

The sweet spot for cryogenic CO2 capture

Optimising the capture element, without due consideration of the total cost of the full value chain, results in pushing expenses down the chain and increasing the cost of the end-to-end system. By Stephen B. Harrison, sbh4.

Unit operations must support system boundary conditions

Consider the case that a liquid solvent-based CO2 capture system, such as a twin-tower amine process, is used upstream of a CO2 liquefier to condition the CO2 for transportation by rail and ship to an offshore geological storage facility.

Imagine that the given boundary conditions are an overall CO2 capture rate of >90% from the emissions source to geological storage and that the liquid CO2 must comply with the Northern Lights CO2 purity specifications.

If the amine-based CO2 capture system were optimized in isolation, it would capture just

over 90% of the flue gas CO2. This minimises the size of the absorption tower to reduce

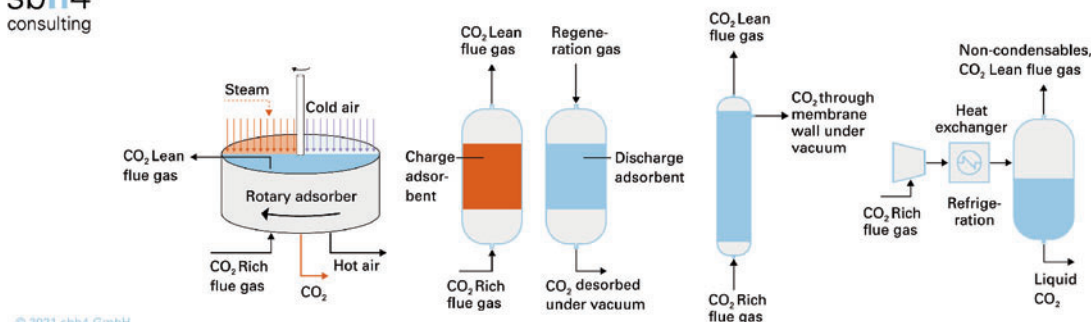
capex, and minimises the reboiler energy to reduce opex.



Optimising CO2 capture to Northern Lights CO2 storage specification requires a holistic approach. Image: ©Torstein Lund Eik, Equinor

Carbon Capture technologies – Adsorption based & others

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	TSA – temperature swing adsorption and desorption	VSA – vacuum swing adsorption and desorption	Selective membrane separation	Cryogenic CO2 liquefaction
Separation principle	Adsorption	Adsorption	Membrane	Physical (phase separation)
Specific energy demand	1.5 GJ/t _{CO2} (mostly waste heat)	1.7 GJ/t _{CO2} (mostly power)	1.20 GJ/t _{CO2} (mostly power)	n.a. (mostly power)
Typical temperature	40-60°C	<40°C	30-50°C	-50°C
Typical pressure	Ambient	Cycling between moderate pressure and vacuum	Moderate pressure flue gas, CO2 under vacuum	20-50 bar _g
Typical CO2 removal	90% (target)	<90%	<80%	>99% (with CO2 feed >50%)
Typical CO2 purity	95% (target)	<95%	95%	>99% (with CO2 feed >50%)
Typically combined with	Standalone	Cryogenic Liquefaction	Amine wash, Cryogenic Liquefaction	VSA, Membrane (eg Cryocap)
Typical plant size (tonnes per year CO2 removal)	200 – 2,000,000	1,000 – 500,000	10,000 – 1,000,000	>100,000
Technology maturity level	Pilot / Commercial, eg Husky Energy SK, Lafarge Holcim Cement, BC	Demonstration / Commercial, eg Air Products Port Arthur SMRs, USA	Demonstration / Commercial	Demonstration / Commercial, eg Air Liquide Cryocap at Port-Jérôme SMR, France

The amine system would typically yield CO2 of around 99% purity with nitrogen as the main impurity. This would then be fed to the CO2 liquefier. In the liquefier, the incompressible nitrogen must be vented from the system. As it is released, it carries with it an amount of CO2 according to the vapour / liquid equilibrium of these two gases. Typically, the vent contains 50% to 60% CO2, in addition to nitrogen which must be purged.

The implication is that the overall capture rate is less than 90% due to the CO2 loss with the purge gas. The end-to-end system no longer meets the given constraints defined in the boundary conditions.

To achieve the >90% rate, it will be necessary to increase the rate in the amine absorption towers, increasing both the energy requirement and the equipment size. Optimising the end to end value chain is essential to avoid one process winning, at the expense of another.

Avoiding a zero-sum game

In the case above, it may be decided that the amine system should be replaced with a pressure / vacuum swing adsorption process using a solid zeolite sorbent to capture the CO₂. This technique is generally able to produce CO₂ of a purity of 95% cost-effectively, with nitrogen being the balance. Whilst the CO₂ capture rate might be high, at 98%, the CO₂ purity may be low.

However, substituting one technology for another, without consideration of full value chain implications is perilous.

The motivation for substituting the amine-based system for the VPSA unit may be sound, for example to reduce the capex or opex of the CO₂ capture aspect of the process. However, the knock on effect is negative consequence to the operation of the CO₂ liquefier.

The electrical energy input required to liquefy CO₂ of 99% purity from the amine system is lower than that required to liquefy CO₂ of 95% purity from the VPSA. This is because the compressors must do un-productive work to handle additional inert nitrogen gas.

Also, the compressor discharge pressure is increased due to the presence of a higher amount of incondensable nitrogen. This also increases the energy requirement.

The net result could be that the savings achieved by implementing the VPSA system are negated by the increased capex and opex in the liquefier compressor.

A holistic approach to optimisation

To optimize the CO₂ capture technology, it makes sense to consider the requirement at the end of the CCTU/S value chain. What is the required purity of CO₂? What is the required temperature and pressure condition?

If the goal is to compress supercritical CO₂ into a geological storage site, and CO₂ transmission is by pipeline, the CO₂ capture tech-



Chart's Cryogenic Carbon Capture process (CCC) exploits the gas to solid deposition phase change that is unique to CO₂. Image: ©Chart Inc

nology can be selected to produce CO₂ gas (rather than liquid) which can be compressed.

On the other hand, if the end-game is utilisation of the CO₂ in an e-methanol or Fischer Tropsch e-fuels production process, and liquid CO₂ will be transported by rail, there is a requirement to produce liquid CO₂ at the capture location, or at a CO₂ transfer terminal, where liquid CO₂ can be loaded onto the train.

Cryogenic CO₂ capture to the fore

If CO₂ is required as a gas for transmission in a pipeline, expending additional energy required to liquefy CO₂ is wasteful. On the other hand, if liquid CO₂ is the requirement, the energy for liquefaction must be consumed at some point in the value chain. In this case, it makes sense to integrate CO₂ capture with CO₂ liquefaction. This is the essence of cryogenic CO₂ capture.

The physical property of CO₂ that makes cryogenic CO₂ capture technically feasible is that CO₂ liquefies at a much higher temperature than nitrogen and oxygen which are major components in post-combustion flue gases.

Cryogenic CO₂ capture processes cool the entire flue gas stream to the point where the CO₂ forms a liquid or solid, but the other components remain as gases. Several critical aspects influence the operability and energy efficiency of this process.

1) Moisture must be removed from the flue gas using a drying process, prior to cooling the flue gas below 0 °C. This is prevent water forming ice, which would block the process.

2) Nitrogen and oxygen in the flue gas are cooled along with the CO₂. This serves no benefit at the outlet of the process, so the cold energy must be recovered from these gases. This is achieved using a heat exchanger to cool the incoming flue gas against the cold oxygen and nitrogen exiting the process.

3) CO₂ forms a solid directly from the gas under certain temperature and pressure conditions. If solid CO₂ accumulates, it will block the process. The transition of CO₂ from gas to liquid must be carefully managed through appropriate process control and respect of CO₂'s unique phase diagram.

Several pioneers have overcome the issues associated with cryogenic CO₂ capture.

SES and CCC

Sustainable Energy Solutions (SES), founded in 2008 by Dr. Larry Baxter and based in Orem, Utah. In 2020, Chart Industries acquired SES as part of their drive to focus their business towards the energy transition. Chart has since become an acquisition target for Baker Hughes.

Chart's Cryogenic Carbon Capture process (CCC) exploits the gas to solid deposition phase change that is unique to CO₂. The entire flue gas stream is cooled to around -120 °C which causes deposition of CO₂ as solid particles. After the solid CO₂ particles are formed, they are converted into liquid CO₂ through carefully controlled temperature and pressure changes.

During cooling of the flue gas, condensable pollutants such as oxides of sulphur (SO₂) and nitrogen (NO_x) are liquefied before CO₂ deposits as a solid. These liquids can be separated from the flue gas. Any traces of these pollutants that flow through into the liquid CO₂ are solidified and can be removed by filters.

The simultaneous removal of pollutants is a feature of CCC aligns it well with greenfield projects, because it eliminates the need for additional SO₂ and NO_x removal equipment.

A 1 tonne per day containerised CCC pilot plant has been used to process cement making and power plant flue gases. A 30 tonne per day demonstration plant at Central Plains Cement Company in Sugar Creek, Missouri has also been commissioned.

CarbonCloud from Revcoo

Founded in 2021 by Hugo Lucas and based in Lyon, France, Revcoo's CarbonCloud is exactly that. Cryogenic liquid nitrogen is sprayed into the pre-cooled flue gas. As the CO₂ in the flue gas is cooled by the liquid nitrogen, it solidifies. The solid CO₂ particles are separated from other gases in a cyclone. The solid CO₂ is then warmed to yield liquid CO₂.

To create the liquid nitrogen, mechanical energy is required for the liquefier compressor.



The Orloff process owned by Honeywell yields very pure CO₂ and operates in a manner which prevents solid CO₂ formation. Image: ©Honeywell UOP

This is generally provided from electrically powered motors. To maximize the energy efficiency of the process and minimize the amount of electricity required for the nitrogen liquefier, the cold flue gas leaving the cyclone pre-cools the warm incoming flue gas before it enters the CarbonCloud chamber.

Additionally, cold energy is released from the solid CO₂ as it converts to liquid. This cold energy provide additional cooling for the flue gas entering the CarbonCloud.

A CarbonCloud pilot plant capable of removing 2 tonnes per day of CO₂ was installed at the Eiffage lime kiln in France in 2024. Lime making releases unavoidable geogenic CO₂ as limestone is converted to lime. Similar to cement, the geogenic CO₂ emissions from lime making can only be decarbonized with the use of CO₂ capture.

Building on natural gas processing

Cryogenic technologies for CO₂ removal from natural gas have been implemented for many years. The Orloff CO₂ Fractionation / Dual Refrigerant Fractionation (DRCF) process (owned and licensed by Honeywell

UOP) is ideal to liquefy and capture very high concentrations of CO₂ (between 30 and 80%).

It yields very pure CO₂ and operates in a manner which prevents solid CO₂ formation. On the other hand, due to the vapour liquid equilibrium of the CO₂ and the incondensable gases, around 15 to 20% CO₂ remains in the flue gas. Where partial CO₂ capture is appropriate, this is acceptable. To achieve capture rate of >90%, a polishing technology such as an amine solvent system must be used after the DRCF process.

Chart's CCC is fundamentally similar to the CryoCell process, developed in Australia by Cool Energy Ltd to remove CO₂ from natural gas. ExxonMobil's Controlled Freeze Zone (CFZ) is another gas processing technology that relies on formation of solid CO₂ followed by desublimation of CO₂ to the liquid phase. The main difference is that CCC and CarbonCloud are optimised to remove CO₂ from flue gases, not from a methane-rich natural gas stream.

More information

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