



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

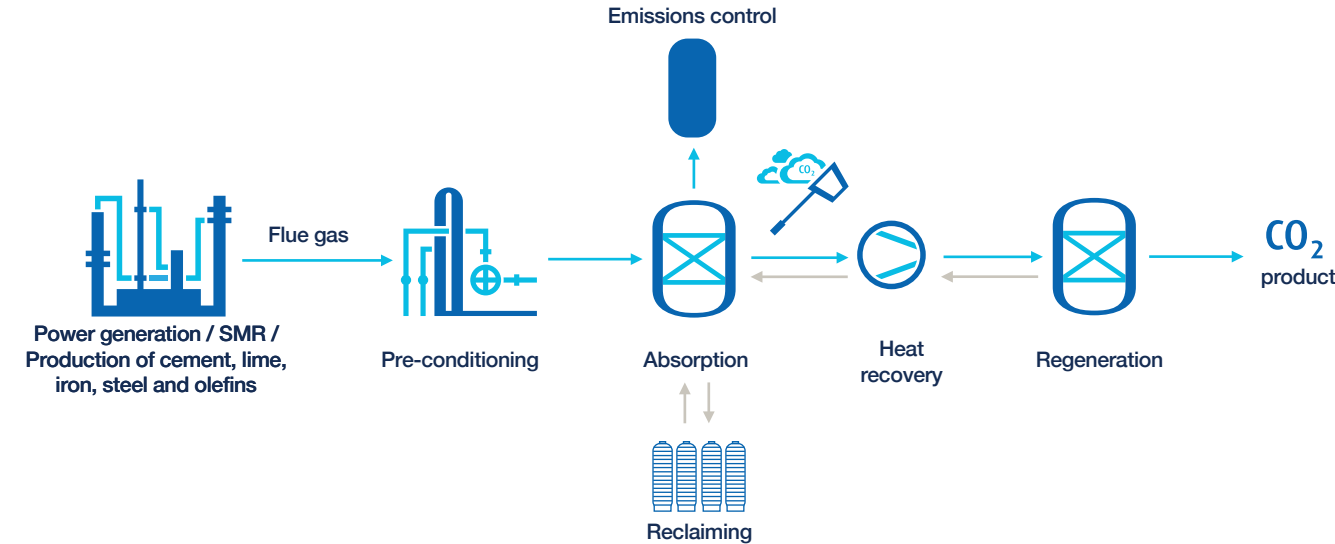
KEY PROJECTS

- 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.

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



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AMINE WASH PRE-COMBUSTION CO₂ CAPTURE

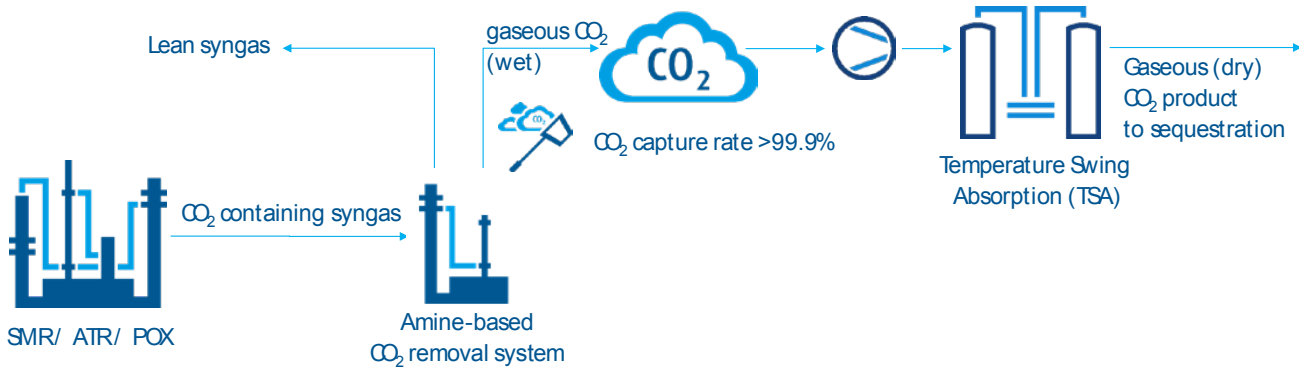


SUMMARY

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				



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CO₂ PSA



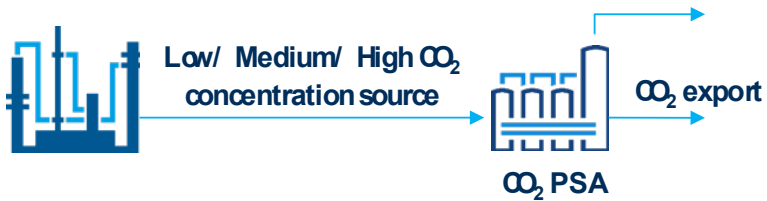
SUMMARY

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

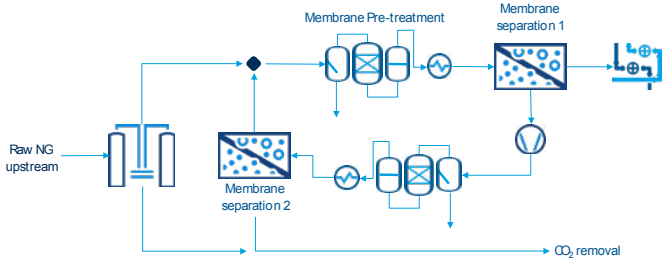


SUMMARY

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

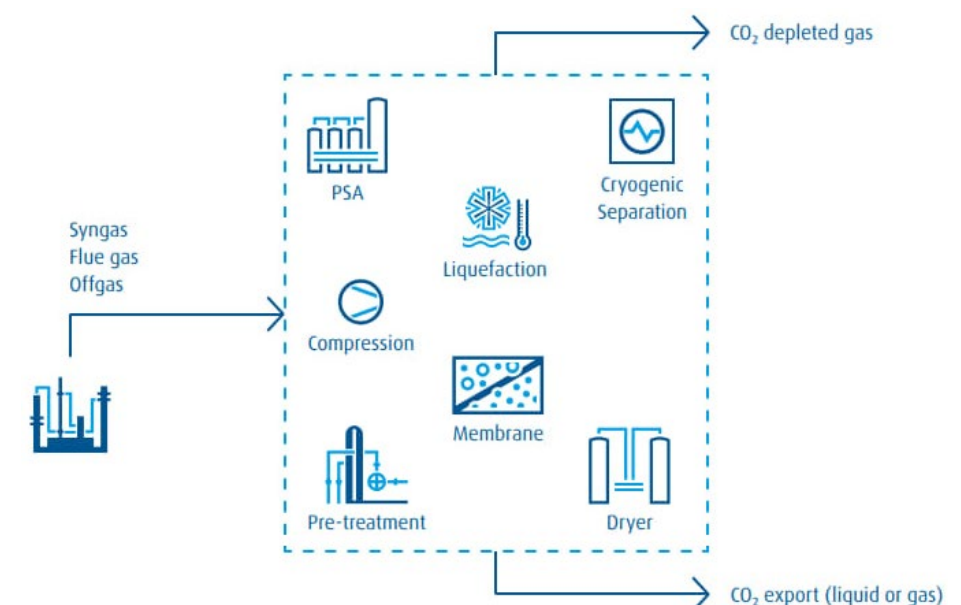
- Linde's in-house technologies are combined for blue hydrogen production, including PSA, TSA, HISELECT® membranes, and cryogenic purification
- Individual concepts for different feed streams in hydrogen production plants
- Flexibility in size and scale, ranging from 100 to more than 10,000 tpd CO₂
-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

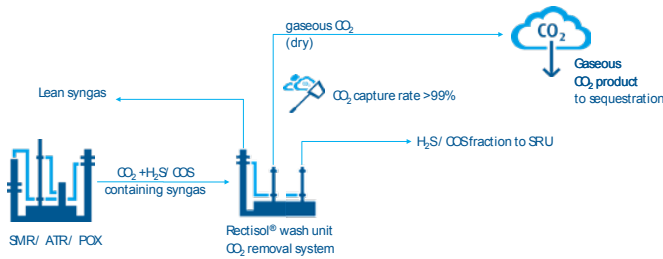


SUMMARY

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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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.

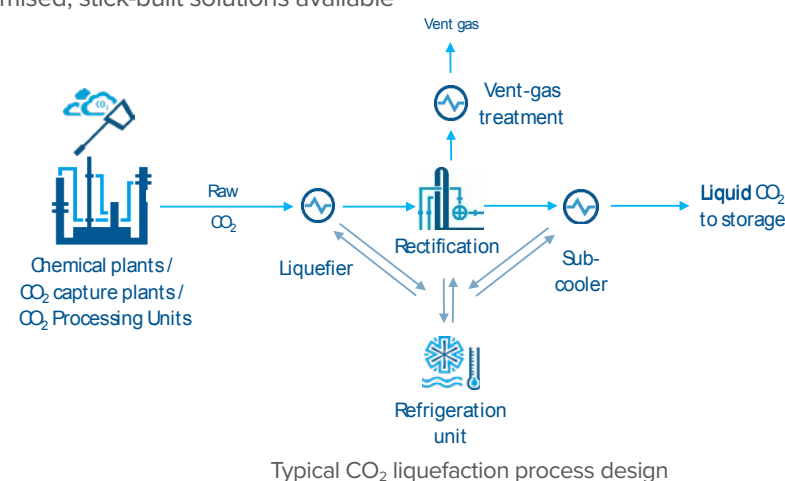
Linde's largest liquefaction plant, in operation since 2015, is producing approximately 1,350 tons of CO₂ per day. The CO₂ is used in enhanced methanol and urea production. Additional large-scale plant references can be found in Norway and the United States for carbon capture and storage (CCS) and food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

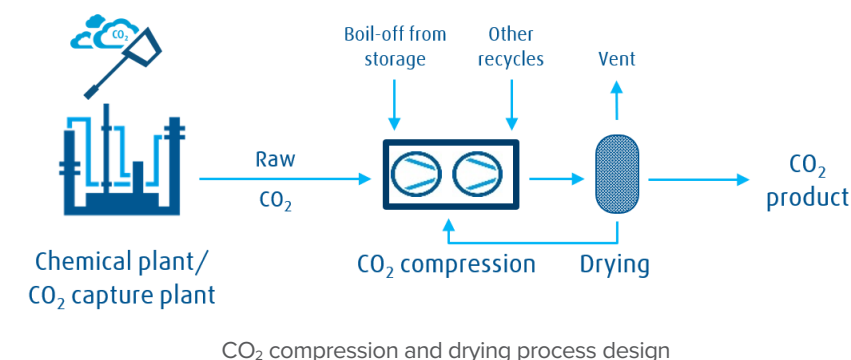
Compressor stations not only compress the main CO₂ feed gas stream, but can also be used to integrate and compress boil-off gases from storage tanks and other CO₂-rich vents from the plant.

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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LINDE 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.

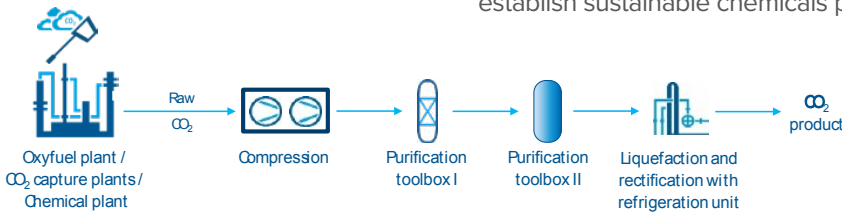
Linde initially developed and commercialised the CPU technology to treat oxy-fuel flue gases at an oxy-fuel lignite-fired power plant at Schwarze Pumpe, Germany. More recently, Linde's CPU has been considered for oxy-fuel projects in the cement industry. Mature CO₂ processing technologies in combination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



LINDE CO₂ TANK FARM AND LOADING STATIONS

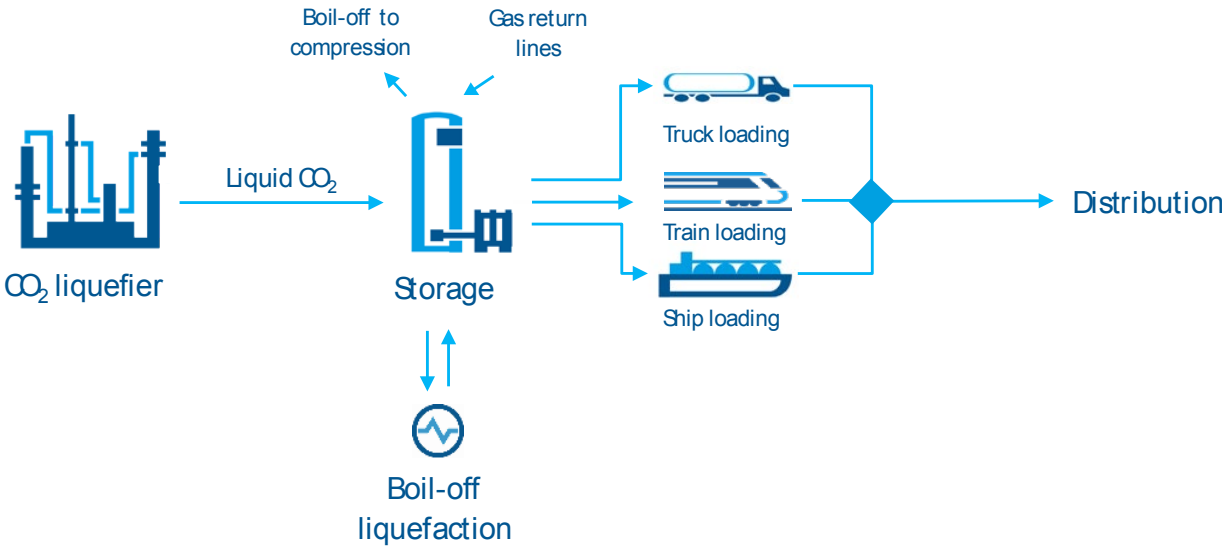


SUMMARY

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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