & VERIFICATION

GEV provides software to enable the energy transition. CERius™ is a centralized cloud application that automates higher accuracy greenhouse gas emissions (GHG) data collection and provides insights to operationalize carbon abatement project accounting.

SUMMARY

By adopting these integrated solutions, industries can achieve significant advancements in decarbonisation, enhancing their contributions to a cleaner energy landscape.

GE Vernova integration solutions have the potential to reduce CCP size and CapEx by enabling smaller CCP designs via EGR, CCP blower elimination and stream integration. Reduced solvent degradation improves operational costs and plant maintenance. EGR and GE Vernova's upgrades improve plant efficiency and output, reducing the impact on NGCC with CCP integration.



SUMMARY

CERI is at the forefront of developing and deploying carbon capture technologies, encompassing advanced technical capabilities including CO₂ capture solvents, process engineering, system integration and standardization. Our independent technology suite has been demonstrated in coal and gas fired power plants. The state-of-the-art amine-based HNC-5 technology, has been validated through >20,000 hours at the 120,000 tonne/annum Shanghai Shidongkou CO₂ capture facility. CERI is commissioning the world's largest post-combustion CO₂ capture and storage (CCS) facility at Huaneng Logndong Energy Base in Gansu, China, capturing 1,500,000 tonne/annum CO₂.

Huaneng pioneers at natural gas combined cycle CO₂ capture, overcoming high energy consumption via innovative hybrid CO₂ capture absorbent, and advanced heat integration. Huaneng's current efforts focus on piloting hybrid solvents and heat pump modules to enable cost-effective, large-scale deployment of CCS technology.

BENEFITS

- Built up on R&D, we can realize the seamless connection from research, to engineering demonstration, to commercial operation.
- Broad spectrum of engineering capabilities from technology engineering design, equipment procurement, construction, commissioning and operation.
- Extensive experience in commercial carbon capture, demonstrated by the 2009 110ktpa Shanghai Shidongkou facility and the 1.5Mtpa CCS project currently under construction at Huaneng Zhengning Energy Base.
- Leading the development of the international standard, i.e. ISO27927. Key performance parameters and characterization methods of absorption liquids for post-combustion CO₂ capture.

KEY PROJECTS

- Shanghai Shidongkou 120,000 tonne/annum Post Combustion CO₂ Capture facility, commissioned in 2009.
- Huaneng Longdong Energy Base 1,500,000 tonne/annum Carbon capture, and storage project in Gansu China, world's largest Post Combustion CO₂ Capture facility to be commissioned in Middle 2025.
- Huaneng international CO₂ capture testing platform for Natural Gas Combined Cycle power plant, 6 tonne/day in Yangpu Hainan Island, China, commissioned in 2023.
- CTSCo-Huaneng Millmerran coal-fired power 110,000 tonne/annum Post Combustion CO₂ Capture project, in Queensland Australia (feasibility and FEED).

KEY DATA

TRL	9	Capture Rate Range (tpd)	6 - 5,000	Capture Efficiency (%)	95%
Source CO ₂ Purity Range	4 - 15%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.0 - 2.6
Number of Commercial Plants	3	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Coal and natural gas fired power, steel, cement and waste to energy plants				

TECHNOLOGY DESCRIPTION



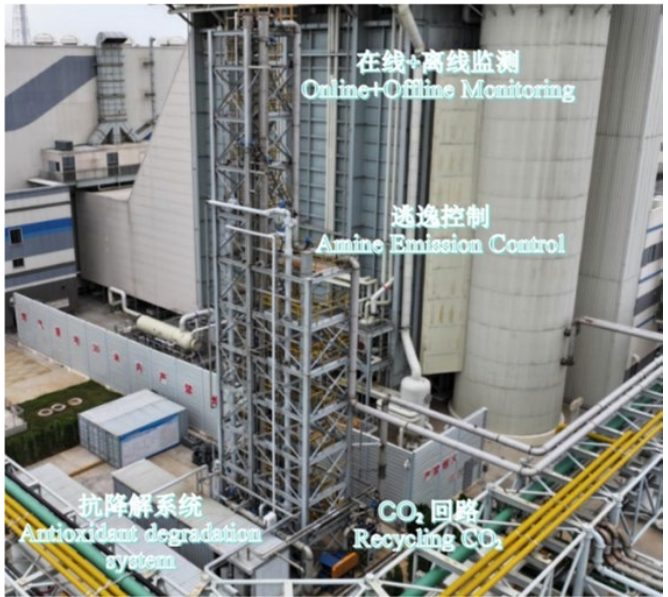
HUANENG'S CO₂ CAPTURE TECHNOLOGY

CERI has developed a broad spectrum of CO₂ capture technology and systems built for the coal and gas-fired power plants, waste-to-energy plant, biomass power plant, steel plant and cement plant. CERI started R&D and engineering demonstration of CO₂ capture technology in the power industry back in 2006. With over 18 years of experience, CERI expertises in providing engineering services including the development of high-performance CO₂ solvents, solvent recovery and purification technology, carbon capture process design and optimisation technology, high-efficiency equipment design, power plant integration technology, engineering design, construction and commissioning technology. The following are CERI's cutting edge commercial absorbent CO₂ capture technology:

Advanced Amine Absorbent: CERI has developed a series of commercial blended amines solvents named HNC-1~HNC-5. The advanced amine, HNC-5 solvent has been validated for more than 20,000 hours in shanghai Shidongkou 120,000 tonne/annum CO₂ capture facility, with the solvent loss rate of 40% of conventional amine MEA and regeneration energy below 2.8 GJ/tCO₂.

Phase Change CO₂ Absorbent: CERI has developed the phase change CO₂ absorbent that can realize the automatic phase separation of rich liquid after CO₂ absorption. Results show a regeneration energy reduction up to 40% than the conventional amine MEA.

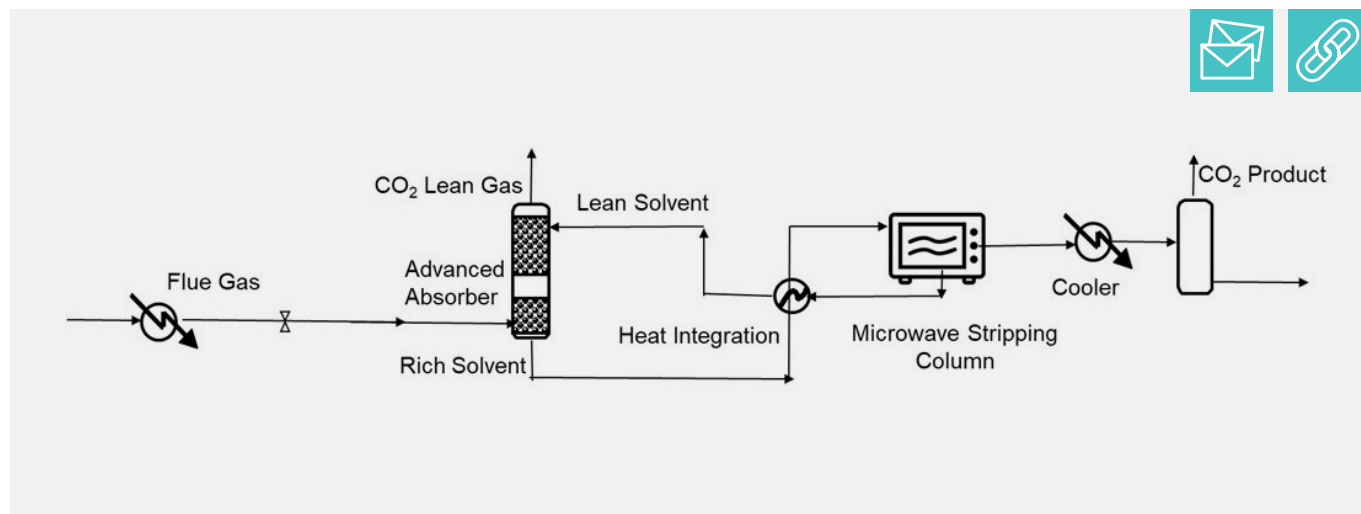
Next-gen hybrid absorbent: CERI has developed the next-gen HNC-7 hybrid solvent, incorporating higher cyclic loading, faster reaction kinetics, lower energy consumption, while inhibiting solvent loss due to degradation, plus attractive technical feasibility (viscosity, wettability) and environmentally benign benefits in terms of low toxicity and volatility.



HUANENG'S HIGHLIGHTED CO₂ CAPTURE PROJECTS

Huaneng Longdong 1,500,000 Tonne/Annum CCUS Project: This million-tonne scale CCUS project is in construction and will become the largest post-combustion CO₂ capture facility in the world. This project deploys China Huaneng's next-generation HNC series CO₂ capture technology. CO₂ will be captured from the slipstream of Unit 1 of the 2x1,000 MW ultra-supercritical coal-fired power plant, at the newly build China Huaneng Longdong Energy Base in Northwest China. The CCUS project will reduce 1.5 million tonnes per annum CO₂ emission, at a regeneration heat duty below 2.3 GJ/tonne CO₂, and CO₂ capture cost is around RMB 220 per tonne CO₂ captured (<USD \$35). The captured CO₂ will be transported via pipeline in the supercritical phase. Around 0.5 million tonne per annum CO₂ will be stored via dedicated geological storage in the nearby geological sites, and 1 million tonnes per year CO₂ will be sent to oil fields for enhanced oil recovery.

Huaneng international CO₂ capture test platform for Natural Gas Combined Cycle power plant in Hainan Island, China: Huaneng Yangpu NGCC CO₂ capture project is retrofitted to #2 unit of the plant, and adopts the chemical absorption technology independently developed by CERI. It is developed to the first international testing platform for solely natural gas-fired CO₂ capture globally. The platform can simulate raw flue gas with CO₂ content ranging from 3% to 20%, offering a variety of testing conditions. The overall height of the facility is 28 meters, with a floor area of 300 square meters. The platform verified Huaneng's HNC-7 hybrid carbon capture solvents and process intensification technologies, as well as the flexible operation strategies. It has established coordinated control and operation between carbon capture unit and peak-shaving power plants.



SUMMARY

Amine processing is a well-established carbon capture technology used in industry for decades. While generally effective, the process lacks efficiency, which impacts operating costs, energy footprint, water requirements, throughput, and the net zero equation.

The primary objective of this project is to develop a de-risked and scaled solution to overcome these inefficiencies experimentally. Applying this knowledge to existing and new amine-based carbon capture units and improving their effectiveness, efficiency, and adoption will significantly impact industrial decarbonisation.

Previously, InnoTech Alberta set up a lab-scale configuration and leveraged learnings from the carbon capture unit at Alberta Carbon Conversion technology Center (ACCTC) to run different process scenarios that allow optimisation to be tested both by stage and as an integrated multi-stage process. Significant efficiencies were observed at the lab scale, warranting a third-party engineering techno-economic analysis to de-risk the scaling from lab scale to pilot scale.

BENEFITS

- One of the most compelling aspects of this process is its potential to significantly reduce the capital and operating costs associated with capturing CO₂. By achieving a 75% reduction in energy requirements compared to conventional amine-based processes, the Amine Intensification Process presents a substantial cost-saving opportunity for industries striving to reduce their carbon footprint.
- This process aligns with global efforts to transition to sustainable energy sources by electrification of the process. Its energy-efficient approach not only reduces operational costs but also contributes to a more sustainable energy consumption pattern, appealing to environmentally conscious industries. Industries utilising the innovation can demonstrate their commitment to carbon intensity reduction and sustainability, enhancing their brand image and positioning them as leaders in their respective sectors.
- With tightening regulations and emission reduction targets, the Amine Intensification Process offers a proactive solution for industries to comply with environmental standards and avoid potential penalties.

KEY DATA

TRL	5	Capture Rate Range (tpd)	1	Capture Efficiency (%)	95%
Source CO ₂ Purity Range	4 - 6%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	1.8
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Oil and Gas and any point source CO ₂ emitter				

TECHNOLOGY DESCRIPTION

One of the challenges limiting the adoption of CCUS technologies is the energy intensity of commercial ready carbon capture processes. To address this challenge, InnoTech Alberta and its partners have demonstrated a concept, with the potential to reduce the energy demand, operational cost and carbon footprint. This process was developed to improve the existing and proven Amine-based CO₂ capture process. The proposed project aims to tackle two major challenges associated with the Amine based processes; high regeneration energy requirement and solvent degradation. The proposed project is called Amine Intensification process (AIP), the intensified process includes three significant improvements to the conventional amine process that, together deliver a step-change in carbon capture energy intensity and operational costs, including:

1 - ALTERNATIVE ABSORPTION TOWER:

The adoption of high-efficiency internal components in the column serves to reduce the size of the absorption column significantly. Numerous gas-liquid contactor designs have been created for gas treatment applications. However, a predominant proportion of currently installed contactors falls into either packed towers or tray towers. With the development of high-capacity, high-efficiency packings, packed towers are progressively gaining a larger share of the market. Structured packing has gained substantial consideration for amine scrubbing in CO₂ capture due to its favorable attributes, including minimal pressure loss, effective mass transfer capabilities, and straightforward installation. Within the CO₂ capture procedure, the efficacy of both the absorber and stripper hinges significantly on the packing's efficient mass transfer surface area.

Characterisation of novel structured packings for CO₂ capture

InnoTech Alberta, in collaboration with Suzler Chemtech, has evaluated the potential utilisation of Suzler's advanced packing material (Mellapak™ CC The structured packing family for carbon capture), designed for CO₂ capture process with the potential to increase the mass transfer by 30% and reduce the pressure drop by 20%. Generally, only structured packing can meet the low-pressure drop requirements for the design of a direct contact cooler and the CO₂ absorber.

2 - MICROWAVE HEATING

Using microwave is motivated by recent literature highlighting microwave heating as an effective means of regenerating solid adsorbents or aqueous solutions for CO₂ capture and storage. Microwave, or dielectric, heating refers to the direct heating of a sample through interaction

with electromagnetic radiation. As such, microwaves offer instantaneous and volumetric heating without heat transfer restrictions associated with conventional conductive or convective heating. For polar solvents, such as water or MEA, microwave heating primarily takes place via the reorientation of molecular dipoles in the presence of the rapidly oscillating electric field. A phase lag between the molecular motion and the electric field causes friction between neighboring molecules, which ultimately leads to the dissipation of the electromagnetic energy into heat. Other important loss mechanisms occur through ion conduction in ionic solutions and Maxwell- Wagner polarization, resulting from interfacial phenomena, in inhomogeneous media. Harnessing these advantages, numerous applications of microwave heating have emerged in recent decades, encompassing fields such as material synthesis, food processing, and chemical reactions. Regarding monoethanolamine (MEA), it was observed that microwave-based regeneration has the ability to release CO₂ at lower temperatures and in a more expedited manner in contrast to traditional regeneration methods. This has the potential to decrease the energy cost associated with a TSA (temperature swing adsorption) process that employs MEA. Similarly, existing literature on microwave-assisted CO₂ desorption from solid sorbents has demonstrated notably quicker CO₂ release rates compared to conventional desorption techniques.

3 - WATER LEAN SOLVENT (WLS)

The primary challenge associated with this process is the significant energy requirement for CO₂ capture, which constitutes roughly 70% of the total cost. This substantial energy demand has been a major obstacle to the widespread adoption of CCUS. It is widely understood that the primary contributor to this energy demand is the heat duty of the reboiler, a crucial component in regenerating the solvent. This energy is essential for breaking the chemical bond between CO₂ and MEA at elevated temperatures in the stripper, encompassing both the necessary sensible heat and the latent heat needed for solvent vaporisation. Additionally, this regeneration process leads to considerable deterioration in the performance of the MEA absorbent, resulting in a rapid decline in its ability to capture CO₂ effectively. From an energy consumption perspective, the use of water as a solvent presents a significant challenge in these aqueous systems due to its high heat capacity and latent heat properties. Therefore, the adoption of water-lean absorbent systems, achieved by substituting water with organic solvents characterised by lower specific heat and volatility, emerges as an attractive alternative to mitigate the substantial energy requirements. Our laboratory findings confirm that the use of Water Lean Solvent (WLS) allows us to cut energy requirements in half compared to conventional solvents.



SUMMARY

ION Clean Energy's ICE-31™ post-combustion carbon capture technology has demonstrated transformational performance at the engineering-scale and large pilot-scale by capturing between 95%-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 low emissions that minimize 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 minimizes 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 minimized while capture efficiency rates of more than 95% are maintained.

KEY PROJECTS

- **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 pilot since September 2023 and accumulated over 6,000 hours of ICE-31™ testing including parametric studies, dynamic and long-term operations. This collaboration feeds directly into ION's partnership with Calpine to implement CO₂ capture onto their Sutter Decarbonisation Project in Northern California. The Enterprise project has received significant funding for development through U.S. Department of Energy programs.
- **Tampa Electric Company's Polk Power Station:** ION is working with Tampa Electric Company to complete a FEED study to design and determine the cost of retrofitting ION's ICE-31™ capture technology onto the CCGT power plant at the Polk Power Station Unit 2 (PK2) in Mulberry, FL, USA. This project will be designed to capture a minimum of 95% of the CO₂ emissions, which equates to nearly 3 million metric tons of CO₂ per year. The carbon captured will be transported for secure geologic storage. The PK2 CCS project has received significant funding for development through U.S. Department of Energy programs.

KEY DATA

TRL	7	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)	No*
Target Industries	CCGT power generation and industrial processes				

TECHNOLOGY DESCRIPTION

EXTREMELY LOW EMISSIONS

In February 2024, ION began operating an ICE-31™ campaign at its Enterprise (ENTP) carbon capture pilot in Pittsburg, CA, USA. Since then, ION has completed over 6,000 hours of successful testing as of February 2025, including parametric and long-term steady-state testing using a flue gas slipstream from Calpine's Los Medanos Energy Center, a commercially dispatched CCGT power plant. The ENTP emissions were continuously monitored out of top of the Absorber using a Proton-Transfer-Reaction Time-of-Flight (PTR-TOF) mass spectrometer during the long-term steady-state portion of the campaign. PTR-TOF mass spectrometry is the state-of-the-art technology for continuous emissions monitoring and can detect and quantify calibrated compounds at the single parts-per-billion (ppb) level. ION measured the emissions of volatile organic compounds (VOC) (quantified as methane equivalent) to be consistently less than 10 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.

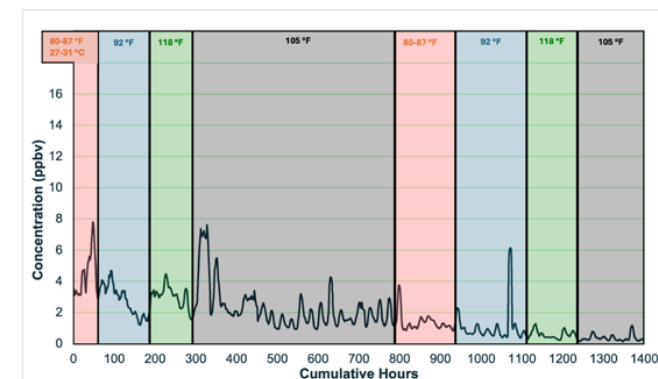


Figure 1: VOC emissions as methane at ENTP during the long-term steady-state portion of the campaign. The temperature of the flue gas entering and leaving the absorber is shown at the top of the graph.

ICE-31™ STABILITY

Lab studies have focused on accelerated oxidative and thermal degradation. ION performed accelerated oxidative experiments at 80 °C with sparged air containing 10% CO₂ while thermal degradation studies were performed in closed vessels at over 135 °C with minimal headspace. The resulting ICE-31™ degradation is remarkably low under these extreme environments, demonstrating unparalleled stability in literature comparison to other amines and amine systems. Heat stable salts that originate from trace contaminants in the flue gas are formed over the course of several years and may be cost-effectively reclaimed in a semi-batch process using electrodialysis or ion-exchange.

THERMODYNAMIC PERFORMANCE OF ICE-31™

A high working capacity, a measure of how much CO₂ can be held by a specific volume of solvent, is a vital requirement in a transformational CO₂ capture solvent and is a function of solvent concentration, desorption energy requirements and circulation rate. This, coupled with a high CO₂ vapor pressure in equilibrium with the solvent at a given lean loading and stripper temperature, results in a more efficient use of stripping steam in the regenerator. The increased working capacity of ICE-31™ also lowers the liquid flow rate required to maintain constant capture, in turn lowering pump power, lean-rich heat exchanger size, and reboiler duty attributed to sensible heat.

LOWER ENERGY USE: SRD VERSUS CAPTURE EFFICIENCY

Another work package focused on varying the capture efficiency while simultaneously choosing optimal L/G ranges to determine minimum Specific Reboiler Duty (SRD) performance at each capture efficiency. 18 m absorber height was tested for each capture efficiency; a 24 m absorber height was also modeled in ProTreat® after parametric testing (Figure 2). With 18 m of packing, the CO₂ mass transfer into the solvent was fast enough to reach a similar rich loading across the entire capture efficiency range. The modeled 24 m absorber improved the measured performance over the 18 m absorber only at very high capture efficiencies above 97%. Due to ICE-31's stability, ION can drive leaner solvent loadings, which results in higher capture efficiency up to 99%. The overall impact of the favorable kinetics and thermodynamics of ION's ICE-31™ solvent demonstrate that there is only a 4% SRD penalty when increasing capture from 90% to 98%, even when using a simple stripper in the drop-in facility that was not optimised for ICE-31™. Further optimisation with ION's cold-rich bypass design allows even leaner optimal lean loadings and a smaller penalty when increasing capture efficiency.

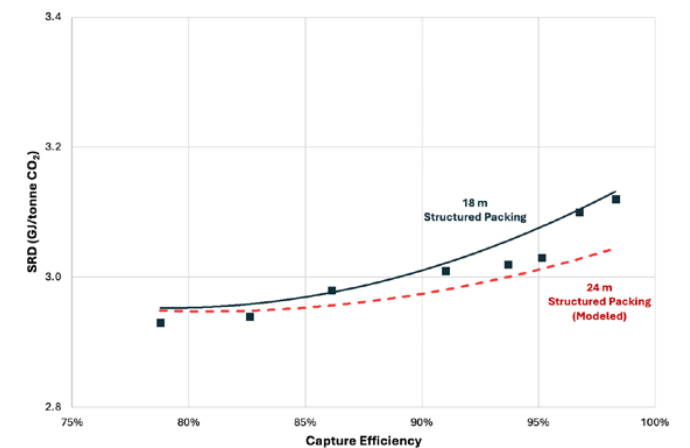


Figure 2: SRD at optimal L/G for varying capture efficiencies with 4.4% inlet CO₂ measured at 18 m absorber packing height and modeled at 24 m absorber packing height.



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 conditioning, 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 with high CO₂ concentrations in the flue gas: K2-CO₂ has extended the usefulness to lower CO₂ concentrations, making it suitable for most combustion-derived flue gas.

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, Steel, Waste to Energy				

TECHNOLOGY DESCRIPTION

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.

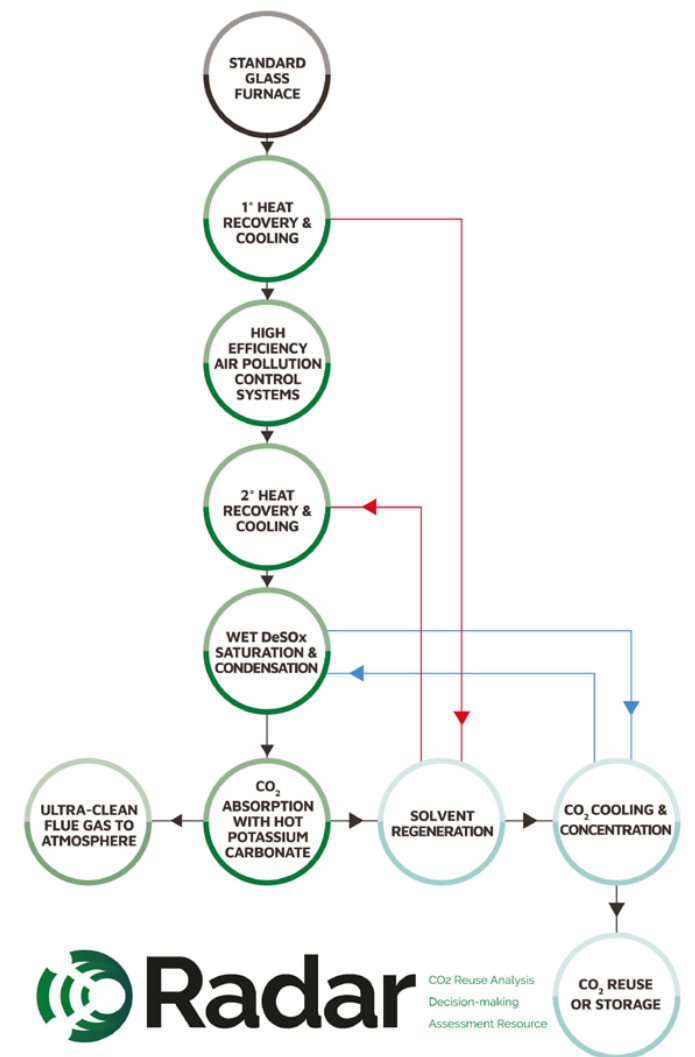
The CO₂-rich HPC solution is then heated to release the highly concentrated CO₂ product in a stripping process. The HPC solution is regenerated and injected into the absorber in a loop system, requiring no continuous make-up of the solution.

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. These include that HPC solution is safe for people and the environment, non-volatile, stable, inexpensive, and based on a readily and worldwide available basic component that is not provided by a propriety source, manufacturer, or licensor.



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 automatized 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.



SUMMARY

KC8 Capture Technologies is commercialising industry leading carbon capture technology that provides an affordable pathway to reduce greenhouse gas emissions from the resource, production and energy sectors across the globe. Our groundbreaking UNO MK 3 technology employs an innovative precipitating potassium carbonate (K_2CO_3) solvent, enabled by our patented solids-tolerant process design. This unique approach allows for increased solvent loading, resulting in decreased CAPEX costs and a smaller plant footprint, in addition to decreased energy usage. Further benefits include elimination of wash stages and major environmental and safety advantages. Moreover, UNO MK 3 boasts superior tolerance to oxygen, SOx, and NOx in source flue gas, broadening its application scope to challenging sectors like cement, steel, waste-to-energy, and gas turbine-based power generation. Two demonstration-scale facilities are set to commence operations in the second half of 2025, which in conjunction with planned FEED studies are forecast to demonstrate carbon capture capabilities at a competitive cost range of \$35-40 per tonne of CO_2 .

BENEFITS

- **Lower cost and energy usage** – achieving up to 50% reduction in cost and 15% reduction in energy usage compared to the best amine equivalent.
- **Oxygen, SOx and NOx tolerant process** – allowing diverse application portfolio including cement, steel and waste-to-energy.
- **Low cost, safe solvent with pre-existing supply capacity** – with current potassium carbonate market orders of magnitude larger than forecast CO_2 capture demand.
- **Small plant footprint and low impact retrofit integration** - all achieved through higher solvent loadings and design innovations which minimise upstream process impact.
- **Superior environmental performance** – environmentally benign solvent with low volatility and no toxic byproduct formation eliminates need for toxic waste disposal, complex wash stages and solvent reclamation unit.
- **Option to time shift energy demands** – large scale solvent storage viable due to unique solvent characteristics.

KEY PROJECTS

- **PACER Demonstration Plant** – 10-15 tpd CO_2 facility being constructed in partnership with Cement Australia and LET Australia, focusing on clinker flue gas processing from a pre-existing industrial plant. Operations will be located at a Cement Australia facility in Gladstone, Australia.
- **UNOGAS Demonstration Plant** – 5-10 tpd CO_2 facility being developed at the National Carbon Capture Centre (NCCC) as the second stage of the US DoE FleCCS project. This project will focus on optimising the performance in lower CO_2 concentrations such as those found in gas turbine flue gas during steady state operation, ramp-up / ramp-down and time-shifting of solvent regeneration to improve flexibility of power generation in high renewable penetration grids.

KEY DATA

TRL	6 - 7	Capture Rate Range (tpd)	50+	Capture Efficiency (%)	90%+
Source CO_2 Purity Range	3 - 25%	System Energy (GJ/t CO_2)	~	Specific Regen. Energy (GJ/t CO_2)	2.2 - 2.6
Number of Commercial Plants	0	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Cement, Steel, Waste-to-energy, Power, BECCS				

TECHNOLOGY DESCRIPTION

THE UNO MK 3

Following the invention of the UNO process within the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), the technology has subsequently been developed over the last decade by KC8 Capture Technologies in conjunction with the University of Melbourne in Australia. The current generation of the technology, the UNO MK 3, consists of a catalytically enhanced precipitating potassium carbonate solvent technology. It is engineered to capture over 90% of carbon dioxide (CO_2) emissions from heavy industry sources such as cement plants, power stations (pre- and post-combustion) and other CO_2 emitting industries.

Potassium carbonate (K_2CO_3) has been used in solvent absorption processes in chemical industries for many years (i.e. the Benfield process). The patented UNO MK 3 process provides a unique update to this established technology, making it highly efficient for CO_2 capture at low pressure. The UNO MK 3 process contains the absorption and regeneration stages of a standard solvent absorption process. However, unlike a standard liquid-based solvent system, a $KHCO_3$ precipitate is allowed to form. This allows UNO MK 3 to use a more concentrated solvent and greater CO_2 loadings. That, in turn, allows for greater working capacities, lower circulation rates and drives down energy requirements.

TECHNOLOGY STRENGTHS

To handle solid precipitation in the process, KC8 Capture has conducted extensive R&D to identify and adapt existing process units to meet the challenging requirements. Central to this has been our patented refinement of Turbulent Bed Contactor technology to not only facilitate suitable solids tolerance in the absorber unit, but also provide process intensification, resulting in reduced column height relative to conventional amine processes.

A key benefit of potassium carbonate-based solvents is the significantly lower volatility compared with amine-based solvents. The volatile emissions from amine-based solvents can be significant and usually requires an additional water wash sections as well as continuous solvent make-up. In contrast, the UNO MK 3 process neither requires a water wash stage, nor complex reclamation sections to achieve economic viability.



Figure 1: NCCC UNOGAS commercial pilot plant prior to installation.

APPLICATIONS

The UNO MK 3 process can handle a wide range of applications, including both pre- and post-combustion electricity generation and other industrial CO_2 emitting processes. It is unaffected by the impurities in a range of fuel source including black coal, brown coal, natural gas and emissions from cement, iron and steel and other heavy industries. Due to its oxygen tolerance and low volatility, it is also highly applicable in capture from natural gas turbines in either open or closed cycle flue gases. It also has the capacity to be applied either as a new build or retrofit application.

KC8 has developed innovative configurations for large-scale contacting systems, such as a novel patented concentric single stream absorption and stripping combined columns. This enables larger column diameters and improves CAPEX performance comparative to conventional steel arrangements.

CURRENT STATUS

Pilot plant testing at Hazelwood Power Station in Australia has been completed, and two demonstration facilities are underway as outlined in Key Projects. These projects will take KC8 Capture through to a TRL of 7-8, at which point we will be ready to commence construction of commercial scale facilities. Current estimates are that typical applications at full scale will be able to achieve CO_2 capture costs of \$35-40 /tonne.

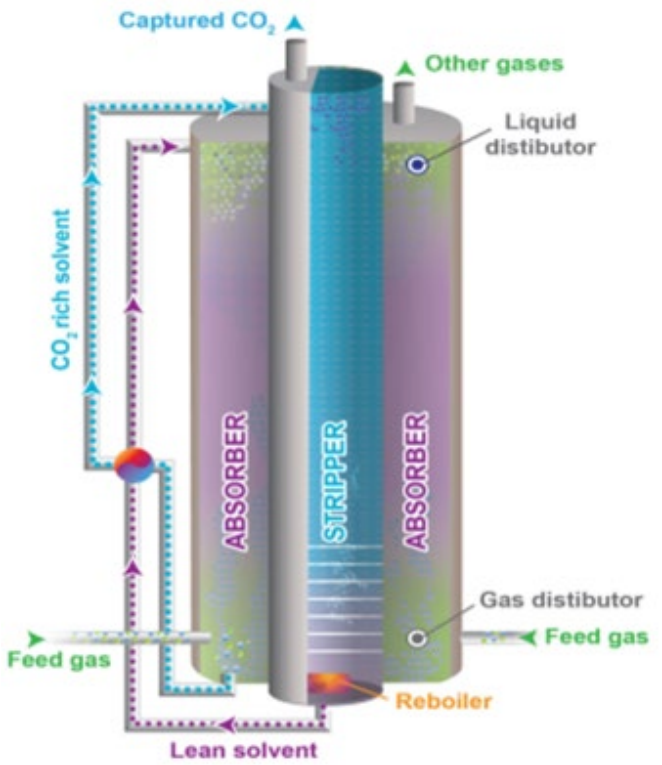


Figure 2: KC8 patented concentric absorption / stripping column.



SUMMARY

Leilac is a strategic technology partner applying its patented indirect heating technology to the cement and lime industries with the aim of providing future-proof solutions that reduce both emissions and costs. Leilac’s technology is proven at pilot scale to separate unavoidable CO₂ process emissions, ready for use or storage, without additional chemicals or energy-intensive processes required by conventional carbon capture technologies. Through our partnership with Heirloom, a Direct Air Capture company, we are also developing a scalable, low-cost pathway for the removal of atmospheric carbon dioxide (CO₂). Leilac, (Low Emissions Intensity Lime and Cement), is a subsidiary of Calix Limited, and was formed in 2021 following the success of the Leilac-1 project.

The Leilac technology does more than capture carbon; it is a versatile decarbonisation tool. The technology is designed to reduce and eliminate fossil fuel emissions by switching to alternative and clean fuels, and operate with low-carbon material feedstocks. The hybrid-fuelled i-Leilac solution aims to deliver reduced operating costs for cement and lime plants that use a flexible combination of electricity and combustion to heat their process, as well as unlock new revenues in return for the provision of balancing services to electricity grids.

BENEFITS

- The Leilac technology aims to deliver the lowest-cost decarbonisation solution for cement and lime.
- Leilac’s core process is designed to be powered by a range of conventional and low carbon fuel sources.
- The core process can be powered by electricity, enabling electrified industrial heating for cement.
- i-Leilac is designed to be grid-integrated and dual-purposed as a grid load balancing unit.
- Leilac’s calciner tubes can process supplementary cementitious materials (SCM’s), such as calcined clays.
- In some scenarios, the technology may de-bottleneck production, increasing overall plant capacity.
- Leilac’s core technology is proven, with multiple pilots delivering more than 12,000 hours of operation.

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	Cement, Lime, and Direct Air Capture				

TECHNOLOGY DESCRIPTION

Leilac’s core technology uses indirect heating to calcine limestone (CaCO₃). Externally-heated tubes pyroprocess raw materials into a decarbonated product. This unique approach re-engineers the process flows of a conventional cement calciner; instead of a direct hot gas, heat exchange, the Leilac tube works by physically isolating the heating process from the raw materials. The CO₂ released directly from the raw material during calcination is kept pure from its point of release and remains uncontaminated by flue gases or air. The Leilac technology therefore enables unavoidable process CO₂ to be simply captured as a high purity stream (proven at 98% at Leilac-1), without additional chemicals, solvents, or energy-intensive processes to separate gases from gases.

LOW-COST, HIGH-PURITY CARBON CAPTURE

When converting cement raw meal into clinker, or when converting limestone into quicklime, CO₂ is inevitably released during the calcination process. This is a direct and unavoidable result of the chemical reaction $\text{CaCO}_3(\text{s}) \rightarrow \text{CaO}(\text{s}) + \text{CO}_2(\text{g})$.

In conventional cement and lime production, this released CO₂ is mixed with combustion flue gases before being released into the atmosphere. The CO₂ released from this process accounts for between 60 and 65% of a cement or lime plant’s facility-wide CO₂ emissions.

In contrast to conventional calciners, the indirect heating method works by keeping the released CO₂ separated from the calciner’s flue gases. The combustion process and the calcination process are physically isolated from one another. The raw material is fed into an inner tube, whilst a combustion system or an electricity source externally heats the tube’s walls. The released CO₂ is then routed to an independent off-take where it can be efficiently captured and compressed, ready for transport, use or storage. The Leilac technology has proven its ability to capture unavoidable process emissions, at the point of their release, converting them into a high purity CO₂ stream (98%). This purity is expected to significantly reduce off-take costs when integrating with regional CCUS networks.

FUEL-FLEXIBILITY

The transition away from fossil-fuels is essential to the deep decarbonisation of the global cement and lime industries. Alternative fuels offer an immediate, low-cost emissions reduction pathway. Clean energy sources such as renewably generated electricity, biomass, and hydrogen can avoid fuel emissions entirely.

Leilac’s indirect heating method separates the fuel source from the chemical reaction. As such, the Leilac technology is compatible with a broad range of fuel sources, including conventional and alternative fuels, as well as electricity. By offering optionality on energy inputs, the Leilac technology is designed to enable a flexible and cost-effective transition away from fossil fuel use.

I-LEILAC: A GRID INTEGRATED, HYBRID-FUELLED APPROACH

Leilac’s hybrid-fuel technology is designed to simultaneously operate on and rapidly shift between combustible fuels and electricity. The technology is being designed to be dynamic and responsive to daily changes in energy markets. This unique feature may enable cement and lime plants to optimise energy operating costs and future-proof their operations.

The ‘i-Leilac’ technology is also designed to function as a grid-integrated load balancing unit, an increasingly valuable service for electricity grids. Its potential to rapidly increase or decrease electricity use on demand, without interrupting production, could enable cement plants to help stabilise electricity grids and create new additional revenue streams in return for grid services.

LOW IMPACT INTEGRATION

The Leilac technology is modular by design. A full-scale Leilac plant consists of multiple Leilac modules, operating in sync but independently. This design allows for flexible, low-risk scale up and integration, potentially carried out module by module. Leilac aims to enable retrofits with minimal to no downtime for the host cement plant.

This multi-module design aims to provide redundancy to the system; if one component fails, others may maintain operations. This aims to support continuous operation alongside staggered maintenance and upgrades.

DIRECT AIR CAPTURE

Leilac and Heirloom have formed a partnership to apply the core Leilac technology to Heirloom’s Direct Air Capture process, which uses limestone as a sorbent for atmospheric carbon dioxide. Leilac will provide its electric calcination and carbon capture technology as a part of all Heirloom Direct Air Capture facilities, including Project Cypress in Shreveport, Louisiana.

BUILDING THE FOUNDATIONS OF A CLEANER FUTURE

At Leilac, we believe that the most effective path to net zero starts with avoiding emissions wherever possible, capturing those that are unavoidable, and removing residual carbon to restore balance.

Our technology reflects these principles in action. By enabling the use of alternative and renewable fuels, we support emissions avoidance. Through our high-purity, low-cost capture process, we offer a practical solution to abate unavoidable process emissions. And through our partnership with Heirloom, we are helping to remove carbon directly from the atmosphere, addressing both current and legacy emissions.

Together, these efforts are designed not just to decarbonise cement and lime, but to help build a more resilient, flexible and sustainable industrial future.



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.

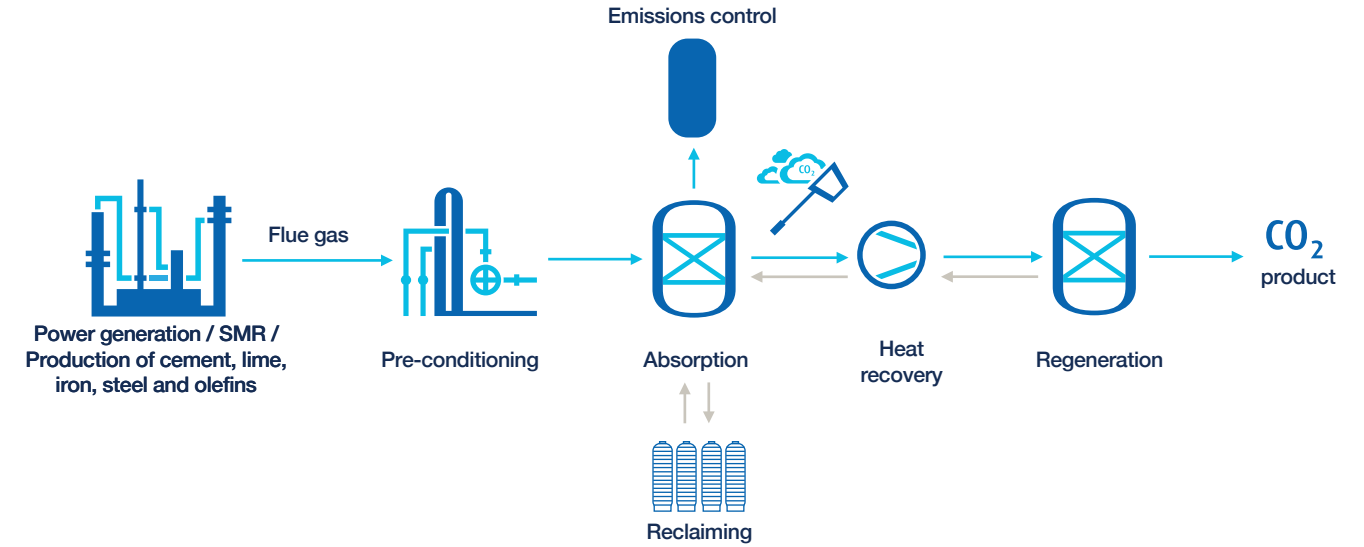
HIGHLIGHTS

- 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

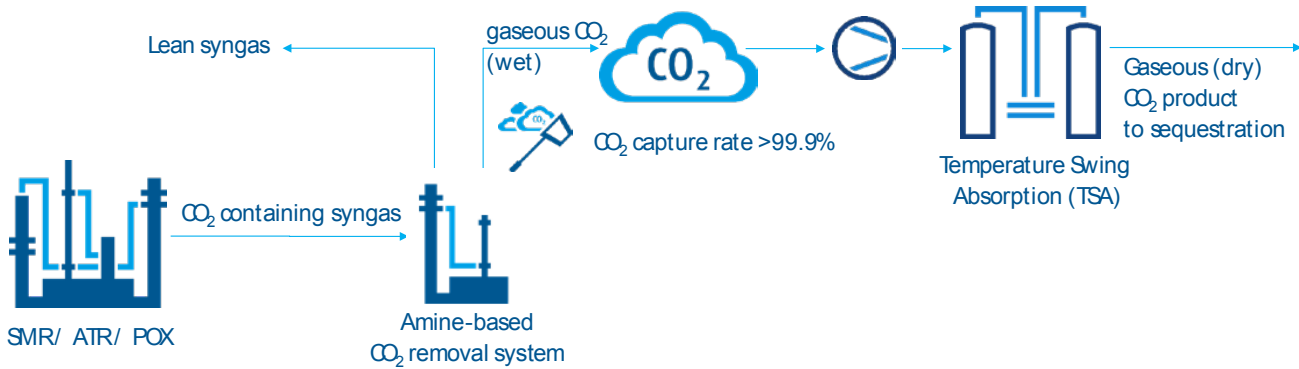


SUMMARY

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 (%)	99.90%
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



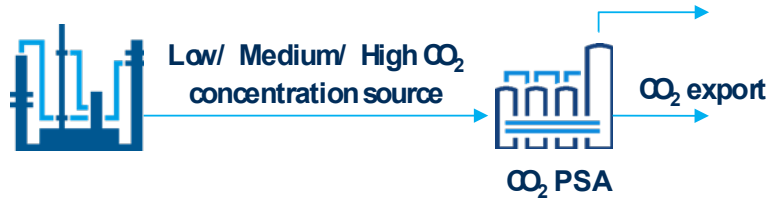
SUMMARY

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

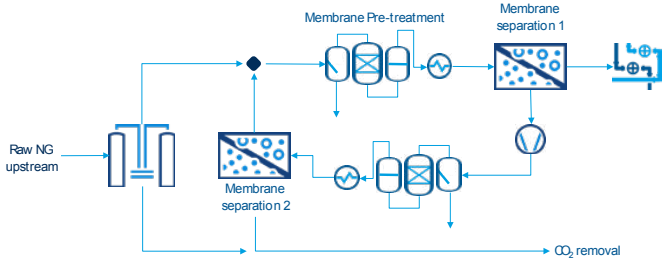


SUMMARY

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 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

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.

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

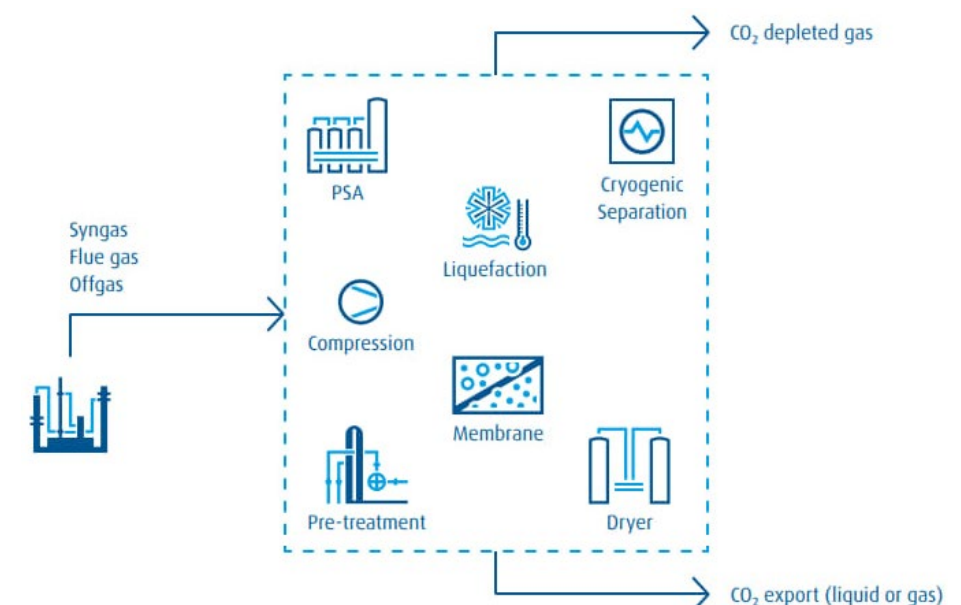
- Linde's in-house technologies are combined for blue hydrogen production, including PSA, TSA, HISELECT® membranes, and cryogenic purification
- Individual concepts for different feed streams in hydrogen production plants
- Flexibility in size and scale, ranging from 100 to more than 10,000 tpd CO₂
-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

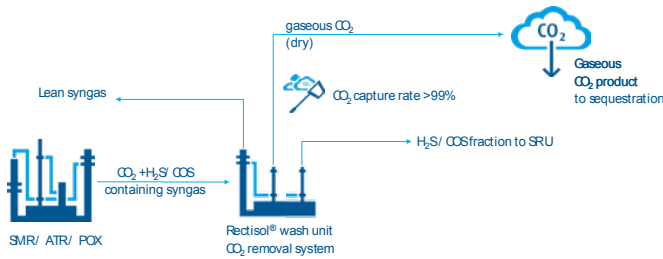


SUMMARY

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

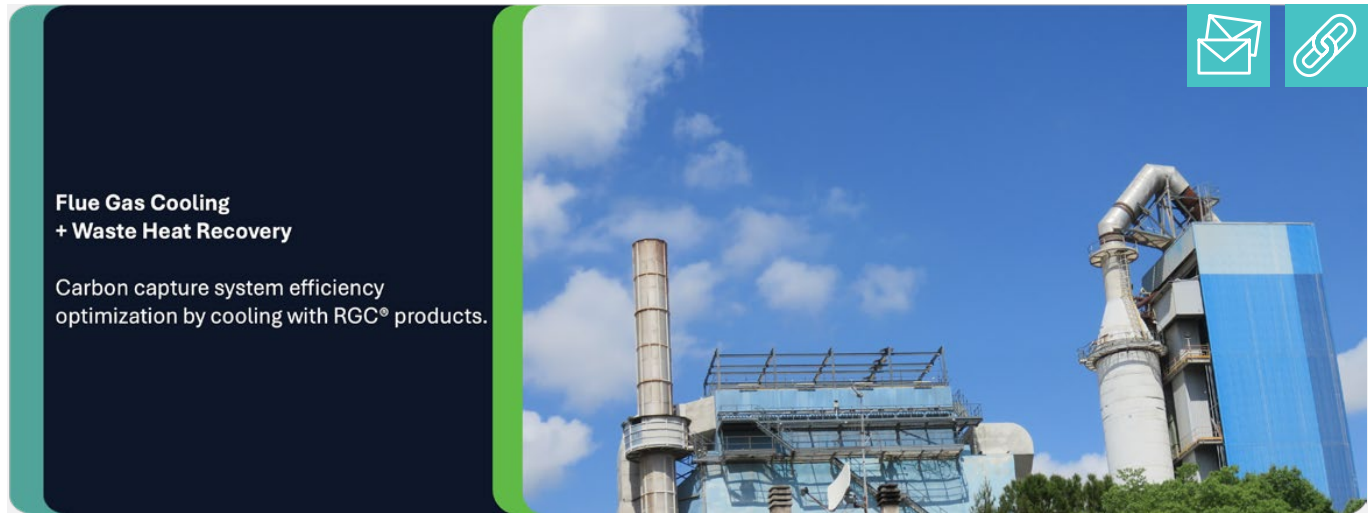


Typical Rectisol process design for CO₂ capture from syngas

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				

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SUMMARY

Since 1923, LJUNGSTRÖM rotary air preheaters have helped reduce global warming by avoiding over 50 billion tons of CO₂ from being released into the atmosphere. In addition to renowned expertise in waste heat recovery and utilisation solutions to improve combustion efficiency, LJUNGSTRÖM technologies are also proven in flue gas pre-treatment applications such as deSulphurization (DeSOx) and denitrification plants (DeNOx).

LJUNGSTROM's RGC® product line builds off this expertise.

A substantial portion of the cooling or the heat rejection equipment associated with a carbon capture plant installation is related to the cooling needs of the DCC (Direct Contact Cooler). LJUNGSTRÖM RGC® heat exchangers are installed upstream of the DCC in the raw flue gas from the plant – supporting removal and utilisation of the sensible heat prior to the DCC.

BENEFITS

- **Size Flexibility:** Operates efficiently in plants of any scale and adapts seamlessly to varying flue gas volumes.
- **Multi-Media Versatility:** Supports a range of applications including gas-to-gas, gas-to-air, gas-to-water, gas-to-oil, and gas-to-steam (HRSG) systems.
- **Ultra-Low or Zero Leakage:** Engineered to deliver minimal leakage tailored to specific application requirements.
- **Compact Footprint:** Reduces construction costs and simplifies installation in confined spaces.
- **Low Pressure Drop:** Minimizes fan workload, thereby lowering overall operational costs.
- **Enhanced Cleanability:** Utilises advanced cleaning technologies to ensure optimal performance in diverse environments and under heavy dust loads.
- **Customizable Duct Connections:** Offers flexible duct solutions designed to meet the unique needs of each project.

KEY PROJECTS

Rotary RGC® Developed from our world leading expertise in Ljungström® air preheater and gas-gas heater technology.

Heat Pipe RGC® Our Heat Pipe RGC® solutions are provided in exclusive collaboration with the world's leading supplier of durable heat pipe heat exchangers for flue gas applications.

KEY DATA

TRL	9	Flue Gas Volumes (Nm3/h)	0.01 - 3.5Mio	Heat Rejection Efficiency	Up to 93%
Source CO ₂ Purity Range	0 - 100%	Pressure Drop (kPa)	0.1 - 1.5	High PM Tolerance	Yes
Number of Commercial Plants	>100	Operating Temperature Range (°C)	25 - 1,000	Modular (Y/N)	Yes
Target Industries	Power Utilities, Oil & Gas, Cement, Lime, Refineries, Waste to Energy, Chemical, Steel, Paper.				

TECHNOLOGY DESCRIPTION

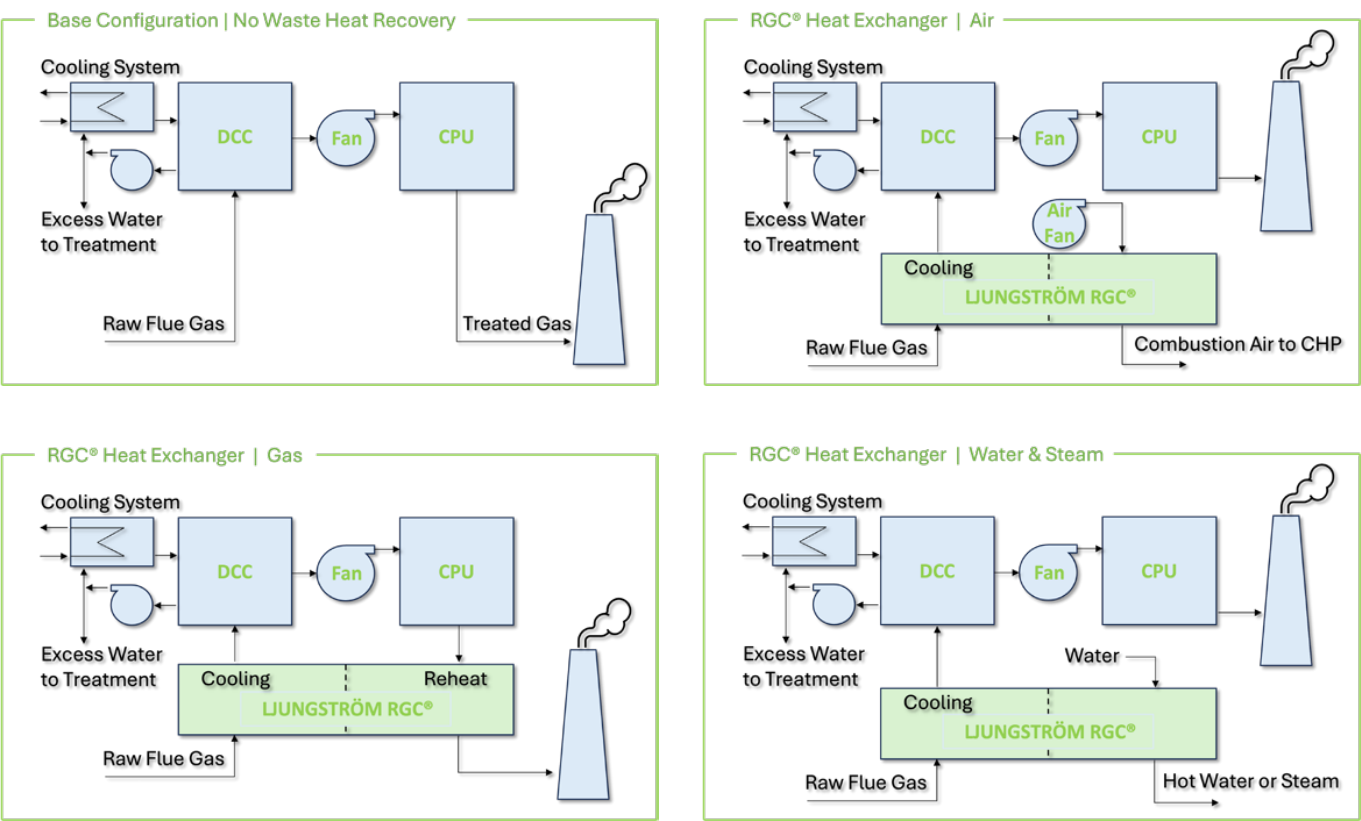


Figure: DCC: Direct Contact Cooler. CPU: CO₂ Processing Unit

LJUNGSTRÖM RGC® HEAT EXCHANGERS

Carbon capture technologies applied to existing plants often face a challenge: the process outlet temperatures are typically too high for direct or cost-effective integration with carbon capture systems. In a standard configuration, a Direct Contact Cooler (DCC) is used to lower the flue gas temperatures to acceptable levels. Introducing a pre-cooling step before the DCC offers significant advantages by reducing both the cost and the size of the DCC's water cooling system.

LJUNGSTRÖM's RGC® Heat Exchanger platform delivers tailored solutions for a variety of projects. Economic benefits increase further when the recovered energy is repurposed elsewhere in the process. With RGC® Heat Exchangers, energy can be efficiently transferred to multiple media including depleted gas, air, oil, and water. Depending on specific project requirements, customers may opt for stack gas reheating, combustion air preheating, or the generation of hot water, oil, or steam.

Illustrative use cases are shown above. Techno-economic analyses have demonstrated significant savings when pre-cooling is applied. Moreover, by reutilizing the recovered heat, a medium-sized carbon capture facility in Europe can achieve annual savings in the seven-digit range while also realizing substantial CO₂ emission reductions.

RGC® PLATFORM ADVANTAGES

With their compact footprint, lightweight design, and flexible duct arrangements, LJUNGSTRÖM's RGC® heat recovery products integrate seamlessly into processes with limited space, all while offering highly competitive investment costs. RGC® products are scalable and suitable for projects ranging from small pilot plants to large-scale power sector applications. Key features include superior thermal efficiency, minimal pressure drops, high availability, and proven cleaning protocols enhance carbon capture efficiency and reduce operating costs.

RGC® products technology has some noticeable benefits to the design of the DCC. First, by significantly decreasing the cooling duty of the DCC, the tower height is reduced, and the pressure drop is lowered. Second, the adiabatic saturation temperature is improved such that the external recycle liquid cooling system can be reduced by as much as 90 percent. Air coolers typically take up a very large space (acres) so this is an appreciable benefit.

In the event of unexpected corrosion or damage, the robust design eliminates the risk of catastrophic failure and avoids the need for immediate shutdown, while maintenance can be conveniently scheduled during regular outages.



SUMMARY

SO₃ can disrupt carbon capture systems, degrading solvents, reducing efficiency, and leading to unintended emissions. Acid gases like SO₃ also accelerate corrosion and equipment fouling, increasing maintenance costs and operational risks.

While CCUS projects often use caustic soda-based scrubbing for SO₂ control, these methods are ineffective against SO₃. LJUNGSTRÖM's SBS Injection™ technology efficiently neutralises SO₃, protecting your system's integrity and performance.

LJUNGSTRÖM provides flue gas evaluations to identify the best SO₃ mitigation strategy for your carbon capture technology and plant layout, ensuring optimal efficiency and long-term reliability.

BENEFITS

Flexibly tailored to process requirements:

- Injection location can be chosen anywhere in the flue gas path based on prevailing process and space requirements.
- Low footprint
- Multiple injection additives possible

Highest removal rates:

- SO₃ >99.9%
- Halogens >60%

Low cost:

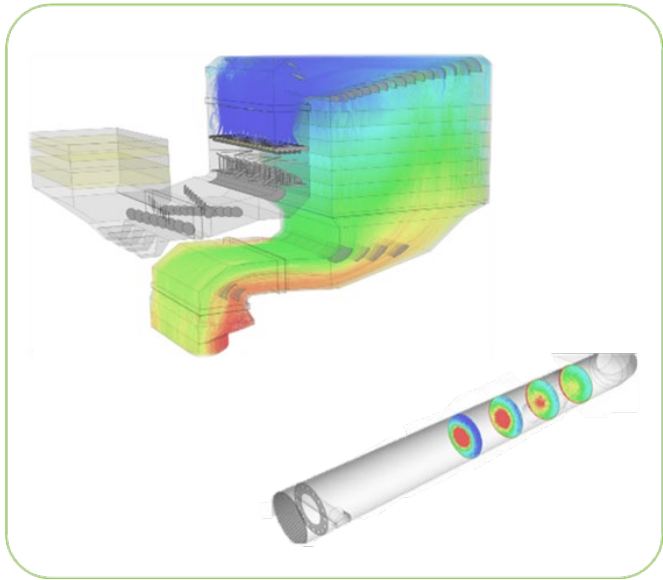
- Lower CAPEX & OPEX when compared to alternatives

Symbiosis with other technologies:

- Beneficial combination with 3rd-party DCC and LJUNGSTRÖM RGC® Products

KEY PROJECTS

CFD - modelling ensures the most advanced operation



KEY DATA

TRL	9	SO ₃ Removal Rate	>99.9%	Achievable SO ₃ Level (ppm)	<0.1 ppm
Source CO ₂ Purity Range	0 - 100%	Operating Temperature Range (°C)	120 - 400	Sorbent Flexibility	Yes
Number of Commercial Plants	>30	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Power Utilities, Oil & Gas, Cement, Lime, Refineries, Waste to Energy, Chemical, Steel, Paper.				

TECHNOLOGY DESCRIPTION

SBS INJECTION™ ACID GAS REMOVAL

LJUNGSTRÖM's proprietary SBS Injection™ technology features a specially engineered lance design that leverages ultra-fine atomization for precise reagent injection. Advanced computational fluid dynamics (CFD) modeling ensures optimal placement of lances and mixing baffles, enabling uniform reagent distribution and intimate contact with the flue gas. This design maximizes SO₃ removal efficiency while minimizing reagent consumption and preventing downstream deposition.

The SBS Injection™ system is highly flexible and simple to install. It delivers industry-leading SO₃ removal performance and is compatible with a range of additives, allowing you to tailor the process to your specific needs while keeping operating costs low.

Because the SBS Injection™ system injects a clear solution, it offers exceptional reliability and control. The solution dries within 0.1 seconds, forming ultra-fine, highly reactive particles that are easily captured by ESPs, baghouses, or wet scrubbers. SBS Injection™ has the only technology proven to reduce SO₃ levels below 0.1 ppm—an essential threshold for the successful operation of carbon capture systems.

In addition to SO₃ removal, the SBS Injection™ process can also mitigate other acid gas contaminants such as halogens and mercury. While carbon capture systems typically include extensive flue gas cleaning, mercury emissions may still exceed regulatory limits. A simple modification to the SBS Injection™ process allows for enhanced mercury reduction to meet even the most stringent environmental standards.

LJUNGSTRÖM - EXPERIENCE THAT COUNTS

Eliminating SO₃ offers a valuable opportunity to enhance the performance of power and industrial systems, while delivering significant economic benefits—including a short payback period and a strong return on investment.

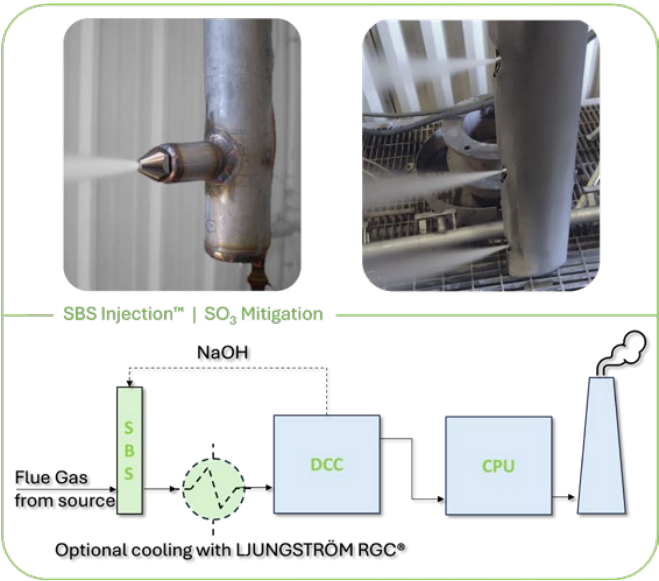
LJUNGSTRÖM's SBS Injection™ process has been successfully implemented on more than 30 power generation boilers and demonstrated in cement plants and refineries. Most installations have consistently achieved SO₃ removal efficiencies of up to 99.9%, all while maintaining low reagent consumption.

With over 20 years of proven operational experience, the SBS Injection system is a commercially demonstrated solution that reliably removes SO₃ and mitigates key challenges associated with carbon capture technologies. These include volatile organic compound (VOC) emissions, solvent degradation, corrosion, and efficiency losses.

In addition, the system enhances energy recovery efficiency and contributes to the safe and effective operation of carbon capture systems.

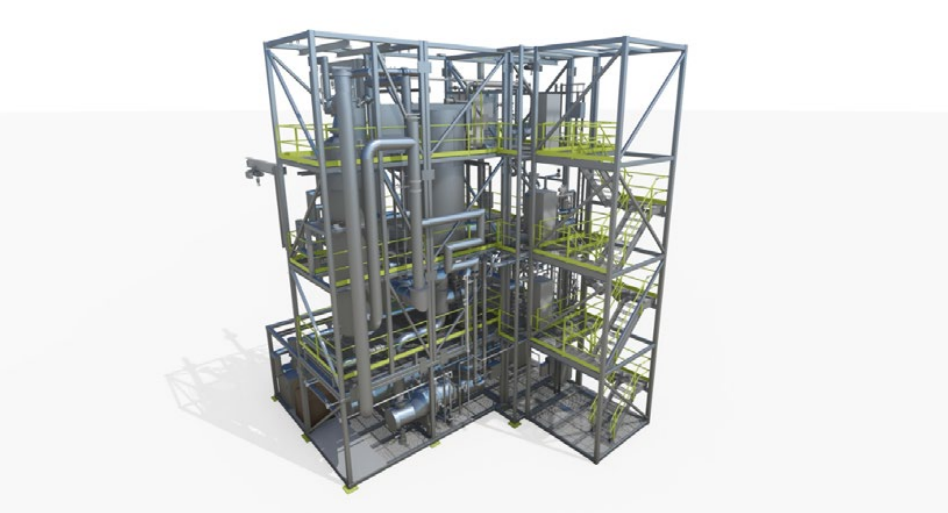
SBS Injection™ is typically installed upstream of the Direct Contact Cooler (DCC), where both the injected reagent and the resulting byproducts are fully removed. Since DCCs commonly use sodium hydroxide as a polishing reagent, any excess from the SBS Injection™ system is effectively neutralised—eliminating waste and improving overall reagent utilisation.

Despite being commercially proven for decades, LJUNGSTRÖM continues to innovate and expand the capabilities of the SBS Injection™ process, including ongoing development for simultaneous NO_x removal.



Stack SO ₃ Emission and Removal Summary				
Plant*	SO ₃ Inlet (ppmv-d, 3% O ₂)	SO ₃ Outlet (ppmv-d, 3% O ₂)	SO ₃ Removal (%)	SO ₂ Control Device
A	32	1.3	ESP	WFGD
B	65	1.6	Venturi Scrubber	WFGD
C	36	1.3	ESP	None
D	66	1.2	ESP	WFGD
E	45	0.2	ESP	WFGD
F	15	0.6	ESP	WFGD
G	44	0.5	ESP	WFGD
H	55	0.3	ESP	WFGD

*Confidential Client



SUMMARY

Mantel Capture, Inc. is pioneering a new class of high-temperature carbon capture technology using molten borates. Mantel’s molten borate technology captures CO₂ at high temperatures (600-800°C) 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 or heat. By reducing capture costs by more than 50% compared to conventional methods, the system is ideal for decarbonising hard-to-abate industrial sectors, including cement, steel, hydrogen production, and 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:** Mantel’s high-temperature operation reduces the energy burden of CO₂ separation, reducing costs by more than 50% compared to amines.
- **Compact footprint:** Mantel’s system is approximately half the footprint of an amines system due to its higher efficiency high-temperature absorption and ability to operate without flue gas pre-cooling 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 CO₂ at high purity, making it suitable for storage or utilisation applications without additional processing.

KEY PROJECTS

- **Pulp & Paper Demonstration:** This first industrial demonstration is located at Kruger's Wayagamack paper mill in Trois Rivières, Quebec. Phase I will be commissioned at 2,000 tpa capture and provide steam to run plant operations. A planned Phase 2 will integrate the system with the site’s lime kiln and increase capture capacity up to 4,000 tpa. This system is currently under construction and is scheduled to be commissioned end of mid 2025.
- **Oil & Gas Deployment:** A 60,000 tpa project at an oil & gas site in Canada has entered the FEED stage with support from provincial funding agencies.
- **U.S. Refinery Feasibility:** Mantel is conducting a DOE-funded feasibility study for a carbon capture system at a refinery in Louisiana, demonstrating the technology’s applicability to oil & gas processing.

KEY DATA

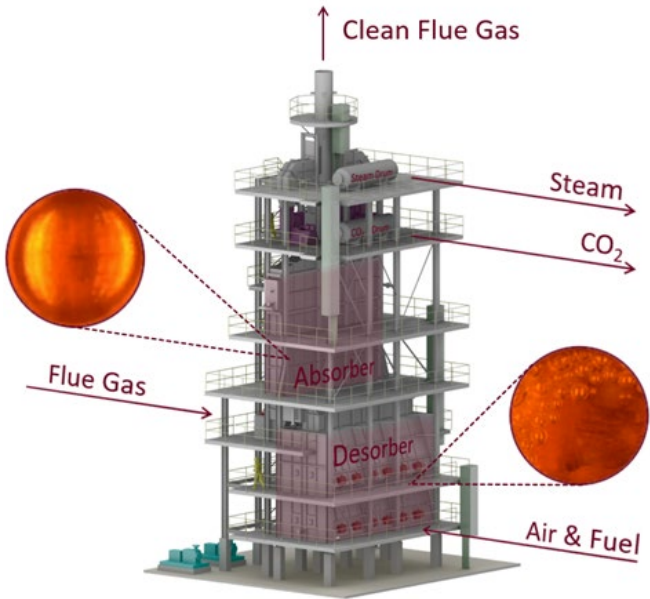
TRL	6	Capture Rate Range (tpd)	150 - 5,000+	Capture Efficiency (%)	95 - 99%
Source CO ₂ Purity Range	1 - 40%	System Energy (GJ/tCO ₂)	0.1	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Pulp & Paper, Oil & Gas, Steel, Cement, Power Generation, Chemicals, Hydrogen, Other Hard-to-decarbonise				

TECHNOLOGY DESCRIPTION

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 inside boilers, kilns, and furnaces. The improved efficiency of high temperature operation comes from utilising the heat of reaction. Capturing CO₂ generates a lot 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.

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 locate the absorber and desorber inside the boiler, increasing thermal efficiency, and reducing 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 & pre-treatment 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 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 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 exhaust 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 in ten countries. MHI's technology has been proven and used on natural gas, fuel oil, and coal-fired exhaust. MHI is working to expand the application of this technology to various power generation facilities such as GTCC, 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 exhaust for many purposes such as Urea, Methanol, EOR and other general usage.
- **Environmentally Friendly:** Improved amine emission reduction system reduces amine emissions by more than 90% compared to conventional systems.
- **Flexible to Gas Load:** Proprietary Auto Load Adjustment Control (ALAC) system smoothly ramps CO₂ production from 50% to 100% in less than 1 hr.
- **Updated Technologies (KS-21™):** Reduced OPEX by lowered amine degradation. Reduced amine emission by stabilized absorbent.

KEY PROJECTS

- **Petronas Fertilizer (1999):** Used to increase production at a urea plant in Malaysia. CO₂ capture from SMR natural gas-fired combustion exhaust gas (capacity: 210 t/d). This is the first CO₂ capture plant to be delivered.
- **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. World's largest delivery record.
- **Ravenna CCS (2024):** Used for injection into a depleted offshore gas field owned by Eni. CO₂ capture from natural gas plant (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 exhaust gas (capacity: 240 t/d). First delivery of Advanced KM CDR Process™.

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)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	16	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

TECHNOLOGY DESCRIPTION

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 exhaust gas of Petronas' fertilizer 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 exhaust gas of coal-fired boilers. Following the durability demonstration tests at 10 t/d (2006-2008) and 500 t/d (2011-2015) in 2016, 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 absorbent (KS-1™) that features low regeneration energy and enables an energy-saving regeneration process by optimising heat exchange between the absorption and regeneration towers, resulting in a significant reduction in energy consumption.

Amine Emission Reduction System

Coal-fired boiler exhaust gas contains aerosols such as soot and SO₃, which increase the loss of absorbent. We have reduced the loss of absorbent by 90% 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 from 50% to 100% in one hour. Even if the CO₂ concentration in the exhaust 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 exhaust gas after combustion of coal for general industrial applications such as urea, methanol, and EOR.

ADVANCED KM CDR PROCESS™ FEATURES

MHI and KEPCO have developed a new absorbent, 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 absorbent durability with lower amine emissions than KS-1™ were confirmed.

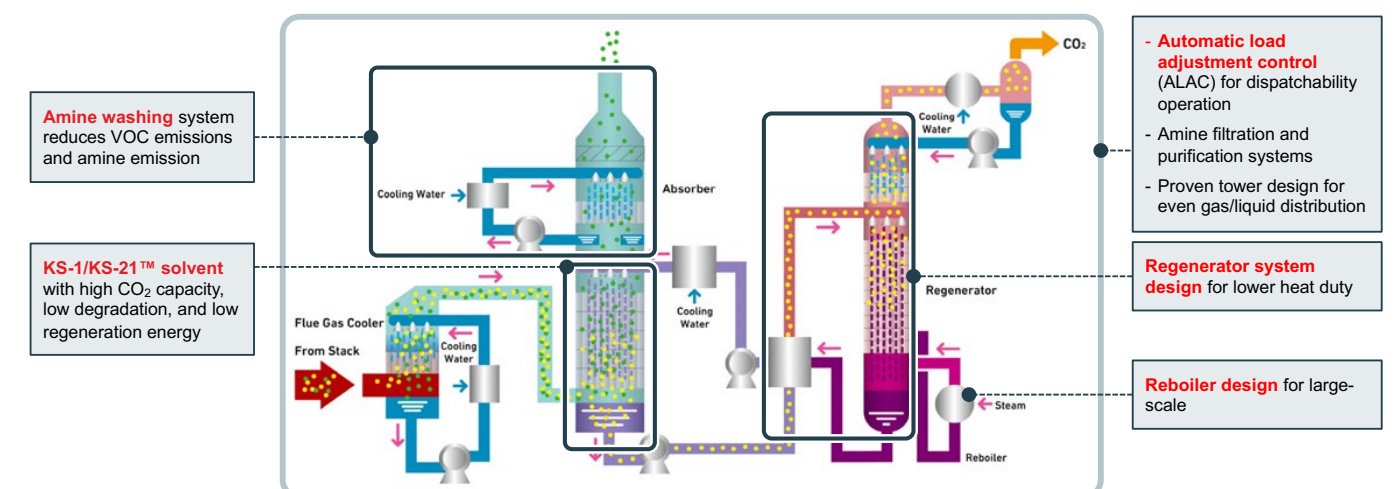
Parameters Relative to KS-1™	KS-1™	KS-21™
Volatility	100	<70
Thermal Degradation rate	100	<50
Oxidation rate	100	<50
Heat of absorption	100	Slightly lower

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.

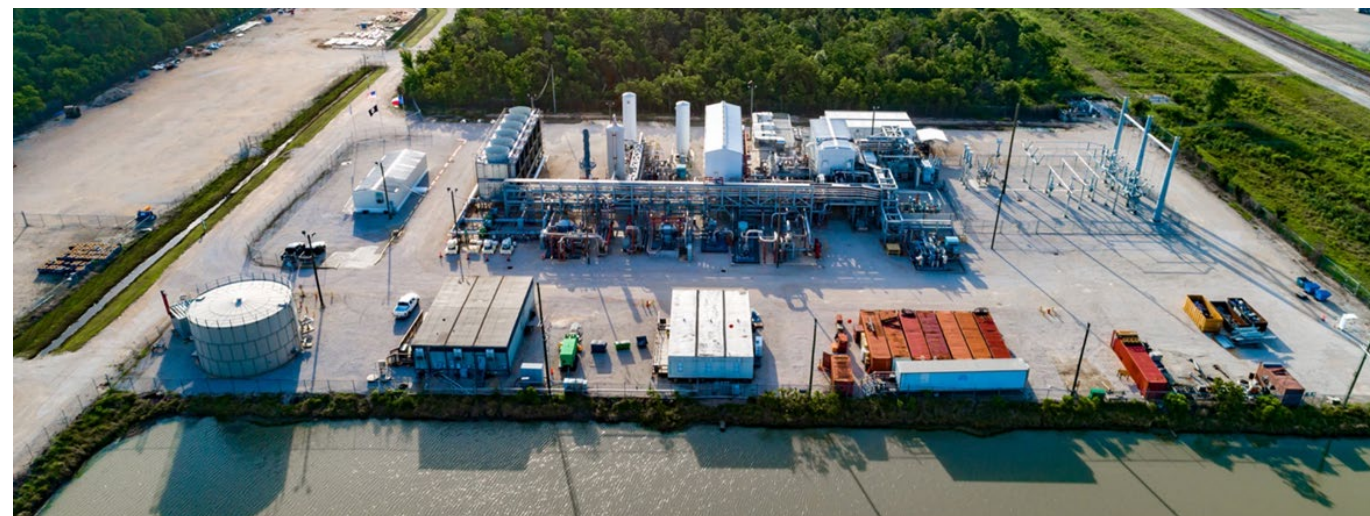
COMPACT CO₂ CAPTURE SYSTEM: CO₂IMPACT™ SERIES

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.





NET POWER NET POWER CYCLE



SUMMARY

Net Power is an energy technology company developing its proprietary Net Power Cycle, which transforms natural gas into clean firm power. Net Power's technology combines oxy-combustion and a supercritical CO₂ (sCO₂) power cycle to deliver on-demand natural gas power while capturing nearly all carbon emissions. At scale, this technology can catalyze the decarbonisation of the electric system by providing ultra-low emission dispatchable power.

Net Power's momentum is built on more than a decade of milestones, including key investments, construction and testing of a 50 MWth demonstration facility, and the ongoing development of its first commercial facility in West Texas known as "Project Permian." During that time, the company also established long-term partnerships with key process equipment suppliers to support the development of Project Permian and product commercialization. Net Power continues to secure such supply agreements as it builds out its supply chain network to enable rapid deployment of future plants.

BENEFITS

The utility-scale Net Power plant is being designed to provide the following benefits:

- **Deliver Clean Power:** Net Power plants are designed to capture CO₂ at unit rates >97% across the operating spectrum.
- **Support Reliable Operations:** Net Power provides 24/7 dispatchable, baseload power with rapid ramp rates and low turn-down capabilities.
- **Produce Affordable Energy:** Net Power's goal is to be the lowest cost form of clean, firm power at a reasonable premium to carbon-emitting alternatives.
- **Utilise Existing Infrastructure:** Net Power plants can leverage existing pipeline and electricity transmission networks for planning and operations.
- **Scalable:** Net Power is creating a standard plant design enabling rapid deployment through modularization and the ability to stack multiple plants together.
- **Harness the Value of Carbon:** The Net Power Cycle inherently captures high-purity, pressurized CO₂ for sequestration or utilisation in eFuels, enhanced oil recovery, synthetic chemicals, and product integration.



Net Power's La Porte Test Facility

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	1	Modular (Y/N)	~
Target Industries	~				

TECHNOLOGY DESCRIPTION

TECHNOLOGY DEVELOPMENT

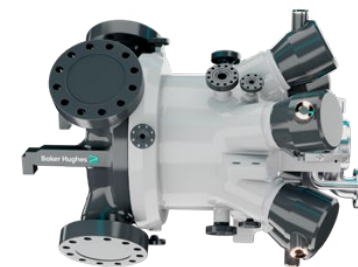
Net Power has developed its technology during more than a decade of research, development, and operational demonstration. From the beginning, the Net Power Cycle was designed to overcome the challenges faced by both conventional and renewable energy technologies pursuing grid-scale decarbonisation.

Net Power utility-scale projects are targeting a net electric output of 200 - 300 MW of clean, dispatchable energy alongside approximately 800 - 900 Mtpa of high-pressure, high-purity CO₂. Electricity output is designed to have competitive ramping with full carbon capture across the operating spectrum. Meanwhile, criteria pollutants are avoided, and CO₂ emissions are inherently captured.

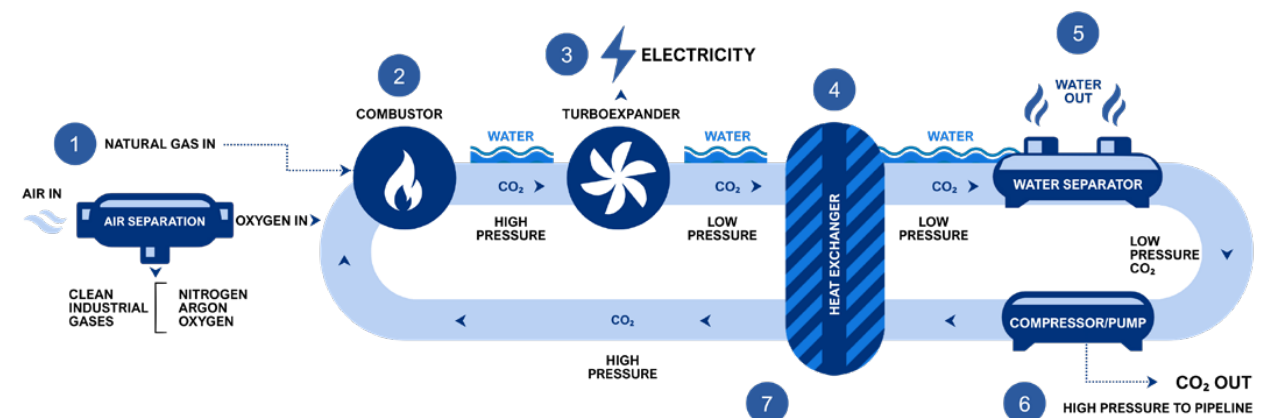
LA PORTE TEST FACILITY

To demonstrate the Net Power Cycle, the company designed and built a test facility in La Porte, Texas. The facility, commissioned in 2018, covers five acres and has performed over 1,500 operational hours since 2018 and an additional 140 fired hours since recommencing operations in October 2024 testing Baker Hughes combustion technology.

The testing has included start-up, shutdown, and transient/excursion tests at key operating points. This involved building CO₂ inventory, shedding CO₂ inventory, verification of process chemistry, validation of control and safety systems, operations of pumps and compressors, and testing of process stability and controllability. The facility has also successfully exceeded numerous utility-scale plant specifications, including turboexpander inlet temperature and balance of plant operating pressures. In late 2021, the facility achieved synchronization with the ERCOT grid.



Baker Hughes Demonstrator turboexpander model



Cautionary Note Regarding Forward-Looking Statements and Projections
Certain statements in this report may constitute "forward-looking statements" within the meaning of Section 27A of the Securities Act of 1933, Section 21E of the Securities Exchange Act of 1934 and the Private Securities Litigation Reform Act of 1995, each as amended. Words such as "believes," "expects," "intends," or other similar expressions may identify forward-looking statements. Forward-looking statements involve known and unknown risks, uncertainties and other factors. These factors, risks and uncertainties include, but are not limited to, those described under the headings "Risk Factors" and "Cautionary Note Regarding Forward-Looking Statements" in the Company's Annual Report on Form 10-K for the year ended December 31, 2024 and in its other filings made with the SEC from time to time, which are available via the SEC's website. Forward-looking statements speak only as of the date they are made. Readers are cautioned not to put undue reliance on forward-looking statements, and NET Power assumes no obligation and does not intend to update or revise these forward-looking statements. NET Power does not give any assurance that it will achieve its expectations.

Further equipment validation efforts are currently ongoing at the La Porte test facility in conjunction with Baker Hughes. The facility has achieved over 140 fired hours of operation since the 2024 testing campaign began and has exceeded cycle pressures achieved previously. Testing is expected to continue through 2025 in parallel with other commercialization endeavors.

KEY TECHNICAL PARTNERS

Net Power is creating the ecosystem of technology partners across the supply chain to scale up future deployments. Net Power established a Joint Development Agreement with Baker Hughes (turbomachinery, pumps, compressors), a strategic supply agreement with Lummus Technology (heat exchanger). Net Power selected Zachry Group to perform the FEED study for the first utility-scale plant. Zachry Group is intended to be the first EPC Partner licensed by Net Power. This suite of partnerships enables Net Power to develop not only the first utility-scale project, but also to create the basis for a standardized plant design for future plants.

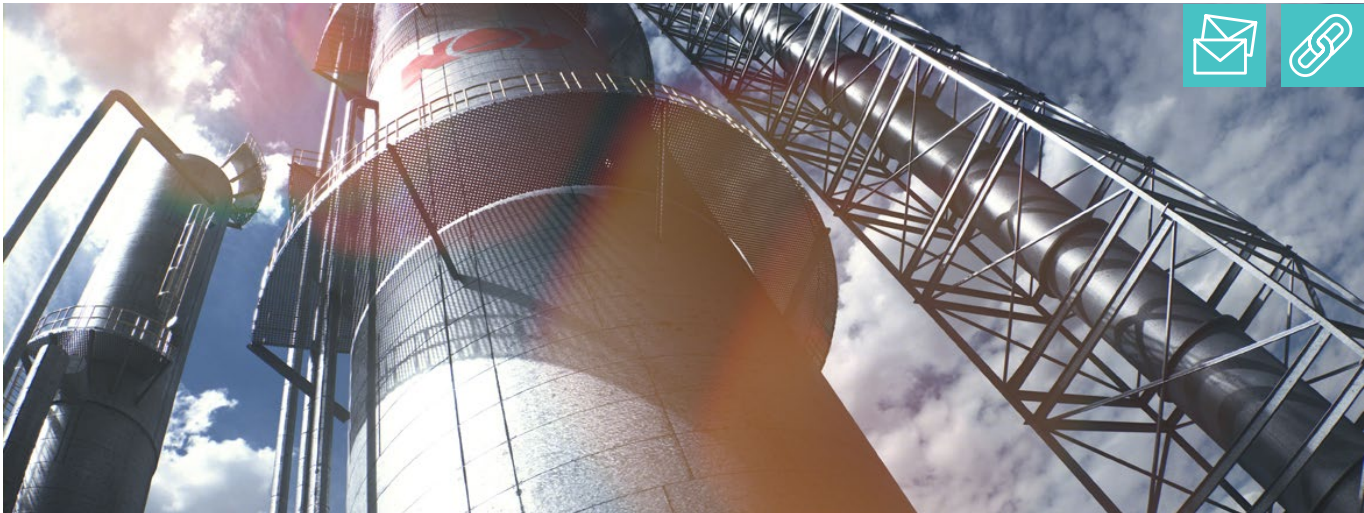
NEXT STEPS

In 2024, Net Power completed FEED for its first utility-scale plant, Project Permian. The plant is targeted to inherently capture CO₂ at unit-wide rates above 97% and utilise operating CO₂ transport and subsurface infrastructure. The captured CO₂ from this project will likely be used for enhanced oil recovery (EOR) but future projects may sequester via both Class II or Class VI wells. The successful deployment of Net Power's first utility-scale plant will pave the way for other commercial projects, including those already in development. In 2025, Baker Hughes and Woodside Energy announced a Technology Development Agreement to explore the commercialization of an industrial-scale sized power plant using Net Power's technology.

Net Power is uniquely positioned to deliver clean firm power and has established the partnerships and pathways to deliver on this mission. Net Power has successfully demonstrated its technology at the 50 MWth scale and will soon deliver its first utility-scale facility. The company, along with its commercial and technical partners, are accelerating the energy transition and the CCUS market.



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				

TECHNOLOGY DESCRIPTION

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 maximize 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.



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

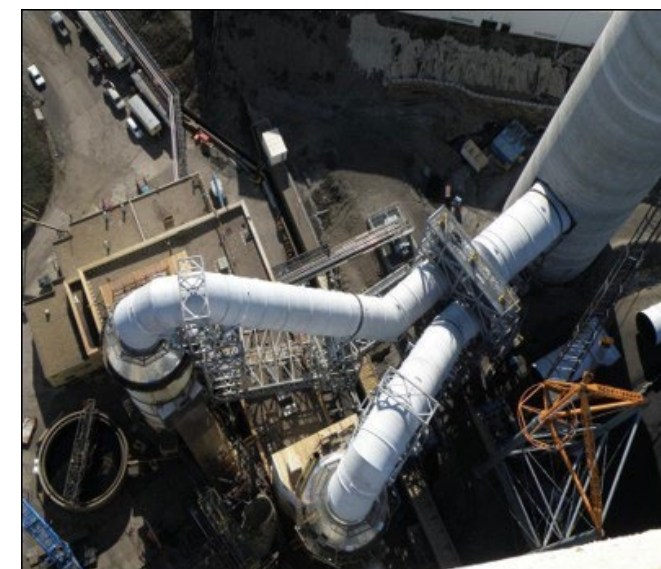
TECHNOLOGY DESCRIPTION

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.

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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.



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.

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

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.



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.

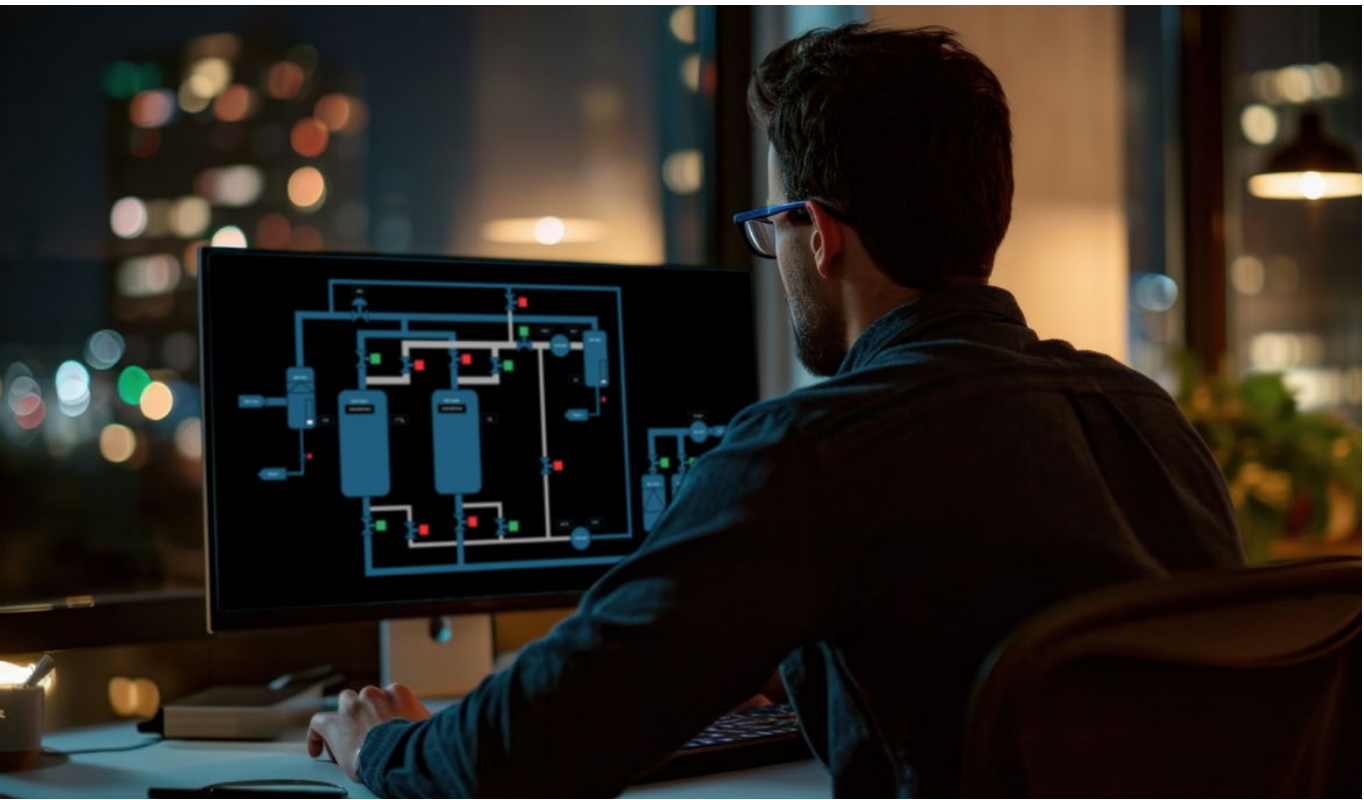
Elevated oxygen in the CO₂ stream must be removed before transport to meet pipeline specifications. NOV's CO₂ deoxygenation process removes oxygen from CO₂ via a catalytic bed with hydrogen. The CO₂ reacts with hydrogen to form a water byproduct. NOV provides integrated deoxygenation and dehydration 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.



novonesis

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)

TECHNOLOGY DESCRIPTION

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 catalyze 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 catalyzed 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 standardized, 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.



SUMMARY

Nuada is a carbon capture solutions provider poised to decarbonise heavy industries through its next-generation point-source capture technology that redefines carbon capture and addresses the energy, cost, and integrational challenges of conventional solutions. 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. While the technology has been successfully pilot-tested in cement and waste-to-energy facilities and further demonstration projects have been lined up, Nuada is planning the first commercial application of its proprietary MOF-VPSA 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:** 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.
- **MLC’s Lime Facility Missouri, US:** Nuada and MLC partnered to demonstrate net-zero lime production at MLC’s Ste. Genevieve (US) facility using Nuada’s carbon capture system to cut CO₂ emissions by 95%.

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				

TECHNOLOGY DESCRIPTION

Nuada’s patented carbon capture process combines the unique properties of a bespoke MOF sorbent material with vacuum technology. This innovative combination distinguishes Nuada’s approach 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

Nuada’s fully electrified EoP process 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.

Nuada’s compact and modular capture process affords 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 the cement 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. Building on these early successes and the inherent scalability of the technology, Nuada is developing its first commercial-scale MOF-VPSA capture plant to be deployed at an energy production facility.





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 Contactor (MBC). This modularised technology seamlessly integrates the strength of solvent-based absorption with the adaptability of membranes. MBC's innovative design achieves 50% reduction in the overall system volume, marking a substantial improvement over conventional carbon capture technologies. More than just its size, the MBC signifies impact, offering new avenues for industries tackling decarbonisation 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 the 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 scalable design, allowing seamless adjustments to match the unique requirements of our clients. MBC adaptable nature ensures flexibility by catering to clients' evolving operational needs.
- **Competitive Cost to Capture:** Lower compression cost due to high regeneration pressure up to 5 barg, and lower solvent circulation rate up to 30%, as first of its kind modular technology. Aimed at achieving CO₂ capture for a competitive cost of US\$30-50 per tonne, MBC ensures maximum value for every investment.
- **Confronting Challenges with Innovation:** By segregating the solvent and gas phases, MBC effectively mitigates

foaming issues, minimising the need for anti-foam agents. By having a differential pressure control system, this not only cuts operational costs but also extends membrane lifespan, guaranteeing sustained performance over time.

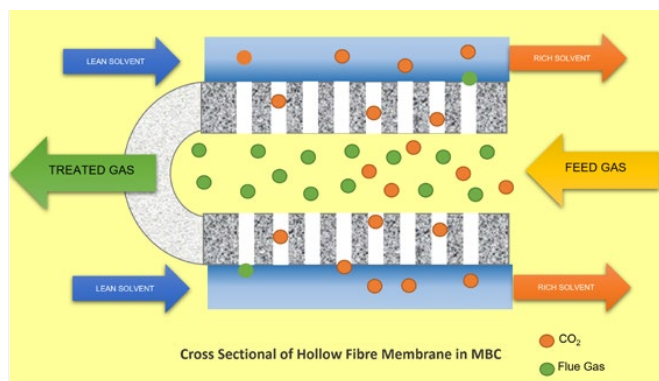


Figure 1: Cross Section of Hollow Fibre Membrane in MBC

KEY DATA

TRL	6	Capture Rate Range (tpd)	10 - 600	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	3 - 30%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	<2.9
Number of Commercial Plants	~	Number of Pilot Plants	4	Modular (Y/N)	Yes
Target Industries	Refineries, Hard-to-abate industries (Cement, Steel, Chemicals and Power & Gas Plants)				

TECHNOLOGY DESCRIPTION

Carbon Capture and Storage (CCS) technology plays a critical role in combating climate change. Despite its potential benefits, the widespread adoption of CCS faces several challenges. Traditional CCS systems often 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 be costly and disruptive, making it a less attractive option for many businesses.

PETRONAS' innovative Membrane Contactor technology is poised to revolutionise the CCS landscape. With a remarkable >20-fold increase in mass transfer area compared to conventional systems, this innovation is designed to deliver high operational efficiency. This enhancement results in a compact and efficient separation system boasting a remarkable 75% reduction in height, 40% reduction in weight, and impressive cuts of 30% in solvent usage. Going beyond its impressive physical characteristics, PETRONAS' modular technology offers scalability and operational simplicity, effectively addressing common challenges like flooding and foaming.

Its versatility, demonstrated by its compatibility with a wide range of solvents, allows it to be tailored to the specific needs of different markets. PETRONAS and Dalian Institute of Chemical Physics (DICP) has taken innovation a step further by enhancing the CO₂ separation performance, boasting superior absorption capabilities, which has a capture efficiency of more than 95%. This breakthrough results in reduced solvent usage and a 25% decrease in regeneration energy consumption, compared to conventional amine packed bed column system.

PETRONAS' proprietary technology incorporates a suite of design enhancements aimed at driving down the cost of CO₂ capture. From shorter MBC columns to streamlined solvent circulation and integrated inter-cooler heat exchanger designs, every aspect is carefully designed for maximum efficiency and cost-effectiveness.

In a landscape where sustainability and economic viability are non-negotiable imperatives, PETRONAS leads the change with transformative CCS solutions, setting new benchmarks for environmental responsibility 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.

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 lean amine solvent. Gas flows into the membrane tube side counter-current with semi-lean solvent which is fed into the shell 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; while the CO₂ rich amine is heated and sent to the MBC regenerator. Heat is added in the reboiler to favour the release of the absorbed CO₂. Two streams leave the desorber: the CO₂ rich gas stream which can either be sequestered to storage or utilised to a higher value product, and the lean amine. The 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.

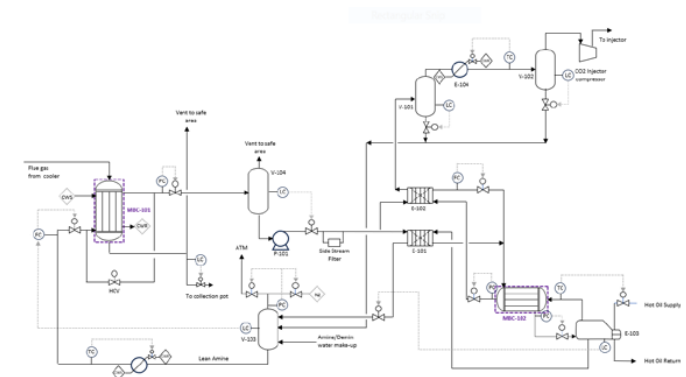


Figure 2: PETRONAS MBC Flue Gas Process Flow Diagram

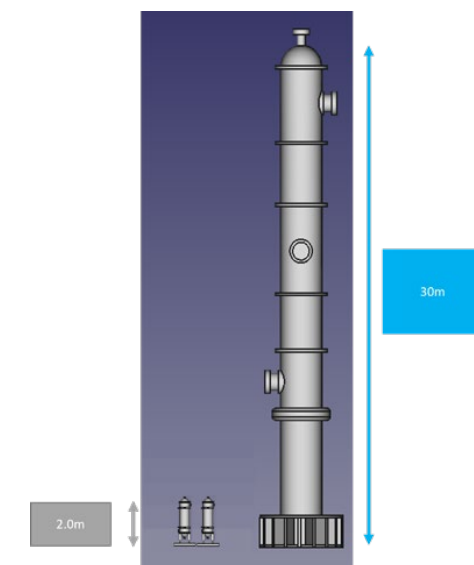
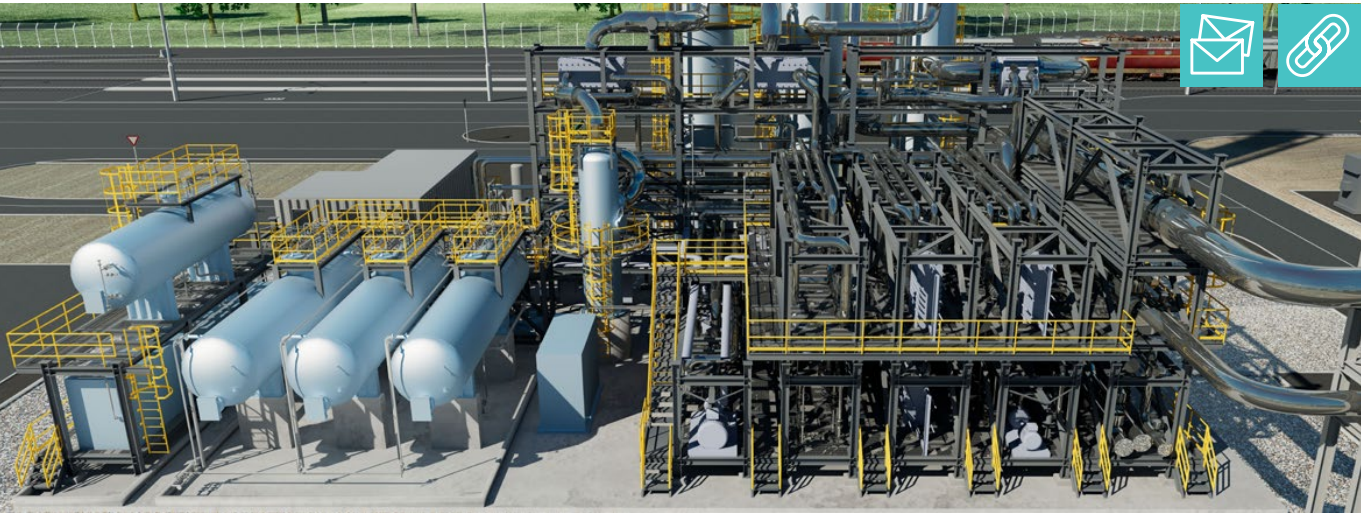


Figure 3: MBC Comparison with the Conventional Column Height

PROOF POINT: PETRONAS'S CARBON CAPTURE DEMO PROJECT.

MBC Capture technology is currently being deployed for Carbon Capture demonstration project at one of PETRONAS's facilities, with a capacity of 10 TPD, a significant stride towards embracing low-carbon solutions. We are in the process of securing a 200 TPD carbon capture project at a local steel plant to mitigate their CO₂ emissions. 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, prioritising emission reduction at its core operations.



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)

TECHNOLOGY DESCRIPTION

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.

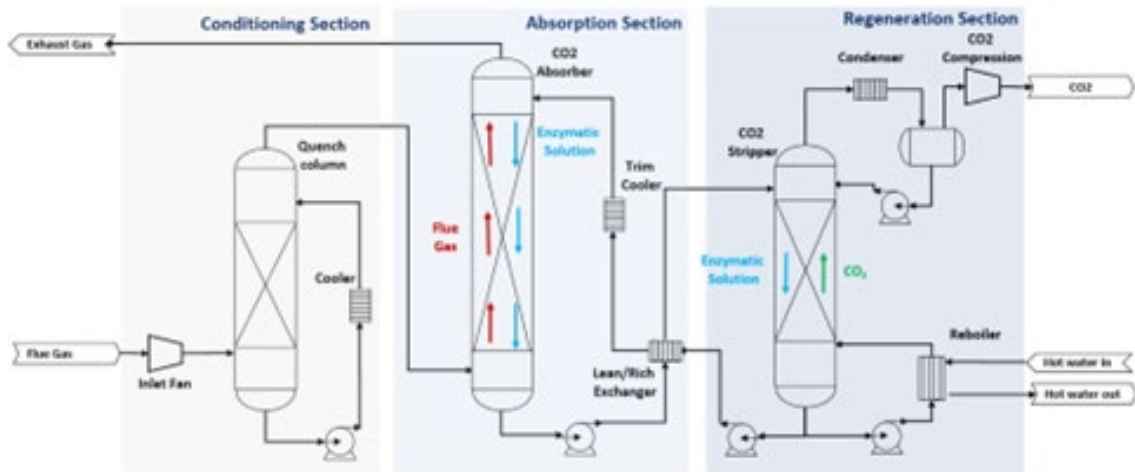
BLUENZYMETM : REVOLUTIONIZING RISK MANAGEMENT

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 offer a leading, amine based, high-capacity carbon-capture technology, ADIP ULTRA. ADIP technology is deployed at more than 500 Shell and non-Shell sites worldwide and has established an enviable record for cost-effective deep CO₂ removal in the natural gas sector. ADIP ULTRA, the latest development, uses an optimised solvent formulation and an improved design based on years of operational learnings. With the latest-generation column internals (Shell Turbo Trays), this technology can maximise CO₂ capture and meet deep specifications for the treated gas while optimising solvent circulation and regeneration duty.

BENEFITS

The Shell ADIP ULTRA pre-combustion gas-treating process cost-effectively treats gases containing high CO₂ levels. It is proven for CCS at a 1-million tonnes/year CO₂-capture scale and, compared with conventional process line-ups, it can help to:

- reduce capital cost through the latest-generation column internals (Shell Turbo Trays) in the absorber;
- low regeneration energy requirements determined using a highly enhanced modelling capability based on many years of operating experience and data;
- availability in advanced energy efficient line-ups that reduce capital and operating costs, depending on the treated gas specifications and application;
- a solvent that is robust to foaming upsets and does not suffer from any degradation, which leads to zero waste from the process; and
- a noncorrosive, nontoxic solvent.
- reduce equipment costs by up to 30%;
- cut regeneration energy requirements by up to 30%; and
- achieve deeper CO₂ removal.

KEY DATA

TRL	9	Capture Rate Range (tpd)	100 - 3,000+	Capture Efficiency (%)	99.5%+
Source CO ₂ Purity Range	1 - 30 vol%	System Energy (GJ/tCO ₂)	Design Specific	Specific Regen. Energy (GJ/tCO ₂)	Design Specific
Number of Commercial Plants	>15	Number of Pilot Plants	N/A	Modular (Y/N)	Yes*
Target Industries	Natural Gas and LNG, Hydrogen Manufacturing (including Blue H ₂) and Refining				

* For smaller capacities of around 200-300 ktpa

KEY PROJECTS

Quest 1-million-t/y CCS project

The Scotford upgrader in Alberta, Canada, generates CO₂ during hydrogen manufacture. As part of the Quest CCS project, Shell's ADIP ULTRA technology captures CO₂ from the three hydrogen manufacturing units' process gas streams. The captured CO₂ is then dehydrated and compressed before being transported about 75 km by pipeline and injected and permanently stored 2 km underground. The facility has a proven CO₂-capture capacity of over 1 million tonnes/year and has captured more than 8.5 million tonnes of CO₂ since coming online in 2015. The facility has better than projected reliability, cost and storage performance, and greater than 99% uptime. Its operating cost is approximately \$25/t of CO₂ and it would cost about 30% less if built today.

TECHNOLOGY DESCRIPTION

ADIP technology dates to the 1950s. In 2000, ADIP-X technology was introduced; this featured a significantly upgraded solvent that unlocked a step change in CO₂ removal capability. The latest generation of this arrived in 2017 with ADIP ULTRA, which has several enhanced design features, compared with previous-generation technology, that further reduce the cost of CO₂ removal. These include a shorter absorber column, reduced solvent circulation, a slimmer regenerator and a smaller reboiler (Figure 1).

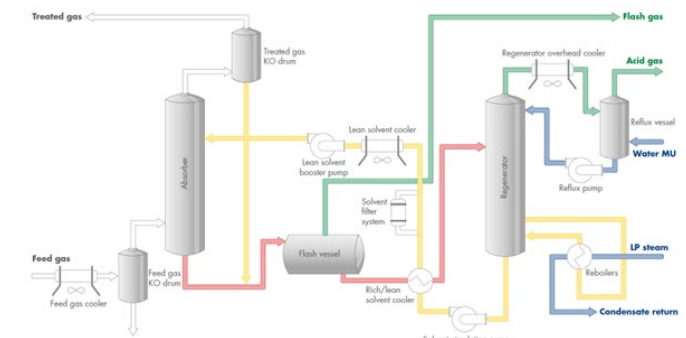


Figure 1. The Shell ADIP ULTRA process.

Combining ADIP ULTRA technology with Shell's new absorption column internals, Shell Turbo Trays, can further enhance process performance. At the column scale, liquid and gas flow counter-currently, that is, gas moves up while the liquid solvent moves down. However, on each tray within each element, gas and liquid flow co-currently within multiple contacting boxes before being separated effectively (Figure 2). Contact between the gas and the liquid is increased significantly, which enables higher mass transfer rates. The net effect is to increase the hydraulic limits of the system, which means operators can process higher CO₂ concentrations and increase capacity by up to 80%, or reduce the column diameter by up to 35% and the weight by up to 50%.

ADIP ULTRA technology uses two amines, methyl diethanolamine (MDEA) as the main reactant and piperazine as the accelerator, and water. It can help to reduce the capital and operating costs of grassroots plants and revamps owing to the solvent's high capacity for CO₂ and its low circulation rate compared with using aqueous MDEA. ADIP ULTRA solvent can facilitate efficient and stable operations owing to its characteristics of low levels of hydrocarbon solubility, foaming, fouling, corrosion and degradation.

The line-up can be varied, for example, using a hot flash instead of the regenerator, depending on the CO₂ removal requirements. This line-up is fully de-risked and part of the Shell Blue Hydrogen Process.

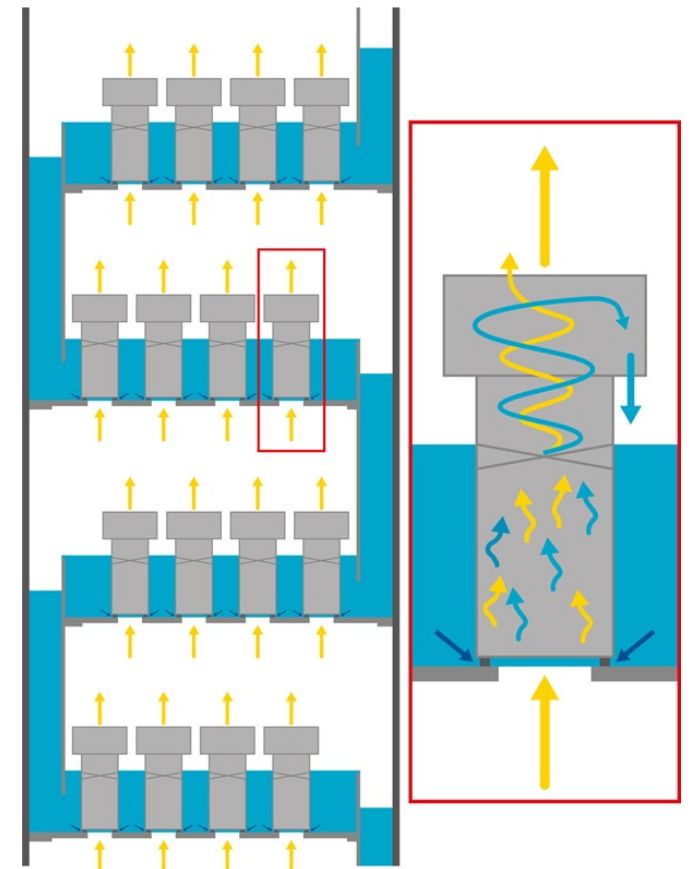


Figure 2. Increased capacity from Shell Turbo Trays.

PORTHOS CCS PROJECT

In September 2021, a final investment decision was made to build an 820,000 tonnes/year biofuels facility as part of the transformation of Pernis refinery, the Netherlands, into the Shell Energy and Chemicals Park Rotterdam, one of five global energy and chemical parks. Once built, the facility will be among the biggest in Europe to produce sustainable aviation fuel and renewable diesel made from waste. Part of the CO₂ emissions from the manufacturing process will be captured using Shell's ADIP ULTRA technology and stored in a depleted North Sea gas field as part of the Porthos CCS project. Final investment decision for Porthos CCS project taken in Oct 2023. Construction activities have started in Jan 2024. Expected to be in operation in 2026.



SHELL & TECHNIP ENERGIES ALLIANCE

CANSOLV* CO₂ CAPTURE TECHNOLOGY



SUMMARY

Shell Catalysts & Technologies, in partnership with Technip Energies, offer a leading, amine-based, high-capacity post-combustion carbon capture technology, CANSOLV* CO₂ Capture System, that is robust and proven, and has an established record of performing cost-effectively in a range of industries. Learnings and expertise developed from 10 years of commercial, at scale, operational experience translate to a robust continuous innovation program and amine technology expertise.

Technip Energies support integration of CANSOLV* CO₂ Capture System into both new build and existing plants. With a strong focus on optimum heat and energy integration, intelligent use of space and tie-ins, enhanced constructability and construction methodologies and project management excellence, Technip Energies ensure the best possible application of CANSOLV*™ System for each facility. The alliance is engaged with the world's largest CCS projects and has secured many competitive FEED and technology selection wins.

BENEFITS

- **Proven track record.** Proven performance in large-scale CCS applications, including 10 years' of continuous CO₂ capture operation from the landmark SaskPower station.
- **Superior solvent management.** SC&T is an established world-class partner for solvent management as required by CCS projects, i.e.: technical services, environmental permitting support, supply chain management, solvent performance, etc;
- **Adaptable.** Highly adaptable for retrofit and greenfield projects, plus a wide variety of plant sizes and industrial applications.
- **Cost effective.** Cutting-edge performance via minimum parasitic energy consumption, fast kinetics and low volatility, combined with modularised approaches and value engineered design to reduce capital and operating costs.

KEY PROJECTS

- **BP Net Zero Teesside Power, UK:** Final Investment Decision was announced on NZT Power, a project to be delivered by the Technip Energies and GE Vernova consortium, including Balfour Beatty, with Shell as licensor for CO₂ capture of 2 mtpa at one of the world's first commercial-scale gas-fired power stations with integrated CCS.
- **Heidelberg Materials, Canada:** The alliance has delivered a FEED to capture 1.5 mtpa CO₂ for what would be the cement sector's first full-scale CCS application and an exciting step in the journey to net-zero cement
- **Calpine Baytown, USA:** Technip Energies and Shell are progressing the retrofit of carbon capture to an 830-MW gas fired power station designed to capture 2.2mtpa CO₂
- **Polaris CCS, Canada:** Shell has taken Final Investment Decision to capture 0.75 mtpa CO₂ at its Scotford facility with the CANSOLV* CO₂ Capture technology

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	2	Number of FEEDs	6	Modular (Y/N)	Yes
Target Industries	Large scale gas-fired power facilities, petrochemical & refineries, gas processing facilities, waste to energy, hard to abate (cement, steel), waste/biomass power facilities				

TECHNOLOGY DESCRIPTION

As a standalone, low-pressure, CO₂ capture technology, CANSOLV* CO₂ Capture System is well-suited for either retrofitting to existing plants or including in greenfield developments. It uses a regenerable proprietary amine to capture CO₂ that is released as a pure stream, which makes the technology highly suitable for both sequestration and utilisation projects. The CANSOLV* CO₂ Capture System can capture up to 99% of the CO₂ from post-combustion streams, is operationally proven for CCS at a 1 Mtpa CO₂ capture scale and has been designed for FEED packages at up to 8 Mtpa capacity. Our units have been designed to date for commercial application for CO₂ concentrations from 3.5 to 27%, and gas flow rates from 11,000 to 4,500,000 Nm³/h.

The CANSOLV* CO₂ Capture System has been in commercial operation at two industrial facilities for 10 years. This unique commercial experience, combined with a world-class continuous innovation program and numerous piloting campaigns at a wide-range of industrial facilities, translates to cutting-edge technology performance.

SASKPOWER: WORLD'S FIRST 1 MTPA POWER GENERATION CCS PROJECT

In 2014, the power station became the first in the world to successfully use CCS at scale. SaskPower chose to add a CANSOLV* SO₂-CO₂ Integrated Capture System for combined carbon capture and flue-gas desulphurisation from a 150-MW unit that was due for refurbishment. The plant now celebrates 10 years of commercial operation with the capacity to capture up to 1 Mtpa CO₂, thereby helping SaskPower to meet strict Canadian regulations on CO₂ emissions from coal-fired power stations and thus retain its licence to operate. The CO₂ is compressed, transported through pipelines and permanently stored in deep geological formations as part of an enhanced-oil-recovery operation. The captured SO₂ is converted to 60 tpd of sulphuric acid that sold as a feedstock for the local fertiliser industry. The learnings from this still-operating, first-of-a-kind deployment continue to help develop Shell's CANSOLV* CO₂ capture technology and promote and develop CCS projects globally.

CONTINUOUS IMPROVEMENT AND TECHNOLOGY DEVELOPMENT

Shell invests in a highly active R&D programme that is designed to address the important questions that projects will face: addressing new and evolving performance requirements; lowering the costs of CO₂ capture; and improving operability. A sample of the numerous development activities underway include amine emissions management, next generation solvent and formulation development, reduction in energy demand and dispatchable operation. This program is yielding strong results as evidenced by recent and upcoming technical publications. Both commercial facilities and projects in development benefit from Shell's continuous innovation technology program.

*CANSOLV is Shell trademark

CANOPY BY T.EN POWERED BY SHELL CANSOLV* CO₂ CAPTURE TECHNOLOGY

Shell Catalysts & Technologies and Technip Energies have been working as an alliance since 2012, developing design improvements to enhance performance and reduce both capital and operational expenditure. We have been working in partnership to deliver a wide range of carbon capture unit sizes and offerings, to meet the needs of every emitter. Our pilot plant facilities offer in-situ testing and performance verification for all types of flue gas, whereas our small to mid-scale modular and containerised units deliver cost and schedule enhancements and project execution risk reduction in comparison with conventional bespoke approaches. Our robust, large-scale bespoke designs have been proven to cater to the most complex of projects and world first applications. Some developments underway include:

- Increased range of standardised and modularised design capacities for both onshore and offshore application.
- Enhanced construction and deployment methods

Canopy by T.EN™ is a flexible, integrated suite of post-combustion carbon capture solutions for any emitter, powered by the proven Shell CANSOLV* CO₂ Capture System. Our products allow clients to de-risk their projects, capture with confidence and meet their targets quickly, efficiently and affordably, regardless of scale, industry or location. From testing and piloting up to the world's largest installations, we've got our clients' carbon capture needs covered.

 PILOT 1.5 ktpa	 C10 10 ktpa	 C100 100 ktpa	 C200 200 ktpa	 C+ Bespoke sizing & design	 MARINE Offshore optimized design
Test anywhere, anytime	Standardized sizes for smaller emitters			Any scale for any facility	Offshore solutions

- **Capture Performance** - Powered by leading Shell CANSOLV* technology, Canopy by T.EN™ solutions deliver CO₂ recovery rates above 95% and feature excellent energy efficiency, low solvent volatility and minimal emissions. Digital by design, our capture plants are fully instrumented and completely automated for unmanned operations and plant performance monitoring.
- **Capture Capacity** - From pilot schemes to custom solutions for large scale-emitters, Canopy by T.EN™ solutions are available in a comprehensive range of sizes to build the carbon capture capacity you need.
- **Capture Support** - Every carbon capture journey is different. So we're with you every step of the way, solving challenges from funding to implementation with our complete Canopy by T.EN™ package.



SUMMARY

NRICI carried out relevant R&D work as early as the 1980s and developed the first generation of technology which uses MEA as the main body while adding active amine, antioxidant, and corrosion inhibitor components. During the 12th and 13th Five-Year Plan periods, based on the national projects, the solvents, and processes developed have been continuously upgraded, and the regeneration energy consumption has been reduced from 4.0 GJ/tCO₂ to 2.4 GJ/tCO₂. The third-generation technology with a regenerative energy consumption of 2.0 GJ/tCO₂ is being developed and is expected to be demonstrated on a large industrial scale by 2025. This technology was industrially applied as early as 1999 in Guizhou Chitianhua's 5,000 tonnes/year flue gas carbon capture plants, and then it has been applied in many coal-fired power plants, such as Huaneng, Sinopec, Huadian, Guoneng, etc. At present, this technology has been applied in 57 domestic and foreign plants, with an annual capacity of more than 1 million tonnes.

BENEFITS

- **High efficiency and low energy consumption:** Optimise and improve the existing carbon capture solvents, processes, and equipment. Under energy-efficient process conditions, regeneration heat consumption has been reduced to 2.0 GJ/tCO₂.
- **Excellent anti-degradation properties:** Developed the corresponding corrosion inhibitor and antioxidant system.
- **Advanced technology index:** Overall at a domestic leading international advanced level in carbon capture technology.
- **Systematic research systems:** Including basic research, laboratory pilot studies, scale-up molding studies, sideline studies, and industrial demonstration studies.

KEY DATA

TRL	9	Capture Rate Range (tpd)	>400	Capture Efficiency (%)	~
Source CO ₂ Purity Range	~11	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	<2.4
Number of Commercial Plants	~	Number of Pilot Plants	10	Modular (Y/N)	No
Target Industries	Power and cement				

KEY PROJECTS

Project One: Industrialised application in Huaneng Shanghai Shidongkou Power Plant 120,000 tonnes/year flue gas CO₂ capture unit.

Project Two: Industrialized pilot study on 40,000 tonnes/year CO₂ capture unit in Sinopec Shengli Power Plant.

Project Three: Industrialised application in the largest coal-fired power plant flue gas carbon capture unit in operation in China - Guoneng Shaanxi Guohua Jinjie Power Plant 150,000 tonnes/year flue gas CO₂ capture unit.

TECHNOLOGY DESCRIPTION

By 2015, NRICI successfully screened a high-efficiency and low-energy capture solvent MA-1 after basic research, lab scale test, and 5 Nm³/h test research. After an industrialised pilot study on a 40,000 t/y CO₂ capture unit in Shengli Power Plant, it successfully carried out an industrialised application in Sichuan Vinylon Plant, and the results showed that compared with the original MEA method, the solvent circulation volume decreased by 34.7%, the regeneration energy consumption decreased by 41.8%, the consumption of circulating water is reduced by 200 t/h, and the cost is significantly reduced under the condition that the production requirements are met.



By 2020, NRICI continued to optimise the solvent and technology and successfully developed a new high-efficiency and low-energy capture solvent MA-2. According to the results of the small-scale and pilot-scale test study, the comprehensive performance of this solvent is better than other existing absorption systems on the market, and finally applied to the largest coal-fired power plant flue gas carbon capture unit in operation in China - Guohua Jinjie Power Plant 150,000 tonnes/year flue gas carbon capture unit. The application results showed that under the optimised test conditions, the capture rate is 96%, the regeneration energy consumption is <2.4 GJ/tCO₂, the operating loss is ~1.0 kg/tCO₂, and the overall level reaches the international advanced level.



By 2024, through coupling solvent, process, and equipment, NRICI has upgraded the latest generation of solvent MA-3, then constructed and operated a set of 1,000 tonnes/year absorption method pilot plant, which can reduce the regeneration heat consumption to 2.0 GJ/tCO₂, and further improve the level of the existing absorption method flue gas CO₂ capture technology.





SUMMARY

NRICI started research on polyamine decarbonisation technology in the 1980s and developed the NCMA decarbonisation technology in 2003. Through proprietary decarbonisation solvents, flexible process flow, and precisely matched process parameters, NCMA decarbonisation technology can achieve customised requirements for CO₂ content in purified gas, down to meet the requirements for CO₂ in the feed gas to deep-cooled separation systems such as LNG, and outperforms similar products in the industry in terms of corrosion and foaming.

BENEFITS

- **Customised CO₂ purification degree:** By controlling the CO₂ purification as required by the process specifications, NCMA can remove CO₂ to a molar fraction of $<20 \times 10^{-6}$.
- **Simultaneous removal of sulphides:** The sulphide is removed without increasing equipment or energy consumption, and the H₂S in the sulphide can be removed to a molar fraction of 1×10^{-6} or less.
- **High absorption capacity:** The CO₂ equilibrium absorption capacity of NCMA is 50-70 L/L, and its absorption capacity can be varied in the range of 15-70 L/L.
- **Low regeneration energy consumption:** Due to the high absorption capacity of the NCMA, the regeneration heat energy consumption is reduced for the same processed gas volume.
- **Less solvent loss:** The vapour partial pressure of NCMA is low, the vapour pressure of pure solvent at room temperature is <0.01 mmHg (1.3Pa), and the gas is less entrained after cooling and separation.

KEY DATA

TRL	9	Capture Rate Range (tpd)	~	Capture Efficiency (%)	70 - 99.9%
Source CO ₂ Purity Range	1 - 40%	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	Steel and petrochemical				

TECHNOLOGY DESCRIPTION

The NCMA decarbonisation technology developed by NRICI can achieve customised demand for CO₂ content in purified gas through proprietary decarbonisation solvents, flexible process flow, and accurately matched process parameters, which is as low as to meet the requirements of LNG and other deep-cooling separation systems for CO₂ in the feed material, and is superior to similar products in the industry in terms of corrosion, foaming, and other aspects.

In 2009, NCMA decarbonisation solvent was awarded the Gold Prize of the 18th National Invention Exhibition issued by the China Invention Association; in 2011, it was also recognised as a national key new product by the Ministry of Science and Technology of the PRC; in 2014, it was awarded the Third Prize of Scientific and Technological Advancement by SINOPEC Group Corporation for its application in decarbonisation of high carbonaceous natural gas; in 2018, it was awarded SINOPEC Group Corporation's Third Prize for Technical Invention; in 2020, one of its main patents, ZL200310106567.9, won the 21st China Patent Excellence Award.



Project 3



Project 1



Project 4



Project 2



Project 5



SUMMARY

SLB Capturi offers a leading, cost-effective portfolio of 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 standardized and modularized 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. SLB Capturi - making carbon capture a reality today.

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 DNVRP-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]**
- First modular Just Catch™ 100 delivered to Twence’s waste-to-energy plant in the Netherlands.
- **Heidelberg Materials Brevik CCS [capture capacity: 0.4 Mtpa]** – Delivering Big Catch™ to Heidelberg Materials, becoming the world’s first industrial-scale carbon capture on cement production. The process utilises waste heat from the cement and CO₂ compression plants via proprietary heat integration.
- **Ørsted Kalundborg CO₂ Hub CCS [capture capacity: 0.5 Mtpa]** - Delivering five Just Catch™ units to Ørsted’s Asnæs and Avedøre bioenergy plants, enabling carbon removal.
- **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. In 2024 a second MTU was introduced, running its first campaign in the US. To date, 14 different flue gases have been tested 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				

TECHNOLOGY DESCRIPTION

PROPRIETARY AND PROVEN TECHNOLOGY

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 more than 60,000 hours of operation to date across a range of carbon emitting industries. The company considers research, innovation, and technology development to be key drivers of competitive advantage, and 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.

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 minimize 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 in total more than 60,000 hours of operating experience from the US, UK, Germany, Scotland, Sweden, Poland, and Norway.

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 prioritized areas. The company offers highly effective solutions for energy optimisation, tailored to specific industrial applications and site-specific conditions. The recommended solution is based on the overall energy performance of the host and the capture plants.

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, 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.

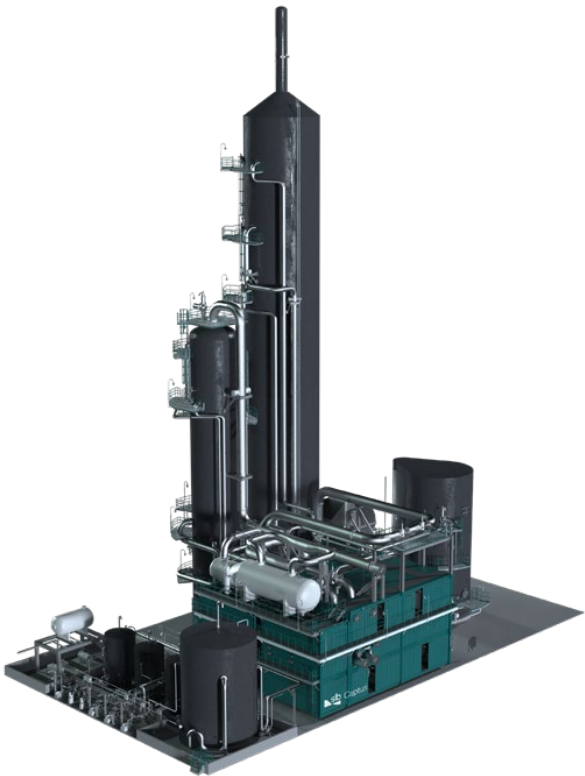
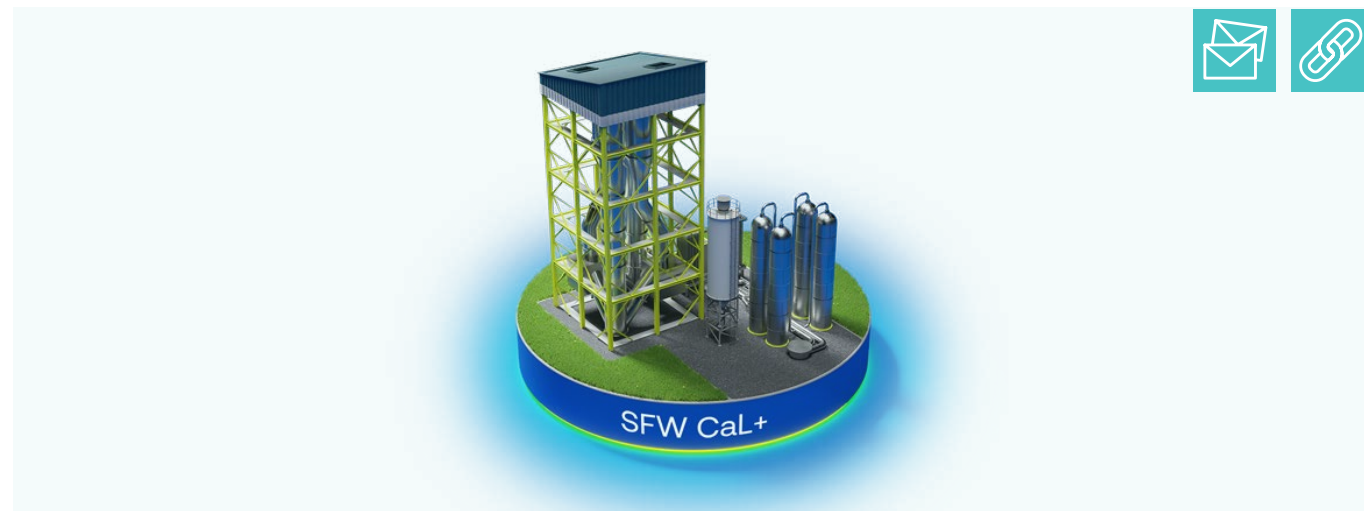


Illustration: Just Catch™ 400



SUMMARY

SFW CaL+ solution based on the Calcium Looping (CaL) capture technology, is a scalable and retrofittable post combustion CO₂ removal system. The solution is built on SFW's experience of delivering over 500 Circulating Fluidised Bed reactors (CFBs) commercial units.

SFW CaL+ is a multi-product, cost- and environmentally effective and highly adaptable solution for capturing carbon emissions. The solution serves the energy from waste, cement, steel, pulp & paper and metallurgical 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 gas sources
- Commercially available, scalable, and cost-effective components
- Can be Integrated to emission source in cement, steel and other carbon intensive industry
- 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	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	~	Modular (Y/N)	No
Target Industries	Cement, Metallurgical and Heavy Industry				

TECHNOLOGY DESCRIPTION

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 calcination of sustainably sourced bio-residues and waste.

CaL creates added value for industrial plant operators in the form of circular economy applications, decarbonising 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.

Like oxyfuel, CaL provides synergy with green hydrogen plants, whereas cheap and available by-product oxygen is utilised for the carbon capture purposes. 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 Pareda power plant, Spain. Sumitomo SHI FW has supplied the demonstration unit and continued to support innovation with our technical advisory services

FEATURED PROJECTS:

1.7 MW CaL demo plant in LaPareda, Spain

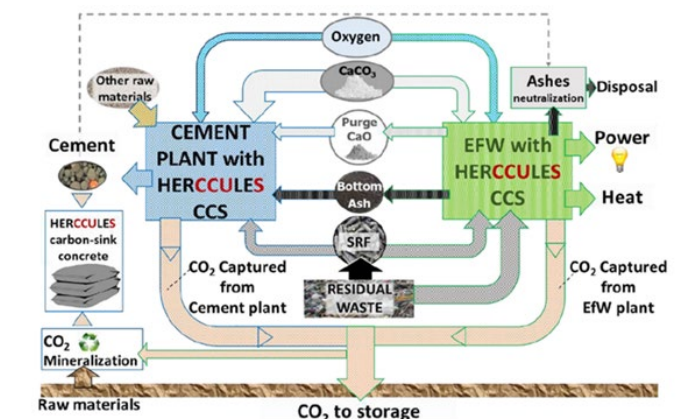
Supplied and commissioned by Sumitomo SHI FW in 2012, the plant (see picture left) demonstrated a capture efficiency of over 90%. The plant has continued to operate flexibly for over 5,000 hours under different process conditions to optimise the technology.

CaLby2030 project for hard to abate sectors

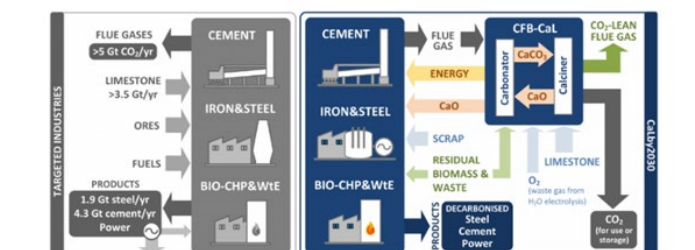
Sumitomo SHI FW will design and engineer three integrated CaL pilot plants to be operated in relevant industrial environment across Europe. The demonstration campaigns will be carried out with the aim of exceeding 90% CO₂ capture rates and even approaching 99% in specific configurations. The demonstrated results will be then scaled up to generate concepts and basic designs for the commercial carbon capture projects for Thomas Zement's integrated cement plant in Karsdorf, Germany, Alleima's Sandviken steelworks plant in Sweden, Hunosa's LaPareda power plant in Spain and IREN's waste to energy plants in Italy.

HERCCULES project for WtE plants

SFW will engineer a CaL carbon capture plant to be installed at the Milan Silla-2 waste-to-energy 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 pilot plant will operate for up to 4,000 hours and the project will conclude with the design and development of FOAK commercial size facility.



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



(left) Reference industries targeted in CaLby2030 and their mass flows; (right) Integrated CaLby2030 concept to avoid CO₂ emissions from high temperature industrial processes and residual-biomass-fired power plants.

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

Funded by the European Union under the Horizon Europe Framework Programme (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.



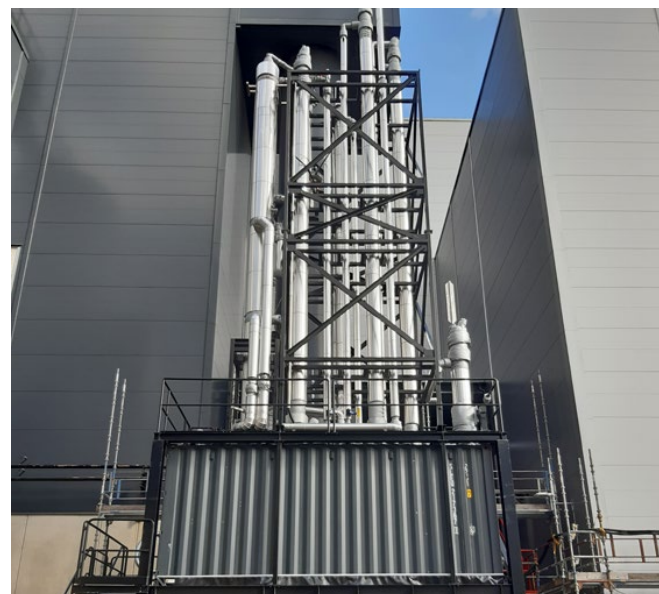
SUMMARY

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 is a widely available, low-cost, 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 solvent is a low-cost with low make-up need, reducing the solvent management cost of the carbon capture plant.
- HPC solvent does not pose risks to environment and health, facilitating simpler permitting.
- SFW HPC+ solution enables flexible configurations and can be retrofitted to any industrial emissions
- SFW HPC+ solution has low energy penalty for capture purposes, whereas consumed energy can be recuperated in the form of low-grade heat.
- SFW HPC+ process gives a high capture rate over 90% and produces a high purity CO₂ product suitable for compression purposes.



Sumitomo SHI FW (SFW), together with partner Capsol Technologies ASA, and Swedish energy company Vaxjö Energi AB collaborate 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				

TECHNOLOGY DESCRIPTION

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:

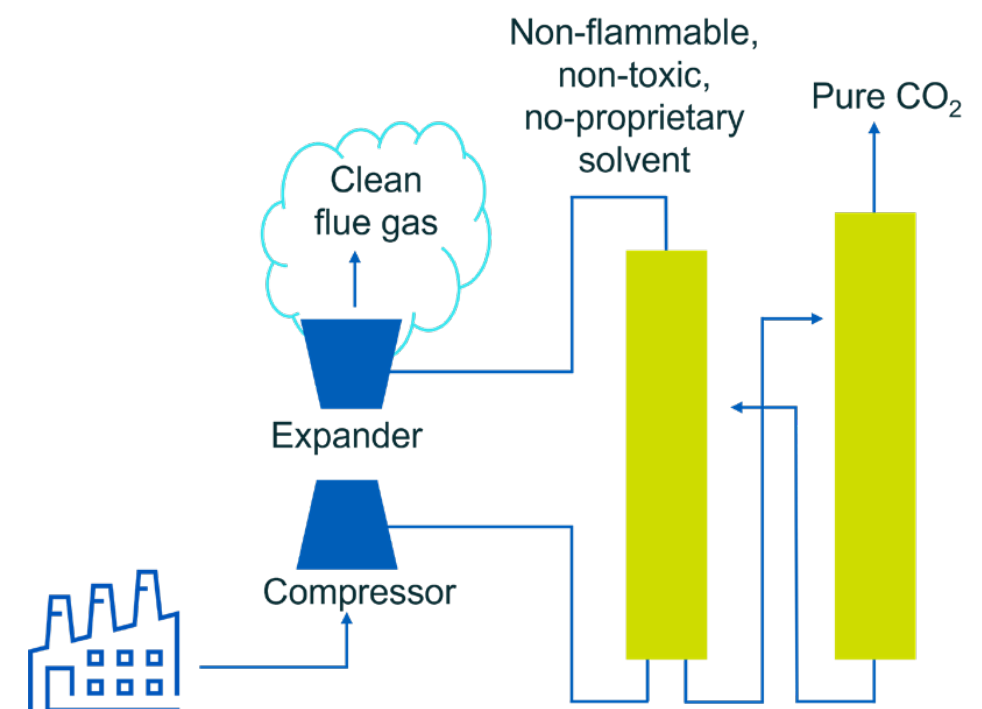


Expanding the CO₂ depleted flue gases over an expander, recovers a large part of the compression energy. The heat recuperated from the flue gas and product CO₂ streams is used internally in the capture system and the remaining heat can be exported to an available district heating network.

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 carbon for e-fuel synthesis.

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

SFW, in partnership with Capsol Technologies ASA, announced the delivery of two SFW HPC+ demonstration campaigns to be executed and hosted at SFW's client base in the Nordics. The campaigns, spanning a combined duration of 8 months, are set to take place at an Energy from Waste (EfW) plant and a Biomass to energy plant.



Schematic of HPC solution (Source: Capsol Technologies AS)



SUMMARY

SFW has developed the oxy-fuel technology for fluidized 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-categories: 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				

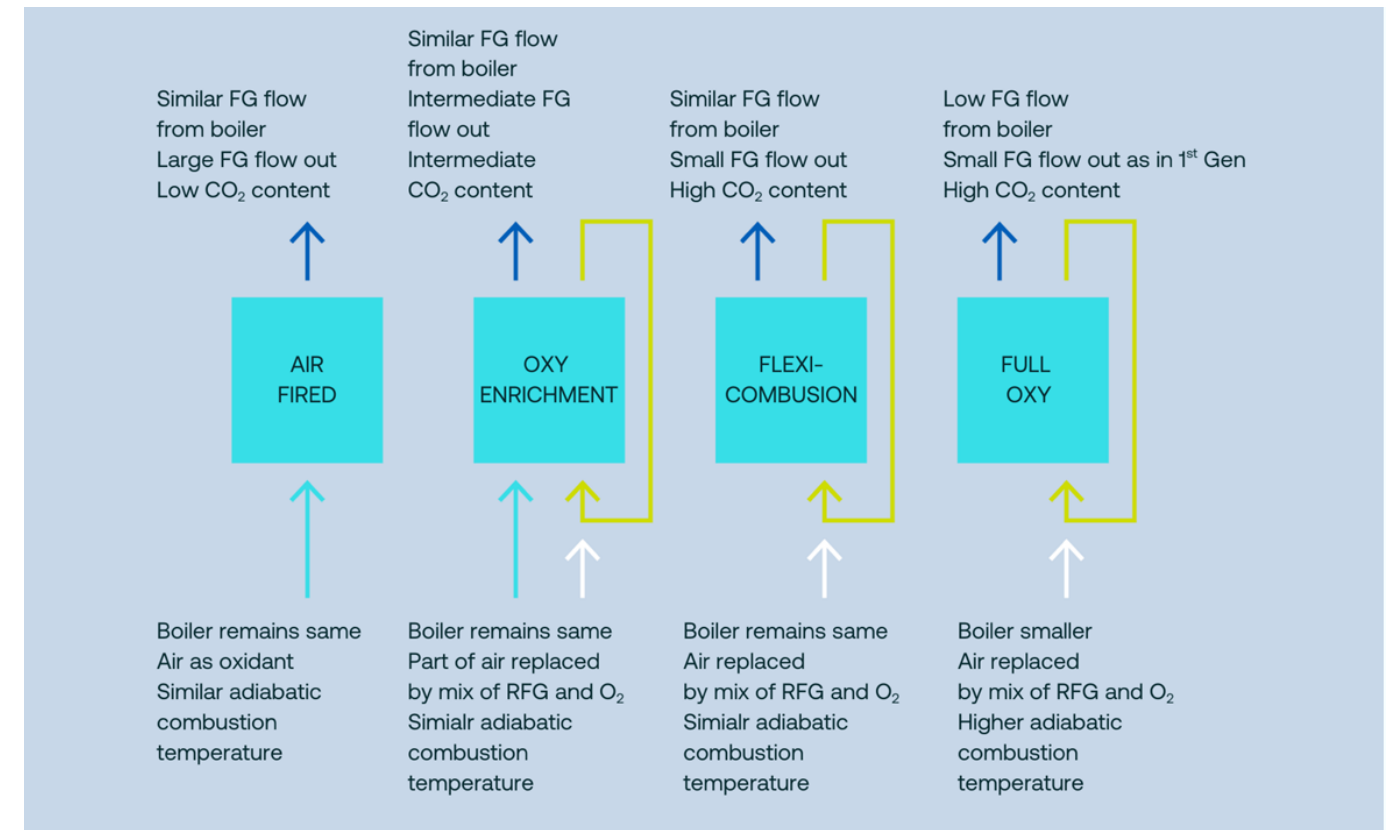
* Including O₂ production plant and CO₂ compressions and liquefaction

TECHNOLOGY DESCRIPTION

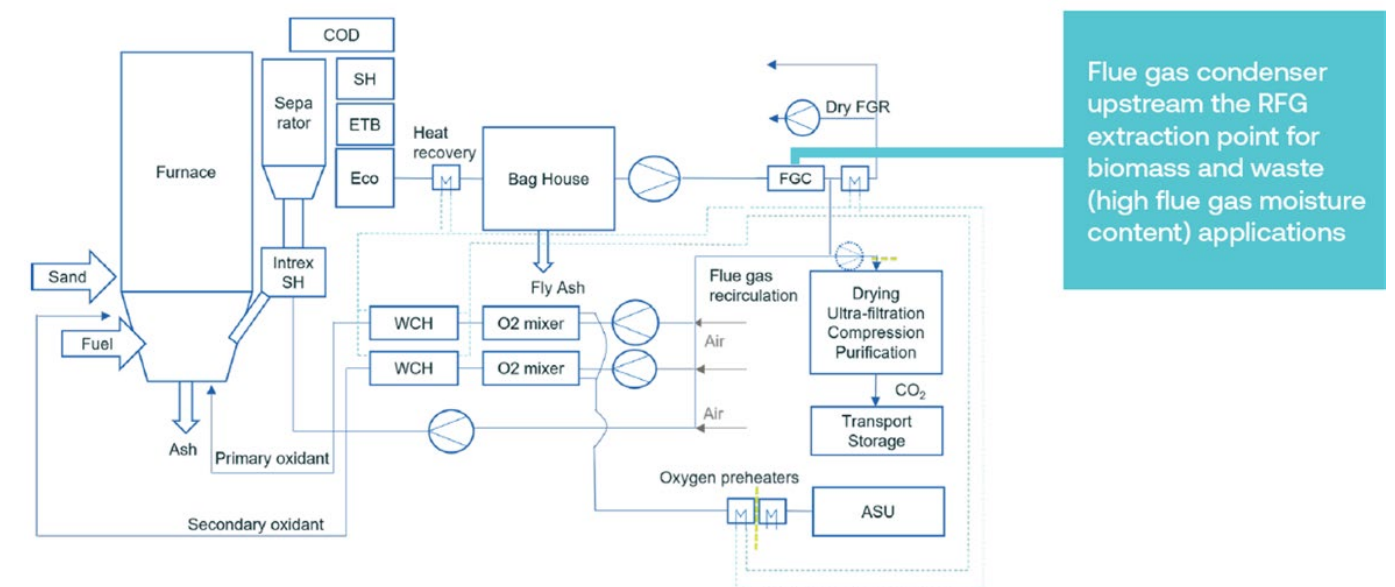
SFW OXY+ GENERIC PROCESS DESCRIPTION

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

Svante Technologies Inc. (Svante) is a leading carbon capture and removal solutions provider, providing solid sorbent-based filter technology for both post-combustion industrial carbon capture as well as direct air capture. This article focuses on Svante’s post-combustion capture technology.

The company’s technology (Svante) leverages solid sorbent-based filters and a unique capture process to trap large-scale CO₂ emissions from hard-to-abate industries such as pulp & paper, cement, steel, hydrogen, oil & gas, petrochemicals, and more. The CO₂ captured can be either safely stored deep underground or used to make other products. Svante’s post-combustion capture technology is being deployed in the field at pilot scale by industry leaders in the energy and cement manufacturing sectors.

Svante’s technology is best suited for CO₂ concentrations of 12% and higher. For customers with multiple stacks and lower concentrations of CO₂ in their post-combustion flue gas, Svante offers BASF’s OASE blue scrubbing liquid.

BENEFITS

- Svante’s solid sorbent - based filters inherently have zero toxic nitrosamine emissions – they are designed to be recycled and don’t require any hazardous chemicals.
- Under slight vacuum operations, Svante can use low-grade or waste heat available on an emitter’s site for the steam step in the capture process. This reduces the heat duty required for carbon capture, minimising and in some cases, eliminating new natural gas production for steam generation.
- Patented rapid temperature swing adsorption process cycle (~ 1 min) responds quickly to intermittent conditions, and there are no additional materials or continuous make-up required.
- Svante consolidates traditional tall capture plant towers into a single rotary adsorption machine at significantly reduced heights – preventing negative community impacts associated with ruined sightlines – making permitting and social license to operate easier.

KEY PROJECTS

- **Chevron USA (25 TPD):**
 - Location: Kern River facility in San Joaquin Valley, CA, USA
 - Source: NG Boiler
 - Status: 2023-present
 - Notes: Funding from the U.S. Department of Energy (DOE project #DE-FE0031944)
- **Delek US (145,000 TPA):**
 - Location: Big Spring refinery in Big Spring, TX, USA.
 - Source: FCCU
 - Status: FEED Study
- **Mercer International (~500 TPD):**
 - Location: Peace River, AB, Canada
 - Source: Pulp Mill Recovery Boiler
 - Status: FEL-2

KEY DATA

TRL	7	Capture Rate Range (tpd)	~	Capture Efficiency (%)	95%+
Source CO ₂ Purity Range	10 - 20%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	1.9 - 2.8*
Number of Commercial Plants	0	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Pulp & paper, biomass, oil & gas, hydrogen, lime, steel, cement, petrochemicals, and direct air capture				

* Fully electrified design

TECHNOLOGY DESCRIPTION

Svante’s technology ecosystem is made up of solid nanomaterials called solid sorbents, namely metal-organic frameworks (MOFs), a rotary adsorption machine (contactor), and structured adsorbent beds (filters), which are housed inside the contactor. The contactor employs Svante’s patented rapid temperature swing adsorption (RTSA) process, which captures diluted CO₂ from post combustion industrial flue gas, concentrates it to 95% purity, and releases it for safe storage or use. This cycle takes less than 60 seconds.

Svante’s RTSA process consists of a series of steps which include passing flue gas, regenerating steam, and conditioning air through filters in a specific order, as follows:

- 1. Adsorption:** The first step in the process is the introduction of the feed gas into the filters, where CO₂ is adsorbed onto the surface of the adsorbent, while the remainder of the flue gas, mainly N₂, O₂ and H₂O, is sent to the stack as spent/exhaust gas.
- 2. Regeneration:** The CO₂-rich filters then rotate to the next process step where low-pressure steam flows through them, requiring only a small amount of superheat to overcome heat losses from the system. This is the first regeneration step, where steam regenerates the adsorbent on the filters, releasing a stream composed primarily of CO₂ and steam.
- 3. Conditioning:** After regeneration low pressure, the filters rotate through to the next process where heated ambient air is used to condition and cool them. The ambient air stream, termed Conditioning Gas, removes most of the water vapor from the adsorbent.

Where does this process cycle take place?

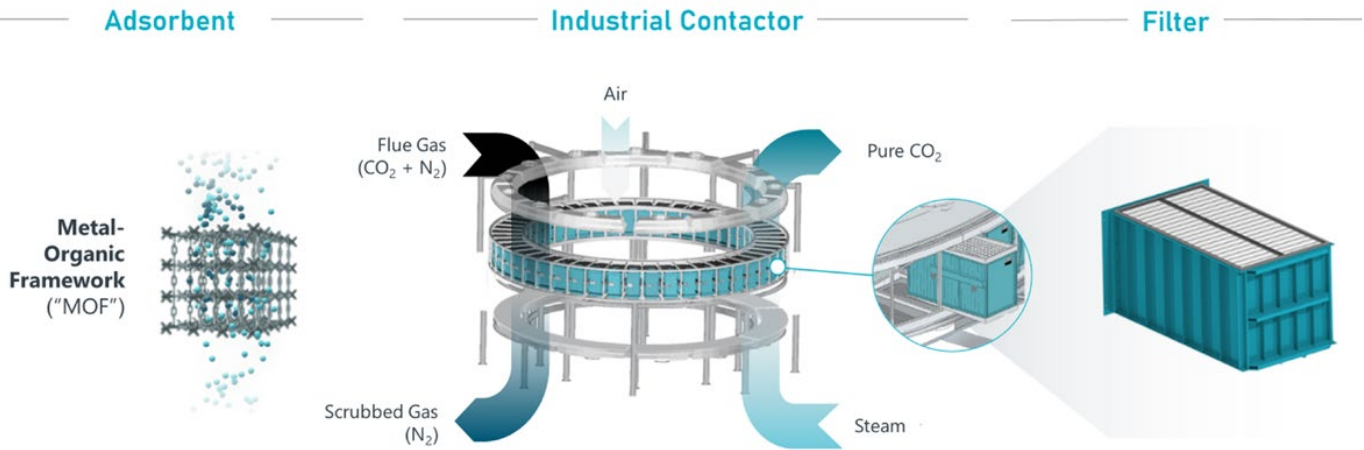
The adsorption, regeneration, and conditioning functions described above are integrated and implemented in the rotary adsorption machine (contactor), as shown in Figure 1. The technology is integrated into a Svante carbon capture plant (balance of plant included) and can be retrofitted to new and existing industrial facilities.

COMMERCIAL-SCALE MANUFACTURING CAPACITY

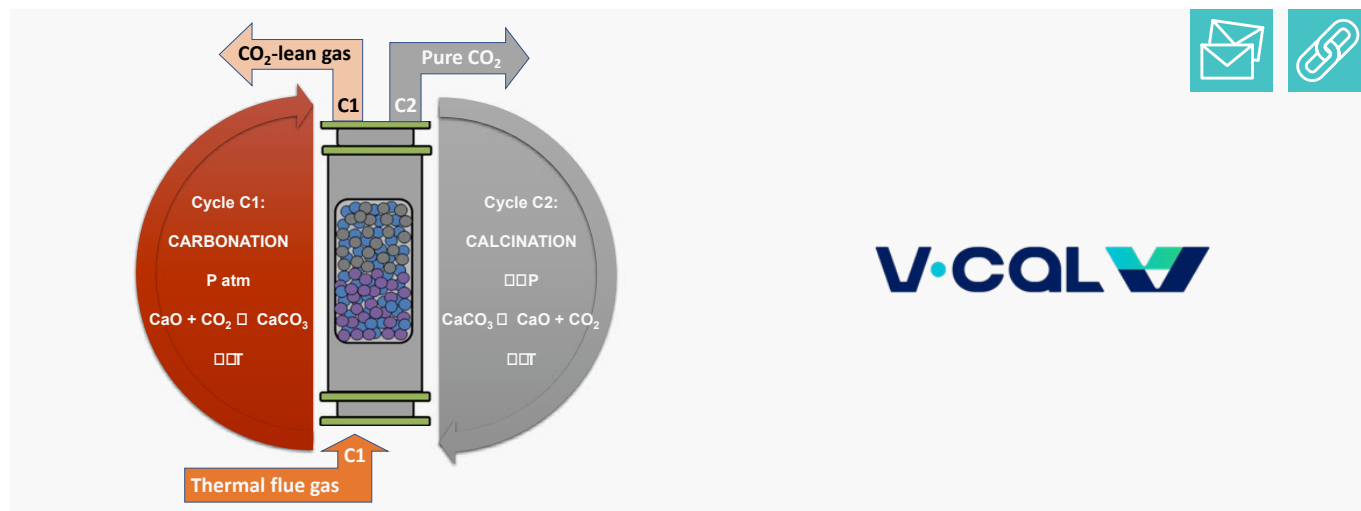
In May this year, Svante commisioned its world-class commercial filter manufacturing facility, The Centre of Excellence for Carbon Capture & Removal, in Vancouver, Canada, which now has the capacity to manufacture enough filters to capture 10 million tonnes of CO₂ annually.

Svante is on TIME & Statista’s World’s Top Greentech Companies of 2025, *2025 Global Cleantech 100* and *is now a member of the Global Cleantech 100 Hall of Fame*.

For more information about Svante, visit svanteinc.com.



TECNICAS REUNIDAS SA VACUUM-ASSISTED CALCIUM LOOPING



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				

TECHNOLOGY DESCRIPTION

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)

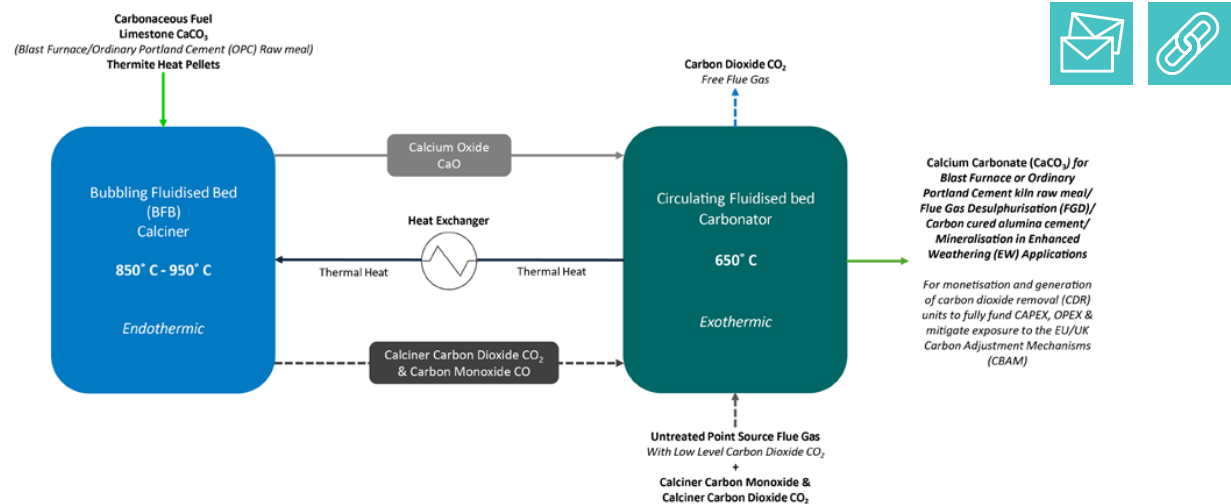


Figure 1. Picture image of the TRL-5 V-CaL prototype.



AEL CCS

DUAL FLUIDISED BED REVERSE CALCIUM LOOPING THERMOCHEMICAL ENERGY STORAGE REACTORS



SUMMARY

AEL CCS Calcium Looping carbon dioxide (CO₂) capture technology is based on the reversible mechanics of limestone's endothermic thermal decomposition that releases CO₂, lime and lime's exothermic CO₂ absorption. In the calcinator, limestone is heated to 850° Celsius decomposing into CO₂, lime that is transferred to the carbonator, at 650° Celsius, where lime cascades, contacts the blend of the calcinator, post combustion industrial process CO₂ which have an affinity to the lime and the resultant exothermic reaction produces calcium carbonate. The heat generated is utilised in the carbonator and the surplus heat is coupled with steam boiler/turbine power generation. Unlike traditional calcium looping systems, this single carbonation cycle routes the carbonator's CO₂ lean flue gas to a terminal circulating fluidised bed carbonator which utilises an incandescent lime stream to capture the residual CO₂ as calcium carbonate that is permanently stored in the built environment or mineralised for enhanced weathering applications.

BENEFITS

- Benefit One:** Net Zero is achieved by utilising multi-functional refractory lined reactors that switch from bubbling fluidised bed calcination, circulating fluidised bed carbonator, terminal circulating fluidised bed carbonator and sorption enhanced steam methane reforming process (SE-SMR) roles/modes with associated steam boiler/turbine CHP power generation to guarantee a zero energy penalty.
- Benefit Two:** The multi-functional AEL CCS calcium looping reactors, in a retrofit role capture carbon dioxide (CO₂), as newbuilds complete the biochar, blast furnace, Ordinary Portland Cement (OPC) production processes, whilst complementing PtX, Bioenergy with Carbon Capture and Storage (BECCS) technologies.
- Benefit Three:** In the calcinator, steam methane reforming (SMR) carbonator, due to pyrolytic thermal decomposition, kinetic parameters, the carbonaceous fuel volatilises into tars, a syngas containing carbon dioxide, carbon monoxide, hydrogen, methane for product island pathways to hydrogen, methanol and sustainable aviation fuel (SAF).
- Benefit Four:** RD&D for direct air capture (DAC) & internal combustion engines (ICEs)

KEY DATA

TRL	5	Capture Rate Range (tpd)	1,500	Capture Efficiency (%)	99%+
Source CO ₂ Purity Range	<0.1 - 60%	System Energy (GJ/tCO ₂)	<1	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Carbonaceous fuel combustion in cement, chemical, fertilizer, oil & gas, pyrolytic, steel, thermal power generation and hard-to-abate industries				



AIRHIVE

DIRECT AIR CAPTURE (DAC)



SUMMARY

Direct Air Capture (DAC) is an innovative technology designed to mitigate the rising levels of atmospheric CO₂ 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 CO₂ 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 CO₂, resulting in CO₂-free air exiting the reactor. The carbonated solids are then circulated into a connected electro-calciner, where it is regenerated, yielding pure CO₂ for utilisation or storage and refreshed sorbent for successive cycles of carbon capture.

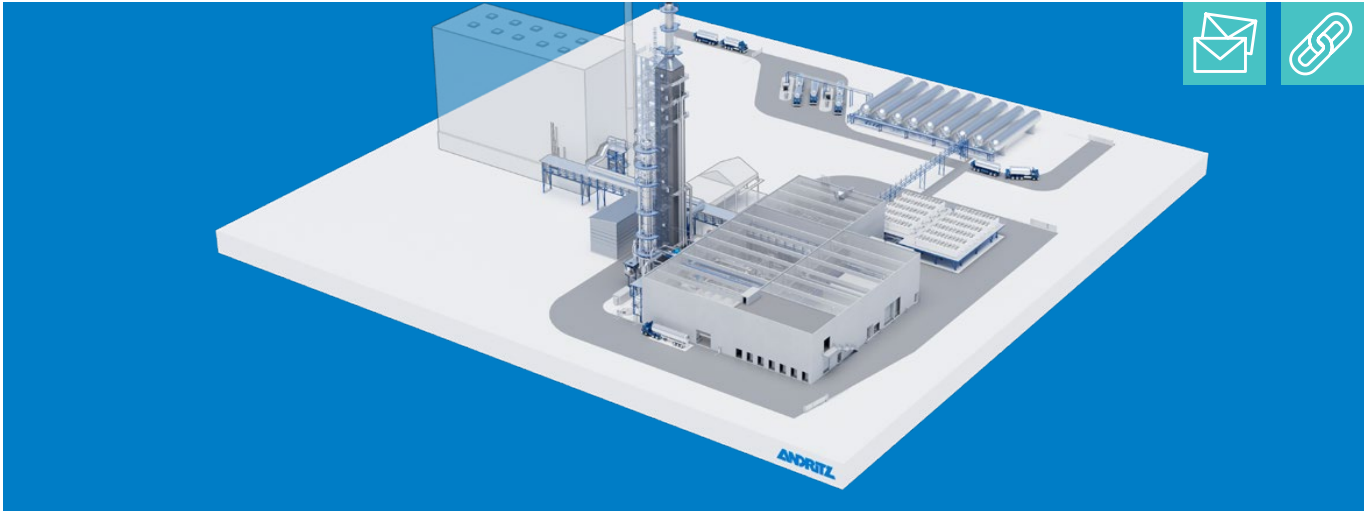
BENEFITS

The Airhive DAC system is:

- Fast:** The nano-structured sorbent removes 99% of CO₂ 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 tCO₂ with pathways to estimate at-scale costs of <\$100 per net tCO₂.
- Energy efficient:** The system is targeted at 1.5 MWh/tCO₂, 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%	Energy Consumption (GJ/tCO ₂)	3.6 GJ/tCO ₂ (1 MWh/tCO ₂)	Specific Regen. Energy (GJ/tCO 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				



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 solution, 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).

KEY PROJECTS

- **Westenergy (Finland):** FEED study for carbon capture solution with optimised district heating integration in the waste-to-energy industry. Size: 25t/hour.
- **ARGO (Denmark):** FEED study for a carbon capture project in the waste-to-energy industry. Size: 50t/hour.
- **Kredsløb (Denmark):** FEED study for carbon capture solution including CO₂ compression for pipeline transport using OASE[®]blue technology for the waste-to-energy and biomass plant near the city of Aarhus. Size: 70 t/hour.
- **Pori (Finland):** Feasibility study for reducing carbon emissions from a biomass plant size: 13t/hour.
- **Rohrdorf (Germany):** First demonstration plant in the German cement industry. Size: 2t/day
- **Pilot Project:** voestalpine/K1-MET (Austria): Collaboration in the iron and steel industry.
- **Mobile Test Units:** Various Mobile Test Units (MTU) are available for rental for different applications.

KEY DATA

TRL	9	Capture Rate Range (tpd)	As per need	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	4 - 30%	System Energy (GJ/tCO ₂)	1.1 - 3.3	Specific Regen. Energy (GJ/tCO ₂)	2.5 - 2.8
Number of Commercial Plants	0	Number of Pilot Plants	4	Modular (Y/N)	No
Target Industries	Pulp & Paper, Iron & Steel, Cement, Biomass, Energy from Waste/Waste to Energy				



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

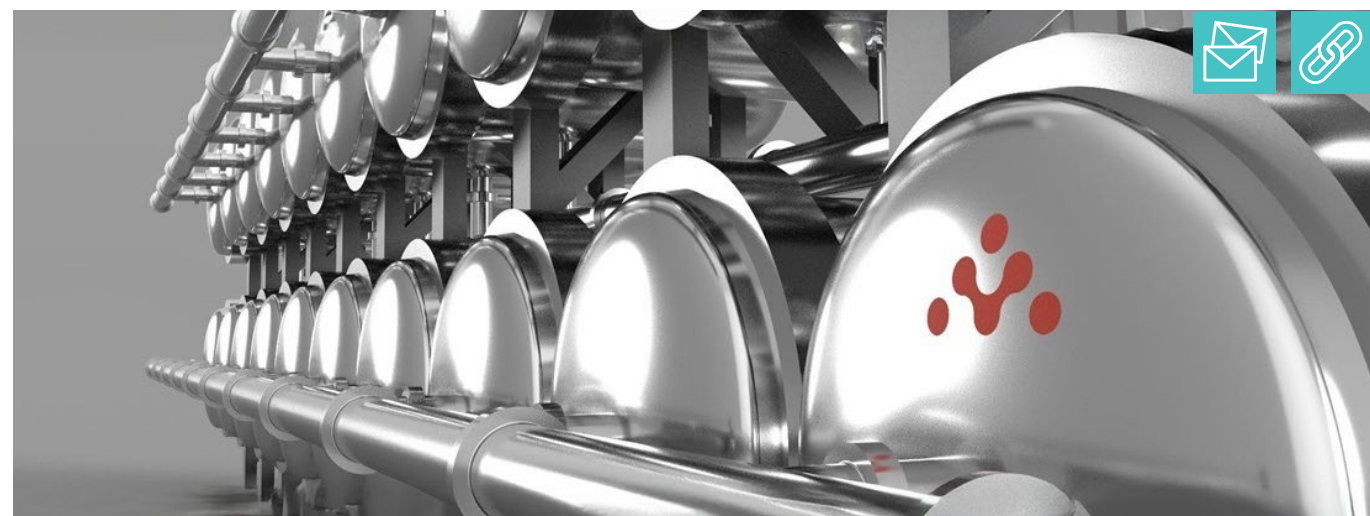
- **Safe Operations & Eco-Consious:** The process is non-volatile and contamination-free, ensuring a secure and clean environment. The system is fully closed, preventing any environmental contamination.
- **Clean Output:** No solvent is present in the final product, making it eco-friendly and safe for 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 achieves over 90% efficiency in capturing 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 maximizes 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 - 95%
Source CO ₂ Purity Range	>15%	System Energy (GJ/tCO ₂)	0.7 - 1.8	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	150	Number of Pilot Plants	~	Modular (Y/N)	Optional
Target Industries	Power (WtE, Biomass, CHP), Steel, Cement, Pulp & Paper, Refining & Petrochemical, Gas Processing				



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 over 2,000 hours of operation across multiple pilot projects in a wide variety of industries, including steel, kiln, petrochemical, and oil & gas, 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 leading companies across the carbon value chain to deliver end-to-end solutions and is backed by key strategic partners including Chevron, Technip Energies and Syensqo.

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.
- **Enabling Other Technologies:** Ardent has expertise in designing optimised hybrid systems with Optiperm™ membranes to unlock a wider range of operating conditions for other process technologies. For example, Optiperm™ can be combined with cryogenics to deliver high purity CO₂ (99.9%+) at conditions ready for transport.

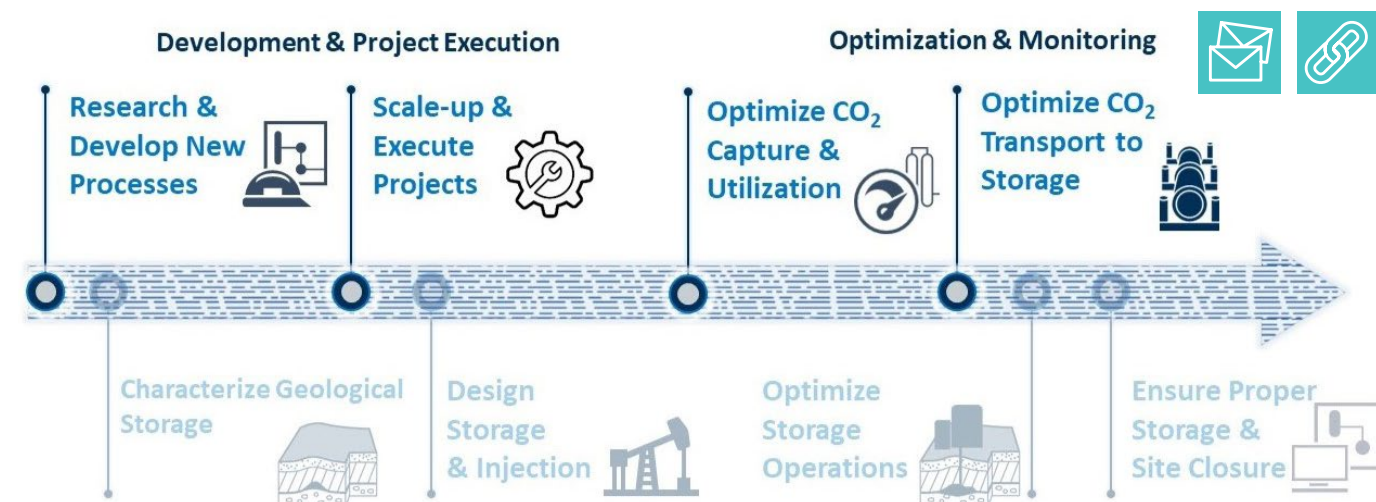
KEY PROJECTS

Five Optiperm™ pilots are already 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, paving the way for a large-scale field deployment.
- **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 is preparing deployments in Waste-to-Energy plants and in other industrial applications across North America, Europe and Asia.

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	5+	Modular (Y/N)	Yes
Target Industries	Smaller point-sources such as small boilers (incl. biomass), fired heaters, recip. engine and waste-to-energy applications				



SUMMARY

AspenTech 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

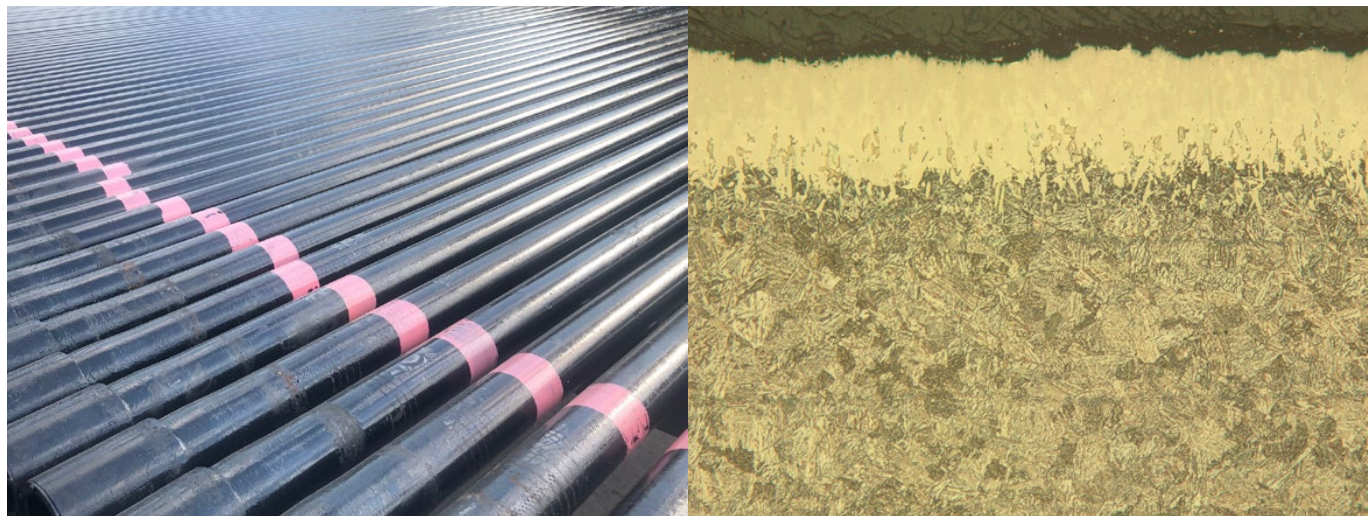
- **Techno-Economics:** Well-known process simulators Aspen Plus® and Aspen HYSYS® help to further optimise processes, identifying right trade-offs between capture efficiency and energy use.
- **Investment Certainty:** Dynamic, event-driven modelling with Aspen Fidelis™ guides investment and operational 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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BLUEWATER THERMAL SOLUTIONS

BORONISING – CORROSION/WEAR RESISTANCE



SUMMARY

Boronising (a.k.a. Boriding) is a case hardening heat treatment process that is known to increase both corrosion resistance and wear resistance of steel components used downhole. This treatment is used on downhole production tubing used in oil wells along with sand control equipment and other downhole components. Corrosion resistance of components subjected to H_2S , CO_2 , high temperatures and pressures along with produced brine water can be increased by 8x compared to plain carbon steel and can compete with high cost corrosion resistant alloys. Boronising also increases the surface hardness to 1500 Vickers and is often used to extend the useful life of sand control and sand separator equipment as the wear resistance is increased by nearly 20x compared to carbon steel components. Any carbon capture tubing, casing or other downhole components that are prone to failure due to corrosion, wear and/or erosion over time could benefit from a boronizing treatment.

BENEFITS

- Nearly 8x improvement in corrosion resistance when exposed to H_2S , CO_2 , brine water in combination with high temperatures and high pressure.
- Nearly 20x improvement in wear resistance where metal on metal wear may be occurring.
- Nearly 20x improvement in erosion resistance when exposed to abrasive sand or slurries.
- Improved galling resistance of metal components, particularly useful in valves and pumps

KEY PROJECTS

- Have doubled the mean time between failures in many oil wells with boronised production tubing installed to prevent hole in tubing failures
- Generally two to five times increased service life of many components that are exposed to extreme corrosion, wear, and erosion and can require constant replacement parts.

KEY DATA

TRL	5	
Target Industries	Oil and gas production wells, carbon capture, sand control equipment	

CAPTIVATE TECHNOLOGY

MUF-16 ADSORBENT

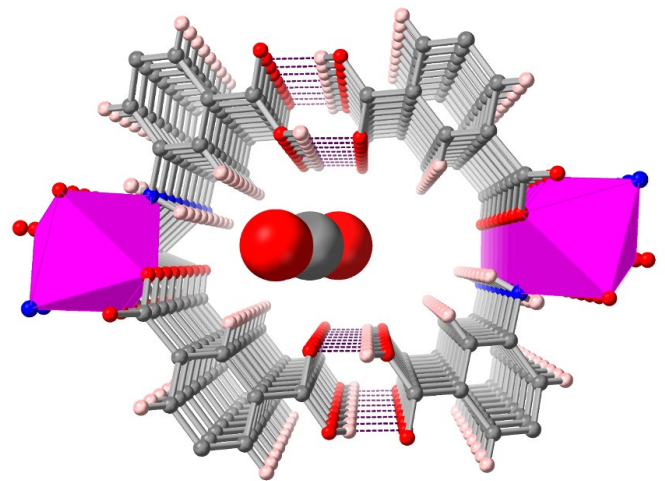


SUMMARY

The team at Captivate Technology has developed a porous, solid-state material that acts as a sponge for carbon dioxide. This novel metal-organic framework (MOF), named MUF-16, has the potential to significantly reduce greenhouse gas emissions through the sieving of CO_2 from industrial flue gases using pressure-swing adsorption. The process is continuous and recyclable, generating a continuous stream of carbon dioxide to be stored or used. MUF-16 is low-cost, stable to all impurities, and has a long lifetime. Captivate is rapidly moving to pilot and demonstration scales in collaboration with partners and end-users. Ultimately, our vision is to produce capture units that will remove CO_2 from industrial emissions on the gigaton scale to deliver substantial environmental and economic benefits. MUF-16 will couple CO_2 capture to its value-added deployment as industry pivots away from viewing carbon dioxide as a waste by-product toward it being valuable raw material.

BENEFITS

- Robust, scalable and inexpensive solid-state adsorbent
- High selectivity for CO_2 over other gases such as nitrogen and methane
- Tolerant of impurities such as water vapour and acid gases with no unwanted side-reactions
- Low energy penalty for CO_2 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
- Spent adsorbent easily regenerated at its end-of-life
- Applicable to flue gases, cement manufacturing, natural gas and biogas purification etc
- Maintains carbon capture performance with humid gas streams.



KEY DATA

TRL	5	Capture Rate Range (tpd)	1 - 1,000	Capture Efficiency (%)	>95%
Source CO_2 Purity Range	>4%	System Energy (GJ/t CO_2)	~	Specific Regen. Energy (GJ/t CO_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				



SUMMARY

Carbon America's patented cryogenic point-source carbon capture technology, FrostCCTM, stands to significantly enable rapid decarbonisation across all industrial and power sectors. The innovative cryogenic approach utilises standard industrial turbomachinery, similar to air compressors and expanders, and requires no solvents, chemicals, or water supply. It achieves up to 99% CO₂ capture and additionally captures other pollutants like NO_x, SO_x, heavy metals, and particulates. The commercial FrostCC product will leverage mature commodity equipment and low-cost materials proven at scale in versatile, standardised trains, enabling high volume manufacturing to drive down costs. Its small footprint and electric-only load enables easy retrofitting of existing plants while minimising site host disruption.

BENEFITS

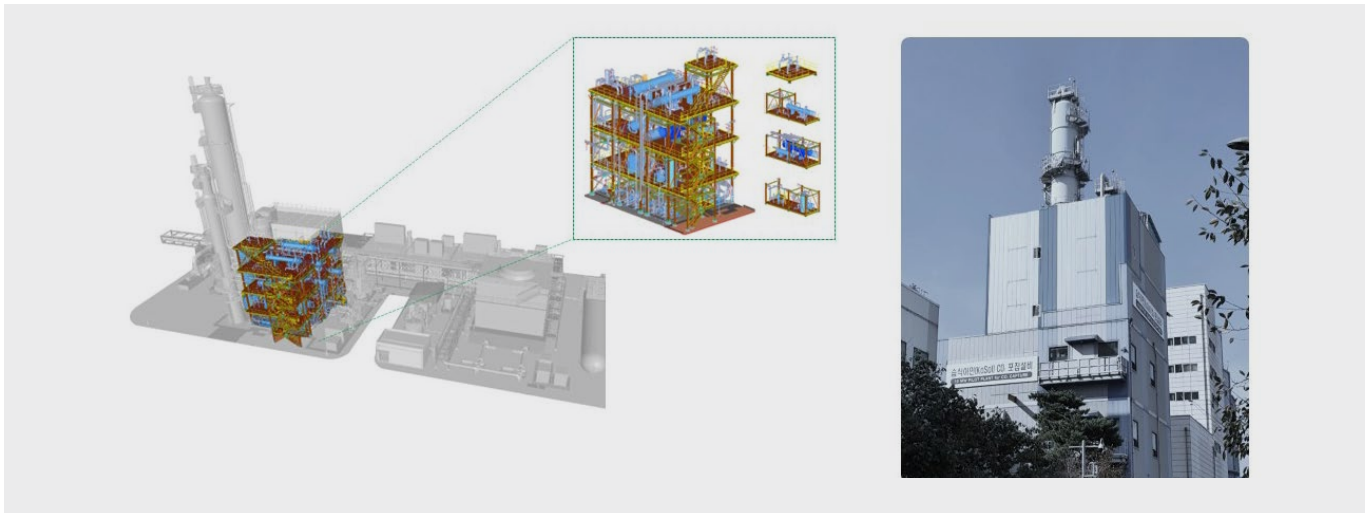
- **Maximum Co-Benefits:** Captures up to 99% of CO₂ and NO_x, SO_x, heavy metals, and particulates while requiring no chemicals, solvents, water supply, or pre-treatment of the flue gas
- **Low Cost:** Anticipated to be one of the lowest CapEx of any capture technology with comparable OpEx
- **Ease of Integration:** Utilises a full electric load with no thermal load, small footprint, and high modularity for easy, minimally-disruptive retrofits
- **Rapid Deployability:** Leverages equipment and materials already proven at scale to enable rapid manufacturing of commercial modules, and scale is achieved via replication, enabling massive decarbonisation across sectors with varying CO₂ concentrations using one system architecture
- **Robust and Reliable:** Robust operations regardless of contaminants or operational variability

KEY PROJECTS

- **R&D at Arvada, CO Test Facility:** Over 350 tests covering over 2000 hours of testing have been performed across a range of concentrations and rates at our laboratory-scale integrated system. Custom, empirically-validated models are enabling technology scaling and enhancement. Testing at Arvada achieved TRL 5 in 2022.
- **National Carbon Capture Center (NCCC):** An engineering-scale system of the fully integrated process, capable of capturing 1,000 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. The project elevated FrostCC to TRL 6
- **Commercial Demonstration Plant Capturing 100ktpy CO₂:** Carbon America is pursuing deployment of initial commercial modules in 2027-2028, achieving TRL 8 to 9.

KEY DATA

TRL	6	Capture Rate Range (tpd)	250+	Capture Efficiency (%)	90 - 99%
Source CO ₂ Purity Range	4 - 40 mol%	System Energy (GJ/tCO ₂)	1 - 2 (elec) depending on flue gas	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	First anticipated in 2027- 2028	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Post combustion capture				



SUMMARY

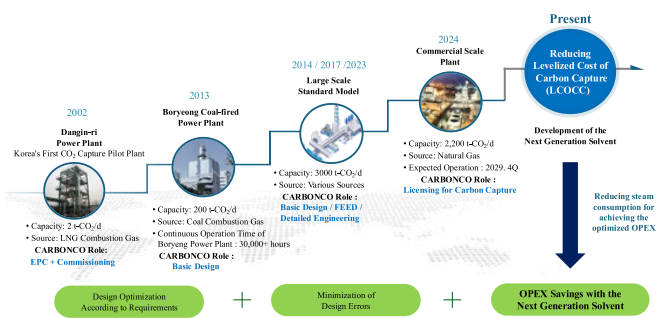
CARBONCO is a technology provider that specializes in post-combustion carbon capture through the supply of its proprietary amine-based solvent. As a licensor, CARBONCO offers customised and cost-effective designs tailored to diverse industrial applications, utilizing its own optimal standardized engineering models. With extensive experience, technical knowledge, and operational know-how stacked through various global decarbonisation projects, CARBONCO's cutting-edge technology has been developed accordingly and is now golden for deployment at any scale of carbon capture facility, in range with small scale modular (2TPD) to commercial scale project (several Mil. TPA).

Through a strategic global partnership with major CCUS stakeholders, CARBONCO's technology has been thoroughly validated across different operational environments. By integrating the cutting-edge engineering with this state-of-the-art solvent technology, CARBONCO is redefining the CCUS landscape, delivering sustainable solutions that empower industries to achieve their climate change target more effectively.

CARBONCO's R&D center plays a central role in continuously upgrading its technology, focusing on 1) energy efficiency, 2) operational stability, and 3) solvent innovation. The center consistently conducts rigorous pilot testing, solvent performance evaluations, and system integration studies to ensure scalability, reliability, and future-readiness of the carbon capture systems.

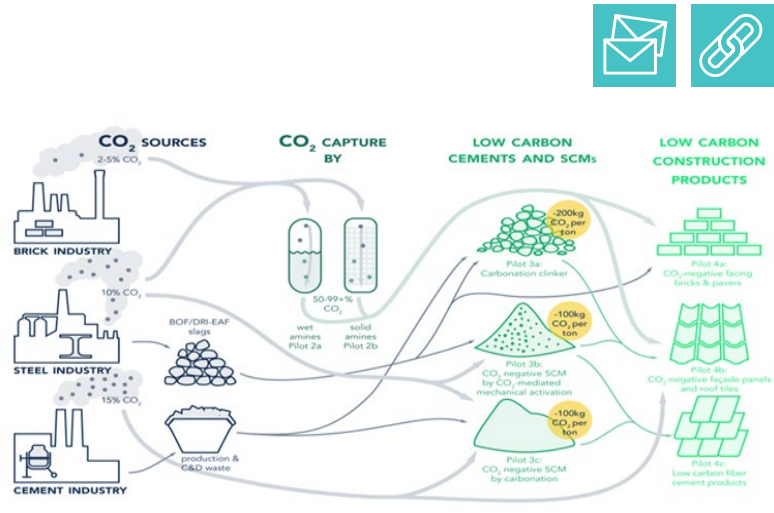
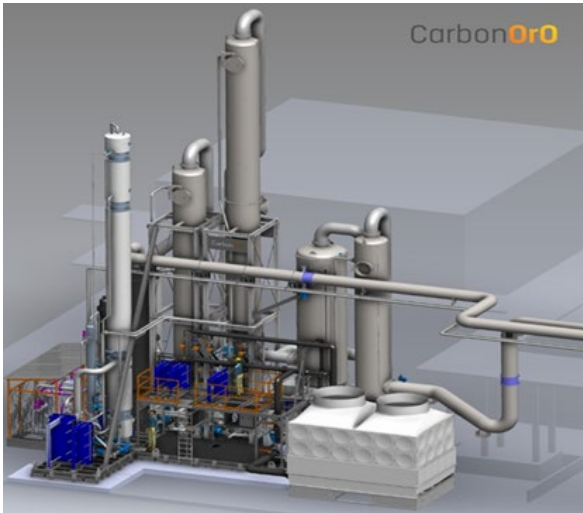
BENEFITS

- Advanced carbon capture
- Flexibility to meet the specific needs and conditions of customers through a diverse portfolio of solvents, including in-house developed solvent
- Proven technology with commercial facility located in Korea in continuous operation over 10 years
- High efficiency with low energy consumption, achieving over 95% recovery rate and 99.9% + purity, tailored to the customer's demand
- Competitive energy consumption through continuous and consistent process innovation (≤2.3 GJ per tonne of CO₂)



KEY DATA

TRL	9	Capture Rate Range (tpd)	~3,000	Capture Efficiency (%)	95%
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)	Available
Target Industries	Oil & Gas, Power Plant, Petrochemical, Wast-to-Energy, Cement, Steel, Glass & Chemicals, Fertilizer & Urea				



SUMMARY

CarbonOrO delivers post-combustion carbon capture solutions to industrial CO₂ emitters across industries including waste management, energy, oil & gas, chemicals, steel and cement. CarbonOrO’s proprietary technology uses a unique bi-phasic amine solvent. It was developed with a strong focus on effectiveness in chemical absorption/desorption of CO₂, high loading characteristics (small footprint/lower CAPEX), energy efficiency and stability (low degradation). Due to the unique properties of the solvent, desorption of CO₂ is not just driven by chemistry but also by a physical process (phase-shift).

Traditional solvents release more CO₂ if temperature is raised in a straightforward chemical process. The CarbonOrO mixture encompasses an effect seen only in bi-phasic solvents: CO₂ is released in bulk above a threshold temperature (70°C), triggering the phase shift in the solvent. This allows for desorption of CO₂ at lower temperatures, with significantly less energy use than existing amine solvents. Applications are for a 5-50% range of CO₂ emission sources.

BENEFITS

- The unique properties of the bi-phasic solvent translate into:
- Low energy consumption from the combined chemical and physical effect. Energy consumption, expressed as ‘reboiler duty’, is at 2.3-2.6 GJ/t CO₂, significantly below the current industry (MEA) benchmark (3.6 GJ/t CO₂);
- Production of CO₂ at an even increased temperature (95-120°C) with thermal heat will provide CO₂ at 4-6 bar, which saves up to 20% in electricity costs for compression and liquefaction in downstream CO₂ transport;
- Increased solvent lifetime (less degradation) due to low operational temperatures (thermal degradation) and reduced oxidative degradation.
- Compact units up to 100 kton capacity, delivered on 20 ft container frames, that can be built off-site and in-series to reduce CAPEX and on-site installation. The units are built with off-the-shelf parts from a variety of trusted suppliers.

KEY DATA

TRL	7	Capture Rate Range (tpd)	~	Capture Efficiency (%)	>90%
Source CO ₂ Purity Range	5 - 50%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	2.3 - 2.6
Number of Commercial Plants	0	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Industries with emissions from post-combustion and energy/oil/gas industries				

KEY PROJECTS

- AVR Afvalverwerking, the largest Dutch waste company, has entered into a pilot-contract with CarbonOrO to test our technology at their WtE plant in Duiven, the Netherlands. The pilot will focus on 2,000 hours of testing, starting in Q2 2024. AVR was the first company in NW-Europe to realise a CCUS-project (100 kton/yr capacity) and CO₂ delivered to greenhouses. In its newly designed Mobile Testing Unit (capacity of 10 ktpa, CarbonOrO will incorporate 3 pending patents, focused on reducing amine degradation and energy consumption. The pilot's goal is to demonstrate that the technology/process can capture CO₂ at industrial scale with significant energy savings, with low amine degradation and emissions.
- CarbonOrO has been awarded an EU-grant with Belgian research institute VITO and steel/brick/cement producers. CarbonOrO will capture CO₂ for mineral carbonation from waste streams, creating building materials at an industrial site of Vandersanden (brick manufacturer), in Belgium. www.carbon4minerals.eu



SUMMARY

CarbonQuest Distributed Carbon Capture System™ (DCCS) solution captures CO₂ from a number of applications with fully modular, stackable, small footprint systems that use solid sorbents and do not rely on toxic chemicals and large towers to capture CO₂. Our technology can be scaled up from smaller applications of 1000 tons/year to 300,000 tons/year.

The low carbon onsite power (Co-gen/CHP and fuel cells) with DCCS™ is an innovative solution CarbonQuest developed to address growing power and reliability needs at manufacturing facilities and data centers. CarbonQuest has clients in multiple market segments ranging from campus settings (universities), food and beverage, diverse industrial, utility and biogenic CO₂ sources. Our approach has been validated by internationally recognised 3rd party engineering firms.

BENEFITS

- Modular & Expandable:** Modular, containerized systems can be stacked for larger applications by using parallel systems to achieve up to 300,000 tons/year.
- Small and Environmentally Friendly Footprint:** no need for large, stationary amine towers that often require additional height permits; no toxic water as a byproduct; no harsh chemicals.
- Cost Effective:** Depending on the CO₂ concentration and other factors ranges from \$40-\$150/ton.
- End-to-end carbon solution:** We partner with many CO₂ offtakers to utilise it in a number of applications or mineralize or sequester the CO₂. We monetize the CO₂, pass on the benefit to the project, and take care of the CO₂ offtake.

KEY PROJECTS

- Project One:** 5 commercial pilot projects that capture CO₂ in large buildings. These projects were built to prove out the technology in a commercial setting, showing that solid sorbents and small physical footprint can capture CO₂.
- Project Two:** Security of CO₂ supply and Scope 3 emissions: a project in the food & bev market that captures and re-uses the CO₂ onsite, reducing emissions and uncertainties from cross-country CO₂ transportation. In manufacturing stage.
- Project Three:** 3 Fuel cell+carbon capture projects coming online in 2027. These projects provide power 5MW power each while reducing CO₂ emissions from the gas-fueled fuel cell.
- Project Four:** feasibility study on a WTE facility.

KEY DATA

TRL	7 - 8	Capture Rate Range (tpd)	2 - 822	Capture Efficiency (%)	~
Source CO ₂ Purity Range	4 - 85%	System Energy (GJ/tCO ₂)	0.72 - 5.00	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	4	Number of Pilot Plants	3	Modular (Y/N)	Yes
Target Industries	Industrial or data centers with onsite power needs; industrial boilers; food & bev; utility infra, Biogenic/biomass; campus settings				



SUMMARY

The CATACARB® process offers an efficient, reliable, and environmentally responsible method for capturing CO₂ without modification to upstream technologies. Over six decades CATACARB® has focused exclusively on Hot Potassium Carbonate (HPC) CO₂ capture while optimising the process through experience and data amassed from 35,000,000 plant operating hours. CATACARB® technology can be licensed directly to clients or through select partnerships. The CATACARB® process includes optimal HPC design, performance additives when desired, and ongoing support. CATACARB® can design both Basic HPC utilising stainless steel construction, as well as Enhanced HPC with proprietary performance additives. Advantages of performance additives include corrosion protection allowing carbon steel construction, significant improvement of efficiency for CO₂ removal, and reduced construction footprint. These qualities lower both CAPEX and OPEX. The large number of existing custom-designed CATACARB® plants to date, along with ongoing support, troubleshooting, and data collection, allows CATACARB® to optimise designs and day-to-day performance for clients.

BENEFITS

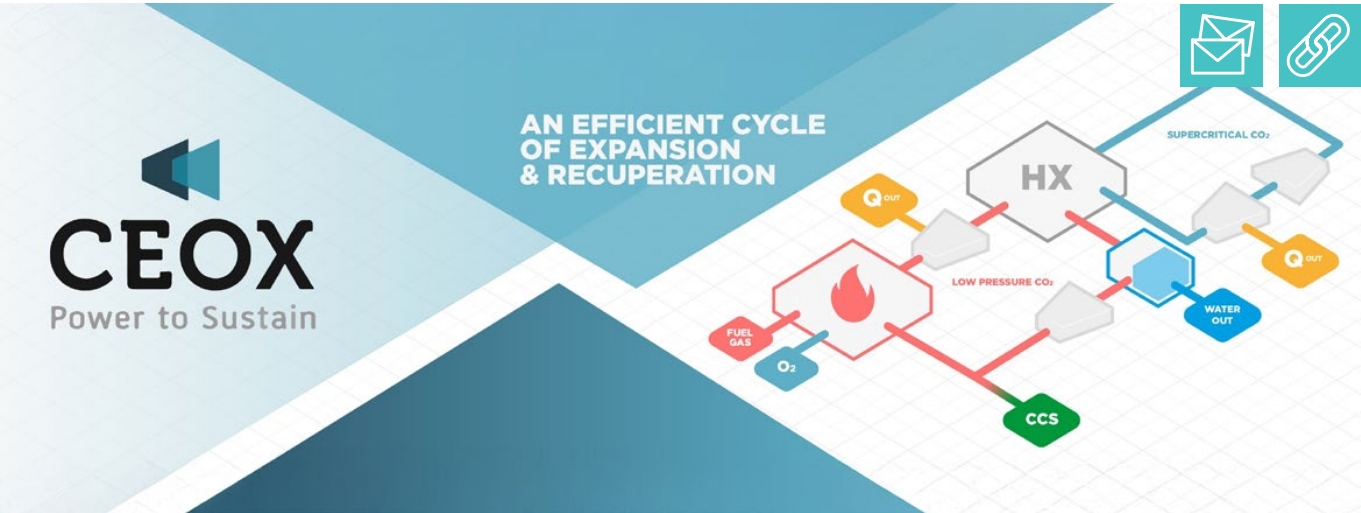
- CATACARB® prioritises health and environment. The HPC solution is non-volatile and the process forms no carcinogens. There is no solvent in the high purity captured CO₂.
- CATACARB® HPC with performance additives inhibits corrosion enabling carbon steel construction. The additives increase CO₂ removal efficiency 30-40% more than Basic HPC and do not degrade, thereby minimising solution makeup and decreasing OPEX. These qualities also allow a smaller footprint and lower CAPEX.
- Low energy requirements for solvent regeneration and reduced steam demand compared to other technologies allows for an electricity focus when needed. CATACARB® is a fully closed system capable of heat recovery for district heating.
- CATACARB® has vast experience and leverages data from ongoing support to over 150 clients in 34 countries totalling 35,000,000 plant operating hours.

KEY PROJECTS

- Stockholm Exergi's (SE) biomass-powered CHP plant Värtaverket in Stockholm Sweden licensed CATACARB® HPC technology. CATACARB® provided Enhanced HPC design for post-combustion CO₂ capture at 800 kta. CATACARB® is working closely with Saipem (SE's chosen provider for detailed engineering).
- Karbon Korea's 100% electric Demonstration Unit was built in 2023 capturing 1.5 tons per day of CO₂ with post-combustion capture rate of 90-96% at multiple sites in South Korea. HPC technology, design, and support provided by CATACARB®.
- Gulf Coast Growth Ventures has one of the world's largest EO plants in Gregory Texas and relies on CATACARB® HPC capturing 260 kta at a 90% CO₂ capture rate.
- The Pemex ammonia plant in Cosoleacaque Mexico entrusts CATACARB® HPC to capture 1250 kta at a 99.6% CO₂ capture rate.

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	201	Number of Pilot Plants	1 Flue Gas	Modular (Y/N)	Optional
Target Industries	Power (WtE, Biomass, CHP), Steel, Cement, Pulp & Paper, Refining & Petrochemical, Gas Processing				



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.

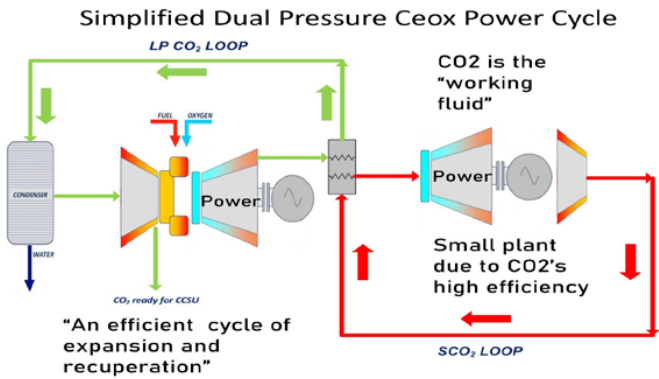
The post-oxy-combustion mix of CO₂ and water is inherently contained at pressure within the process, eliminating the need for CO₂ capture and compression. CEOX has application for any hydrocarbon power and heat generation, where a CCS network is available to dispose of the CO₂.

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 50MW modular power plant to pave the way for developing a full-scale demonstration plant.



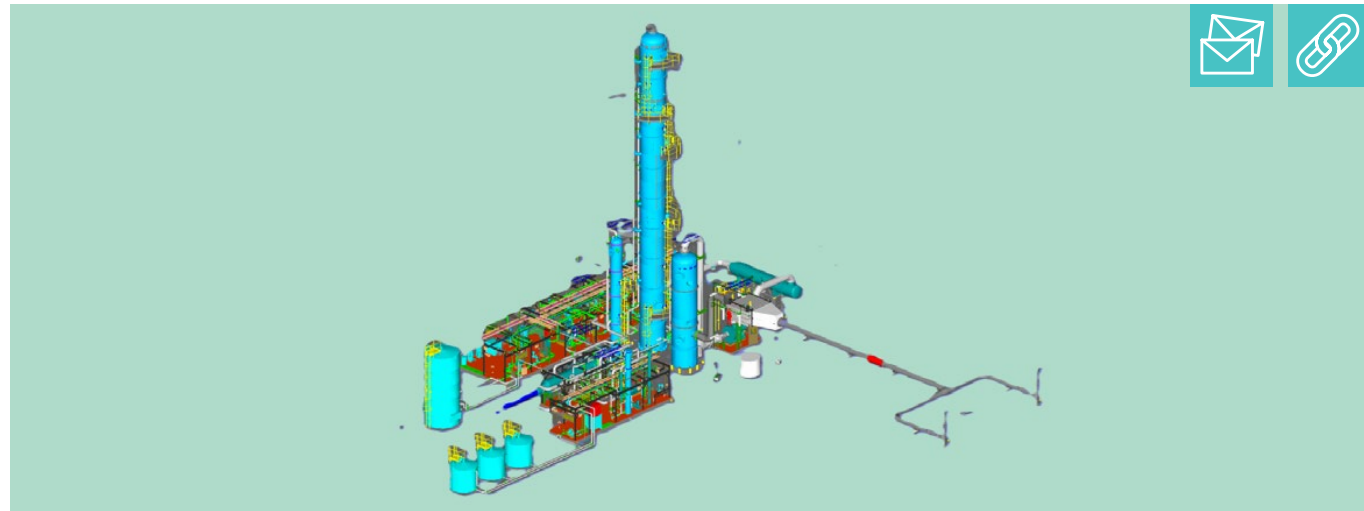
KEY DATA

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.				



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:** DELTA’s carbon capture and solvent reclamation modules are available from 1 to 1,200 TPD.
- **Simplicity:** Combining DELTA’s solvents with their modular carbon capture and solvent reclamation solutions greatly simplifies design and operation.
- **Affordability:** DELTA’s pre-engineered modular solutions and licensed open-access SolvX solvents are optimised to minimize both CAPEX and OPEX.
- **Performance:** DELTA can capture CO₂ from any post-combustion gas stream from 2.5 to 70% CO₂ (by volume) at recovery ratios up to 99%.
- **Solvent Availability:** DELTA’s SolvX licensed solvents are open source and commercially available locally with no royalty fees added.
- **Expertise:** DELTA’s team of professional engineers and designers are experienced with all aspects of carbon capture design, optimisation, and after-sale support and, as a member of the Scovan Group of Companies, now able to offer full engineering, procurement, fabrication, and construction services.

- **Maturity:** Technology readiness Level (TRL) is 9 and commercially available.

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				



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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SUMMARY

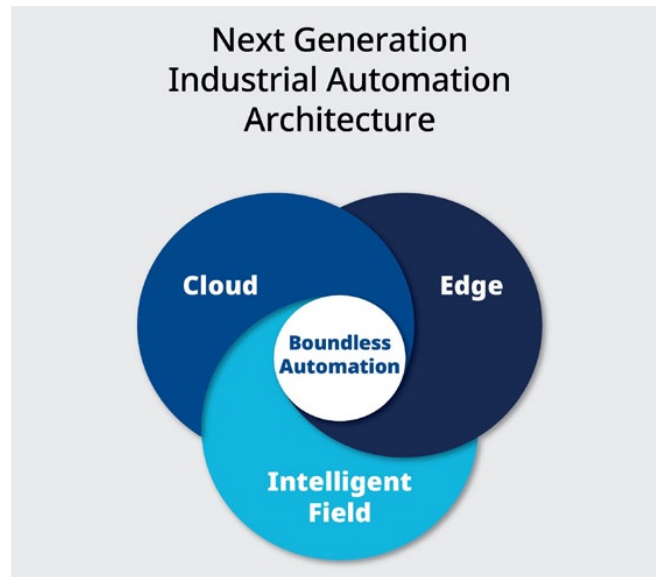
Carbon capture, utilisation and storage is a central part of many industry's efforts to reduce emissions and move toward achieving sustainability goals. To ensure a profitable and efficient operation, it will require an end-to-end solution that optimises automation processes. Global technology, software and engineering company Emerson provides this solution with its Boundless Automation™ next-generation architecture, which is designed to break down data silos, liberate information and unleash the power of the intelligent field and industrial software.

As companies wrestle to extract the incremental value from their decarbonisation efforts with technology stacks built around each functional department, islands of fragmented data are difficult to integrate or use.

To address this challenge Emerson's next-generation architecture will empower companies and drive operational excellence by removing silos with intelligent field devices, data-centric software, and flexible automation, delivering operational technology (OT) and information technology (IT) seamlessly across the enterprise.

BENEFITS

- Emerson's industrial computing ecosystem includes the flexibility to deploy software across the intelligent field, a software-defined edge, and the cloud.
- This allows carbon capture operations to leverage automation to its fullest potential with secure OT data access, putting data to work across layers to optimise process, reliability, safety, and sustainability simultaneously. New technologies and applications combined with carbon market needs – including “born digital” companies, decentralised operations and the move toward self-optimised plants – have created a new automation paradigm where a unified software environment streams data across the enterprise effortlessly, when and where it's needed.
- Emerson's software-defined automation architecture breaks down hierarchical networks, securely democratising and contextualising data enabling your business needs from artificial intelligence engines to providing a trail of auditable data for carbon monetisation. This technology mindset provides a foundation from the field to the boardroom for the future of data and automation in complex, disparate CCUS operations .



KEY DATA

TRL	9
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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.

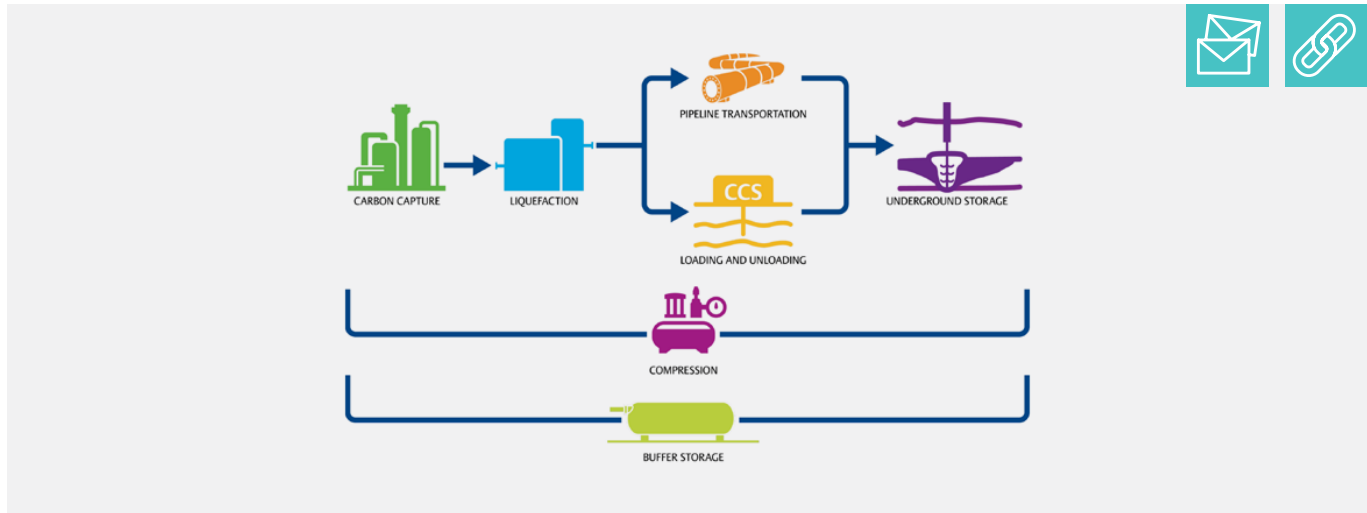


KEY DATA

TRL	9
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EMERSON AUTOMATION SOLUTIONS

PRESSURE SAFETY VALVES



SUMMARY

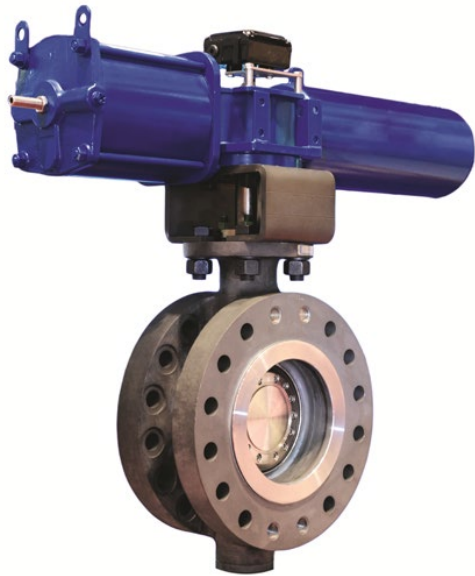
As carbon capture and storage (CCS) gains traction as a means of reducing emissions from large point sources, such as power plants and fuel processing facilities, it is critical for process manufacturers to specify and install equipment that facilitates efficient CCS, along with safe and reliable everyday 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.

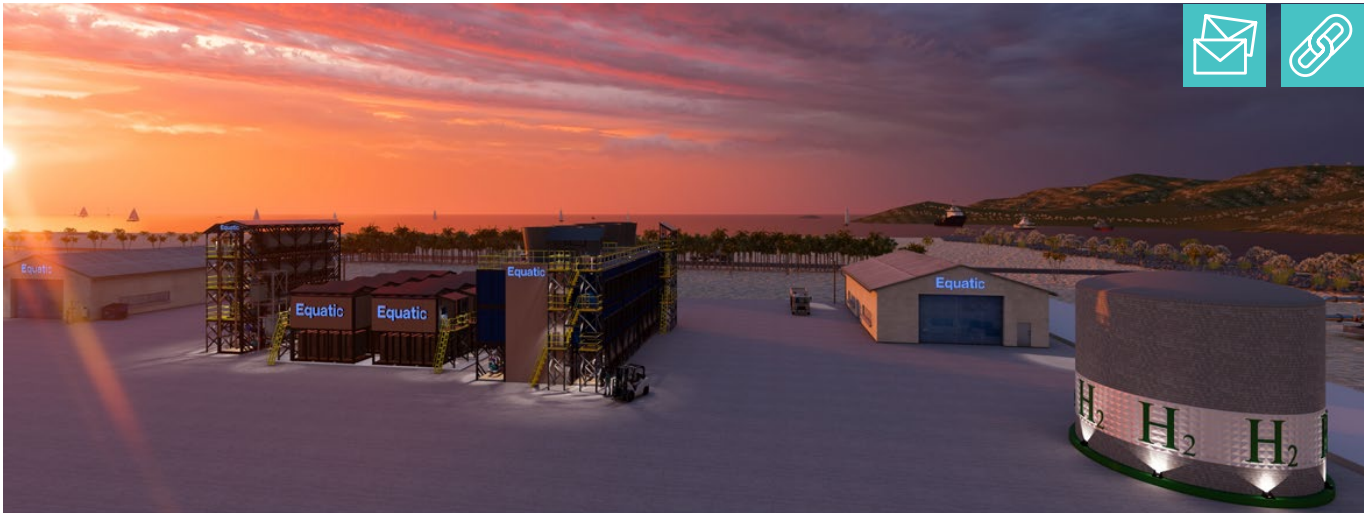
BENEFITS

- 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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SUMMARY

Equatic removes carbon dioxide from the atmosphere or from a point source. The process for doing this involves (1) seawater electrolysis with proprietary, oxygen-selective anodes, and (2) direct air contact to immobilise the CO₂ as (bi) carbonates. Green hydrogen is produced at a ratio of 30kg of H₂ for every 1 tonne of CDR. The immobilised carbon is stored permanently in the ocean for between 10,000 and 1 billion years.

BENEFITS

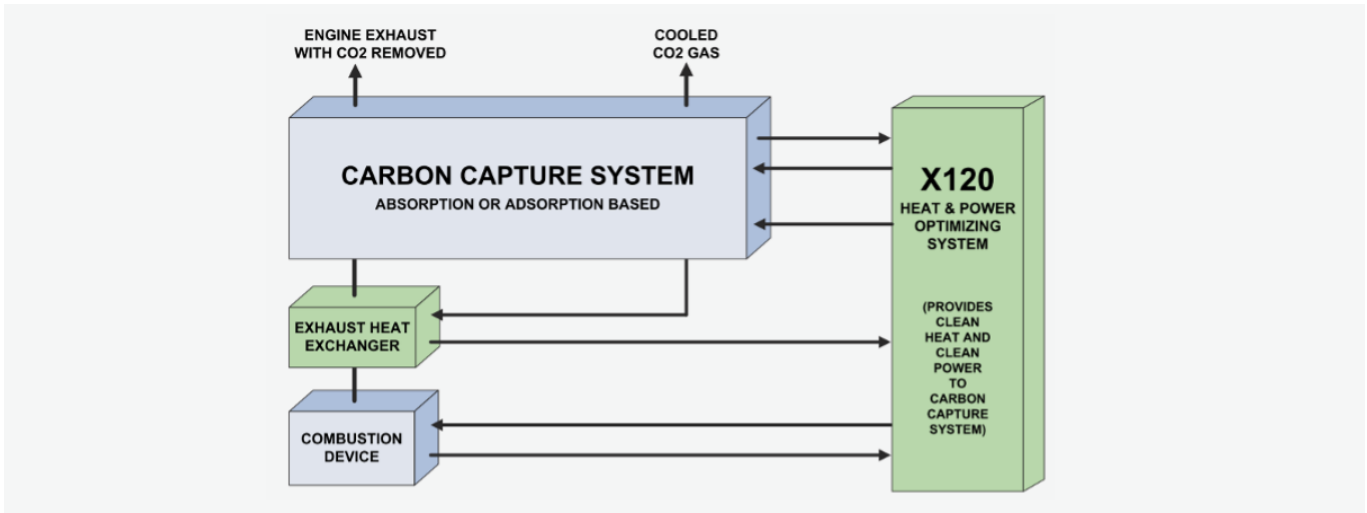
- **Low net energy intensity:** Equatic produces green hydrogen as part of the process, thereby lowering the net energy intensity to ~1.2 MWh/t CDR.
- **No storage or transportation costs:** Equatic stores immobilised carbon in the ocean, avoiding the costs and risks of CO₂ storage post-capture.
- **ISBL MRV:** Equatic measures the extent of the carbon drawdown within the boundaries of the plant and this forms the basis of the issuance of high-quality, verifiable CDR credits.
- **Flexible siting:** Equatic requires renewable energy, seawater, rock and air. The electrolyzers operate at ambient temperature and pressure, enabling use of intermittent renewables.

KEY PROJECTS

- **Equatic-1:** World’s largest ocean-based CDR plant under construction in Singapore in 2024. This plant has the capacity to generate 3,650 tpa CDR credits and 110 tpa green hydrogen.
- **Commercial Plant:** Currently in engineering stage, this 100,000tpa CDR plant will use the same, modular approach as Equatic-1 with multiple electrolyzers that each remove 1tpd of CO₂ and store it permanently as carbonates and bicarbonates. Operational by 2028.

KEY DATA

TRL	7	Capture Rate Range (tpd)	Each 100kW electrolyzer is 1TPD	Capture Efficiency (%)	>99%
Source CO ₂ Purity Range	>=0.04%	System Energy (GJ/tCO ₂)	4.3	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	2	Modular (Y/N)	Yes
Target Industries	Carbon dioxide removal, non-geologic CCS (gray to blue hydrogen or ammonia, steel, cement), green hydrogen				



SUMMARY

The X120 introduces a revolutionary approach to post-combustion carbon capture, merging waste heat recovery, ORC systems, and AI optimisation for net-zero emissions with exceptional cost efficiency. It tackles the dual challenges of energy efficiency and carbon recovery efficiency by:

1. Boosting ‘Net’ carbon recovery by ~1.5x by eliminating parasitic CO₂ loads from utilities (natural gas and electricity), achieving Scope 1 and Scope 2 reductions.
2. Cutting operating costs by approximately 50% by utilizing waste heat to produce the necessary heat and power the carbon capture system requires to operate, thus reducing or eliminating utility expenses.
3. When paired with a combustion device and carbon capture system, the X120 boosts capital recovery efficiency by ~10x, despite a 15% increase in capital costs, fostering rapid return on investment.

This technology is safeguarded by patents: US 20240042370A1 (granted January 14, 2025) and WO 2024/018441 A1 (pending in Europe and Canada) and is applicable across industries such as cement, steel, power generation and oil & gas. Its economic benefits position it as a transformative solution for achieving climate neutrality.

BENEFITS

- **Reduces Parasitic Electric Loads:** Because the ORC is recovering and using exhaust heat, the exhaust cooler and CO₂ cooler do less work (approximately 80% less load), therefore reducing the amount of electrical load consumed by the carbon capture system.
- **Retrofitting to Existing CCS:** Adaptable to any gas treating system, allowing integration with any absorption- or adsorption-based carbon capture system.
- **Scalable/Modular:** compatible with existing market equipment from 20 to 2500 tons/day of carbon capture, it utilises proven technologies.
- **AI-Enhanced Operation:** Utilises AI to optimise system performance and operation. Enhances CO₂ yield and minimizes energy consumption, via real-time adjustments.

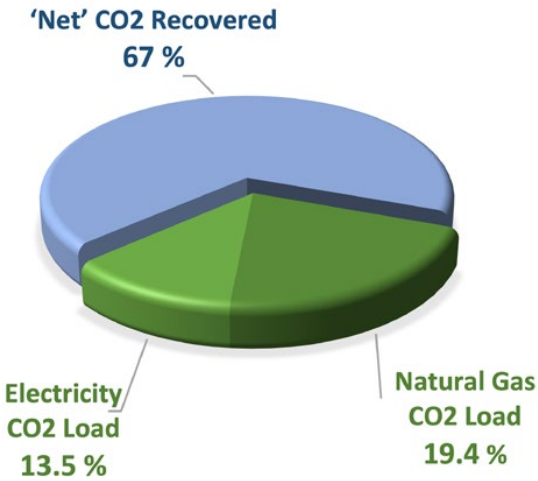


Figure 1: ‘Gross’ vs. ‘Net’ Carbon Recovered

KEY DATA

TRL	>5	Capture Rate Range (tpd)	20 - 2,500	Capture Efficiency (%)	99%+
Source CO ₂ Purity Range	>5%	System Energy (GJ/tCO ₂)	~0	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	~	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	All CO ₂ emitting sources in oil and gas, power generation, manufacturing, cement, etc.				

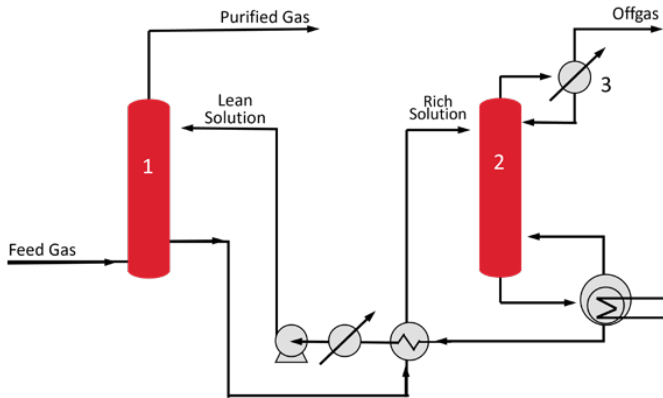


SUMMARY

Honeywell UOP Amine Guard™ process technologies combine high-performance solvents with Honeywell UOP engineering expertise for acid gas removal applications. Amine Guard processes are designed for applications of high-volume gases where removal of CO₂ and H₂S are present such as natural gas, syngas, gasification, blast furnace gases, and more, removing and purifying gases to meet specifications as appropriate. In Amine Guard processes, acid or flue gases are scrubbed out in an absorber column using UCARSOL solvent for the application. The rich solvent then flows from the bottom of the absorber through heat exchange process and is stripped out in a stripping tower, where the lean solvent is then recirculated to absorber for additional CO₂ absorption. In addition to CO₂ and H₂S, the thermal or flash regenerated solvent process removes COS and other Sulphur components.

BENEFITS

- UCARSOL solvent options enable optimised regeneration energy requirements for process conditions.
- Two-stage configurations can be implemented where appropriate for lower-energy operation.
- Minimal hydrocarbon, H₂, and CO losses due to low solubility in the solvent.
- Process optimisations, such as a flash-only solvent regeneration flow scheme for bulk CO₂ removal, are available to enable higher energy efficiency.
- Waste heat can commonly be utilised to provide the stripping steam.
- Amine Guard and Amine Guard Formulated Solvent (FS) is considered TRL 9 and has been in commercial operation since the 1990s with over 400 units worldwide.
- 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	400+	Number of Pilot Plants	~	Modular (Y/N)	No
Target Industries	Biomass Gasification, Coal Gasification, Natural Gas, Ammonia Syngas, Hydrogen Syngas, Synthetic Natural Gas, GTL Front End Treatment				

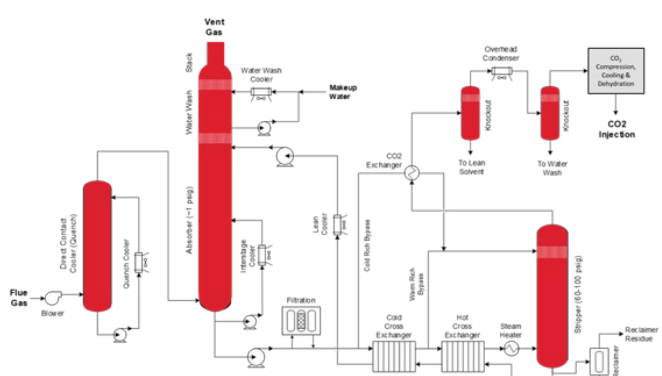


SUMMARY

For flue gas applications, Honeywell UOP offers Advanced Solvent Carbon Capture (ASCC) technology which is a second generation (2G) amine scrubbing process. ASCC is designed for applications of low concentration, high volume gases such as flue gas from power generation, cement, steel, industrial (boilers & fired heaters), pulp and paper, fluid catalytic crackers & more. In the ASCC process, Flue gases are scrubbed out in an absorber column using a proprietary solvent (AZ-108). The rich solvent flows through a patented series of heat exchange process and is stripped out in a high-pressure stripper, where the lean solvent is recirculated to the absorber for additional CO₂ absorption. ASCC can efficiently capture >95% of produced CO₂ from a variety of flue gas applications, including the flue gas output of coal fired power plants.

BENEFITS

- Reduced adsorber footprint can enable 30% lower capital expenditures.
- Low energy of regeneration requirements (2.1 Gj/MT of CO₂).
- Stripping at high pressure (6-8 barg) eliminates compression requirements, saving capital and operational expenditures.
- Backed by 20+ years of ongoing development and testing, 8,500+ hours of successful testing at the National Carbon Capture Center on flue gas range 2-15%, and additional testing at Technology Centre Mongstad processing 200 tons per day of flue gas from FCC and power generation.
- Honeywell provides extensive warranty and performance guarantees.
- 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	7	Capture Rate Range (tpd)	~	Capture Efficiency (%)	~
Source CO ₂ Purity Range	2 - 15%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	1.8 - 2.4
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				

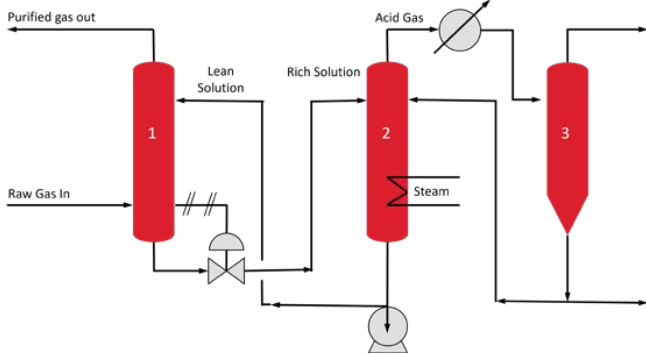


SUMMARY

Originally developed at the U. S. Bureau of Mines in the early 1950s, the hot potassium carbonate (HPC) process has been modified and optimised by Benson and Field and, subsequently, Honeywell UOP. The Honeywell UOP Benfield™ process is designed for applications of high-volume gases where CO₂ and H₂S are present, such as natural gas, ammonia syngas, hydrogen syngas, gasification, flue gases, partial oxidation, and more, removing and purifying gases to meet specifications as appropriate. Honeywell UOP's Benfield uses a thermally regenerated cyclical solvent process involving an activated, inhibited HPC solution, including additives for improved performance and corrosion prevention, to remove CO₂, H₂S and other acid gas components.

BENEFITS

- LoHeat and HiPure versions are available to reduce energy requirements or reduce flue and acid gases to very low levels.
- Optimise regeneration energy requirements through selection of optimum additives for the potassium carbonate solution.
- Waste heat can commonly be utilised to provide the stripping steam.
- TRL 9 and with over 700 units commercially operated worldwide—including widespread use in ammonia and hydrogen production, more than 50 natural gas plants, and direct iron ore plants—since the 1960s.
- 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.
- Available via 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)	~
Target Industries	Power, Steel, Cement, Refining & Petrochemical, Waste to Energy, BECCS, Pulp & Paper, Gas Processing, & Industrial Flue Gases				

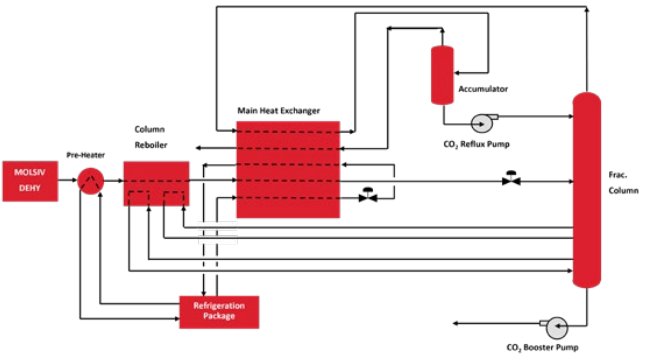


SUMMARY

Honeywell UOP's CO₂ Fractionation technology is an all-electric solvent-free option that captures CO₂ as a high-purity liquid product. Honeywell UOP's Cryogenic Fractionation technology uses temperature and pressure controls to separate materials of varying boiling points and isolate specific chemicals from a given industrial process stream. It is designed for applications of recovery of natural gas liquids (NGL), liquified petroleum gas (LPG), liquified natural gas production (LNG), refinery off gas and carbon capture to meet pipeline specifications. When applied to CCUS, CO₂ is condensed out while the rest of the process stream remains in a gaseous state. The Orloff Dual Refrigerant CO₂ Fractionation (DRCF) provides bulk CO₂ removal and liquid product recovery while reducing energy consumption.

BENEFITS

- All electrically driven technology.
- High purity liquid product which can be pumped to the desired pressure for transport and storage.
- Lower equipment counts and reduced plot area relative to amine solutions.
- Potential to combine with a physical solvent, like Selexol™, a PSA, or a membrane system for optimised and integrated carbon capture flow schemes.
- TRL 9 with more than 400 units commercially operated since 1976.
- 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	400+	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Blue Hydrogen, Blue Ammonia, Steam Craker, Steel, Cement, Refining & Petrochemical, and Gas Processing				

Honeywell

HONEYWELL

POLYBED™ PRESSURE SWING ADSORPTION (PSA)

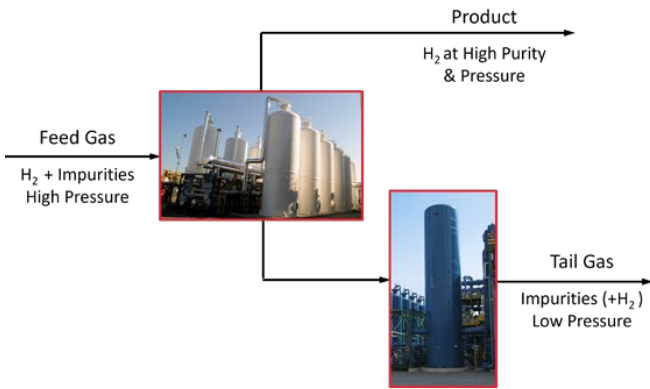


SUMMARY

The Polybed™ Pressure Swing Adsorption (PSA) System is optimised for H₂ purification and CO₂ rejection. It uses a series of pressurization and depressurization cycles with a bed of adsorbents to selectively provide high-pressure and high-purity hydrogen from a wide variety of gas streams. PSA technology can completely adsorb impurities enabling production of high purity hydrogen (typically 99.9+ mol-%) in a single unit with little consumption of utilities, contrary to the traditional multiple-unit flow schemes utilizing acid gas removal wash systems and methanation reactors. Units contain between 4 to 16+ absorber vessels, where one or more vessels is on adsorption step while others are in various stages of regeneration. All systems use advanced proprietary adsorbents and patented void-gas recovery techniques to provide maximum product recovery. The technology is thoroughly proven, with the first commercial PSA unit going on stream in 1966. Today, more than 1,150 Honeywell UOP PSA systems have been designed, fabricated and delivered worldwide. PSAs can also be selective for CO₂ capture in post-combustion applications.

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 modularized 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	1150	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Blue Hydrogen, Blue Ammonia, Steam Craker, Steel, Cement, Refining & Petrochemical, and Gas Processing,				

Honeywell

HONEYWELL

POLYSEP™ MEMBRANES

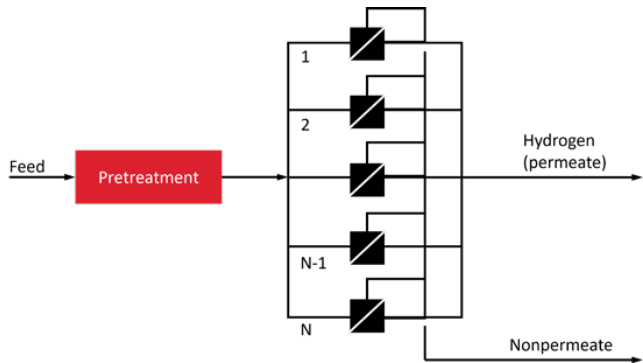


SUMMARY

Honeywell's Polysep™ systems combine state-of-the-art composite membrane technology with advances in polymer science for hydrogen recovery and purification or rejection. The Polysep membranes offer separation characteristics (permeability, selectivity, and contaminant resistance) that allow optimal system designs to fit a variety of process needs. Applications include refinery streams such as catalytic reformer off-gas, hydrotreater and hydrocracker purge gases, and fluid catalytic cracker off-gas, as well as petrochemical and chemical process streams like ethylene off-gases, ammonia plant purges, methanol plant off-gases, synthesis gas streams from steam reforming, partial oxidation and other gasification technologies. Polysep membrane systems are modular units containing hollow fiber membrane cartridges optimised for mechanical integrity and flow distribution. The cartridges are housed in modules, which are mounted on a skid in series or parallel configurations depending upon feed gas volume and product requirements. High membrane packing density minimizes system size and cost. Polysep features a pressure-driven process that minimizes moving parts and operator involvement, making it an innovative solution with applications in various industries.

BENEFITS

- Automatic startup.
- Capacity and product purity controls.
- Auto depressurization and turn-up / turn-down.
- Hollow fibers are packed in a proprietary counter-current-flow bundle configuration that maximizes the separation driving force and minimizes required membrane area.
- Pressure driven process requires minimum moving parts, utilities or operator intervention.
- TRL 9 with more than 85 commercially operated units since 1985—the largest of which processes more than 350MMscfd of synthesis gas.
- 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	85	Number of Pilot Plants	85	Modular (Y/N)	Yes
Target Industries	Refining & Petrochemical, Waste to Energy				

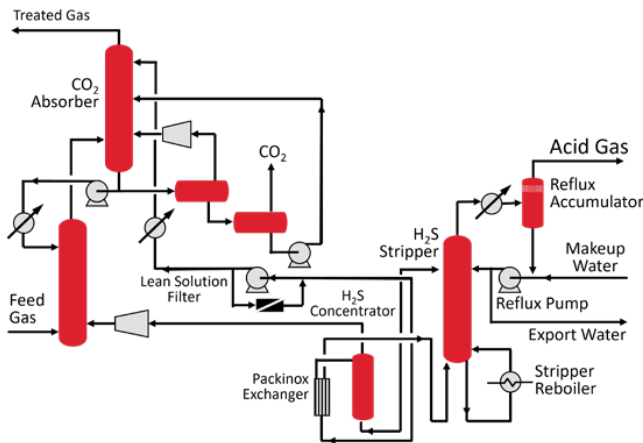


SUMMARY

The SeparALL process is a well proven commercial process that is driven by partial pressure and uses Honeywell UOP’s Selexol™ physical solvent, comprised of dimethyl ethers of polyethylene glycol, to remove acid gases from synthetic or natural gas streams. Applicable processes include coal or biomass gasification, natural gas, ammonia syngas, hydrogen syngas, hydroprocessing upgraders, synthetic natural gas, chemicals, fertilizer and molecular sieve regeneration in CNG, LNG, and GTL front end treating removing and purifying gases to meet specifications as appropriate. It is ideally suited for the selective removal of H₂S and COS and/or CO₂ to very low levels in the treated gas. Low Sulphur levels can be achieved with variable and optimised CO₂ capture levels. The SeparALL process can be tailored and optimised for either bulk or trace acid gas removal.

BENEFITS

- SeparALL process efficiency is typically high in CO₂ capture service, with removal efficiencies of up to 99%.
- Reliable and easy to operate process with >99% on-stream availability.
- Operators report simple startup with plants being brought online within 2 to 3 hours.
- Chemically inert Selexol solvent is not subject to degradation.
- Reclaiming and/or purging of solvent is not required.
- Low corrosivity without the use of corrosion inhibitors.
- Proven TRL 9 process, with more than 110 units having begun commercial operation worldwide since the 1960’s.
- 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	110	Number of Pilot Plants	~	Modular (Y/N)	No
Target Industries	Blue Hydrogen, Blue Ammonia, Steam Craker, Refining & Petrochemical, and Gas Processing, Biomass & Coal Gasification				

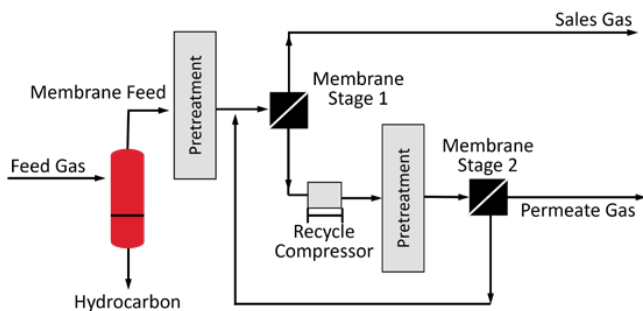


SUMMARY

Separex™ membranes are a bulk purification technology used to remove CO₂ and water from natural gas. They also remove H₂S in roughly the same proportion as CO₂. Hybrid systems, with membranes performing bulk removal of CO₂/H₂S followed by a solvent unit to meet low level specs are economically attractive. Separex membrane systems are designed for high, partial-pressure CO₂ capture in industrial applications. They are compact and lightweight, making them easy to install and operate, and can be used for a wide variety of gas streams. Separex systems are particularly well suited to remote locations where logistics are challenging. The ‘single stage’ design has no moving parts and is very low maintenance. They have simple, rapid startups and shutdowns and very high reliability. For offshore applications, Honeywell UOP modular designs are smaller and lighter, lowering the total installed cost.

BENEFITS

- Designed for operational simplicity, requiring minimal rotating equipment, no chemical reagent or replacement, and minimal services
- Technology is delivered on prefabricated skids to minimize cost and plot space
- Proven TRL 9 process, with more than 150 units having begun commercial operation worldwide since 1981
- 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	150	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Gas Processing, Biogas Upgrading, Renewable Natural Gas				

KEPCO

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 fuel with air. In this 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 90% 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. Jointly designed by KEPCO RI and the Korea Institute of Energy Research (KIER), and constructed by Hyundai Heavy Industries Power Systems (EPC), the facility will support the design and development of a 100 MWth commercial boiler and power system 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-based power, 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 1 MW 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				



SUMMARY

Messers carbon capture technology utilises advanced amine-based solvents to efficiently capture CO₂ from flue gases. This system achieves high capture rates even at low CO₂ concentrations (>4%), delivering highest CO₂ purity exceeding >99.9%, always reaching the specification requested for transport or storage. Its scalable design accommodates capacities from 60 to 3,000 tpd, suitable for various industrial applications. The technology enables flexible energy integration (e.g. use of process heat) to significantly reduce or even completely eliminate the need for additional thermal energy. The specially formulated carbon capture solvent is resistant to oxygen degradation, enhancing system efficiency and longevity. By converting flue gas emissions into high-purity CO₂, this solution provides a reliable and sustainable approach to carbon capture.

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.

KEY PROJECTS

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				



SUMMARY

MTR Carbon Capture, a division of Membrane Technology and Research Inc., has developed the Polaris® membrane carbon capture technology over the past 17 years with significant support from the U.S. Department of Energy (DOE). This modular, environmentally-friendly capture approach has been validated in a series of progressively larger field tests accumulating thousands of operating hours at coal power plants and other industrial sites over the last decade. Recently, a 150 tonnes CO₂/day (TPD) demonstration system was designed, built and started operation in early 2025 at a coal power plant in Wyoming, USA. This system – the largest membrane capture plant in the world – recovers up to 90% of the CO₂ in the flue gas and produces pipeline-quality liquid CO₂. MTR is currently engaged in multiple engineering studies, Pre-FEEDs, FEEDs and piloting activities for power and industrial projects in Europe, Scandinavia, North America and Asia.

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 much 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 in will start operation in late 2025 in Taiwan.

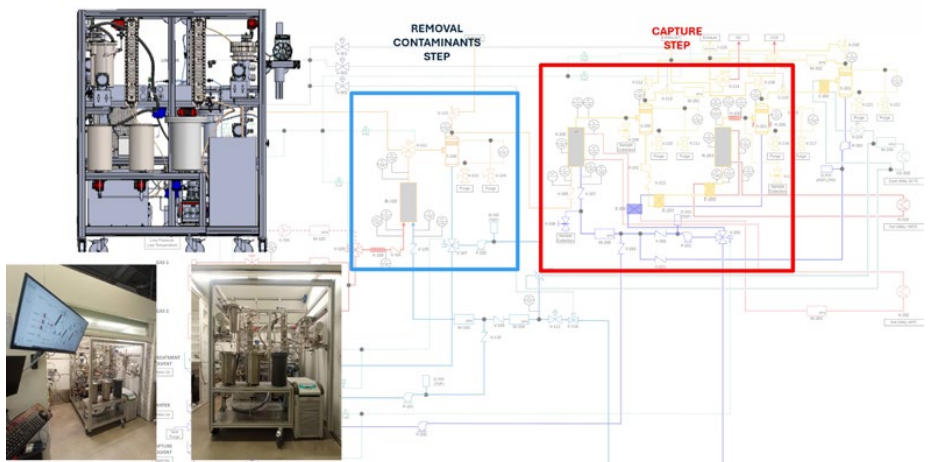
KEY DATA

TRL	8	Capture Rate Range (tpd)	30 - 3,000	Capture Efficiency (%)	50 - 95%
Source CO ₂ Purity Range	8 - 25%	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)				



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 optimising regeneration while reducing excess solvent use.

NetCap is currently being validated at an industrial setting, within the glass industry, in Porto, Portugal, where it is treating flue gas volumes ranging from 12 to 50 kg/day (see image below).

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 15%, validated with industrial gases from the ceramic and glass industries.
- **High CO₂ capture performance:** Achieves at least 90% CO₂ capture and 98-99% CO₂ purity.



KEY DATA

TRL	6*	Capture Rate Range (tpd)	~	Capture Efficiency (%)	>90%
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)	Yes
Target Industries	Glass, Ceramics, Chemicals, Food and Beverage, Pharmaceuticals, Plastics, and Biogas.				

* A pre-industrial unit is currently operating at BA Glass facilities in Porto, Portugal, treating 50 kg/day maximum of flue gas and moving to meet TRL 7.



NOVOMOF AG

DISRUPTIVE MOF-BASED CO₂ CAPTURE TECHNOLOGY



SUMMARY

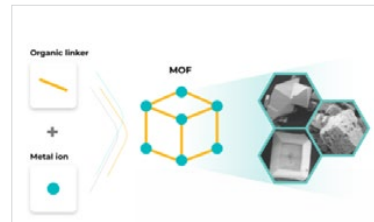
Disruptive CO₂ capture technology surpassing state-of-the-art capture cost.

novoMOF's disruptive technology delivers significant CAPEX and OPEX savings, enabling smaller, less capital-intensive capture units and reducing energy demand by 2-3x 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 seamlessly integrates with TSA, VPSA, PSA, and TVSA processes, ensuring adaptability across different flue gases and industrial setups.

Our proprietary, industrially scalable Metal-Organic Frameworks (MOFs) provide a low-cost, scalable, and eco-friendly alternative to conventional amine scrubbing. With **high adsorption capacity and efficient regeneration**, MOFs make CO₂ capture both affordable and sustainable, setting a new benchmark in carbon capture efficiency for industries seeking cost-effective decarbonisation.

BENEFITS

- **Significant CAPEX Savings:** Flexible MOFs adapt to various flue gases and capture processes (TSA, VPSA, PSA, TVSA).
- **Lower OPEX:** Unique material properties drastically cut energy consumption.
- **2-3x Lower Energy Demand:** Compared to conventional amine-based systems.
- **Low-Temperature Regeneration:** reduces energy costs.
- **Low-Pressure Regeneration Capability:** Further reducing operational expenses.
- **Compact & Cost-Effective Capture Units:** Smaller, modular systems reduce infrastructure investment.
- **Optimised for Humid Conditions:** No need for expensive flue gas drying.

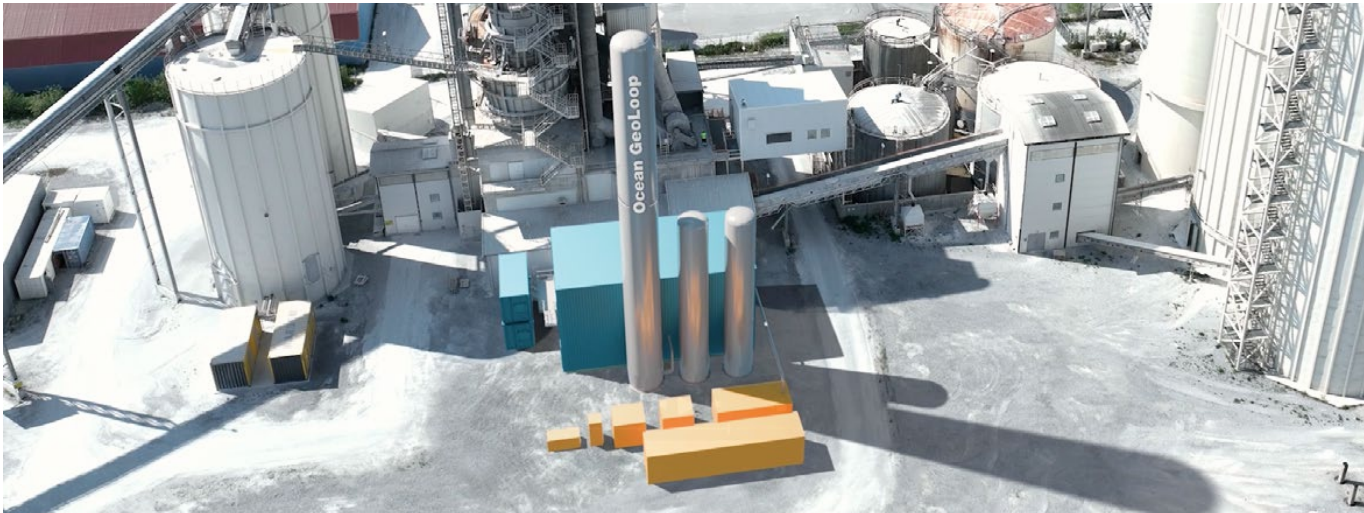


KEY DATA

TRL	6	Capture Rate Range (tpd)	1 - 4,000	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	1 - 20%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	1.9
Number of Commercial Plants	0	Number of Pilot Plants	~	Modular (Y/N)	Yes
Target Industries	Power Generation, Steel, Oil & Gas, Chemicals, Cement, Glass, Ceramics, Chemicals, Maritime, Transport				



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 maximizes 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. Planning for realization of demo plant.
- Planned feasibility study for a 40,000 tpa carbon capture plant at the recent expansion of Yara’s calcium nitrate plant at Herøya, Norway.
- 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

With Advanced Amine Technology from Pentair, carbon dioxide can be captured from any gas stream based on the combustion of fossil fuels. References include steam reformer flue gas, combustion of municipal waste, natural gas, LNG and biomass-fired steam boilers, natural gas-fired gensets, and gas turbines.

Moreover, the technology has been applied to capture carbon dioxide from non-power generation sources, such as lime and cement kilns.

The capture plants from Pentair are based on the most well-proven absorption technology currently available on the market, namely mono-ethanolamine (MEA) in high concentration.

Furthermore, the purification steps in the compression and liquefaction plant downstream of the amine unit purify CO₂ from various sources, ranging from food-grade through CO₂ for sequestration to even medical and electronic grade CO₂.

BENEFITS

- Open-source solvent that has been thoroughly studied for decades, mapping subjects like ATEX considerations, trace emissions to the atmosphere, and HSE and where the active ingredient can be sourced worldwide.
- Several in-house proprietary associated technologies for combatting NO_x both in terms of solvent degradation and carry over to CO₂ product; for minimizing the need for steam consumption and for solvent maintenance and reclaiming.
- Decades of experience in CO₂ capture from flue gases for the production of food-grade CO₂.

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				



SUMMARY

Revcoo's CarbonCloud® technology represents a significant advancement in Carbon Capture, Utilisation, and Storage (CCUS). This innovative cryogenic technology captures flue gas carbon dioxide (CO₂) at low concentrations and converts it into high-purity liquid CO₂. Its versatility allows integration with various industrial processes and installation sizes, making it a promising solution for immediate deployment. The pilot stage trial at BOCAHUT establishments, part of the EIFFAGE group, aims to evaluate the practical application and effectiveness of CarbonCloud® in an operational environment, designed to produce 2 tons of liquid CO₂ per day. This trial involves integrating the technology into existing industrial installations to capture and condition CO₂ emissions from flue gases. The primary objectives are to assess operational challenges, efficiency, and scalability. Preliminary results indicate that CarbonCloud® can significantly reduce CO₂ emissions, demonstrating its potential for broader implementation in industrial settings.

The the CarbonCloud® Pilot stage trial has yielded several key findings. Firstly, the technology has demonstrated high efficiency in capturing CO₂ from industrial flue gases, achieving over 95% recovery rates. Secondly, the integration of CarbonCloud® into existing installations has proven operationally feasible, causing minimal disruptions to ongoing processes. Additionally, the technology can be scaled up effectively, making it suitable for larger industrial applications. The trial has shown that the technology can be deployed at a relatively low cost, offering a cost-effective solution for CO₂ emissions reduction. Finally, the captured CO₂ is converted into high-purity liquid CO₂, which can be utilised in various applications. Overall, CarbonCloud® offers a cost-effective and efficient approach to reducing CO₂ emissions in industrial environments.

BENEFITS

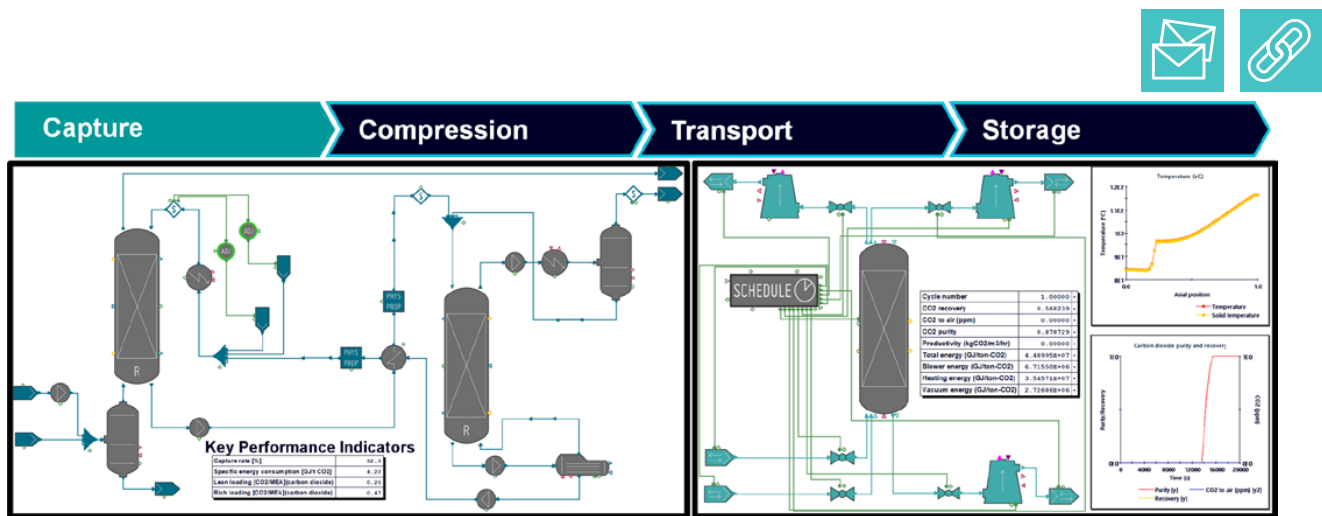
- Innovative technology:** The CarbonCloud® solution uses a patented cryogenic process that operates without solvents or polluting emissions, effectively capturing industrial CO₂ while minimizing environmental impact.
- Simple and adaptable installation:** Designed to be installed without major modifications to existing infrastructure, the system easily integrates into industrial sites, enabling to extract ready to use ultrapure CO₂.
- Minimal consumption and low environmental footprint:** The technology runs solely on electricity, requiring no water or chemical products. This significantly reduces its ecological footprint, making it one of the cleanest and most resource-efficient carbon capture solutions on the market.

KEY DATA

TRL	7	Capture Rate Range (tpd)	>2	Capture Efficiency (%)	>95%
Source CO ₂ Purity Range	10 - 90%	System Energy (GJ/tCO ₂)	~	Specific Regen. Energy (GJ/tCO ₂)	~
Number of Commercial Plants	0	Number of Pilot Plants	1	Modular (Y/N)	TBC
Target Industries	Lime, Cement, Biomass boilers, Waste to energy, Chemistry				

KEY PROJECT

- Key Project – First Pilot Unit Deployment:** In 2025, Revcoo is finalizing the deployment of its first pilot unit at an industrial site in France. The CarbonCloud® system is being installed to capture CO₂ emissions from a mid-sized heat treatment facility, with a target capture efficiency of up to 95%. Fully electric, solvent-free, and water-free, the system demonstrates Revcoo's commitment to low-impact, modular decarbonisation solutions. This pilot will serve as a launchpad for commercial-scale installations across various hard-to-abate 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

- 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.



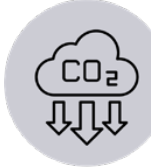
Solvent-based capture:
Model standard solvent CO₂ capture processes for optimal performance



Solvent Regeneration via electro dialysis:
Simulate advanced regeneration methods to minimize energy use



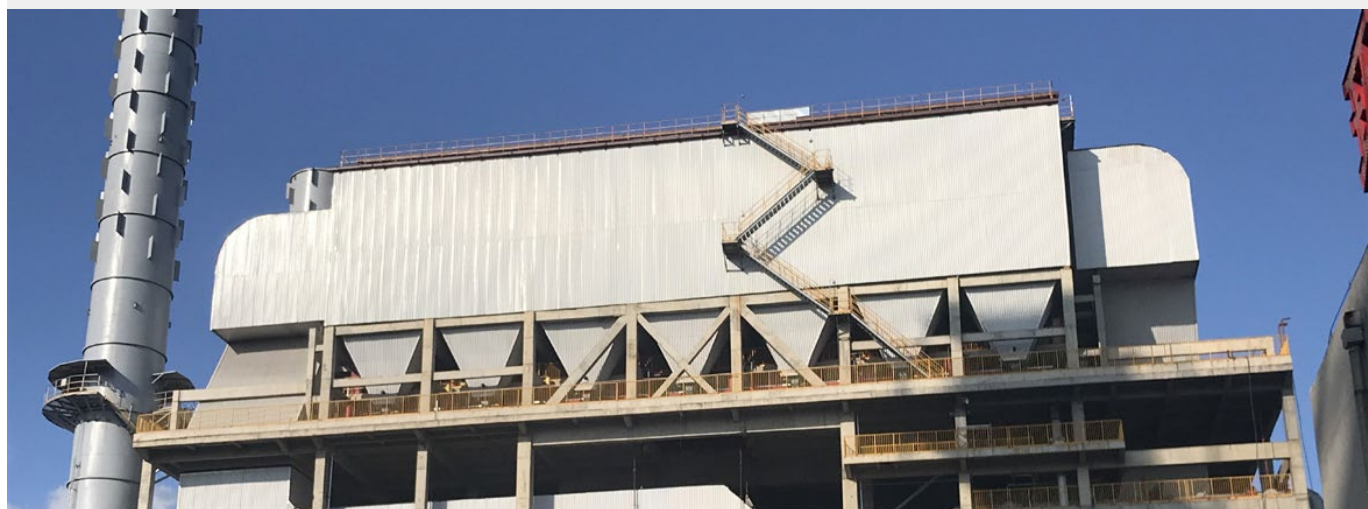
Adsorption (PSA and TSA):
Optimize adsorption-based CO₂ capture through PSA/TSA cycle simulations



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.				



SUMMARY

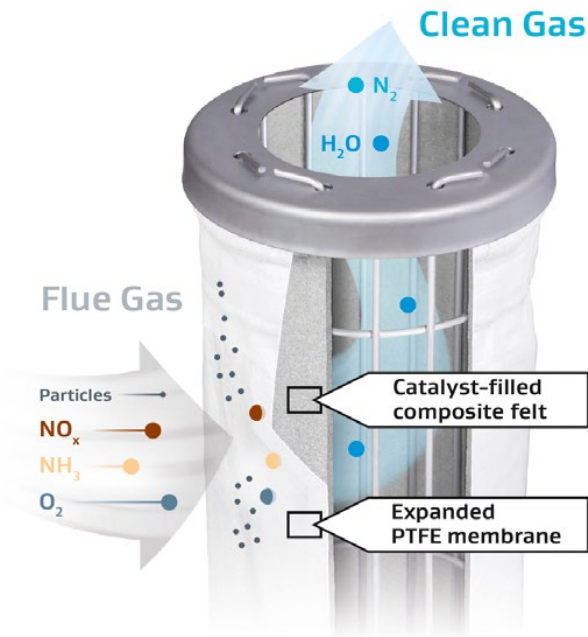
Choosing CCUS Pretreatment can be complex. Flue gas characteristics are different at every industrial plant. Particulate (PM), NOx and SOx complicate operation, causing solvent degradation, nitrosamine emissions and equipment corrosion, affecting CCS efficiency and cost. Even trace impurities can make 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® DeNOx 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® DeNOx 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

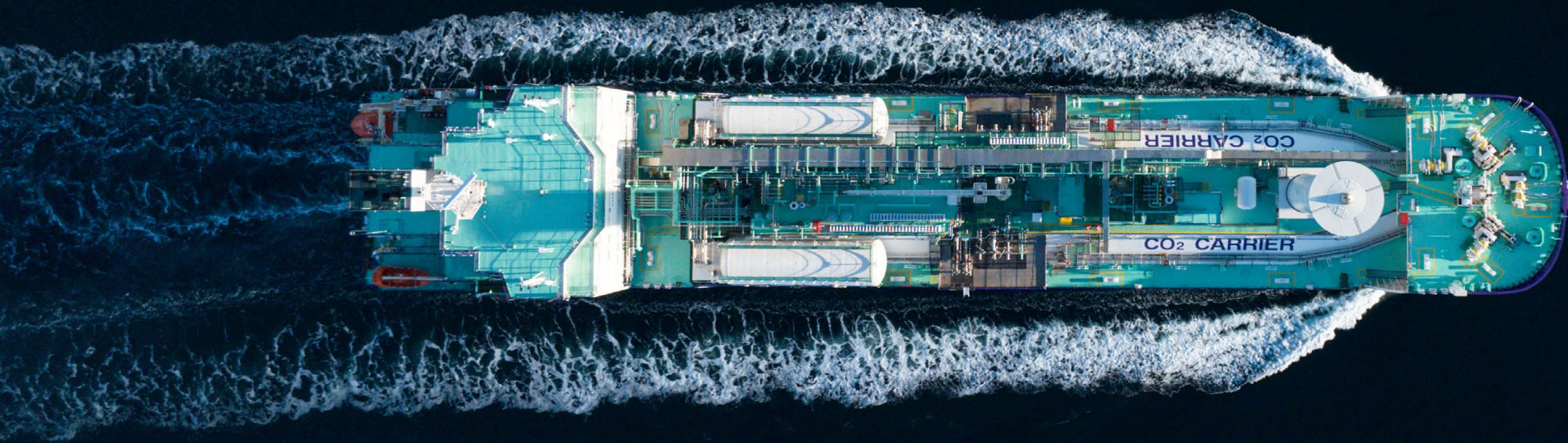
- **Fewer Unit Operations:** One baghouse acts as an FGD, SCR and filter combined, to remove NOx, SOx, and PM from the flue gas. With only one unit, CAPEX, OPEX and footprint are minimized.
- **Lower Operating Cost:** More than 95% reduction in NOx, SOx and PM can be reliably achieved at a low pressure 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.

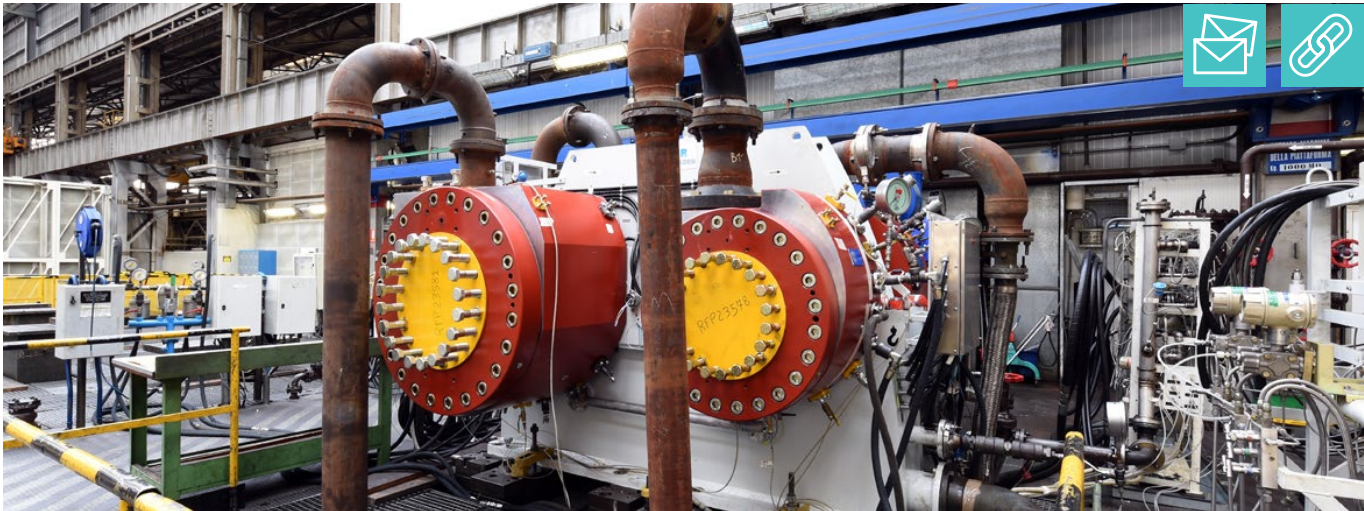


KEY DATA

TRL	9
Target Industries	Cement, Lime, Steel, Waste to Energy (WTE), Chemicals, Coal-fired Boilers

TRANSPORT





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.



SUMMARY

Baker Hughes can deliver technological pumping solutions that accomplish the end users’ stringent requirements and best fit variable operating conditions which characterize 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 characterized 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 pressurized 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.



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.



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 pressurized 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

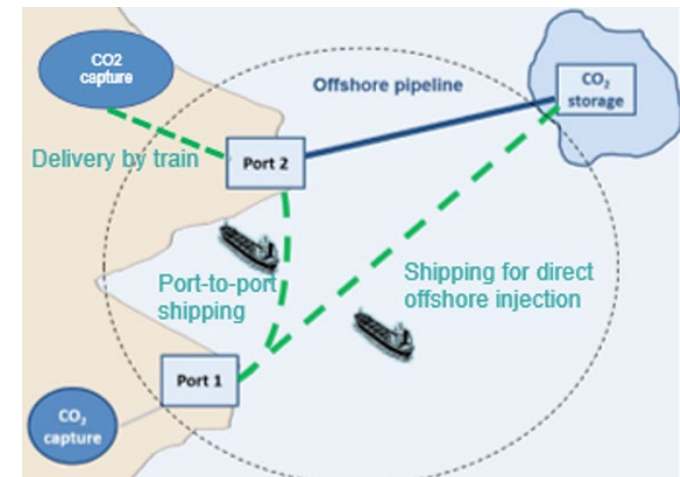
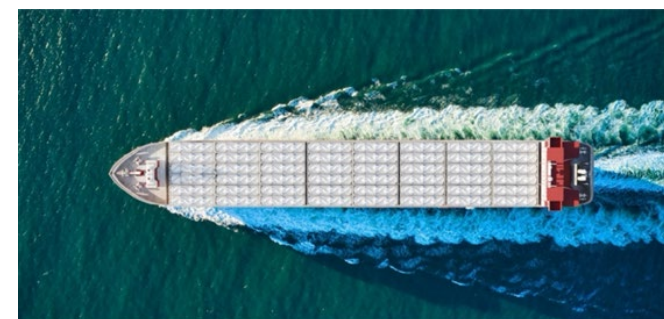
Our innovation begins with the fabrication of a non-load-sharing stainless steel liner, engineered for high pressure conditions and long-term durability. Using high-precision manufacturing and welding techniques, we ensure gas-tightness even after tens of thousands of fatigue cycles.

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 pressurized 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, decentralized, 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.



SUMMARY

Knutson NYK Carbon Carriers AS ("KNCC") is a joint venture company between Knutson 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.

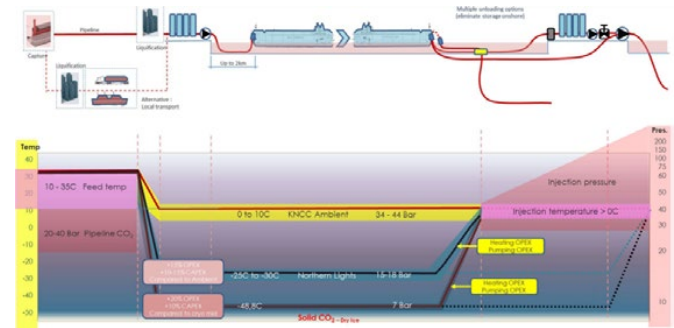


Figure 1: Energy conditions of LP/MP/EP through CCS value Chain

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.

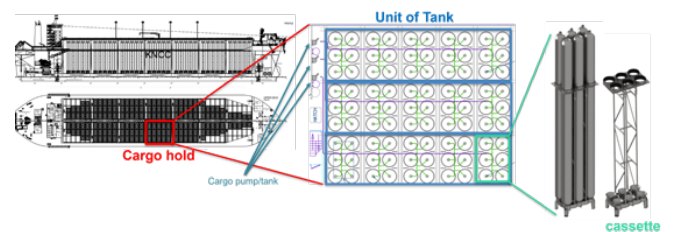


Figure 2: CTC arrangement sample for a LCO₂-EP

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

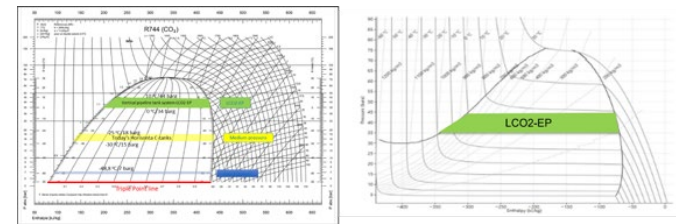


Figure 3: Phase diagram (pure CO₂, 99%CO₂/0.5%H₂/0.5%N₂)

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

HIGH PRESSURE INTEGRALLY GEARED CENTRIFUGAL COMPRESSOR



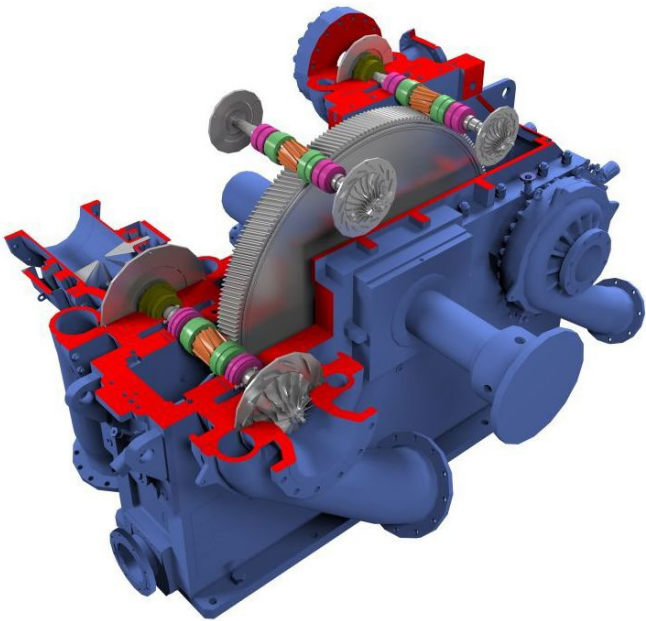
SUMMARY

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

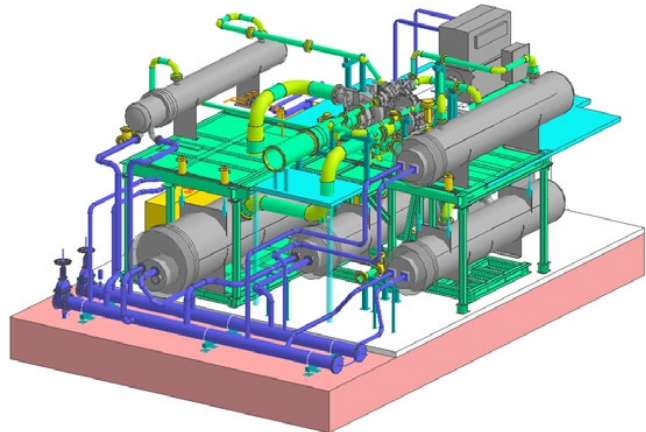
KOBELCO is one of the leading steel manufacturers in Japan, as well as a major supplier of aluminium and copper products. Other business segments include machinery, construction machinery, power supply, and others.

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.

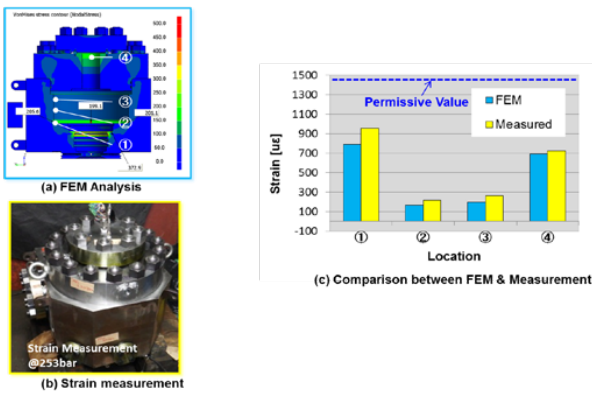


Figure 1: FEM Analysis and Strain Measurement Results of Compressor Casing



LINDE 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.

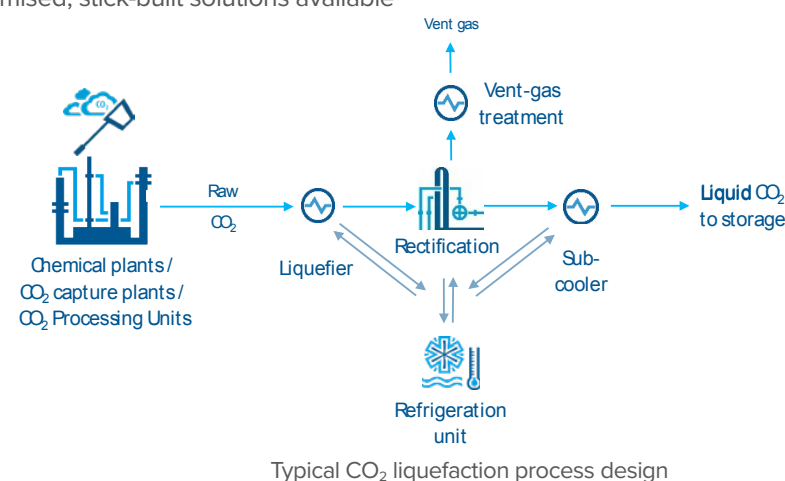
Linde's largest liquefaction plant, in operation since 2015, is producing approximately 1,350 tons of CO₂ per day. The CO₂ is used in enhanced methanol and urea production. Additional large-scale plant references can be found in Norway and the United States for carbon capture and storage (CCS) and food 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.



KEY DATA

TRL	9
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LINDE 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.

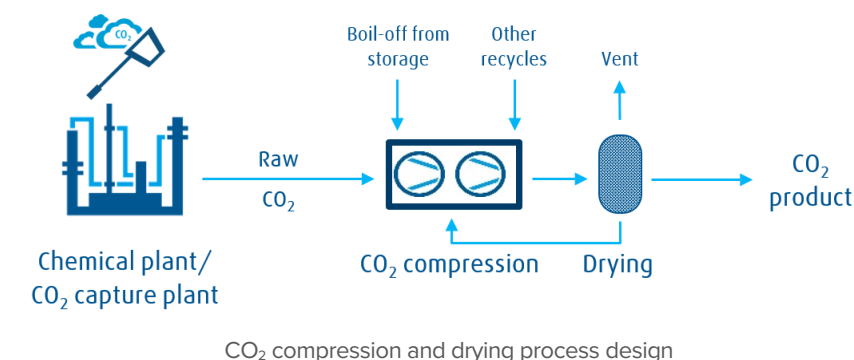
Compressor stations not only compress the main CO₂ feed gas stream, but can also be used to integrate and compress boil-off gases from storage tanks and other CO₂-rich vents from the plant.

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.



KEY DATA

TRL	9
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CO₂ PROCESSING UNIT



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.

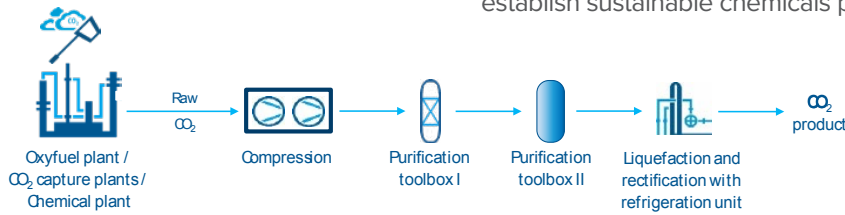
Linde initially developed and commercialised the CPU technology to treat oxy-fuel flue gases at an oxy-fuel lignite-fired power plant at Schwarze Pumpe, Germany. More recently, Linde's CPU has been considered for oxy-fuel projects in the cement industry. Mature CO₂ processing technologies in combination 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

- Recently, Linde has signed an Engineering, Procurement and Construction (EPC) contract with the CI4C consortium, which is made up of four major European cement producers. The contract is for the construction of the first-ever CO₂ capture and processing plant downstream of an oxyfuel cement process at an existing cement plant in Mergelstetten, Germany.
- 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				



CO₂ TANK FARM AND LOADING STATIONS

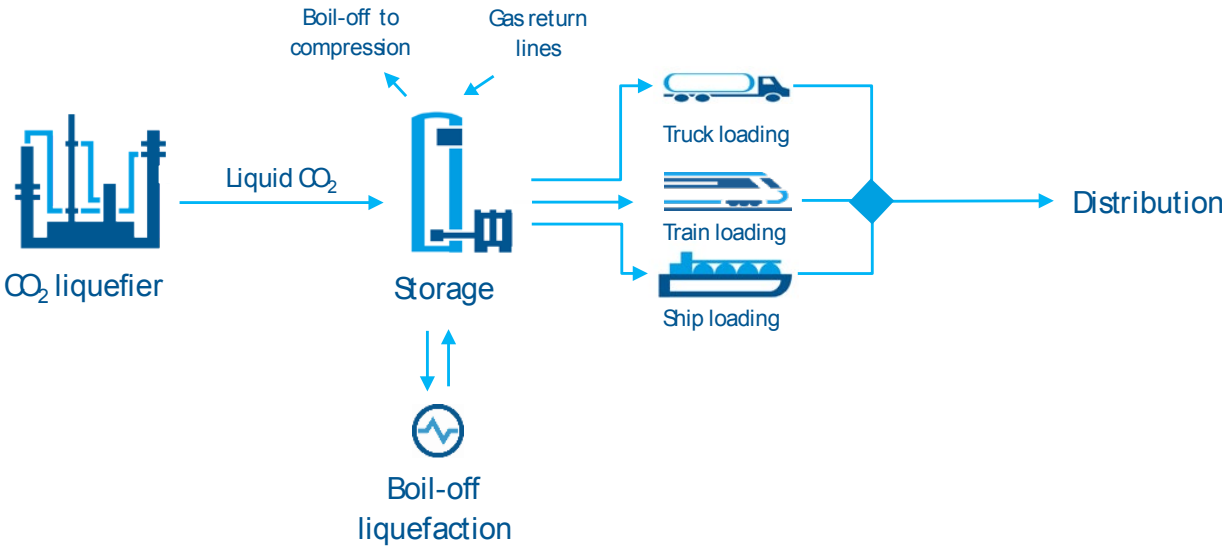


SUMMARY

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
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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.



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				



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
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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)

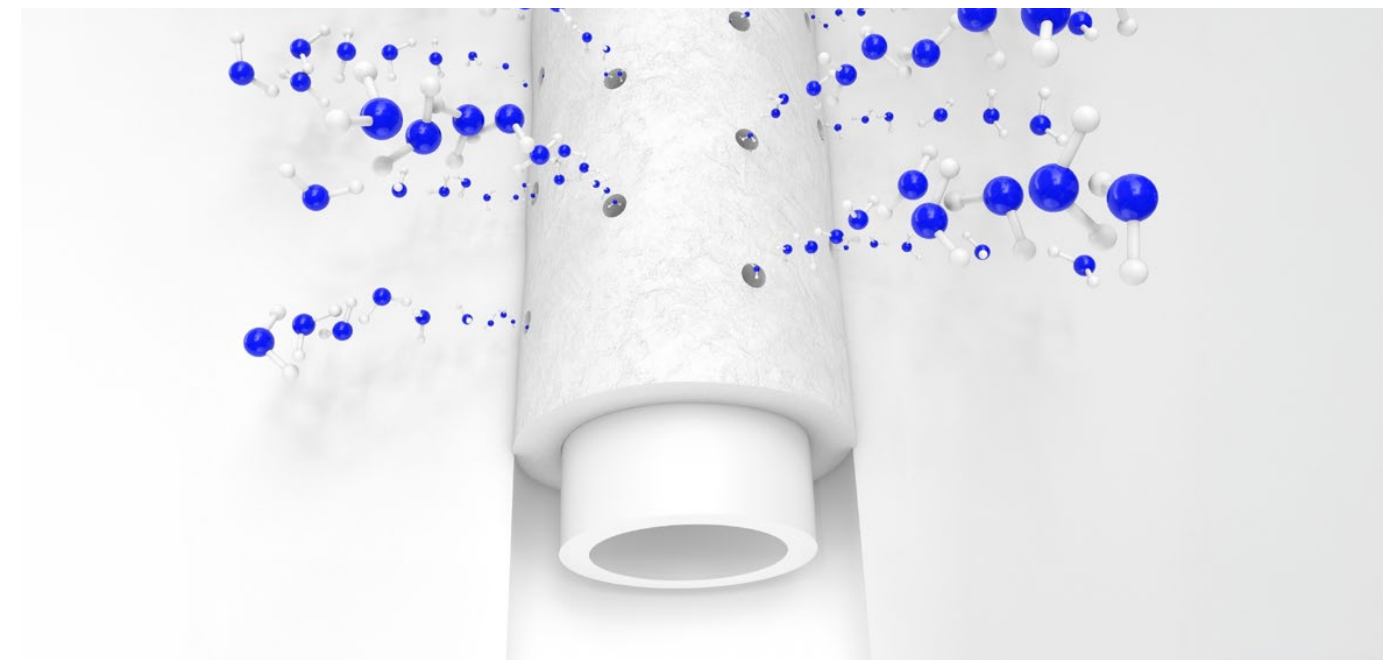
From 2018 to 2021, the CO₂ Flow Assurance for Cost-effective Transport (FACT) Joint Industry Project (JIT) focused on generating data for validation of multiphase CO₂ flow simulators. FACT was supported by several industry partners and the Norwegian Research Council through Gassnova, with the aim of 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.





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

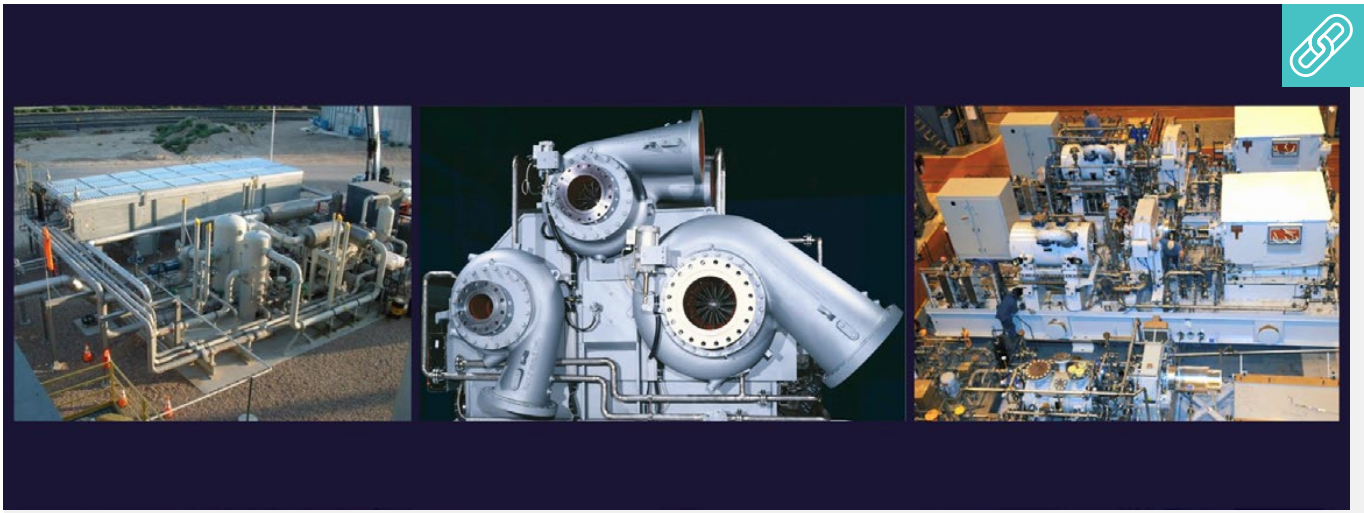
- Comprehensive range of CRA tubing grades including Super Duplex – SAF™2507 and high nickel alloys like Sanicro®28 and Sanicro®29 that can offer an extended service life in downhole injection conditions.
- API Q1 manufacturing facility with an integrated production route ensures high quality and material 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	



SUMMARY

As CCUS systems tend to be very energy-intensive and deliver CO₂ typically at a low pressure. Equipment selection is critical to maximizing efficiency and reducing total cost of ownership. Outside of the capture process itself, compressors are essential devises. They contribute a lot to system OPEX and CAPEX. Siemens Energy is offering a wide range of centrifugal (single shaft and IGC) as well as reciprocating compressors for CO₂ applications with many references. Integrally geared compressors (or IGCs) are multi-shaft compressors with up to five pinion shafts around a central bull gear with one or two impellers per stage. IGCs provide the advantage of high efficiency and potential intercooling after each stage. They allow multi fluid operation in one compressor.

In recent years, we have initiated several research and development (R&D) projects focused on optimizing IGCs for the CO₂/CCUS market.

BENEFITS

- **Reduced downtime:** Remote Diagnostic Service (RDS) enable advanced services for integrally geared CO₂ compressors reducing scheduled downtime by 25%.
- **Package modularization:** Siemens Energy has developed an advanced IGC package concept that reduces cost on equipment, transportation, and I&C.
- **Waste heat recovery:** Up to 80% of the steam required for an amine system can be provided by recovering the heat CO₂ of compression.
- **CO₂ Liquefaction:** One joint compressor for CO₂ compression and liquefaction cycle reduces cost and footprint. Using CO₂ as the refrigerant improves safety.
- **Water removal:** Taking out water from a CO₂ stream to the required level by means of compression and integrating other drying processes as required.

KEY PROJECT

- **DAC:** Compressors for the world’s first large-scale (~500 kt of CO₂/a) Direct Air Capture (DAC) plant in Texas.
- **LNG:** Integrally geared compressors to inject CO₂ sequestered from natural gas into a subsea pipeline for reinjection at a LNG facility in Norway.
- **EOR:** Hundreds of reciprocating CO₂ injection compressors supporting enhanced oil recovery in the US.
- **FPSO:** High pressure discharge (up to 550bar) single shaft compressor for CO₂ reinjection service on FPSO in Brazil.

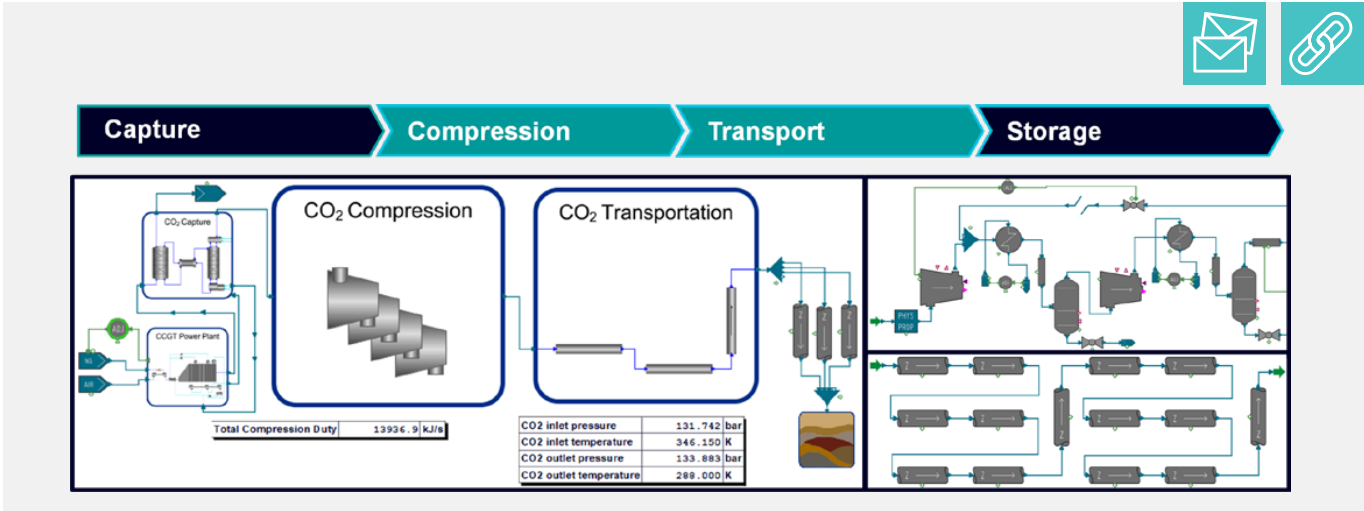
KEY DATA

TRL	9	
Target Industries	Oil and Gas; process industry's; CCUS for all industries	

SIEMENS

SIEMENS INDUSTRY SOFTWARE LIMITED

gPROMS PROCESS FOR CO₂ TRANSPORTATION & STORAGE



SUMMARY

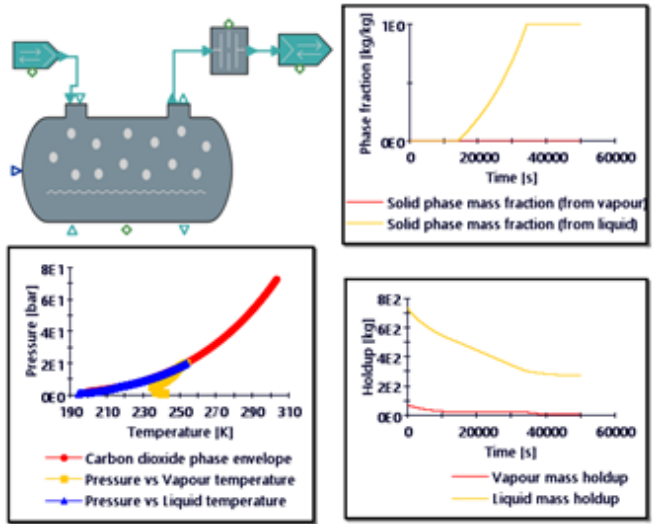
Siemens' gPROMS platform is a leading modelling environment for digital process design. It is used to map system interactions and predict process responses, also in transient scenarios. The platform enables users to optimise equipment and system designs, predict plant performance, and operate closer 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 NOX 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.	

solartronISA

SOLARTRON ISA

AMETEK

CARBONSTREAM CO₂ FLOW METER



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. With key applications including multiphase measurement of wet gas in gas condensate fields and injection measurement for gas lift or water/inhibitor injection for subsea oil or gas developments, Solartron ISA has introduced its range of Carbonstream CO₂ Flow Meters. Operating in either gas or dense phase, our 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 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 (ATEX Ex approved). Low energy – ideal for remote locations. Perfectly suited for unmanned facilities with low power needs (can be solar powered) plus both Ethernet and RS485 communications.
- High accuracy, real time mass flow, differential pressure, pressure and temperature outputs. Low maintenance with no need for through life recalibration (Venturi technology with high performance instrumentation).

Subsea Meter

- Highly reliable meter designed for installation depths up to 3,000m. The meter has fully redundant sensors and electronics providing a minimum design lifespan of over 25 years.
- The meter comes with built in Equations of State which can be remotely updated during its life as process conditions change. With low power requirements the meter comes with SIIS Level 2 Canbus and Modbus (485) communication outputs.



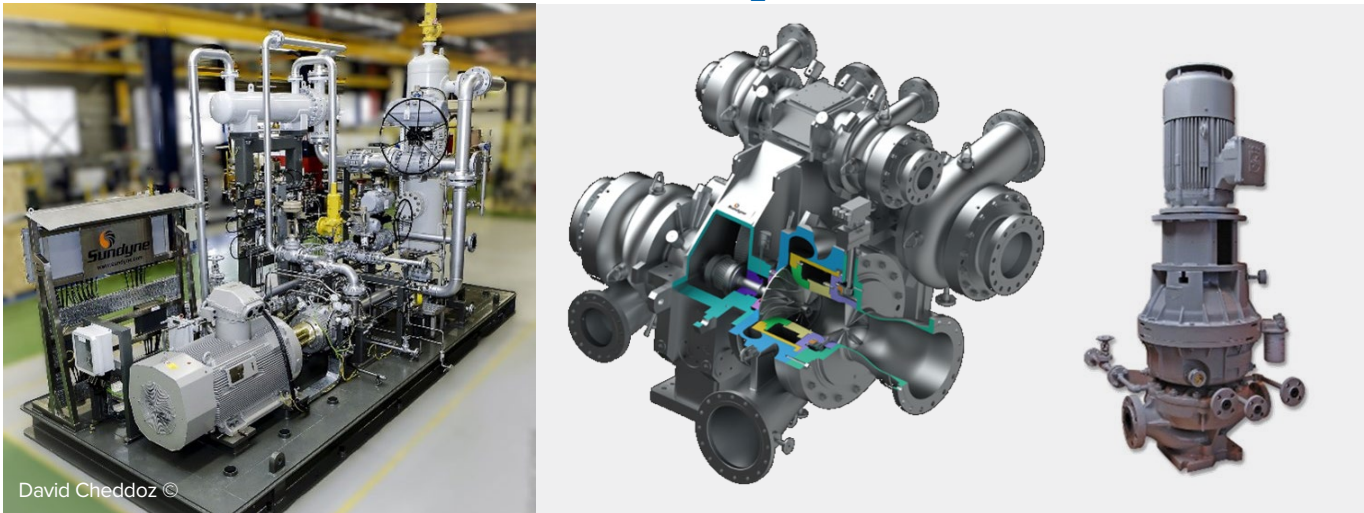
KEY DATA

TRL	5	Capture Rate Range (tpd)	Duplex or better	Design Life	Better than 25 years
Typical Uncertainty (95% Confidence)	Better than +/- 2%	Turndown (typical)	8:01		
Target Industries	CO ₂ Transport and Storage – both gas and dense phase measurement				



SUNDYNE

INTEGRALLY GEARED MULTISTAGE CO₂ AND SUPERCRITICAL CO₂ COMPRESSOR



SUMMARY

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.

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.

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BENEFITS

- **Centrifugal Design:** Range from 100 to 22,000 m3/h combining high 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

KEY PROJECTS



- **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, FEED of **CO₂ Compression for Power Plant carbon capture & storage**

KEY DATA

TRL	7 - 9	Flow Rate Range (tpd)	0 - 1,200	Working Pressure (bar)	250
Maximum Power (kW)	7,500	Maximum Flow (m3/h)	22,000	Reliability	API 617 Part 3
Number of Commercial Plants	73	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				

STORAGE





SUMMARY

In geological sequestration, completion integrity for any well penetrating the target storage interval is key to maintaining storage integrity over the life of the project. Chemical corrosion inhibitors and reservoir’s environmental factors can be damaging to elastomer seals over time. The most common sealing elastomers in the industry today often force a choice between effectiveness at low temperatures or chemical compatibility with corrosion inhibitors. Aptum™ seal systems, along with industry-leading packers such as the Premier™ NXT removable production packer, perform at lower, more appropriate temperatures for CCUS and yet maintain excellent chemical compatibility and mechanical properties. With Aptum™ seals in the completion, operators can better protect their metal tubulars and equipment without fear of elastomer degradation.

BENEFITS

- Delivers high performance across a wide temperature range
- Compatible in a range of environments including corrosion-inhibited fluids and reservoir fluids
- Resistant to sour conditions
- Single compound simplifies material recommendations and testing for well planning across all seals including packing elements, O-rings, and bonded seals
- Extends life of seal, further improving reliability
- Meets ISO 23936-2 and API 11D1 standard

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

In typical well completions, the injection or monitoring tubing string is isolated from the well casing by a production packer. This packer creates a mechanical anchor and a seal between the tubing and casing. The four main elastomers currently used in these packer element systems to seal between the tubing and the casing are Nitrile (NBR), hydrogenated Nitrile (HNBR), Aflas (FEPM), and Viton (FKM). These elastomers provide an excellent range of capabilities for most applications. However, in each case, there are trade-offs, which can introduce risks

and costs to an operation. For instance, NBR has balanced mechanical properties and performs well even at lower temperatures. However, its chemical resistance, particularly to corrosion inhibitors, is quite low. Aflas, on the other hand, is excellent for use in many inhibited brines, but has significant limitations in lower temperatures. Baker Hughes set out to develop a balanced element system that could be used confidently in a broader range of applications – carbon storage being a prime example.

	TEMPERATURE 40 °F (4 °C)	TEMPERATURE 350 °F (177 °C)	INHIBITED BRINE >200 °F (93.3 °C)	BROMIDE RESISTANCE	OIL-BASED MUD RESISTANCE	H ₂ S RESISTANCE >10%	BALANCED MECHANICAL PROPERTIES	PRODUCED RESERVOIR FLUIDS
MATERIALS								
Aptum Seal	○	○	○	○	○	○	○	○
Nitrile (NBR)	○	X	X	X	○	X	○	X
Hydrogenated Nitrile (HNBR)	○	○	X	X	○	X	X	○
Viton (FKM)	○	○	X	X	○	○	○	X
Aflas (FEPM)	X	○	○	○	○	○	○	○

Due to excessive swelling, limit exposure to oil-based mud (OBM) during run-in
Due to excessive swelling, O-rings and packing elements require back-up mechanisms to reduce extrusion

Aptum™ seals are compatible with a range of industry standard corrosion inhibitors while still maintaining sealing capabilities in low downhole temperatures. Carbon storage applications can create corrosive environments when CO₂ becomes mixed with water and other fluids in the wellbore. Completion equipment can often be exposed to hydrocarbons, formation water, CO₂ and a host of other corrosive fluids. A common and effective way of combating this corrosion is to treat the completion fluids with corrosion inhibitors. These corrosion inhibitors protect the metallic components of the completion including the casing, tubing, and packer body. However, they can also degrade the elastomer. As mentioned earlier, elastomers with excellent compatibility with inhibited fluids often have temperature limitations.

Many target formations for sequestration are shallow and have lower temperatures, making them difficult applications for elastomers such as Aflas. Add the potential for significant cooling during various phases of CO₂-injection operations, and a new solution is needed. Aptum™ provides excellent performance at 4 °C (40 °F) yet maintains long-term compatibility with bromide- and chloride-inhibited brines. When used as a part of the Premier™ removable production packer, Aptum™ seals enable a secure seal between the tubing and the casing, create a reliable mechanical anchor for the tubing string throughout extreme temperature and pressure changes, and is easily removed from the well for workover or plug and abandonment activities.



SUMMARY

CarbonEdge™ redefines how CCUS projects are managed by combining real time data, predictive intelligence, and seamless integration across the entire value chain from capture and transportation to storage, ensuring every molecule is accounted for and verifiable. Its integrated asset model approach not only enhances risk management, but also deliver a detail operational plan with the operating envelopes digitally defined for monitoring. Its modular design allows scalability, interoperability and ease of upgrade as required. CarbonEdge™ unlocks operational efficiency, streamlines regulatory compliance and supports decarbonisation goals as well as simplifies carbon credit reporting with reliable audit-ready data.

BENEFITS

- **Surface to subsurface integration:** A single pane of glass for a unified view connecting sensors, measurements and models for increased efficiency.
- **Mitigate risks across the value chain:** Proactively identifies and recommends mitigation using real time sensor data, dynamic risk catalogue, customizable alarms and advanced analytics.
- **Optimise operational gains:** Enhanced efficiency through integrated modeling and automation, reducing downtime and enabling smarter decisions throughout the project lifecycle.
- **Compliance without complexity:** Automated reporting tools streamline CO₂ tracking and ensure alignment with globally evolving regulations and credit reporting.
- **Scalable and flexible deployment:** The platform is modular and scalable which makes it highly interoperable and agile with ease of upgrades, as it is also vendor agnostic.
- **Expediting carbon credits:** Automated workflows and audit-ready documentation streamline carbon credit verification and submission, expediting credit realization with minimal human intervention.

KEY DATA

TRL	6
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TECHNOLOGY DESCRIPTION

DATA INTEGRATION AND MMV PLANNING

Unlock the full potential of your carbon capture, utilisation, and storage (CCUS) operations across the value chain with real time, accurate, and actionable data from CarbonEdge™, powered by Cordant. The industry’s first risk based CCUS digital solution, CarbonEdge™ provides complete and accurate data to support reliable measurement, monitoring, and verification (MMV) of CO₂ as it is captured, transported, and sequestered underground. Its workflow processes are focused on achieving three key objectives: Capacity, Injectivity and Containment.

The platform aggregates data from multiple sensors into intuitive, persona-based dashboards. This delivers key performance insights and timely alerts from customizable alarms to precisely track CO₂ flow during capture and compression to pipeline transportation, injection, and long-term subsurface storage. With seamless surface to subsurface connectivity combined with advanced project management and engineering support, CarbonEdge™ deployment optimises project de-risking, simplifies regulatory compliance, and reduces operating expenses while maintaining high safety and performance standards.

CarbonEdge™ enables comprehensive risk management throughout the project lifecycle. It delivers real-time monitoring to quickly identify and respond to risks, while predictive analytics help prevent system failures and minimize downtime. By processing data closer to the source, the platform enhances data security and enables faster reaction times. Integrated safety protocols trigger alerts or shutdowns when abnormal conditions arise, helping maintain safe operations. Its scalable design ensures it can adapt to changing operational needs as projects expand.

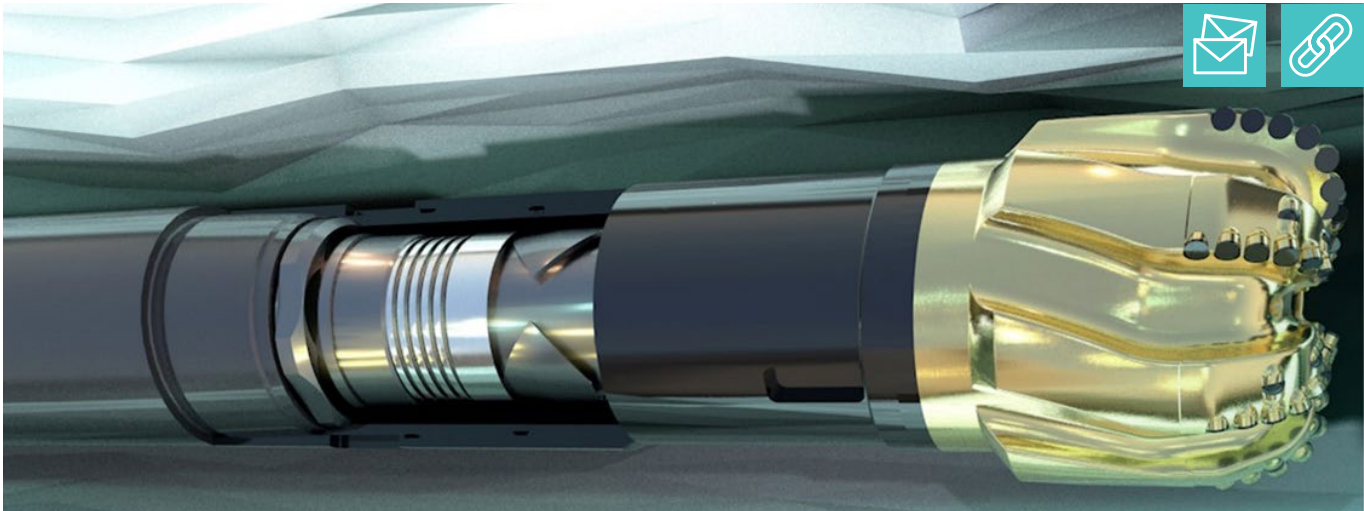
DATA INTERPRETATION AND MMV EXECUTION

The platform is designed to increase project profitability through modular and cost-effective implementation. CarbonEdge™ supports scalable carbon management that grows with your operational footprint. Process automation reduces manual labor and minimizes the potential for errors, while predictive maintenance capabilities extend asset life and reduce downtime. Its edge to enterprise integration model ensures that data is processed where it provides the most value, further enhancing overall operational efficiency.

CarbonEdge™ supports full CCUS asset integration, enabling seamless transitions from data aggregation to operational execution. It enhances MMV planning and execution with advanced analytics and delivers tailored CO₂ reporting to support both tax and carbon credit requirements.

The platform improves productivity by integrating sensing hardware, software, and engineering expertise to generate real time insights. In addition, it simplifies regulatory obligations by offering continuous traceability of CO₂ across the entire value chain. CarbonEdge™ provides secure access to trustworthy data that simplifies carbon reporting and accelerates the monetization of carbon credits. Its audit ready documentation supports compliance with evolving regulatory frameworks, while automated updates help maintain alignment with current standards. Built-in auditing tools make inspection and reporting more efficient and transparent while real-time tracking of emissions enables more accurate reporting. The solution is compatible with a wide range of global emissions and storage protocols, supporting both regulatory and voluntary carbon markets.





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.

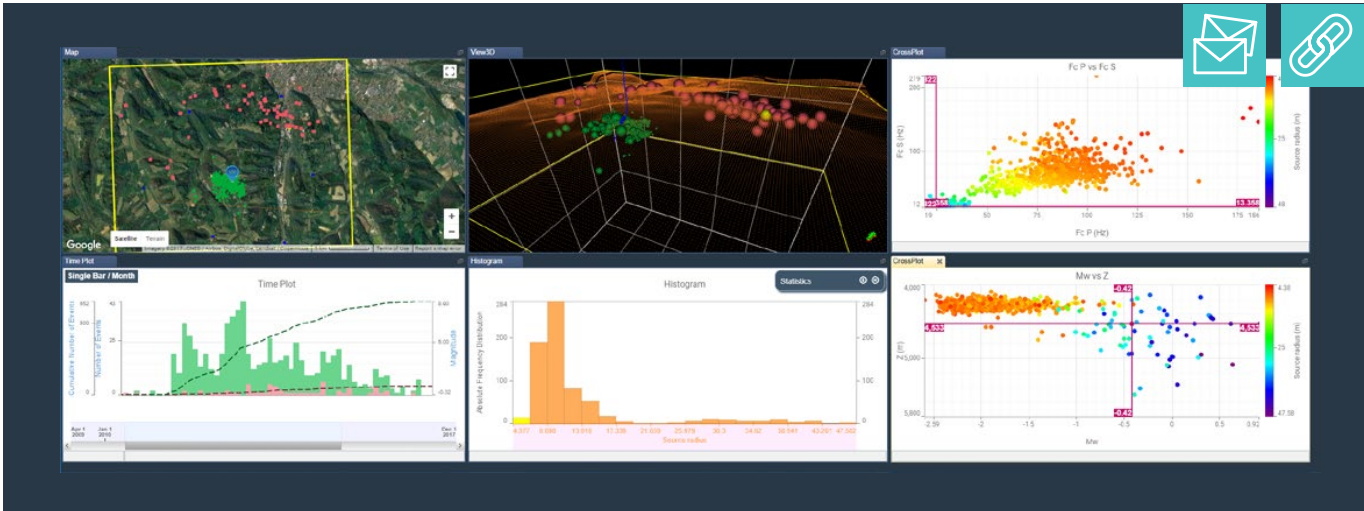
Baker Hughes combines the benefits of various technologies to improve the efficiency of coring operations in complex formations. With its CORTIVA™ full-closure system with jam mitigation technology, Baker Hughes combines the JamBuster™ jam mitigation coring system

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.





SUMMARY

Monitoring seismicity is essential to guarantee the integrity of geological sequestration reservoirs and caverns. In terms of physical integrity, seismicity in the cap rock is an indicator of the risk of catastrophic failure. At the reservoir scale, seismicity at faults can identify the reactivation by fluid injection or that they provide a pathway to the surface for the stored fluids. With more public attention towards induced seismicity and environmental impact of human activity, reputational integrity is becoming as important as physical integrity. It is therefore becoming essential to detect growing activity trends before critical situation happens to support operators' injection program. Baker Hughes provides the whole range of customised microseismic services and instrumentation to provide lifetime monitoring of CCS assets.

BENEFITS

- Maximize storage capacity within safety limits
- Compliance with regulations
- Monitor structure integrity (cap-rock & faults)
- Distinguish induced versus natural seismicity
- Avoid water breakthrough

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

The range of the monitoring solution can be described in 3 distinct stages that can be performed as a whole or as independent services.

NETWORK DESIGN

In this phase, consideration is given to the project's constraints (regulatory, geological, operational and logistical) and advanced modelling is used to determine the most cost-effective network that will meet the project's objectives. This network can consist of a specific technology (surface or downhole solutions with analogic geophone or fibre optics) to be deployed, but can also have a combination of them to benefit from their different capabilities.

INSTALLATION AND MAINTENANCE

Baker Hughes ensures supply of all the required instrumentation: surface sensors, shallow buried sensors (100 m), borehole sensors, surface electronics, fibre optics, digitizers, and fully equipped seismic cabinets. Where not internally developed, Baker Hughes works with trusted suppliers with long-term relationships to develop reliable hardware (Mean Time Between Failures of more than five years) with advanced capabilities.

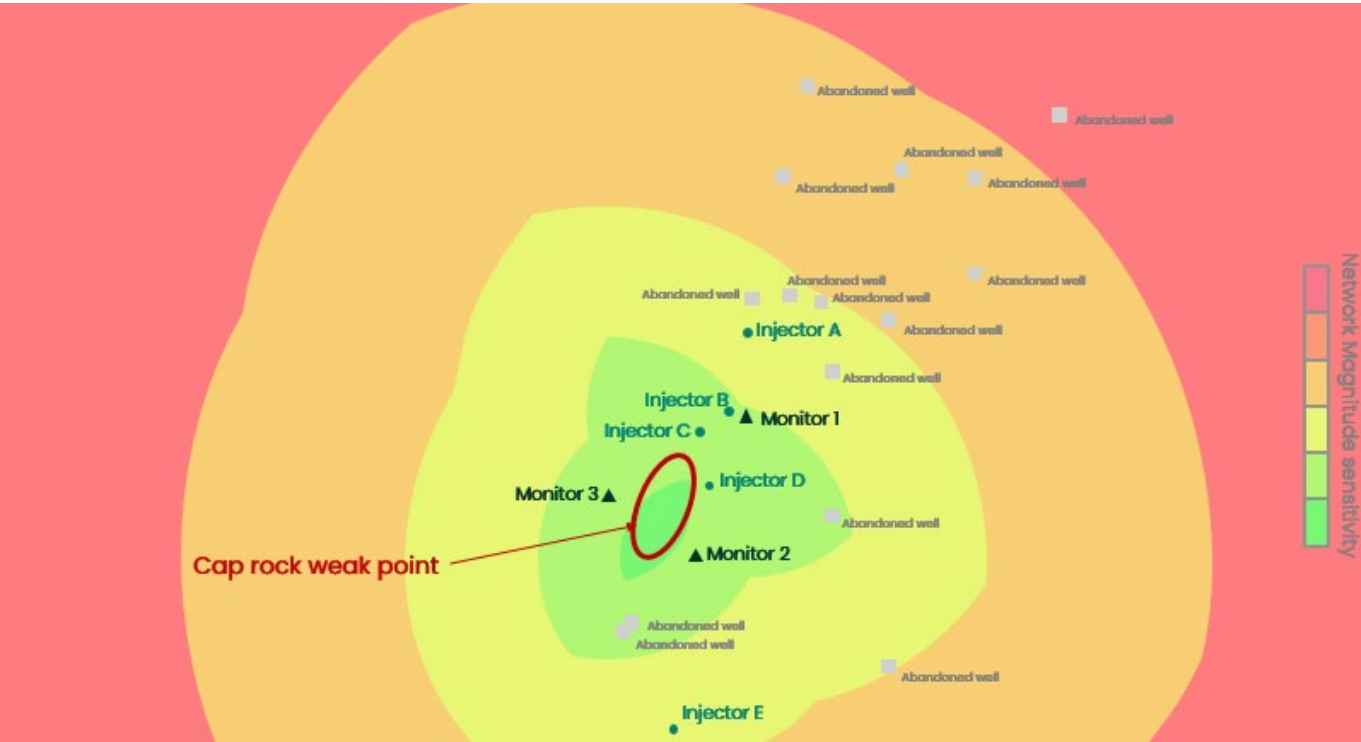
Baker Hughes installs and maintains all the instrumentation, including borehole sensors. The requirement for preventive maintenance is extremely low (one visit a year at most). This allows us to operate sites all over the world. Most of the sites are totally autonomous, relying on solar panels for power and 4G networks for communications.



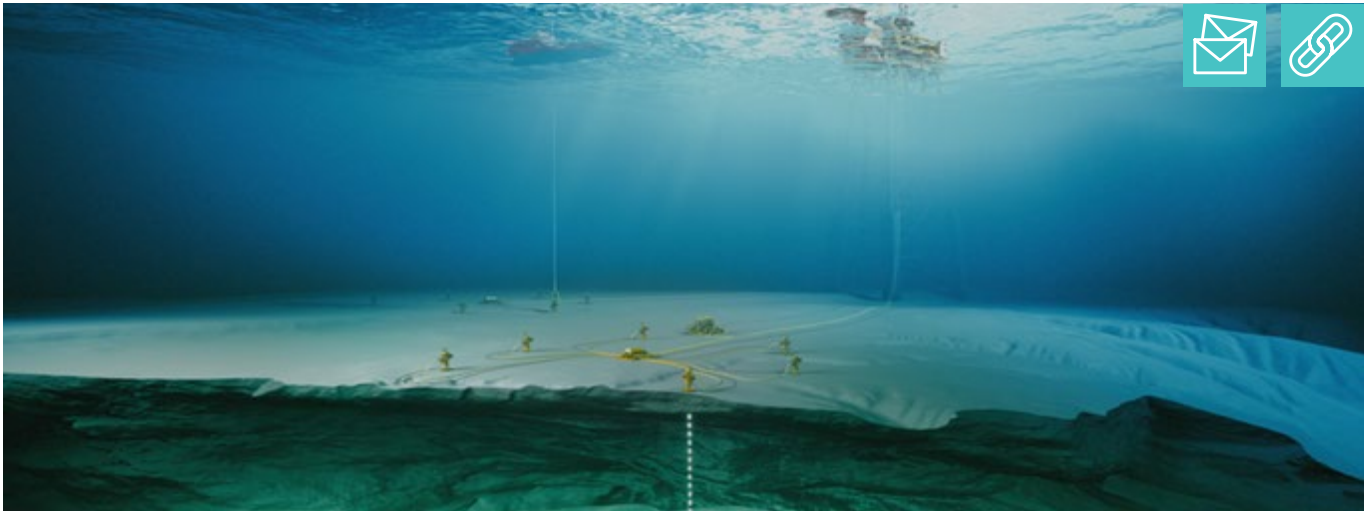
MONITORING - PROCESSING

A dedicated team of experts processes the data and reports on the seismicity through a dedicated web portal. The portal allows the operator to visualise the seismicity in two-dimensions (2D) or 3D along with the well trajectories and formation interfaces and offers statistical analysis capabilities. It also plays the monitoring network's state of health and expected sensitivity in real time. Pressure and/or flow rate curves can be displayed along with seismic rates to easily relate any seismic activity to its probable cause.

Automation of the process can be utilised to enhance the processing solution by adding 24/7 services such as traffic light systems that will alert the operator when critical seismicity is reached, and the prediction of the level of seismic risk for the upcoming hours using machine learning.



¹ tedTemperatures Under Hydrogen Conditions", SEAFOM Industry Meeting (Dec. 2012)



SUMMARY

Offshore CO₂ Storage demands low cost, reliable, long-term solutions across the full project lifecycle, since CO₂ injection activities may last for many decades, with an extended period monitoring the well storage sites following injection operations.

As an industry leader in energy technology, Baker Hughes integrated offshore CO₂ injection solutions leverage our wide portfolio encompassing the latest subsea and surface well system technology, to provide cost-effective solutions for your energy and carbon reduction needs.

Baker Hughes subsea CO₂ storage systems are built upon decades of Oil & Gas heritage, including our industry leading Wellhead and Xmas Tree systems. These systems have configure-to-order functionality for CO₂ service and are able to tackle extreme temperatures and harsh well conditions, ensuring safe and secure storage of CO₂.

BENEFITS

- Configurable solutions support faster delivery, cost-effective completion activities and early start up.
- Compact size and weight translates to lower lifecycle CO₂ emissions, including use of smaller, lower cost vessels
- Flexible functionality; supports electric control and intelligent completions, including fibre optic monitoring.
- Reliable, safe performance in extreme well environments.
- Technology that builds upon field proven designs, with a CCS track record since 1996



KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

SURFACE WELL TECHNOLOGY SOLUTIONS FOR THE HARSHTEST OFFSHORE ENVIRONMENTS

With challenging field and operating conditions, the key to delivering performance requires customised well system solutions.

Our latest CCS wellhead solutions are drawn from Baker Hughes’ decades of proven technologies, designs and expertise. These systems are developed and tested based on the latest industry standards. The types of wellhead systems available are the Compact Wellhead Solution and Conventional Wellhead Solution.

MS-TTL COMPACT WELLHEAD SYSTEM

The MS-TTL is available for 13-5/8” NOM and 18-5/8” NOM 10,000 PSI application. This design is optimised for offshore platform CCUS applications by reducing OPEX and CAPEX while ensure high standards of performance.

The MS-TTL wellhead Solution are built on the legacy of our MS-metal seal family to deliver true metal-to-metal seals, while providing an optional single-trip running tool to test both the casing hanger and the annulus seal. The metal-to-metal sealing design enables the wellhead system to perform under the harshest operating field conditions. The MS-TTL system maintains high standards of reliable and safe operations. An optional integration of a cutting-edge metal-to-metal sealing stem packing further enhances fugitive emissions reduction.

MS SERIES SUBSEA WELLHEADS

The Baker Hughes MS family of subsea wellheads enable value delivery and innovation, for drilling and completions strategies to build on.

The MS-300 J is designed for Jack-up drilling in shallow water. As a highly cost-effective solution, especially when paired with our Aptara-S subsea XT, makes it well suited for CCS applications.

The MS-700 and MS-800 are designed for all water depths and offer even more configuration options for drilling in deeper waters and more complex and deeper reservoirs.

All our wellheads feature our industry leading MS sealing technology.

APTARA WELL SYSTEMS, OPTIMISED FOR SUBSEA

Our range of subsea well system solutions enable lower cost operations in shallow water using Jack-up drilling rig (JUDR), or in deeper water with Semi-submersible.

The Aptara CO₂ systems are an element of the wider Aptara suite of products from Baker Hughes that provide configure-to-order solutions. With designs that incorporate decades of CO₂ injection experience, while incorporating the latest technologies that Baker Hughes have developed. This combination best manages the challenges associated with subsea activities whilst keeping design and cost efficiencies in mind, aiding customers project economics.

APTARA-S TREE SYSTEM

The Aptara-S (AXTS) tree system comprises a 13-5/8” Shallow Water vertical tree system that simplifies installation and intervention with use of Jack-up Drilling Rigs (JUDR’s). The AXTS works seamlessly with our portfolio of cost-effective shallow water solutions, including Wellhead, Well Access, Manifold, Distribution and connection systems.

Engineered for up to 6,500 psi and 500 ft (150 m) water depth, with a standard operating temperature range of -20°F to 250°F (-29°C to 121°C). The system includes several innovative features to reduce cost, size and weight, and a slimbore tubing hanger, packed with hydraulic, chemical and electrical functionality, giving operators more flexibility to improve and monitor well performance.

Operating in Shallow Water, the Aptara-S solution can be installed and operated without the need for divers or ROV, increasing your operating window by addressing the environmental challenges of weather, sub-surface currents, poor visibility, and fishing interaction.

APTARA-L TREE SYSTEMS

To suit operations in deeper water, or when a large bore option is demanded for higher flowrate CO₂ injection, the Aptara-L (AXTL) system is a concentric bore 18-3/4” vertical tree system, designed to simplify the manufacture, test and installation activities, hence providing a cost-effective solution for CCS.

Engineered for up to 10,000 psi and 10,000 ft (3,048 m) water depth, the system includes several key technology features, including a high-capacity tree connector and an Integrated Process Module® (IPM). The IPM allows for flow measurement and control instruments to be combined in a single forged body, resulting in a compact and lightweight arrangement.

DIGITALLY ENABLED AND FUTURE READY

Our well systems are also designed to support full field electrification, simplifying the offshore architecture and reducing costs associated with complex hydraulic distribution and the need to top up of fluids throughout well life.

Digital sensing technology, in combination with a customised control system, will further enhance digitalization while supporting predictive maintenance and remote operations through the life of field.





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

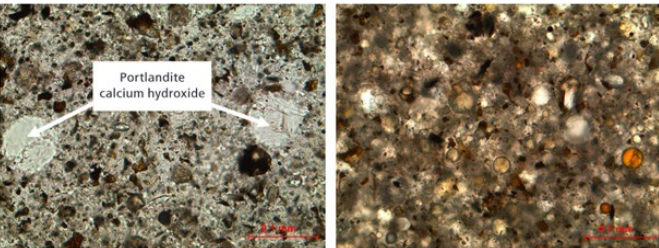


Fig.1: Thin sections of set samples at 15.8 ppg (1893 kg/m3) under a light microscope indicating absence of portlandite in PermaSet Ultra

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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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

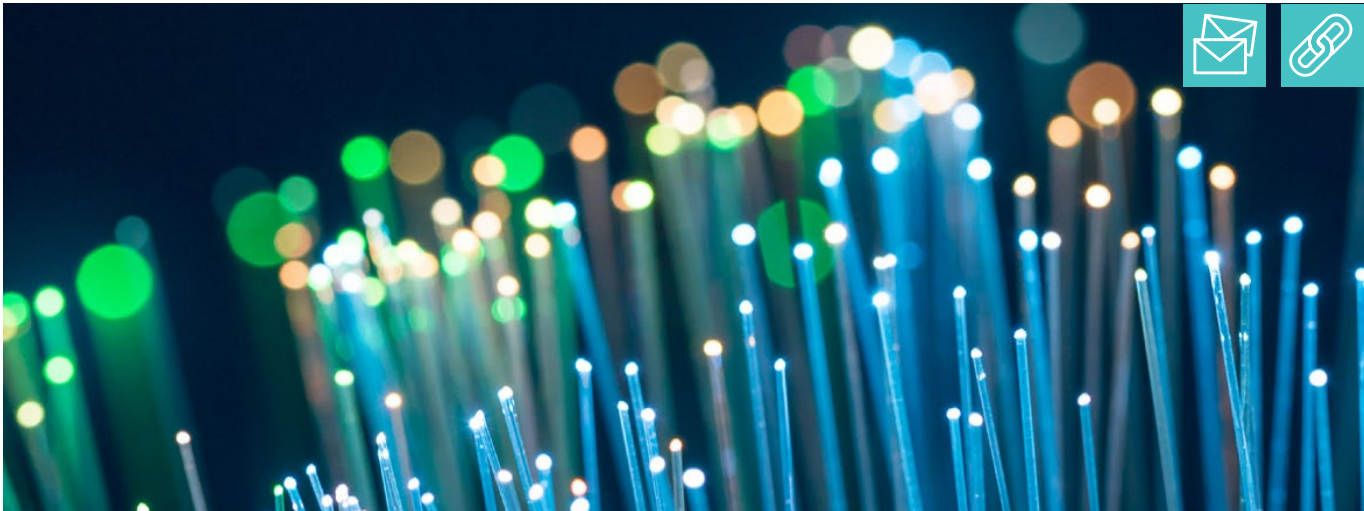
redundancy or be ported to record three independent pressure measurements. The shorter carrier for a side-by-side triple-gauge assembly also retains a slim hole running outside diameter.

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



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.





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.

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 maximize 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, underpressurized, 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 with \$40 million of investment.
- Worldwide applicability – we currently have a pipeline of commercially viable projects under development, in the US, Europe, Australia, Canada, and India.
- Black Hills Energy (BHE) and CGC have partnered to install a CCS operation for a coal-fired power plant at the Neil Simpson Complex in Gillette, Wyoming.
 - This ongoing pilot demonstration will confirm the modelled economics of the full-scale CCS system.
 - That demonstration began in September 2024 and will be completed in early 2026. At full scale, this project is expected to capture and sequester 3+ million metric tons of CO₂ annually from the coal-fired units at the Complex.

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				

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. Only sequestering carbon in coal can occur with 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 underpressurized 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 for energy leadership. 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 coal-assisted CCS technology allows countries to meet growing 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 resource 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 \$40 million of investment. Currently, we have a pipeline of commercially viable projects under development, including in the US, Europe, Australia, Canada, and India.

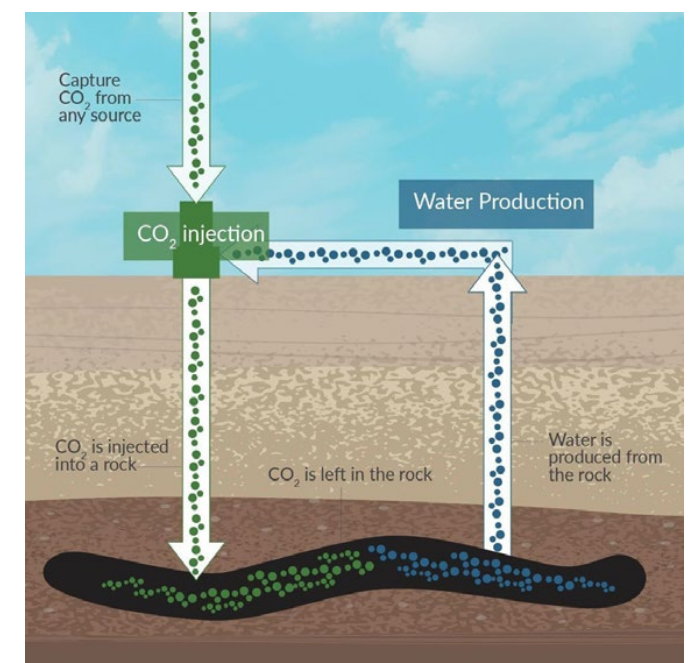
CGC's unique process was designed to be resilient, flexible and modular to work with various carbon dioxide volumes, sources, capture technologies, power sources, and rock formation types. Our approach captures and stores carbon dioxide from a variety of emission sources, including power plants, and 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 hundreds 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.

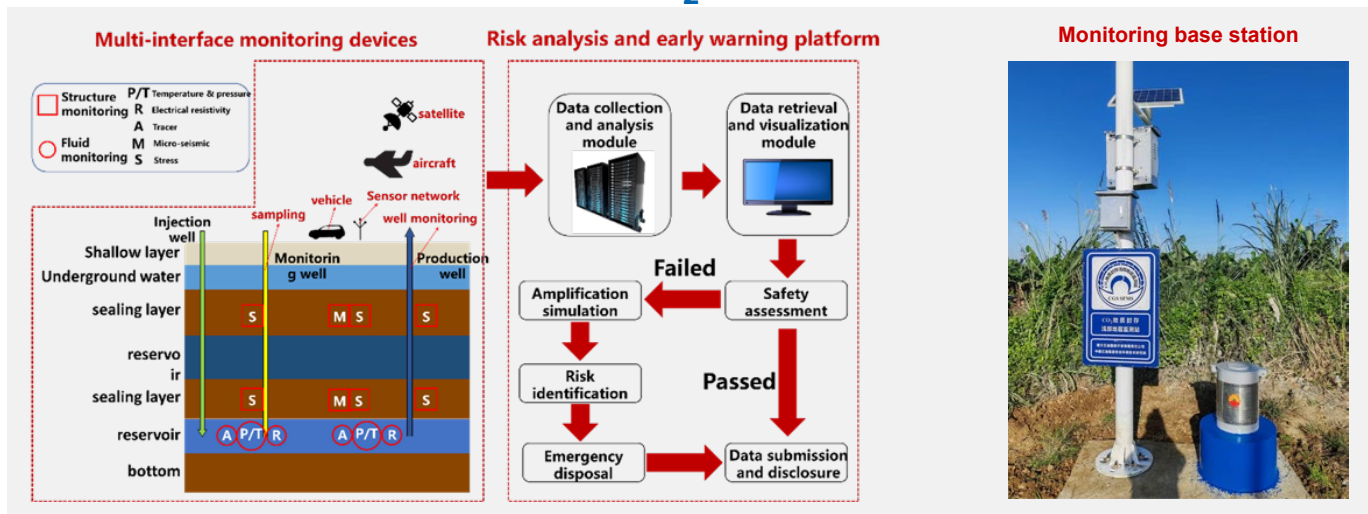
WellDog has also pioneered a number of different gauge architectures and deployment methods that allow one or more gauges of the same or different type, to be installed in the same well, either on tubing, coil, and/or behind casing. This high degree of flexibility enables permanent downhole monitoring systems to be configured to exactly suit well and reservoir conditions, and data needs.





CHINA NATIONAL PETROLEUM CORPORATION

MULTI-INTERFACE REAL-TIME MONITORING SYSTEM FOR CO₂ GEOLOGICAL STORAGE



SUMMARY

To address the potential leakage risks associated with CO₂ geological storage, a multi-interface real-time monitoring system has been developed by integrating microgravity detector, multiple parameter sensors, and the Internet of Things (IoT). This system enables continuous acquisition of ppm-level parameters at a frequency of 0.2 Hz and utilises a real-time computational model to synchronize data aggregation and hydrodynamic inversion. It facilitates deep fluid monitoring and inversion analysis, real-time surveillance and data aggregation of shallow and near-surface environmental factors, and predictive analysis of CO₂ distribution within geological formations. This technology supports CO₂ geological storage projects (including CO₂-EOR) in leakage risk prevention, on-site environmental integrity management, and the quantitative verification of carbon emission reductions.

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

TECHNICAL BACKGROUND AND DEVELOPMENT

The Real-Time Multi-Interface Monitoring System for Geological CO₂ Sequestration is an advanced technological solution designed to address the potential leakage risks associated with carbon capture and storage (CCS) projects. By integrating microgravity measurements, multi-parameter sensors, and Internet of Things (IoT) technologies, this system enables continuous, high-precision monitoring across various geological interfaces. Operating at a data acquisition frequency of 0.2 Hz, it collects parameters at parts-per-million (ppm) levels, allowing for real-time data aggregation and hydrodynamic inversion through computational models. This facilitates comprehensive monitoring of deep fluid movements and real-time surveillance of shallow and near-surface environmental factors. Key features of the system include comprehensive coverage of deep, shallow, and near-surface interfaces for three-dimensional leakage risk monitoring; all-element monitoring encompassing groundwater quality, atmospheric CO₂ concentration, and surface deformation; all-weather operation through IoT-enabled real-time data collection under various environmental conditions; and full life-cycle monitoring, covering pre-injection, injection, and post-injection site maintenance phases. These attributes collectively provide a robust framework for leakage risk prevention, on-site environmental integrity management, and quantitative verification of carbon reduction efforts in CCS projects.

In practical applications, this monitoring system has demonstrated significant efficacy across various projects. In the China Hainan Onshore Saline Aquifer Carbon Sequestration Project, it successfully implemented full life-cycle monitoring, ensuring adherence to safety and environmental standards throughout the pre-injection, injection, and post-injection phases. In the CNPC Jilin Oilfield CO₂-EOR Project, the system facilitated long-term continuous monitoring and accurate prediction of oil, water, and gas phase distributions, with results exhibiting high consistency with geophysical surveys and numerical simulations, thereby validating its precision and reliability in complex enhanced oil recovery operations. Furthermore, in the National Energy Group Yulin Multi-layer CO₂ Geological Sequestration Project, the system achieved coordinated monitoring across multiple formations, including saline aquifers and coal seams, concurrently predicting the vertical and horizontal distribution of CO₂ within the strata. These applications underscore the system's capability to provide detailed, real-time insights into subsurface processes, addressing the critical need for robust monitoring solutions in the field of carbon capture and storage.

TECHNOLOGY APPLICATION AND FUTURE PROSPECTS

The system's technical specifications are noteworthy for their precision and reliability. It achieves millimeter-level accuracy in surface elevation measurements, microgal-level sensitivity in microgravity assessments, and temperature readings accurate to 0.1°C. Pressure measurements are precise to 0.01 MPa, oxidation-reduction potential to 1 mV, and electrical conductivity to 5 μS/cm. Water level monitoring maintains millimeter-level accuracy, while geostress and formation dip measurements are accurate to 0.01 MPa and 0.1°, respectively. The system's data acquisition frequency of 0.2 Hz ensures continuous and detailed monitoring, providing a comprehensive understanding of subsurface dynamics.

The integration of microgravity measurements enhances the system's ability to detect subtle mass changes associated with CO₂ migration and accumulation. This capability is crucial for early detection of potential leakage pathways and for ensuring the integrity of the storage site. The use of multi-parameter sensors allows for the simultaneous monitoring of various environmental factors, providing a holistic view of the subsurface environment. The incorporation of IoT technologies facilitates real-time data transmission and analysis, enabling prompt decision-making and response to any anomalies detected during the sequestration process.

In addition to its technical capabilities, the system's design emphasizes ease of deployment and scalability. It can be tailored to suit different geological settings and project scales, making it a versatile tool for various CCS initiatives. The system's modular architecture allows for the integration of additional sensors or technologies as needed, ensuring that it remains adaptable to emerging monitoring requirements and technological advancements.

Overall, the Real-Time Multi-Interface Monitoring System represents a significant advancement in the field of geological CO₂ sequestration. Its comprehensive monitoring capabilities, high precision, and adaptability make it an invaluable asset for ensuring the safety, efficiency, and environmental compliance of CCS projects. As the global community continues to seek effective solutions for carbon management, such innovative monitoring systems will play a pivotal role in facilitating the successful implementation and operation of CO₂ sequestration initiatives.



SUMMARY

For clients working across the entire well life cycle, Expro is one of the 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 P&T operating envelope.
- Up to 45x improvement in data volume and 4x improvement in system life compared with the previous generation.
- 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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TECHNOLOGY DESCRIPTION

MONITORING APPLICATIONS

INTERFERENCE TESTING

Instrumenting an abandoned or suspended well with a CaTS system enables interference testing within the reservoir during appraisal testing, extended flow/injection testing and into first CO₂ injection.

This pressure data gives a better understanding of the reservoir characteristics and connected volumes, which will help with field development plans, aid optimal well placement and provide data to feed into plume migration and subsurface models.

This application is commonly used for exploration and appraisal campaigns in the oil and gas industry and has immediate synergies when evaluating new saline aquifers as CO₂ stores.

The gauge systems can be run in untested exploration wells or appraisal wells that have been tested. Equally the gauges can be used in saline aquifer or depleted oil and gas fields, and are suitable for lateral interference monitoring in the field or vertical interference monitoring between different zones and intervals.

LONG-TERM PRESSURE BUILD-UP / FALL-OFF

CaTS gauges can be installed in appraisal wells that are either production tested or injection tested. The gauges remain in the well after the test has been completed to gather reservoir pressures and temperatures after the well has been suspended or abandoned.

This application allows the rig to move location in a timely manner following the end of the test, and the data provides a deeper look into the reservoir to evaluate features further from the well bore (far field boundaries, baffles, faults etc.).

This means well testing no longer has to end at well abandonment and the pressure build-ups can be extended from days to years, enabling a greater understanding of the reservoir and a derisking of the field development.



PRESSURE FRONT AND CO₂ PLUME TRACKING

Once a well is instrumented with a CaTS gauge system, it then becomes a high-value data asset. The pressure and temperature data becomes invaluable during appraisal and development activities within the field and can act as a primary method to detect the pressure front related to injecting CO₂ and the CO₂ plume itself as it moves through the reservoir as operations commence.

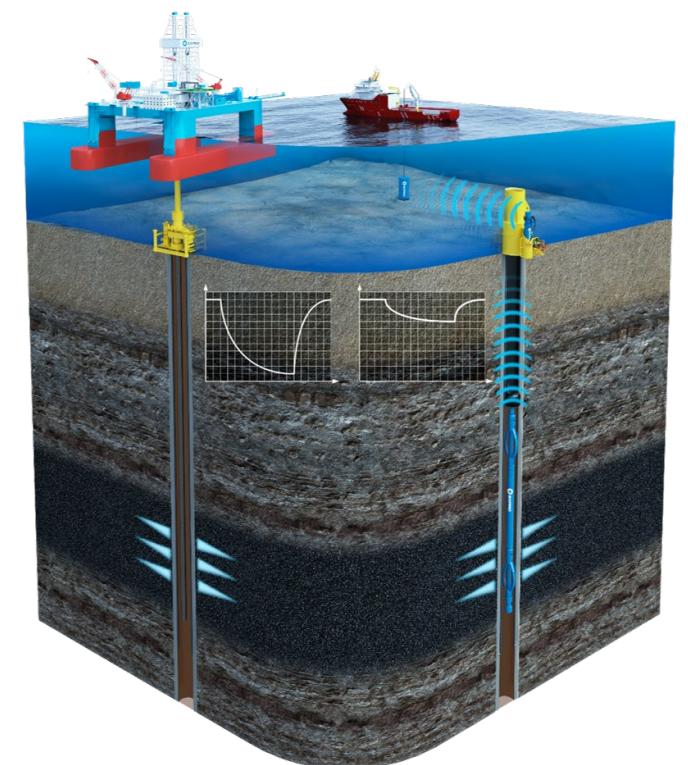
The extended battery life of the CaTS EMX system means that gauges installed in exploration and appraisal wells could be used for pressure and CO₂ plume tracking many years into the future.

While seismic monitoring is an established method of detecting plume migration, it is no substitute for actual subsurface data. The downhole gauge data will be used to improve reservoir models and enable more accurate plume tracking as time passes.

WELL INTEGRITY AND LEAK DETECTION

CaTS gauges can also be installed for well integrity and leak detection purposes. Common application include below plug/packer monitoring, barrier verification, well bore leak detection and behind casing monitoring.

For carbon capture and storage projects, understanding the well and formation integrity is paramount. Instrumenting wells with CaTS gauge could improve the overall Well Integrity Management System (WIMS) by providing accurate data to detect potential leaks in the completion, casing, cement or the formation (e.g. cap rock or overburden).





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.

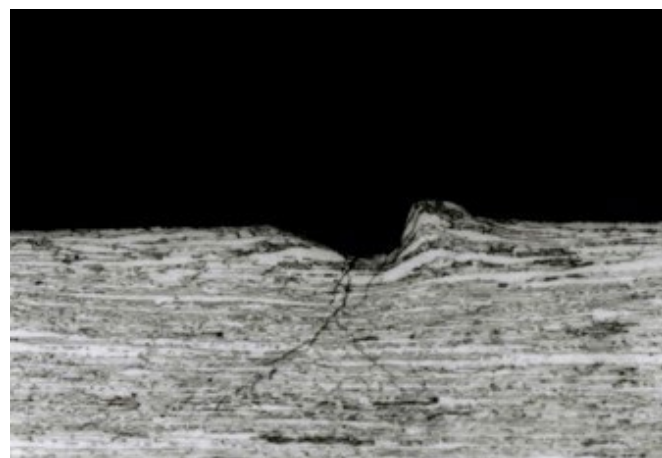


Figure 1 - CRA Tubular Containing Die Mark and Crack Initiation and Propagation



Figure 2 - Screenshot of Expro's iCAM® Intelligent Connection Evaluation System

KEY DATA

TRL	9
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TECHNOLOGY 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. Non-marking spiders, elevators, and tong systems, not to be confused with low-marking technologies, completely eliminate the risks explained above. Expro's Collar Load Support (CLS™) System uses load transfer bushings that are directly transferred from an elevator to a shock absorbing landing spear system mounted within the rig's rotary. When utilising the CLS™, loads are limited by the bearing capacity of the coupling rather than the tubular slip crush capacity, as often seen with slip type handling equipment. Additional 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

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. By comparison, stresses imparted by conventional tong systems are localised and significantly higher, in some cases even exceeding the yield strength of the tubular.

Additionally, the integrity of all threaded connections is another critical component in ensuring long-term well integrity. Utilising thread compensation systems can help prevent damage to these connections during stabbing and make-up procedures. Machine learning and big data analytics are now being used to provide automated evaluation of connection make-up data, which improves accuracy, consistency, and reliability in connection integrity assessment. Expro's iCAM® system offers flexible integration with equipment such as power tongs and CRTs to produce optimal connection integrity and accelerate the make-up process, with the potential to reduce personnel on location.

CHALLENGES AND RISKS

- For carbon storage wells, the significance of long-term well integrity cannot be overstated. With the threat of accelerated corrosion and an increasing pressure regime from CO₂ injection, maintaining mechanical integrity means the absence of significant leakage within the injection tubing and casing. The avoidance of any front-end damage to these CRA tubulars during deployment will help preserve the durability and reliability of these barriers for the entire project life cycle, which can extend to 100 years post-abandonment to meet regulatory requirements.
- During the handling and installation of tubulars, loads are typically transferred to the tubular via hardened dies and inserts, which create impressions on the outer surface of the tubular. This occurs primarily when hoisting and lowering the string, supporting the string in the rotary table and during make-up of additional joints into the string. It is well known that impressions resulting from make-up and installation are common areas for the initiation of corrosion often leading to failure.
- Cold worked CRA tubular materials like 22Cr and 25Cr are commonly used in carbon storage wells. These materials are sensitive to localised impressions as they.
 - Induce localised work-hardening at the root of the impression
 - Create stress concentrations in the gripping areas of the tubing
 - Are preferential sites for corrosion
 - Are especially sensitive to iron transfer
- Figure 1 shows a crack that has been initiated at the site of a die mark resulting from handling a CRA tubular string

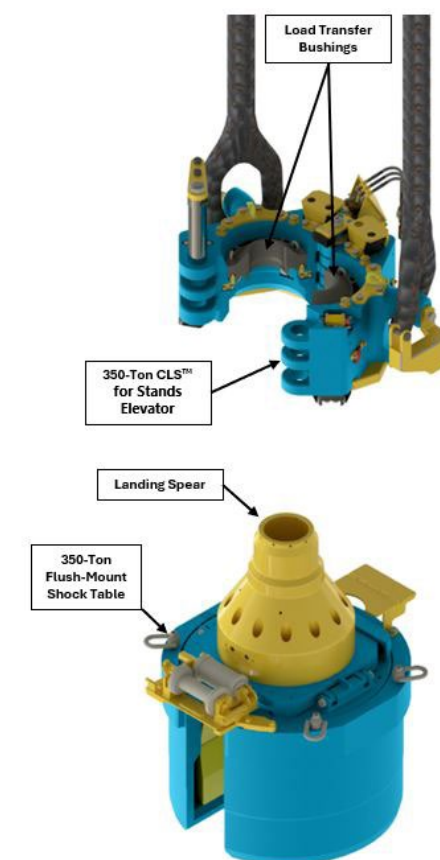


Figure - Expro's CLS™ Non-Marking Handling System

 INNOVEX

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 specializes 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

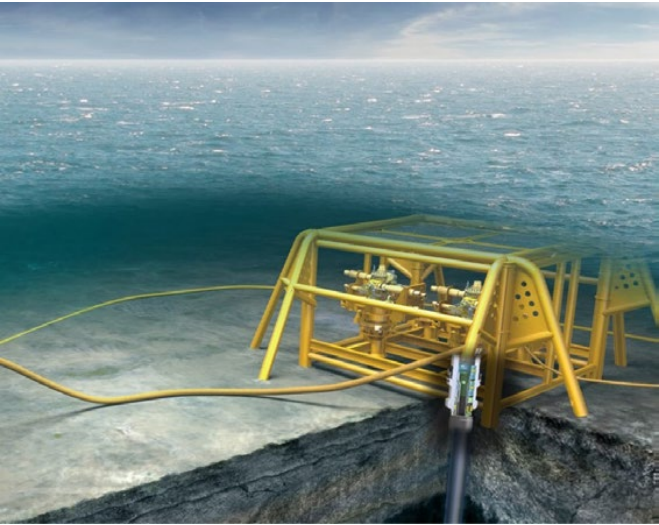
TRL	7 - 9	Source CO ₂ Purity Range	No Limit	Temperature Range	-75°F to 250°F (-60°C to 121°C)
Injection Pressure Rating	Up to 15 kpsi (104 Mpa)				
Target Industries	~				

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

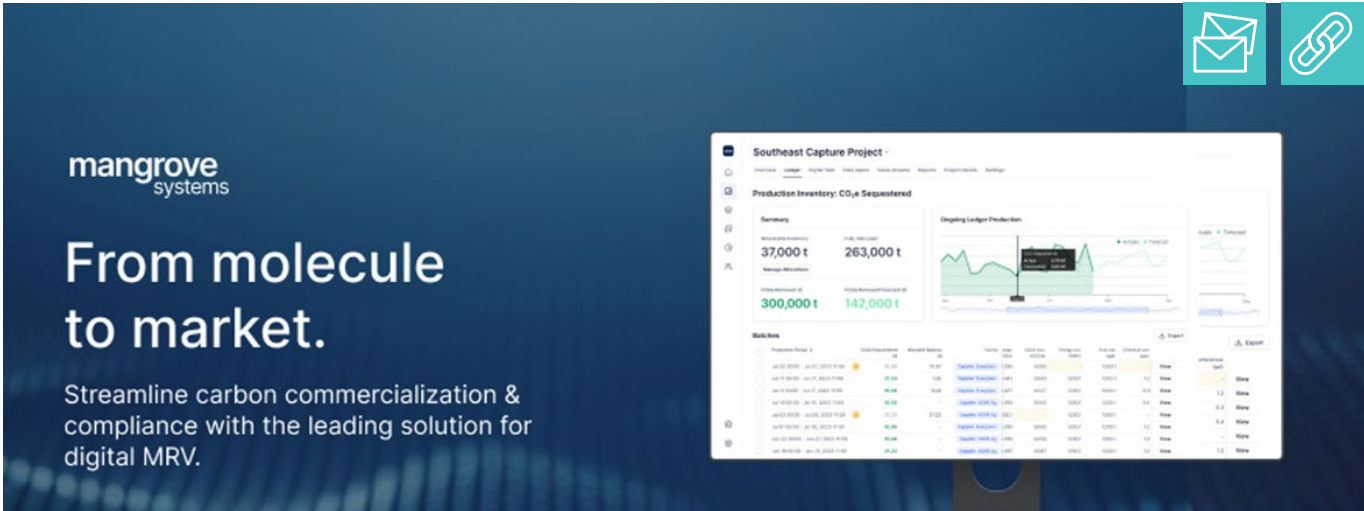
Innovex's Platform Wellheads reside on semi-permanent platform structures, providing offshore access to CO₂ storage reservoirs beneath the seabed. Because these wellheads remain above the ocean surface, they provide similar MMV advantages to onshore wellheads, but can be located in remote offshore locations. 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 minimized 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.





SUMMARY

Mangrove Systems provides the leading digital MRV solution for carbon capture & storage (CCS) and carbon dioxide removal (CDR) projects. Mangrove offers robust production carbon accounting that streamlines measurement, monitoring, reporting, and verification for project commercialization.

Mangrove processes data from multiple sources along the project value chain, aggregating operational and non-operational data and supporting the production carbon accounting required to meet regulatory and commercial reporting requirements to engage government programs (45Q, 45Z, 45V), compliance markets (LCFS, EU ETS, CBAM), as well as the voluntary carbon market (VCM). The platform enables streamlined verification with independent validation & verification bodies (VVB) and simplifies credit issuance and serialization with registries.

Mangrove Systems is trusted by many of the world’s largest carbon projects to bring trust, transparency, and integrity to carbon project operations. For more information, visit www.mangroveystems.com.

BENEFITS

- Streamline reporting for voluntary, compliance, and tax programs
- Accelerate the cash conversion cycle of your projects
- Report fully-traceable data for easy project verification via automated registry integrations
- Increase revenue with data-backed environmental attributes
- Conduct production carbon accounting across multiple CO₂ sources and storage points
- Future-proof operations with monetization pathway optionality

KEY PROJECTS

- **Summit Carbon Solutions:** An 18M+ tCO₂/yr Biogenic CCS (BiCRS) project in the Midwest US. Mangrove will process data from across Summit’s value chain, streamlining verification and commercialization across monetization pathways.
- **Carbon Alpha:** A 70K+ TPA Bio CCS (BECCS) project in Meadow Lake, Saskatchewan. Mangrove will provide end-to-end traceability of each molecule of CO₂, Mangrove’s solution ensures complete visibility across the entire carbon removal process, fostering trust and confidence among stakeholders.
- **Cowboy Clean Fuels:** A BiCRS+RNG project developer based in Wyoming. Cowboy leverages renewable biomass to produce RNG and sequester CO₂. Mangrove’s digital MRV platform enables full traceability across Cowboy’s production and carbon removal chain — from feedstock sourcing to carbon storage — ensuring transparent, verifiable data for regulatory and voluntary markets
- **Yet to be announced:** A 500K+ tCO₂/yr CCS project in the South US.

KEY DATA

TRL	9
Target Industries	CCS, CCUS, CDR, SAF, Hydrogen

TECHNOLOGY DESCRIPTION

DIGITAL MRV FOR CCS & CDR PROJECTS

Carbon projects today are confronted with a rapidly evolving landscape to monetize their efforts. New compliance & tax regimes are emerging. Regulations are evolving on an international level. Reporting requirements for monetization pathways are increasing in complexity.

To manage this rapidly evolving landscape, carbon projects require a robust digital MRV solution that is:

- Built for Scale — allows the platform to scale and support future project arrangements and structures
- Flexible & Adaptable — ensures the platform adapts to emerging regulations and value streams
- Foundational and Secure — provides a robust system that remains constant, even as the industry, markets, and technologies evolve.

Mangrove Systems offers the leading digital MRV solution for carbon capture & storage (CCS) and carbon dioxide removal (CDR) projects. The solution enables project developers to streamline commercialization within one central system, powering project developers’ ability to monetize project operations and maintain project compliance.

Mangrove aggregates operational and non-operational data from across your project boundary and supports the production carbon accounting required to meet regulatory and commercial reporting requirements to engage government programs, compliance markets, as well as the voluntary carbon market.

HOW MANGROVE WORKS FOR CCS

1. Ingests Operational Data From Upstream, Midstream and Downstream Stakeholders. Mangrove ingests and centralizes disparate, disconnected data across your project operations and value chain from multiple sources including the operational technology (O/T) environment, manually inputted or uploaded production data, and partner data sources.
2. Operational Data is Processed and Normalized. Your project operations are replicated in a digital model, mirroring your carbon value chain, allowing you to have validated and normalized data of all value chain activity for downstream use.
3. Production Carbon Accounting Entries Track Production. Production carbon accounting entries are inserted into the carbon ledger, which performs an end-to-end accounting of record of CO₂ sequestration. The carbon ledger automatically validates your operational data for completeness and ensures complete traceability, resulting in a detailed emissions data behind every sequestration event and an audit trail that’s compliant for monetization.
4. Generate compliant reports for verification and submission to administration bodies. Automatically create program-compliant reports and data packages to streamline the verification process and accelerate cash conversion.

5. Verified Production Inventory is Converted into Credit Inventory. Confidently allocate production across monetization pathways (45Q, 45Z, LCFS, TIER, VCM and more) while enforcing stackability, meeting offtake obligations, preventing double counting and optimising revenue given a unit of output’s emissions profile.

KEY BENEFITS

Streamline reporting across monetization pathways

Through a detailed production inventory, Mangrove Systems supports CCS operators in tracking batches of gross CO₂ production and underlying calculations, along with evidence, all in a centralized MRV platform for robust audit & traceability. Using this centralized production accounting, our platform powers external BI solutions through robust API, and built-in reports analyse production, allocations, and commercialization.

Accelerate the cash conversion cycle

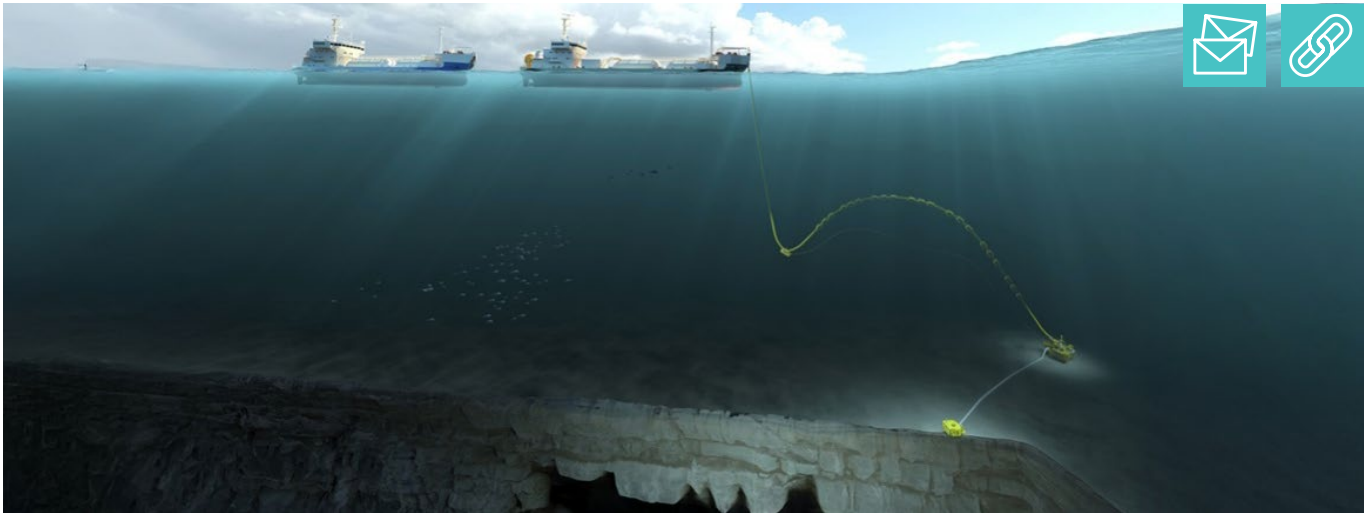
Mangrove provides verification bodies (VVBs) & auditors with a central hub to review underlying production data and supporting evidence. By performing upfront validations to ensure data completeness for verification, and centralizing data, accounting, and evidence in one accessible location, Mangrove significantly reduces the time and effort required for verification, leading to quicker validation of credits and faster access to revenue for projects. Project developers can then track the real-time position of their verified credit inventory across the full life-cycle (offtakes, orders, and deliveries).

Seamlessly integrated into your operational technology environment

As a hardware-agnostic solution, Mangrove offers secure flexible data ingestion options to ingest data from sources across your value chain, including meter data, third-party data, data warehouses, and third-party monitoring data.

Operate your CO₂ hub with confidence

Request and share data from upstream, midstream, and downstream partners across the carbon chain of custody to provide end-to-end carbon accounting across multiple CO₂ sources and storage points to correctly attribute CO₂ volumes and characteristics back to CO₂ sources. Provide production carbon accounting data back to CO₂ sources for them to execute their commercial strategy (45Q, 45Z, 45V, EU ETS, CBAM, VCM).

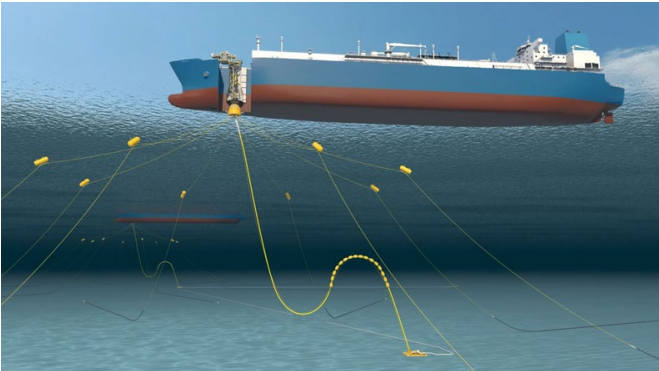


SUMMARY

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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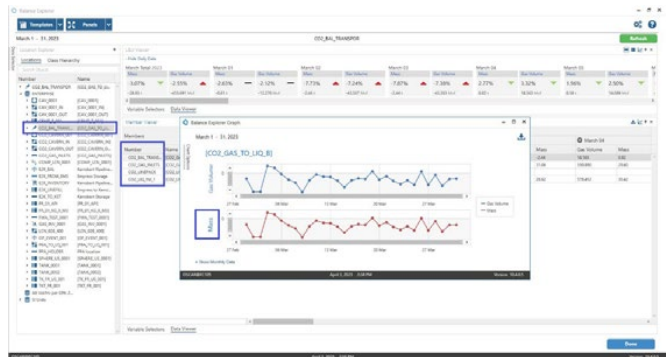
SUMMARY

The Carbon Capture and Storage (CCS) process involves collecting (capture) CO₂ from industrial processes or from the atmosphere, transporting the CO₂ via pipelines and injecting it into underground geologic formations. During this highly technical process, CO₂ is handled in both gas and liquids (supercritical) phases making accurate measurement data management both a challenge and a requirement for successful and ongoing profitability of CCS projects.

The responsibility of custody transfer measurement points means CO₂ must be measured and correctly accounted for at the capture point, pipeline inlets, pipeline outlets, pipeline linepack/inventory, storage injection points, and finally, the storage inventory must also be tracked and balanced. A CCS operator must have a strong toolset to consolidate, review, correct and distribute an immense amount of measurement data across the organisation. In addition, the CCS operator must perform this with the knowledge that the measured CO₂ and inventory are accurate to minimise legal and financial exposure and maximise revenue. FLOWCAL by Quorum is the tool that enables CCS operators manage CO₂ measurement data.

BENEFITS

- Support for CO₂ measurement in both gas and liquids (dense) phase.
- Support for a wide range of metering technologies such as coriolis, ultrasonic, orifice, linepack/linefill, caverns, etc.
- Compliance with measurement industry standards and regulations.
- Physical balancing by volume and mass.
- Meet internal and external audit requirements.
- Financial risk reduction/elimination.



KEY DATA

TRL	9	FLOWCAL Installations	200+
Technology	Gas and Liquid Measurement Solution	CCS Project Maturity	Operational or Pilot
Deployment	Self-hosted or cloud-hosted	Years of Proven Accuracy	25+
Target Industries	Operators of CO ₂ Transportation Infrastructure or Storage Resources		

TECHNOLOGY DESCRIPTION

FLOWCAL by Quorum Software is one of the most robust measurement data management systems available, streamlining the measurement process and optimising data integrity. Designed to operate as a data warehouse capable of serving the needs of an entire organisation, FLOWCAL provides a corporate solution for the most demanding system requirements. It can be applied to CO₂ measurement, hydrocarbon measurement (gas and liquids), helium and hydrogen measurement.

FLOWCAL is used by the largest energy producers and midstream operators to ensure every drop of hydrocarbon is reviewed and accounted for. New CCS operators are starting to rely on FLOWCAL to ensure their stringent measurement needs are met in support of their financial goals. FLOWCAL has an extensive toolset to avoid costly errors by using validation routines that flag erroneous data and identify issues in the field, reduce measurement uncertainty, identify ‘Lost And Unaccounted For’, physical system balance, and minimise risk by ensuring compliance, data transparency and a complete secure audit trail.

In summary, FLOWCAL enables CCS operators to review, correct, and account each CO₂ molecule whether it is in gas or dense phase, in the pipeline or in underground storage. FLOWCAL can manage CO₂ custody transfer data, balance the captured versus the injected CO₂, keep

track of CO₂ inventories in the pipe and underground, and provide a holistic view of the CO₂ moved across the CCS operation. System balancing can be managed from gas volume balance, liquids volume balance, and mass balance perspective providing a bird’s eye view of the entire CCS system.

QUORUM SOFTWARE

Quorum Software is a leading provider of energy software worldwide, serving more than 1,800 customers across the entire energy value chain in over 55 countries. Quorum’s solutions power growth and profitability for energy businesses by connecting people, workflows, and systems with decision-ready data. Twenty years ago, we delivered the industry’s first software for gas plant accountants, and today our solutions streamline business operations with industry-forward data standards and integrations. The global energy industry trusts Quorum’s experts and applications to successfully navigate the energy transition while delivering value today and into the future. Please see our website:

<https://www.quorumsoftware.com/solutions/measurement/gas-liquid-measurement/>

CO2 MASS STATEMENT											
November 2024											
Meter #: GM_9861_CO2_OPEN											
Name: [GM_9861_CO2_OPEN]											
Pressure Base:	14.650 psia	Meter Type:	Coriolis	Meter Status:	Active	CO2	N2	C1	C2	C3	IC4
Temperature Base:	60.00 °F	Calc Method:	AGA11			99.845		0.034	0.030		
Atmos Pressure:	14.400 psi	Meter Size:									
Contract Hr.:	7 AM	Interval:	1 Hour			C7	C8	C9	C10	Ar	CO
										H2	O2
										He	H2O
											H2S
Day	Pulses (Counts)	Pressure (psia)	Temp. (°F)	Relative Density	K-Factor (counts/lbm)	Mass (t)	Mass % CO2	CO2 Mass (t)	Volume (Mcf)		
1	59,779,287	1861.38	98.45	1.5269	100.00	271.15	99.833	270.70	5,157.68		
2	59,675,447	1873.44	101.46	1.5270	100.00	270.68	99.850	270.28	5,148.39		
3	61,521,848	1827.46	99.13	1.5269	100.00	279.06	99.862	278.67	5,308.14		
4	60,957,655	1848.55	100.05	1.5270	100.00	276.50	99.833	276.04	5,259.00		
5	61,053,703	1868.64	100.90	1.5270	100.00	276.94	99.837	276.48	5,267.20		
6	58,172,539	1866.45	100.35	1.5271	100.00	263.87	99.844	263.46	5,018.58		
7	58,990,313	1871.69	98.56	1.5270	100.00	267.58	99.849	267.17	5,089.49		
8	57,468,825	1817.80	101.19	1.5270	100.00	260.67	99.833	260.24	4,958.16		
9	59,451,226	1828.92	99.71	1.5269	100.00	269.67	99.844	269.24	5,129.47		
10	58,258,591	1853.00	98.78	1.5269	100.00	264.26	99.844	263.84	5,026.67		
11	59,737,050	1856.04	99.05	1.5267	100.00	270.96	99.855	270.57	5,154.64		
12	58,314,142	1865.72	101.54	1.5270	100.00	264.51	99.846	264.10	5,030.87		
13	59,276,006	1838.51	97.36	1.5270	100.00	268.87	99.835	268.43	5,113.92		
14	60,240,733	1882.08	101.02	1.5269	100.00	273.25	99.841	272.81	5,197.60		
15	62,042,259	1850.29	101.78	1.5268	100.00	281.42	99.835	280.95	5,353.31		
16	60,064,714	1843.00	101.15	1.5270	100.00	272.45	99.839	272.01	5,182.18		
17	58,914,901	1852.09	99.03	1.5270	100.00	267.23	99.839	266.80	5,082.81		
18	61,784,428	1838.67	99.29	1.5270	100.00	280.25	99.854	279.84	5,330.42		
19	59,709,315	1845.26	99.57	1.5271	100.00	270.84	99.837	270.40	5,151.01		
20	61,771,890	1864.19	99.08	1.5268	100.00	280.19	99.852	279.78	5,329.94		
21	59,627,994	1886.50	99.94	1.5270	100.00	270.47	99.849	270.06	5,144.37		
22	58,801,525	1858.33	98.78	1.5271	100.00	266.72	99.853	266.33	5,072.83		
23	57,478,844	1860.34	99.84	1.5272	100.00	260.72	99.839	260.30	4,958.41		
24	60,075,595	1840.09	101.72	1.5271	100.00	272.50	99.852	272.09	5,182.67		
25	62,033,819	1839.44	99.20	1.5270	100.00	281.38	99.851	280.96	5,352.05		
26	60,497,665	1850.65	99.89	1.5269	100.00	274.41	99.846	273.99	5,219.64		
27	57,380,085	1822.96	98.76	1.5271	100.00	260.27	99.836	259.85	4,950.24		
28	57,781,160	1843.37	100.19	1.5270	100.00	262.09	99.867	261.74	4,984.97		
29	61,243,445	1851.76	101.50	1.5270	100.00	277.80	99.861	277.41	5,283.79		
30	60,251,864	1876.81	100.51	1.5269	100.00	273.30	99.845	272.87	5,198.54		
Total	1,792,356,868	1852.81	99.93	1.5270		8,130.00	99.845	8,117.42	154,636.99		



SUMMARY

In a low-carbon environment, underground CO₂ storage has the potential to be a cash-flow generating asset. This includes both mature, operational CCS projects as well as immature, future CCS projects. Like all corporate assets, CO₂ storage owners should track and estimate the value of all CO₂ storage assets. Quorum's Carbon Storage Resources Management solution enables CCS operators to analyse the capacity of their CO₂ storage assets and understand how that capacity is changing over time.

BENEFITS

- Track and analyse the full portfolio of CO₂ storage assets – Quorum's Carbon Storage Resources Management application serves as a single source of truth for a full portfolio of CO₂ storage assets.
- Supports SPE's CO₂ Storage Resources Management System (SRMS) - align with the industry standard framework for managing and reporting CO₂ storage resources.
- Spend less time gathering data – engineers will have more time to analyse storage resources data and support decision-making.
- Reduce risk of data entry errors – company-specific data quality checks to identify errors early in the data gathering workflow.
- Scalable for companies of all sizes - from small independents to international supermajors, companies around the world can take advantage of our solution.
- Future proof your CO₂ storage business – capture and report CO₂ storage resource estimates in a structured manner in preparation for future regulatory requirements.

KEY DATA

TRL	9	Deployment	Software-as-a-Service
Technology	SRMS, UNFC or company-specific reporting frameworks	CCS Project Maturity	All - Operational and Under Development
APIs Available	Odata		
Target Industries	Storage Resource Owners		

TECHNOLOGY DESCRIPTION

Quorum's Carbon Storage Resources Management is a cloud-based solution that captures storage estimates across a resource owner's full portfolio of assets from mature, operational projects to less mature contingent or prospective storage resources. It is a best practice for a resource owner to gather estimates for all storage assets – to understand their value in the context of all corporate assets and prioritize investment accordingly.

The capacity of CO₂ storage assets changes year-over-year for a variety of reasons such as reservoir performance or economic conditions. Quorum's Carbon Storage Resources Management solution reconciles year-over-year changes allowing a CO₂ storage owner to understand which factors are driving fluctuations in estimated reservoir capacity. The diagram below illustrates the change in CO₂ storage estimates over the course of a year. The starting estimate is represented by the bar on the left side. The ending estimate is represented by the bar on the right side. The items in between reconcile the difference in starting and ending estimates due to technical or economic factors.

Quorum's Carbon Storage Resources Management application is an extension of one of Quorum's world-class software applications. Our application, Quorum Reserves, is used by oil and gas producers to track, estimate, and analyse oil and gas volumes in underground reservoirs. The same technology in Quorum Reserves has been used for Quorum's Carbon Storage Resources Management software application.

The diagram illustrates the structure of the SRMS framework. It has two axes. The vertical axis indicates the maturity of a CCS project which is measured by the chance of commerciality. The most mature projects are accounted for as "capacity", followed by 'contingent storage resources' and finally the least mature "prospective storage resources." The horizontal axis indicates the range of uncertainty of CO₂ storage capacity in a resource. As a project matures toward commerciality there is typically a narrower range of uncertainty. Resource owners usually capture three deterministic estimates of a CO₂ storage resource: a low estimate, a best estimate, and a high estimate.

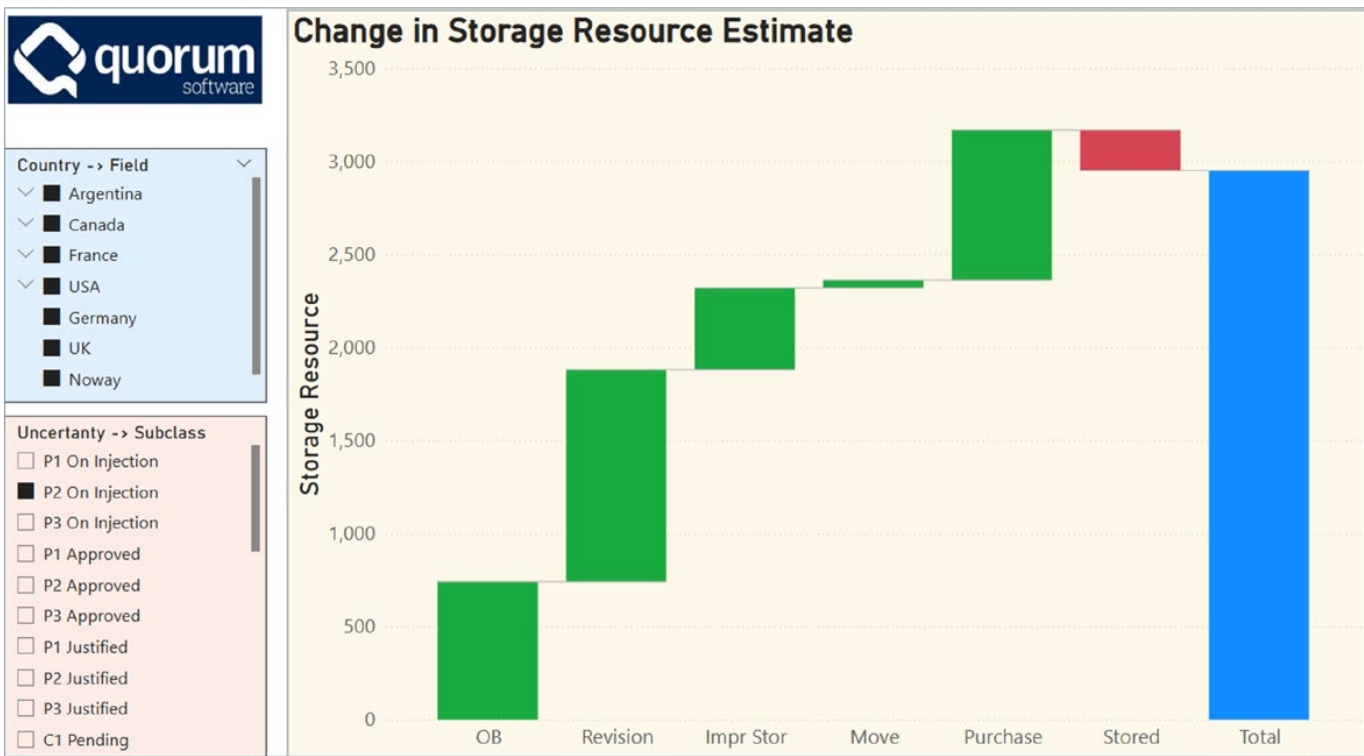
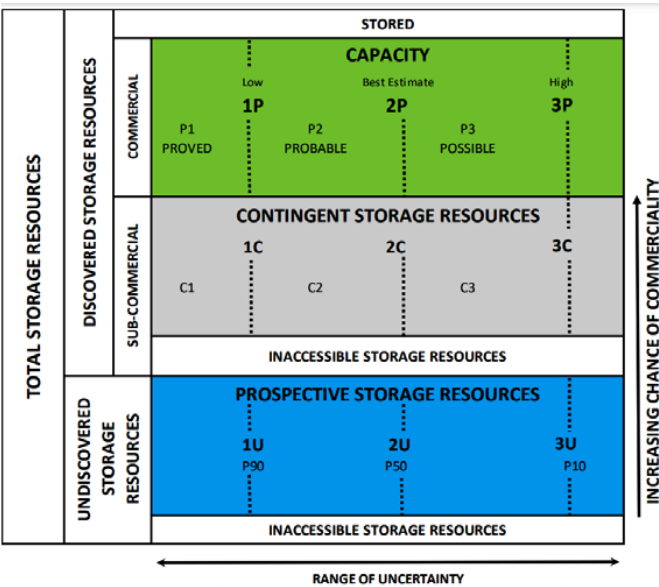
QUORUM SOFTWARE

Quorum Software is a leading provider of energy software worldwide, serving more than 1,800 customers across the entire energy value chain in over 55 countries. Quorum's solutions power growth and profitability for energy businesses by connecting people, workflows, and systems with decision-ready data. Twenty years ago, we delivered the industry's first software for gas plant accountants, and today our solutions streamline business operations with industry-forward data standards and integrations. The global energy industry trusts Quorum's experts and applications to successfully navigate the energy transition while delivering value today and into the future. Please see our website:

<https://www.quorumsoftware.com/solutions/energy-transition/carbon-capture-utilisation-and-sequestration/carbon-storage-resources-management>

STORAGE RESOURCES MANAGEMENT SYSTEM (SRMS)

The Society of Petroleum Engineers (SPE) has developed a common framework for resource owners to account for CO₂ storage resources called the Storage Resources Management System (SRMS). Quorum's Carbon Storage Resources Management application aligns with the SRMS framework.





SUMMARY

Planning and developing Carbon Capture, Utilisation and Storage projects necessitates the integration of the input of many technical and commercial functions. The quality of this integration, together with the ability to assess effectively and transparently all alternative development options, is essential to maximising the value of these projects. Furthermore, these projects are fraught with uncertainties, from the storage capacity, the costs and performance of all the wells and facilities involved as well as scheduling of the execution and operational activities. Throughout the maturation of these projects, storage owners are faced with decisions such as how many CO₂ injection wells are needed, what should the capacity of transmission pipelines and/or processing facilities be, and how to manage risks associated with the development? Each of these decisions will impact the success of the project both in terms of financial success and amount of CO₂ that can be captured and safely stored. Quorum's PetroVR application empowers engineers and planners to assess and compare all the development alternatives available, factoring in the impact of the risks and uncertainties into the decision-making process throughout the maturation process of these large and complex CCUS projects.

BENEFITS

- Enhance and streamline CCUS project evaluation through integrated simulation covering all technical and commercial aspects into a single, comprehensive application.
- Manage production goals and net-zero commitments – actualise the challenges of net-zero development with easily configurable tooling to enable development planning and production optimisation.
- Understand the impact of the project risks and uncertainties and factor this into the decision-making process.
- Improve the quality of the CCUS project development decisions throughout the project maturation process with the ability to assess and compare transparently and consistently the various development alternatives available, understand the trade-offs between these, and select the one that fits best your corporate strategic objectives.
- Simulate the development of your CCUS project under uncertainties through Monte Carlo analysis.

KEY DATA

TRL	9	CCS Project Maturity	Under Development
Technology	Discrete and Continuous Dynamic Event Simulator	Deployment	Self-hosted
Target Industries	Storage Resource Owners or Potential Users		

TECHNOLOGY DESCRIPTION

Quorum's PetroVR application is a comprehensive fullcycle, integrated simulation software for exploration and development projects including specific functionalities to cover the CCUS use-case.

PetroVR is built on more than 20 years of oil & gas field development experience. It permits engineers and planners to configure the model of their asset as necessary to reflect specific areas of complexity. It has an integrated simulation capability where users can specify any object and associated activities necessary to model their project throughout its life cycle. This includes reservoirs, wells, and facilities but also specific CO₂ storage: CO₂ injection wells and CO₂ injection facilities. An illustration is provided in the figure below.

The application simulates the project execution and operation in a time step fashion covering the entire life of the project, consistently applying inputs, constraints and rules as specified by the user and thereby computing the expected production and injection volumes as well as the associated costs incurred through time, allowing the assessment of the economic viability of the project.

In addition to simulation capabilities, PetroVR has an advanced scenario manager enabling the easy and transparent generation of alternative development scenario models. This functionality facilitates the comparison of the development alternatives identified by the user making the “what if” analysis easy, transparent, and greatly enhancing the ability to generate insights into the trade-offs between decisions.

Many project engineers and planners rely on aggregating inputs from various spreadsheets to model their field development plan and possible alternatives. While spreadsheets are flexible, they are prone to errors. The approach is often cumbersome, time-consuming and does not offer any standardisation across asset teams. PetroVR permits companies to replace spreadsheet modelling with a powerful business simulation approach that integrates all the elements of their project.

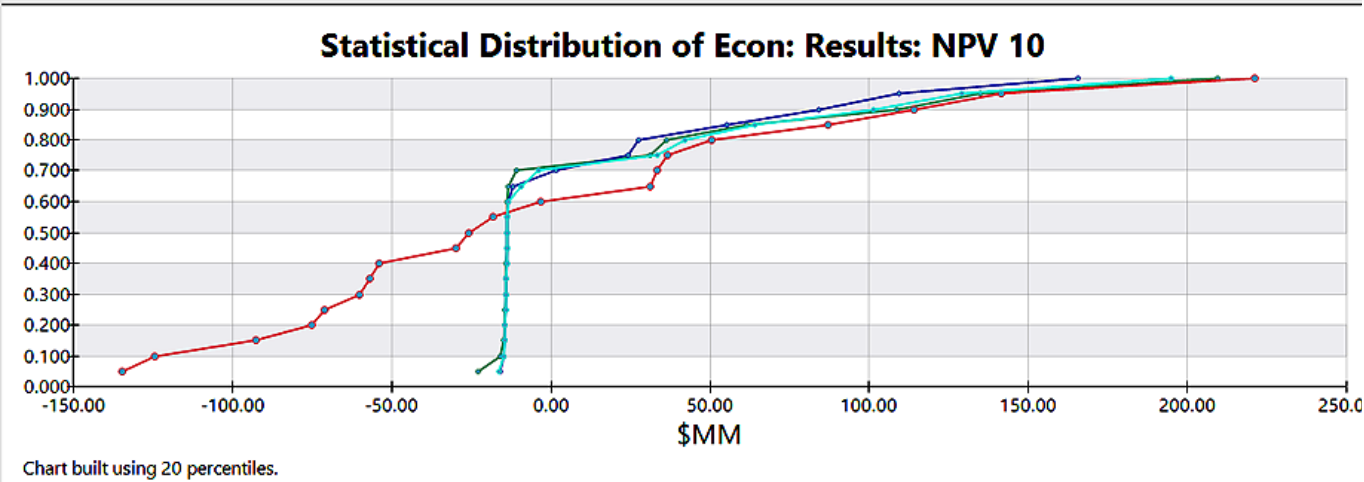
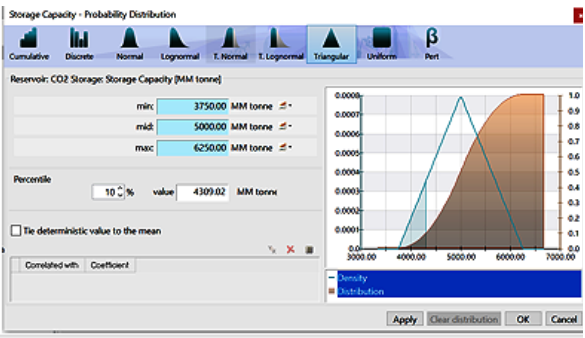
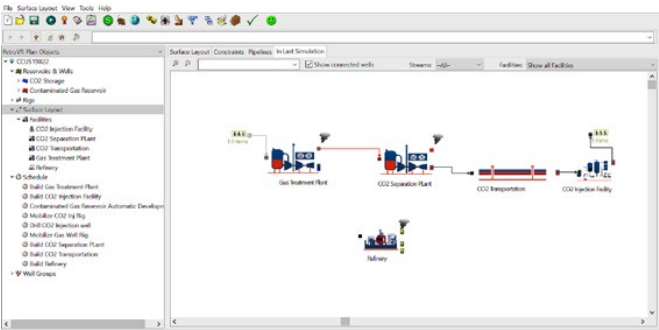
The PetroVR application facilitates probabilistic analysis through its easy-to-use Monte Carlo functionality. Users can specify the range of uncertainty for every input variable and generate the full range of expected outcome for any selected value measure reflecting all the uncertainties specified (see example below). CCUS are large and complex projects with many technical uncertainties as well as commercial. Factoring these uncertainties in the decision-making process is essential.

Quorum's PetroVR application has a long-standing track record of adding value and reducing risks associated with field development. CCUS operators can take advantage of this application's powerful simulation, scenario analysis and probabilistic evaluation capabilities to guide and support their project development decision-making.

QUORUM SOFTWARE

Quorum Software is a leading provider of energy software worldwide, serving more than 1,800 customers across the entire energy value chain in over 55 countries. Quorum's solutions power growth and profitability for energy businesses by connecting people, workflows, and systems with decision-ready data. Twenty years ago, we delivered the industry's first software for gas plant accountants, and today our solutions streamline business operations with industry-forward data standards and integrations. The global energy industry trusts Quorum's experts and applications to successfully navigate the energy transition while delivering value today and into the future. Please see our website:

<https://www.quorumsoftware.com/solutions/planning-economics-reserves/asset-development-planning/petrovr/>





SUMMARY

Saipem is a global leader in the engineering, drilling, and construction of large projects for the energy and infrastructure sectors and provides a full range of net zero-oriented services for its clients operating in both the energy transition and the offshore and onshore oil & gas sectors.

Saipem's subsidiary, Moss Maritime, has designed some of the world's largest and most advanced semi-submersible drilling platforms. A total of 29 Moss CS platforms are built or under construction, including rigs of the low environmental footprint Moss CS Eco™ series. All offer excellent operability and an unmatched track record in harsh environments. The latest design, the Moss CS Eco-X™, is the rig technology for the future, ideally suited and optimised for drilling CO₂ injection wells.

BENEFITS

- The Moss CS semi-submersible catamaran platform is a proven and robust design with 29 platforms already built or under construction.
- Excellent operability confirmed by operators and unmatched track record in harsh environments.
- The last-generation Moss CS Eco™ platform series offers low environmental impact and reduced operating costs thanks to the latest rig technology, fully electric drilling operations, and a hybrid power system.
- Saipem's drilling fleet, currently consisting of 15 vessels, includes drillships, jack-ups and semi-submersibles capable of operating at all depths as well as in harsh environments.
- The Moss CS ECO-X™ is the rig design for the future, enabling safe and environmentally sustainable drilling operations, ideally suited for drilling of CO₂ injection wells:
 - Reduced unit size and cost
 - Maximised and flexible deck space with flush working deck/drill floor
 - Modularised solutions
 - Alternative (clean) fuels
 - Automated and remotely operated equipment
 - Minimum manning

KEY DATA

TRL	9
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TECHNOLOGY DESCRIPTION

DRILLING FLEET

Drilling is in Saipem's DNA. Did you know that the "P" in SAIPEM stands for Perforazione (Drilling)?

Saipem's drilling operations date back to when the company began more than 60 years ago, with the first operations taking place in 1959 off the coast of Gela in Sicily.

Saipem owns and operates a world-class offshore drilling fleet capable of conducting operations in the most demanding conditions, drilling the deepest and most technically challenging wells. The fleet includes several high-tech and advanced drilling units, including the Moss CS semi-submersible catamaran platforms.

Saipem's offshore drilling fleet has the latest drilling technology, ensuring clients receive safe, efficient, and reliable drilling services. The fleet is operated by highly qualified, committed, motivated personnel with a strong safety culture, capable of facing any situation and responding promptly in the most complex scenarios.

This is not just a question of offshore drilling. It is true passion coming from an extraordinary past, a proud present and an exceptionally promising future.



Saipem Scarabeo 8 – a Moss CS semi-submersible drilling rig

MOSS MARITIME ECO DRILLING FLOATERS

The Moss CS-series of semi-submersible catamaran platforms has established itself over the last 25 years as one of the most successful and widely used platform designs. Ranging in size from only 25,000 tons displacement up to 75,000 tons, the CS-series platforms are rugged and long-lived with excellent motion characteristics. Their success comes from the flexibility and versatility of the design and the ability to meet a large variety of requirements. The structural layout of the lower hull allows alternative deck arrangements and installation configurations.

Field-proven in the harshest environments, the Moss CS guarantees a long life with outstanding performance.

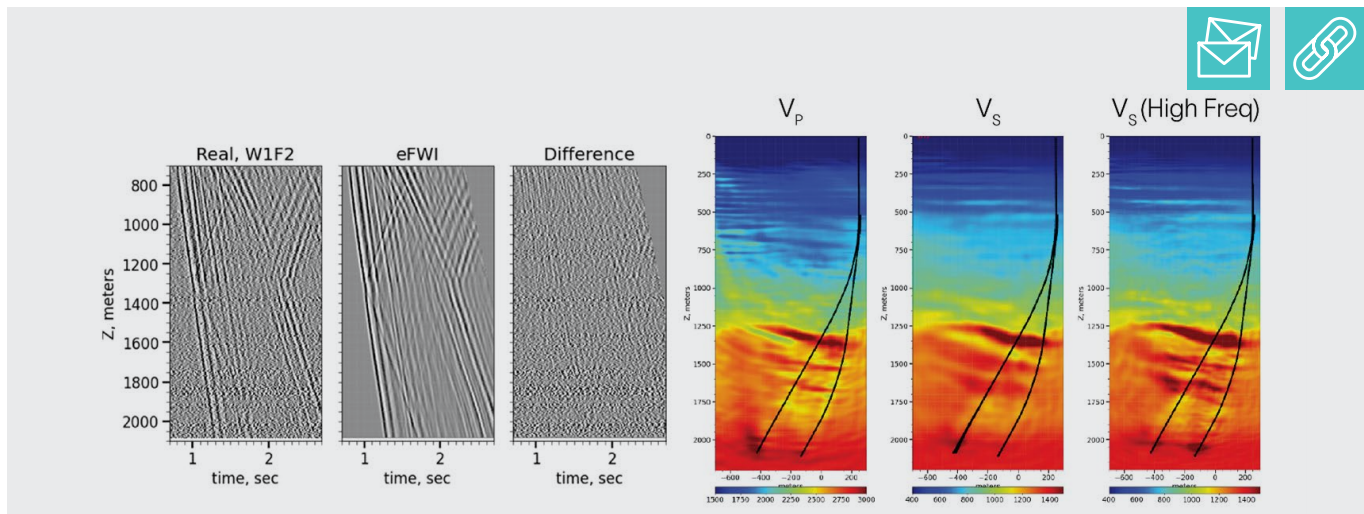
RIG FOR THE FUTURE – MOSS ECO-X™

Building on the proven and safe Moss CS design, the ECO-X™ is a quantum leap towards more sustainable drilling operations, taking the Eco™ design even further into the future. Alongside the decarbonisation effort in a time of energy transition, the concept will save cost through reduced OPEX coupled with unmatched uptime and operating efficiency. The aim has been to offer a design with limited to no emissions, enabling clients to meet their targets and ambitions of decarbonised operations. This is achieved through a hybrid power system, exhaust cleaning, the introduction of clean fuels and a plug-in option.

The CS ECO-X™ concept is ideally suited for drilling CO₂ injection wells. It implements the latest state-of-the-art technologies for digitalisation and automation to increase the operational safety while optimising crew efficiency over time. Further, maintenance is condition-based rather than calendar-based, using a digital platform for collecting and analyzing performance data of critical equipment, resulting in optimum asset operation.

The Moss CS has already been successfully utilised for well-drilling operations around the globe, demonstrating its effectiveness and reliability. Its advanced design and capabilities make it an ideal platform for developing carbon storage projects worldwide.





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 minimizes 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 minimize 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:

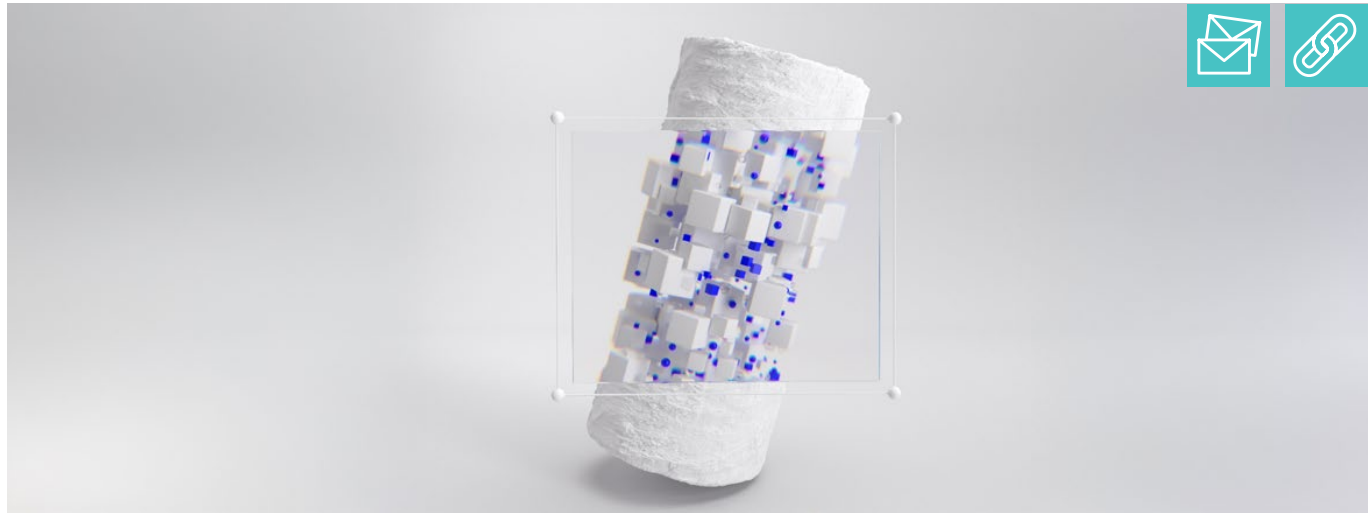
- Simultaneous inversion of fiber and conventional sensor data was performed.
- The deep part of the model, covered better with conventional sensors, was better updated.
- Further improvements are needed for simultaneous DAS and conventional data inversion due to some artifacts caused by inaccurate scaling 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

The document highlights the effectiveness of eFWI 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

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.

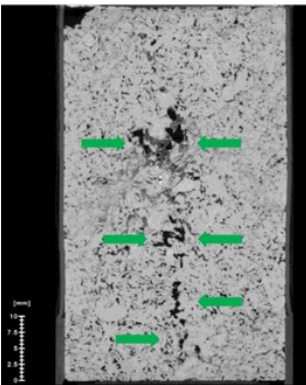
BENEFITS

- 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 pressurized 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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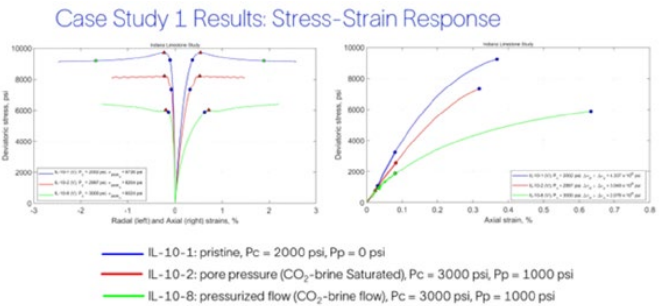
TECHNOLOGY DESCRIPTION

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 synthesized 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 pressurized 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 pressurized 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% ↓)	--

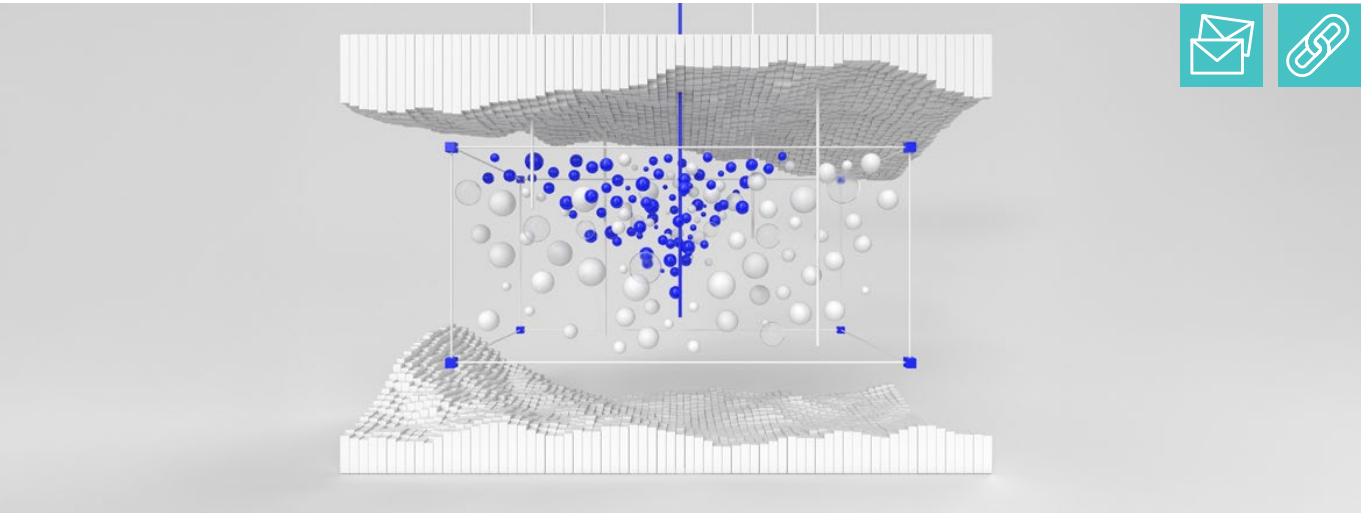
*Elastic properties evaluated over similar axial strain ranges for comparison.

To learn more, visit www.slb.com/sequestri



SLB

SEQUESTRI™ STRATIGRAPHIC INSIGHTS



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 summarize 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 summarized 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:** Organize 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 organized 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 summarizes 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.

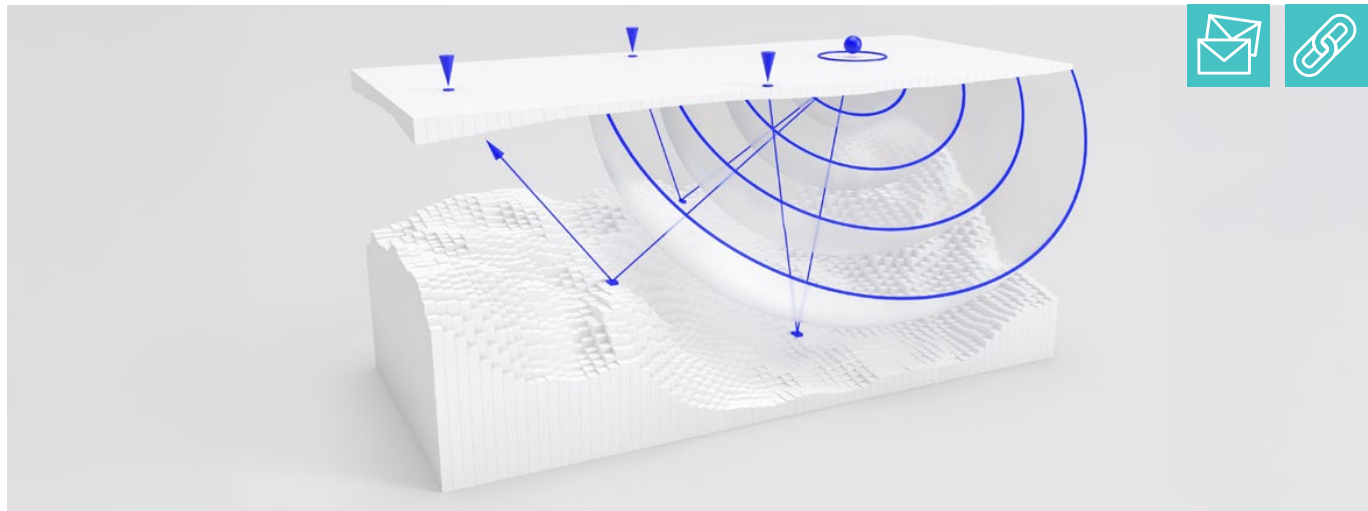
Zone Name	Top Depth	Bottom Depth	Gross Thickness	Net Thickness	Net NaCl Salinity	Net Average Porosity	Average CO ₂ Accessible Porosity	Net Average Horizontal Permeability	Net Water Injectivity	Net CO ₂ Injectivity	Static Free CO ₂ Storage Capacity/Acre
	ft	ft	ft	ft	ppk	ft ³ /ft ³	ft ³ /ft ³	mD	Bbl/day	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



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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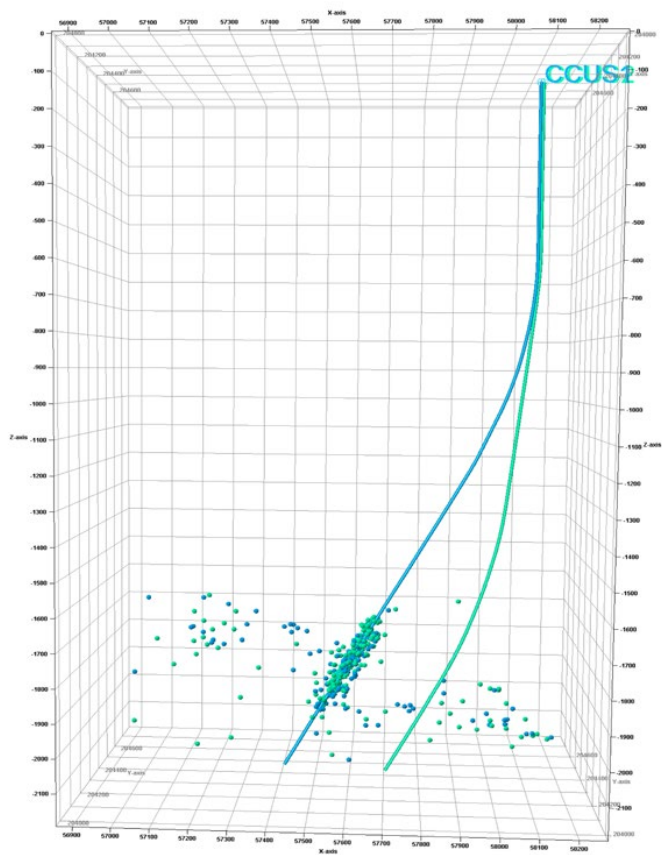
TECHNOLOGY DESCRIPTION

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.



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.

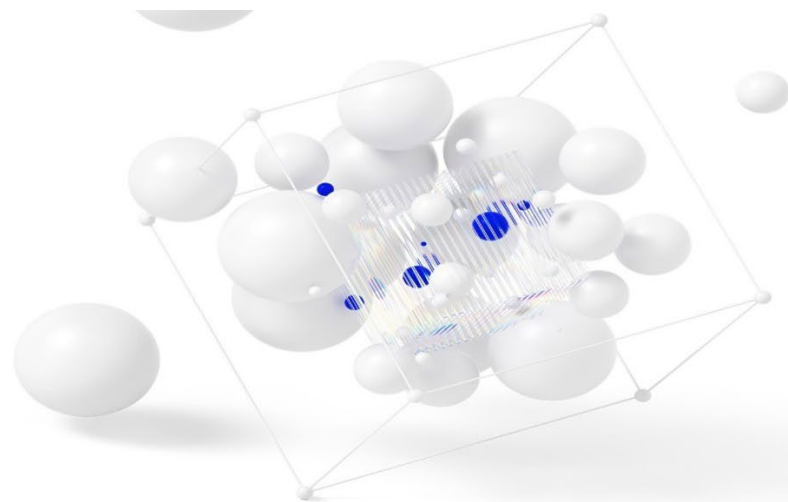
Overall, the Minami-aga pilot project demonstrated that DAS technology offers a cost-effective, scalable solution for comprehensive subsurface monitoring in CCS projects. By revolutionizing traditional MMV approaches, our induced seismicity monitoring (ISM) together with our full offering of DAS technology 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

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



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 prioritize 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.

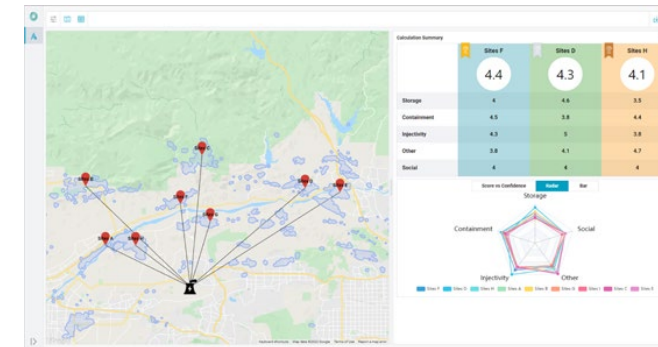
CASE STUDIES

- **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 1](#), A. Parent et. al., DOI: [Link 2](#).
- **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. Source: [Link 1](#)

KEY DATA

TRL	9
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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.

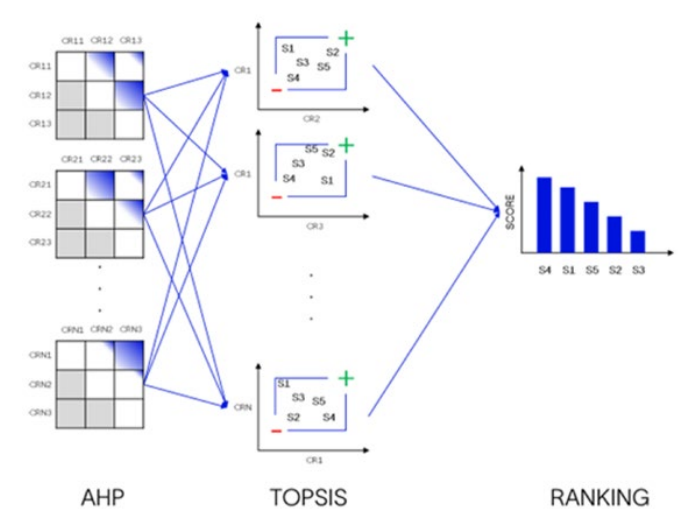
CRITERIA SELECTION AND WEIGHTING

Robust screening and ranking of carbon storage sites requires a thorough evaluation of both technical and non-technical criteria.

Technical criteria are categorized 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

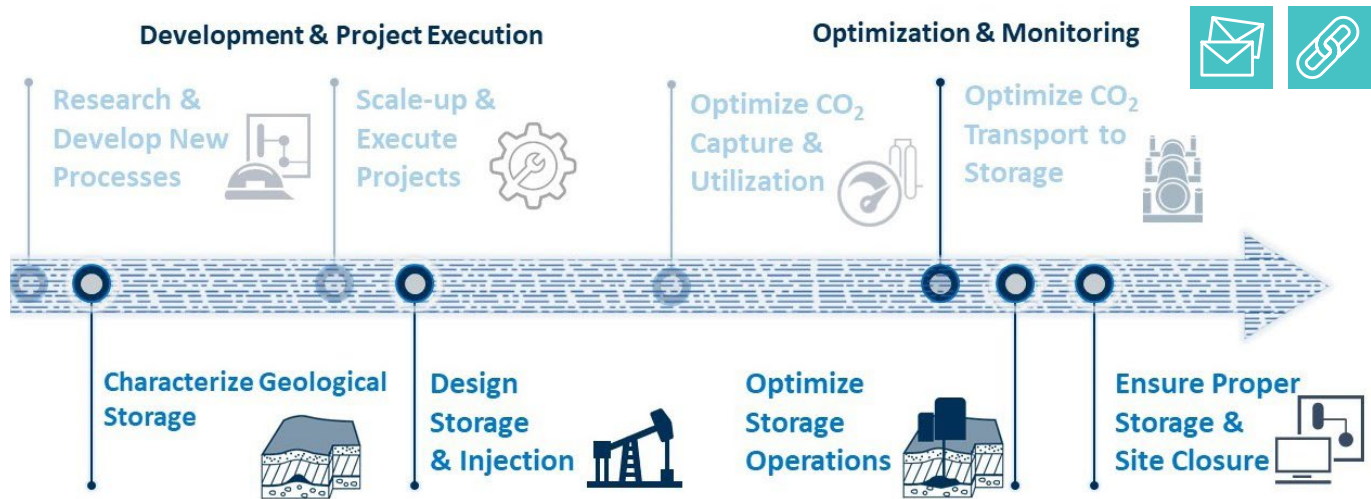
AHP is used to define the relative importance of each criterion and sub-criterion in the evaluation hierarchy. By leveraging structured pairwise comparisons, AHP enables the balanced weighting of a wide range of factors—both quantitative and qualitative—ensuring that final weights reflect expert insights, 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 normalized 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



SUMMARY

AspenTech 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

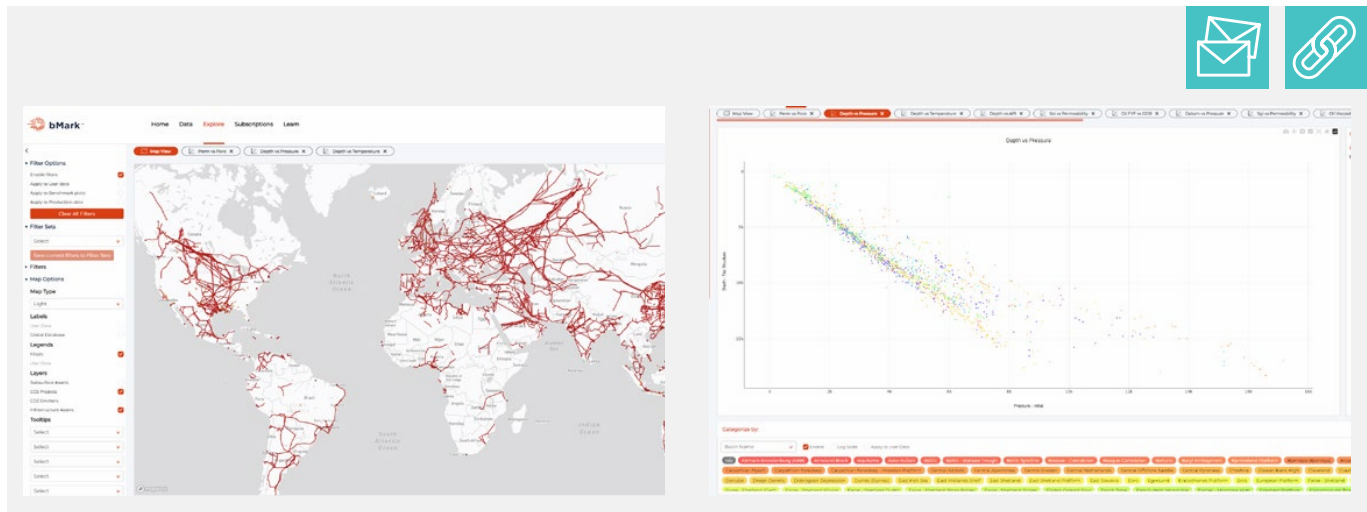
- Streamline the carbon storage site selection process
- Ensure project viability with a thorough evaluation of storage capacity, containment, and site ability for injection and permanent storage
- Reduce geological risk in carbon storage to make informed investment decisions
- Optimise injection conditions 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 reservoir modeling, 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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SUMMARY

bMark™>CCS platform offers a robust data-driven approach to the screening and benchmarking of Carbon Capture & Storage (CCS) project concepts.

bMark™ enables users to build a comprehensive CCS project portfolio with access to global data on potential CO₂ sources, transport and 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 hydrocarbon fields and saline aquifers, a growing suite of potential storage aquifers, 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.
- Book & Audit Storage Resources.** bMark™>CCS provides guidance for users in preparing their project concepts for classification using the SRMS resource classification system within a dedicated portfolio dashboard.

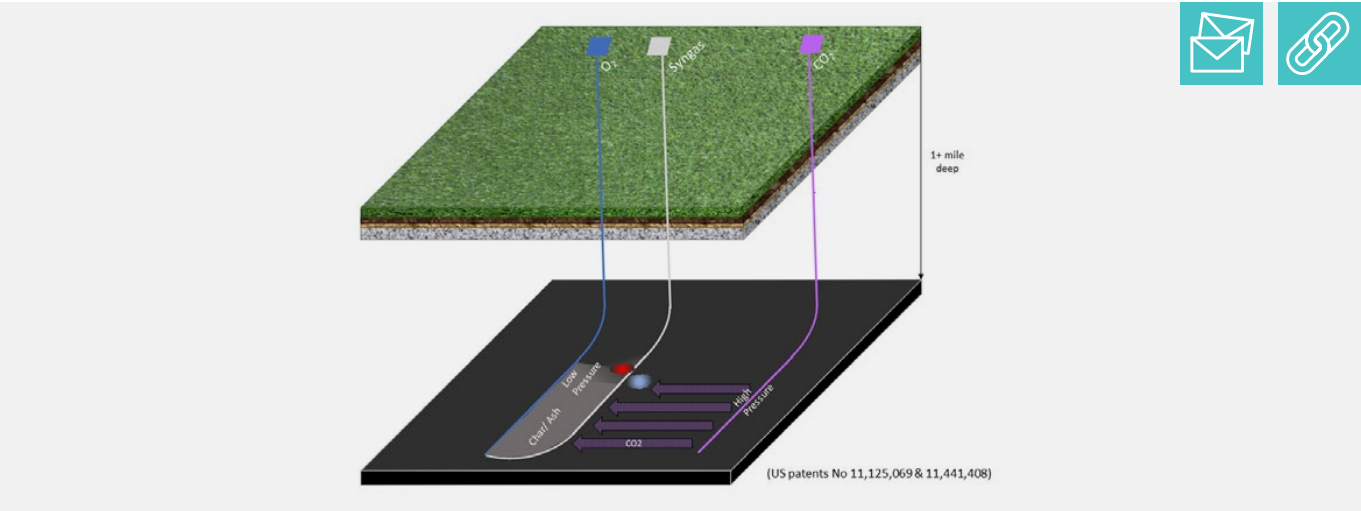
EXPAND YOUR CCS PORTFOLIO

- Integrated Data Analytics.** bMark™>CCS enables you to integrate your data securely and privately into any analysis via easy-to-use data import and management facilities. As it is fully integrated into the existing bMark™ Cloud platform, bMark™>CCS datasets and assessments also integrate with analytics users may prepare in the wider upstream energy space.
- Global Impact.** bMark™>CCS, is revolutionising the way professionals evaluate and manage CCS projects across the globe. We take pride in seeing the transformative effects of our product on a global scale, having partners across continents helping us tailor our solution to the industry fast-changing needs.



KEY DATA

TRL	9
Target Industries	O&G companies, CO ₂ Emitters, Energy Regulators



SUMMARY

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 (UGC) and CCS to produce the lowest cost, lowest carbon intensity chemical feedstocks.
- UGC 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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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™.

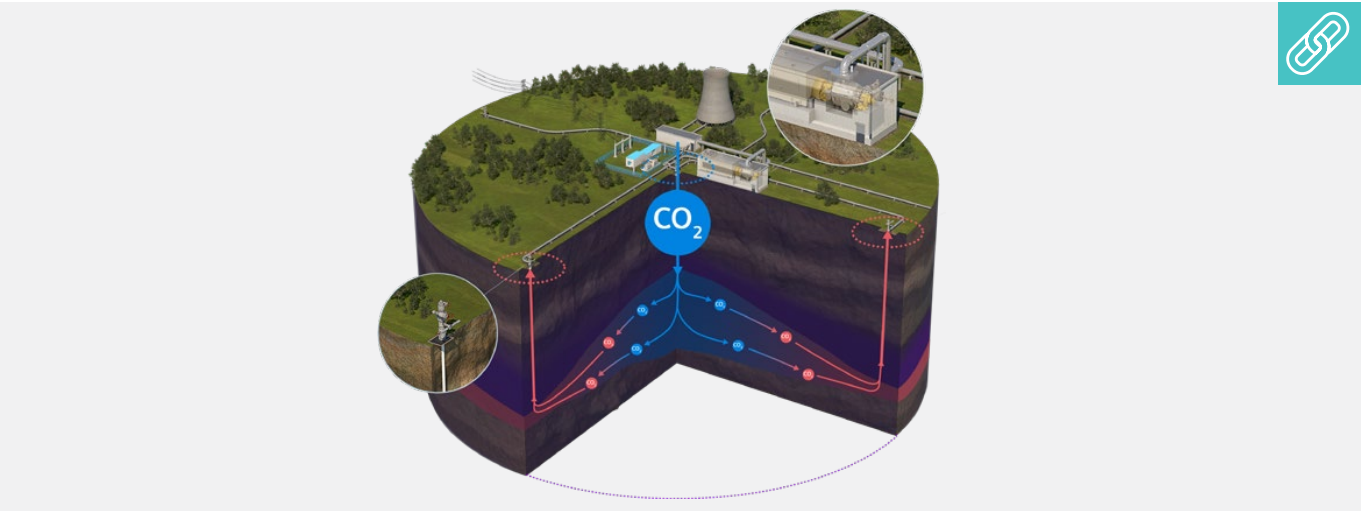
A [recent peer reviewed paper](#) in the International Journal of Coal Geology summarises analysis and results from the program and outlines the potential for deep coal as a sink for CO₂ sequestration.

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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SUMMARY

CO₂-based geothermal energy represents a groundbreaking synergy between renewable energy generation and carbon capture and storage technologies. By utilizing CO₂ as the working fluid in an open-loop geothermal system, this approach not only generates electricity but also facilitates the effective storage of captured CO₂. The utilisation of CO₂ as geothermal working fluid leverages its unique thermodynamic properties—such as lower viscosity —allowing for higher energy production rates than those of water. The natural thermosiphon effect, driven by temperature-induced density changes, enables the supercritical CO₂ to circulate through the system without additional pumping, enhancing fluid circulation and heat transfer efficiency. Moreover, CO₂-based geothermal systems can operate at lower depths and temperatures than conventional geothermal systems, unlocking new geothermal sites. This dual functionality not only provides a sustainable, emissions-free energy source but also transforms CO₂ from a waste product into a valuable resource, addressing both energy needs and climate change challenges simultaneously.

BENEFITS

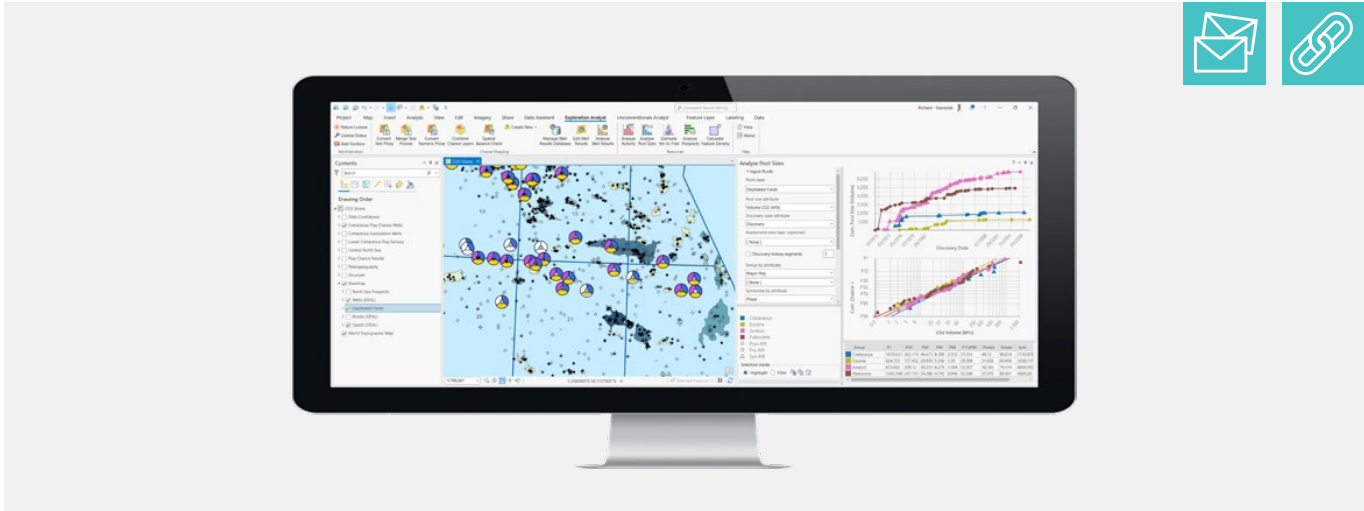
- **Delivering Baseload Capable Energy:** CO₂-based geothermal systems provide a reliable and continuous power supply, ensuring a stable energy source that complements intermittent renewables.
- **Increase Scalability for Geothermal:** This technology allows for geothermal energy development in a wider range of locations by operating effectively at lower depths and temperatures, enhancing overall accessibility.
- **Adding a Value Stream to CCS:** By utilizing captured CO₂ for energy generation, these systems create an additional revenue stream for carbon capture and storage initiatives, improving their economic feasibility.
- **Utilizing Existing O&G Know-How and Assets:** Leveraging existing oil and gas infrastructure and expertise reduces costs and accelerates deployment, facilitating a smoother transition to renewable energy solutions.

KEY PROJECT

- **Incubated within Siemens Energy:** Factor2 Energy is a spin-out company originating from Siemens Energy. Since 2019, Siemens Energy has developed and incubated CO₂-based geothermal power technology, leading to the founding of Factor2 Energy as an independent company in 2025.
- **Proof of Concept:** This project marks a significant milestone, as it successfully demonstrated the feasibility of CO₂-based geothermal systems, building on academic research dating back to the early 2000s. The unique proof of concept was delivered in 2022/2023, showcasing the technology's potential for sustainable energy generation.
- **Project One:** Factor2 Energy is developing a pioneering small commercial power plant. This first-of-its-kind facility aims to validate the practical application of CO₂-based geothermal technology in a commercial setting, paving the way for future scalability and deployment.

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	0	Number of Pilot Plants	1	Modular (Y/N)	Yes
Target Industries	Utility and Oil and Gas				

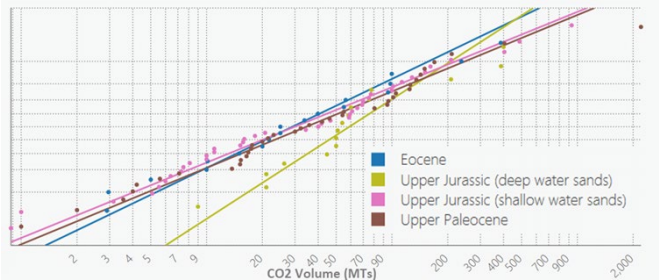
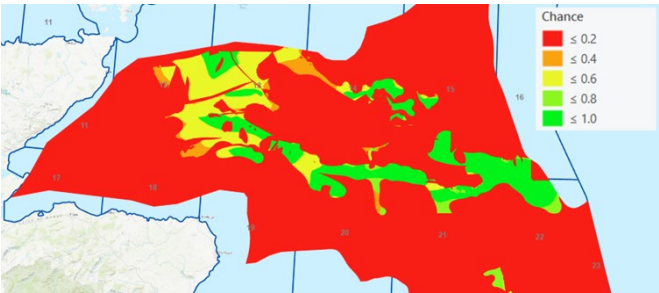


SUMMARY

Exploration Analyst is an extension to Esri's ArcGIS Pro software that assesses potential carbon-dioxide storage capacity across a region or in specific traps, maps storage segments with common risk profiles, and high-grades storage areas with the best Chance of Success (COS). Exploration Analyst can validate COS maps against well results, calculate prospect volumetrics, perform multi-criteria block or lease analyses, as well as evaluate competitor positions and support portfolio strategy. Exploration Analyst creates individual COS layers for separate geological elements that contribute to successful storage, including reservoir, trap, and seal factors. Layers can be constructed from data or sketched from concepts, and are then combined into a geologic play-chance model. Additional environmental, regulatory, infrastructure, or other elements can be added to the analysis as required. Exploration Analyst provides a wide range of summary maps, graphs, and reports to quickly and intuitively communicate results.

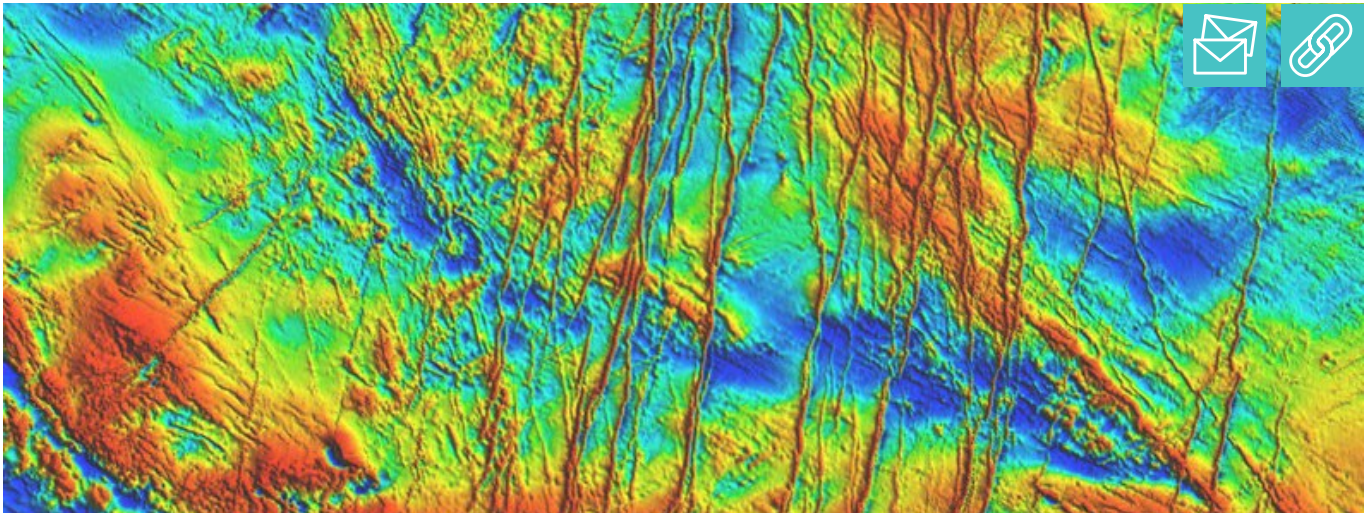
BENEFITS

- Agnostic compilation of proprietary, vendor, and public data.
- Efficient integration of inputs from multiple disciplines that facilitates communication among diverse team members.
- Auditable conclusions that can be validated against well results.
- Volumetrics and risk evaluated in a single application.
- Inputs may be rigorously derived from data, loosely sketched from concepts, or anything in between.
- Workflows can be standardised and shared using Tasks, as well as run in batch using Exploration Analyst's geoprocessing tools.



KEY DATA

TRL	9	Number of Commercial Plants	25	Number of Pilot Plants	5
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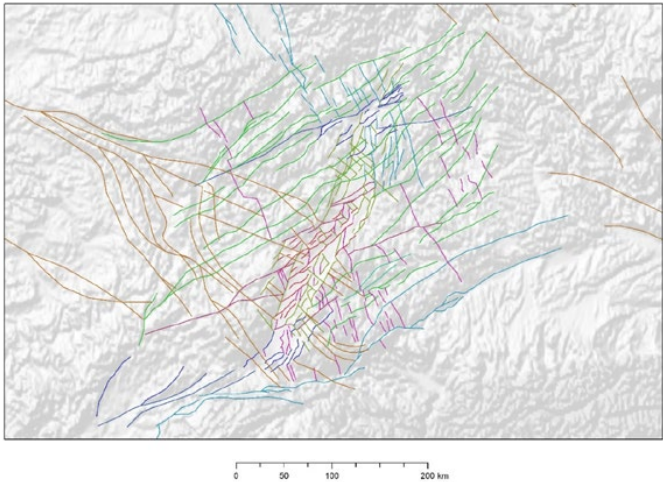


SUMMARY

Getech’s regional ($10^2\text{--}10^5\text{ km}^2$) fault mapping helps quantify seal and seismicity risk. We start with the world’s most comprehensive, highest quality gravity and magnetics database, apply advanced processing (including high-pass filtering, total horizontal derivative, and tilt angle), create robust 2D, 2.5D, and 3D inversions, and pick potential faults using Automated Coherent Lineament Analysis and Selection (ACLAS), a process developed and published by Getech. Client geophysical data can be integrated to enhance the analysis, but is not required. Potential faults are iteratively validated and classified into temporal and kinematic families using topographic, remote-sensing, and geologic (including seismic) data and Getech’s plate-tectonic models. Fault-segment azimuths are compared to local stress measurements to evaluate the chance for fault segments to be under extension or compression. The regional fault framework can be used on its own or serve as the basis for more detailed local interpretation, including planning seismic-monitoring networks or 3D seismic acquisition.

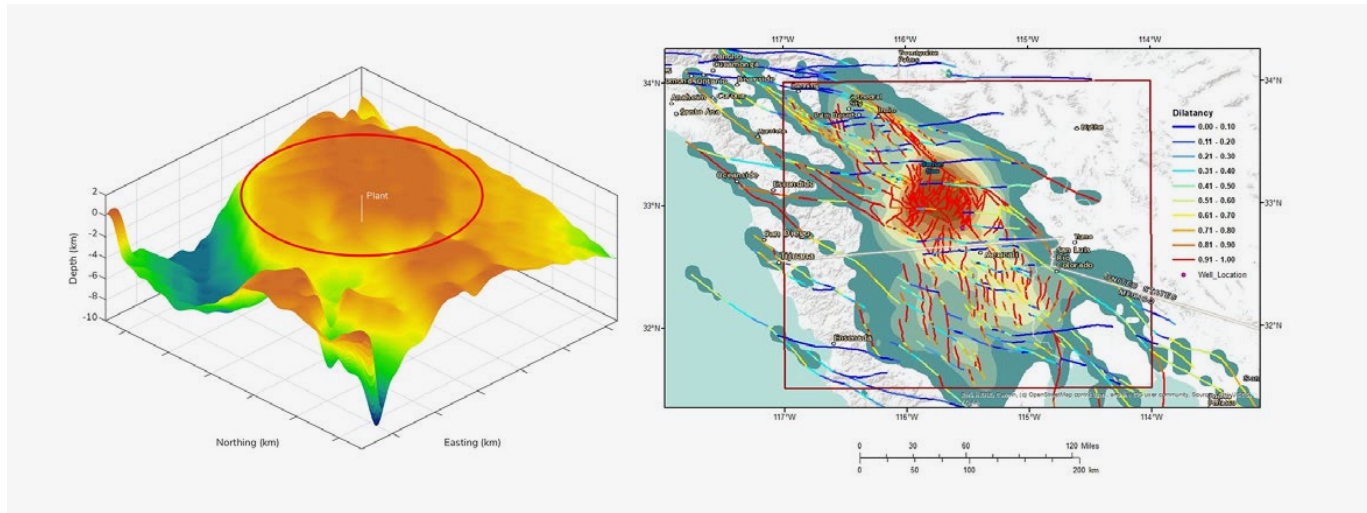
BENEFITS

- Can be applied anywhere, even where seismic or well data are sparse.
- Existing Getech database, especially good in US Lower 48 onshore and shallow water, allows immediate project initiation without additional geophysical data acquisition.
- Total project time from kick-off to final delivery can be weeks instead of months or years.
- Existing Getech datasets are regionally consistent, they do not require compilation and QC of diverse legacy data, for example seismic surveys of varying vintage, quality and acquisition/processing parameters.
- Proven approach has been validated over many years in hydrocarbon and geothermal applications worldwide.



KEY DATA

TRL	7	Number of Commercial Plants	1	Number of Pilot Plants	2
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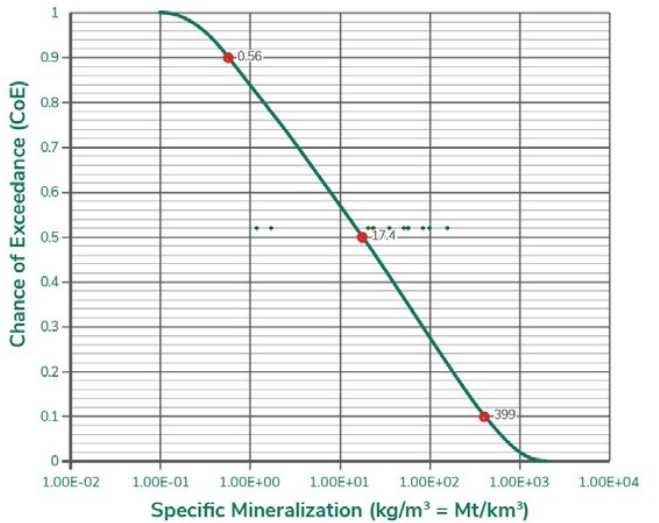


SUMMARY

Getech identifies and quantifies the storage capacity of subsurface rock bodies that can safely and permanently immobilize CO_2 through natural mineral reactions. Getech hold the world’s largest and most geographically extensive collection of gravity and magnetic data, with which we identify calcium- and magnesium-rich rocks in the subsurface, based on the high density and magnetic susceptibility of these rocks. Our proprietary fault-mapping and rock-damage evaluation techniques document the range of surface area on faults and micro-fractures that could be accessible to injected CO_2 -bearing fluids. We use a geochemical Monte Carlo simulation to bracket the range and cumulative probability distribution of volumes of CO_2 that could be bound by the estimated subterranean reactive surface area. The volumetric modeling is analogous to common hydrocarbon assessment methodologies. The probabilistic range of sequestration volumes is an effective metric to rank alternative regions or sites compared to each other, and to establish screening economics.

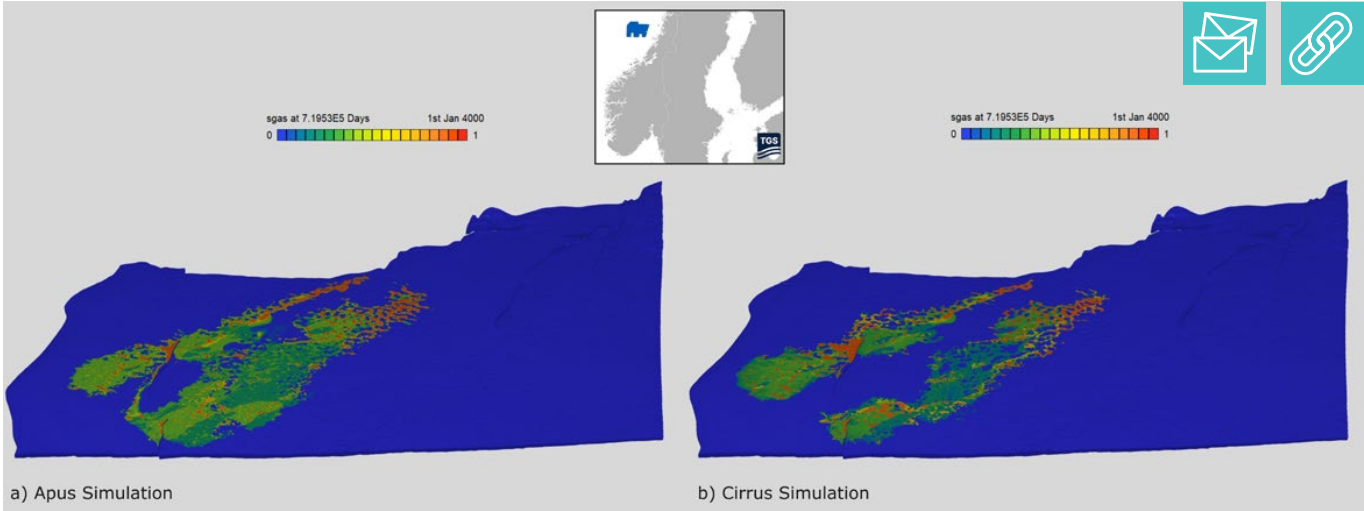
BENEFITS

- Off-the-shelf data allows rapid, consistent, evaluation anywhere in the world.
- Analysis conducted by top professionals in the field with decades of experience in these techniques, which have been proven in other industries.
- No additional data collection is needed, so no permitting or other public disclosure is required.
- Estimates can be made more precise with additional local geophysical data $\pm$ laboratory rock calibration data, but they are not essential.



KEY DATA

TRL	9
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SUMMARY

OpenGoSim (OGS) have developed Apus, a reduced-physics reservoir simulation package that allows for rapid simulation and assessment of geological CO₂ storage in saline aquifers.

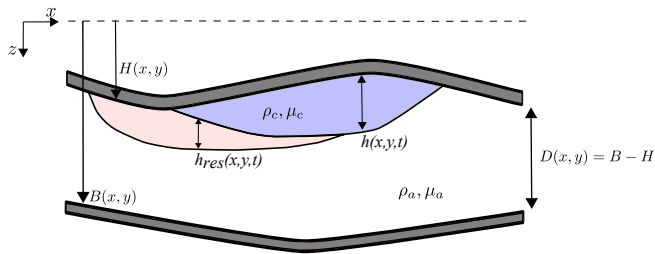
Based on a vertically integrated model for gravity-dominated flow, Apus is widely applicable and allows for faster simulations compared to traditional full-physics simulators while still capturing the key physics that control the behaviour of the CO₂. This allows a much larger ensemble of scenarios to be surveyed as part of the initial screening process.

The figure above shows 2000-year simulations for The Elephant, a potential open-saline-aquifer storage site near Norway. With good agreement between the two, Apus has a distinct runtime advantage: only 1.5hrs on a typical laptop, versus 4.5hrs for a full-physics simulator (Cirrus) using 128 MPI processors on two cluster nodes.

Apus is fully integrated into OGS’s existing Stratus interface, providing a seamless geomodelling workflow for assessment, simulation, and post-processing of geological CO₂ storage scenarios.

BENEFITS

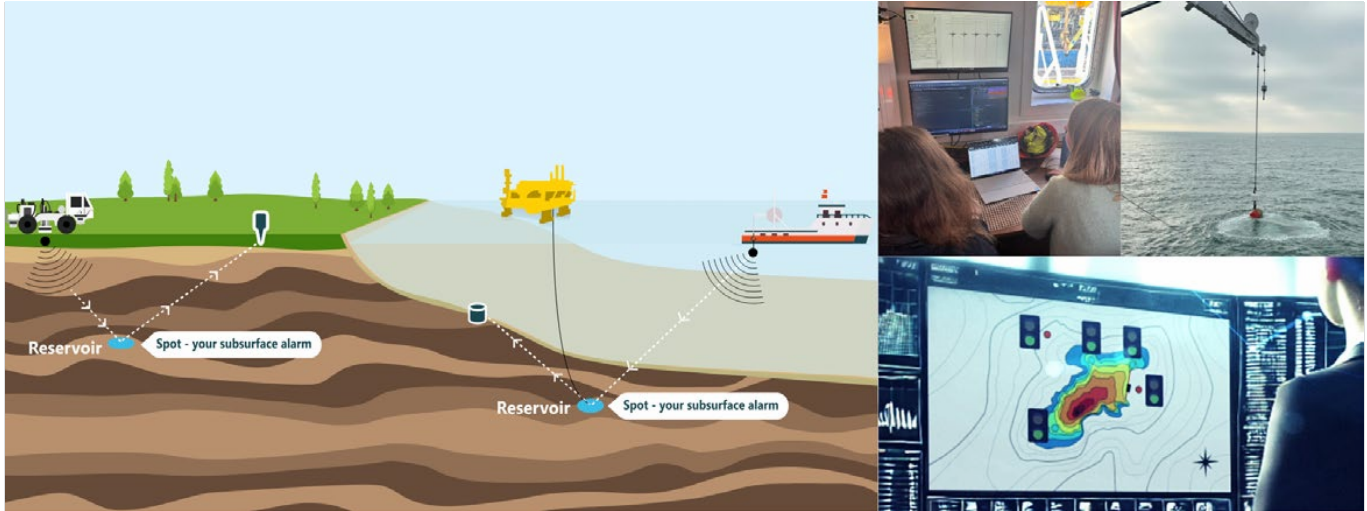
- Rapid flow simulations, allowing for a wider range of storage scenarios to be considered
- Suites of simulations allow for assessment of sensitivity and uncertainty
- A convenient simulation workflow allowing for rapid iteration



Schematic for the reduced-physics model used by Apus. The mobile CO₂ is shown in purple, while the residually trapped CO₂ is in pink

KEY DATA

TRL	5				
Target Industries	MMV planning, CO ₂ storage site screening, Uncertainty quantification				



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 spot seismic campaign (less than a day of acquisition).. This patented technology is fast, with a low environmental impact and cost-efficient. SpotLight has been awarded Top Innovator 2024 by Darcy Partners.

Spot seismic campaigns occur every year or twice a year: a higher frequency than other active seismic solutions, offering early warnings in case of deviation between the actual & the forecast CO₂ plume. For conformance, it is used to calibrate flow models & simulations, for containment it is used to monitor the major risks identified. Spot seismic is a risk-based and model driven surveillance strategy, use frequently as subsurface alarms to triggering timely response actions when deviations are detected.

BENEFITS

- Increasing site safety with frequent focused active-seismic monitoring, demonstrating conformance and ensuring to evidence the CO₂ plume behave as predicted.
- 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.
- Being cost-effective with a low initial investment without compromising result quality. Spot seismic enables competitive and robust MMV plan using on the shelf conventional seismic equipment.
- Enhancing acceptability from regulatory and stakeholder perspectives: Frequent controls and data point to evidence safety and build confidence between the operator and the regulator.

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	Operational Synergies	Yes
Target Industries	Storage, CC(U)S (onshore, offshore)		



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

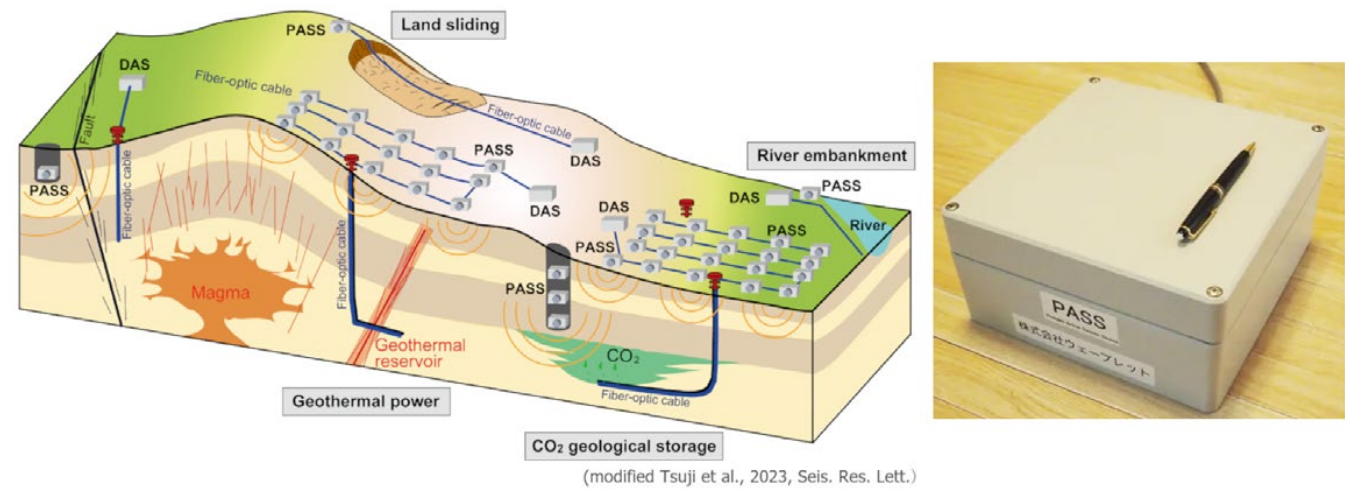
- SQUID-TEM method enables detection of CO₂ plume in a reservoir as a resistivity change in a wide range of CO₂ saturation level.
- SQUID-TEM method enables shallow and deep reservoir monitoring of CO₂ storage operation with a superior spatial resolution than conventional methods.
- SQUID-TEM method is applicable for both onshore and offshore (shallow water application).
- SQUID-TEM's low-cost acquisition makes it an ideal CO₂ plume monitoring tool 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				



SUMMARY

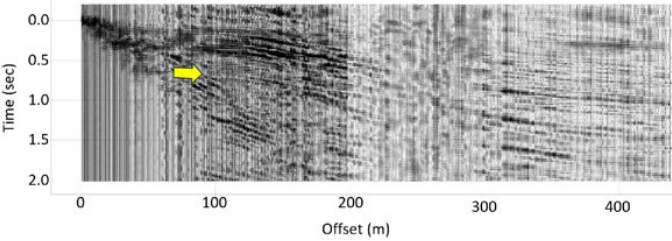
Conventional CCS field monitoring methods have typically relied on large seismic source equipment, with costs reaching millions of dollars per survey. As a result, it was challenging to conduct monitoring surveys repeatedly and to continuously capture the behavior of stored CO₂, leading to a risk of being unable to respond promptly to sudden CO₂ leaks.

Portable Active Seismic Source (PASS) developed by the Tsuji Laboratory at University of Tokyo, is a compact and cost-effective device. It allows the continuous deployment of multiple PASS units at CO₂ storage sites, including hard-to-reach locations, enabling the detection of sudden movements of CO₂.

The signal generated from the PASS can enhance penetrating energy through superposition and correlation processing.

BENEFITS

- **Compact and Lightweight:** Human-portable system facilitates both installation and transportation.
- **Low Operation Power:** Can be operated with battery.
- **Low Operation Noise:** Environmentally friendly and usable even in urban areas.
- **Cost Effective:** Can be deployed multiple PASS units along CO₂ frontier reasonably.



Reflection from 1 km reservoir depth by PASS, 50Hz, 360N (Tsuji et al., 2024)

KEY DATA

TRL	5	PASS P28 Dimensions	24x24x12cm	PASS P28 Weight	6 kg
PASS P28 Operation Power	200W	PASS P28 signal frequency	30~60 Hz		
Target Industries	CCS and Geothermal, Site exploration and long-term continuous monitoring				

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