Efficient MAN CCUS

MAN Energy Solutions
Future in the making

Decarbonization with carbon capture, utilization, and storage

List of standard abbreviations

cf.	confer (compare)
e.g.	for example
et al.	et alii (and others)
fig.	figure
p.	page
tab.	table

List of technical abbreviations

°C	Degree Celsius
°K	Degree Kelvin
bara	Bar absolute
BECCS	Bioenergy with carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CO_2	Carbon dioxide
DME	Dimethyl ether
EOR	Enhanced oil recovery
F-T	Fischer-Tropsch
GJ	Gigajoule = 10^9 joules
GJ/kg	Energy density per mass of fuel
Gt	Gigaton = 10^9 tons
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kPA	Kilopascal
MWh	Megawatt hour
PSA	Pressure swing absorbtion
SDS	Sustainable Development Scenario
SMR	Steam methane reformer
t CO_2	Ton carbon dioxide
VLE	Vapor-liquid equilibrium

Synopsis

Carbon dioxide will become a raw material to produce renewable fuels. A new infrastructure capturing and purifying carbon dioxide from industrial sources will be built, including distribution to users who transform carbon dioxide into marketable products. Capture capacity will be in excess of use because more carbon dioxide must be removed to comply with the Paris Climate Agreement. This same infrastructure will be leveraged to transport excess carbon dioxide to permanent storage in secure geological reservoirs. This white paper describes the carbon capture, utilization, and storage (CCUS) value chain. It elaborates how the most technically and economically challenging tasks of capture, purification, and compression can be optimized by integrating carbon dioxide purification processes and integrally geared compressors.

Author

Peter Klotzsche
MAN Energy Solutions SE,
Augsburg, Germany

Head of Sales
peter.klotzsche@man-es.com

Christian Rufer
MAN Energy Solutions
Schweiz AG,
Zürich, Switzerland

Head of Business
Intelligence and
Development
christian.rufer@man-es.com

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Climate change has severely affected fragile ecosystems. Even robust ecosystems which support our livelihoods are under increasing stress. The Intergovernmental Panel on Climate Change (IPCC) has correlated total carbon emissions with surface temperature change and gives guidance about the link between the total amount of carbon dioxide in the atmosphere and surface temperatures (cf. IPCC 2018). Our remaining carbon budget as of 2022 for a 1.5 °C rise is around 430 ±169 Gt. At the 2020 emission rate of 32 Gt per year (cf. IEA 2021), we will have consumed our CO_2 budget by 2035.

The Sustainable Development Scenario (SDS) pathway described by the IEA (2020) estimates that by the year 2050, 5.6 Gt per annum of CO_2 will have to be stored to keep climate change within the limits set forth in the Paris Climate Agreement with the aim of "[...] holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C [...]" (cf. United Nations 2015: p. 3).

In addition to geological storage of carbon dioxide, an industry utilizing an even larger amount of carbon dioxide will emerge as renewable hydrogen and other uses of carbon dioxide are developed. The total carbon dioxide capture and distribution capacity will be a multiple of the carbon storage stated above.

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The CCUS value chain

An energy infrastructure centered around carbon dioxide and hydrogen

Our task is to build an energy infrastructure centered around carbon dioxide utilization and renewable hydrogen. The use of carbon dioxide in marketable products will closely follow the increase of renewable hydrogen. This new infrastructure will become the source of our prosperity in the coming decades, and carbon dioxide capture and distribution will continue even after we have reached carbon neutrality.

Large point sources, such as power plants, cement factories, refineries, petrochemical plants, and steel plants, emit carbon dioxide. After capture, purification, and compression, a pipeline distributes the carbon dioxide to industrial producers who use it as a raw material input in their processes. Most direct uses of carbon dioxide are temporary sinks, because the carbon dioxide is released when the product is consumed (beverages, dry ice, synthetic fuels, and most chemicals). These minimal distributed emissions cannot be economically recovered and will be released to the atmosphere. Therefore, the carbon dioxide balance for these synthetic products using CO_2 is circular at best. Very few uses of carbon dioxide result in permanent removal, such as polycarbonates and concrete curing.

Most carbon chemical compounds have a much higher enthalpy than CO_2, therefore substantial amounts of renewable energy, in the form of hydrogen, are necessary to convert carbon dioxide into marketable products. The greater the availability of renewable energy, the greater the opportunity to avoid or convert the carbon dioxide, and the lower the amount that ends up in storage. Geological storage will remain necessary, and according to the IEA SDS, at least 5.6 Gt per annum of sequestration capacity will be necessary by 2050 and beyond.

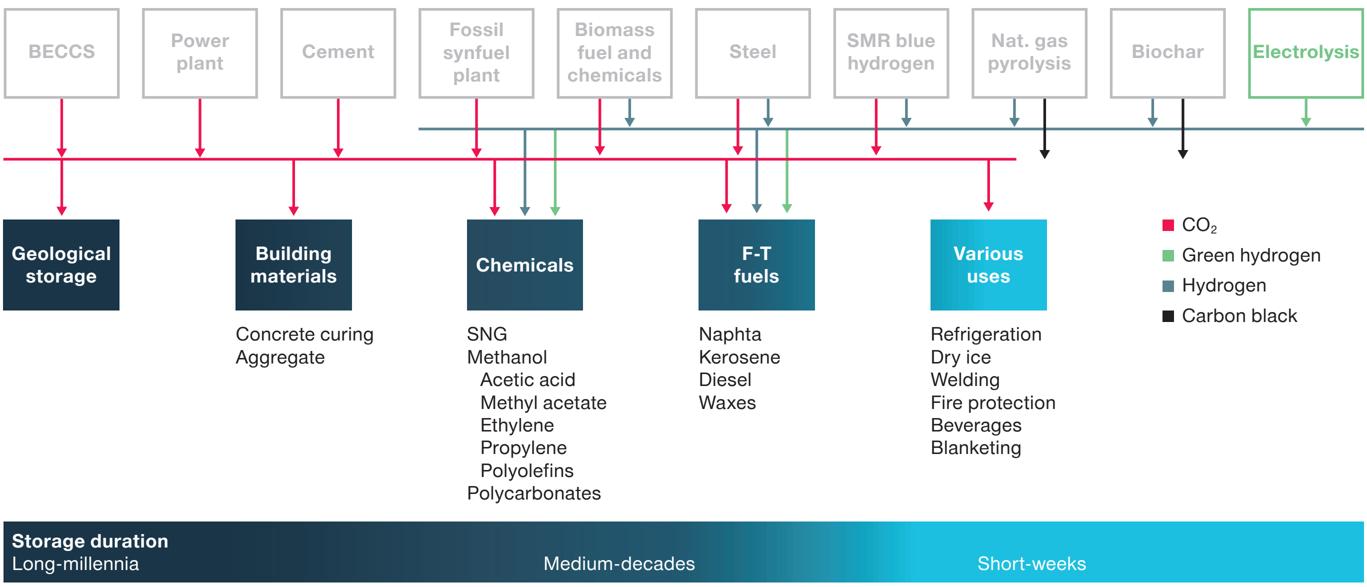


Fig. 1: Carbon dioxide value chain and duration until release to atmosphere

Capture and purification

Most large point sources emit low-concentration CO_2 flue gases. Energy demand as well as equipment dimensions increase with lower concentrations of CO_2, as shown in the Global CCS Institute (2021) study below. Although carbon dioxide separation technology has been in use for many decades and in various chemical processes, purification of low-concentration flue gases remains a costly and unprofitable venture despite major research efforts to cut capital cost and energy requirements.

Capturing and purifying is the most costly step in the carbon dioxide value chain. The Global CCS Institute (2021) study considers low energy costs of USD 2.1 per GJ of coal and USD 4.2 per GJ of gas with an asset life of 30 years. This means that 15 to 20 % of the aforementioned cost of carbon capture is attributable to energy. Energy is a key factor and prices tripled in early 2022, thereby fundamentally changing the economics of carbon capture and storage.

Some large-scale industrial processes are ideal opportunities for capture because the CO_2 flue gas concentration is high and purification costs are lower. Despite lower capture costs, few sources have been tapped.

Process	USD per ton CO_2	Cost in %
CO_2 capture (separation and purification)	50 – 100	60
CO_2 compression and dehydration	15 – 25	15
Pipeline transportation	5 – 25	10
Storage	5 – 25	10
Monitoring	5 – 10	5

Tab. 1: Cost of capturing and purifying carbon dioxide

Process	CO_2 concentration	Reference plant
Ethylene oxide	> 90 %	-
Ethanol fermentation	> 85 %	Archer Daniel Midlands, 2017[1]
Coal gasification syngas	> 40 %	Dakota Gasification, 2000[2]
Natural gas reforming syngas	> 30 %	-
Steam methane reforming	> 30 %	Air Products, Port Arthur, 2018[3]
Natural gas processing	> 40 %	Sleipner gas field, 2012[4]

[1] cf. ADM 2017
[2] cf. Dakota Gasification Company 2021-1
[3] cf. IEAGHG 2018
[4] cf. MAN Energy Solutions 2020

Tab. 2: CO_2 concentration in different processes

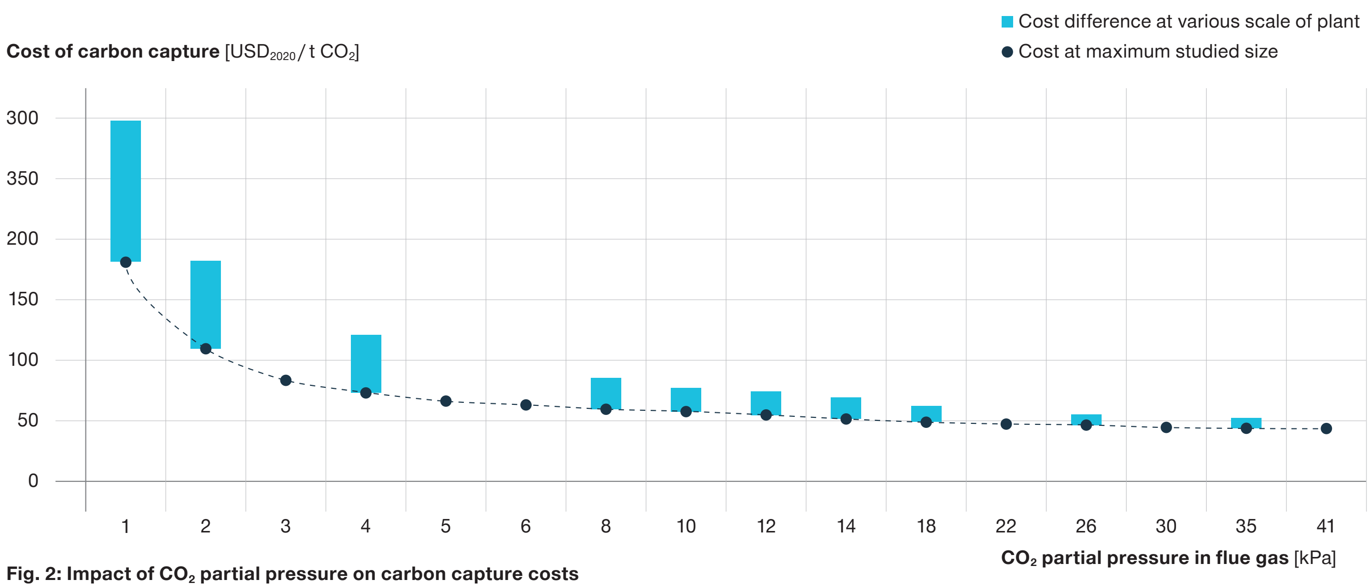


Fig. 2: Impact of CO_2 partial pressure on carbon capture costs

Carbon capture

The methods for capturing carbon dioxide can be grouped into three categories: Post-combustion capture, oxy-fuel combustion capture, and pre-combustion capture.

Post-combustion capture

Post-combustion capture technologies separate carbon dioxide from other flue gases after combustion. Selective chemical solvents with a high affinity to CO_2, such as amines, are best suited to flue gases with low CO_2 partial pressure, and most current industrial emissions can be captured using this technology. Amine absorption is mature technology, and a retrofit usually does not affect the existing process or require extensive design changes. This is what Aker Carbon Capture proposes, with modular plants using CO_2 compression heat for amines (cf. MAN Energy Solutions 2020). Amine absorption is well documented, with several large-scale industrial units in operation: SaskPower Boundary Dam, 2016 (cf. MIT Energy Initiative 2016), Petra Nova, Texas, 2017 (cf. U.S. Department of Energy 2017), HeidelbergCement, Brevik, 2021 (c.f. HeidelbergCement 2021). The drawback of absorption technology is the high additional energy needs for solvent regeneration that requires 20 to 30 % more energy input.

Fig. 3: Block diagram of post-combustion carbon capture and its main characteristics

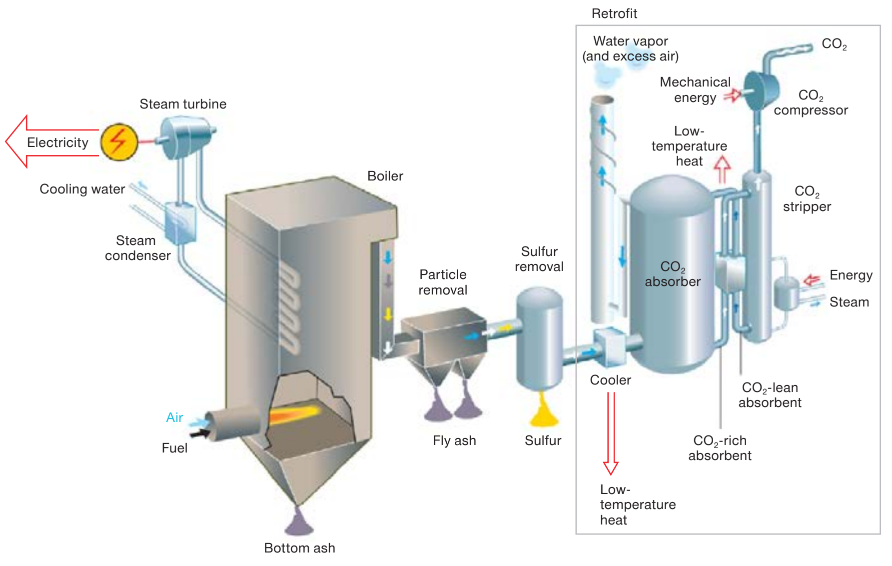


Fig. 4: Post-combustion capture

Oxy-fuel combustion capture

New infrastructure is an opportunity for oxy-fuel combustion technology. Instead of air, pure oxygen is mixed with recycled exhaust gas. After combustion, water and other residues are easy to separate from the carbon dioxide. Vattenfalls energy study of a coal power plant shows a 19 % reduction in the electrical power output (cf. Strömberg 2008). This method of pre-combustion capture is slightly more efficient than post-combustion capture but requires investment in an entirely new power plant.

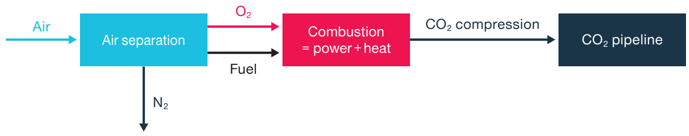


Fig. 5: Block diagram of oxy-fuel combustion carbon capture and its main characteristics

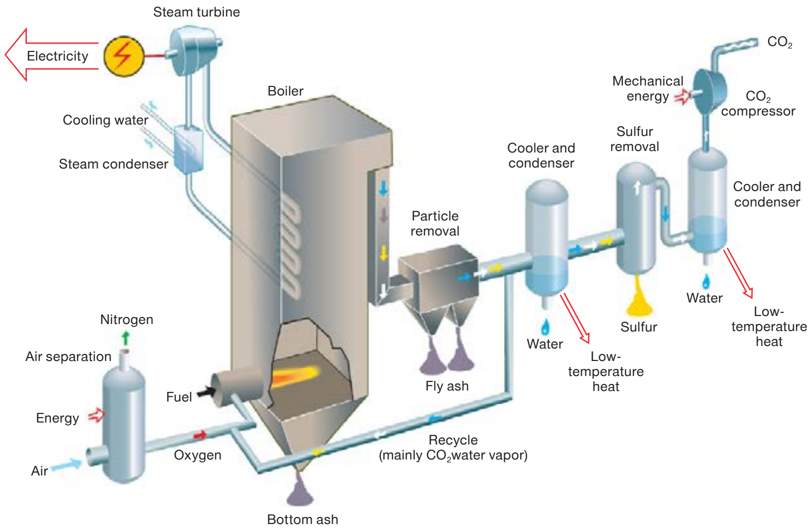


Fig. 6: Oxy-fuel combustion capture

Pre-combustion capture

Pre-combustion capture removes the carbon dioxide before combustion. Here, steam methane reforming or gasification of fuels (such as natural gas coal or biomass) produces syngas. The syngas then undergoes a water-gas shift reaction that converts carbon monoxide and water to hydrogen and carbon dioxide. The carbon dioxide concentration is high and carbon dioxide can be separated, leaving hydrogen as fuel.

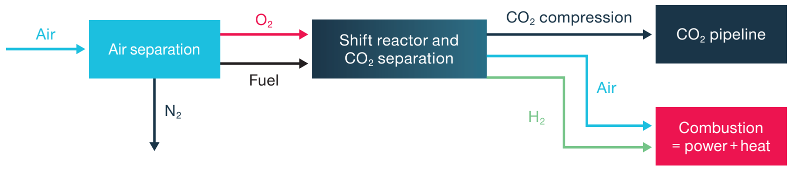


Fig. 7: Block diagram of pre-combustion carbon capture and its main characteristics

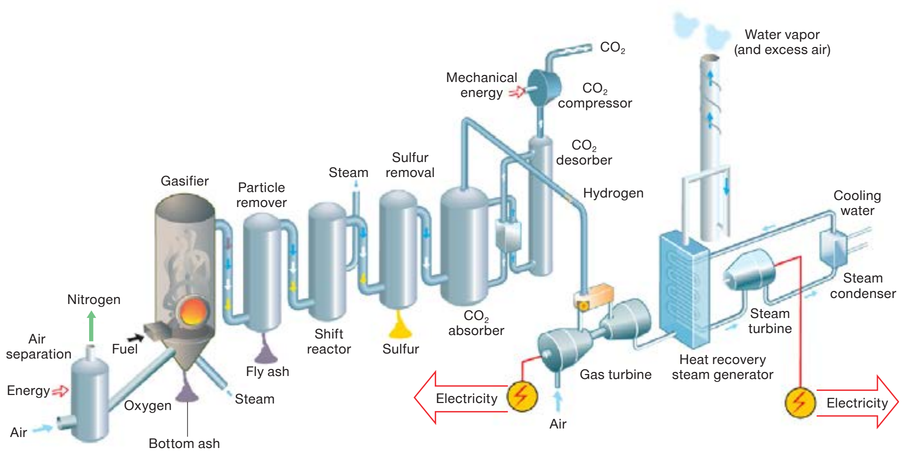


Fig. 8: Pre-combustion capture

Utilization

Captured CO_2 can be used as a feedstock for many industrial processes. The development of these opportunities requires wide-ranging collaboration on infrastructure questions and extensive collaboration between infrastructure designers, producers, and operators.

Transportation

After capture, carbon dioxide begins its journey to industrial users or the sequestration site. The Port of Rotterdam is building a collection network to consolidate and distribute carbon dioxide (cf. WorldOil 2020). Most carbon dioxide emitters lack the knowledge to manage their emissions. Here, utilities can step in because power generation is the largest emitter, and they will have to act. They can then combine their expertise in carbon dioxide capture with the rights of way they own to build industrial hubs with CO_2 distribution and provide carbon dioxide management as a service.

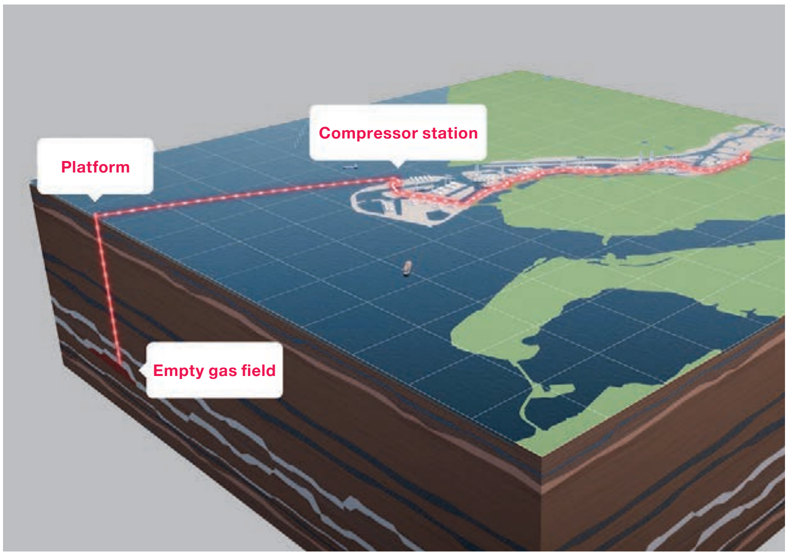


Fig. 9: Porthos: The full scope of carbon dioxide management

Carbon dioxide utilization

CO_2 utilization refers to the use of CO_2 directly or as a feedstock in industrial or chemical processes to produce valuable carbon-containing products (cf. Hepburn, C. et al. 2019). Not all utilization routes permanently remove CO_2 and most require a lot of renewable energy.

Use	Product	Storage duration	Energy input	Comment
Chemicals for use	Methane, methanol, urea, DME	Weeks, months	High	Catalytic chemical conversion of CO_2
Transportation fuels	Naphtha, diesel, kerosene, waxes	Weeks, months	High	Catalytic hydrogenation processes (Fischer-Tropsch)
Fuels, food	Growth enhancement: Microalgae, greenhouse	Weeks, months	Very low	Photosynthesis to produce biomass as a feedstock for biofuels, biomass, or bioproducts
Building materials	Curing: Concrete blocks, aggregate from carbonated industrial waste: Steel slag, fuel ash	Centuries	Low	Acidic, not suitable for steel-reinforced concrete due to corrosion
Enhanced oil recovery	Oil	> 100,000 years	Medium	Between 300 and 600 kg CO_2 can be injected per barrel produced. A barrel of oil releases around 400 kg CO_2: Life-cycle emissions could be neutral when CO_2 storage rather than oil output is maximized.

Tab. 3: Carbon dioxide utilization routes

Storage

Storing CO_2 underground is also known as sequestration. Oil and gas fields or saline aquifers are generally used. This technology has been around since the 1970s.

Carbon dioxide storage

Sequestration of CO_2 involves injection into deep underground geological reservoirs of porous rock such as saline aquifers, depleted oil and gas reservoirs or rock formations with high concentrations of reactive calcium and magnesium ions to form stable carbonates. A detailed analysis by IEA (2020) shows that 70 % of the emissions in industrial countries are released within 100 to 300 km of a potential storage location and at least 8,000 Gt storage is available.

Geological storage must be at depths greater than 800 meters to maintain the CO_2 in a dense liquid state. This requires injection pressures typically between 130 and 250 bar. The Center for Climate and Energy Solutions (cf. C2ES 2021) lists over 20 sites that have accumulated decades of experience in various geological settings.

Some of the largest, best-documented plants with decades of operational experience are (cf. Global CCS Institute 2016):

- 1972, 1.3 mta, EOR, Texas: Terrell gas processing plant (cf. Bluesource 2021)
- 1986, 7.0 mta, EOR, Wyoming: Shute Creek gas processing plant (cf. EPA 2018)
- 1996, 1.0 mta, offshore sandstone reservoir, Norway: Sleipner gas processing (cf. Equinor 2019)
- 2000: 3.0 mta, EOR, South Dakota: Great Plains synfuels plant (cf. Dakota Gasification Company 2021-2)
- 2014, 1.1 mta, EOR, Saskatchewan: SaskPower coal-fired power plant (cf. Power Technology 2021)
- 2015, 1.0 mta, deep saline formation, Edmonton: Shell Quest blue hydrogen plant (cf. MAN Energy Solutions 2021)

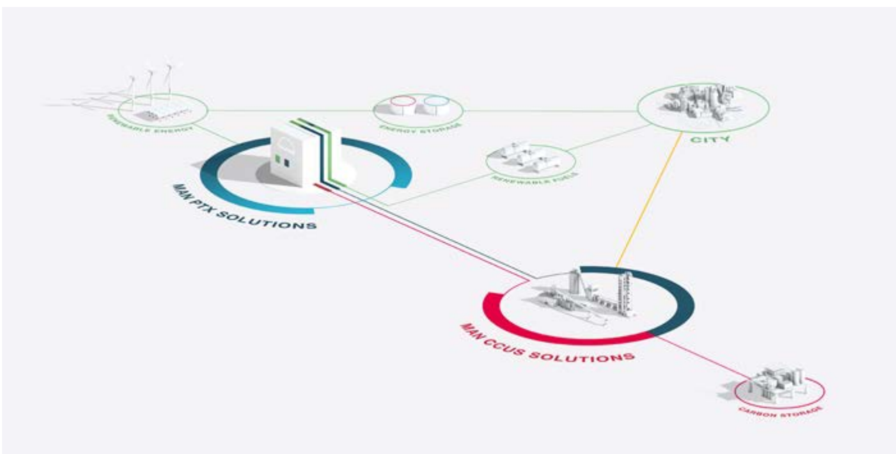


Fig. 10: MAN carbon capture, utilization, and storage solution

Compression technology

Compression is necessary for distribution by pipeline or in a liquid phase for injection. Compression and dehydration represent about 15 % of the costs in the carbon dioxide capture value chain and about 25 % of the total energy.

Efficient integrally geared compressors

Reducing compression costs becomes important in an environment of increasing energy costs, and the choice of compressor design makes a difference. Integrally geared compressors outperform in-line designs in terms of their efficiency, intercooling, total number of impellers, flexibility for process extractions/side streams, and inlet guide vane flow control.

Integrally geared compressors offer ideal conditions for a design with the best efficiency: Axial inlet flow, choice of optimal impeller speed when multistage compression is needed, intercooling downstream of each impeller, and individual flow control.

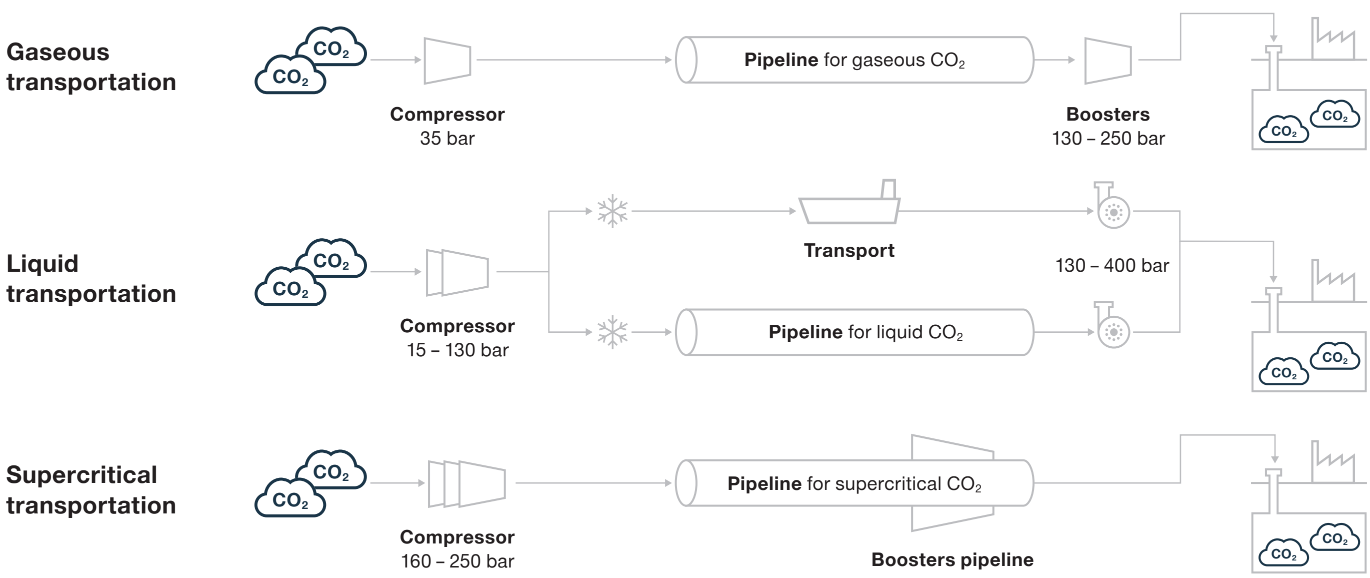
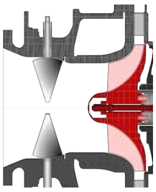


Fig. 11: Distribution methods of CO_2 to users and geological storage

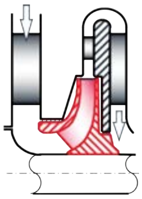
Geared compressor



Direct unhindered
axial inlet flow

Lower inlet eye
mach number

In-line compressor



Radial inlet flow
restricted by shaft

Higher inlet eye
mach number

Fig. 12: Axial inlet vs. radial inlet impellers

Axial inlet flow

Contrary to integrally geared compressors, the stage inlet flow for in-line compressors must first be redirected prior to entry into the impeller, resulting in losses and rotation of flow. For axial inlet flow impellers, the surface area is larger. Thereby allowing for higher flow coefficients and tip speeds without reaching inlet eye mach numbers that affect efficiency and operation range. If necessary, each compression stage of an integrally geared compressor can be fitted with inlet guide vanes to increase the operation range and part-load efficiency.

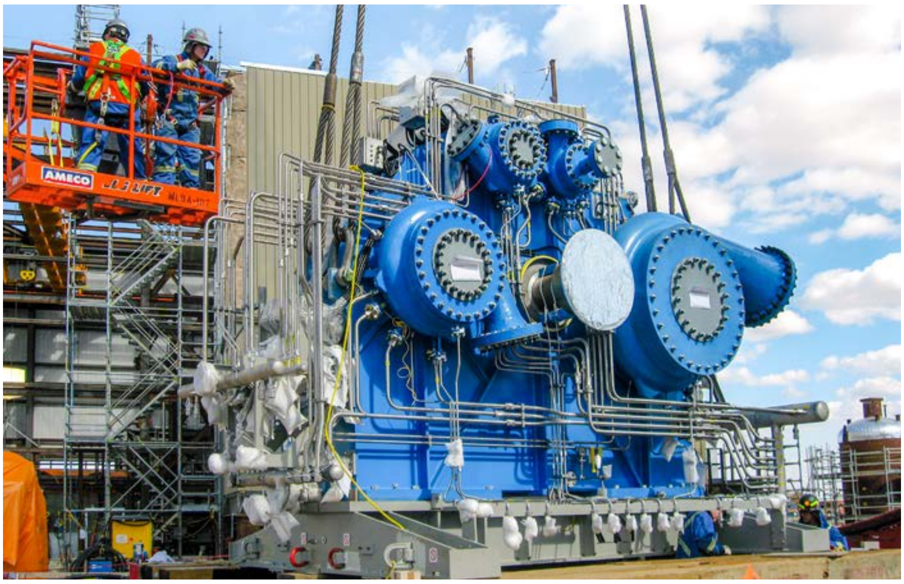


Fig. 13: Eight-stage wet CO_2 compression from 1.7 to 174 bara for carbon dioxide capture in the SaskPower Boundary Dam Power Plant

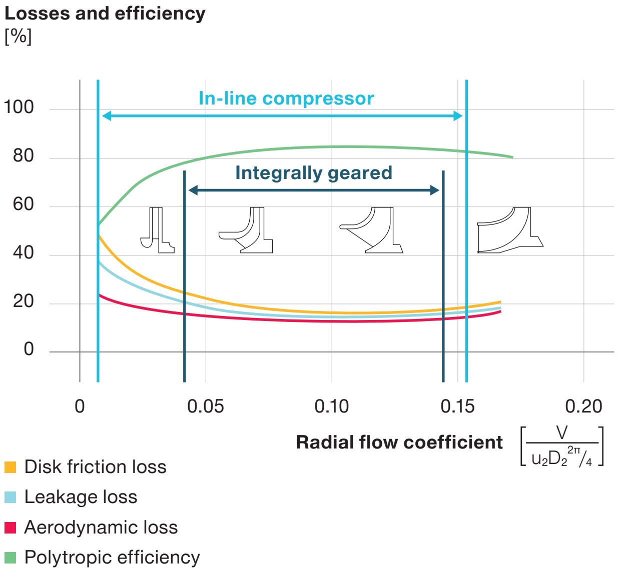


Fig. 14: Impeller losses in relation to radial flow coefficient

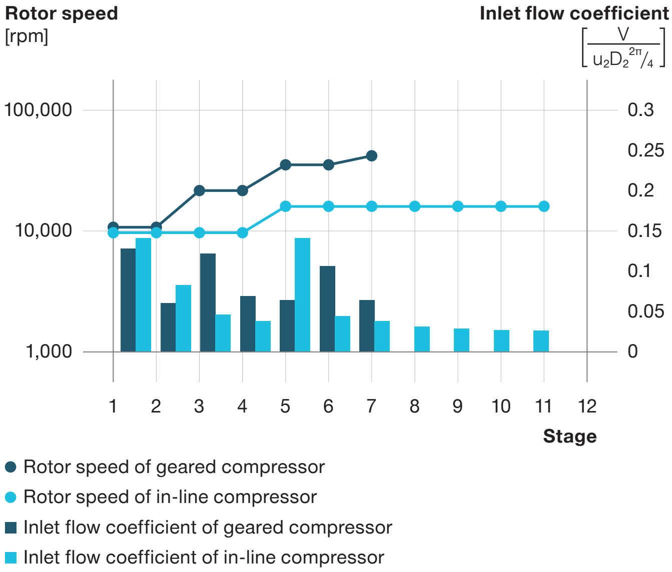


Fig. 15: Rotor speed in relation to inlet flow coefficient at different stages

Impeller flow coefficient and efficiency

Leakage losses and the boundary layer (friction losses) increase disproportionally as the flow path narrows in impellers. These losses decrease as flow increases, but aerodynamic losses increase slowly, thus creating a range where efficiency is maximal. Integrally geared compressors offer greater scope for optimizing speed and can be designed to keep impeller flow coefficients within the range of best polytropic efficiency. This makes a difference for gases with a high molecular weight, such as carbon dioxide, where volume decreases quickly and in-line compressors resort to narrow impellers to achieve sufficient head as the gas is compressed in the subsequent stage.

Isothermal compression

Isothermal compression is the most efficient way to increase gas pressure. Removing compression heat at constant temperature is not technically possible, so sections of polytropic compression alternate with cooling. Unlike in-line compressor designs, integrally geared compressors can be intercooled between each compression stage, making compression as similar to isothermal cooling as is technically feasible.

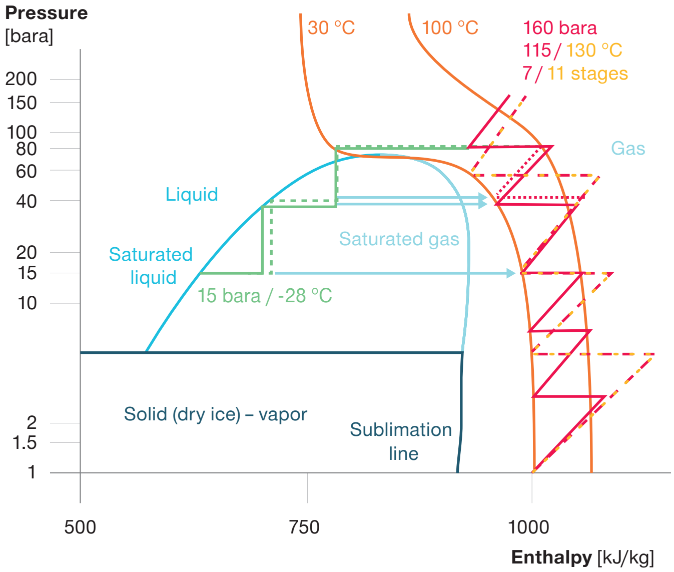


Fig. 16: Compression path of dry CO_2 for integrally geared compressors (dark) and in-line compressors (light)

Process integration

Compressors are part of a process. Compressor manufacturers have an interest in collaborating with process licensors to find novel ways of integrating compression.

Flexibility and value

The flexibility to deliver flow at different pressures or accept side streams from the process improves overall plant efficiency. Integrally geared compressors are ideal for these services and deliver value to the end user.

The CCUS landscape will require compression to distribute carbon dioxide to users and storage, either as a high pressure gas in a pipeline (80 to 200 bar), or as a liquid in isolated low-temperature pressure vessels (15 bar, -28 °C). Using the compression heat for regeneration of chemical absorbents considerably reduces the total energy requirement. For example, MAN Energy Solutions works together with Aker Carbon Capture to integrate compression heat in the amine absorption process and with Air Liquide to integrate compression in a hybrid membrane-cryogenic distillation unit.

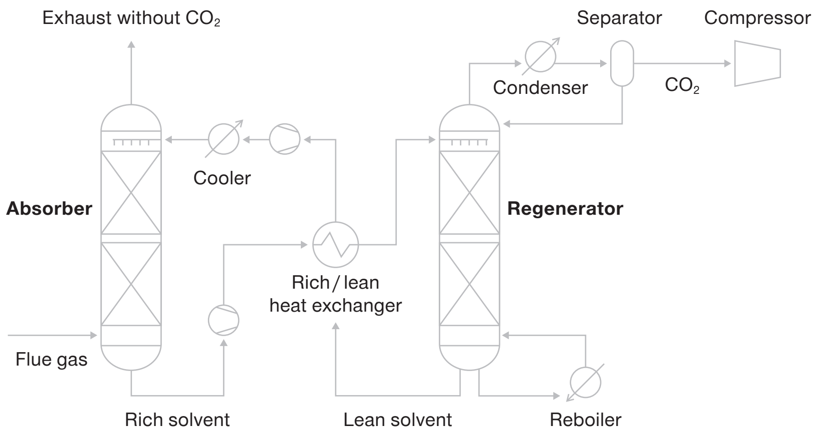


Fig. 17: Process diagram of chemical absorption

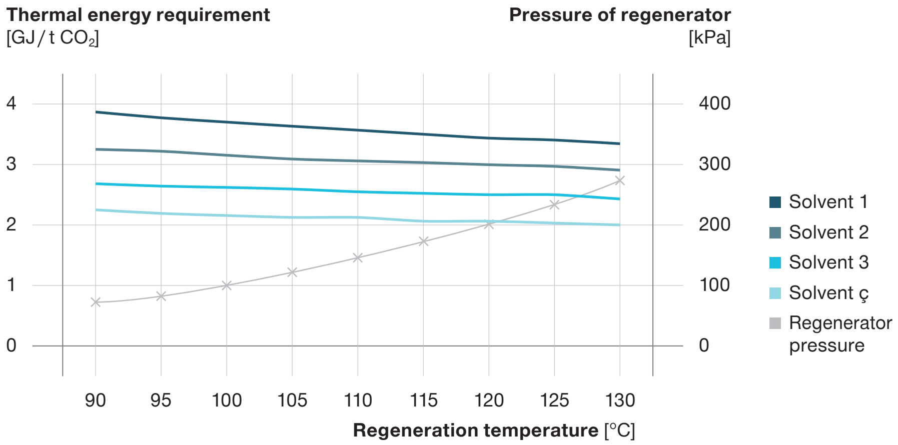


Fig. 18: Effect of regeneration temperature on thermal energy requirement for CO_2 capture shown by the example of four solvents with different VLE

Amine absorption

Amine absorption is suitable for most industrial flue gases with CO_2 concentrations below 20 %. The exhaust is fed to the absorber where the amine solution (lean solvent) absorbs the CO_2, leaving mostly nitrogen at the top, which is released into the atmosphere. The rich solvent collects at the bottom, from where it is pumped through an exchanger and receives heat from the hot lean solvent. The rich solvent enters the hot regenerator, where the solvent releases CO_2 at temperatures between 90 and 130 °C. Chemical absorption requires thermal energy in the order of 2.5 to 3.5 GJ per ton of CO_2 (cf. Goto, Kazuya et al. 2016: p. 1133 - 1141), which is typically provided by steam in the reboiler.

Energy costs of CCUS

The ratio of energy consumption for CO_2 purification is high in comparison to the energy available in the fuel. When put into the context of the hydrocarbon fuel's energy content, the need for energy improvement becomes obvious.

After purification, a compressor raises the pressure to 140 to 180 bar for pipeline distribution or liquefaction for transportation. Both options require around 0.4 GJ of electric power per ton of compressed CO_2. The power plant must generate this additional electric power, resulting in an increased fuel consumption.

Energy prices have surged since 2021 and most prior studies consider significantly lower costs. Energy is important and must be carefully considered in economic evaluations.

	Unit	Coal	Natural gas
Lower heating value of fuel	GJ/t fuel	26.0	50.0
CO_2 emissions	kg_{CO2}/kg_{Fuel}	2.4	2.8
Energy for amine capture	GJ/t CO_2	2.5	2.5
Energy for amine capture	GJ/t fuel	6	7
Available energy lost	%	23	12

Tab. 4: Ratio of energy consumption for CO_2 purification

	Unit	Coal	Natural gas
Electric power from 1 to 160 bar per ton of CO_2	GJ_{el}/t CO_2	0.4	0.4
Thermal efficiency	%	45	60
Thermal energy at plant efficiency	GJ/t CO_2	0.89	0.67
Additional fuel usage (amine and compression)	GJ/t fuel	6.89	7.67
Available energy lost	%	26	15

Tab. 5: Increased fuel consumption resulting from additional electric power generation

	Coal		Natural gas	
Year	2019	2022	2019	2022
Fuel cost	€90/t	€300/t	€20/MWh	€90/MWh
	€3.5/GJ	€11.5/GJ	€5.6/GJ	€25/GJ
Fuel cost in € per ton of CO_2	10	33	15	68

Tab. 6: Energy prices for coal and natural gas

Integration of the compression service

The optimal amine regeneration temperature is between 90 and 120 °C, a temperature range where steam generators instead of intercoolers recover the compression heat. Integrating the compression service is key to reducing fuel consumption and improving de-hydration of the wet CO_2 steam. With Aker Carbon Capture, MAN Energy Solutions has unlocked the full potential of the integrally geared compressor to integrate the compression service with the regenerator and the CO_2 liquefaction cycle.

Process optimization:

- Direct feed of wet CO_2 from the regenerator to the compressor
- Intercooling of wet CO_2 flow with steam generation in four locations
- Separation of water condensate downstream of each intercooler
- Drying of CO_2 upstream of the last compression stage
- Side streams for returning CO_2 from the liquefaction process
- Inlet guide vane control for each side stream

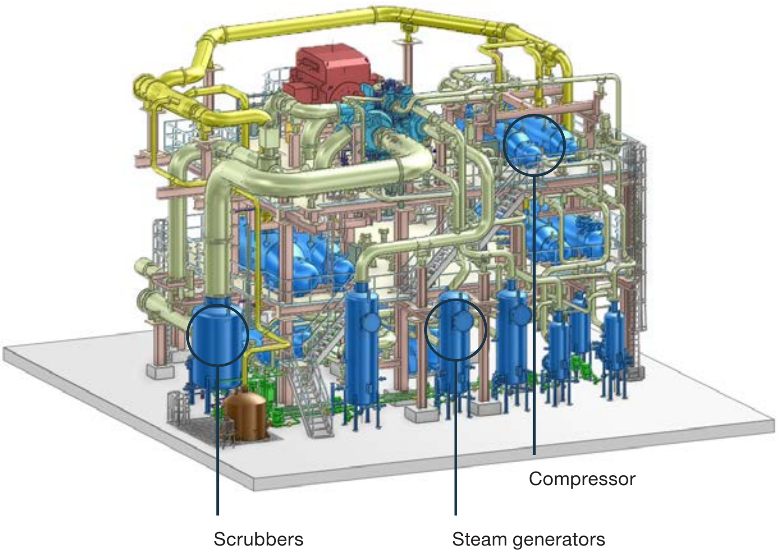


Fig. 19: 3D layout of an integrally geared compressor and auxiliary equipment with a high level of process integration

Membrane-cryogenic distillation

Hybrid purification systems make use of the strengths of different technologies to develop an economically attractive CO_2 separation method. Air Liquide's Cryocap™ hydrogen technology uses cryogenic technology and membranes to purify the CO_2 in a PSA off-gas from a steam methane reformer (SMR) (cf. Font-Palma, C. et al. 2021). This is a technology that concurrently reduces CO_2 while increasing the hydrogen production by up to 20 %, thus providing multiple benefits (cf. Air Liquide 2021).

This hybrid technology requires multiple separate compression and expansion services. MAN Energy Solutions and Air Liquide have combined these services in separate process loops on a single integrally geared compressor, thereby reducing both investment costs and energy consumption.

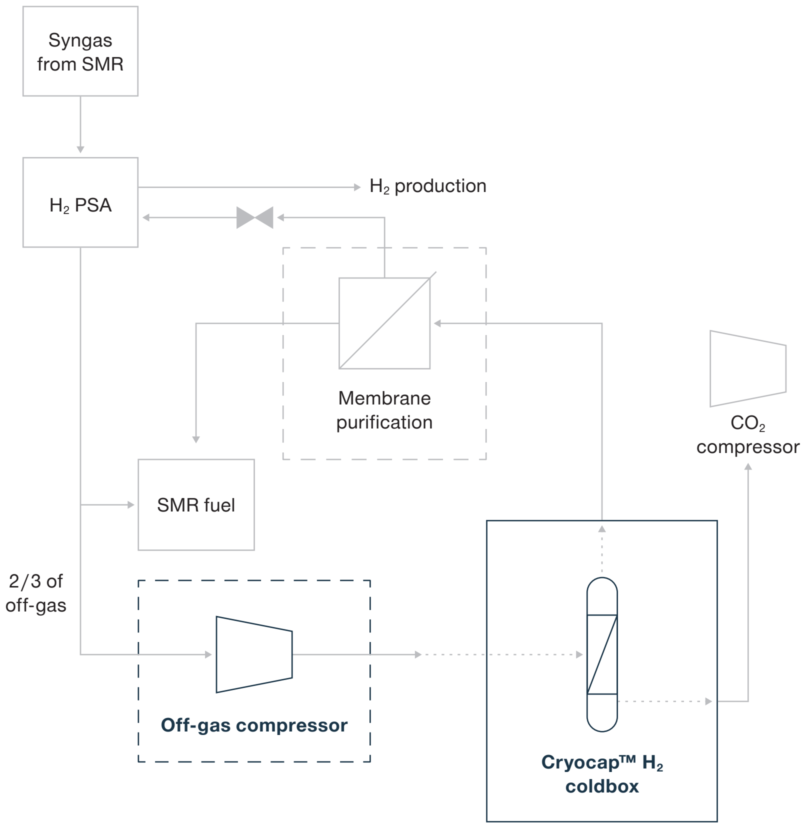


Fig. 20: Block diagram of the Cryocap™ process

Conclusion

Capturing carbon dioxide from point sources is a capital- and energy-intensive technology that poses an economic obstacle to the use of carbon dioxide. The flexibility of integrally geared compressors allows the integration of multiple compression services with low-temperature heat recovery, represents a vast improvement in energy and cost, and will bootstrap a value chain where carbon dioxide is removed from the atmosphere and put to economic use.

Figures

Tables

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MAN Energy Solutions
86224 Augsburg, Germany
P + 49 821 322-0
F + 49 821 322-3382
info@man-es.com
www.man-es.com