

VPSA for Industrial CO₂ Capture: Process Basis, Limiting Factors and How to Evaluate a Project

Technical report for carbon capture engineering service

Scope	Vacuum and vacuum–pressure swing adsorption (VSA/VP SA) for CO ₂ capture from industrial flue gases and process off-gases
Prepared	October 2026
Basis	Published research, technical literature and engineering synthesis

Central finding

VP SA is a strong candidate where the gas is CO₂-rich or pressurised, can be dried and cleaned economically, and electricity is cheaper or lower-carbon than steam. For dilute, wet or contaminated flue gas, feed CO₂ partial pressure and the vacuum achievable at scale dominate, and a two-stage design or a solvent may be more economic. Decide on cost of CO₂ avoided at a defined energy boundary, using tests on the real gas.

Engineering note

This is a mechanism-based report, not a substitute for the VP SA vendor's process design and performance guarantees, site-specific gas testing or the site's process-safety and management-of-change review.

Executive summary

Vacuum pressure swing adsorption (VP SA) holds CO₂ on a solid adsorbent as gas flows through a bed, then releases it as a CO₂-rich product under vacuum. Regeneration is by pressure, not heat, so no solvent or regeneration steam is needed and the energy is mainly electrical. Performance is governed by feed CO₂ partial pressure, the vacuum practical at scale, water and acid gases, and the adsorbent and cycle chosen to balance purity, recovery, productivity and energy [1–5].

Feed concentration is the first screening variable. For feeds of 15% CO₂ or less, one study on zeolite 13X concluded that exceeding both 90% purity and 90% recovery was not possible without vacuum of about 1 kPa, whereas its authors regard vacuum below about 5 kPa as impractical at large scale [1]. Across capture technologies, the IEA's 2021 indicative costs ranged from USD 15–25/t CO₂ for highly concentrated streams to USD 40–120/t CO₂ for dilute streams such as cement and power [6].

Energy figures need care: a pilot on dry 15% CO₂ feed measured 339–583 kWh per tonne of CO₂ captured, significantly different from isentropic estimates [5], while an optimised model of the same feed predicted 154–186 kWh/t for 95–97% purity at 90% recovery [4]. VSA has operated at commercial scale on reformer syngas [7]; the flue-gas evidence reviewed here is pilot-scale [5,8], and cost studies point both ways [9,10].

Table 1. Key factors and their impact on VP SA performance

Factor	Direct mechanism	Expected impact	Overall judgement
Feed CO ₂ concentration	Sets CO ₂ partial pressure and per-stage enrichment	Dilute feeds need deeper vacuum or a second stage	High: first screening variable
Water vapour	Adsorbs strongly on zeolites and displaces CO ₂	Capacity loss; advancing water front	High for zeolites; controllable by drying
SOx, NOx, O ₂ and particulates	Acid gases alter adsorption; O ₂ partly reports to product; dust fouls	Performance drift; off-specification product; valve wear	Medium-high, site-specific
Adsorbent choice	Isotherm shape, CO ₂ /N ₂ selectivity, kinetics, water tolerance, cost	Fixes vacuum level, energy and bed size	High
Cycle design and stages	Step sequence, bed count and stage count	Sets the purity–recovery–energy balance	High
Vacuum level	Lower evacuation pressure desorbs more CO ₂	Better purity and recovery; larger vacuum machines	High: main energy driver
Temperature and heat of adsorption	Bed heats during adsorption and cools during desorption	Narrower working capacity	Medium
Pressure drop and hydraulics	Particle size and gas velocity set pressure drop	Higher machine power; attrition dust	Medium
Valve and cycle reliability	Many fast-cycling valves under sequence control	Leakage cuts purity; trips can upset the host process	Medium-high for availability

Source: engineering synthesis from [1–5,7–10]. Judgements describe mechanism potential, not universal thresholds.

Priority actions

1. Characterise the feed over its full operating range, including water, SOx, NOx, O₂, particulates and trace species. (2) Fix the CO₂ product specification and the energy boundary. (3) Screen single- and two-stage VPSA against a solvent baseline on cost of CO₂ avoided. (4) Test the adsorbent on representative wet, contaminated gas over extended cycling. (5) Design integration and trips so that a VPSA upset cannot disturb the host process.

Conclusions at a glance

- **Feed and vacuum:** CO₂ partial pressure and practical vacuum are the first limits; dilute flue gas pushes designs towards two stages.
- **Contaminants:** water matters most for zeolites; test SO₂ and NO effects on representative gas.
- **Energy:** mainly electrical, in the vacuum machines; quote every figure with its boundary.
- **Versus solvents:** VPSA avoids regeneration steam and amine emissions; amines have the longer record. Cost ranking depends on CO₂ concentration and adsorbent.

1. Process basis and performance criteria

1.1 How the cycle works

Several beds operate out of phase, each repeating three steps. During **adsorption**, gas flows through the bed at or slightly above atmospheric pressure; CO₂ is retained and the CO₂-lean gas (mainly N₂, or H₂-rich gas from syngas) leaves as the light product. During **evacuation**, a vacuum machine lowers the bed pressure and desorbed CO₂ is withdrawn as the heavy product; a CO₂ rinse or a blowdown can raise purity. During **repressurisation**, purge, pressure equalisation or light-product pressurisation (LPP) restores the bed. VSA usually denotes near-atmospheric feed; VPSA (or PVSA) adds feed compression.

The driving force is CO₂ partial pressure. A 15% CO₂ feed at about 1 bar has a CO₂ partial pressure of about 15 kPa, so a near-pure product can only be drawn below that pressure, and in practice well below it. This is why feed concentration and vacuum level dominate design.

1.2 What “performance” means

KPI	Definition	Primary indicators	Failure signature
Purity	CO ₂ fraction in product (dry), with named impurity limits	Product analyser; N ₂ , O ₂ , H ₂ O	Falls at steady recovery: vacuum short of setpoint, air in-leakage, passing valves
Recovery	CO ₂ in product divided by CO ₂ in feed	CO ₂ in vent; mass balance	Rising CO ₂ slip: capacity lost to water or contaminants
Productivity	CO ₂ product per unit adsorbent per unit time, e.g. t/m ³ /day [5]	Product rate at target purity	Throughput cut to hold purity
Specific energy	Electrical energy per tonne of CO ₂ at a stated boundary	Power by machine	Rises at constant duty: wear, leaks, higher pressure drop
Bed size factor	Adsorbent inventory per unit product rate	Adsorbent mass per t/d of CO ₂	Capacity decline; more adsorbent needed for the same duty

Source: definitions are conventional; indicators and signatures are engineering synthesis.

2. Feed gas and pre-treatment

2.1 CO₂ concentration and pressure

Experiments on zeolite 13X at 15%, 30% and 50% CO₂ and 20–120 °C found purity and recovery significantly affected by vacuum pressure, operating temperature and inlet concentration; the authors concluded that, for feeds of 15% CO₂ or less, more than 90% purity at more than 90% recovery was not possible without vacuum of about 1 kPa [1]. Pressurising a dilute feed raises its CO₂ partial pressure but compresses mostly N₂, so feed pressure and vacuum level should be optimised together.

2.2 Water vapour

Water matters most for zeolite-based VPSA: on type X zeolites the CO₂ Henry constant declines exponentially with water loading [2]. If the pressure swing does not remove strongly held water every cycle, a water-loaded zone can grow from the feed end, so its stability is a key test item. A pilot at a coal-fired power station removed water from desulphurised flue gas by alumina adsorption ahead of two VPSA stages [8]. Cooling with condensate removal, then a desiccant dryer or protective pre-layer, is the usual response.

2.3 Acid gases, oxygen and particulates

Tests on 13X monoliths found that SO₂ and NO, especially SO₂, caused dramatic changes in adsorption performance, underlining the need to evaluate adsorbents under realistic conditions [3]. Whether such effects reverse over long-term cycling must be measured, not assumed. O₂ is weakly adsorbed, but part reports to the product and must be checked against the CO₂ specification. Particulates and acid aerosols foul beds, raise pressure drop and wear valve seats, so filtration and, where needed, desulphurisation precede the unit; trace species such as H₂S, NH₃, HCl or siloxanes need guard beds or upstream removal.

3. Adsorbents and cycle design

3.1 Adsorbent selection

Working capacity between feed and evacuation conditions matters more than capacity at feed conditions. A steep CO₂ isotherm captures CO₂ at low partial pressure but releases it only under deep vacuum; a shallow one desorbs easily but holds less. A cost-limit study found ideal adsorbents spanning a range of CO₂ affinities with close to zero N₂ adsorption, and stressed optimising particle morphology together with process conditions [9].

Zeolite 13X features in several studies cited here [1,5,8,10]; it is selective but water-sensitive. Kinetic adsorbents behave differently: in a biogas VPSA study, a carbon molecular sieve gave methane recovery close to 80%, against close to 60% for 13X, with methane purity above 98% for both [11].

3.2 Cycle configuration

For dry 15% CO₂ feed, a simulation-based optimisation found that a four-step cycle with LPP gave the lowest energy, the minimum rising from 154 to 186 kWh per tonne of CO₂ captured as the purity target rose from 95% to 97% at 90% recovery [4]. A two-column pilot using that cycle achieved 94.8% purity at 89.7% recovery [5].

3.3 Two-stage arrangements for dilute flue gas

Where one stage would need impractically deep vacuum, a first stage can enrich the gas at high recovery and a second can purify it. A pilot at a coal-fired power station used alumina dehumidification, then a three-bed, eight-step VPSA packed with zeolite 13X, followed by a two-bed, six-step VPSA with activated carbon beads [8]. The second stage sees a CO₂-rich feed, so its adsorbent can be chosen for easy desorption. Two stages add vessels, machines and controls, so choose between one and two stages on cost of CO₂ avoided.

4. Energy and equipment

4.1 Where the energy goes

Energy is mostly electrical work in the feed machine, vacuum machines, product compression and drying, and auxiliaries such as chillers. A specific-energy figure means little without its boundary, purity, recovery and delivery pressure.

4.2 Vacuum machines

At low suction pressure CO₂ occupies a large actual volume: halving the suction pressure doubles the volumetric flow. Deep vacuum therefore means large or multiple machines and more risk of air in-leakage. Measured pilot energy differed significantly from isentropic calculations [5], a reformer flue-gas study stressed accounting for vacuum-pump efficiency [10], and the Port Arthur report highlights the large size of the evacuation blowers [7]. Use vendor efficiency curves across the suction range.

4.3 Product compression and conditioning

CO₂ leaves the vacuum train near atmospheric pressure and must be compressed, dried and, if the specification requires, purified. The minimum work to separate CO₂ from coal-fired flue gas and compress it to 150 bar has been estimated at 0.11 MWh per tonne [12]; VPSA figures often exclude compression, so check boundaries.

4.4 Valves, vessels and controls

Vessels and valves need cyclic-service design, and valve leakage directly erodes purity and recovery. At Port Arthur, evacuation valves isolate adsorbers that can exceed the blowers’ design pressure; relief valves were impractical in the numbers needed, so rupture disks with additional protective systems were adopted [7]. Control logic and a full-flow bypass kept the reformer and hydrogen PSA running through VSA trips [7].

5. Comparison with solvent-based capture

Amine scrubbing, used to separate CO₂ from natural gas and hydrogen since 1930 [12], is the usual benchmark; Environment Agency guidance covers amine-based capture in England [13]. Neither route is better in general.

Table 2. VPSA and amine-based solvent capture compared

Criterion	VPSA	Amine-based solvent	Engineering implication
Regeneration energy form	Mainly electrical; no regeneration steam, though dryers may need heat	Mainly heat, plus power; guidance expects both to be supplied from the main plant [13]	VPSA suits sites short of low-cost heat
Degradation and emissions	No solvent or amine emissions; adsorbent ageing, dust and replacement	Thermal and oxidative degradation; nitrosamines and nitramines to monitor; water and acid washes [13]	VPSA avoids amine-specific controls
Footprint	Many vessels, valves and vacuum trains; excessively large footprint reported for post-combustion PSA [14]	Columns, heat exchange, solvent storage	Compare layouts at equal capacity
Turndown and start-up	No solvent to heat; limited by machine turndown and cycle re-tuning	Thermal inertia; capture during start-up and shutdown expected as BAT [13]	Test dynamics; agree expectations early
Maturity at scale	Operated commercially on reformer syngas [7]; flue-gas evidence reviewed here pilot-scale [5,8]	Long record in gas treating [12]	Lower technology risk for solvents on flue gas
Sensitivity to impurities	Strongly affected by water [2]; SO ₂ and NO alter performance [3]	SO _x forms heat-stable salts; NO _x to be minimised; SO ₃ droplets and fine particulates excluded [13]	Both need pre-treatment

Unreferenced entries are engineering synthesis.

The cost evidence is mixed. With an idealised zero-cost adsorbent, excluding conditioning, transport and storage, PVSA CO₂-avoided costs fell from €87.1/t to €10.4/t as feed CO₂ rose from 3.5 to 30 mol%, against €76.8–54.8/t for MEA using heat from a natural gas plant [9]. With real adsorbents on dried reformer flue gas of 20 mol% CO₂, VSA cost more per tonne avoided than the MEA baseline [10]. Adsorbent properties, vacuum-pump efficiency and energy prices can therefore reverse the ranking.

6. Applications and fit

Fit depends on the stream more than the sector.

Table 3. Where VPSA can fit

Application	Relevant gas features	Where VPSA can fit	Deciding questions
Reformer syngas	Pressurised, CO ₂ -rich, low in O ₂ and SO _x ; H ₂ -rich light product	Before hydrogen purification; a commercial-scale example is documented [7]	PSA tail gas, burners and NO _x ; trips
Reformer and heater flue gas	Near-atmospheric, wet, O ₂ -bearing; one study used 20 mol% CO ₂ dry [10]	Where steam is scarce; costlier than MEA in that study [10]	Drying, NO _x and SO _x , staging
Biogas upgrading	CO ₂ -rich; methane is the product; may contain H ₂ S and siloxanes	VPSA studied for fuel-grade methane [11]; CO ₂ off-gas a potential source	Methane slip, CO ₂ purity, scale
Cement and lime	Fuel and calcination CO ₂ with dust, SO _x , NO _x , O ₂ and water; IEA groups cement with dilute streams [6]	With thorough pre-treatment, probably in two stages	Dust, SO ₂ , plot space, power versus heat
Refinery streams	Hydrogen-plant syngas; dilute FCC and fired-heater flue gases	Hydrogen units usually screened first; flue gases as post-combustion duty	Stream-by-stream screening

Source: as cited, plus engineering synthesis. Fit describes potential, not demonstrated outcomes.

Illustrative example (independent project). Air Products retrofitted VSA units to two steam methane reformers at the Valero Port Arthur refinery in Texas, treating cooled syngas upstream of the hydrogen PSA units; the CO₂ was dried, compressed and piped for enhanced oil recovery. Operation began in December 2012 and reached a cumulative four-million-ton milestone in October 2017 [7]. Removing CO₂ upstream raised the heating value and flame temperature of the PSA purge gas burned in the reformer, prompting new burner tips for metal-dusting risk and an expected two- to three-fold rise in SCR ammonia use [7]. The results are operator-reported and specific to syngas.

7. Project evaluation programme

7.1 Data package

Category	Data required	Decision supported
Feed gas	Flow, pressure, temperature and full composition, with variability	Feasibility, staging, sizing
Contaminants	SO ₂ , SO ₃ , NO _x , H ₂ S, NH ₃ , HCl, particulates and trace species	Pre-treatment, adsorbent risk
Product	Purity, impurity limits, delivery pressure, end use	Cycle, polishing, compression
Capture target	Recovery, annual tonnes, availability, turndown	Trains, sparing, guarantees
Site and utilities	Power price and carbon intensity, steam, cooling, plot space, noise limits	VPSA versus solvent; layout
Integration	Tie-ins, back-pressure limits, return-gas specification, trip philosophy	Host-process impact

7.2 Staged programme

1. **Screening:** balances and cost of CO₂ avoided for single- and two-stage VPSA and a solvent baseline at one boundary, with sensitivities to power price, machine efficiency and adsorbent cost and life.
2. **Laboratory:** CO₂, N₂ and H₂O isotherms; breakthrough tests and extended cycling with humid, contaminated gas.
3. **Pilot or slipstream:** real gas at representative vacuum, recording purity, recovery, productivity and energy by machine to validate the process model.
4. **FEED:** vendor design and guarantees, machine and valve scale-up, integration and process-safety studies, and the cost estimate.

7.3 Acceptance criteria

Stage gate	Evidence required	Acceptance criteria
Screening to laboratory	Balanced flowsheets; cost against a solvent baseline	Competitive within estimate uncertainty; no fatal flaw
Laboratory to pilot	Breakthrough and cycling data on wet, contaminated gas	Stable capacity and selectivity; pre-treatment specification defined
Pilot to FEED	Purity, recovery, productivity and energy at a stated boundary	Targets met reproducibly at practicable vacuum; model validated
FEED to investment	Vendor guarantees; HAZOP and trip studies; cost estimate	Guarantees cover purity, recovery, energy and availability; cost within case

Numerical acceptance values are set per project; none are implied.

8. Trade-offs

Design or control knob	Potential benefit	Principal trade-off
Lower evacuation pressure	Higher purity and recovery	More vacuum power and machines; in-leakage risk
Higher feed pressure	Higher working capacity	Compresses the whole feed, mostly N ₂ in flue gas
Shorter cycle time	Smaller beds	Valve wear; mass-transfer and pressure-drop limits
CO ₂ rinse	Higher purity	Lower net productivity; more vacuum duty
Purge or LPP	Higher recovery	Consumes light product
Pressure equalisation	Saves gas and compression work	More beds, valves and control complexity
Second stage	Purity from dilute feed	More equipment, footprint and controls
Lower feed temperature	Higher adsorption capacity	Harder desorption; chilling duty
Deeper pre-treatment	Protects the adsorbent	Cost and extra pressure drop
Smaller particles	Faster mass transfer	Higher pressure drop; attrition

9. Conclusions

VPSA performance is governed first by the feed: CO₂ partial pressure and the practical vacuum level fix what one stage can achieve, and dilute flue gas may need impractically deep vacuum or a second stage [1,8]. Concentrated, pressurised process gases are the most favourable duties [7].

Water is the most consequential contaminant for zeolites, and acid-gas effects must be tested on representative gas [2,3]. Modelled and measured energy figures differ widely, so each needs its boundary [4,5].

Against solvents, VPSA avoids regeneration steam, solvent degradation and amine emissions, while amine scrubbing offers a longer record and established regulatory expectations [12,13]. VPSA competes best at higher CO₂ concentrations, and adsorbent properties and vacuum-pump efficiency can reverse the ranking [9,10].

Recommended decision rule

Shortlist VPSA when the stream is CO₂-rich or pressurised, can be dried and cleaned economically, meets the product specification at a vacuum level that vendors will guarantee, and electricity is cheaper or lower-carbon than heat. Treat dilute, wet or contaminated flue gas as pilot-dependent, benchmarked against a solvent at the same boundary. Do not select a capture technology on purity and recovery alone.

References

- [1] Ling, J.; Ntiamoah, A.; Xiao, P.; Webley, P. A.; Zhai, Y. "Effects of Feed Gas Concentration, Temperature and Process Parameters on Vacuum Swing Adsorption Performance for CO₂ Capture." *Chemical Engineering Journal* 265 (2015): 47–57. [DOI](#)
- [2] Brandani, F.; Ruthven, D. M. "The Effect of Water on the Adsorption of CO₂ and C₃H₈ on Type X Zeolites." *Industrial & Engineering Chemistry Research* 43 (2004): 8339–8344. [DOI](#)
- [3] Al-Naddaf, Q.; Lawson, S.; Rownaghi, A. A.; Rezaei, F. "Analysis of Dynamic CO₂ Capture over 13X Zeolite Monoliths in the Presence of SO_x, NO_x and Humidity." *AIChE Journal* 66 (2020): e16297. [DOI](#)
- [4] Haghpanah, R.; Nilam, R.; Rajendran, A.; Farooq, S.; Karimi, I. A. "Cycle Synthesis and Optimization of a VSA Process for Postcombustion CO₂ Capture." *AIChE Journal* 59 (2013): 4735–4748. [DOI](#)
- [5] Krishnamurthy, S.; Rao, V. R.; Guntuka, S.; Sharratt, P.; Haghpanah, R.; Rajendran, A.; Amanullah, M.; Karimi, I. A.; Farooq, S. "CO₂ Capture from Dry Flue Gas by Vacuum Swing Adsorption: A Pilot Plant Study." *AIChE Journal* 60 (2014): 1830–1842. [DOI](#)
- [6] Baylin-Stern, A.; Berghout, N. "Is Carbon Capture Too Expensive?" IEA commentary, 17 February 2021; accessed October 2026. [Source link](#)
- [7] Busse, A.; Power, G.; MacMurray, J. (Air Products and Chemicals, Inc.). "Demonstration of Carbon Capture and Sequestration of Steam Methane Reforming Process Gas Used for Large-Scale Hydrogen Production." Final report, US Department of Energy award DE-FE0002381, March 2018. OSTI ID 1437618. [DOI](#)
- [8] Wang, L.; Yang, Y.; Shen, W.; Kong, X.; Li, P.; Yu, J.; Rodrigues, A. E. "CO₂ Capture from Flue Gas in an Existing Coal-Fired Power Plant by Two Successive Pilot-Scale VPSA Units." *Industrial & Engineering Chemistry Research* 52 (2013): 7947–7955. [DOI](#)
- [9] Subraveti, S. G.; Roussanaly, S.; Anantharaman, R.; Riboldi, L.; Rajendran, A. "How Much Can Novel Solid Sorbents Reduce the Cost of Post-Combustion CO₂ Capture? A Techno-Economic Investigation on the Cost Limits of Pressure-Vacuum Swing Adsorption." *Applied Energy* 306 (2022): 117955. [DOI](#)

[10] Subraveti, S. G.; Roussanaly, S.; Anantharaman, R.; Riboldi, L.; Rajendran, A. “Techno-Economic Assessment of Optimised Vacuum Swing Adsorption for Post-Combustion CO₂ Capture from Steam-Methane Reformer Flue Gas.” Separation and Purification Technology 256 (2021): 117832. [DOI](#)

[11] Grande, C. A.; Rodrigues, A. E. “Biogas to Fuel by Vacuum Pressure Swing Adsorption I. Behavior of Equilibrium and Kinetic-Based Adsorbents.” Industrial & Engineering Chemistry Research 46 (2007): 4595–4605. [DOI](#)

[12] Rochelle, G. T. “Amine Scrubbing for CO₂ Capture.” Science 325 (2009): 1652-1654. [DOI](#)

[13] Environment Agency. “Post-combustion Carbon Dioxide Capture: Emerging Techniques.” GOV.UK guidance, first published 2 July 2021, last updated 29 September 2026; accessed October 2026. [Source link](#)

[14] Riboldi, L.; Bolland, O. “Overview on Pressure Swing Adsorption (PSA) as CO₂ Capture Technology: State-of-the-Art, Limits and Potentials.” Energy Procedia 114 (2017): 2390–2400. [DOI](#)

Evidence limitations

- The pilots cited are small and used dry synthetic or pre-treated gas; their energy data are not full-scale benchmarks.
- Techno-economic results depend on adsorbent, machine-efficiency and cost-year assumptions; figures across studies, and the IEA ranges, are not directly comparable.
- The commercial example is operator-reported and concerns syngas, not flue gas.
- The impurity studies are short-term; long-term cyclic effects of SO_x, NO_x and water are less well documented.
- This review found no verified commercial-scale VPSA reference on dilute flue gas or cement kiln gas. That is a limit of the evidence reviewed, not proof that none exists.