JUNE 6, 2024

CUTTING COSTS FOR CUTTING CARBON

Low-Cost Pathways for Direct Air Capture

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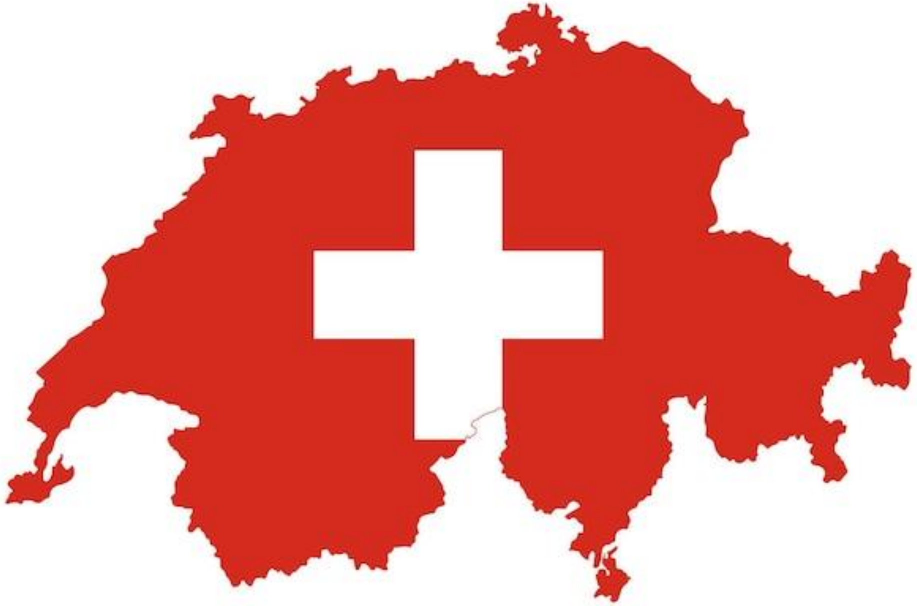
How high are DAC costs?



The need despite the cost

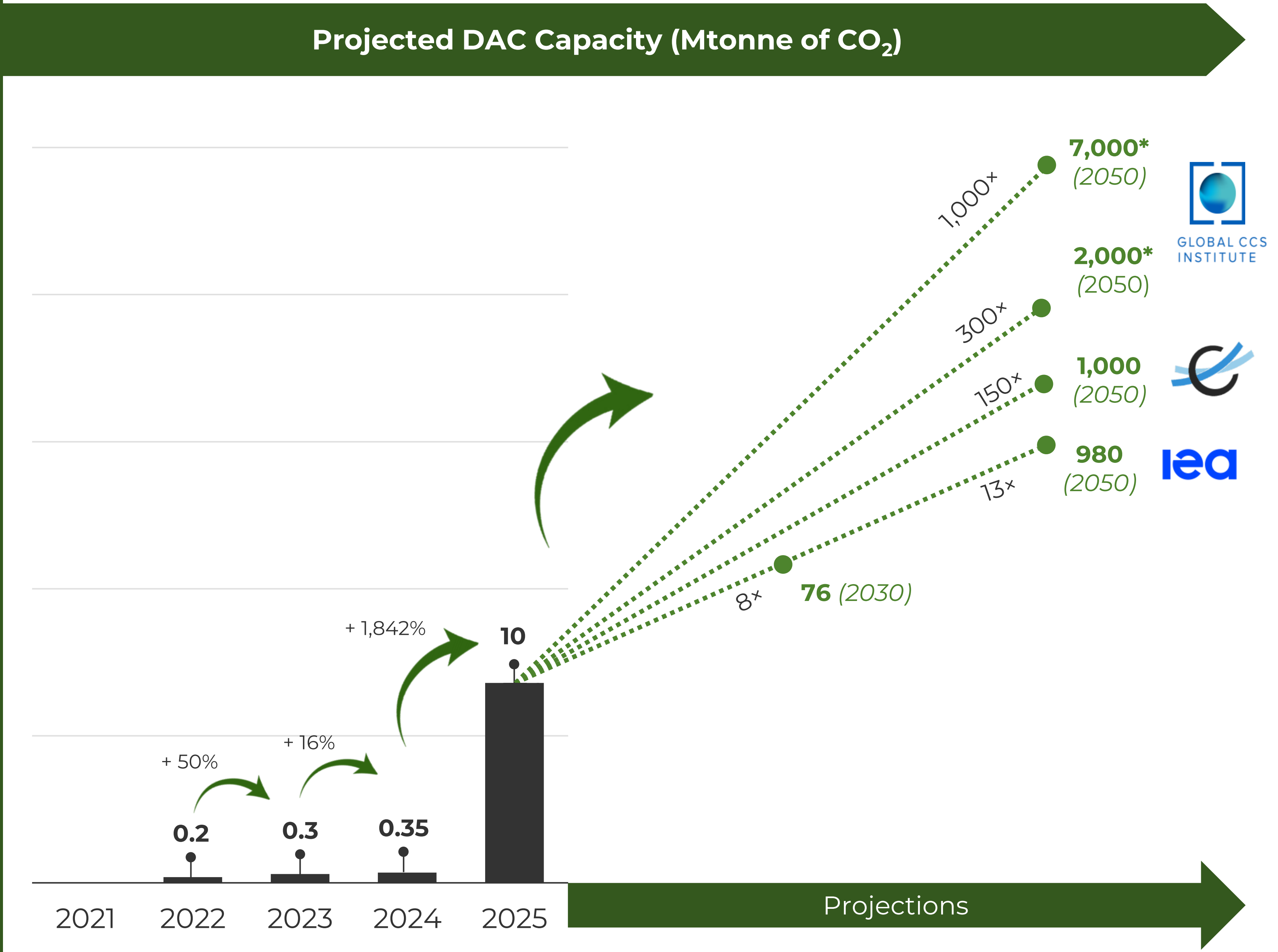
Refossilizing carbon

Securing nonfossil CO_2 feedstock

Offsetting hard-to-abate emissions

Growth in global DAC has 3 main drivers:

- Refossilizing carbon
- Need for a nonfossil CO_2 source
- Offsetting hard-to-abate emissions

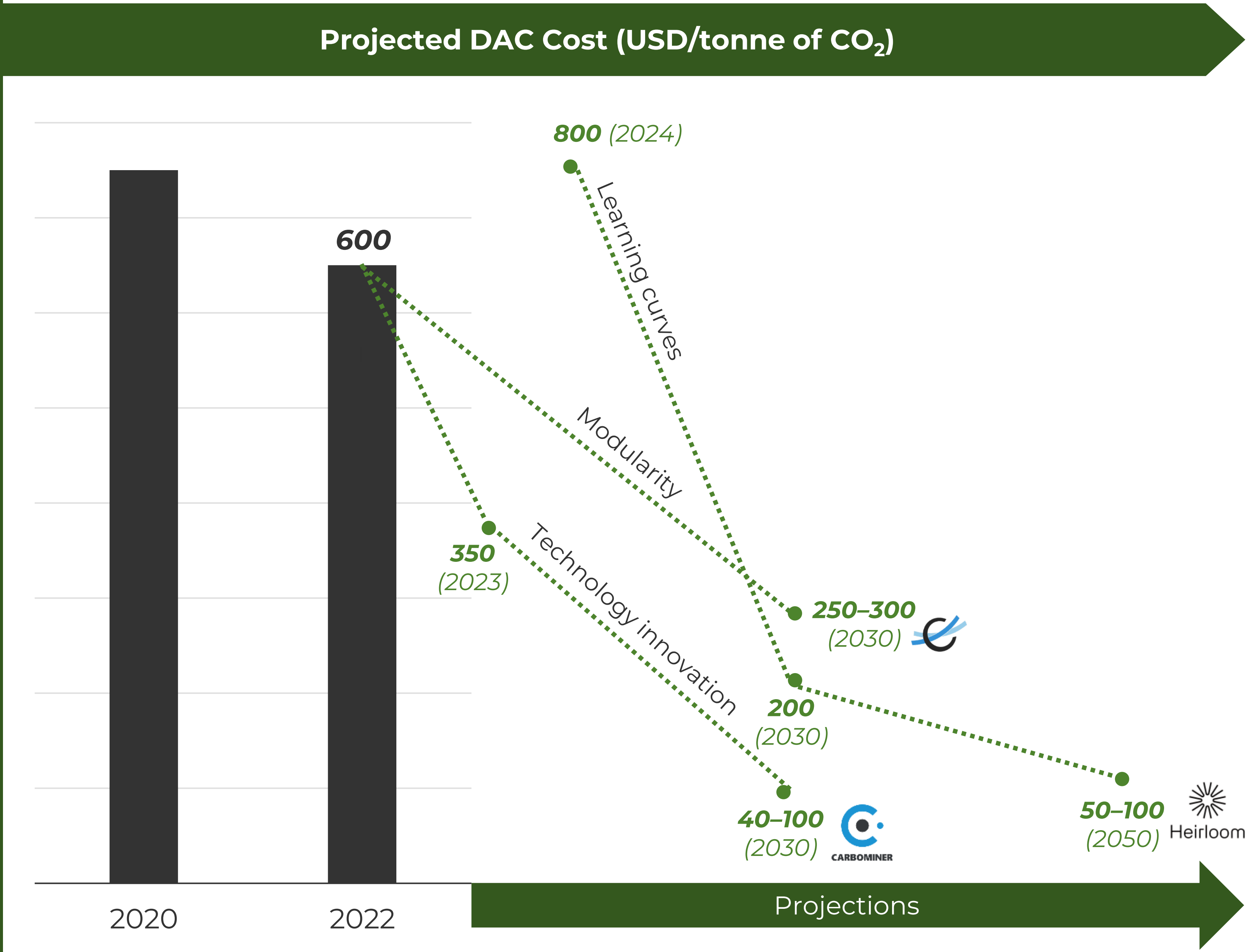


*The Global CCS Institute projects 7,000 Mtonne of capacity at DAC costs of USD 137/tonne and 2,000 Mtonne of capacity at DAC costs of USD 237/tonne.

The decade-long promise of reaching USD 100/tonne CO_2

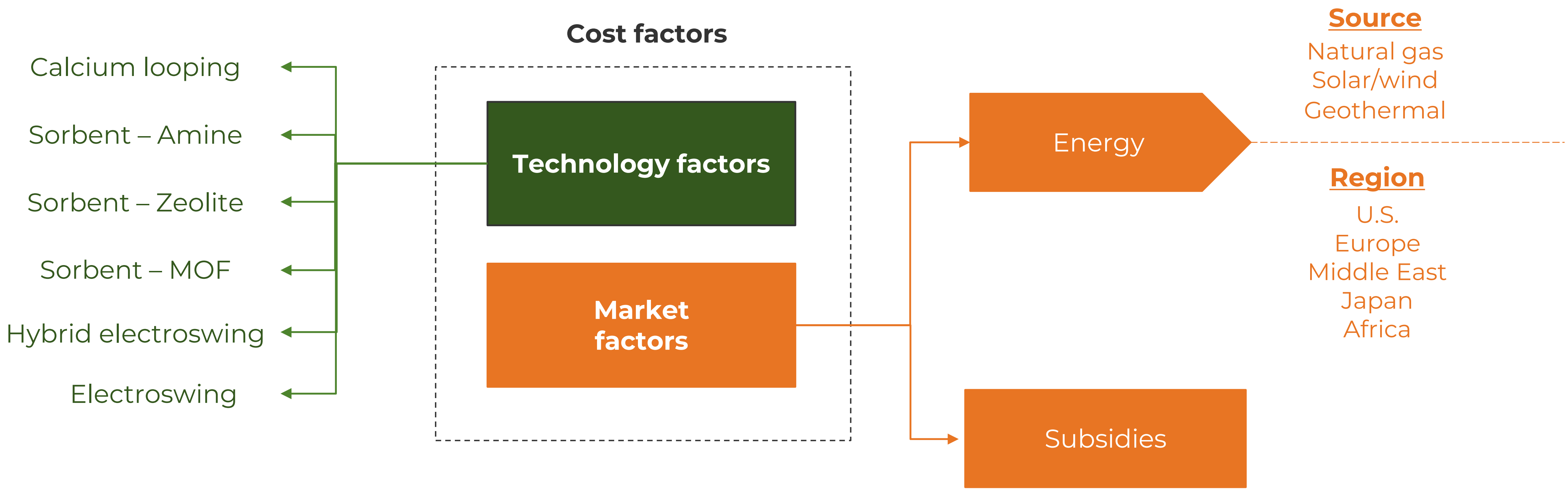
There are three avenues for cost reduction

- **Learning curves**
- **Modularity**
- **Technology innovation**



Note: The costs shown here are direct claims and targets set by the stated entity. Lux analysis on DAC costs begins in the following section.

DAC economics are influenced by a confluence of technology and overlying market factors that need to be analyzed



Methodology: The cost of a reference 1-Mtonne/y DAC facility

Inputs

Project capacity – tonne CO_2/y
Capital expenditure (capex)
System cost – USD/tonne CO_2
Material cost – USD/tonne CO_2
Operating expenditure (opex)
Electricity requiremt. – GJ/tonne CO_2
Cost of electricity – USD/GJ
Heat requirement – GJ/tonne CO_2
Cost of heat – USD/GJ
Other inputs
Engineering costs – USD/tonne CO_2

Output

Cost of DAC – USD/tonne CO_2

DAC Technologies

Calcium looping

Sorbent – Amine

Sorbent – Zeolite

Sorbent – MOF

Hybrid electroswing

Electroswing

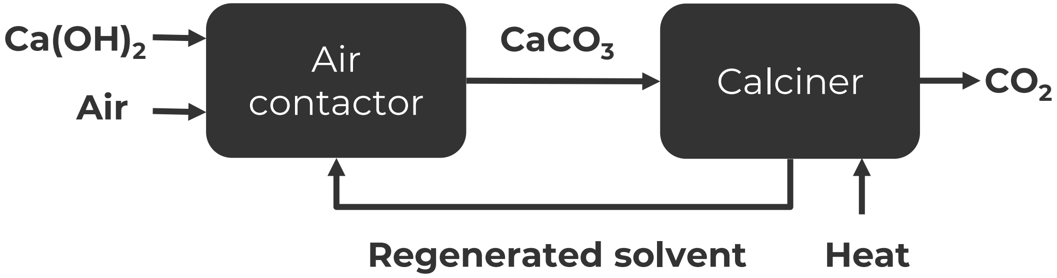
DAC technology – Calcium looping

Technology overview, cost forecast, and developer spotlight

Calcium looping: Nonfunctionalized liquid-phase capture but requires a significant amount of high-temperature heat for desorption

Technology Overview

- CO_2 reacts with alkali metal hydroxides and is then decomposed back to the oxide and CO_2
- Requires high-temperature heat between 700 °C and 1,000 °C
- Commercially ready



Example Developers

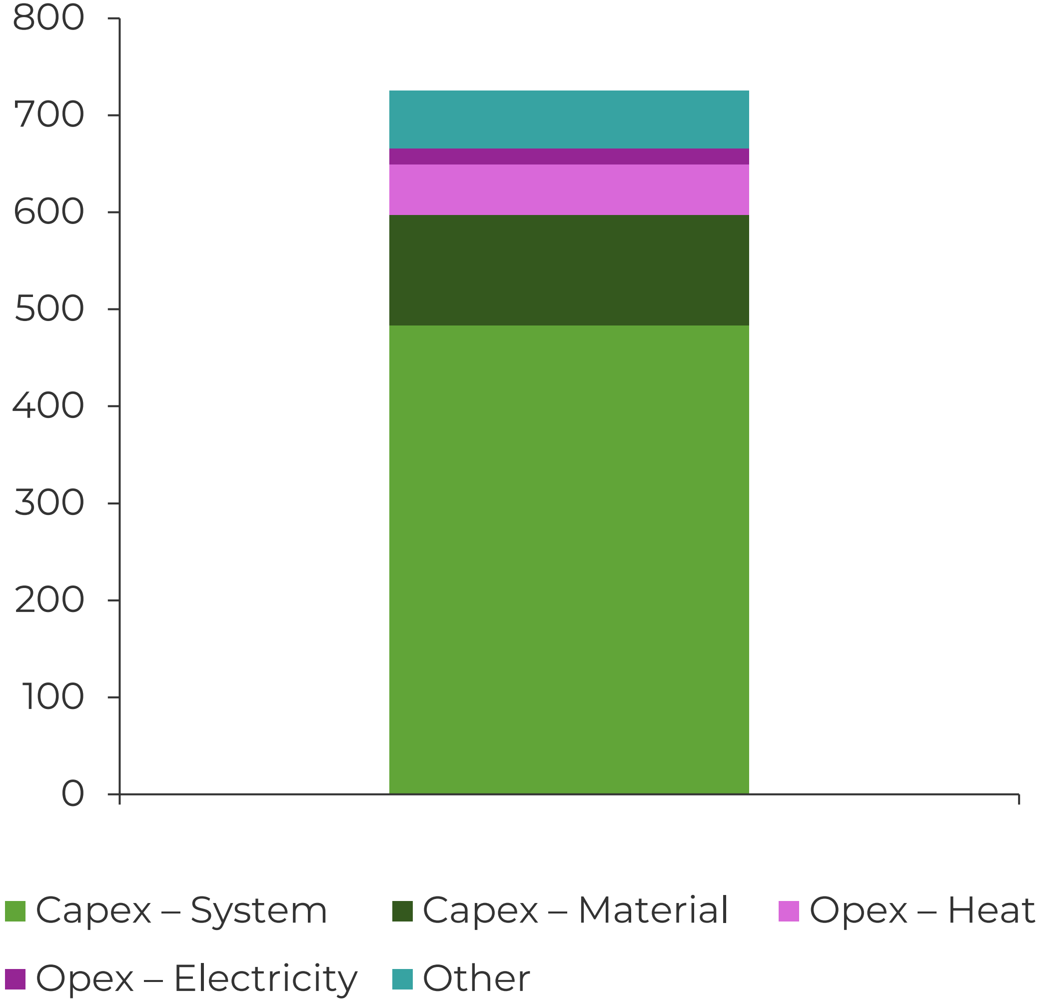
Carbon Engineering
Heirloom
8 RIVERS
Airhive

Calcium looping DAC costs are estimated at USD 725/tonne CO_2

Technology Profile and Assumptions	
Heat requirement	5.25 GJ/tonne CO_2
Electricity requirement	1.3 GJ/tonne CO_2
Cost of heat	USD 10/GJ
Cost of electricity	USD 12.5/GJ
Reference capacity	1 Mtonne/y
Capacity factor	0.8
Capex learning rate	10% (from IEA*)
Maturity	Commercial

Note: System components include an air contactor, pellet reactor, calciner and slaker, separation unit, turbine, filter, and transformer.

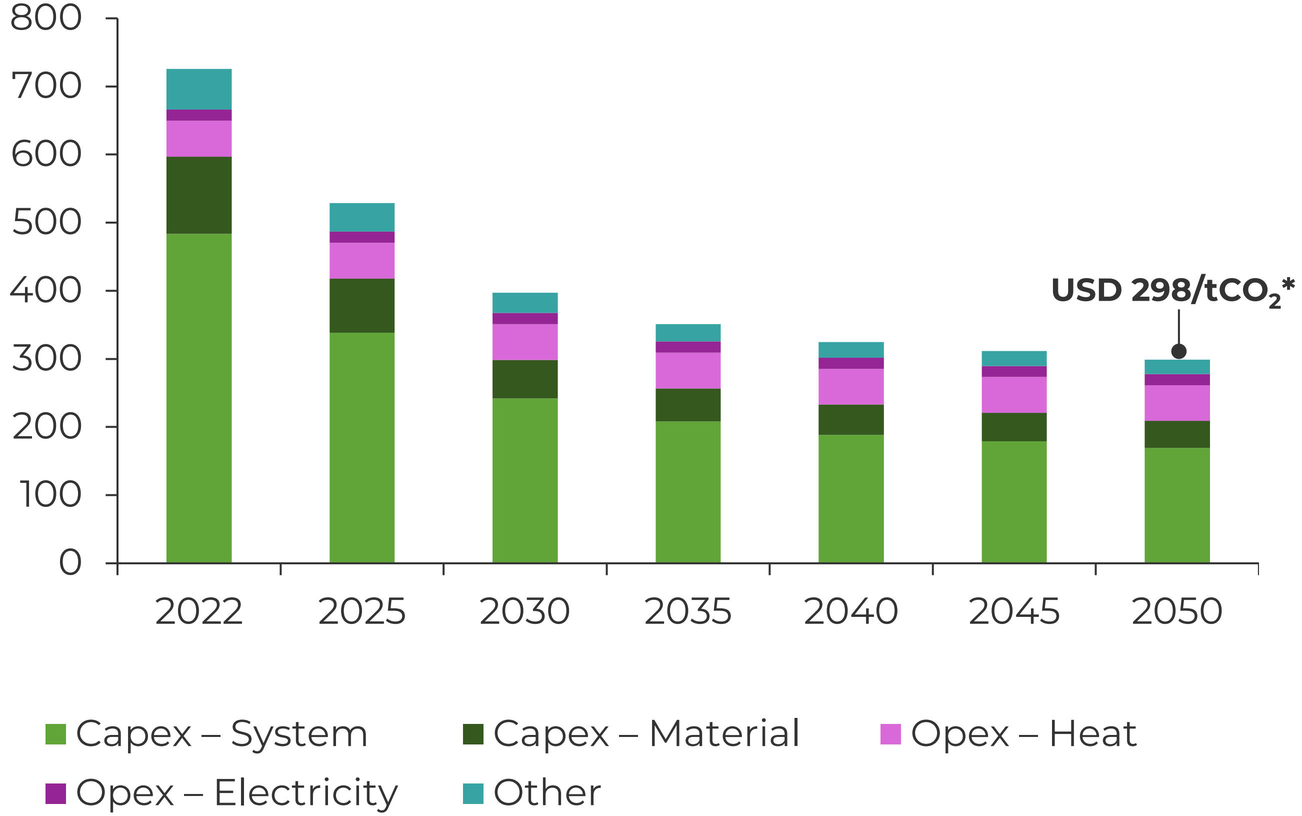
Cost Breakdown (Current) – Calcium Looping
USD/tonne CO_2



*IEA, International Energy Agency

DAC with calcium looping will see a 60% cost reduction by 2050

Cost Forecast – Calcium Looping
USD/tonne of CO_2



Lux Take

- **Need for large stick-built systems makes calcium looping capex intensive.**
- **Need for high-temperature heat locks the technology into a natural gas infrastructure.**
- **Cost decreases to USD 298/tonne CO_2 in 2050.**

*tCO_2, tonne of CO_2

CASE STUDY

Heirloom plans to electrify its calcium looping process in partnership with the Leilac Group.

The company already operates a 1-ktonne/y facility in the U.S. and will be part of the U.S. DOE hub, Project Cypress.

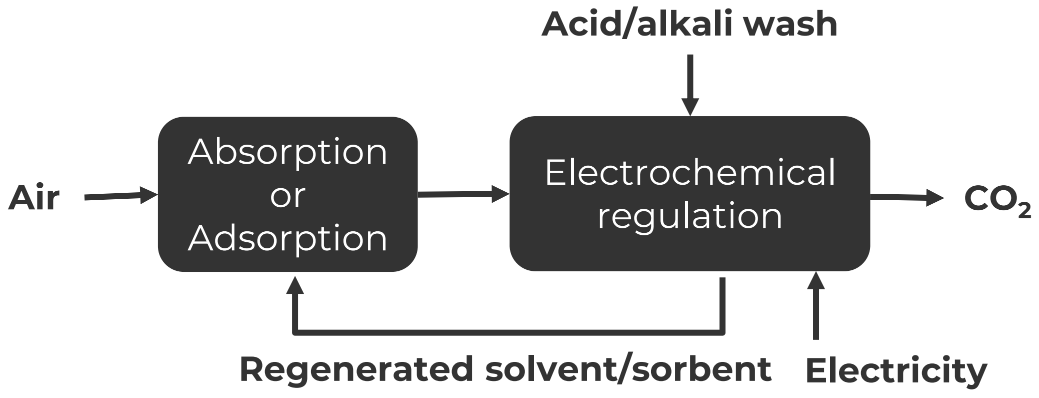
DAC technology – Hybrid electroswing

Technology overview, cost forecast, and developer spotlight

Hybrid electroswing: Uses solvents or sorbents but pointedly swaps high-energy thermochemical desorption with an electrochemical alternative

Technology Overview

- Utilizes alkali metal hydroxides to capture CO_2 but with an electrochemical desorption pathway
- Zero-heat, all-electricity-driven process with near-ambient-temperature operations
- Commercial momentum in hybrid electroswing is fast ramping up



Example Developers

MISSION ZERØ TECHNOLOGIES
CARBOMINER
CO2CirculAir Smart Direct Air Capture
REPAIR CO₂ CAPTURE
CARBON BLADE
CARBON ATLANTIS

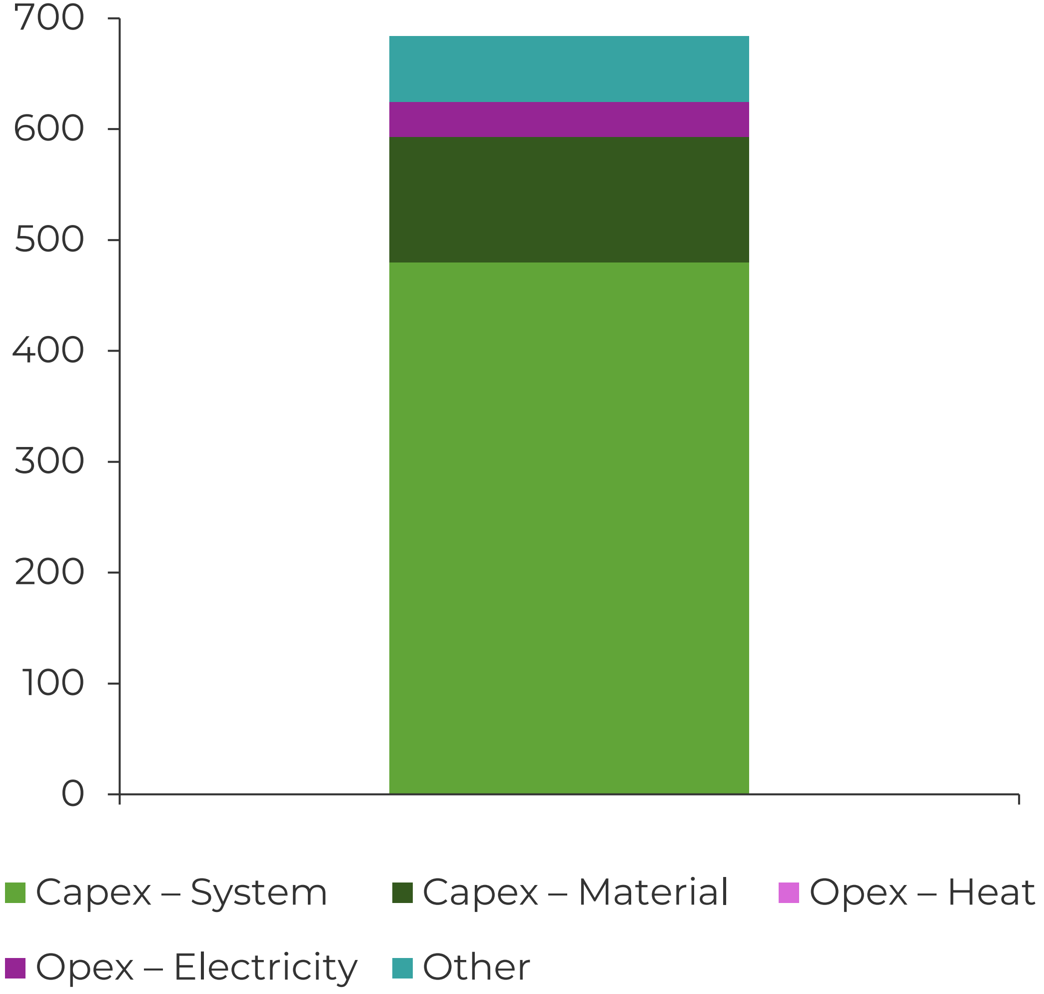
Hybrid electroswing DAC costs are estimated at USD 683/tonne CO_2

Technology Profile and Assumptions	
Heat requirement	0 GJ/tonne CO_2
Electricity requirement	2.5 GJ/tonne CO_2
Cost of heat	USD 10/GJ
Cost of electricity	USD 12.5/GJ
Reference capacity	1 Mtonne/y
Capacity factor	0.9
Capex learning rate	20%
Maturity	Development

Note: Analysis of hybrid electroswing is based on limited data from early stage projects and studies, and the results are indicative at best. Lux used cost data from a pilot facility and applied a 0.6 scaling factor to estimate costs for a reference 1-Mtonne/y facility. Range of compatible solvents include alkali hydroxides or carbonic anhydrase and is assumed to be readily available commodities.

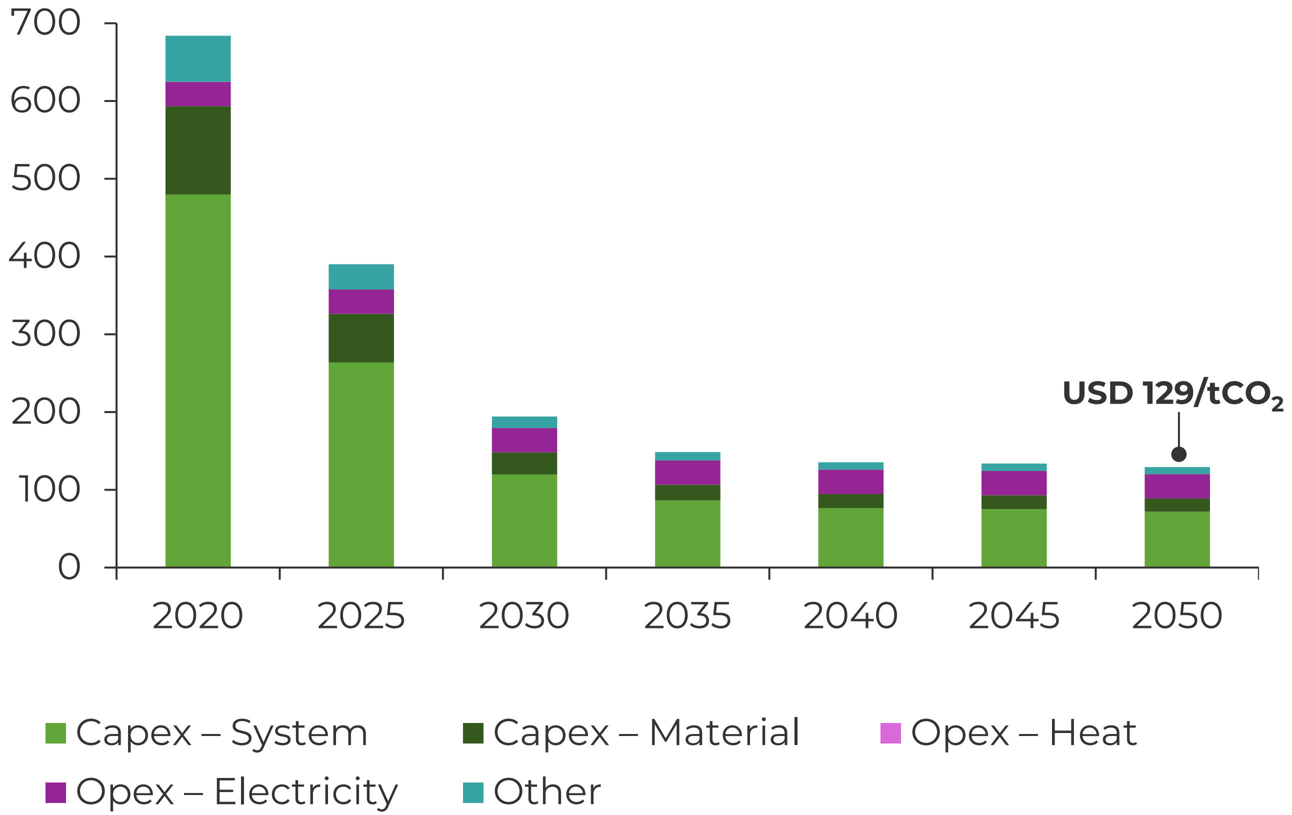
Cost Breakdown (Current) – Hybrid Electroswing

USD/tonne CO_2



DAC with hybrid electroswing will see an 81% cost reduction by 2050

Cost Forecast – Hybrid Electroswing
USD/tonne CO_2



Lux Take

- **Base-case electricity consumption for near-term pilots will likely be higher.**
- **Component-level scaling will look different for hybrid electroswing.**
- **Cost decreases to USD 129/tonne CO_2 in 2050.**

CASE STUDY

SOLVENT + ELECTROSWING

Carbon Atlantis develops a pH-swing version of a hybrid electroswing system.

The company is involved in several pilots, including an undisclosed-capacity partnership with Cella Mineral Storage in Kenya.

CARBON ATLANTIS

cella

CASE STUDY

SORBENT + ELECTROSWING

Carbominer is a Ukrainian startup that develops a multistage sorbent system that utilizes ion-exchange resins and alkaline solutions.

The company completed one pilot in 2023 and recently raised a EUR 1.5 million funding round.

CARBOMINER

CASE STUDY

MEMBRANE + ELECTROSWING

RepAir's system utilizes electrolysis to drive CO_2-saturated solvents through a membrane.

The company launched its field prototype on the roof of its lab in 2023.

Outlook

Technology review and conclusions

Calcium looping and amine sorbents have scaled because of players' first-mover advantage but have several competing alternatives

Calcium Looping

Current cost: USD 725/tCO_2

2050 cost forecast: USD 298/tCO_2

+ Large-scale facilities with industrially ready equipment and low material risk

– Need for high-temperature heat makes it challenging to reduce energy demand and integrate with renewables

Sorbent – Amine

Current cost: USD 420/tCO_2

2050 cost forecast: USD 140/tCO_2

+ Uses low-temperature heat and strongly benefits from system modularity

– Still has a high energy consumption and can have improved sorbent lifetime

Sorbent – Zeolite

Current cost: USD 490/tCO_2

2050 cost forecast: USD 287/tCO_2

+ Readily available sorbent that allows immediate and near-term scale-up

– Highest energy demand of all DAC pathways; competing selectivity for water

Electroswing skirts the majority of DAC opex by reducing or completely avoiding heat but will need low-cost renewable electricity

Sorbent – MOF

Current cost: USD 4,560/tCO_2

2050 cost forecast: USD 1,274/tCO_2

+ Lowest energy demand of all sorbents; compatible with vacuum/moisture desorption

– Current manufacturing costs are highly prohibitive of adoption

Hybrid Electroswing

Current cost: USD 683/tCO_2

2050 cost forecast: USD 129/tCO_2

+ No-heat process uses established acid-base chemistry; lower need for heat tolerance reduces system capex

– Component-level scalability is yet to be fully analyzed; will need low-cost renewables

Electroswing

Current cost: USD 216/tCO_2

2050 cost forecast: USD 136/tCO_2

+ Zero-heat process that shows potential to mimic scalability of energy storage technologies

– At lab scale and will require significant R&D investments before commercialization

Key Takeaways

1 Early pilots will have higher costs; scale and R&D will need to occur in parallel.

2 Technology innovation is the future of cost-competitive DAC – hybrid electroswing is a high-potential solution.

3 Regional spread of future DAC hubs will be a function of energy prices and subsidies.

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