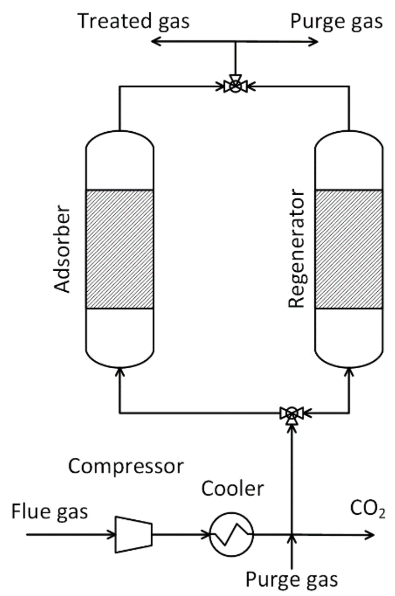
PRESSURE SWING ADSORPTION

Pressure swing adsorption (PSA) is a cyclic adsorption and desorption process allowing continuous separation of gas streams. It is the most used technology based on adsorption at an industrial scale for CO_2 capture.[1] A PSA process may consist of several columns, steps, and different cycle times to achieve a certain performance. A basic PSA configuration has two beds and comprises four steps, namely **pressurization** using a compressor, CO_2 **adsorption** at high pressure, **blowdown** countercurrently by depressurization to atmospheric pressure, and **purge** using a portion of purified gas. Each PSA system uses specialised adsorbent materials such as zeolites, molecular sieves, activated carbon, etc. For a post-combustion process, zeolites are considered the natural candidates for a PSA process.[2] In the MAP-IT CCU project, pressure swing adsorption (PSA) is distinguished from other adsorption technologies by the assumption that the PSA feed operates at high pressure, while the PSA product stream is delivered at atmospheric pressure. In contrast, the vacuum swing adsorption (VSA) feed operates at atmospheric pressure , while the VSA product stream is delivered at vacuum pressures. *More details on VSA are given in alternate processes section.*



Pressure Swing Adsorption

TECHNICAL ASPECTS (all % are volume-based)

Point sources: Iron and steel industry (blast furnace off-gases)[3], steam-methane reforming[3], cement and lime[4], natural gas sweetening.[5]
CO_2 concentration range: min. 10%[3]
CO_2 capture efficiency: > 90%[6], max. 99%[4]
CO_2 purity: 95%[3]
Min. feed gas pressure: 8[3] bar
Max. feed gas temperature: 40 °C[7]
Typical scale: Small to Large (3,650 – 1,825,000 tCO_2/yr)[4]
Primary energy source: Electricity
Impurity tolerance: SOx = 10 ppm[7]

FUNCTION IN CCU VALUE CHAIN

- Capture CO_2 from higher concentration flue gases.
- Adsorbents such as zeolites are highly affected by the presence of water in feed gas, requiring an upstream dehydration step.[8]
- Highly affected by flue gas impurities such as SOx and NOx, requiring appropriate pre-treatment steps.[8]

LIMITATIONS

- High energy requirement due to feed gas compression, especially at lower CO_2 concentrations.
- CO_2 purity is lower than the chemical absorption systems, likely requiring post-capture purification steps to achieve the high purities required in certain applications.
- The physical size of PSA units can be quite large compared to the amine-based CO_2 scrubbers, which may not be feasible for all industrial applications.[6]
- Adsorbent material may degrade over time, reducing overall capture efficiency.
- Higher capital cost due to larger beds and longer cycle times.

ENERGY

- Electricity is used by the compressor to pressurize the feed gas.

CONSUMABLES

- Cooling water may be required to cool the feed gas after compression.
- Adsorbents, in particular non-zeolite or carbon materials, have lifetimes of about 5 years and are replaced.
- No chemicals are used.

Energy and Consumables

Parameter	Value
Electricity (kWh/tCO_2) *	210[a] – 321[b 9]
Cooling water (ton/tCO_2)	-NA-
Adsorbent (kg/tCO_2)	-NA-

**Depends on feed pressure and CO_2 concentration, zero electricity if feed gas is already pressurized to the desired pressure.*
[a & b] 10 bar feed pressure with 20% CO_2. More information is given below in the COSTS section.

COSTS

CAPEX: 3[a] – 4[b] €/tCO_2 [9]
Main CAPEX: adsorption column and compressor
OPEX: 23[a] – 35[b] €/tCO_2 [9]
Main OPEX: electricity and adsorbent
CO_2 capture cost: 26[a] – 39[b] €/tCO_2 [9]
Depends on scale, CO_2 concentration, and purity requirements.
[9] *Cement plant; PSA two column configuration; CO_2 concentration – 20%; 8000 hr/yr; adsorption column lifetime – 10 yrs; adsorbent life – 5 yrs; interest rate – 5%; 2020 euros; electricity price – 110 €/MWh.*
[a] *CO_2 capture capacity – 0.6 MtCO_2/yr; adsorbent – pillared clay; adsorbent price – 500 €/t; CO_2 purity – 76.6%; recovery – 72.1%.*
[b] *CO_2 capture capacity – 0.42 MtCO_2/yr; adsorbent – zeolite 13X; adsorbent price – 1650 €/; CO_2 purity – 50%; recovery – 36.6%.*
***Note**: Cost data on commercial adsorbents such as zeolite is not publicly available. The costs shown above are for the low-purity and low-recovery case. Higher purity and recovery are achievable by commercial PSA systems and thus will have higher CO_2 capture costs.*
CO_2 avoidance cost: ±28 €/tCO_2 avoided [9] **
***same conditions as above but now with 6-column configuration; CO_2 purity – 78 %; recovery – 71.3 %.*

ENVIRONMENTAL

CO_2 footprint: 128[10] – 181[11] kgCO_2eq/tCO_2 captured (estimated for zeolites, 11-14% CO_2)
Spatial footprint: 13,320 m^2 for 4.6 MtCO_2/yr[6]
Two-stage PSA process (first stage: 1 bar → 0.1 bar, second stage: 2 bar →1 bar); includes only spatial footprint of columns, assuming maximum column diameter of 8m;[6] depends on feed pressure and adsorbent capture capacity.
(MEA amine scrubber columns footprint = 674 m^2) [6]
Environmental issues: Disposal or recycling of spent adsorbents[12] (less issue than the solvents since zeolites have a lower environmental impact).

ENGINEERING

Maturity: Commercial (TRL 9)[4]
Proven technology.
Retrofittability: Feasible
Compatible with wide CO_2 concentration range; electricity is the only energy source; phased implementation due to modular nature; can be hybridized with other capture systems.[3,13]
Challenges due to large spatial footprint requirements and effective pre-treatment steps are essential to handle impurities.
Scalability: High[4]
Well suited for capturing CO_2 at a wide capture rate range due to its modular nature.
Process type: Solid stationary adsorbent-based without chemical reactions.
Deployment model: Centralized only.
Each column with adsorbent undergoes cyclical CO_2 adsorption and desorption.
Technology flexibility: Hybridization with other capture technologies is feasible. It can be used to increase CO_2 concentration.

MAIN TECHNOLOGY PROVIDERS

- HIPURE® CC by **LINDE**, Ireland
  (PSA; 95% purity)
- PolyCapture by **PolyCapture**, United Kingdom
  (PSA; polymer adsorbent; >95% purity)
- CARBOGEN by **ALLISON**, United Kingdom
  (VPSA; 99.9% purity; OPEX <150 kWh/tCO_2)
- POLYBED™ PSA by **HONEYWELL UOP**, United States
  (Adsorbent)
- CO2SORB by **CO2CRC**, Australia
  (Adsorbent)
- MUF-16 by **CAPTIVATE TECHNOLOGY**, New Zealand
  (Adsorbent)
- MOF-based VPSA by **NUADA**, Northern Ireland

ALTERNATE PROCESSES

Vacuum swing adsorption (VSA)[14]
VSA segregates CO_2 from flue gas at near ambient pressure; the process then swings to a vacuum to regenerate the adsorbent material. This configuration avoids the expensive and energy-intensive feed gas compression. However, a vacuum pump is required to maintain the required vacuum pressures during desorption.
Process: 6-step[14] [4-step][15] VSA cycle with UTSA-16 MOF adsorbent.
Evacuation pressure: 0.2 bar[14] [0.1 bar][15]
Point sources: Iron and steel industry (blast furnace off-gases), steam-methane reforming[15], coal-based power plant, integrated gasification combined cycle,

cement and lime, (petro)chemical, oil and gas, natural gas sweetening.

CO_2 concentration: 15 mol.% (7.5%)[14] [20%][15]

CO_2 purity: 94.5% (93.9%)[14] [95%][15]

CO_2 capture efficiency: 91% (89%)[14] [90%][15]

Power: 174 (339)[14] [300][15] kWh/tCO_2 captured.

CAPEX: 22 (47)[14] [27][15] €/tCO_2

OPEX: 38 (73)[14] [38][15] €/tCO_2

[14]Electricity is ~34% of OPEX with price – 68 €/MWh, economic lifetime – 15 years, discount rate – 9%.

[15]Electricity is ~34% of OPEX with price – 58 €/MWh, economic lifetime – 25 years, discount rate – 8%.

Technology providers: CarboPac-C by **Bright**, The Netherlands; VSA using MOFs by **Nuada CO_2**, UK.

Apart from alternate regeneration processes, new adsorbent materials and structures are currently being developed for pressure-based adsorption processes to achieve high CO_2 recovery and purity.

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