Carbon capture for use or sequestration

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Carbon capture is applicable for a range of large stationary combustion and process emitters

***Industrial:** Concentrated CO_2*

Petrochemicals
Byproduct from production of methanol, carbon black, etc.

Ammonia
Byproduct from use of fossil fuels to produce hydrogen for ammonia

Ethanol
Byproduct of fermentation of glucose for ethanol production

Nearly all applications also produce combustion emissions for **industrial heating**

***Industrial:** Dilute CO_2*

Refining
Mostly fuel combustion for boilers & furnaces to refine raw materials

Cement
Byproduct of calcination of limestone to produce clinker

Iron & Steel
Several sources of CO_2 including coking coal, blast furnaces

Aluminium
Reduction process creates CO_2 from alumina electrolysis

Power sector (not focus of this fact base)

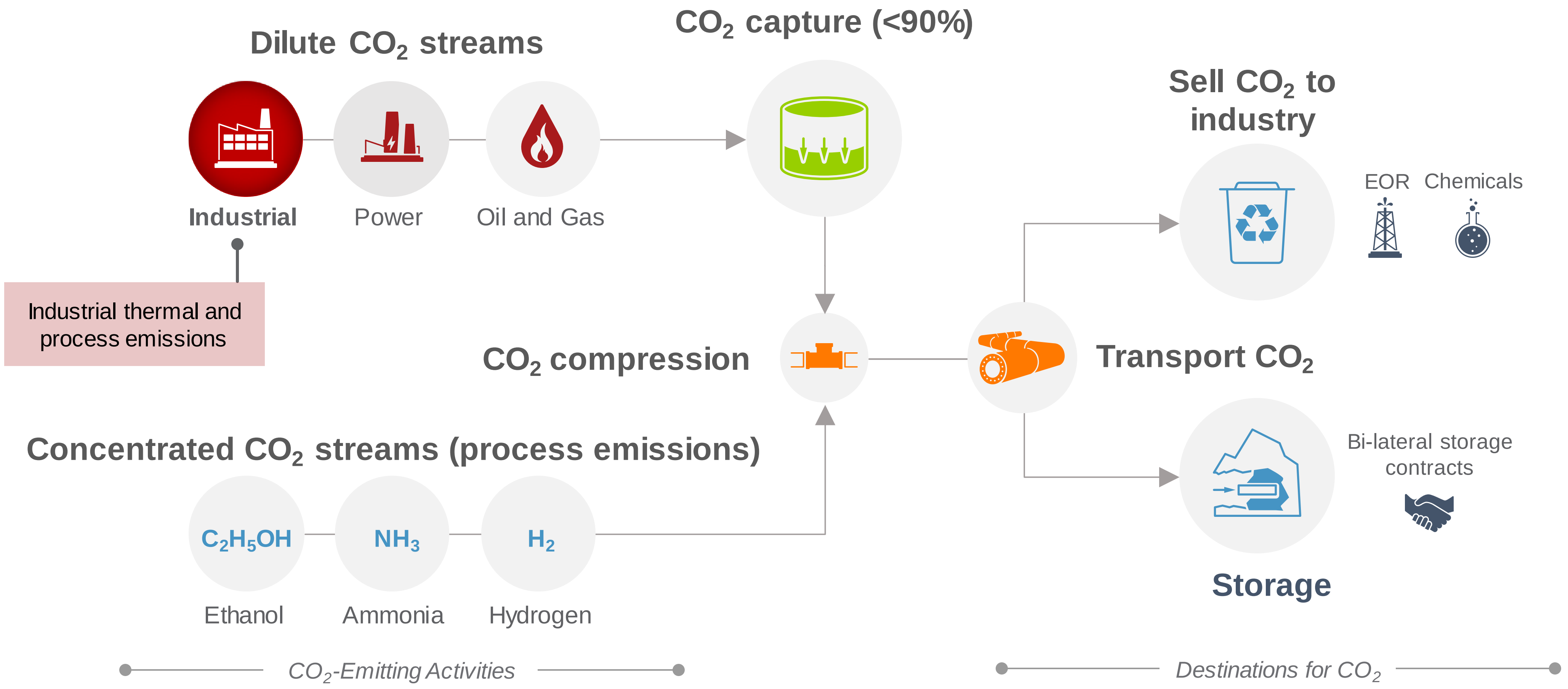
Coal-to-Power
Combustion of coal for electric power produces dilute CO_2 offgas

Gas-to-Power
Combustion of gas for electric power produces dilute CO_2 offgas

Biofuels-to-Power
Combustion of biomass for electric power produces dilute CO_2 offgas

List not exhaustive, many smaller emitting industrial sectors also appropriate for CCUS

CCUS captures up to 90% of CO_2 from stationary emitters and transports it for storage or utilisation



Four main drivers determine the technical and economic viability of CCUS for thermal combustion applications

Concentration

- Cost of carbon capture inversely correlated with level (i.e., partial pressure) of CO2 in capture stream

Location

- CO2 source location important for:
  - aggregating emission streams
  - transport of captured CO2
  - storage or use of CO2

Source of Heat

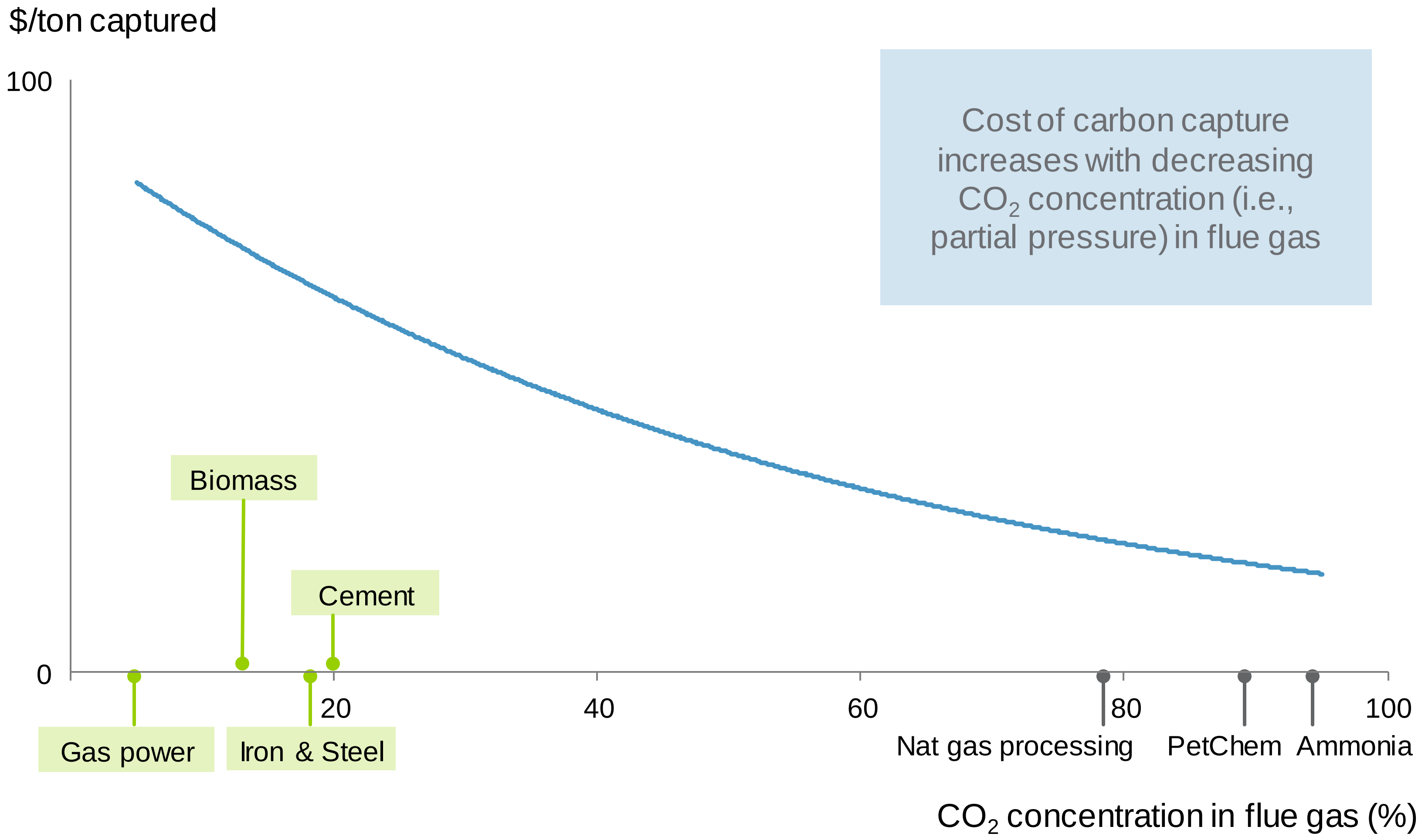
- Regeneration of carbon capture solvent typically requires low-cost heat at ~120ºC

Process Emissions

- Opportunity to simultaneously capture non-combustion process emissions

Concentration

Level of CO2 in flue gas is a key cost driver



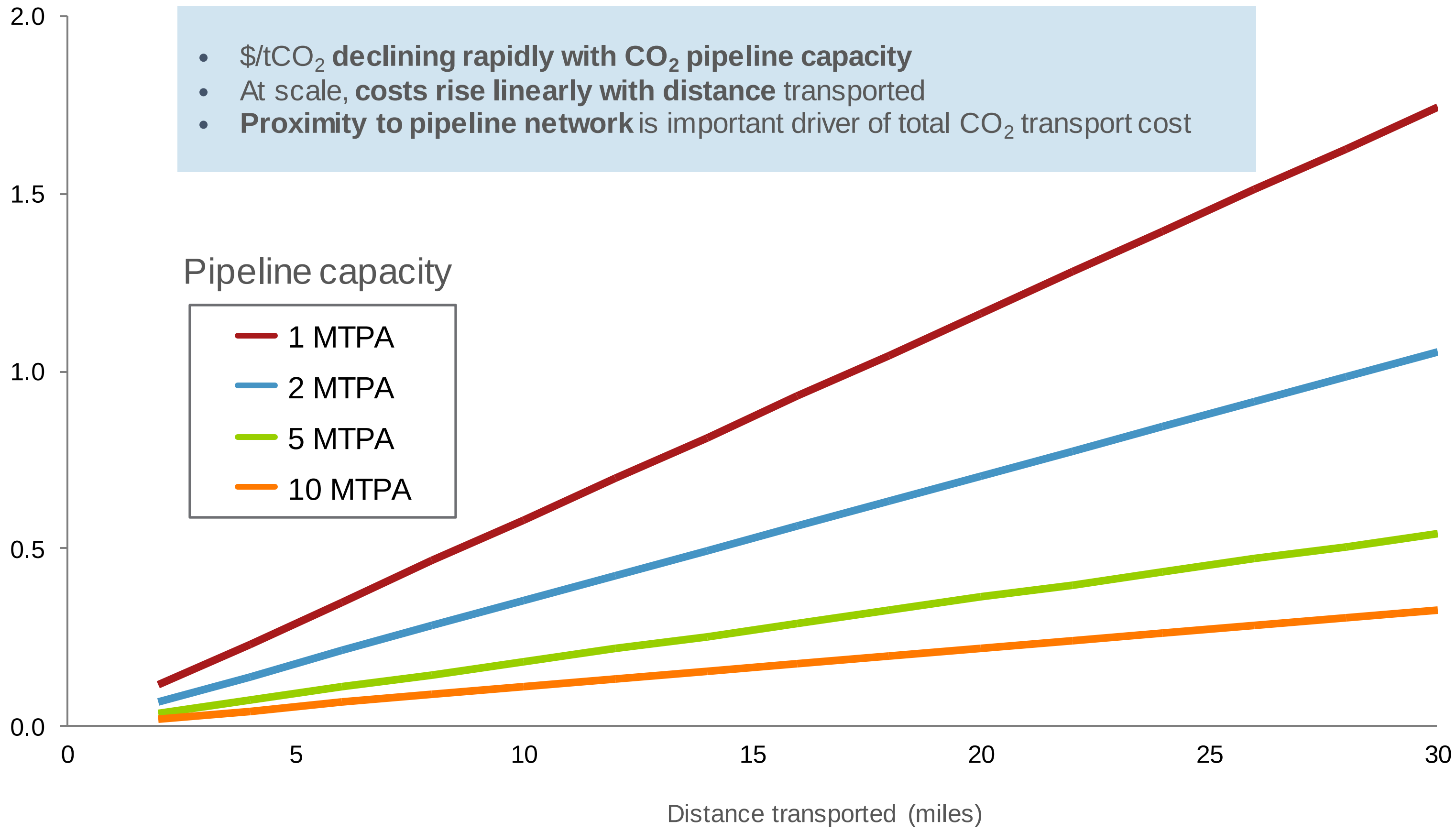
Note: Assuming 8% WACC, 85% utilization rate, 20-year lifetime
Source: Industry Sources, NPC, IEAGHG, BCG Analysis

- Flue gas from industrial thermal combustion typically contains <10% CO2, resulting in higher carbon capture costs relative to process emissions
- *Note: Cost of CO_2 capture ($/ton) is independent of emissions intensity (kg CO_2 per MMBtu) and fuel costs*

Location

Carbon capture costs increases proportionally with CO2 transportation distance, but decline with increasing pipeline capacity

Trunk pipeline total cost ($/tCO$_2$)



- Pipeline network development is likely necessary to unlock CCS potential for a wider set of industrial players.
- Joint or national development of CO$_2$ pipeline will accelerate CCS for industrials, who may be currently geographically challenged to deploy CCS

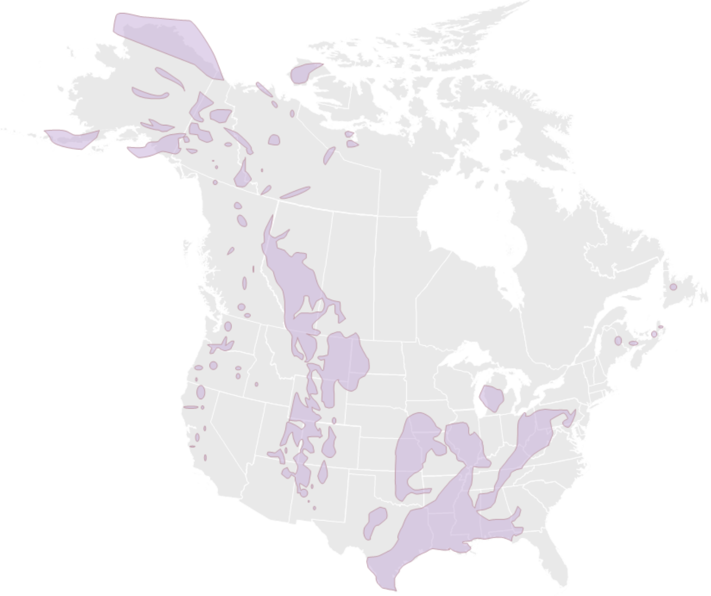
Source: Zero Emissions Platform (ZEP); Global CCS institute; BCG analysis

Location

Viable geologies for CO2 sequestration available in large portions of North America, providing potential sites for carbon capture and storage

Saline aquifers

Proven technology, likely solution for short to medium term



Coal/O&G

Uncertain storage durability

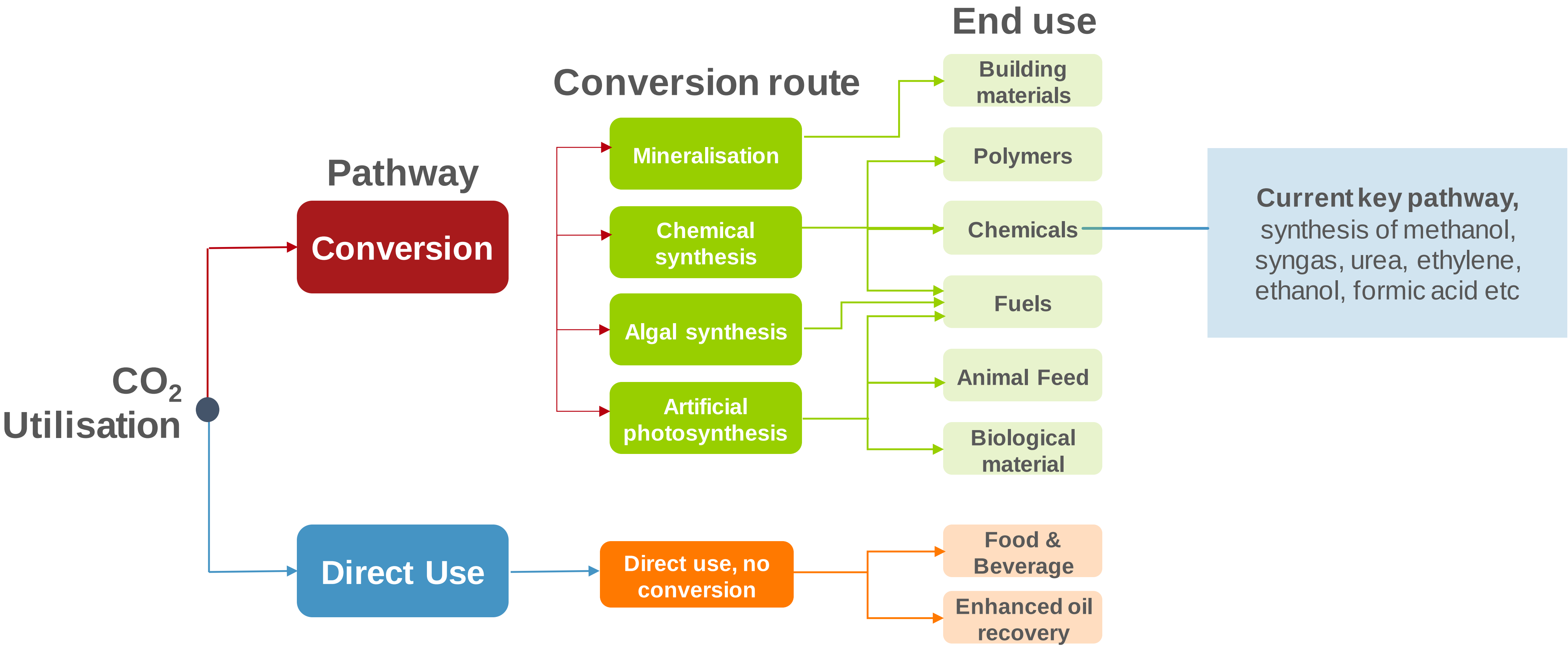
Basalt deposits[1]

Emerging technology

1. Not yet fully proven but with high expectation as a form of permanent CO2 sequestration given the chemical reactions within basalt to form solid carbonates
Source: USGS, NETL NATCAB

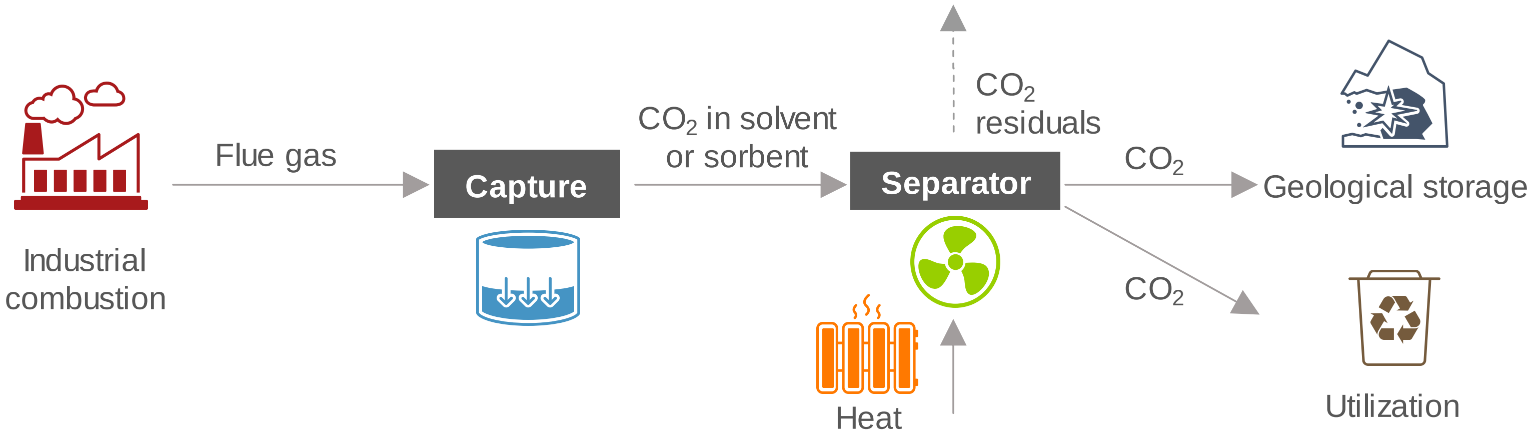
Location

Similar to storage, utilization of captured CO2 also depends on proximity between source of emissions and end use location



Source of Heat

Thermal energy used to drive carbon capture is a major component of CCUS cost



- Existing CCUS systems typically use a solvent (e.g., MEA) to capture CO_2, while novel CCUS systems are being developed using pressure-swing or electrification processes
- Heat at approximately 120ºC is applied to the solvent to release CO_2
- Depending on flue gas CO_2 concentrations, source of heat, and other factors, cost of solvent regeneration heat can constitute 20-50% of total carbon capture costs per ton of CO_2
- Waste heat streams is the most effective way to provide heat to drive the carbon capture process

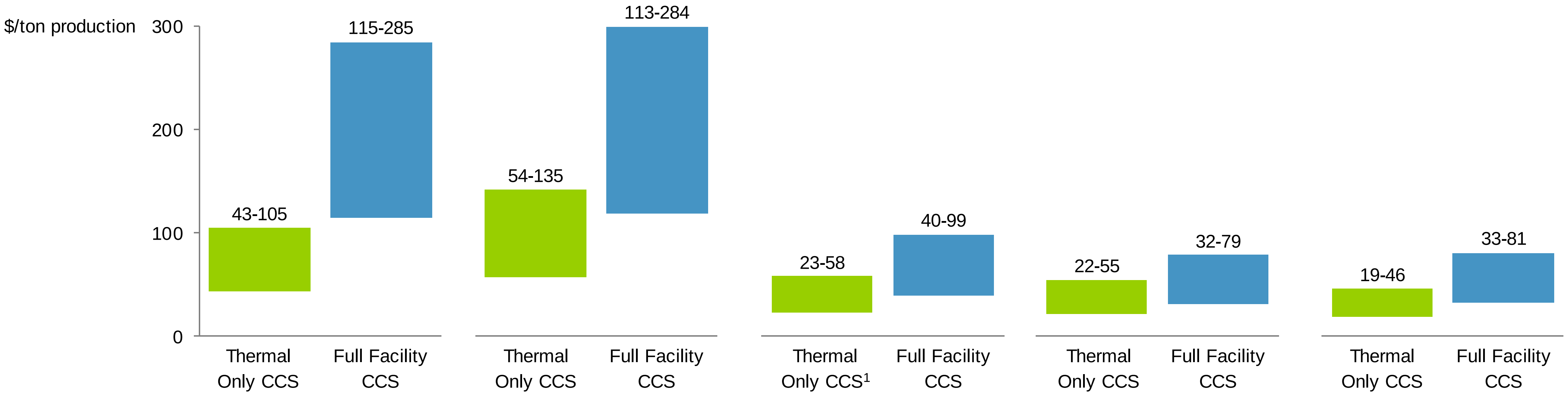
Source: Global CCS Institute

Forms of regeneration heat (in order of descending cost)

- Electric resistance
- Low temperature steam
- Hot water
- Waste heat streams

Beyond thermal-related CO2 capture, CCS is likely required to decarbonize process emissions in various hard to abate sectors

Range of cost increase per ton of material produced, with coal or natural gas as original heat source

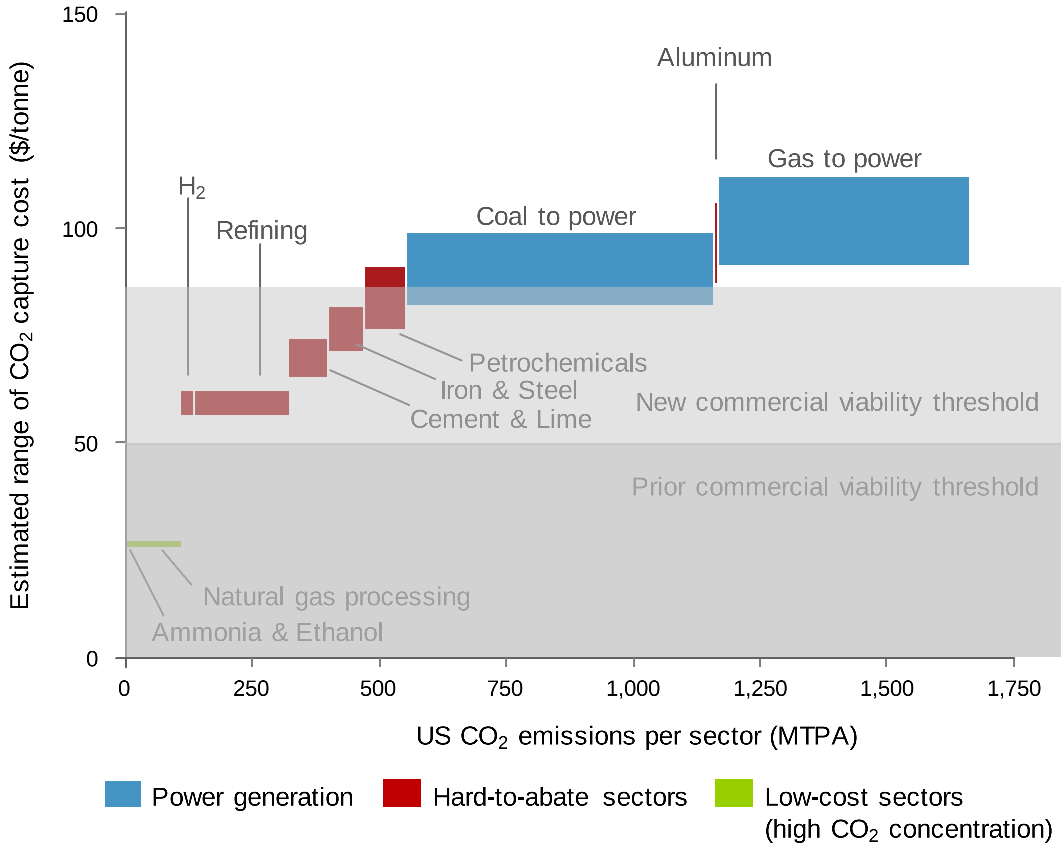


	Ammonia	Steel	Cement clinker	Glass	Methanol
Baseline commodity cost ($/ton)	500	400	100	300	430
Original heat source	Natural gas	Coal	Coal	Natural gas	Natural gas
CCUS as part of sector decarbonization	Required in short term	Required in short to medium term	Required	Low requirement	Low requirement

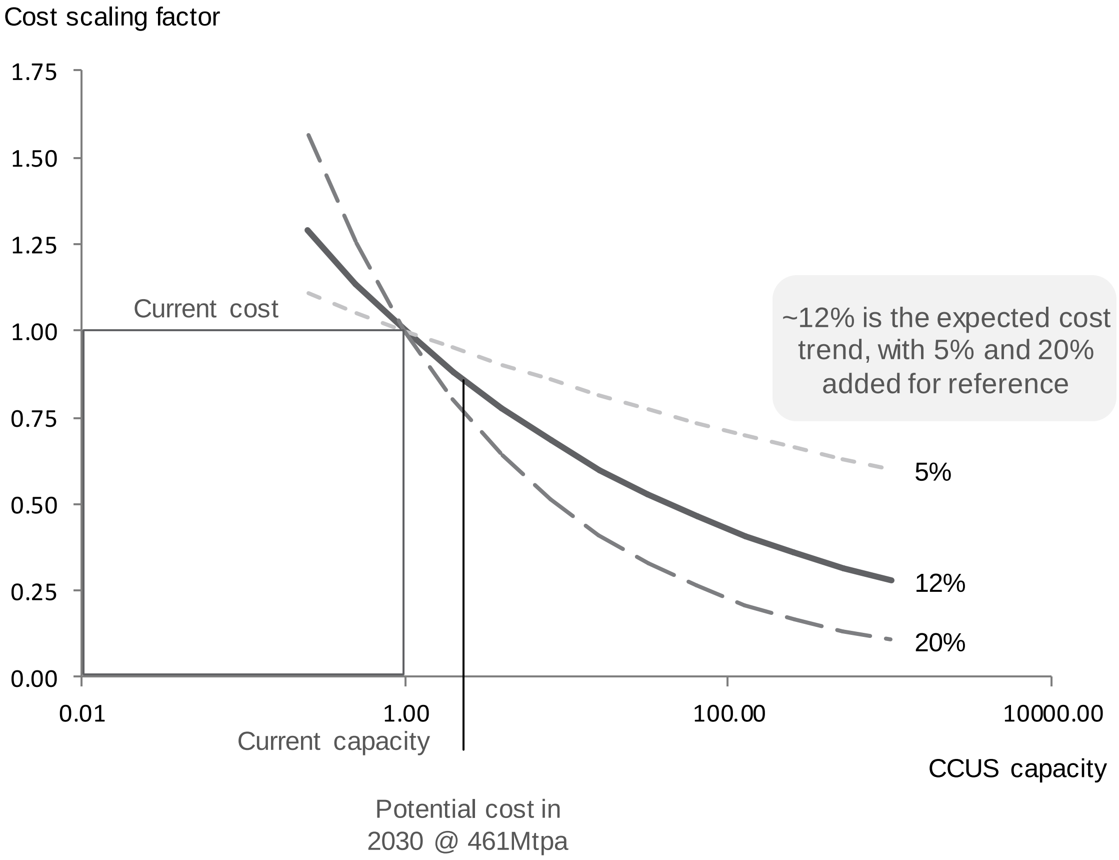
1. Cement clinker production likely not able to separate thermal vs full facility emissions in kiln | Source: Columbia University

Inflation Reduction Act increases 45Q tax credits to $85/t making CCUS potentially viable for refining, hydrogen, cement, & steel sectors

$85/ton incentives significantly expand CCUS commercial viability

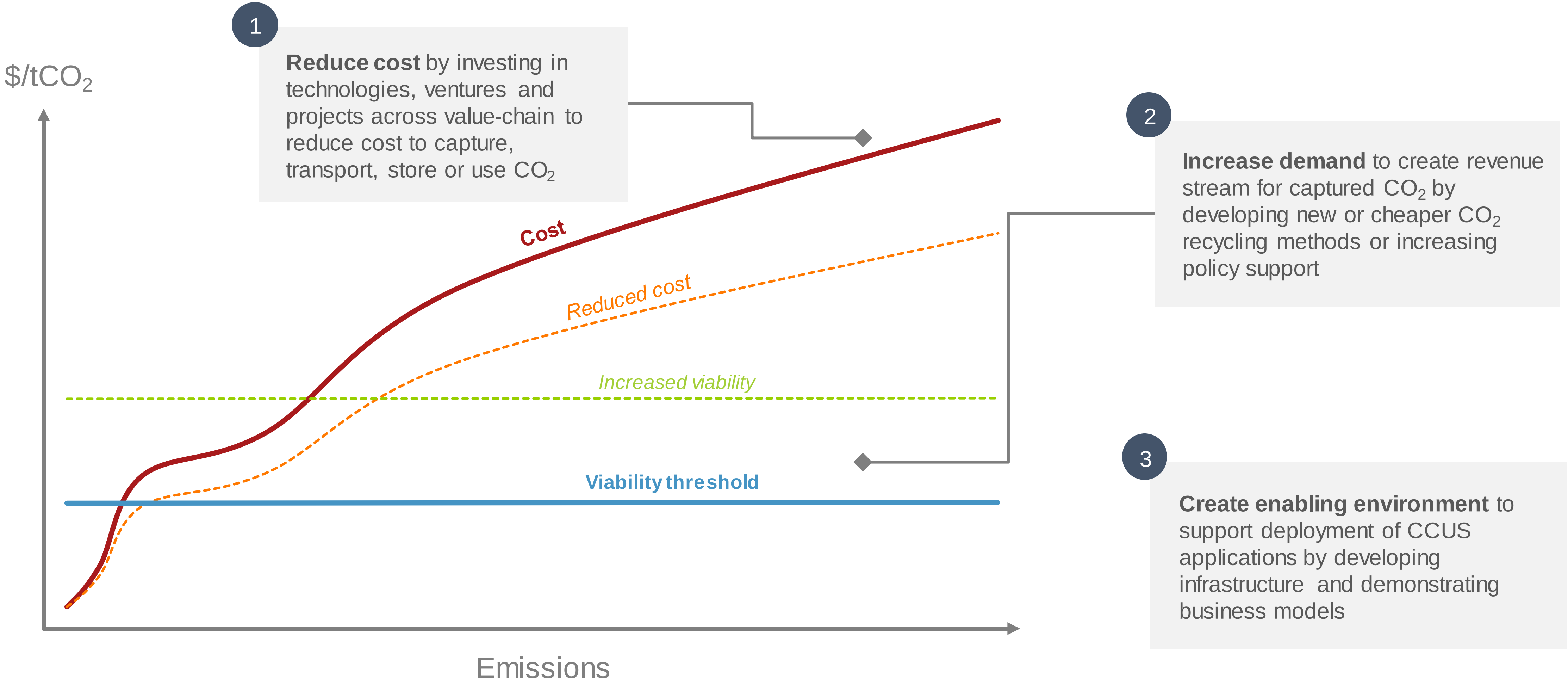


…and further cost reductions of ~12% are expected as deployment doubles, making coal+CCUS potentially viable



Source: BCG Analysis

Three broad strategies can increase the viability of CCUS for industrial heating decarbonization



CCUS for industrial heating decarbonization has many advantages and unique features, but faces several key barriers to adoption

Advantages

- No major modification required to the industrial process
- May be more cost effective than alternative renewable heating options
- Technical capacity to store CO2 underground is functionality unlimited
- Can simultaneously capture CO2 from process emissions

Barriers

- Cost can be high and does not add value unless there is a price on carbon
- Extensive supplemental infrastructure required
- Non-renewable and not a long-term solution
- Does not capture 100% of CO2 emissions

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