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Driving Efficiency: Energy Optimisation in CCU Processes

sbh4 GmbH, Stephen B. Harrison

12th European Carbon Dioxide Utilisation Summit

Antwerp, 25th September 2025

10:35 to 11:05

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Agenda

Driving Efficiency: Energy Optimisation in CCU Processes

1. Key social, economic, and policy factors that will shape the future landscape of the industry
2. Balancing operational efficiency with emissions reduction to achieve net-positive environmental impacts
3. Emerging innovations that could revolutionise CCU capabilities and applications

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1. Key social, economic, and policy factors that will shape the future landscape of the industry

Policy and CO_2 emissions costs drive the business case for CO_2 capture for CO_2 utilisation

CO2 emissions costs, or opportunity costs around the world are progressively rising and geographic coverage is increasing.

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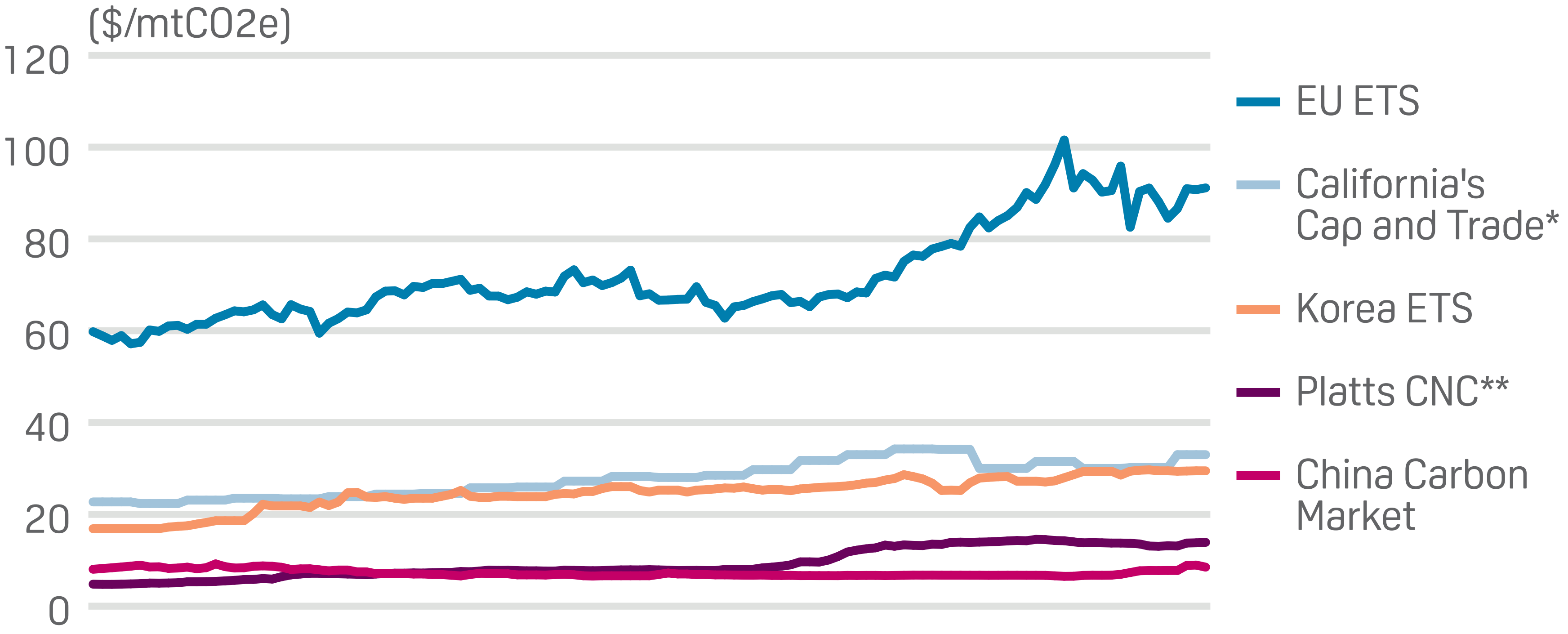

https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/010622-commodities-2022-chinas-carbon-market-to-expand-build-capabilities

Two views of CO2 capture at Holcim, Brevic. Social acceptance was and remains key.

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https://www.brevikccs.com/en

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1.1 Processes that require no (additional) energy for CO_2 capture

Lowest incremental capex and opex, brownfield sites, minimal disruption.

Best economics.

Best social acceptance?

Best policy support?

Syngas, Towngas – 3,500km of pipelines in Hong Kong for 1.9 million domestic, commercial and industrial customers

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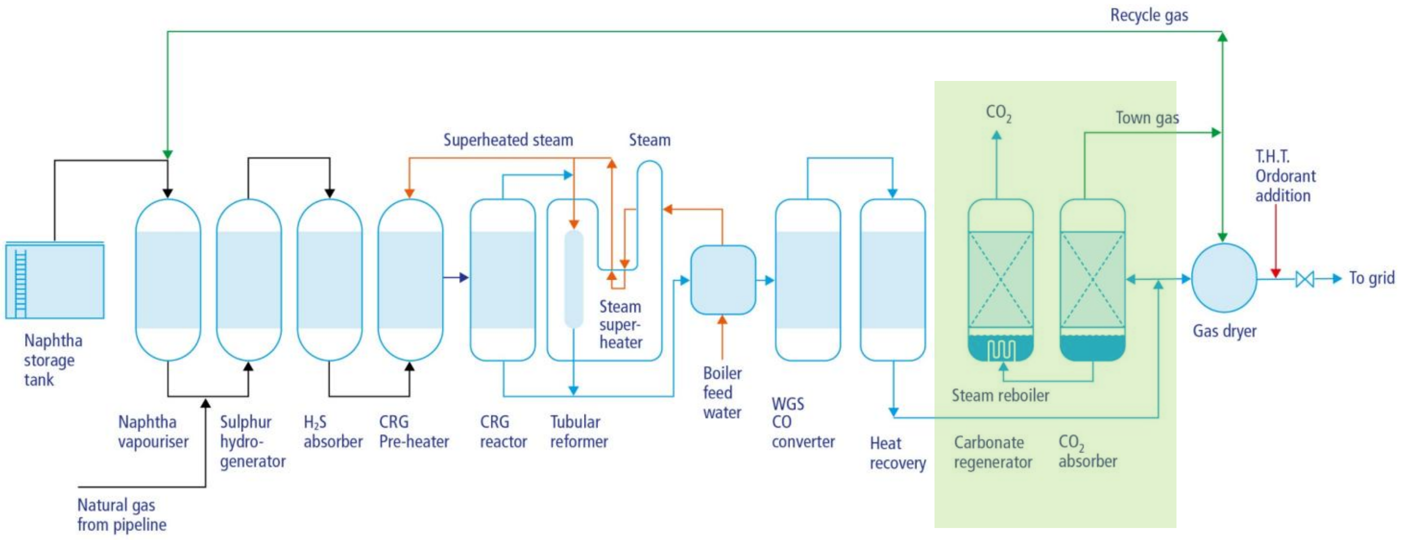
https://www.towngas.com/en/About-Us/Hong-Kong-Gas-Business

Hong Kong Town Gas – Tai Po Catalytic Rich Gas naphtha / methane reformer and CO_2 capture process



Town gas composition

Carbon Dioxide	16.3 % – 19.9 %
Carbon Monoxide	1.0 % – 3.1 %
Methane	28.2 % – 30.7 %
Hydrogen	46.3 % – 51.8 %
Nitrogen and Oxygen	0 % – 3.3 %

Town gas energy value

Calorific Value	17.27 MJ/m³
Specific Gravity	0.52
Wobbe Index	24

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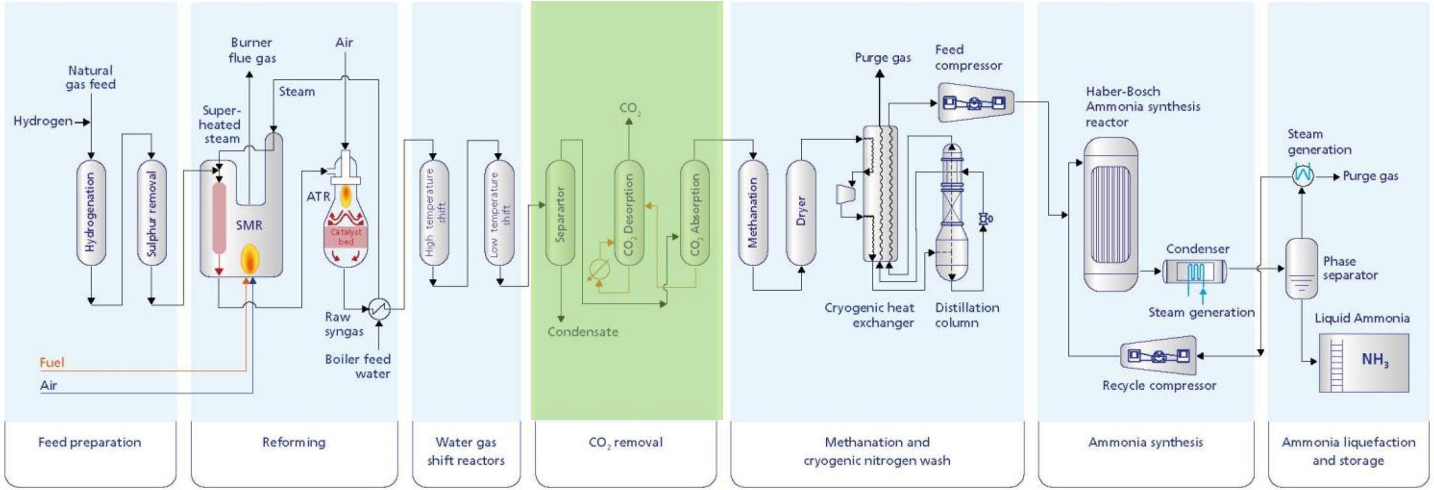
Hong Kong Town gas

- Cooking and heating fuel
- More than 1 million domestic and commercial customers
- Naphtha reforming on SMR
- CO_2 captured to increase the calorific value of the town gas
- High purity (>95%) CO_2 vented to atmosphere

CO2 capture and removal (with vent to atmosphere) is integrated into ammonia production.

Image courtesy of KBR. Dyno Nobel, Waggaman, Louisianna.

Air-fed Ammonia Production Process



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Grey ammonia

- The reforming stages for grey ammonia can either be air- or oxygen-fed
- Use of an SMR is with the subsequent use of an ATR is common
- If the ATR is oxygen-fed, pure nitrogen must be added in the ammonia synthesis loop
- Pure oxygen is introduced to the ATR to make hydrogen
- CO2 emissions from reforming are removed to protect the ammonia synthesis catalyst
- Most of the CO2 is vented to atmosphere
- Some captured CO2 is used to make urea or used for food and beverage applications
- Alternatively, CO2 can be sequestered

Oxygen-fed Ethylene Oxide Production with Integrated CO_2 Capture

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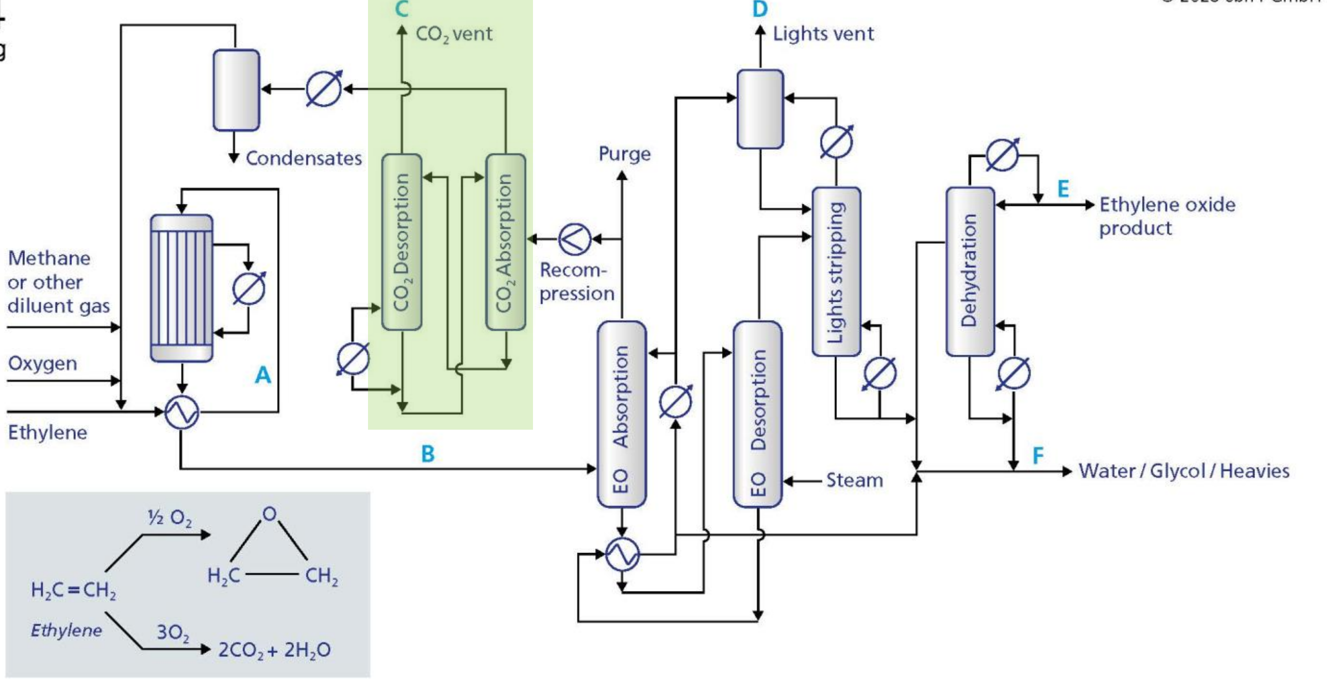

	A: Reactor feed	B: Reactor outlet	C: CO_2 vent	D: Lights vent	E: EO Product	F: Water
Ethylene	34.6 %	25.4 %	0.4 %	64.6 %		
Ethylene oxide (EO)		2.1 %			99.7 %	5.8 %
Oxygen	23.4 %	3.9 %		0.8 %		
Methane	34.6 %	57.2 %	0.4 %	11.0 %		
Water	4.2 %	3.7 %	1.7 %		0.2 %	94.2 %
Carbon Dioxide (CO_2)	3.2 %	7.7 %	97.5 %	23.6 %	0.1 %	

Ammonia is not unique…

- Ethylene oxide production also captures CO2 from within the process
- Some EO plants have been accessed as a low-cost source of CO2 for commercial applications
- As with ammonia, the CO2 capture costs are taken by the EO product.
- The incremental capex and opex to transition from grey EO to reduced CO2 EO is purification (drying in this case) and liquefaction or compression and sequestration.

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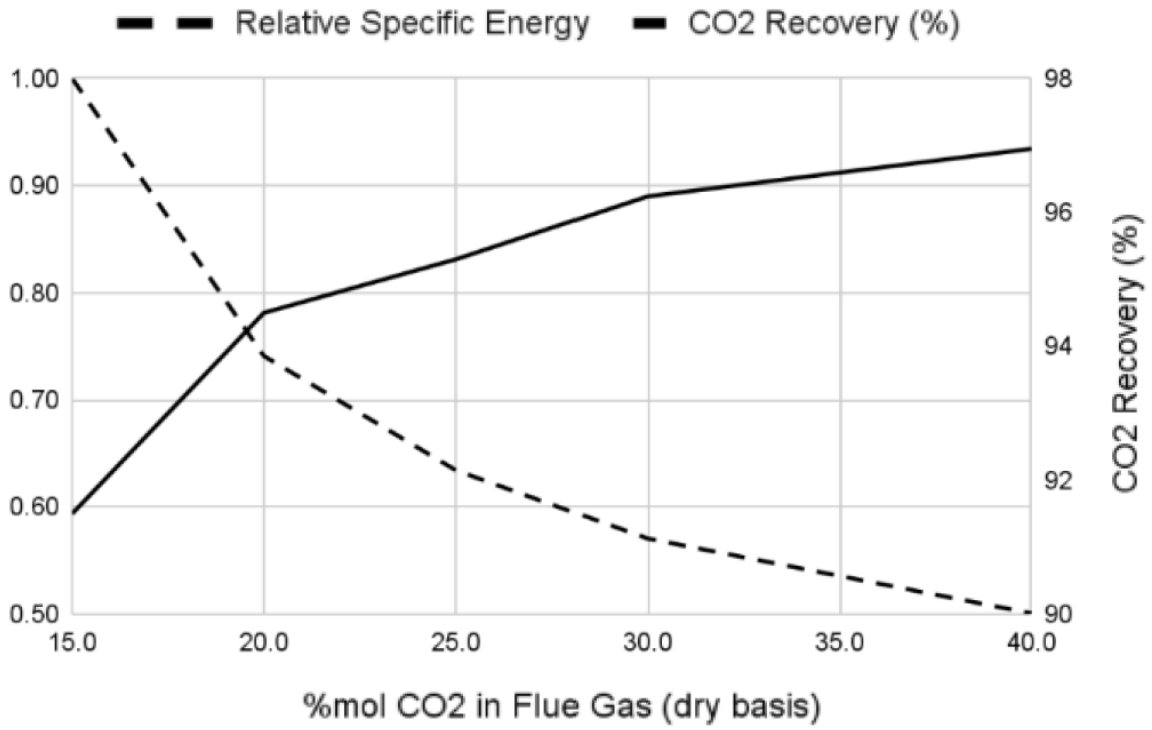
2. Balancing operational efficiency with emissions reduction to achieve net-positive environmental impacts.

You can't fight science, but you can choose the right science to work for you.

Technology selection must fit the flue gas input and required CO2 output.

The energy requirements are driven by fundamental thermodynamics and the relevant heat and mass balances for the chosen technology.

For each technology, the specific energy requirement falls as the flue gas CO2 concentration increases. A high CO2 capture rate also increases the specific energy requirement.



https://netl.doe.gov/sites/default/files/netl-file/24CM/24CM_PSCC_6_Sarkar.pdf

High purity CO_2 feed to the liquefier results in less CO_2 losses from the liquefier inert gas (N_2/CH_4/O_2/CO) purge. Also (not shown on this diagram) dry CO_2 to the liquefier results in less CO_2 losses on the liquefier dryer unit. The holistic system CO_2 losses, or CO_2 capture rate must be analysed.

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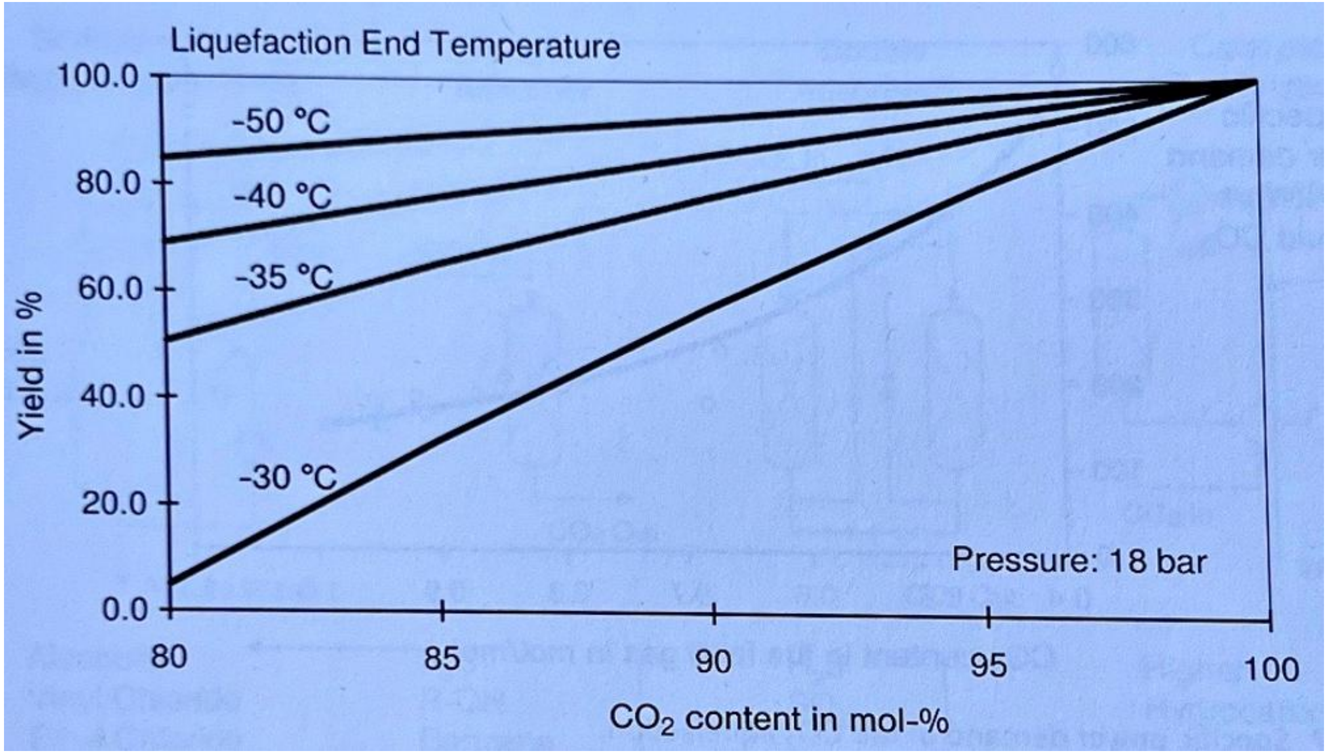

The CO2 capture system inlet and outlet partial pressures of CO2 are important factors for technology selection and within each technology, heavily influence the process efficiency.

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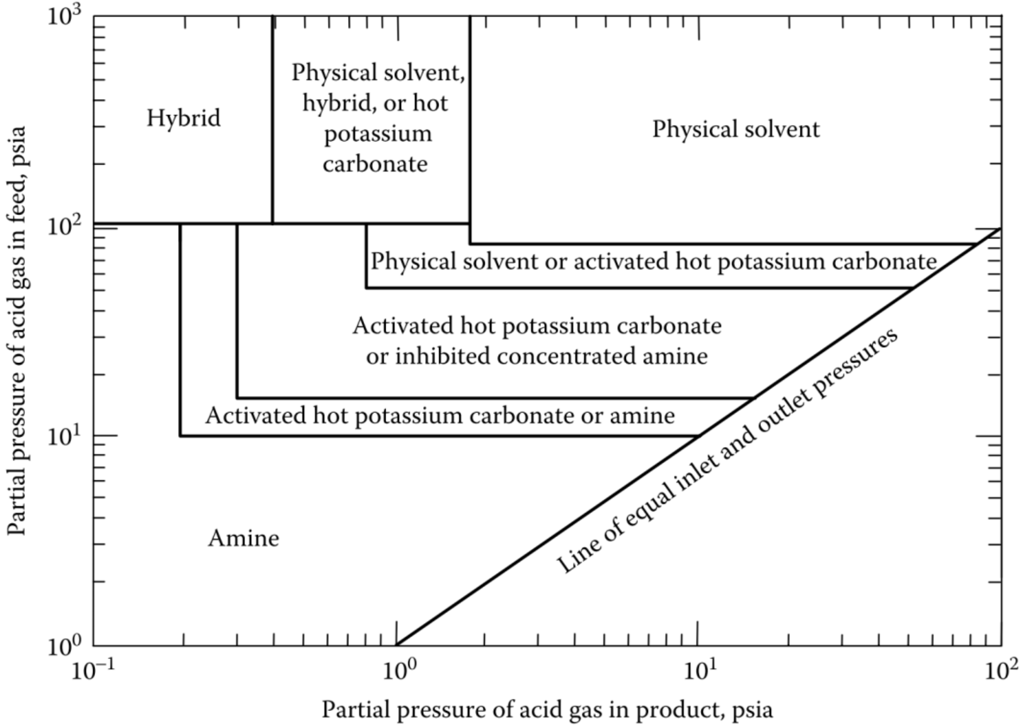

Chemical solvents (amine and HPC) react with the CO2 (chemisorption) and require high regeneration energies.

Physical solvents use physical absorption (physisorption) based on Henry’s law. They require high partial pressure CO2 but benefit from reduced regeneration energy.

- Selexol (Honeywell UOP, Glycol / PEG)
- Rectisol (Linde / AL, methanol)
- Purisol (AL (Lurgi), NMP)
- Sulfinol (Shell, Sulfolane and amines)

This is analogous to solid adsorption systems where MOFs rely on physisorption, and solid amines rely on chemisorption.

https://netl.doe.gov/sites/default/files/netl-file/Carbon-Dioxide-Capture-Handbook-2015.pdf

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3. Emerging innovations that could revolutionise CCU capabilities and applications

To revolutionise CCU, we must cut the cost of CO2 capture.

Leveraging the right science for each application.

A review of established, emerging and disruptive technologies.

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3.1 Chemisorption or physisorption in solvent-based CO_2 capture systems

Physisorption works well with high partial pressure of CO_2 and has a lower regeneration energy since CO_2 is loosely bound to the adsorbent

Shell ADIP ULTRA, as implemented at Shell Quest for pre-combustion CCS from SMRs. Amine solvent with a flash between the absorption and stripping columns utilises SMR process gas pressure to reduce regeneration energy.

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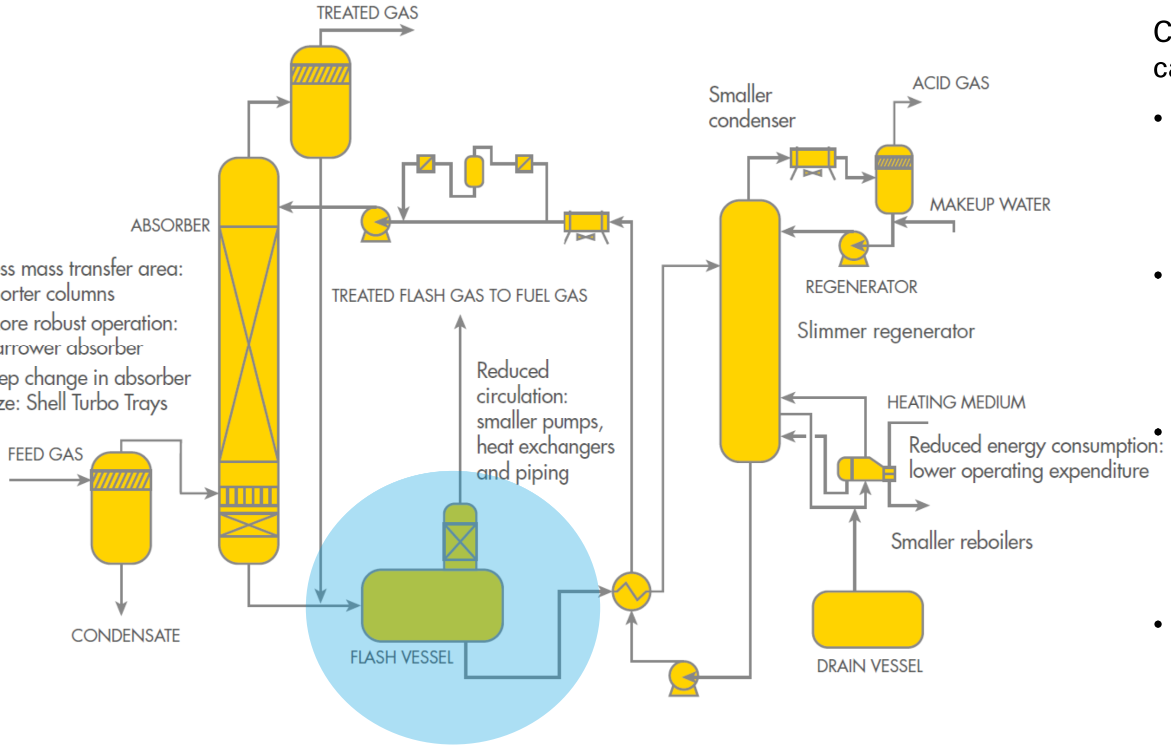
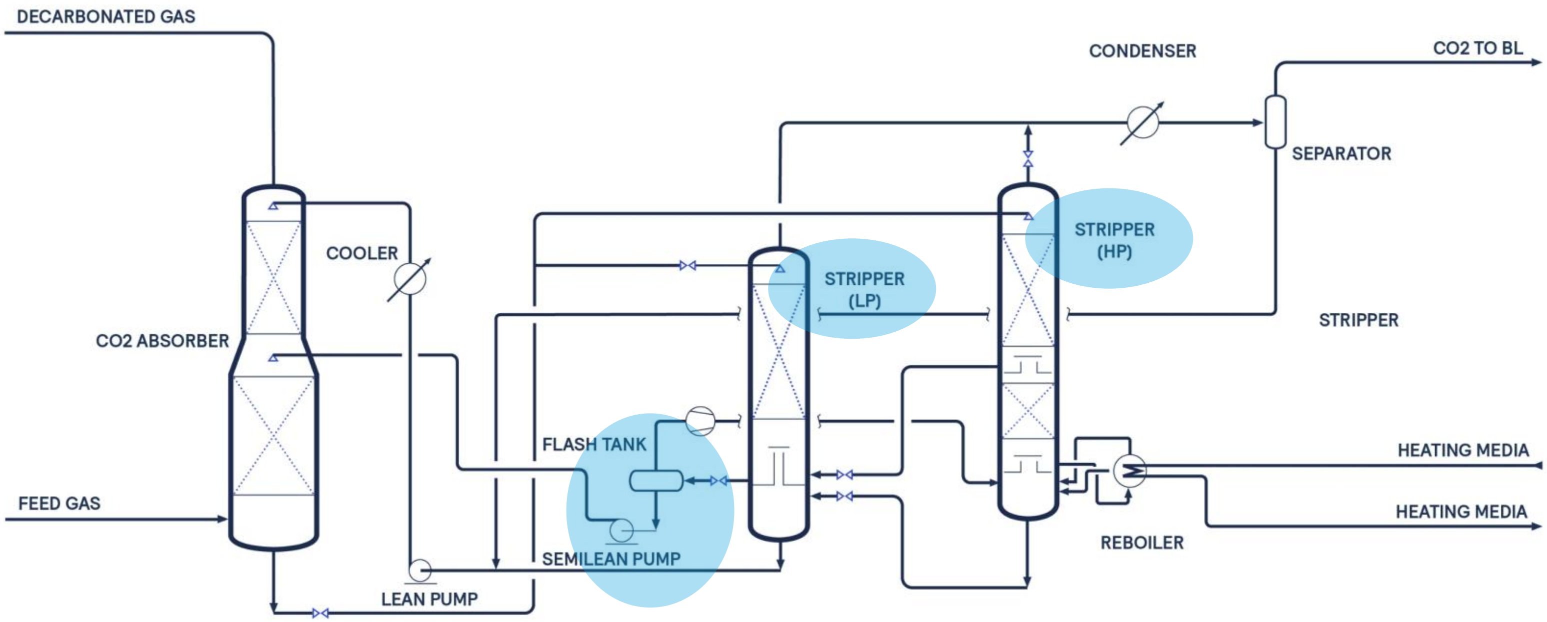


CO_2 capture at pressure has multiple capex and opex benefits

- The CO_2 flash in the high pressure CO_2 capture process releases CO_2 and reduces the heating energy requirement by about 30%.
- High pressure operation means that the solvent regeneration temperature is lower, meaning that lower grade steam can be used.
- The high pressure system is smaller and despite being a pressurised system, capex is reduced by about 30% compared to the very large low-pressure system.
- Footprint is significantly reduced.

Giammarco Technologies NovaFlash®: high-efficiency Hot Potassium Carbonate CO_2 capture for high-pressure streams. A flash between the high-pressure and low-pressure stripper columns, and an additional flash tank reduce the energy input requirement.



Graphic courtesy of Giammarco Vetrocoke

Baker Hughes chilled ammonia process (CAP). Previously developed by GE / Alstom. CAP has been demonstrated at various scales. It can either precipitate ammonium bicarbonate or operate fully in the liquid phase. Chilling reduces ammonia carry over with the flue gas vent. Energy demand is in the range 2 to 3 GJ/tonne CO2, like amines.

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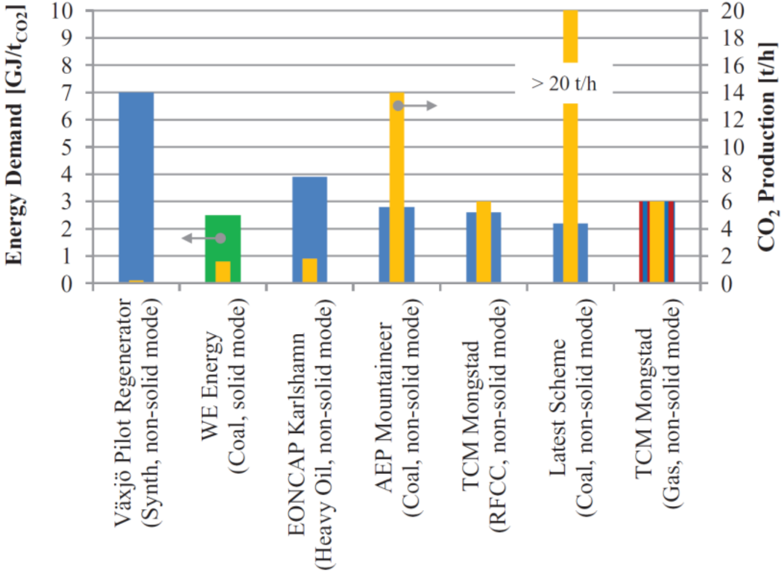

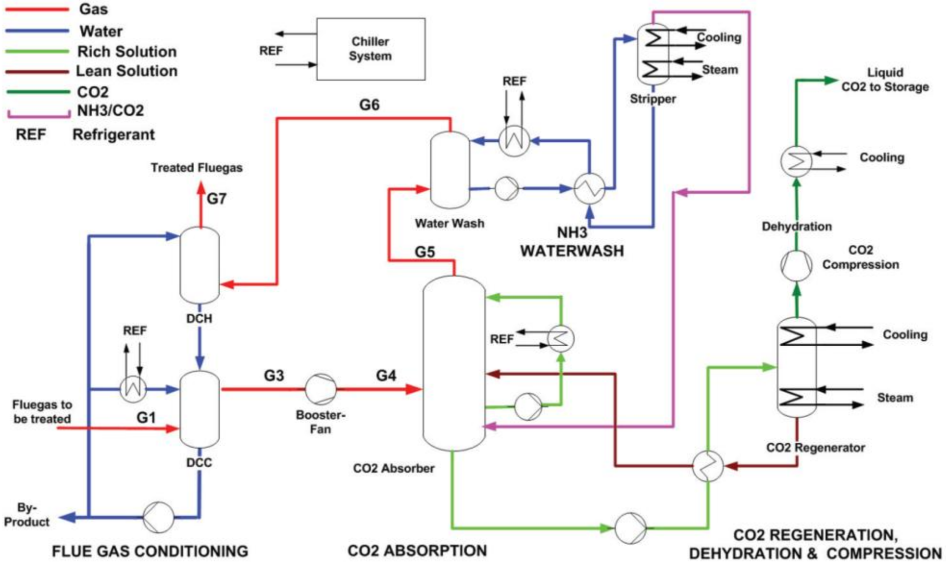

Air Liquide Rectisol™ recovers sulphur chemicals, ammonia, humidity and CO2 from the syngas in different stages. Heavy metals can also be removed.

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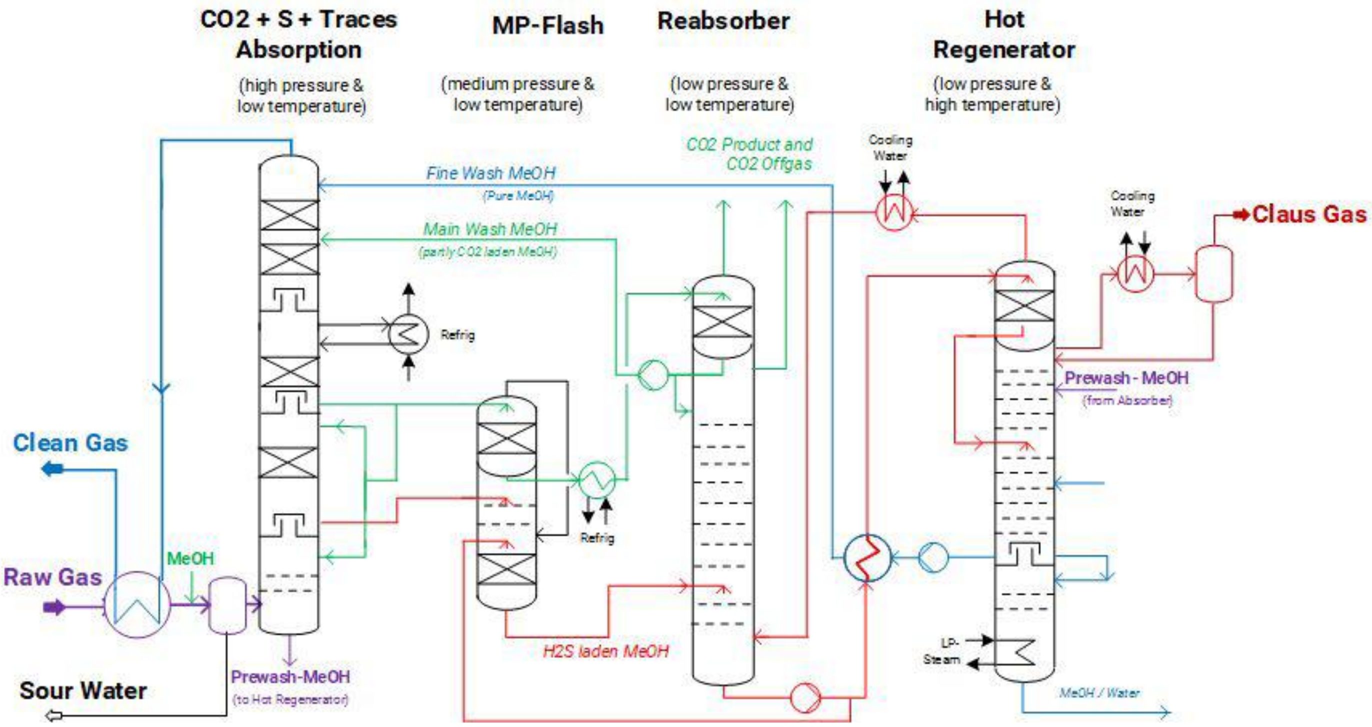

Rectisol™ goes green, A Rösch et al, 2023

Linde (50 references globally) and Air Liquide / Lurgi (110 references globally) offer Rectisol™ using a chilled methanol solvent. The main energy input is compression energy for the methanol chiller circuit.

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Rectisol™ goes green, A Rösch et al, 2023
Stepwise Extension of a Gas Cleanup for IGCC Application, Lars Kirchner, CCT 2009

At large scale, Rectisol™ can offer a lower total cost of ownership (capex, opex and maintenance) than MEA (Amine), CAP (Chilled Ammonia Process) and DMC (Di-methyl carbonate).

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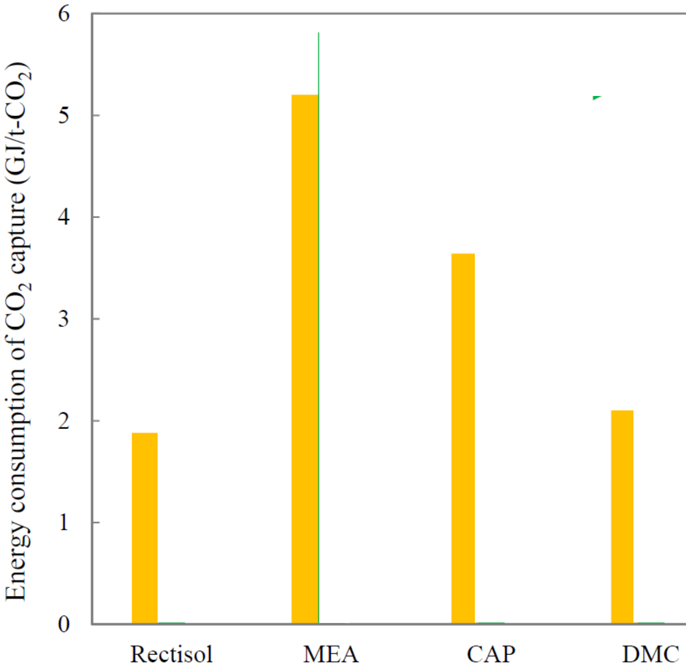

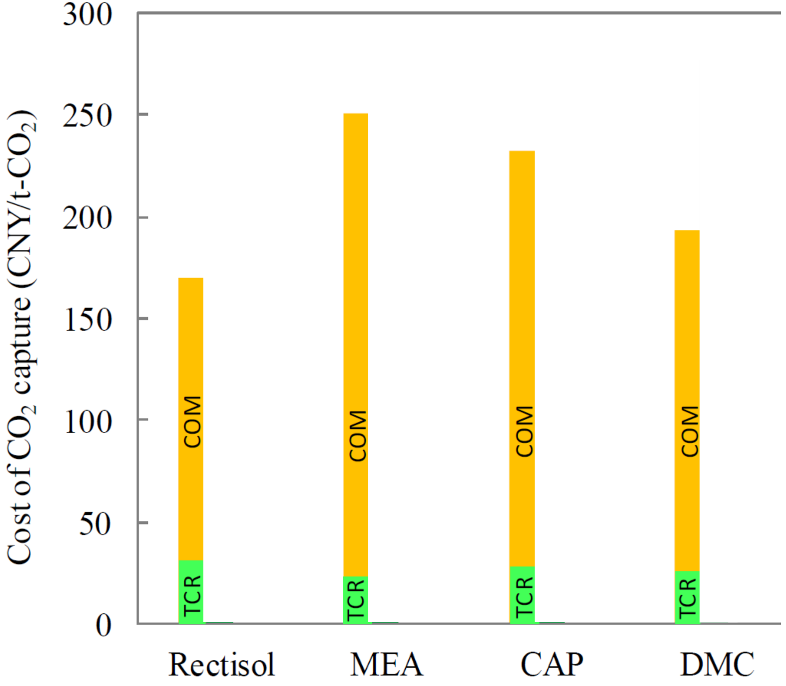

TCR: Total Capital Requirement. COM: Cost of Operation and Maintenance.

Review, modeling, Heat Integration, and improved schemes of Rectisol-based processes for CO2 capture Manuele Gatti et al, 2014

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3.2 Physisorption in solid adsorbent CO_2 capture systems

Physisorption works well with high partial pressure of CO_2 and has a lower regeneration energy since CO_2 is loosely bound to the adsorbent

Potential Locations for CO_2 Capture from Steam Methane Reforming

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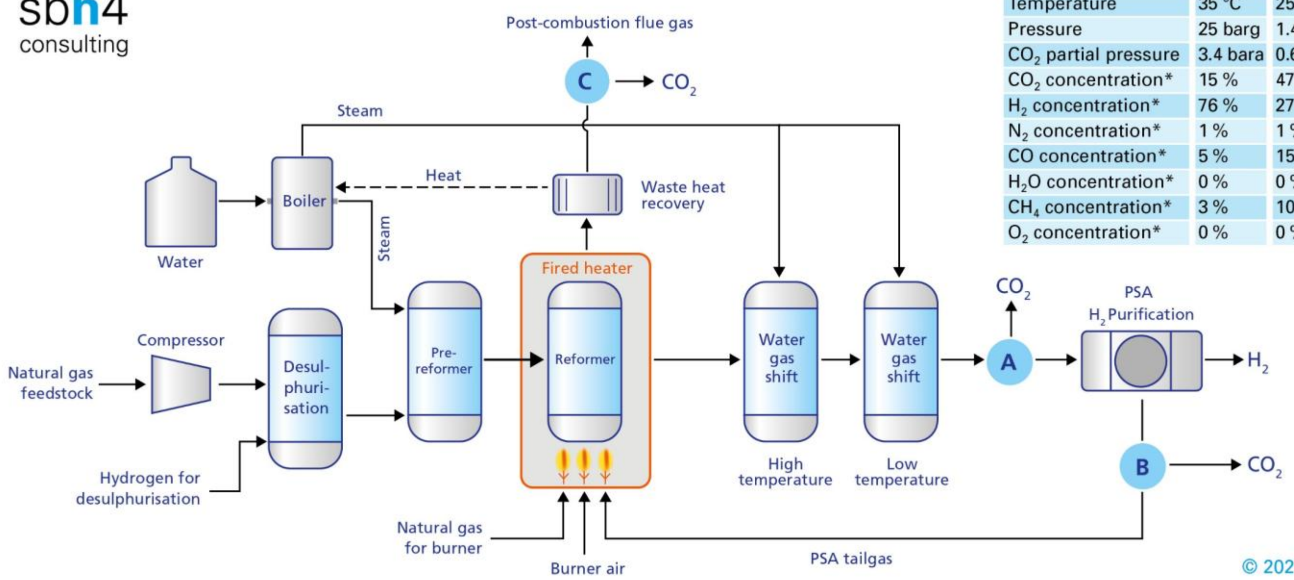

Location	A	B	C
Temperature	35 °C	25 °C	150 °C
Pressure	25 barg	1.4 barg	0.2 barg
CO_2 partial pressure	3.4 bara	0.6 bara	0.2 bara
CO_2 concentration*	15 %	47 %	20 %
H_2 concentration*	76 %	27 %	0 %
N_2 concentration*	1 %	1 %	62 %
CO concentration*	5 %	15 %	0 %
H_2O concentration*	0 %	0 %	17 %
CH_4 concentration*	3 %	10 %	0 %
O_2 concentration*	0 %	0 %	1 %

*Molar

	Location A	Location B	Location C
Process stage	Pre-PSA	Post-PSA	Post-combustion
Advantages	High pressure, high CO_2 concentration, highest CO_2 partial pressure, lowest unit cost of CO_2 capture from Amine Solvent or VSA processes	Low flowrate (H_2 removed), highest CO_2 concentration	More than 90 % capture rate possible (captures process CO_2 and burner CO_2 emissions), low pressure location can be suitable for emerging CO_2 capture techno-logies such as TSA and mineralisation
Disadvantages	Max 70 % CO_2 capture rate possible (burner CO_2 emissions not captured), high flowrate (H_2 included)	Max 70 % CO_2 capture rate possible (burner CO_2 emissions not captured), low pressure	Low pressure, lowest CO_2 concentration, high flowrate due to combustion air, highest unit cost of CO_2 capture from Amine Solvent or VSA processes

Retrofit existing SMRs

- Circa 2,000 SMRs operate worldwide from 10 to 500 TPD H2
- Existing SMRs can be decarbonised with CO2 capture retrofits.
- Location of CO2 capture influences unit cost and efficiency of CO2 capture
  - Stream pressure changes
  - Stream CO2 composition changes
  - Maximum potential CO2 capture rate changes

VSA (Vacuum swing adsorption) with molecular sieve CO_2 adsorbents - proven for carbon capture at two Air Products SMRs feeding the Valero refinery in Port Arthur, USA.

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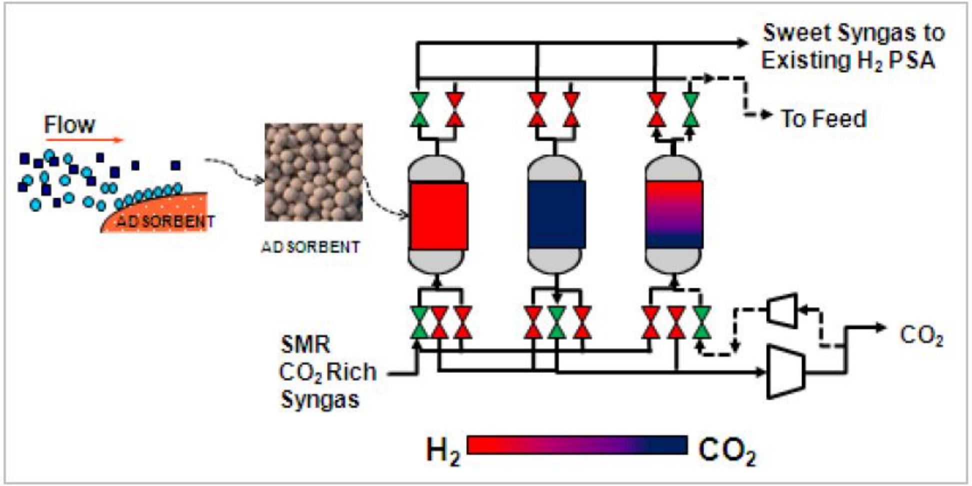
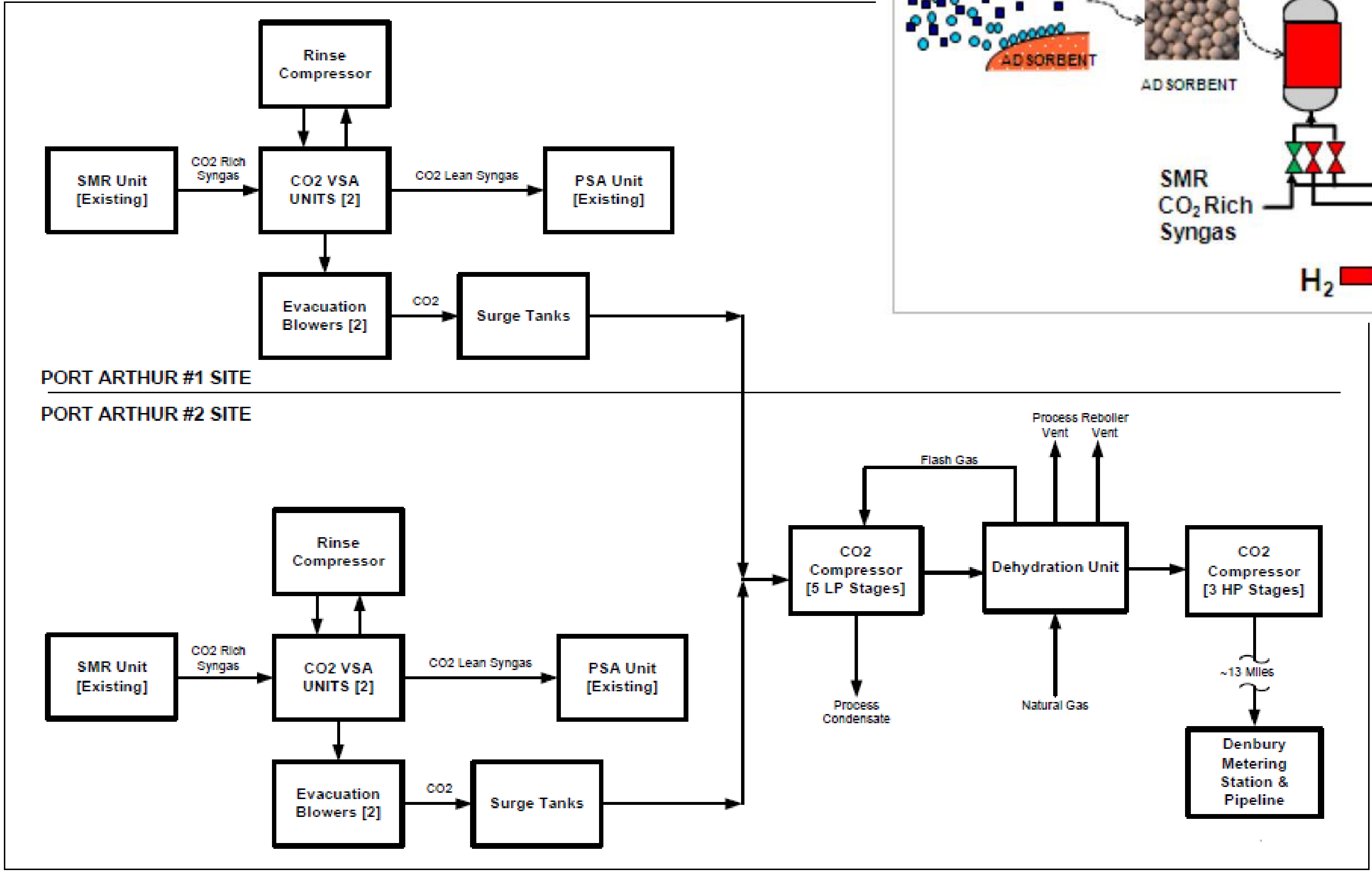
Image courtesy of APCI Inc

Air Products VSA and CO2 compression process layout





Demonstration of Carbon Capture and Sequestration of Steam Methane Reforming Process Gas Used for Large-Scale Hydrogen Production

FINAL REPORT

Reporting Period:
September 2009 – September 2017

Principal Author(s):
Amy Busse
Gloria Power
Joel MacMurray

Date Report Issued:
March 2018

DE-FE0002381

Air Products and Chemicals, Inc.
7201 Hamilton Blvd.
Allentown, PA 18195

MOFs can operate in a similar process to VSA with molecular sieves. They have the advantage of using physisorption of CO2 which reduces the regeneration energy requirement.

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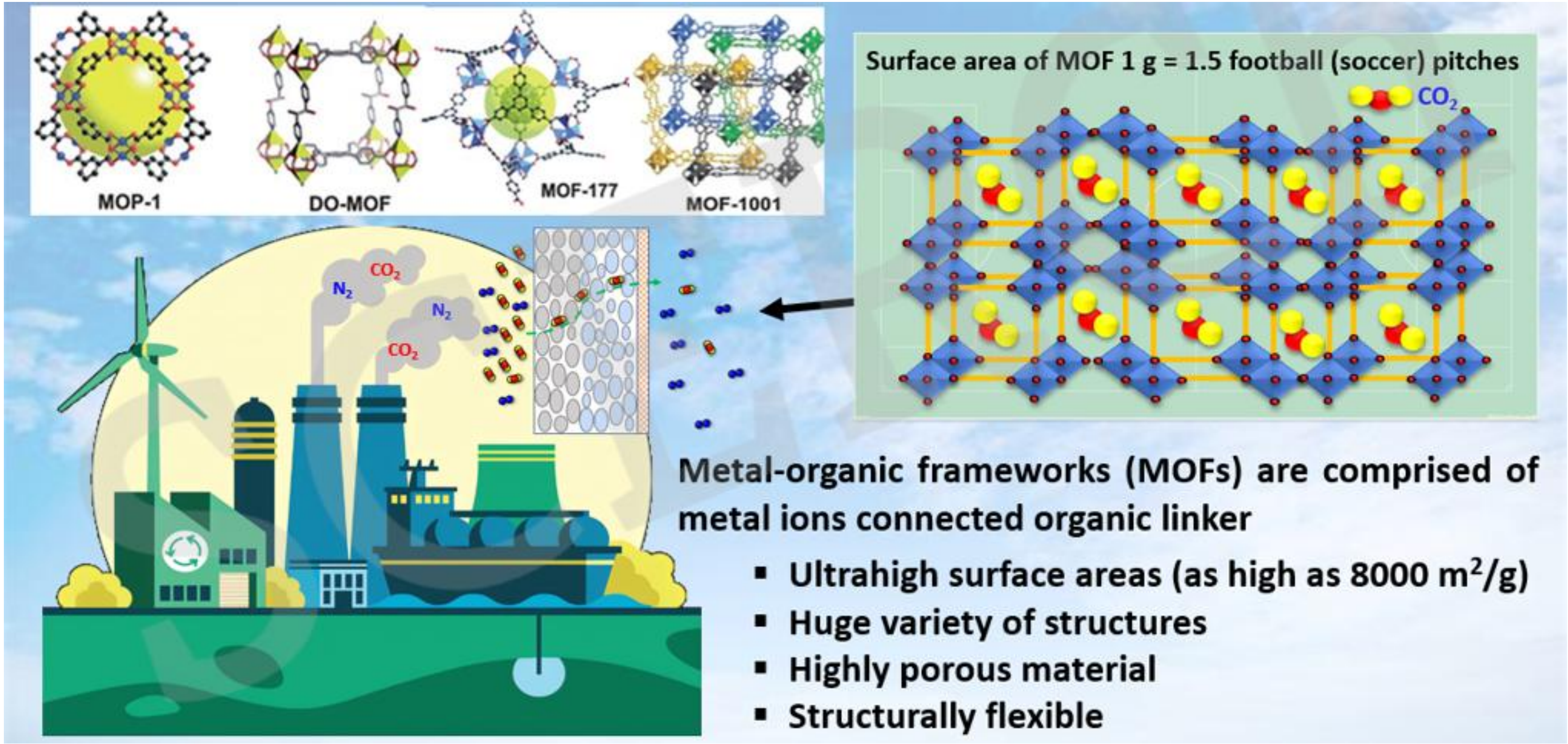

https://www.cetri.ca/metal-organic-frameworks-for-co2-capture

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3.3 Solvent regeneration energy from steam (dewpoint swing), heat (temperature swing) or electrical power (pressure swing)?

Which energy source is most freely available at the site?

Which can be more easily decarbonised in the future?

Partial electrification to use MVR (mechanical vapour recompression: a type of heat pump). The energy input to the HPC process can be reduced to less than 1.5 GJ energy per 1,000 tonnes of CO2 captured.

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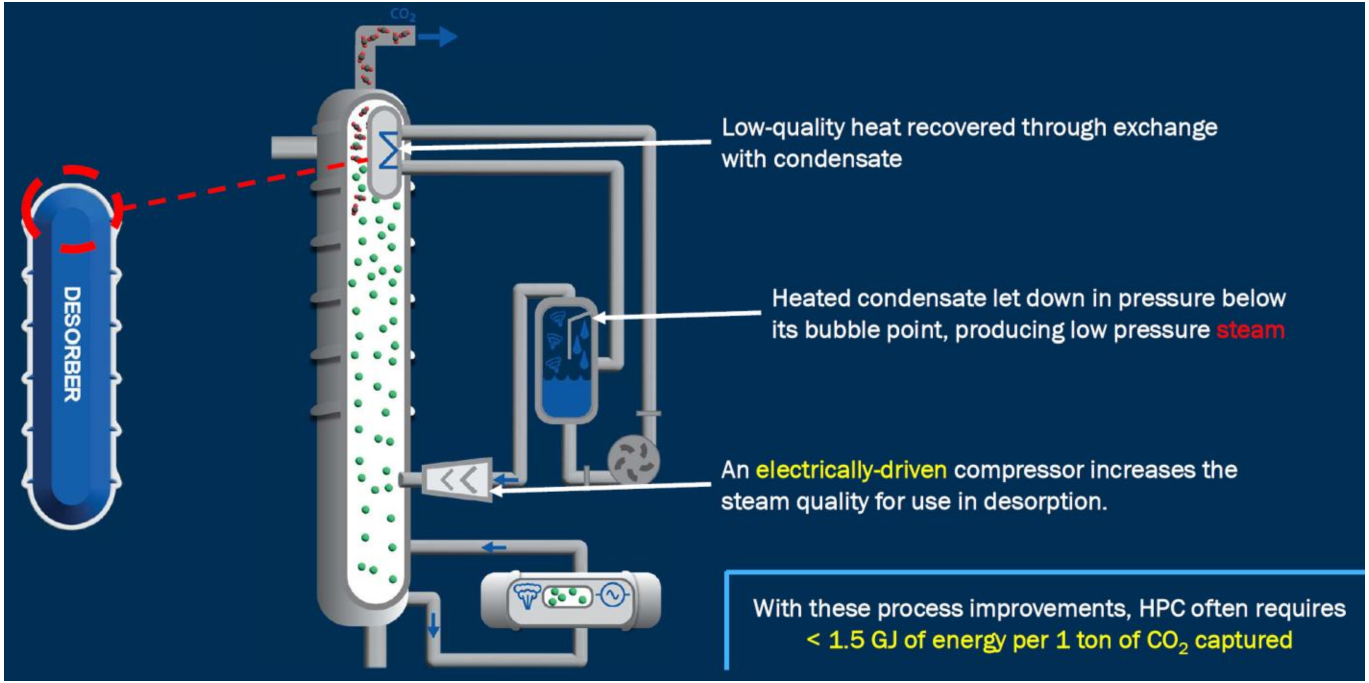

https://content-cdn.sessionboard.com/content/Zeebs6yjQSaqee7OTfyA_POWERGEN%20-%20CATACARB.pdf

Full electrification: CapsolEoP™ claims 0.7 to 1.5 GJ Electrical power required per 1,000 tonnes of CO2 captured. The compressor / expander (compander) is key to operating the high pressure HPC process with a flash and recovering pressure energy from the flue gas.

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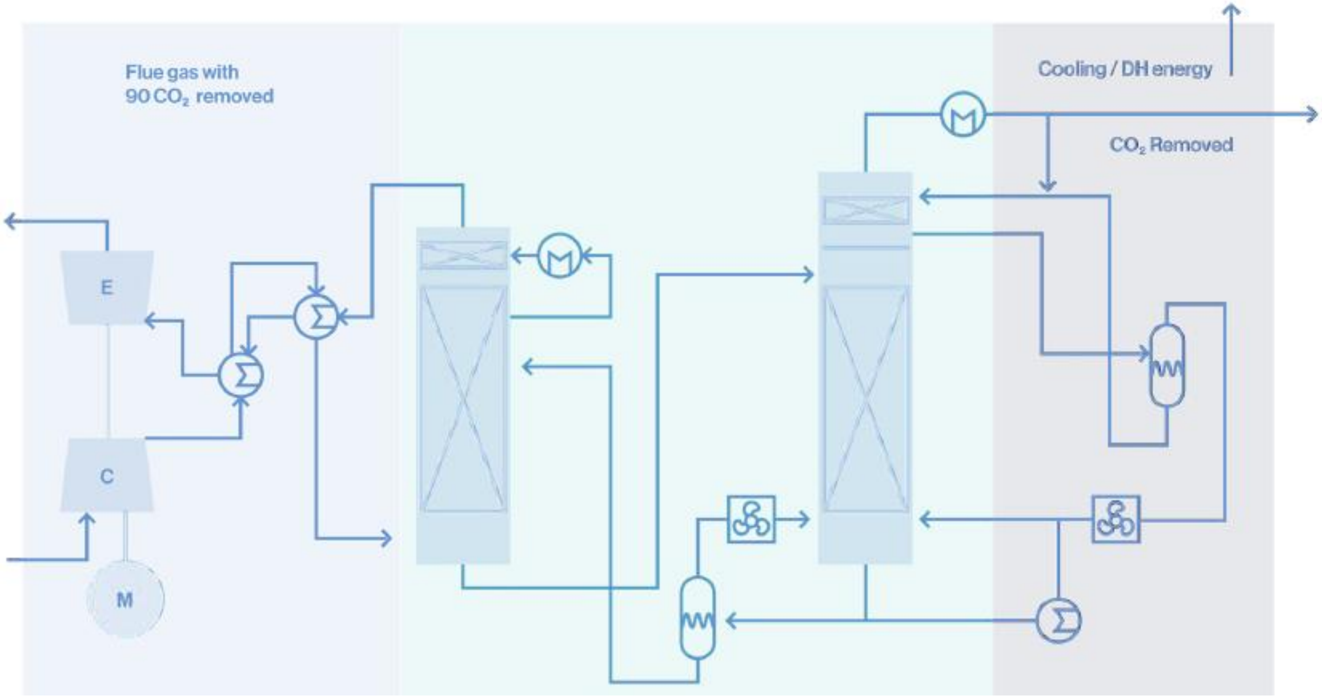

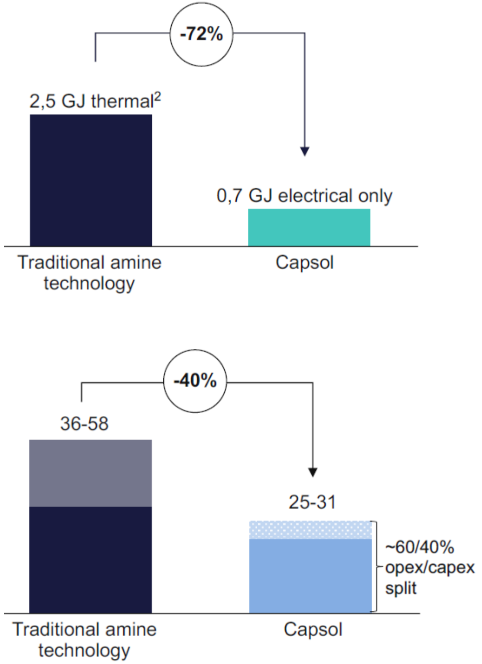

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Introduction to Stephen B. Harrison and sbh4 consulting

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Stephen B. Harrison is the founder and managing director at sbh4 GmbH in Germany. His work focuses on decarbonisation and GHG emissions reduction. E-fuels, hydrogen, ammonia and CCTUS are fundamental pillars of his consulting practice.

Stephen has extensive M&A and investment due diligence advisory experience in the energy and clean-tech sectors. Private Equity firms, investment fund managers and green-tech start-ups are regular clients. He also supports operating companies in their mission to decarbonise their scope 1, 2 and 3 GHG emissions.

In 2023, Stephen evaluated seven CCTUS, hydrogen and e-fuels submissions to the European Commission's Third Innovation Fund. The fund allocated €2 billion to large-scale decarbonisation projects in Europe. In 2024 he supported the European Commission with venture capital investment due diligence and assessed eight Horizon grant applications. Again in 2025, Stephen is assessing seven Innovation Fund applications related to e- and bio-methanol production.

Stephen has served as the international expert and team leader for three ADB projects related to CCTUS and renewable hydrogen deployment in Pakistan, Palau and Viet Nam. He has also supported the IFC and world bank on e-fuels and green hydrogen strategy development projects in Namibia and Pakistan.

With a background in industrial and specialty gases, including 27 years at BOC Gases, The BOC Group and Linde Gas, Stephen has intimate knowledge of e-fuels, hydrogen, ammonia and carbon dioxide from commercial, technical and operational perspectives. For 14 years, he was a global business leader in these FTSE100 and DAX30 companies.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for the leading hydrogen-focused international publications. Through H2 VIEW, World Hydrogen Leaders and Sustainable Aviation Futures, he has led Masterclasses covering many hydrogen, SAF and hydrogen derivatives themes in virtual and live sessions.

Stephen was session chair for the e-fuels and hydrogen propulsion track at the Bremen Hydrogen Technology Exhibition in September 2023 and chaired the same stream at that conference in Hamburg in 2024. He was also conference chair for the CO2 utilisation Summit in Hamburg in 2023 and the same event in Berlin in 2024.