POV on Global Carbon Capture Use and Storage (CCUS)
Short version

April 2023

BAIN & COMPANY

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Bain beliefs on Carbon Capture, Utilization and Storage – Key messages

Carbon Capture, Utilization and Storage ('CCUS') refers to technologies aimed at capturing carbon dioxyde (CO_2) from sources of emissions (e.g. ethanol plant, gas or coal power plant) or the atmosphere directly, compressing it for transportation, and then using it to manufacture valuable products or storing it permanently deep underground.

CCUS is part of the **portfolio of solutions to reduce CO_2 emissions** and meet climate targets at lowest cost (in particular for power and industrial point sources). It is expected to play **an emerging role by 2030** in decarbonization efforts (0.16-0.5 Gtpa vs. 40 Mtpa today) followed by **an acceleration by 2050** (>1.5-2.5Gtpa[1], up to 5-8Gtpa for some agencies[2]). CCUS adoption will be driven by cost reductions, providing that **stable policy support** and **carbon pricing mechanisms** are in place.

The main **barrier to adoption at scale** is the combination of capital intensity (capture costs ranging between $25-125/ton CO_2 for point source emissions, infrastructure needs) coupled with the **lack of a clear economic case for CO_2 use** outside of Enhanced Oil Recovery with storage, low volume use cases (e.g. carbon fiber) or short storage lifetime ones (e.g. food and beverage, fertilizers).

Costs are expected to come down (flat-30% between 2020-30 depending on source) and technology **may unlock new use cases**, but **3 uses only** combine both large volumes and long-term storage potential: EOR, cement & aggregates (early stage today), and geological storage. Among those, geological storage only can accommodate the magnitude (multiple Gtpa by 2050) required to meet climate targets.

While CCUS may represent a small part of the total decarbonization effort by 2030, **a sizeable market for CCUS technologies** is expected to develop, the larger part at the capture step of the value chain (CCS equipment, EPCs).

In the medium term CCUS will continue to **rely heavily on policy and government support** to accelerate deployment while longer term **carbon pricing** should become the main enabler for the economic viability of CCUS.

Note: (1) Assuming a carbon price ranging from $90 to $150; (2) Some agencies have set higher estimates (e.g. IEA with 5-6 Gtpa by 2050 in SDS scenario and 7.6Gtpa in NZE scenario) but this would likely require a higher carbon price, a faster ramp-up, and accelerated governmental support in infrastructure and CCUS facilities development.

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Bain Intersect$_{SM}$ forecasts higher carbon capture and removals of ~8 Gt CO_2 captured to ensure grid stability and decarbonize hard-to-abate sectors

Commentary

- **Intersect$_{SM}$ forecasts higher overall carbon capture and removal** than the IEA and ETC – PBS scenarios, driven by prolonged requirements for fossil fuel use in electricity generation enabled by CCS (53 EJ from coal and gas in IEA NZE, ~150 EJ in Intersect$_{SM}$)
- Prolonged requirements for fossil fuel usage + CCS in electricity generation is driven by two factors:
  - **Increasing need for grid stability:** as VRE share increases, managing supply/ demand fluctuations will require dispatchable power (e.g. coal/ gas); Intersect$_{SM}$ assumes higher requirements for grid flexibility vs. IEA
  - **Higher energy intensity:** IEA assumes energy intensity will drop off to 2 EJ/ $T GDP by 2050 vs. ~7 today); Intersect$_{SM}$ expects a more conservative drop off to 3-4 EJ/ $T GDP to account for developing countries increasing energy intensity

Note: ETC's ACF (Ambitious but Clearly Feasible) scenario is equated to APS, and PBF (Possible But Stretching) scenario is equated to NZE; ETC values directional based on FFT report
Source: Intersect v55, IEA WEO 2023, Energy Transition Committee – Fossil Fuels in Transition (Nov 2023)

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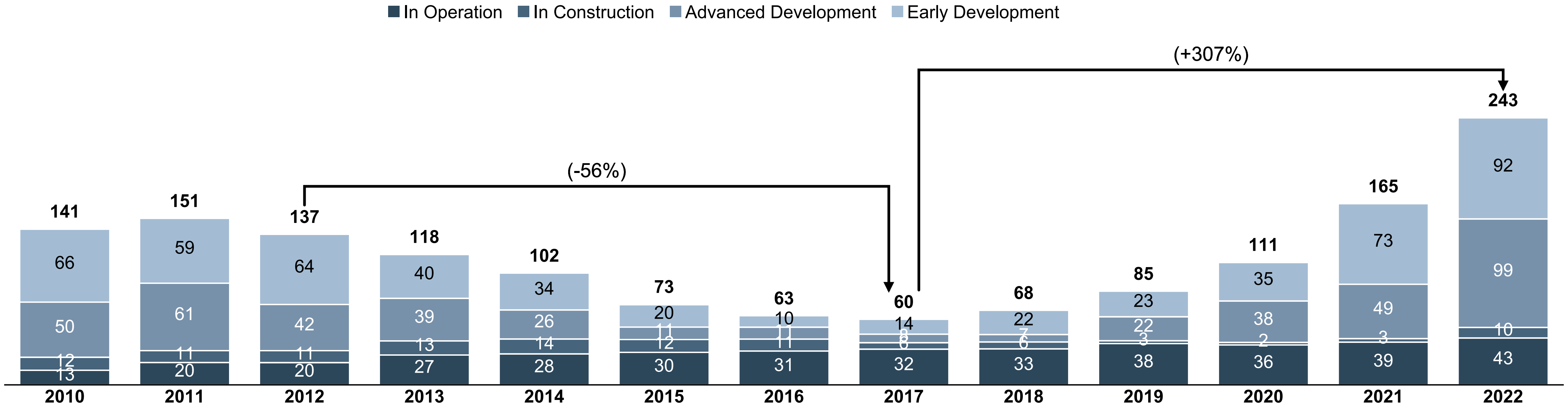
Strong momentum in CCS capacity pipeline growth in past few years with 30 large scale facilities in operations today (43 MTPA)

Pipeline development of commercial CCS facilities by CO_2 capture capacity (2010-2022, $MtCO_2$ p.a.)



- Growth towards 2011 mainly driven by large **Natural Gas Processing projects**:
  - Snøhvit CO_2 storage, NO (2008, 0.7 Mt/year)
  - Century Plant, US (2010, 5 Mt/year)
  - Petrobras Santos Basin, BR (2011, 4.6 Mt/year)

- **Continuous decrease** in both early and advanced development phase projects from 2011-2017 driven by
  - Need for recovery after financial crisis of '08-09 in private and public sector
  - Low/stagnating carbon emission costs in Europe (EUA) and the US (LCFS) until 2017
- **Operational capacity saw a slow and steady growth** during the same period from 20 to 32 Mt/Year (2012 to 2017)

- Strong growth in dev. pipeline driven globally by **growing interest in CCUS** to reach net zero emission targets
  - 83% of countries now with CCS in national long-term strategy
  - Recognized as a decarbonisation lever at COP26
  - Strong policy makers and investors appetite for committing to new projects (e.g. IRA's 45Q boost in the USA, Fit for 55 in Europe, dedicated CCUS funds in UK, NL, USA, etc.)
- Majority of projects expected to materialize by 2030

Note: Large-scale defined as > 0.4Mtpa of CO_2 capacity; 2021 and 2022 figures retreated with a new methodology, 2 suspended operational facilities excluded in 2021 and 2022 (2 Mtpa, Petra Nova and Lost Cabin Gas plant)
Source: Global CCS Institute Report, 2019, 2020, 2021 and 2022

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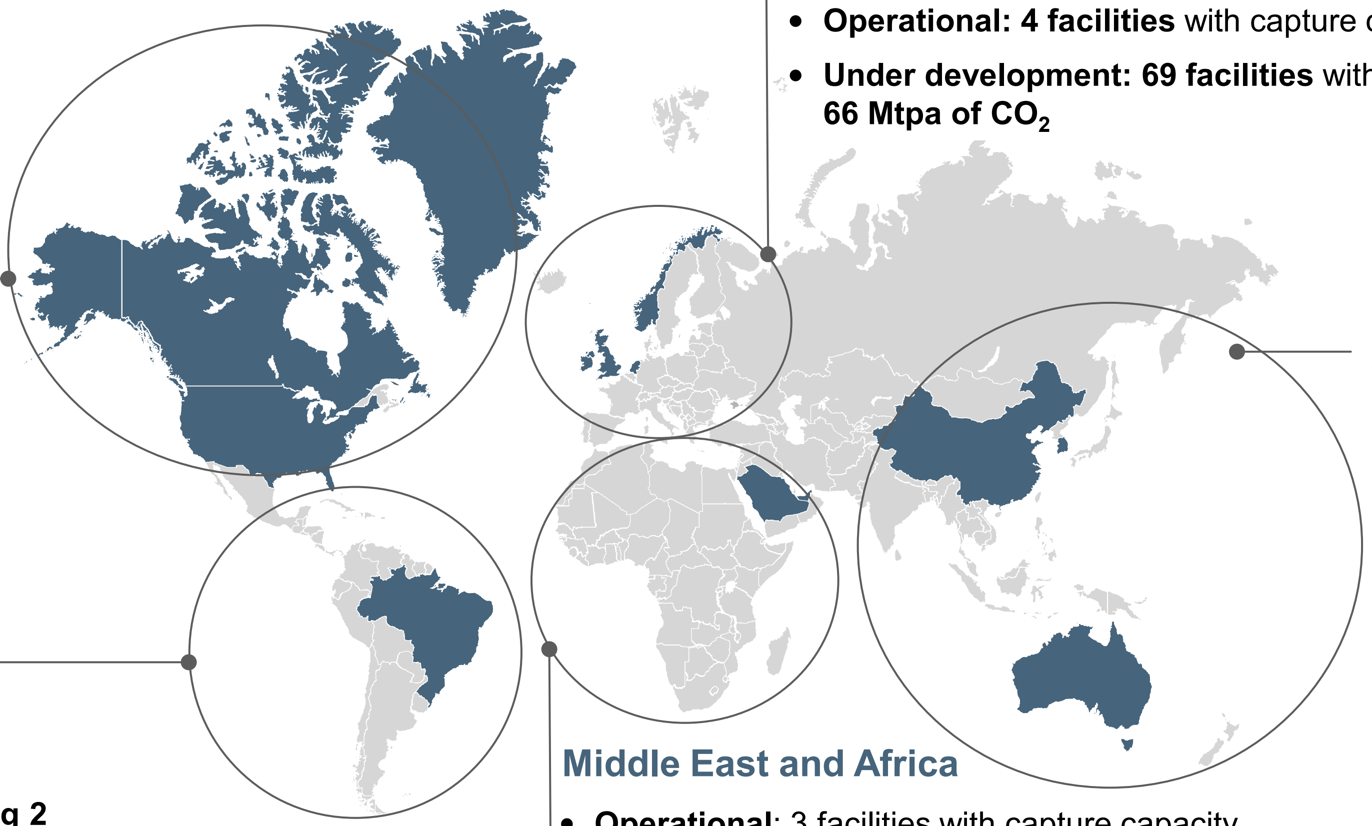
Currently, there are 30 operational CCS facilities (19 large-scale[1]) with ~43Mtpa combined CO_2 capture capacity; Majority of facilities are located in North America



North America

- **Operational: 18 facilities** with capture capacity of **24 Mtpa of CO_2** (13 facilities in the US, 5 in Canada)[2]
- **Under development:** 76 facilities with combined capture capacity of **94 Mtpa**

South America

- **Operational:** 1 **facility** in Brazil with capture capacity of **7 Mtpa of CO_2**
- **World Bank** CCS Trust Fund **funding 2 CCS pilot projects in Mexico**

Europe

- **Operational: 4 facilities** with capture capacity of **1.86 Mtpa of CO_2**
- **Under development: 69 facilities** with combined capture capacity of **66 Mtpa of CO_2**

Middle East and Africa

- **Operational**: 3 facilities with capture capacity of **4 Mtpa of CO_2**
- **Under development:** 3 facility with combined capture capacity of **3.3 Mtpa of CO_2**

Asia Pacific

- **Operational: 4 facilities** with capture capacity of **5.7 Mtpa of CO_2**
- **Under development: 17 facilities** with combined capture capacity of **37 Mtpa of CO_2**

Note: (1) Large-scale defined as > 0.4Mtpa of CO_2 capacity; (2) Excluding two USA facilities currently suspended: Petra Nova coal station and Lost Cabin Gas Plant; Includes commercial facilities > 0.1MTPA and Orca DAC plant (Europe, 4ktpa)
Source: Global CCS Institute Report, 2022; Lit search

Multiple projects are coming online in the coming years, reaching total CO_2 capture capacity of ~245Mtpa (153 Mtpa excluding projects at “early development” stage)

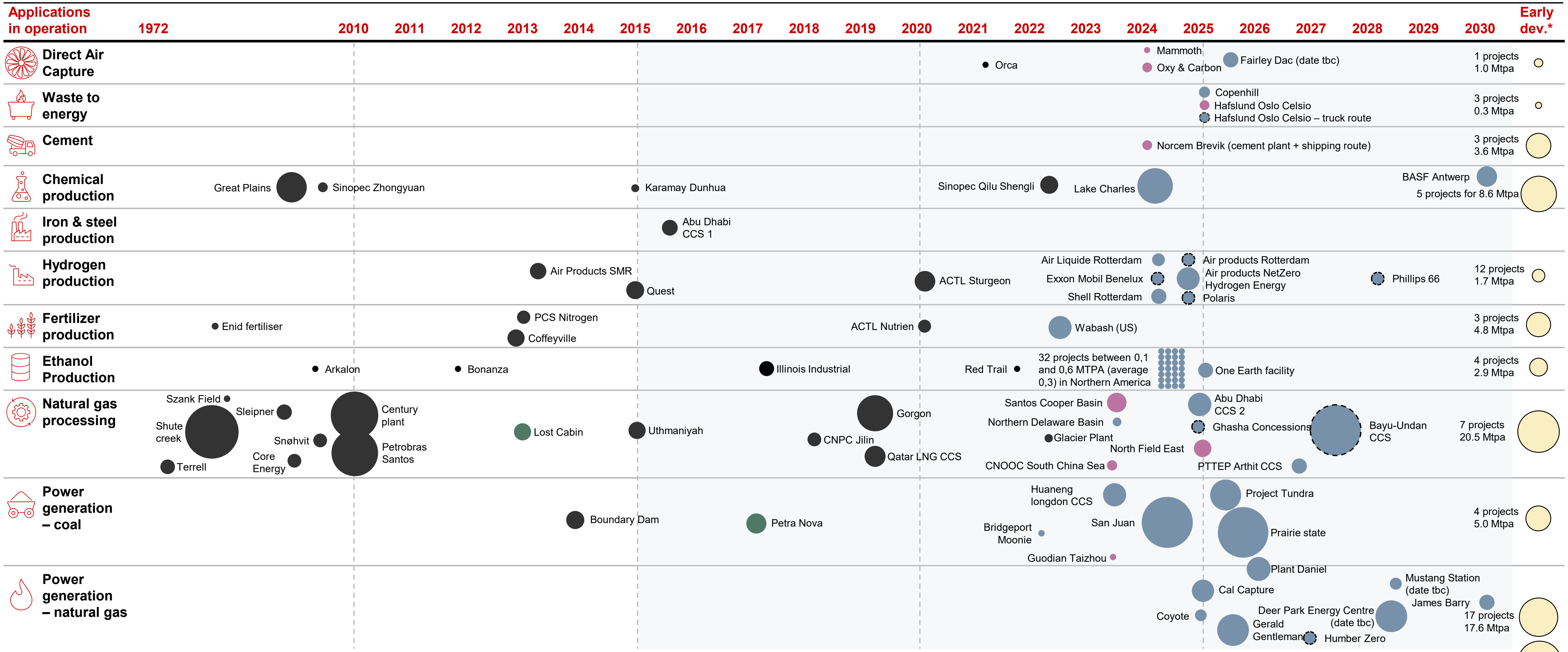
CCS PIPELINE BY APPLICATION

/Q4 2022

In operation · In construction · Advanced development · Operation suspended · Early development

1MTPA CO2, circle area proportionate to capacity · Bubble size not to scale

Commercial CCS facilities by industry, commencement of operation, & CO_2 storage option



Other applications: 16 projects 25.9 Mtpa

Note: Petra Nova paused operations in May 2020, due to low oil prices (E&E News, accessed 2020, November 11); (*) Capture capacity currently evaluated (not always estimated for each project)
Source: Global CCS Institute Report, 2022

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CCS projects are emerging in a number of different applications; majority of new projects coming online in the mid 20’s

A range of CO_2 capture technologies are available today, with varying maturity levels

Post combustion (Solvent Absorption, Sorbent Adsorption, Membrane separation, Cryogenic separation)

Technology	Description	Technology Readiness Level	Potential Uses	Example of players
Solvent Absorption	• Chemical solvents (traditionally amines) capture CO_2 from a gas stream via chemical bonding. Heating releases CO_2 and regenerates the solvent – used for low CO_2 partial pressure • For high CO_2 partial pressure physical solvents are used (e.g., Selexol, Rectisol) – reducing pressure releases the CO_2	• Mature: Proof of stability reached 0 … **9-11**	• Power generation (amine) • Natural gas processing (physical) • Industrial processes (e.g. cement, iron & steel, chemical manufacturing) • *More suited for retrofits*	Shell (*Cansolv*), Mitsubishi Heavy Industries (*KM CDR, KS1*), BASF, CO2 Solutions by Saipem, Fluor, Aker Carbon Capture, Honeywell UOP, Linde, Air Liquide
Sorbent Adsorption	• CO_2 adsorbs to the surface of a solid sorbent, chemically or physically (e.g. alumina, zeolite, activated carbon, MOF) • CO_2 is released via elevated temperature (for low CO_2 partial pressure), pressure (for high partial pressure), or electric current	• Prototype: Full prototype at scale 0 … **5-7** … 11	• Natural gas processing • Chem. manufacturing, H2, Fertilizers • *More suited for retrofits*	Svante, Air Products, InnoSepra
Membrane separation	• Permeable membranes allow selective passage of gases through them (membrane made from polymers such as polyamide or cellulose acetate, or from ceramic materials). High TRL for nat. gas, lower for others	• Demonstration: Pre commercial demonstration 0 … **6-7** … 11	• Natural gas processing • Industrial processes (iron & steel) • Desalination	Air Liquide, Honeywell UOP, gti, MTR, SINTEF
Cryogenic separation	• Compression and cooling of flue gas stream in multiple stages to separate condensed CO_2 (and other gases e.g. SO_2, NOx), with a high capture efficiency	• Prototype 0 … **5** … **8*** … 11	• Liquefied industrial gas products • Most point source (theoretical)	Air Liquide, Linde, MTR, Air Products
Oxy-fuel combustion - Direct firing	• Fuel is burnt in high concentration O_2 instead of air, reducing fuel consumption and generating flue gas rich in CO_2 that is easy to separate. Can also make use of supercritical CO_2 in the process (e.g. Allam-Fetvedt cycle)	• Large prototype for cement • Pre commercial (demo) for coal 0 … **5** … **7** … 11	• Power generation • Hydrogen production • Cement • Iron & steel • Oil and gas processing • *More suited for new builds*	NET Power, Linde
Oxy-fuel combustion - Chemical looping	• Type of oxy-fuel combustion, where combustion is done in separate oxidation reactors with metal oxides as oxygen carriers. The reducer flue gas produces steam and CO_2 easy to separate.	• Demonstration: Pre-commercial demonstration 0 … **7** … 11	(see above)	Carbon Engineering, calix (*Advanced calciner*)

Note: (*) Used since 2015 by Air Liquide & Esso in H2 plant in US (1st of kind); To be used in lime production by Air Liquide & Lhoist (MoU, 1st of kind); Technology readiness level framework from IEA

Source: NETL: Accelerating breakthrough innovations in carbon capture, utilization and storage (2017), IEA 'CCUS in Clean Energy Transition' (2020), NPC: Meeting the dual challenge (2019); Lit search

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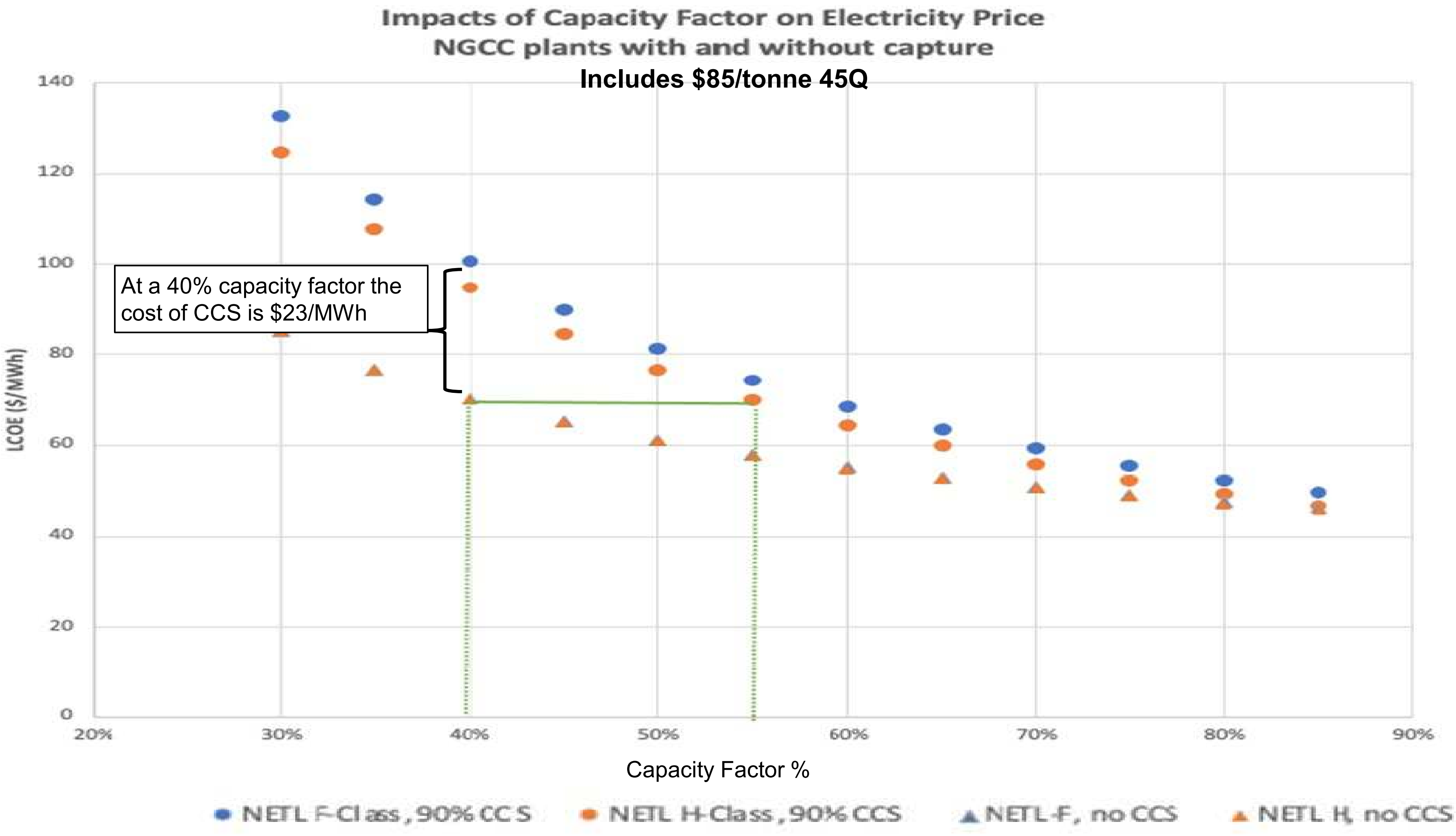
Electricity price with and without carbon capture at various capacity factors



- Costs shown for new natural gas plants with CCS (greenfield)
- At 0.40 tonnes of $C0_2$ per MWh of gas produced electricity, $23/MWh for CCS translates into $57.50/tonne CO_2
- At 55% capacity utilisation the MWh cost differential drops to $12/MWh (with CCS) which translates into $30/tonne $C0_2$.

Assumptions: 12-year amortization, 7 percent interest rate, $3.69/MMBtu natural gas, $85/tonne 45Q tax credit, and $10/tonne TS&M costs. Costs are based on 2021 dollars.
Source: National Energy Technology laboratory (NETL): cost and performance baseline for fossil energy plants volume 1: bituminous coal and natural gas to electricity. October 14, 2022

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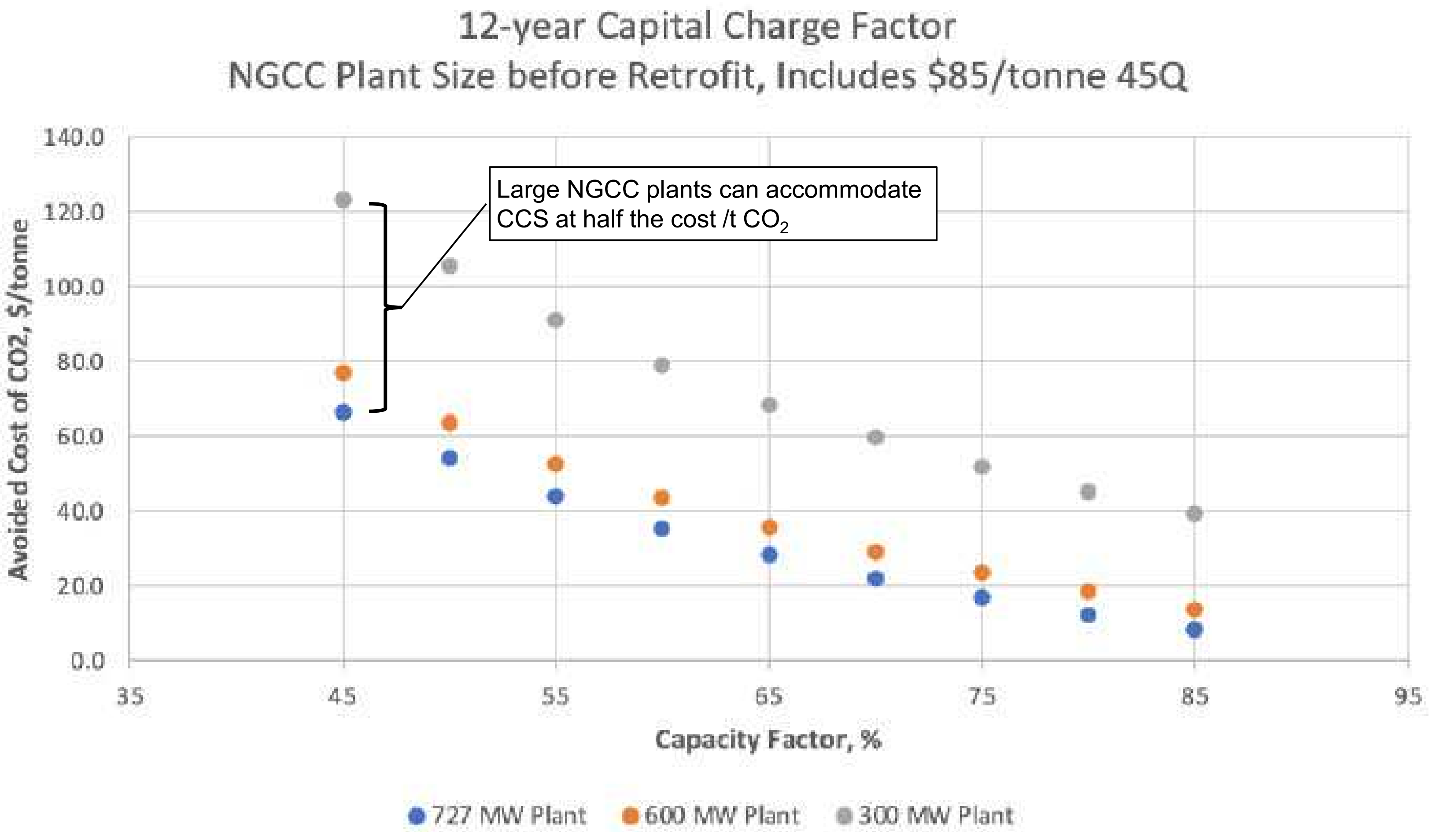
Cost of $C0_2$ avoided by NGCC plant size and capacity factor



From NETL Report:

"The cost-effectiveness of CCS at existing gas units tends to increase with the size of the facility at which they are located, as shown in the figure below and discussed further in Appendix A.

There are significant economies of scale, especially regarding storage and transportation infrastructure.

Covering single stand-alone units or a few larger units at a plant of multiple units inefficiently utilizes transportation infrastructure.

Larger plants tend to have correspondingly larger footprints and therefore more space to install CCS infrastructure and equipment.

Additionally, larger plants generally produce more CO2 (if operated frequently), and thus can earn greater 45Q tax credits to more rapidly defray installation capital costs and fixed operations and maintenance."

Assumptions: 12-year amortization, 7 percent interest rate, $3.69/MMBtu natural gas, $85/tonne 45Q tax credit, and $10/tonne TS&M costs. Costs are based on 2021 dollars.
Source: National Energy Technology laboratory (NETL): cost and performance baseline for fossil energy plants volume 1: bituminous coal and natural gas to electricity. October 14, 2022

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Confirm that this excludes transport and storage costs but 45Q slide does

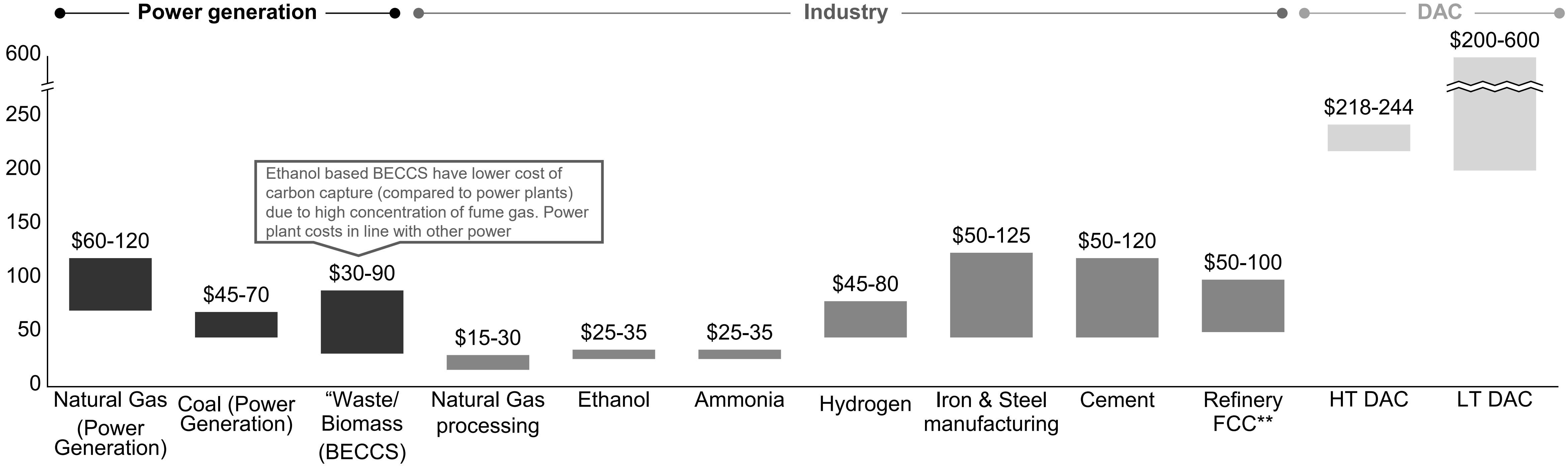
CO_2 capture costs differ across technologies, concentration being a key driver

CAPTURE | COSTS

Q4 2022

Currently Carbon price (Taxes or ETS) varies by country, generally higher for advanced economies. In Dec 2022 European ETS reached ~$85/ton

Current CO2 Capture Cost by source ($/ton)



	Natural Gas (Power Generation)	Coal (Power Generation)	"Waste/ Biomass (BECCS)	Natural Gas processing	Ethanol	Ammonia	Hydrogen	Iron & Steel manufacturing	Cement	Refinery FCC**	HT DAC	LT DAC
% of emissions	13%	11%	n.a	1%	3%	1%	<1%	7%	5%	2%	← n.a. (in theory total CO_2 atmospheric stock) →	
Concentration of fume gas*	~4%	12-14%	15-100%	95-100%	95-100%	95-100%	30-100%	21-27%	15-30%	16%	← 0.04% →	

Note: Includes compression / dehydration ($12-22); capture rate generally 85-95%; operating life of 30 years, cost of capital of 8%; other cost drivers include stream purity, capture volume, energy costs, heat integration, facility type (new build vs. retrofit)
(*) Post-combustion (**) Does not include higher purity SMR/hydrogen plant; Iron & Steel: hot stove & smelting process concentration (lower for lime calcining / sinter plant); Not shown: Aluminium (1% concentration), Pulp & Paper (15% concentration)
Source: IEA 2022, GCCSI 'Technology Readiness and Costs for CCS' (2021), IEA 'Is carbon capture too expensive?' (2021), IEA 'CCUS in Clean Energy Transition' (2020), NPC: Meeting the dual challenge (2019), IEA: Future of Hydrogen (2019); 'A Process for Capturing CO2 from the Atmosphere' Keith, (2018); Ember Climate

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45Q scheme has been continuously evolving to match US emission goals; with the latest revision, US is aiming to boost CCS deployment by 200Mtpa by 2030

POLICIES

45Q key evolving elements since bill inception

	2008	2018	2020	2022
Legislation	**Energy Improvement and Extension Act**	**FUTURE Act**	**Consolidated Appropriations Act**	**Inflation Reduction Action Act**
Status	Passed	Passed	Passed	Passed *in August 2022*
Incentive value	Sequestration: **\$20/tCO_2** EOR: **\$10/tCO_2**	Sequestration: **\$50/tCO_2** EOR: **\$35/tCO_2**		Sequestration: **\$85/tCO_2** / DAC + Seq.: **\$180/tCO_2** EOR: **\$60/tCO_2** / DAC + EOR: **\$130/tCO_2**
Eligible CO_2 use cases	**EOR**	**CO_2 to fuels, chemicals, other products (e.g., cement)**		
Inflation adjustment	Annual adjustment for inflation	Credit to be adjusted for inflation post 2026		
Expiration	**75 million tons of CO_2** on a first-come first-served basis	Construction commencement by **2024**	Construction commencement by **2026**	Construction commencement by **2032**
Timeline		Up to **12 years** after first capture year		Up to **20 years** after first capture year
Emitter size (minimum KTPA)	**Power plants:** 500 KTPA **Industrial:** 500 KTPA	**Power plants:** 500 KTPA **Industrial facilities:** 100 KTPA		**Power plants:** 19 KTPA **Industrial facilities:** 13 KTPA
Incentive pay-out mechanism	**Tax rebate**			**Tax rebate or Direct Pay**

Source: BetterEnergy; CarbonCapture coalition; CAFT;GCCSI; IRS; Lit.Search

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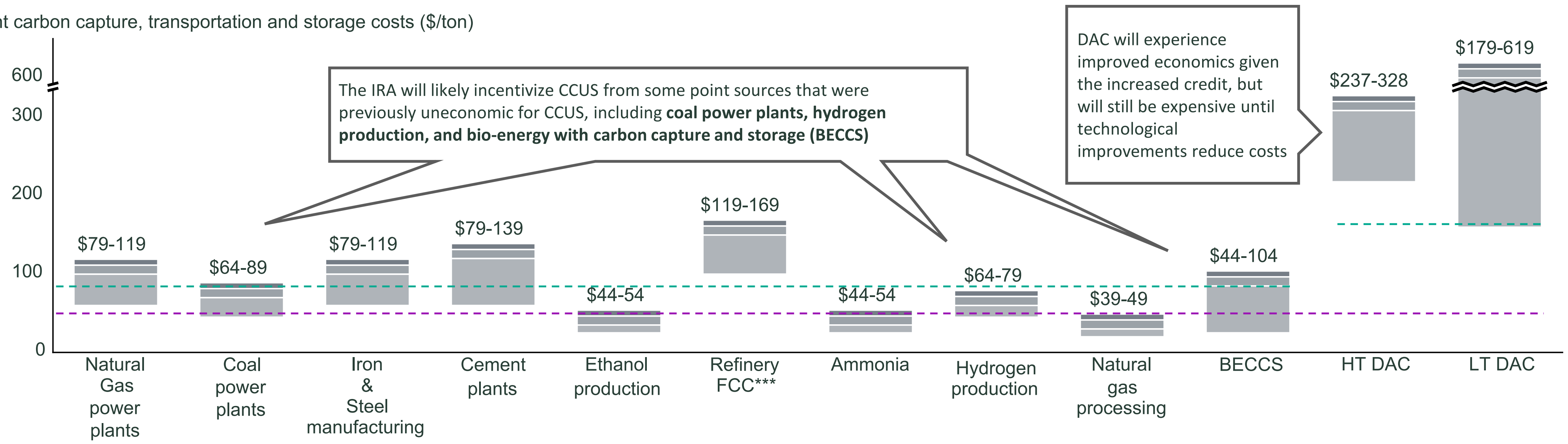
IRA impact | The IRA makes point source carbon capture more economically viable, but less so for DAC despite higher credits

ALTERNATIVE VIEW INCLUDING TRANSPORT & STORAGE (AVERAGES USED, NEEDS TO BE TAILORED AS NEEDED)

CAPTURE | COSTS

PRELIMINARY

Current carbon capture, transportation and storage costs ($/ton)



	Natural Gas power plants	Coal power plants	Iron & Steel manufacturing	Cement plants	Ethanol production	Refinery FCC***	Ammonia	Hydrogen production	Natural gas processing	BECCS	HT DAC	LT DAC
% of emissions	13	11	7	5	3	2	1	<1	1	n.a	n.a. (in theory total CO2 atmospheric stock)	
Concentration of fume gas**	~4%	12-14%	21-27%	15-30%	95-100%	16%	95-100%	30-100%	95-100%	95-100%	0.04%	

Average Storage Cost
Avarage Transportation Cost
Capture Cost Range
New credit for stored carbon ($85/ton for industrial facility; $180/ton for DAC)
Previous credit for stored carbon ($50/ton)

Note: *Current costs are for stored carbon include storage costs; **Heat integration in point-source capture also a driver of cost *** Except hydrogen plant, with high purity .
Source: IEA 'CCUS in Clean Energy Transition' (2020), NPC: Meeting the dual challenge (2019), IEA: Future of Hydrogen (2019); 'A Process for Capturing CO2 from the Atmosphere' Keith, (2018); The Costs of CO2 Transport ZEP; Expert interviews

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In addition to CO_2 concentration, multiple other factors impact capture costs and explain differences between sources and sectors

2 CAPTURE COSTS

Key factors driving costs	Comments
CO_2 concentration	• Capture from higher CO_2 concentration (and/or partial pressure) sources is easier and cheaper – As concentration goes down a higher surface area / larger separation tower is required, increasing Capex – Generally, dehydration/compression or physical solvents are sufficient for high concentration streams while chemical solvents/sorbents with higher energy needs for regeneration are required for low concentration • Percentage of CO_2 captured also impacts costs (higher rate drives costs up)
CO_2 purity	• Higher levels of contaminants in the fume gas along with CO_2 (e.g. NOx, SO_2, SO_3, HCl) complicates the separation process and increases equipment Capex • Purity of CO_2 required downstream of the capture process also impacts costs
CO_2 volumes / facilities scale	• Higher volume point sources and larger plants can leverage economies of scale – **Capex**: capital costs (e.g., machinery including compressors, separation tower) do not increase proportionally to volumes captured, lowering costs per tonne CO_2 as scale increases – **Opex:** Easier to optimize processes (e.g., running solvent) at scale lowering costs; energy penalty might also be lower for large scale installations
Energy cost	• Energy is required to regenerate capture media and dehydrate & compress CO_2 compress to high pressures for transport & storage
Energy usage	• Re-using energy from parts of the plant's processes lowers energy needs to operate CCS system
CO_2 access	• CO_2 can be harder to access in some configurations – e.g. steel mills have three major CO_2 emission sources, requiring multiple capture plant or other configurations that complicates the process, refineries have multiple emissions sources also
New build vs. Retrofit	• Plants suitable for retrofitting usually cheaper than building new CO_2 capture plants

These factors vary by facility and industry, which generates different needs for technology and drives cost disparities across (and within) facilities and industries

Note: Cost of capital also a cost factor, focus above on technical / physical drivers; Source: IEA 2020, NPC: Meeting the dual challenge (2019), GCCSI 2021, Leeson, N. Mac Dowell, N. Shah, C. Petit, P.S. Fennell 'Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources ' (June 2017), Expert interviews, Lit search

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Point Source: Cost reduction is expected to be driven by a combination of factors

COST CURVES

Key factors driving costs	Impact	Comments
Technology advances	• Capital cost • Variable O&M • Fuel cost	• Developments of higher efficiency technologies (e.g., solvents with lower regeneration energy or reduced degradation), new designs (e.g., heat integration), new capture routes with lower energy penalty (e.g., cryogenic)
Plant economies of scale	• Capital cost • Variable O&M • Fixed O&M	• Larger plants provide economies of scale as equipment cost is not proportional to capture volume (incl. hubs reducing unitary costs) • Optimizing operations easier to achieve on large scale plants • Higher volumes could decrease the energy penalty
Modularisation	• Capital cost	• Modular capture plants design developments (using standardized, mass-produced modules off-site, standardized design, etc.) lowering equipment cost and construction time
CCS equipment	• Capital cost	• Higher volumes drive cost down for equipment and machinery suppliers e.g., compressors, separation unit, solvents etc.
Competition between EPCs	• Capital cost	• Increasing competition between EPCs to adopt CCS technology is driving prices of project integration down
Project efficiency (‘Learning by doing’)	• Capital cost • Variable O&M • Fixed O&M	• Experience would enable optimization of plant size, better technology, optimized equipment choices, and more efficient running processes

“Scaling and technological developments are the main drivers behind the cost reduction in the CO_2 capture.”
Head of CCS business development, Global EPC

“The unit cost is reduced by economies of scale as higher volumes enable more cost-efficient investment and maintenance of machinery.”
Assistant Head CCUS R&D and Innovation Policy, UK Government

“Significant cost reductions can be achieved from one generation of plants to the next through technology refinement and efficiency improvements, as well as capital & operating cost reductions, based on lessons learned from plants already in operation.”
The role of CCUS in low-carbon power systems, IEA

“The developers of these facilities (Petra Nova and Boundary Dam) advised that if they built the facility again, they could reduce the capital cost by at least 20% by applying what they had learned from their first project.”
Carbon capture and storage, GCCSI

Note: Financing costs costs are also a driver – higher volumes of projects and support (e.g., loan guarantees, low-cost finance) could reduce uncertainty / risks and lower capital costs
Source: Expert interviews, CCUS in Clean Energy Transition IEA, Lit research

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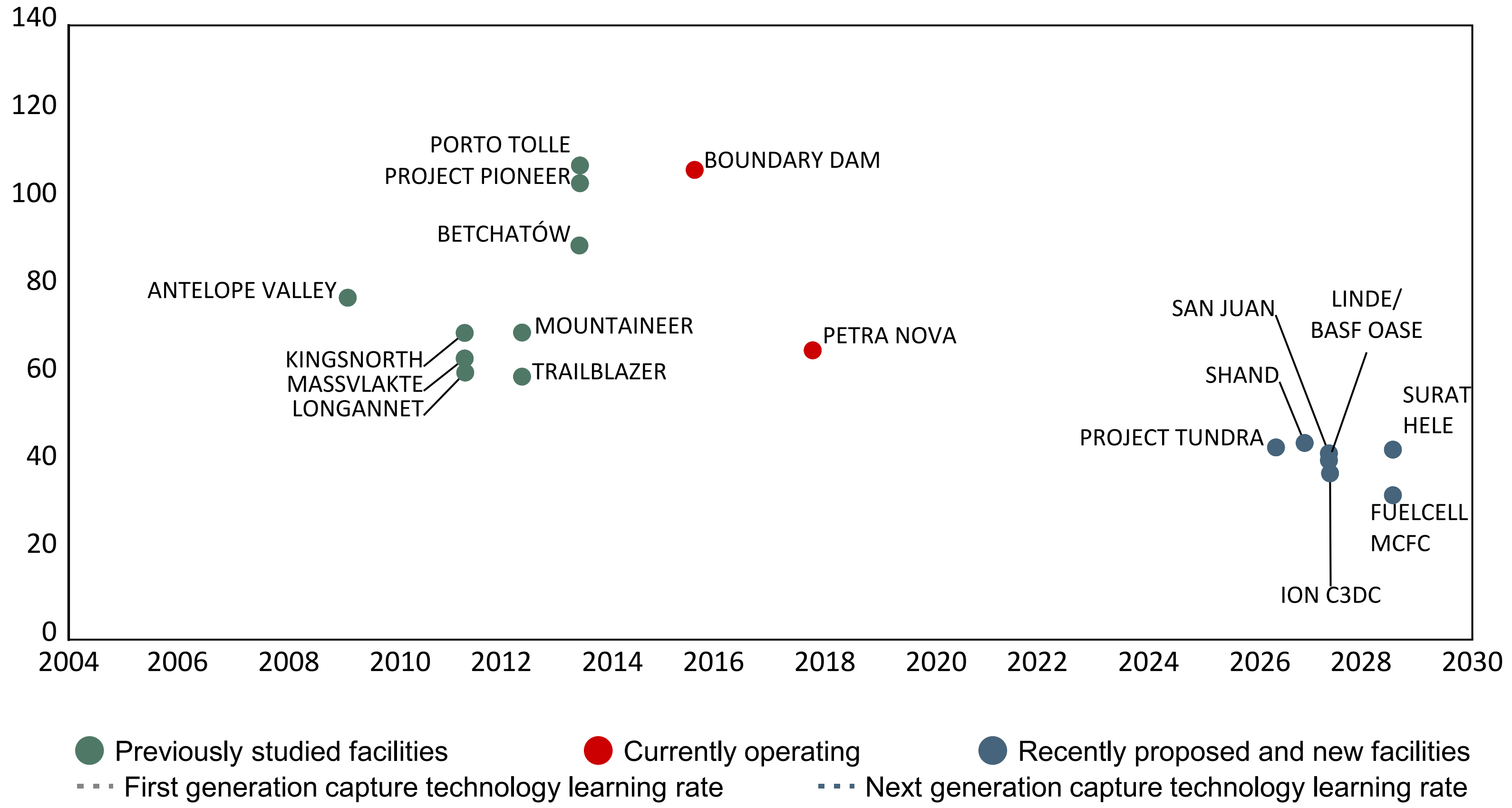
Point Source: CO_2 capture cost per ton has been shifting downwards to below $50-$60/ton in current proposed facilities (North America coal power generation example)

Levelized cost of CO_2 capture for large-scale coal power generation (US$ 2017/tCO_2)



Levelized cost of CO_2 capture for selected plants (US$ 2017/tCO_2)

Note: Post combustion amine-based capture systems; 8% discount rate, 30 years project life, 2.5 years construction time, capacity factor of 85%. Cost data are normalized to 2017 values. Expected accuracy range: Boundary Dam and Petra Nova: -10% to +15%, Shand: -25% to +40%. * Petra Nova paused operations in May 2020, due to low oil prices (E&E News, accessed 2020, November 11)
Source: Global CCS Institute Report, 2019

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Majority of amine technologies owned or exclusively served by an EPC, while other technologies are more open

2 CAPTURE

NOT EXHAUSTIVE

	Amine technologies	Other CO_2 capture technologies
Technology embedded within EPC	Mitsubishi Heavy Industries, Ltd.; Fluor; Aker Carbon Capture	Baker Hughes *(purchased Compact Carbon Capture)*; Saipem *(purchased CO_2 Solutions)*
Announced EPC partnership	Shell + Technip Energies: • No equity investments • Global bidding relationship BASF + Linde: • No equity investments • Tech development and bidding relationship	NetPower + McDermott: • McDermott minority investment • Global bidding relationship Svante + Kiewit (US) + Technip Energies (EMEA): • EPC services coupled with Svante's solution
No EPC partnership	Carbon Clean	Carbon Engineering; Climeworks; CO2 Capsol; ION Clean Energy; C-Capture; IFP Energies nouvelles (DMX process); Global Thermostat

Source: Lit. search

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Carbon capture: A high-level mapping of the CCUS value chain shows the important players driving development in central areas of the industry

BUSINESS MODELS

NOT EXHAUSTIVE

	Carbon capture	**Carbon transport and storage**	**Carbon utilization**
	Capture CO_2 from industrial facilities (or direct from air)	Transport compressed CO_2 by pipeline (or truck/ship) to end-user or storage (incl. storage identification)	Purification and utilization of CO_2 to form valuable products or for enhanced oil recovery
Energy/ Industrial companies	**Independent CCS plant operators** Utilities (Coal, Gas, Biomass, W2E) O&G (platforms, refineries) Cement & Concrete Iron & Steel Chem & Petrochem Pulp & paper, etc. Mobility OEMs	**Storage operators** E.g. O&G (storage) **Other operators** Pipeline operators Transportation infrastructure manufacturers (pipelines, ships, trucks)	**Users of CO2** Upstream O&G (EOR) Utilities (working fluid) **Manufacturers of carbon products** Cement & Concrete Iron & steel Chemicals & plastics Food & Beverage Material tech
'Pure Plays'	E.g. DAC plants operators	E.g. Pure players storing CO2	Multiple applications E.g. Carbon nano tubes, Synfuel

EPCs and Technology providers

- EPC
- Services / specialist advisors
- OEMs and technology providers
- *Research institutions and Universities*

Source: Bain experience

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Major O&G players are pursuing CCUS as part of their operations

CCUS FOR O&G PLAYERS

/ NOT EXHAUSTIVE

Company	Country	2019 revenues	Technologies development	Pilot project	Full scale project
Shell	UK / Netherlands	$345B	✓ Participation in the Technology center Mongstad (Norway)		✓ Quest; Northern Light (Norway); Gordon in Australia
Saudi Aramco	Saudi Arabia	$329B	✓ Mobile capture technology, CO_2 usage (polyols with Converge)		✓ Uthmaniyah oil field EOR from nat. Gas processing capture (0.8Mtpa)
bp	UK	$277B	✓ Feasibility study for the "Clean gas" project		✓ Operator of Net Zero Teesside (10 Mtpa CO_2 starting ~2025) in UK
ExxonMobil	US	$256B	✓ Partnerships with FuelCell and Global Thermostat to develop CC technologies		
Total	France	$176B	✓ Participation in the Technology center Mongstad (Norway)		✓ Northern light project in Norway (1.5 Mtpa CO_2 starting 2024) Holcim Portland project in the US (0.7 Mtpa CO_2 starting 2026)
Chevron	US	$140B			✓ $1B+ invested on CCUS projects; e.g. Gorgon or Bayou Bend in Australia
eni	Italy	$85B	✓ Partnership with Adnoc – UAE		
equinor	Norway	$63B	✓ Participation in the Technology center Mongstad (Norway)		✓ 40 CCUS projects of which Northern light in Norway
Repsol	Spain	$51B		✓ DAC and usage in Synfuel production	

O&G companies are co-investing (e.g. Technology center Mongstad) and working together (e.g. Northern Light project) to develop their expertise in CCUS

Source: Lit. search; Bain expert interviews

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CCUS Adoption – Executive Summary

- Currently, there are **30 facilities operational CCS facilities** (of which 19 large-scale > 0.4MTPA) with ~43Mtpa combine CO_2 capture capacity; the majority of facilities are located in North America with the United States leading (13 facilities, ~45% of the capacity)
  - Operating capacity gradually increased between 2010–22; project pipeline decreased until 2017 but is showing signs of recovery since then
  - By source, most of capacity goes to **natural gas processing**, with several facilities dedicated to ethanol, hydrogen, fertilizers, iron & steel
  - By use, most of the volume in Enhanced Oil Recovery (storing ~31Mtpa), the remaining dedicated to permanent geologic storage
- Going forward, **multiple projects should come online** by 2030, bringing combined capture capacity to **~243Mtpa**, led by natural gas processing (27% of the additions) together with select projects across most other sectors
- Despite these, CCUS is currently off-track in IEA's clean energy tracker to meet the **Sustainable Development Scenario or the Net Zero Scenario**, across both power and industry applications – today and in terms of planned capacity (e.g., 240Mtpa+ by 2030 under SDS)
- While the viability and attractiveness of CCUS is expected to vary by use case and region, several critical factors will play a role, namely (1) Capture and Transport costs (2) Policy incentives, and carbon pricing (3) use cases (4) capacity build-up
- We considered **two scenarios** for CCUS capacity by 2030 based cost evolution and carbon price: in our **base case** ($35/ton) ~160Mtpa could come online; in our **aggressive case** ($70/ton) capacity could reach ~550Mtpa
  - Lower cost high purity sources (Nat. gas processing, ethanol, fertilizers, H_2) together with coal are expected to see the highest CCS capture volumes
  - Under the base case, EOR is the largest use case followed by cement and high value uses (polycarbonates, medical, food & beverage), while under the aggressive case aggregates and large scale storage becomes economically viable and see sizeable uptake
  - The cost associated with this capture would range from **$6-38B p.a., or $30-160B cumulative**
- By 2050, **1.7 to 2.5Gtpa** could come online based on a carbon price ranging from **$90-150/ton** (base case vs. aggressive case)
  - Increasing role of **storage** in 35-50% of volume abated. Main use cases being **EOR**, **cement** and **aggregates** while other chemicals become economically viable
- In addition to cost reductions and carbon pricing, the above will require **strong policy & investment support** as well as **continued stakeholder management,** including institutions, businesses, and the general public

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We considered two scenarios for global volume of yearly CO_2 capture by 2030; Ranging from 160Mtpa to 550Mtpa depending on costs evolution and carbon price

SCENARIOS

/ 2030 ESTIMATE

The world in ***2030***	**Conservative case**	**Accelerated case**
Overall CCUS abatement capacity	**~160 M ton CO_2 / year**	**~550 M ton CO_2 / year**
Equivalent CO_2 cost	**~$6B/year** (carbon price of $35/ton)	**~$38B/year** (carbon price of $70/ton)
Costs	• **Capture**: Evolution of **0-20% reduction**[1] over 20-30 depending on the sources • **Transport**: Evolution of **1-3% reduction** over 20-30	• **Capture**: Evolution of **10-30% reduction**[1] over 20-30 depending on the sources • **Transport**: Evolution of **3-5% reduction** over 20-30
Regulations & carbon price	• Carbon taxes and / or ETS pricing at **~$35/ton CO_2** globally	• Carbon taxes and / or ETS pricing at **~$70/ton CO_2 globally (key driver of adoption / volume captured)** • Strong government support to **develop and scale CCUS infrastructure** (storage and transport, driving cost reductions)
Use cases	• Mostly **EOR** (~40-45%), **carbon-cured concrete** (~30%) and to a lesser extent **Food & Beverage** and other uses (~10%)[2]	• **Storage** becomes economically viable **: ~200 $MtCO_2$** (~35%) • Main uses: **EOR** (~15-20%), **cement aggregates** become viable (~15%) and **carbon-cured concrete** (~15%)[2]
Capacity	• **Fertilizer use case excluded** from abated capacity (deferment) • Among abated capacity, **~80% of long lifetime abatement** (~140 $MtCO_2$ pa)	• **Fertilizer use case excluded** from abated capacity (deferment) • Among abated capacity, **~90% of long lifetime abatement** (~500 $MtCO_2$ pa)

Given strong pipeline growth from 2021 to 2022 (165 to 243mtpa by 2030), Conservative case now less likely; however completion rate has historically been lower than 100%

Note: (1) Excl. for DAC (estimated between 30-40% cost reduction over 2020-30) (2) Under both scenarios, use cases with high economic viability are represented (low volumes): medical uses, carbonates, F&B
Source: IEA, GCCSI, NPC, Lit search, Expert interview, Bain analysis

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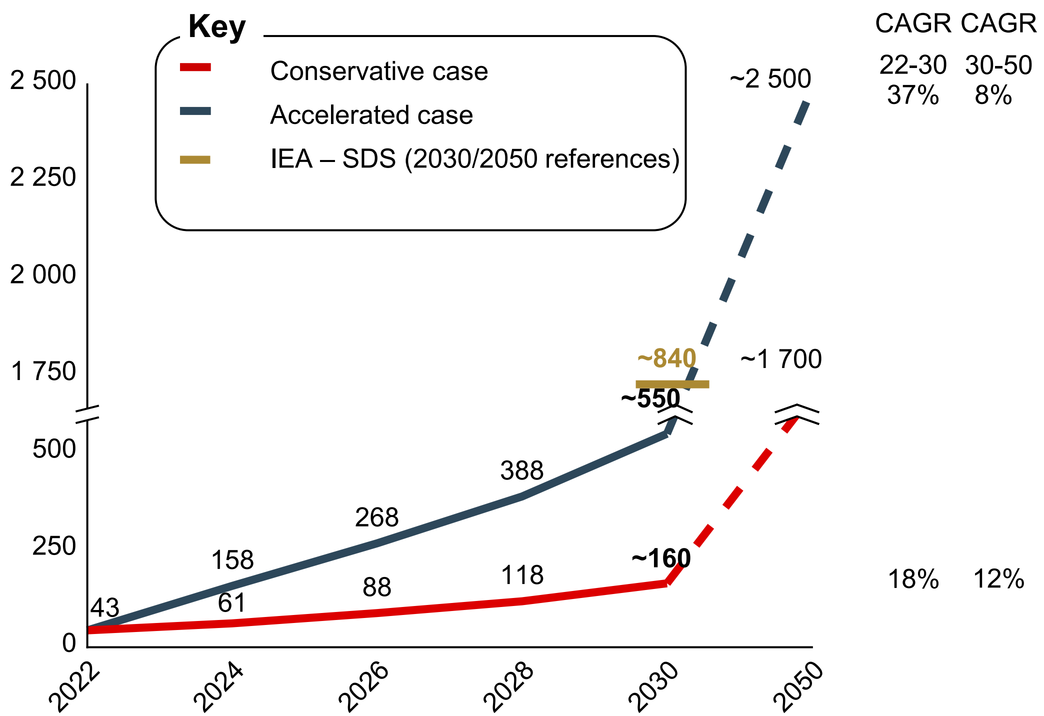
Significant volatility between cases with important implications on abatement cost from carbon price – 160Mtpa to 550Mtpa CO_2 capacity by 2030

160-550 Mtpa CO_2 expected to be abated in 2030 and 1.7-2.5 Gtpa CO_2 by 2050

Global yearly CO_2 abated – Conservative vs. accelerated scenario
(2022-50; in $MtCO_2$ p.a.)



Carbon price ($)	2022	2024	2026	2028	2030	2050
Conservative	29	31	33	34	35	90
Accelerated	29	49	63	67	70	150

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China’ CCUS development accelerated significantly in 2023

- China has around 40 CCUS demonstration projects in operation or under construction, with a total annual capture capacity of around 3 million tonnes per year, the CCTV report said.
- July 12 2023: China’s first carbon capture facility at a **NGCC facility** commences operation in Hainan Island, developed by Huaneng Group. This pilot plan aims to capture 2,000 tonnes of CO2 per year with Huaneng’s own post-combustion capture technology. (assume this is a tiny pilot plant).
- Once China Energy’s Yulin Jinjie 150 ktpa **coal-fired power plant** carbon capture project came online in June 2021 in Shaanxi province, the company immediately started to plan a 500 ktpa amine-based post-combustion coal power project in Taizhou, Jiangsu province.
- Learning from the 150 ktpa project, the new facility not only shortened the time of planning, designing and construction, but also greatly improved the amine solvents performance and reduced overall costs. This 500 ktpa project commenced construction on 22 March 2022, finished construction on 31 December that year, was commissioned in May 2023 and officially became fully operational on 2 June.
- Dr. Dong Xu, the project head from China Energy, suggested the overall capture cost has been reduced by 30% and the overall capture energy consumption is now less than 2.4 GJ/tonne CO_2. With these improvements, the overall capture cost has reduced to Chinese Yuan 250/tonne CO_2 **(US$35/tonne CO_2).**
- US and China each will advance at least 5 large-scale cooperative Carbon Capture, Utilization and Storage projects by 2030, including carbon capture from industrial and energy sources, according to Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis, jointly released by both governments. Nov 15, 2023

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Calpine Case Study

Calpine Corporation is America's largest generator of electricity from natural gas and geothermal resources with robust commercial, industrial and residential retail operations in key competitive power markets. Founded in 1984, we use advanced technologies to generate power in an efficient, cost-effective and environmentally responsible manner

Baytown Carbon Capture Project

Located in Baytown, Texas, The Baytown Energy Center is being actively assessed for a carbon capture project designed to capture 95% or more of CO2 emissions from turbines and auxiliary boilers at this facility. Located less than 10 miles from Calpine's Deer Park Energy Center, this facility is near significant CO2 storage resources along the Texas Gulf Coast. As a combined heat and power generation facility, carbon capture at this facility will enable it to provide low-carbon industrial heat to co-located facilities and low-carbon power to the Texas grid.

Deer Park Carbon Capture Project

The DOE has awarded us a grant to support the carbon capture project at our Deer Park Energy Center, located in Deer Park, Texas. In collaboration with industry leader Shell Cansolv, this project is set to be one of the world's largest carbon capture projects and will be designed to capture 95% or more of total CO2 emissions from flue gas generated from all five turbines at Calpine's Deer Park Energy Center. As a combined heat and power generation facility, carbon capture at this facility will enable it to provide low-carbon industrial heat to co-located facilities and low-carbon power to the Texas grid.

Los Medanos, California Carbon Capture Project

Installing carbon capture technology in California is essential to eliminating greenhouse gas emissions by 2045 without compromising reliability. Calpine is utilizing federal incentives at the Los Medanos Energy Center (LMEC) to test the newest CCUS technology needed to achieve California's emissions goals. LMEC, developed in 2001, is a highly efficient, natural gas-fired, combined-cycle cogeneration facility with advanced air emissions control technologies located in Pittsburg, California. On July 14, 2023, Calpine unveiled Project Enterprise at LMEC, a first-of-its-kind carbon capture demonstration pilot that is testing advanced technology optimized to support a cleaner electricity grid.

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