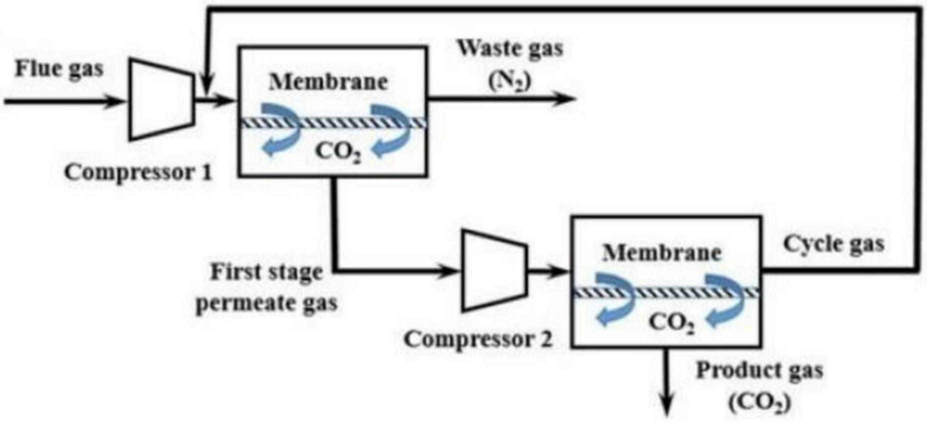
POLYMERIC MEMBRANE

Polymeric membranes are synthetic materials widely used for gas separation, particularly in CO_2 capture applications. They consist of polymer chains with specialized structures that enable the selective permeation of specific gases, such as CO_2, over others like N_2 or O_2. The separation process is pressure-driven and relies on the solution-diffusion mechanism, where CO_2 molecules dissolve into the polymer matrix and diffuse through it more readily than other gases. This selectivity depends on the membrane material's chemical and physical properties.
Gas separation using membranes can be done in single or multi-stage processes. Single-stage processes need high selectivity for high CO_2 purities and recoveries, but this is challenging due to low CO_2 content and the recovery-purity trade-off. Multi-stage processes, as shown in the figure, with gas recycling, achieve higher purity and recovery but require more power and membrane area. The main goal is to minimize energy consumption and membrane area.[1]



Two-stage membrane process

TECHNICAL ASPECTS (all % are volume-based)

Point sources: Natural gas plants, power plants, cement, steel, waste-to-energy, paper & pulp hydrogen production, biogas upgrading, and ammonia production facilities.[2]
CO_2 concentration range: 10-70%[2]
CO_2 capture efficiency: >90%[2]
CO_2 purity: >95% (3-stage)[3]
Min. feed gas pressure: 1[3,4] – 6[5] bar
Max. feed gas temperature: 30-60 °C (post-combustion) and 150-200 °C (pre-combustion)[6]
Typical scale: Small to Large (modular)
Primary energy source: Electricity
Impurity tolerance: No tolerance.[7]

FUNCTION IN CCU VALUE CHAIN

- Capture CO_2 from flue gases.
- Increase CO_2 concentration for a hybrid system.
- Purify CO_2 streams.

LIMITATIONS

- Polymeric membranes are susceptible to degradation or fouling when exposed to impurities such as SOx, H_2S, or particulates (PM), requiring pretreatment steps.[7,8]
- Achieving high CO_2 purity in the permeate stream typically necessitates multi-stage membrane systems or hybrid approaches.[3]
- Polymeric membranes generally operate best within a moderate range of temperatures and pressures.[7]
- Certain polymeric membranes are sensitive to moisture, which can impact their selectivity and permeability over time.[7]

ENERGY

- Electricity is primarily used by the compressor or blower to pressurize the feed gas and by a vacuum pump, if used on the permeate side.

CONSUMABLES

- Membranes themselves need to be replaced periodically.
- Cooling water is required to cool the feed gas and intermediate streams after compression.

Energy and Consumables

Parameter	Value
Electricity (kWh/tCO_2) *	207[5] - 500[9]

*Variable depending on number of stages, membrane flux, feed gas, and vacuum pressures.
[5] Two-stage polyactive™ membrane system; feed gas: 13.5% CO_2; purity 96%; feed pressure – 6 bar; vacuum pressure – 0.2 bar; excluding compression.
[9] Three-stage; CO_2 conc. – 12% dry; flue gas stream – 5000 t/d; capture efficiency – 90%; CO_2 purity – 96%; inlet pressure – 1.6-2.3 bar; includes CO_2 compression to 110 bar.

COSTS

CAPEX: 35 – 40 €/tCO_2[9]
Main CAPEX: compressors, vacuum pumps, and membranes.
(lower range – high flux and upper range – low flux)
OPEX: 35 – 75 €/tCO_2[9]
Main OPEX: electricity for compressors and vacuum pumps.
(lower range – low flux and upper range – high flux)
CO_2 capture cost: 75 - 110 €/tCO_2[9]
(lower range – low flux and upper range – high flux)

[9] *Three-stage; CO_2 conc. – 12% dry; flue gas stream – 5000 t/d; capture efficiency – 90%; CO_2 purity – 96%; inlet pressure – 1.6-2.3 bar; includes CO_2 compression to 110 bar; CRF – 0.154; 2019 euros; 8000 hr/yr; membrane price – 45 €/m^2; electricity price – 62.5 €/MWh.*
CO_2 avoidance cost: 84 €/tCO_2 avoided[10]
[10] *2-stage membrane system; IGCC plant; CO_2 conc. – 38.6%; lifetime – 25 yrs; discount rate – 8%; 2015 euros; includes CO_2 compression to 110 bar.*

ENVIRONMENTAL

CO_2 footprint: 287 kgCO_2e/tCO_2[5]
[5] *Two-stage polyactive™ membrane system; feed gas: 13.5% CO_2; purity 96%; feed pressure – 6 bar; vacuum pressure – 0.2 bar; including compression; cradle-to-grave.*
Spatial footprint: 3900 m^2 for 0.2 MtCO_2/yr[11]
[11] *land cost – 25.6 €/m^2; estimation includes flue gas cooling, CO_2 capture, compression and liquefaction.*

418 m^2 for 13750 tCO_2/d[12] (only membrane system)

Although membrane systems require a significant membrane area, their physical footprint can be more compact compared to other CO_2 capture technologies like solvent absorption systems[4].
Environmental issues: Membrane disposal due to degradation over time.

ENGINEERING

Maturity: Commercial (TRL 9)[2]
Most companies offer membrane-based capture systems commercially.
(MTR has been awarded a full-scale FEED project for a 3 MtCO_2/yr capture plant)
Retrofittability: Good[1]
Technology's modularity makes it versatile, however, gas pretreatment and compression may be needed.
Scalability: High[1]
Well suited for capturing large amounts of CO_2 from industrial point sources, considering its modular nature.
Process type: Solid stationary membrane-based without chemical reactions.
Deployment model: Centralized only.
Each membrane module separates CO_2 from the feed gas.
Technology flexibility: Hybridization with other capture technologies is feasible. Membranes can be used to increase CO_2 concentration for other technologies for cost-effective capture.

TECHNOLOGY PROVIDERS

- Polaris™ by **MTR Carbon Capture**, United States
- Separex™ by **Honeywell,** Belgium
- HISELECT® by **Linde Engineering**, Ireland
- Optiperm™ by **Ardent Technologies**, United States
- SEPURAN® by **Evonik Industries**, Germany
- MEDAL™ by **Air Liquide**, France
- HyCaps by **CO2CRC**, Australia
  (Hybrid with solvent absorption and membrane separation)
- Membrane capture by **Cool Planet Technologies**, United Kingdom

INNOVATIONS

Mixed Matrix Membranes (MMMs): These membranes combine polymer matrices with inorganic fillers like metal-organic frameworks (MOFs), zeolites, or carbon nanotubes to enhance selectivity and permeability.[13]
Membrane-cryogenic hybrid systems: This hybrid system combines membranes with cryogenic separation to achieve higher CO_2 capture efficiency and low energy consumption. The CO_2 concentration is increased by using membranes as a pretreatment step, followed by separation via phase change in a cryogenic unit.[14]
Surface-modified membranes: Membranes with surface modifications, such as grafted CO_2-philic (CO_2-attracting) polymer chains, to enhance separation performance.[15]

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