CET Partnership

Report on the state-of-the-art of carbon capture technologies

CETP CO2RR – Deliverable 1.4 [*interim*]

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Capture

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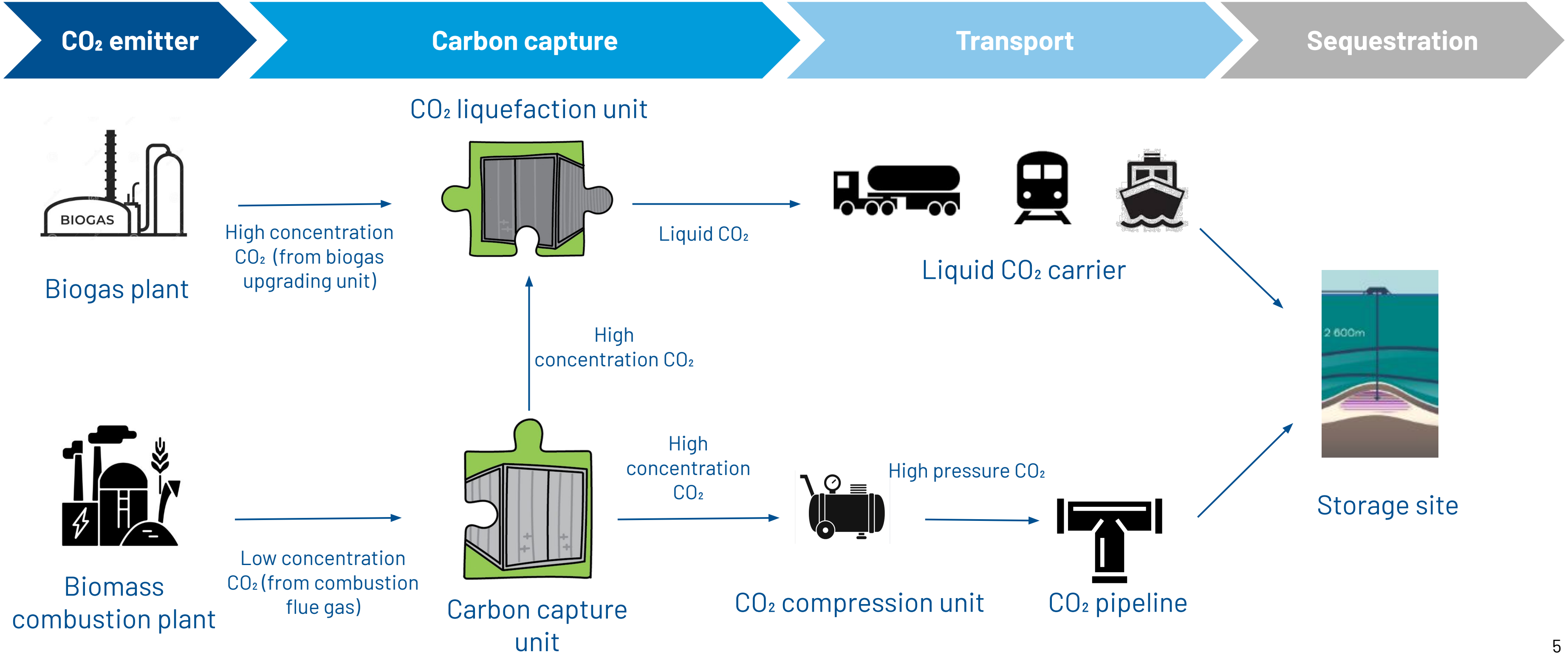
CCS projects require integration of multiple steps



CO_2 emitter → **Carbon capture** → **Transport** → **Sequestration**

Biogas plant → High concentration CO_2 (from biogas upgrading unit) → CO_2 liquefaction unit → Liquid CO_2 → Liquid CO_2 carrier → Storage site

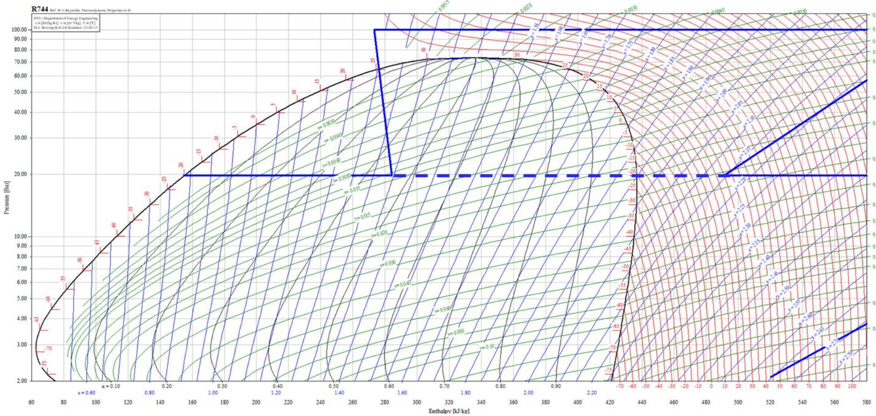
Biomass combustion plant → Low concentration CO_2 (from combustion flue gas) → Carbon capture unit

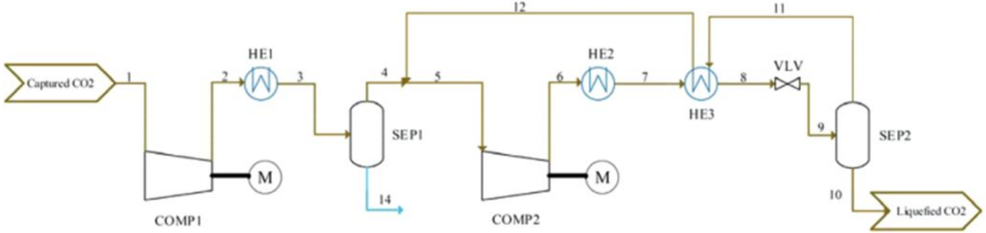
Carbon capture unit → High concentration CO_2 → CO_2 liquefaction unit

Carbon capture unit → High concentration CO_2 → CO_2 compression unit → High pressure CO_2 → CO_2 pipeline → Storage site

CO_2 liquefaction basics

CO_2 liquefaction is a mature technology with some potential for improvement



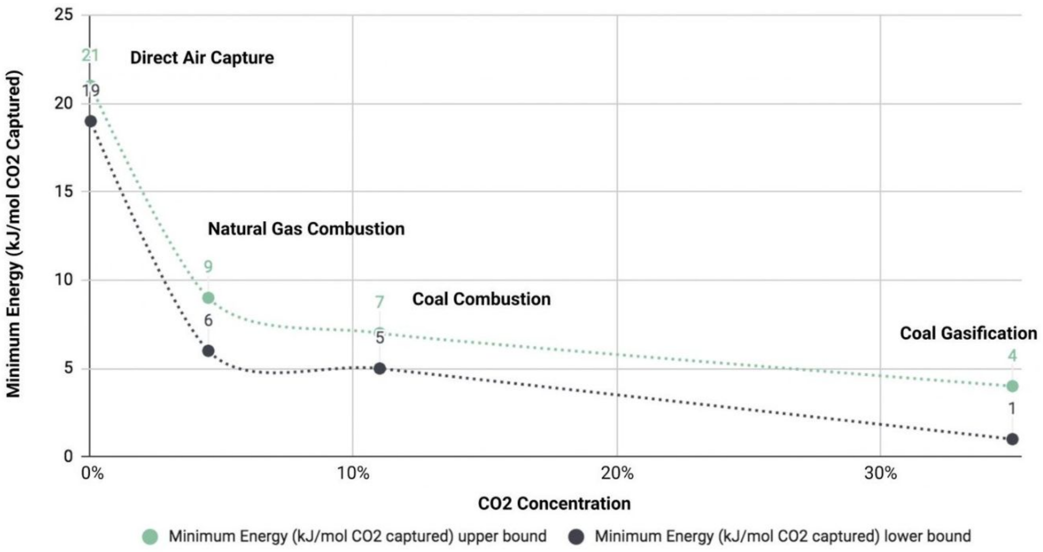


- Cryogenic liquefaction is based on known physical principles (discovered end of 19th century by Linde & Hampson)
- These principles are applied industrially to air separation, but also other gases
- **In practice, CO_2 is dehydrated, purified and compressed up to 20 bars, then cooled to condensation temperatures**

Source: Kasra Alyion et all, 2020

CO_2 capture basics

CO_2 capture energy consumption is driven by thermodynamics



- CO_2 capture is a gas separation process, its energy consumption is driven by CO2 concentration in the initial gas mix.
- CO_2 source (and concentration) is the main driver for energy consumption – the largest operational cost of capture.
- CO_2 capture cost is also driven by capital expenditure (CapEx), process efficiency and scale of the unit.

Source: Wilcox & all, Annual Review of Chemical and Biomolecular Engineering

Current global CCS projects status

CCS deployment is slowly progressing

- **50 projects in operation**, representing **51 million** tons of CO₂ captured per year. **102 million tonnes of CO₂** per year operational or in construction.
- Growing pipeline of projects, with up to **365 million tonnes of CO₂** per year in construction or development.
- The majority of mature projects relate to natural gas processing and other **oil & gas applications** (refining, synfuels, etc).
- The rest of mature projects are in hydrogen/fertilizer production, bioethanol, power and industry (e.g. steel, cement, chemicals).
- Carbon removal projects (e.g. DACS, BECCS) are emerging.

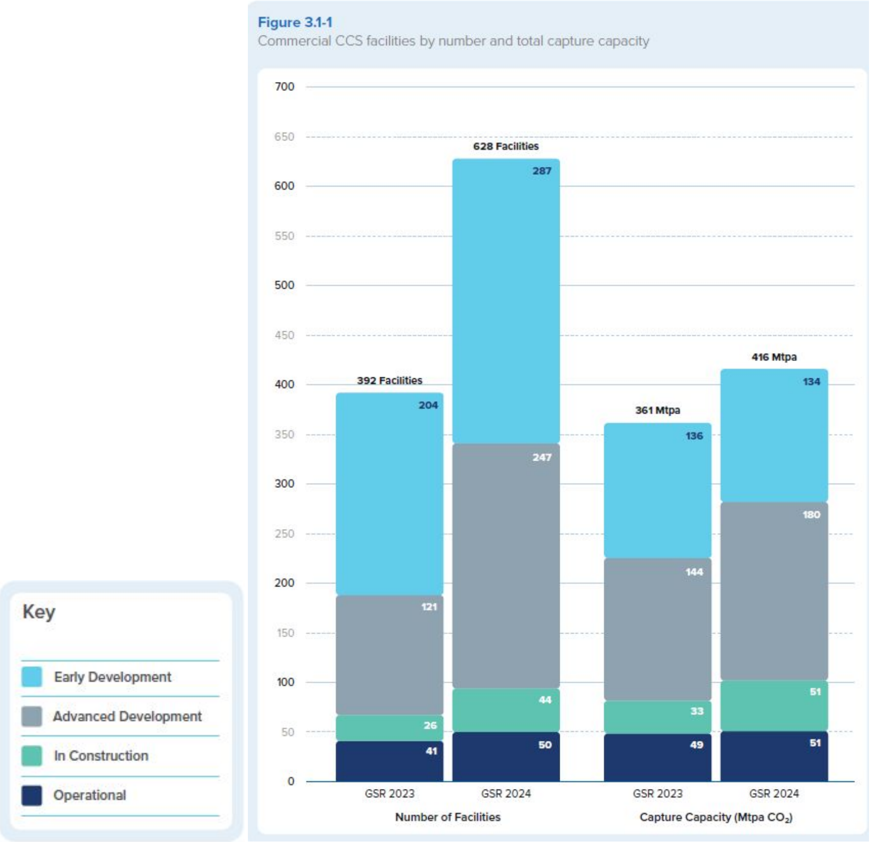


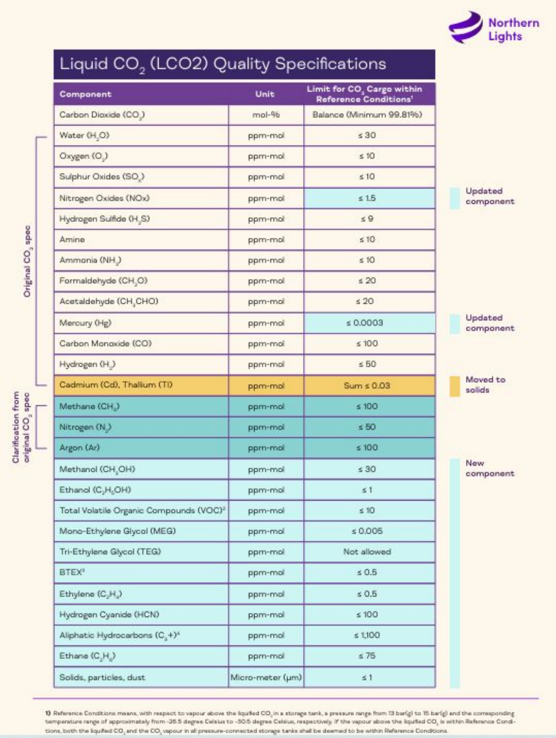
Figure 3.1-1
Commercial CCS facilities by number and total capture capacity

Source: Global CCS Institute status report 2024

Focus on CO_2 liquefaction

CO_2 liquefaction for biogas/biomethane

Design has to be integrated with biogas upgrading and storage processes



Northern Lights

Liquid CO_2 (LCO2) Quality Specifications

	Component	Unit	Limit for CO_2 Cargo within Reference Conditions[1]	
	Carbon Dioxide (CO_2)	mol-%	Balance (Minimum 99.81%)	
Original CO_2 spec	Water (H_2O)	ppm-mol	≤ 30	
	Oxygen (O_2)	ppm-mol	≤ 10	
	Sulphur Oxides (SO_x)	ppm-mol	≤ 10	
	Nitrogen Oxides (NOx)	ppm-mol	≤ 1.5	Updated component
	Hydrogen Sulfide (H_2S)	ppm-mol	≤ 9	
	Amine	ppm-mol	≤ 10	
	Ammonia (NH_3)	ppm-mol	≤ 10	
	Formaldehyde (CH_2O)	ppm-mol	≤ 20	
	Acetaldehyde (CH_3CHO)	ppm-mol	≤ 20	
	Mercury (Hg)	ppm-mol	≤ 0.0003	Updated component
	Carbon Monoxide (CO)	ppm-mol	≤ 100	
	Hydrogen (H_2)	ppm-mol	≤ 50	
	Cadmium (Cd), Thallium (Tl)	ppm-mol	Sum ≤ 0.03	Moved to solids
Clarification from original CO_2 spec	Methane (CH_4)	ppm-mol	≤ 100	
	Nitrogen (N_2)	ppm-mol	≤ 50	
	Argon (Ar)	ppm-mol	≤ 100	
	Methanol (CH_3OH)	ppm-mol	≤ 30	New component
	Ethanol (C_2H_5OH)	ppm-mol	≤ 1	
	Total Volatile Organic Compounds (VOC)[2]	ppm-mol	≤ 10	
	Mono-Ethylene Glycol (MEG)	ppm-mol	≤ 0.005	
	Tri-Ethylene Glycol (TEG)	ppm-mol	Not allowed	
	BTEX[3]	ppm-mol	≤ 0.5	
	Ethylene (C_2H_4)	ppm-mol	≤ 0.5	
	Hydrogen Cyanide (HCN)	ppm-mol	≤ 100	
	Aliphatic Hydrocarbons (C_2+)[4]	ppm-mol	≤ 1,100	
	Ethane (C_2H_6)	ppm-mol	≤ 75	
	Solids, particles, dust	Micro-meter (μm)	≤ 1	

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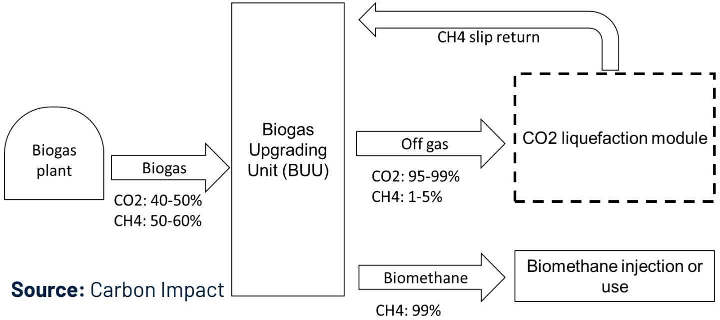
1) Reference Conditions means, with respect to vapour above the liquified CO_2 in a storage tank, a pressure range from 13 bar(g) to 15 bar(g) and the corresponding temperature range of approximately from -26.5 degree Celsius to -30.5 degree Celsius, respectively. If the vapour above the liquified CO_2 is within Reference Conditions, both the liquified CO_2 and the CO_2 vapour in all pressure-connected storage tanks shall be deemed to be within Reference Conditions.

Source: Northern Lights



Source: Carbon Impact

- Biogas is first purified into biomethane using a BUU (Biogas Upgrading Unit); the resulting off-gas is generally vented to the atmosphere.
- Off-gas concentration depends on biogas purification process.
    - PSA (Pressure Swing Adsorption): ~95%
    - **Membranes: 98-99%**
    - Amines: 99%+
- After liquefaction, residual methane (methane slip) has to be recirculated to BUU (or biogas plant directly).
- Liquid CO_2 needs to be compliant with storage quality specifications (e.g. Northern Lights).

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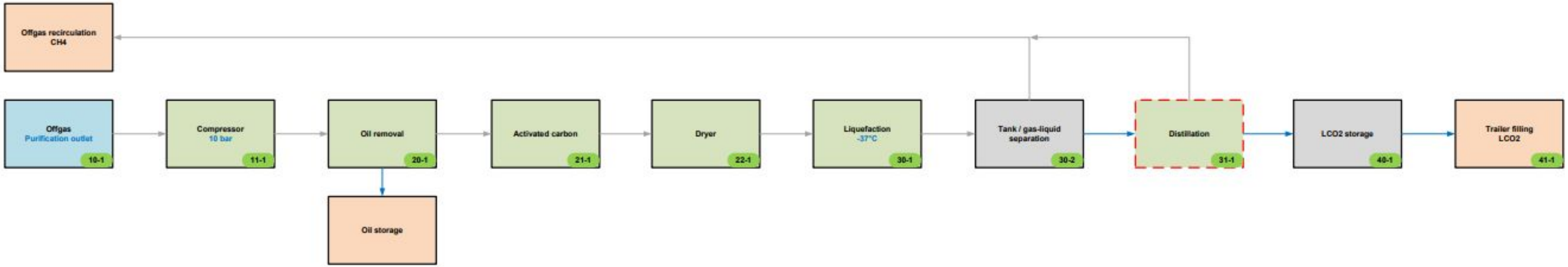
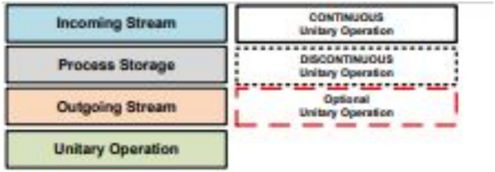
Liquefaction process & power consumption

Cryogenic liquefaction consumes electrical power (comparable to biogas purification)



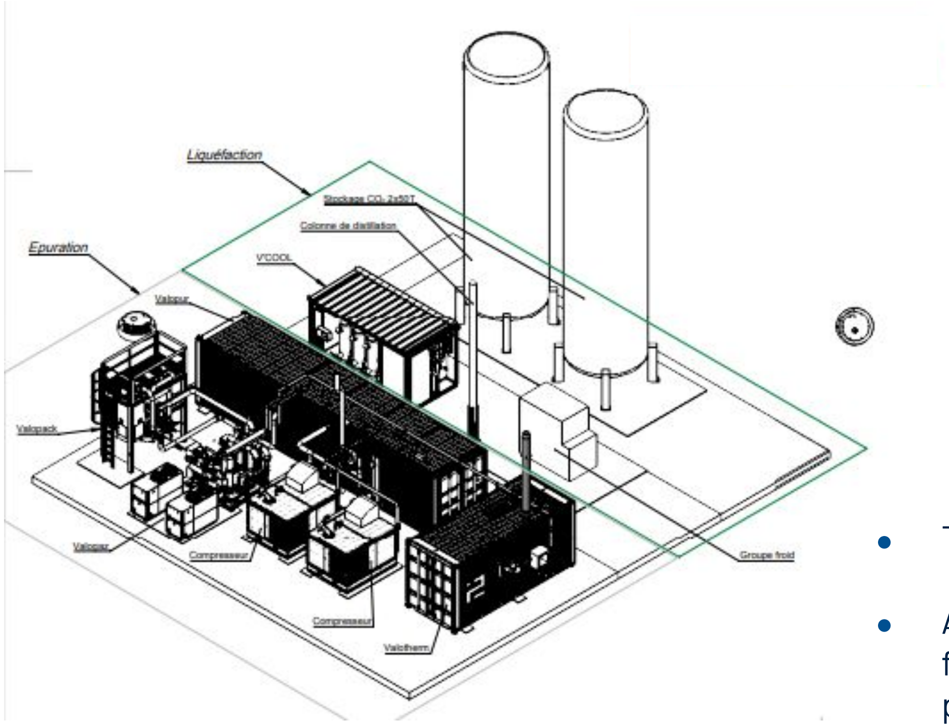


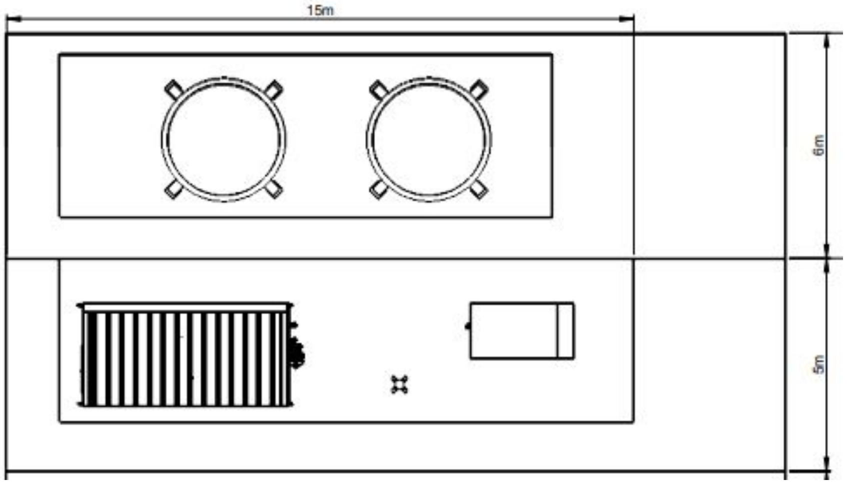
- The process requires electrical power for compression and liquefaction (refrigeration cycle).
- Power consumption per tonne of CO_2: **250–300 kWh**

Source: Carbon Impact

The liquefaction footprint

Space requirement is manageable but must be planned early-on





- Typical footprint for CO_2 liquefaction system: **150–200 m^2**
- As illustrated above, approximately half the space is used for CO_2 storage tanks (in the range of one week of production)

Source: Prodeval design

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Several CO_2 liquefaction suppliers are available

A growing units are installed allowing to get operational returns

Biogas treatment specialists

PRODEVAL
INGÉNIERIE DES SOLUTIONS GAZ

VERDEMOBIL
BIOGAZ

a·r·o·l
energy

ECOSPRAY®
technologies for the planet

HoST

Hitachi Zosen
INOVA

dmt
Environmental Technology

BRIGHT

Industrial CO_2 players

Air Liquide

Linde

ASCO

PENTAIR

COMTECSWISS
Realizing Ideas

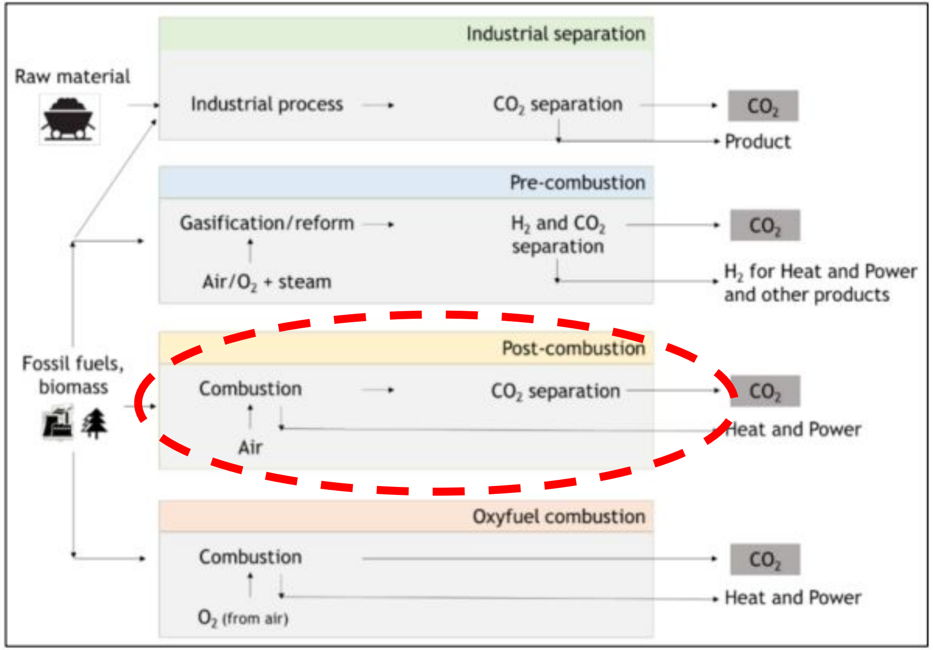
clauger

Focus on CO_2 capture

Capture

Carbon capture technology landscape

Post-combustion technology dominates current developments and deployments



- **Pre-combustion** technologies are suitable for gasification processes (Integrated Gasification Combined Cycle plants or biomass gasification).

➔ **Early stage as there are no commercial projects in operation.**

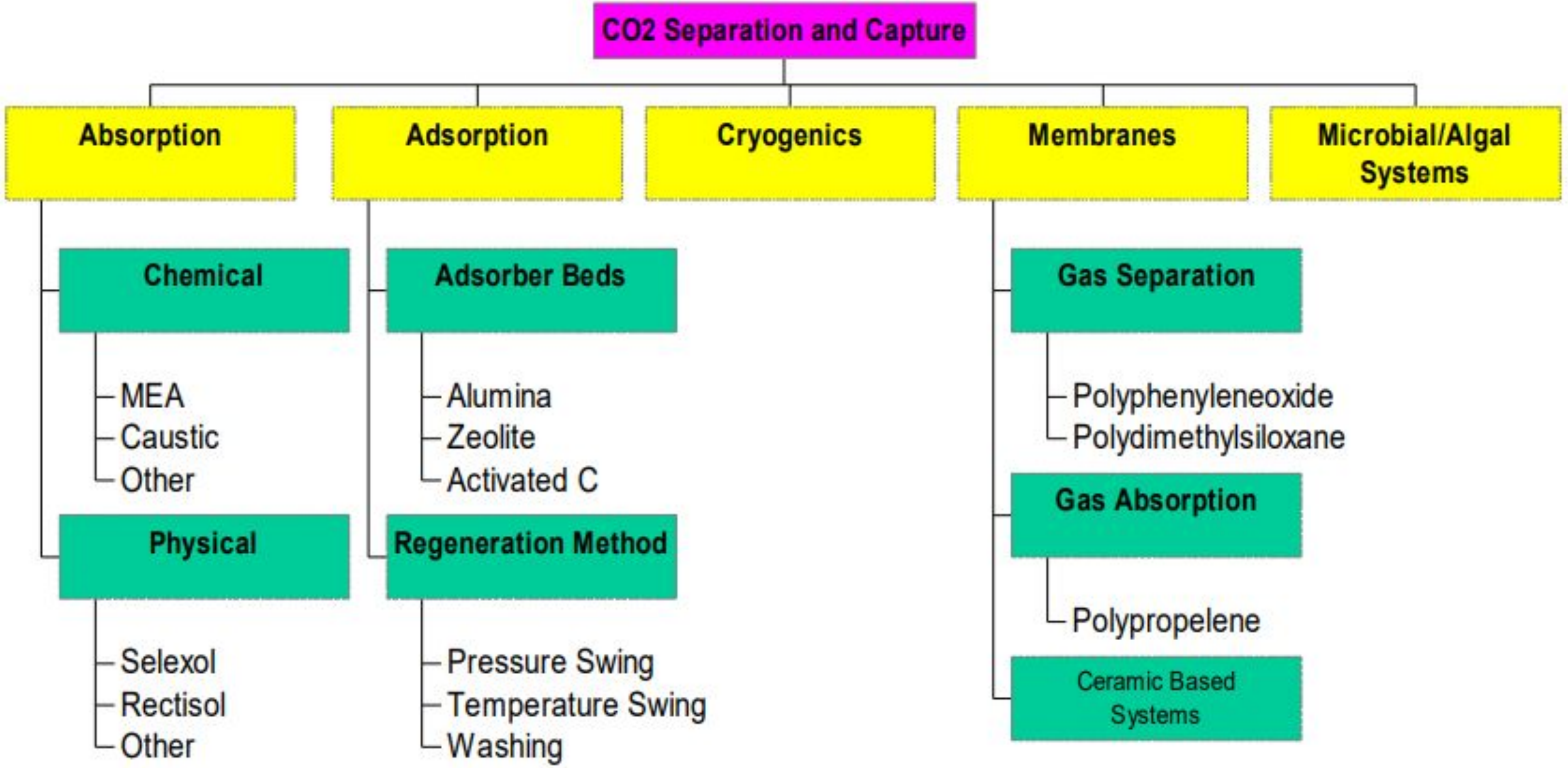
- **Oxyfuel combustion** processes are based on combustion using oxygen instead of air.
- They require an Air Separation Unit (ASU) to produce oxygen.

➔ **Needs to be demonstrated on natural gas plants before being applied to biomass combustion.**

Source: Regufe et al, 2021

Post-combustion landscape

There are 5 main types of post-combustion technologies

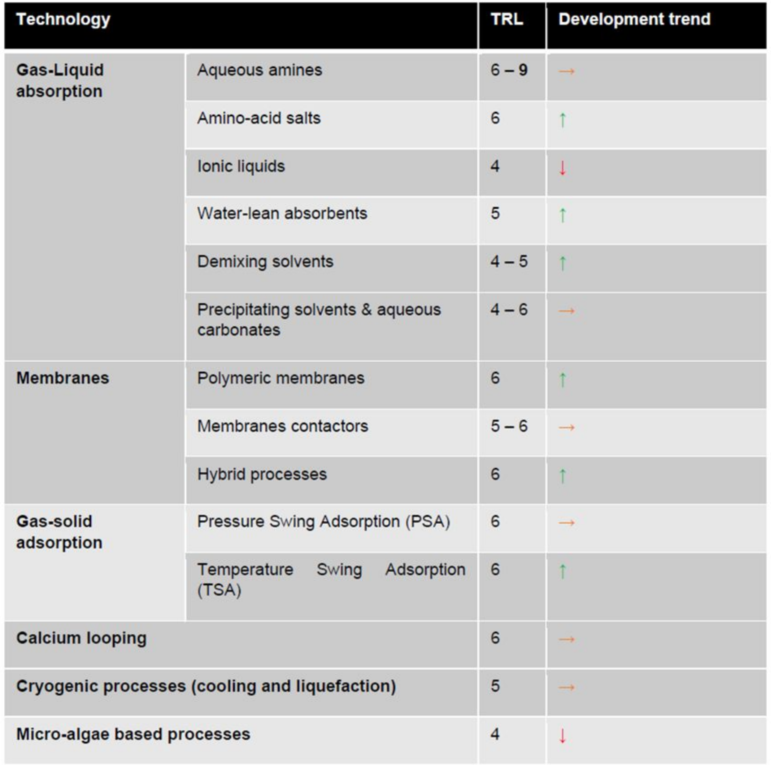


CO2 Separation and Capture

- Absorption
  - Chemical
    - MEA
    - Caustic
    - Other
  - Physical
    - Selexol
    - Rectisol
    - Other
- Adsorption
  - Adsorber Beds
    - Alumina
    - Zeolite
    - Activated C
  - Regeneration Method
    - Pressure Swing
    - Temperature Swing
    - Washing
- Cryogenics
- Membranes
  - Gas Separation
    - Polyphenyleneoxide
    - Polydimethylsiloxane
  - Gas Absorption
    - Polypropelene
  - Ceramic Based Systems
- Microbial/Algal Systems

Post-combustion technology maturity

Liquid solvents are the most advanced post combustion technology



Technology		TRL	Development trend
Gas-Liquid absorption	Aqueous amines	6 – 9	→
	Amino-acid salts	6	↑
	Ionic liquids	4	↓
	Water-lean absorbents	5	↑
	Demixing solvents	4 – 5	↑
	Precipitating solvents & aqueous carbonates	4 – 6	→
Membranes	Polymeric membranes	6	↑
	Membranes contactors	5 – 6	→
	Hybrid processes	6	↑
Gas-solid adsorption	Pressure Swing Adsorption (PSA)	6	→
	Temperature Swing Adsorption (TSA)	6	↑
Calcium looping		6	→
Cryogenic processes (cooling and liquefaction)		5	→
Micro-algae based processes		4	↓

Source: IEAGHG, 2019

- **Post-combustion carbon capture is now an established technology**, based on decades of industrial deployment in the oil and gas sector
- Technology selection **depends on CO_2 concentrations and gas composition** (e.g. concentration of impurities).
- For combustion flue gas, **liquid absorption** with **solvents (mostly amine-based)** is reaching commercial maturity
- **Alternative solvents** are developing (e.g. hot potassium carbonates, demixing solvents), but their deployment is less mature.

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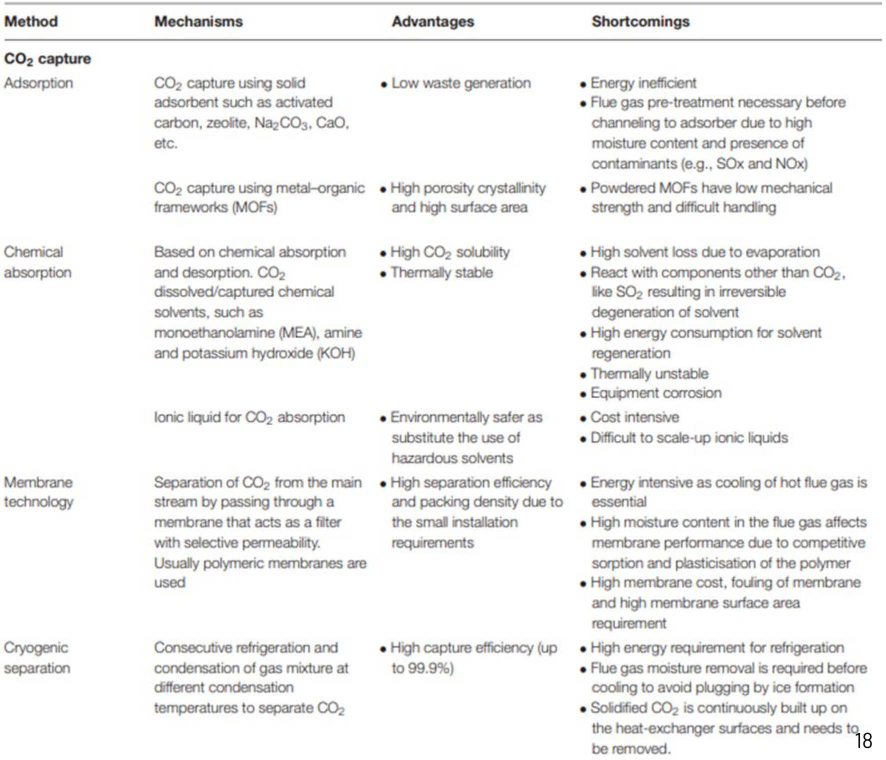
Other technologies to look-out for

Current liquid solvents limitations create space for innovative approaches

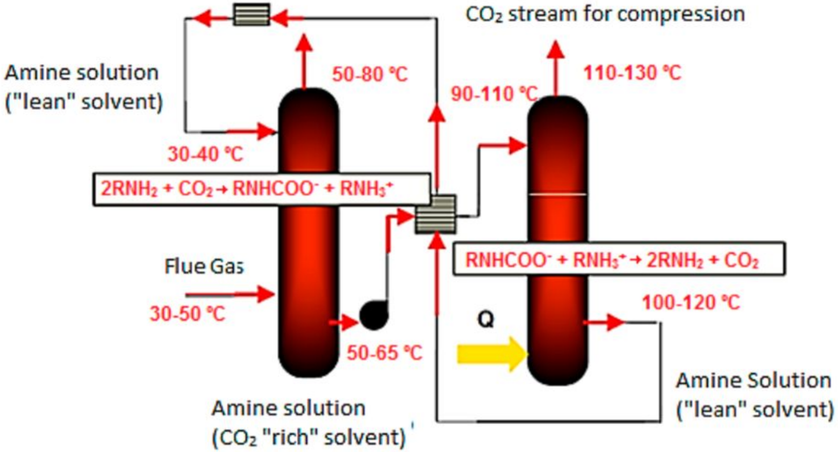
- **Solid sorbents** based on porous materials (e.g. zeolites, MOFs) claim improved energy and environmental performance, but this still needs to be proven at scale.
- **Cryogenics** are mature for high-concentration applications (e.g. steam methane reforming for H_2 production); applications for flue gas are emerging.
- **Membranes materials** are developing fast (with alternatives to polymers e.g. graphene oxides).
- **Algae-based methods and calcium looping** seem less promising at this stage with a decreasing dynamic.
- Longer-term novel approaches based on **electrochemistry** (e.g. electroswing absorption) need to be monitored.



Method	Mechanisms	Advantages	Shortcomings
CO_2 capture			
Adsorption	CO_2 capture using solid adsorbent such as activated carbon, zeolite, Na_2CO_3, CaO, etc.	• Low waste generation	• Energy inefficient • Flue gas pre-treatment necessary before channeling to adsorber due to high moisture content and presence of contaminants (e.g., SOx and NOx)
	CO_2 capture using metal–organic frameworks (MOFs)	• High porosity crystallinity and high surface area	• Powdered MOFs have low mechanical strength and difficult handling
Chemical absorption	Based on chemical absorption and desorption. CO_2 dissolved/captured chemical solvents, such as monoethanolamine (MEA), amine and potassium hydroxide (KOH)	• High CO_2 solubility • Thermally stable	• High solvent loss due to evaporation • React with components other than CO_2, like SO_2 resulting in irreversible degeneration of solvent • High energy consumption for solvent regeneration • Thermally unstable • Equipment corrosion
	Ionic liquid for CO_2 absorption	• Environmentally safer as substitute the use of hazardous solvents	• Cost intensive • Difficult to scale-up ionic liquids
Membrane technology	Separation of CO_2 from the main stream by passing through a membrane that acts as a filter with selective permeability. Usually polymeric membranes are used	• High separation efficiency and packing density due to the small installation requirements	• Energy intensive as cooling of hot flue gas is essential • High moisture content in the flue gas affects membrane performance due to competitive sorption and plasticisation of the polymer • High membrane cost, fouling of membrane and high membrane surface area requirement
Cryogenic separation	Consecutive refrigeration and condensation of gas mixture at different condensation temperatures to separate CO_2	• High capture efficiency (up to 99.9%)	• High energy requirement for refrigeration • Flue gas moisture removal is required before cooling to avoid plugging by ice formation • Solidified CO_2 is continuously built up on the heat-exchanger surfaces and needs to be removed.

Absorption with liquid solvents

Solvent-based liquid absorption is the most mature technology



Basic principle (two-step cyclical process):

1. CO_2 from flue gas reacts with a basic solution (generically amines or R-NH_2).
2. CO_2 is then separated from the solution using energy (heat).

1) Absorber:

Flue gas containing CO_2 enters a packed bed absorber from the bottom and contacts in counter-current with a CO_2-lean absorbent.

2) Regenerator:

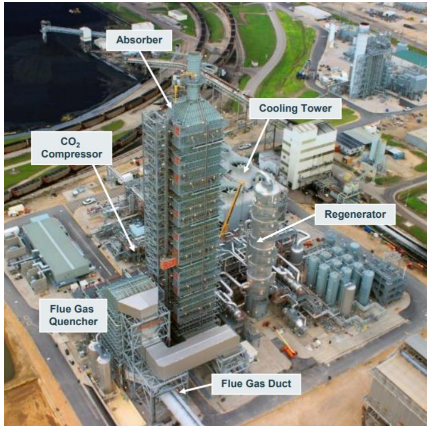
- The CO_2-rich absorbent flows into a stripper for thermal regeneration.
- After regeneration, the CO_2-lean absorbent is pumped back to the absorber.

Considerations for liquid solvents

The technology faces a number of limitations

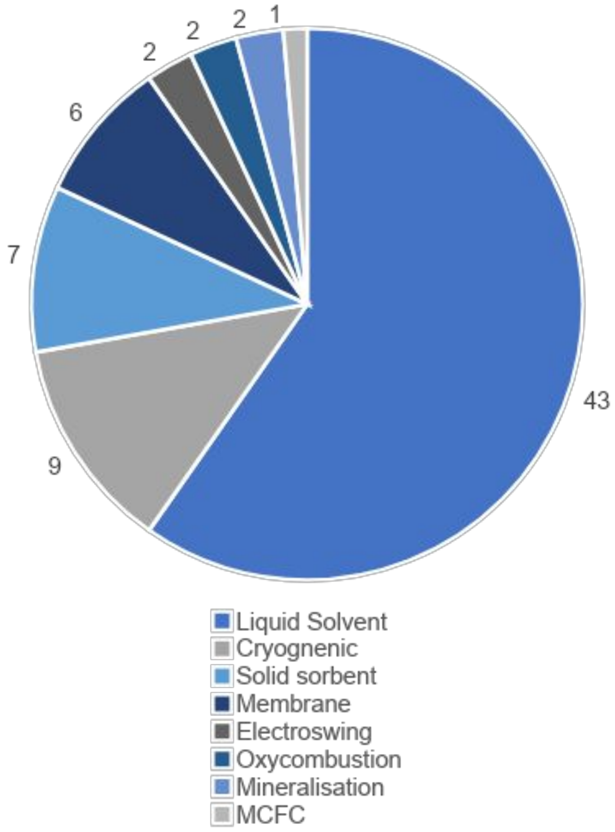
- High energy consumption: **1–1.5 MWh/tonne** CO_2 (of which 80% heat)
- Requires **heat at 120°C**
- Solvent needs to be regenerated, can be degraded by heat, moisture and impurities
- **Pollutants** to be monitored (e.g. NH_3, nitrosamines) in particular for amine solvents (Hot Potassium Carbonate solvents have low toxicity)
- **High CapEx**, in particular for smaller installations
- Significant footprint: e.g. **1,500 m^2** for 150,000 tonnes per year CO_2 with **tall** absorption columns (**up to 60m**)

Petra Nova CCS project in US
(240 MW coal unit, MHI technology, stand-by)



SaskPower Boundary Dam 3 CCS project in Canada
(115 MW coal unit, Shell technology, in operation)

Landscape of suppliers by technology



- We have identified close to 80 active vendors internationally.
- Different stages of maturity: from commercial offering to low TRL vendors
- The landscape is dominated liquid solvents in particular amines.
- Next categories are cryogenic solutions, solid sorbents and membranes.
- Other categories are more limited.

Sample of suppliers

By technology family

Liquid Solvents

Amines or other amine based liquids

MITSUBISHI HEAVY INDUSTRIES
carbon clean
AKER CARBON CAPTURE
Axens Powering integrated solutions
Shell
T.EN TECHNIP ENERGIES
Honeywell
C-Capture
CATENA
TOSHIBA
ENTROPY
GREEN GAS & LIQUIDS
ionada
TPI TECNO PROJECT INDUSTRIALE SIAD Group
ANDRITZ

Other solvents

capsol technologies
ION CLEAN ENERGY
CO₂ SOLUTIONS
K2-CO2 Your key to decarbonization

Other methods

Solid sorbents

Svante
Nuada
mosaic

Cryogenic

Air Liquide
CHART
Revcoo Global cooling
Carbon America
Cryo Pur Une filiale de FDE

Membranes

MTR CARBON CAPTURE
aqualung
Ardent

Other

CARBONFREE™
VERDOX

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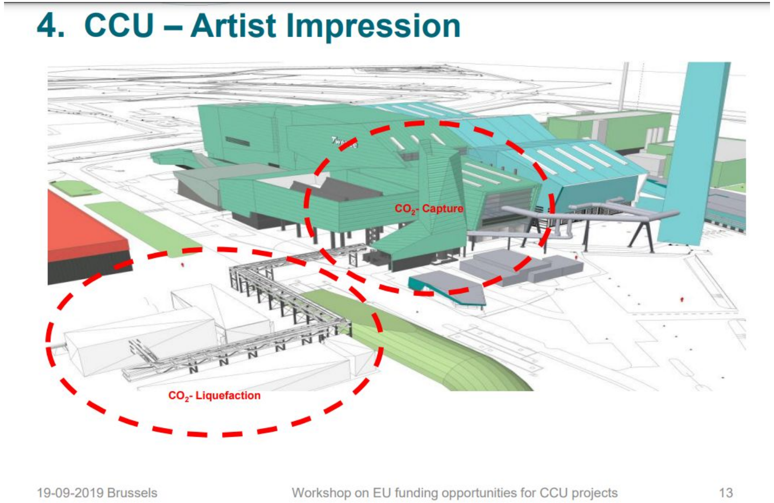
Example of CCS project: AVR Duiven

- AVR Duiven, Waste to Energy plant in the Netherlands, 50,000–60,000 tCO_2 per year
- CO2 used for greenhouses
- Solvent Technology (amines) by manufacturer TPI
- Footprint: 45 m x 37 m ~ 1700 m^2

Example of CCS project: Twence

- Twence, Hengelo, Netherlands, 100,000 tCO_2 per year
- Solvent technologies (amines) by Aker (now part of SLB)
- CO_2 used for greenhouses
- Footprint : ~ 30m x 15m (450 m^2)



4. CCU – Artist Impression

19-09-2019 Brussels Workshop on EU funding opportunities for CCU projects 13

Capture

Example of CCS project: GGL (ex Frames)

- DES BV, Netherlands, 12,000 tCO_2 per year
- Commissioning in 2019 (based on Vyncke boiler), CO_2 used for greenhouses
- Amine sorbent (Green Gas Liquids has purchased Frames capture technology)
- Footprint: 15 m x 5 m (excl liquefaction)
- Energy consumption (heat): 1.6 MWh/tCO_2

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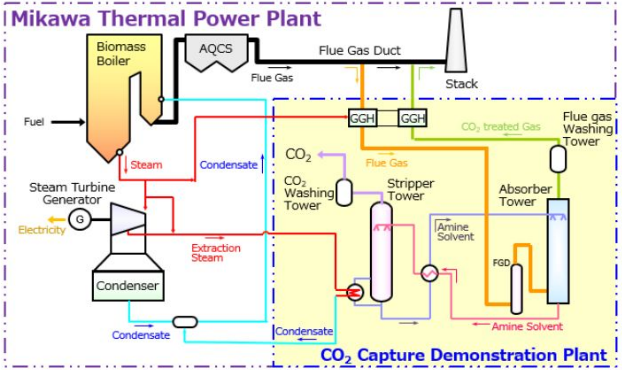
Example of BECCS pilot: Mikawa, Japan

- First operational BECCS project run by **Ministry of Environment in Japan**
- CO_2 capture demonstration plant based on 49 MW biomass plant
- Operation started in October 2020
- **600** tCO_2 per day captured
- Regeneration heat consumption: **0.7 MWh per tCO_2**
- Heat provided by steam turbine extraction
- Technology provided by **Toshiba** (proprietary TS-1 solvent)
- Footprint: **4,050 m^2** (45x90m)



Source: Kitamura, 2019

Capture

Example of alternative solvent: Axens

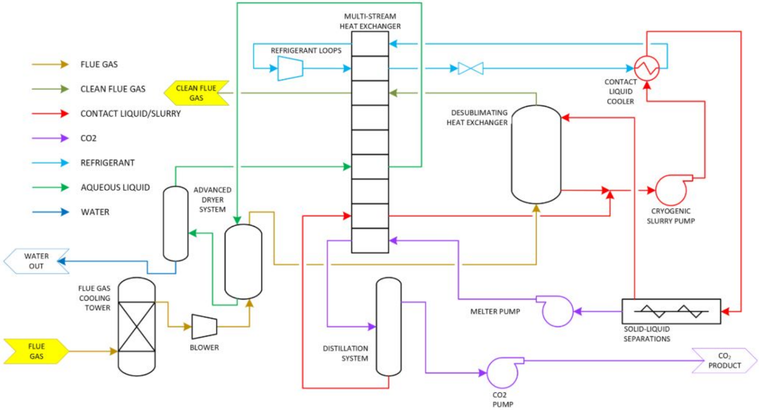
- Amine based demixing solvent developed by Axens (DMX) allowing 30% lower thermal energy consumption and less corrosive than amines
- Pilot operational in steel plant in France (4,000 tCO_2 per year) based on blast furnace gas
- Demonstration project has confirmed initial assumptions and performance in the field

Module of DMX™ Demonstration Pilot Plant

Capture

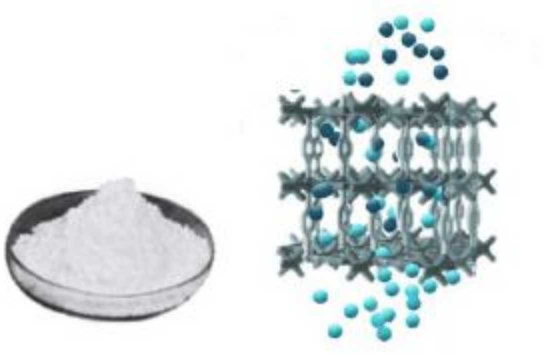
Example of cryogenic pilot: Chart industries

- Chart acquired SES (Sustainable Energy Solutions)
- Pilot size: 10,000 tCO_2 per year (cement and thermal generation)
- Energy consumption (electrical power): 230 kWh/CO_2
- Footprint : 21 m x 9m
- Commercial scale : 100,000 tCO_2 per year



Example of solid sorbent pilot: Svante

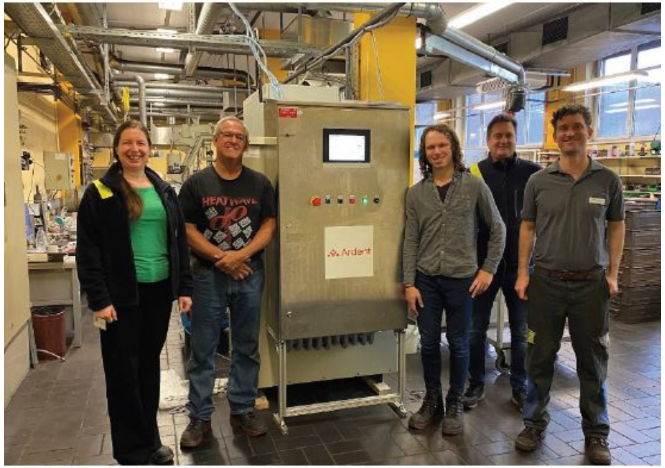
- Solid sorbent separation technology with MOFs (Metal Organic Frameworks)
- 10,000 tCO_2 per year pilot in Canada
- Optimised energy consumption using lower temperatures heat sources than amine solvents



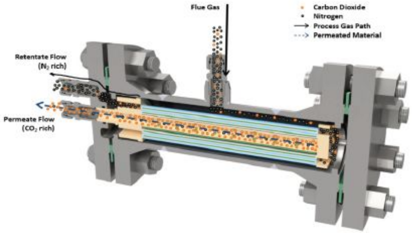
Capture

Example of membrane pilot: Ardent

- Modular, low pressure membrane CO_2 separation technology, tolerant to various pollutants
- High flow of gas at low pressure allows smaller footprint
- Pilot plant at an olefin and (and pilot rig at steel facility)
- Lower energy consumption than solvents: 570 kWh per tCO_2 of electrical power



↑ OPTIPERM™ CARBON PILOT RIG AT A STEEL PRODUCTION FACILITY



Capture

First learnings from early projects

- Current projects in operation and constructions are still pioneers: project complexity, large footprint, need for flue gas treatment (dust, Nox, Sox), liquefaction and storage, CO_2 purity.
- Energy consumption is still an issue at close to 1+ MWh per tCO_2 (mostly thermal energy) which imposes high losses or complex integration processes.
- With liquid solvents full capture costs are still in the 100–150 euros per tCO_2 (valid for 100,000 tCO_2 per year).
- However lots of learnings are allowing existing and new vendors to learn and improve.
- Potential electric powered solutions (e.g. solid sorbents or cryogenics) with much lower energy consumptions may be on the horizon (commercial in 2030s).

Key takeaways

Key takeaways

Learning through the first cycle of deployment

- Carbon capture is a very active field of research, innovation, pilot and increasingly commercial deployments.
- Post-combustion technologies are reaching maturity with solvents (e.g. amine-based, hot potassium carbonates and others) becoming standard and ready to deploy in the next years.
- However, solvents have areas of improvements (in particular energy penalty) which open the door for other methods slightly lower in technology maturity, potentially available in the next decade, such as cryogenic (for low concentration), solid sorbents, membranes.
- Longer-term electrochemical methods may offer an interesting fully electric alternative but it is still (very) early days.

> “
>
> For carbon capture, the time is now, for learning by doing (and improving)