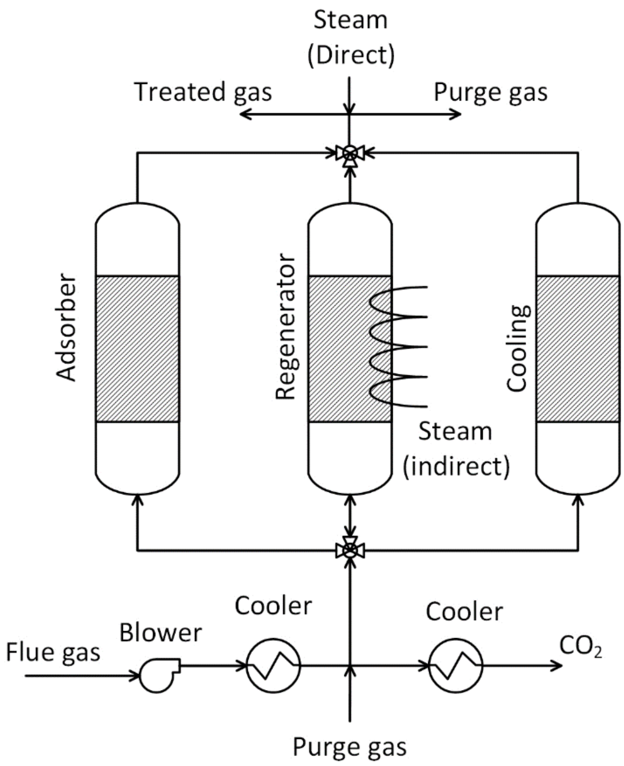
TEMPERATURE SWING ADSORPTION

Temperature swing adsorption (TSA) is a cyclic adsorption and desorption process allowing continuous separation of gas streams. It involves the adsorption of CO_2 gas molecules onto a solid adsorbent material at a lower temperature and then desorbing them by raising the temperature. A TSA process generally consists of three steps, namely **adsorption** at ambient pressure and temperature, **regeneration** countercurrently at a higher temperature, and **purging** (cooling). The regeneration is done by feeding low or medium-pressure steam directly into the adsorbent bed or indirectly by using heat exchanger tubes embedded in the adsorbent bed. The physisorbents, such as zeolites, molecular organic frameworks, activated carbon, etc., are generally used in TSA[1].

The typical TSA process has longer cycle times, making it expensive and unattractive. A rapid cycle TSA (RC-TSA) was invented by Svante called VeloxoTherm™ that uses structured adsorbent based on CALF-20, a metal organic framework (MOFs), and has steam-assisted direct regeneration with fast kinetics (< 1.5 mins cycle time)[2]. The technical, energy, and cost data for this technology are provided in this infosheet as it is complete and publicly available. Svante uses a rotary bed system, which looks physically different than the figure but has similar steps.[3,4] **An example of indirect regeneration is given in the alternate process section.**



Temperature Swing Adsorption

TECHNICAL ASPECTS (all % are volume-based)

Point sources: Pulp & paper, biomass, oil & gas, steam-methane reforming, lime, steel, cement, petrochemicals.[3]
CO_2 concentration range: <20% (Svante 10%-20%)[3,4]
CO_2 capture efficiency: > 90%[3]
CO_2 purity: > 95%[3]
Min. feed gas pressure: 1.1 bar[4] (to overcome pressure drop)
Max. feed gas temperature: 50 °C[4]
Typical scale: Small to large (Svante: 145,000[3] – 1,590,000[4] tCO_2/yr)
Primary energy source: Low/medium pressure steam[3]
Impurity tolerance: SOx = 1.5 ppm[2]; PM = 0.2 mg/m[3]; CALF-20 MOF is robust with regards to steam, O_2, and acidic contaminant gases (such a SOx and NOx).[2]

FUNCTION IN CCU VALUE CHAIN

- Capture CO_2 from flue gases.
- Adsorbents such as zeolites are highly affected by the presence of water in feed gas, requiring an upstream dehydration step.[5]
- Poisoning of adsorbents due to impurities such as SOx and NOx requiring appropriate pre-treatment steps.[5]

LIMITATIONS

- Based on the longer cycle times needed to heat the adsorbent during regeneration, TSA is less attractive than PSA.[6] Typically, TSA processes are more suited than PSA for dilute CO_2 sources.
- Cycle times of minutes are necessary for the large-scale deployment of TSA systems in CO_2 capture.[7]
- Adsorbent material may degrade over time, reducing overall capture efficiency.
- Higher capital cost due to longer cycle times and larger beds.

ENERGY

- Electricity is used by the blower to raise the flue gas pressure to overcome the pressure drop in the reactor bed.
- Low or medium pressure steam is used to increase the adsorbent temperature for regeneration.

CONSUMABLES

- Adsorbent with a certain replacement period.
- Cooling water may be required to cool the feed gas after the blower and during the cooling step.
- Purge gas, such as nitrogen, may be used.[8]

Energy and Consumables

Parameter	Value
Electricity (kWh/tCO_2)	18.6[a]
Heat (GJ/tCO_2) [b]	2.5[8]-3.9[4] [c]
Cooling water (ton/tCO_2)	-NA-
Adsorbent (kg/tCO_2) [b]	0.006[8] [d]

[a] Electricity for blower to increase pressure to 1.1 bar.
[b] SVANTE technology with MOF adsorbent (CALF 20).
[c] Steam at 170 °C and 7.9 bar; equivalent steam = 1.2 – 1.9 t/tCO_2.
[d] Replacement period of 5 years.

COSTS

CAPEX: ~22 €/tCO_2[9]
Main CAPEX: Adsorption columns and components.
OPEX: ~23 €/tCO_2[9]
Main OPEX: steam and adsorbent.
CO_2 capture cost: ~45 €/tCO_2[9]
Depends on scale and CO_2 concentration.

[9] Svante VeloxoTherm™ for a cement kiln; CO_2 concentration – 12.3% (dry); CO_2 capture capacity – 1.6 MtCO_2/yr; 2021 basis; electricity price – 64.5 €/MWh; NG price – 13.6 €/MWh; Cooling water – 0.45 €/m; capture cost dependence on scale is also available on Pg. 30.

CO_2 avoidance cost: ~54 €/tCO_2 avoided[4]

[4] Same specifications as [9], but estimated only for the base case capture plant.
Cost and CO_2 footprint details on Svante's VeloxoTherm™ technology for Linde's steam-methane reforming H_2 plant can be found here. [8]

ENVIRONMENTAL

CO_2 footprint: 273 kgCO_2eq/tCO_2 captured[8]
Estimate includes footprint (scope 1-3) for CO_2 capture plant, compression, and conditioning.
Spatial footprint: 74,420 m^2 (305x244) for 1.6 MtCO_2/yr[4]
Environmental issues: Disposal or recycling of spent adsorbents.[10]

ENGINEERING

Maturity: Pilot (TRL 7)[3]
Large pilot tests to FEED studies for commercial plants.
Retrofittability: Feasible
Heat/steam is the main energy source; phased implementation due to modular nature; handles flue gas impurities depending upon the adsorbent used. Challenges due to large spatial footprint requirement.
Scalability: High
Well suited for capturing CO_2 at a wide capture rate range due to its modular nature[3].
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

- VeloxoTherm™ by **SVANTE**, Canada
- CORAL™ by **CORMETECH**, US *(honeycomb adsorbers with direct steam regeneration)*
- Rotating Honeycomb by **Seibu Giken**, Japan
- Metal Organic Frameworks by **Promethean Particles™**, UK
- Metal Organic Frameworks by **Immaterial**, UK
- Dual Function Materials by **SUSTEON**, US *(cyclic capture and conversion)*

ALTERNATE PROCESSES

Alternative processes to the Svante process with CALF-20 sorbent include other sorbent materials and structures (monoliths versus pellets/beads), reactor concepts, and regeneration modes. Depending on these specifics, the technical and cost data will differ.

TSA by indirect regeneration

Indirect regeneration is performed by supplying a heating medium (steam or hot fluid) through heat exchanger tubes embedded within the adsorbent.
Process: 5-step TSA cycle with UTSA-16 MOF adsorbent [11]
Regeneration temperature: 150 °C [11]
Regeneration time: 1023 seconds [11]
CO_2 concentration: 15% [11]
CO_2 purity: 97.7%. [11]
CO_2 capture efficiency: 91.1%. [11]
Power: 247 kWh/tCO_2 captured [11]
Heat: 833 kWh/tCO_2 captured [11]
CAPEX: ~20 €/tCO_2 [11]
OPEX: ~67 €/tCO_2 [11]

[11] *Electricity and heat are ~25% and ~58% of OPEX with electricity price – 68 €/MWh and heat price – 0.05 €/MWh, economic lifetime – 15 years, discount rate – 9%.*

Technology providers: Not available yet.

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