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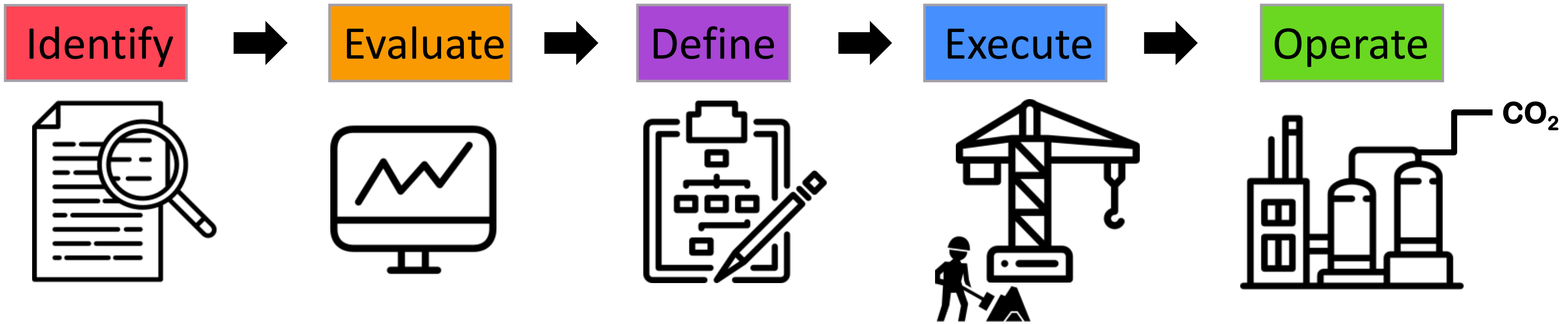
Carbon capture & storage (CCS): the way forward



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Energy & Environmental Science

REVIEW

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Carbon capture and storage (CCS): the way forward

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Source: Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

Overview of the paper

Source: Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

Current status of CCS development

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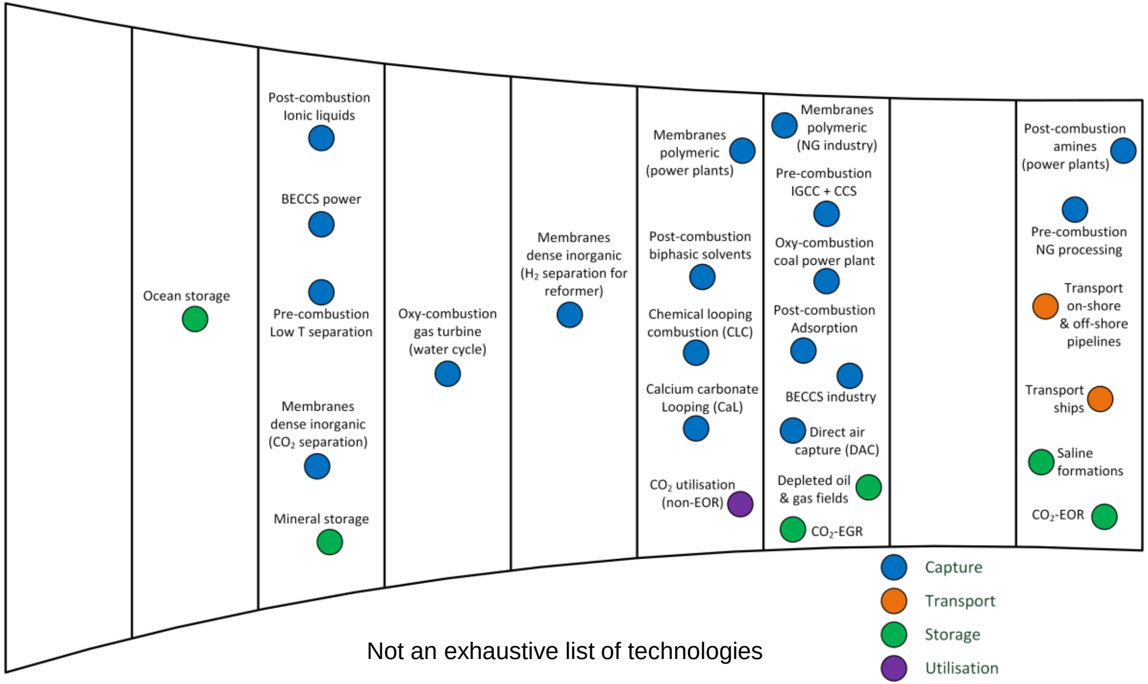
Concept	Formulation	Proof of concept (lab tests)	Lab prototype	Lab-scale plant	Pilot plant	Demonstration	Commercial Refinement required	Commercial
TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9



There is a suite of CCS technologies for capture, transport and storage of CO_2.

Technologies advance through a series of scale-up steps (lab to commercial scale).

Congestion occurs at TRL 3, TRL 6 & TRL 7.

Development tends to be hindered due to technical challenges or insufficient funding.

Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

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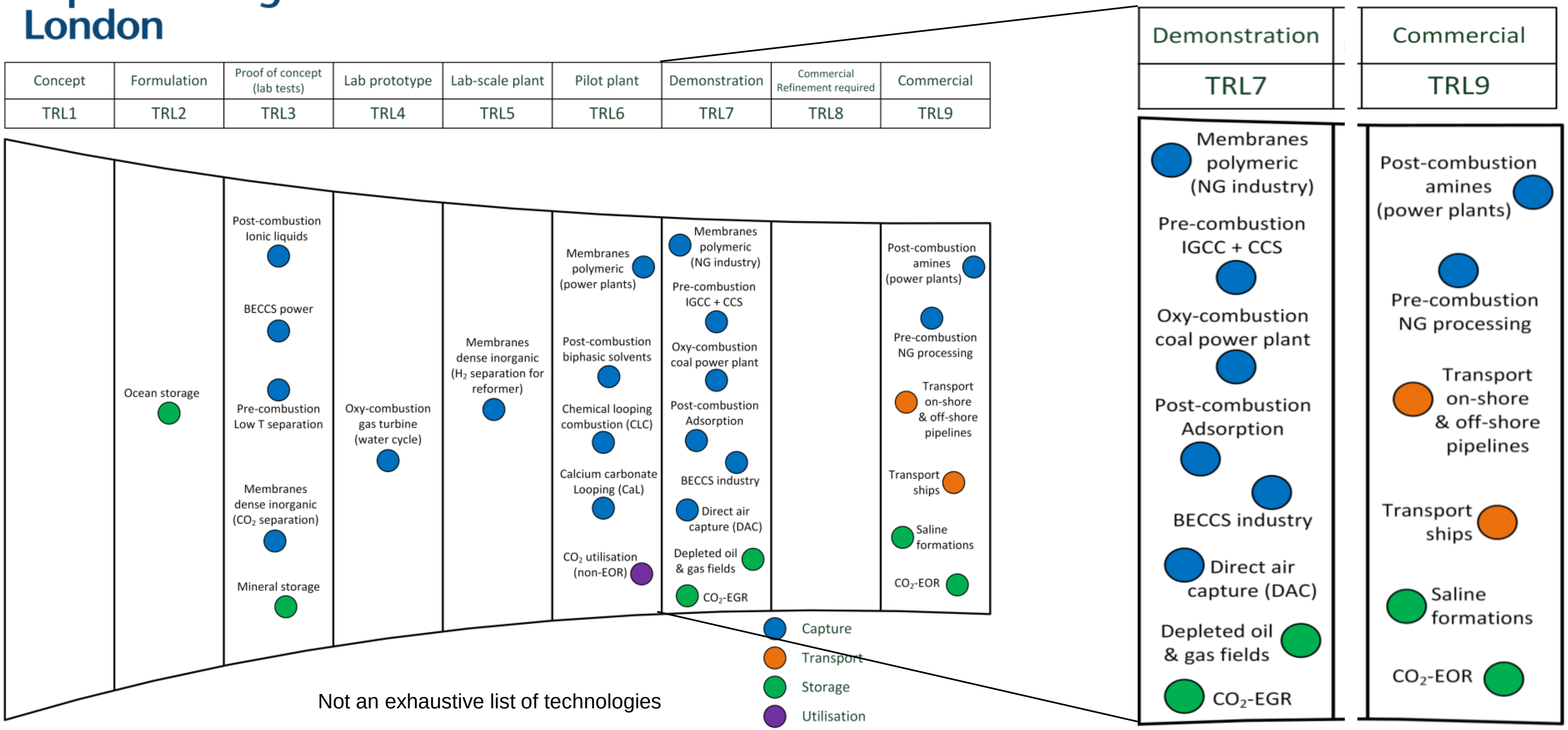
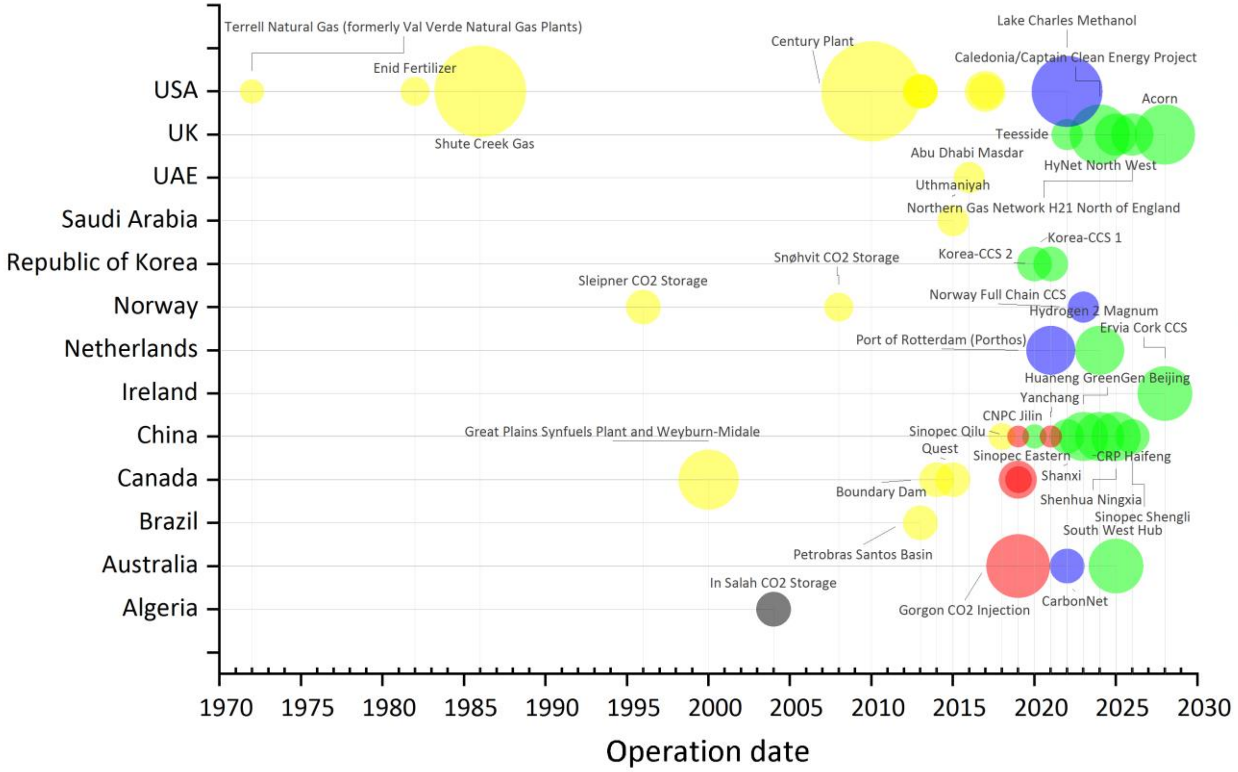
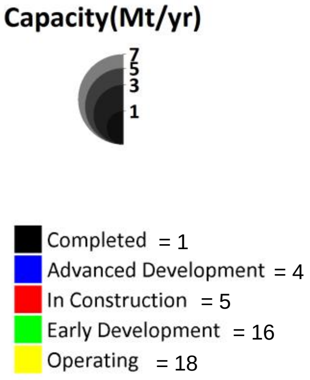
Current status of CCS development



Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

Global status of commercial scale CCS





Total capacity of CO_2 captured = 31.7 Mtpa (operating phase)

IPCC scenarios limiting to 2 °C requires a capture rate of ~10 Gt_{CO2}/year by 2050.

Current CCS deployment rate is insufficient to meet the climate change mitigation targets.

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Need for new benchmarks

To accelerate development, technology benchmarks need to be updated, preferably with current industrial best practice.

30 wt% MEA is still the current sorbent benchmark, despite being outclassed by solvents such as PZ and AMP.

Comparing new materials against obsolete benchmarks is potentially limiting progress.

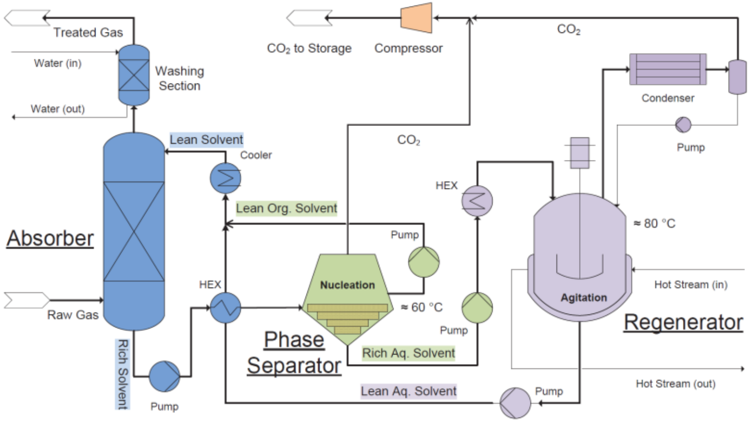
Important that the lab-scale experiments study the materials under conditions representative of the "real world" – high CO_2 partial pressure for desorption, presence of contaminants.

Solvent	Reboiler duty (GJ per t_{CO_2})
30 wt% MEA	3.6–4.0
40 wt% MEA	3.1–3.3
40 wt% (8 molal) piperazine (PZ)	2.9
Cansolv	2.3
32 wt% EDA	3.2–3.8
28 wt% AMP + 17 wt% PZ	3.0–3.2
MEA + MDEA (variable mix ratio)	2.0–3.7
Aqueous ammonia (NH_3)	2.0–2.9*
Aqueous potassium carbonate (K_2CO_3)	2.0–2.5
Amino acids	2.4–3.4*
DEEA + MAPA	2.1–2.4
DMCA + MCA + AMP	2.5 (not including extraction)

Source: Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

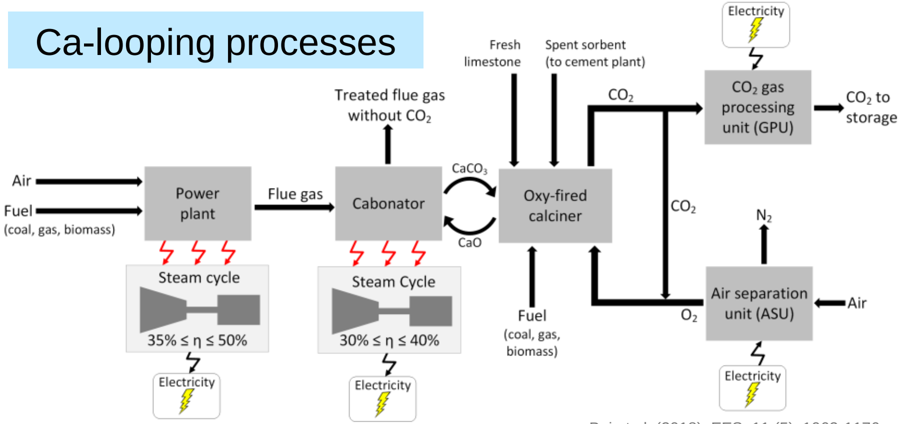
Next generation processes for CCS

Multi-phase absorbents



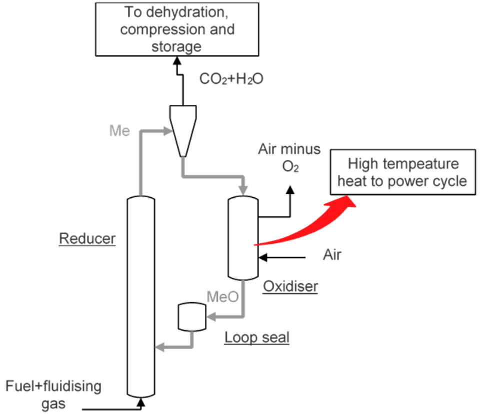
Zhang et al., Energy Procedia, 37, 1254–1261, 2013.

Ca-looping processes



Bui et al. (2018). EES, 11 (5), 1062-1176.

Chemical-looping processes



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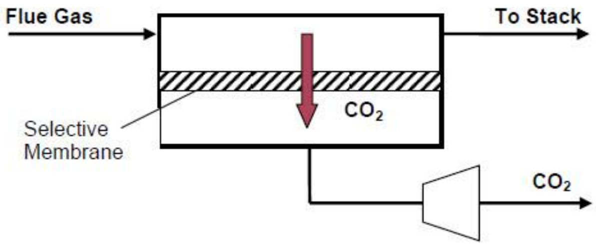
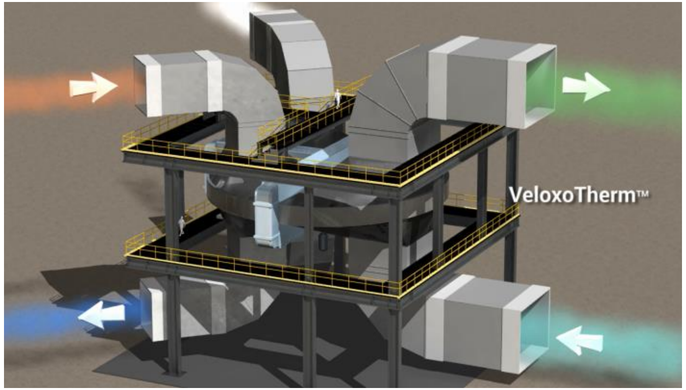
Membrane-based technology



Source: Global CCS Institute, CO_2 capture technologies: post-combustion capture (PCC), Membranes, 2012.

Rotary structured honeycomb adsorber



Source: http://inventysinc.com/

Technologies for atmospheric CO_2 removal

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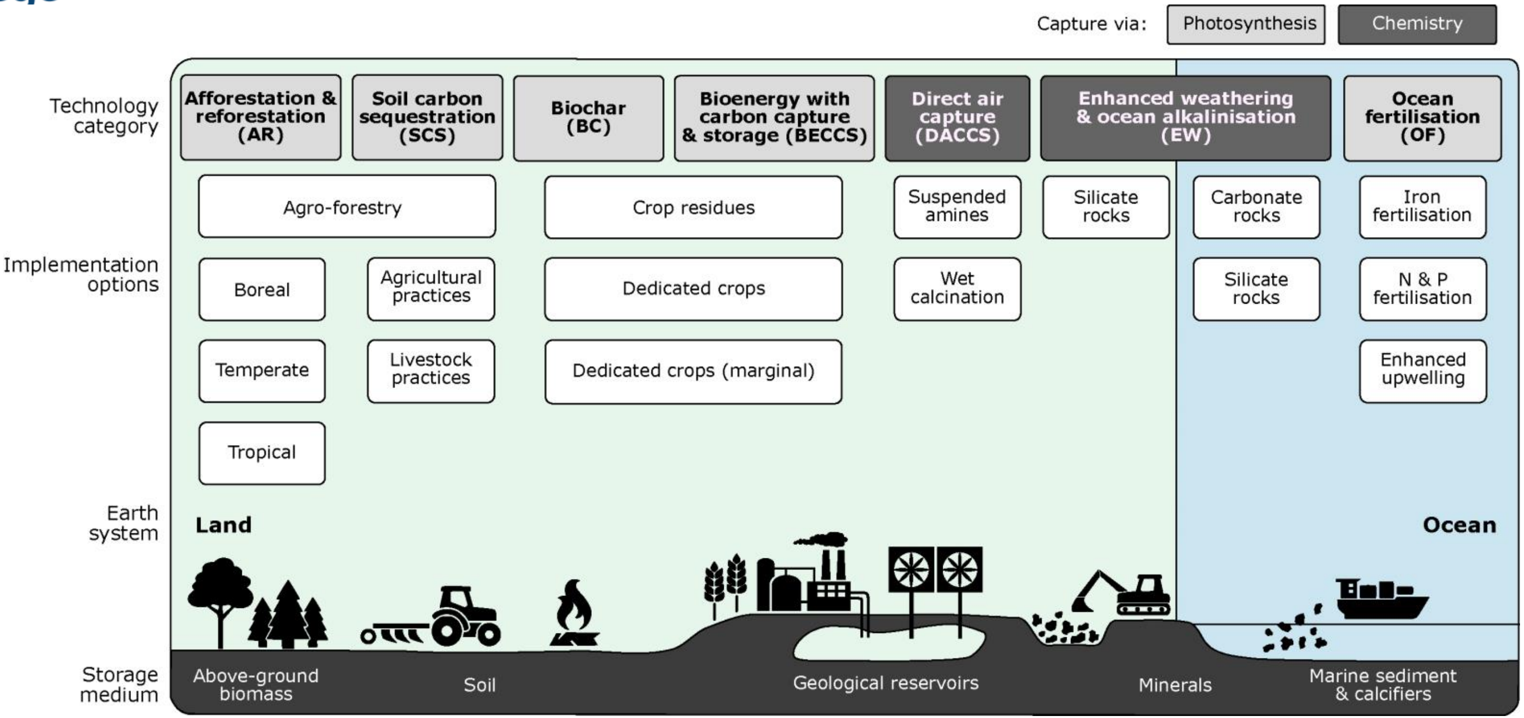
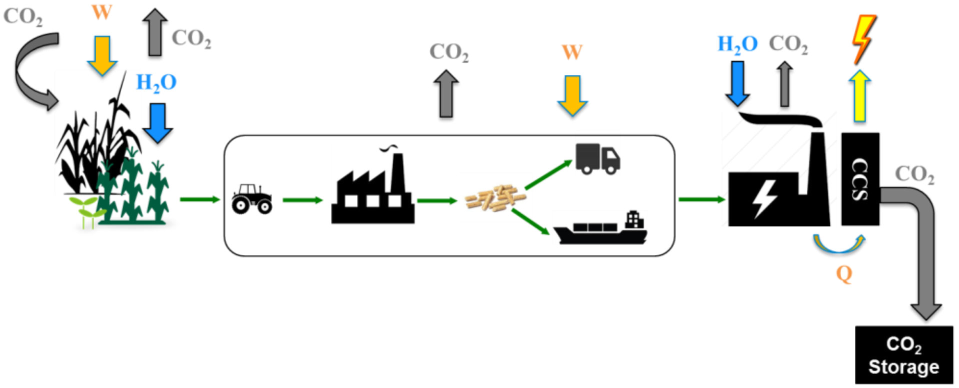


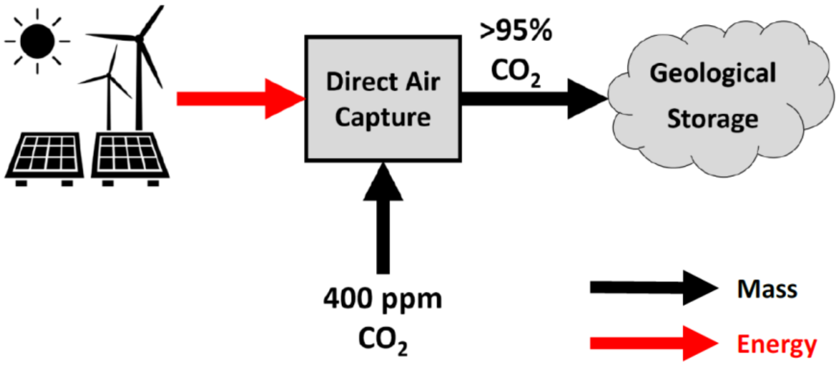
The portfolio of *readily available* technologies that enable negative emissions is very limited, and all solutions should not be regarded as competing but complementary.

BECCS and DACCS rely on accessibility/availability of reliable CO_2 storage. Deploying both in parallel could enable risk sharing, thereby promoting progress of these technologies.

Fuss, S., et al. (2018). Environmental Research Letters, 13 (6), 063002.
Nemet, G. F., et al. (2018). Environmental Research Letters, 13 (6), 063003.

Figure: Minx, J. C., et al. (2018). Environmental Research Letters, 13 (6), 063001.





Bioenergy with CCS (BECCS)

Direct air CO_2 capture with storage (DACCS)

	BECCS		DACCS
Land demand (ha per $t_{CO2,eq}$ per year)	Forest residues	0.27 – 0.46	0.003
	Agricultural residues	0.16	
	Dedicated energy crops	0.03 – 0.11	
Cost estimate (US$/$t_{CO2}$)	60–250		100–1000 (most quoted is APS range 600–800)

Bio-energy with CCS (BECCS)

5 BECCS plants worldwide in the industrial sector – CO_2 from bioethanol production is used in CO_2-EOR.

Major challenges:

- Land availability for sustainable production of biomass feedstock – land demand depends on the selected feedstock (has a given yield).
- In the absence of a mature CCS industry, attempting large-scale BECCS deployment may be challenging.
- Need to understand the region-specific nature of BECCS.
- Also, public perception and acceptance challenges.
- Need to address policy questions around incentivising/ regulating negative emissions.

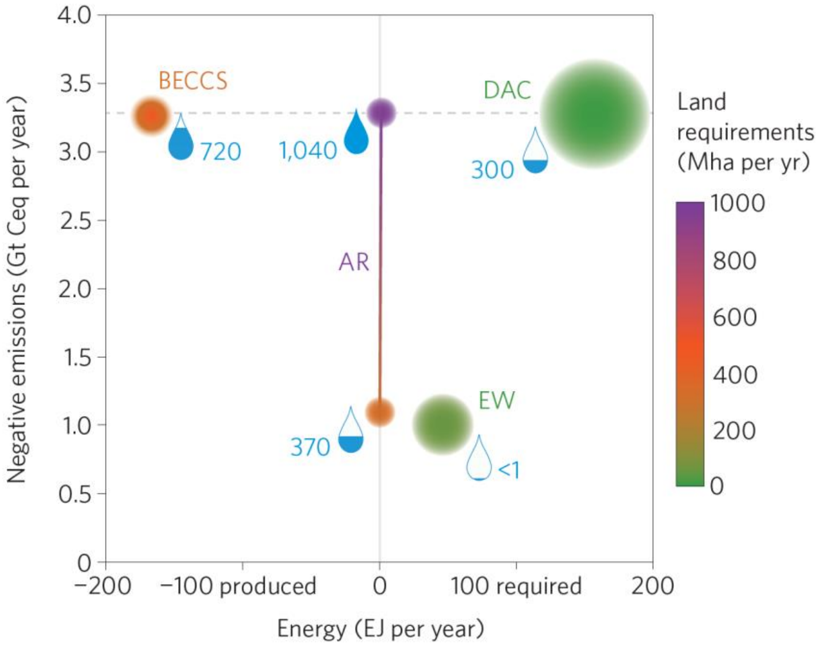


Figure: Smith, P., et al., Nature Climate Change, 6, 42–50, 2016.

Direct air CO_2 capture & storage (DACCS)

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Direct capture of CO_2 from air is possible – demonstrated by Climeworks and Carbon Engineering (not yet full DACCS chain).

Major challenges:

- Due to dilute concentrations of atmospheric CO_2 – DACCS encounters technical and economic challenges.
- Substantially high costs compared to other NETs and CCS technologies.
- Requires sorbent with much higher affinity to CO_2 (~2 orders of magnitude greater than conventional amine-based capture).
- Consequently, sorbent regeneration is much more challenging and necessitates a chemical shift process (instead of TS/PS).
- Treating vast volumes of air in order to capture a meaningful amount of CO_2, e.g., capture of 1 Mt_{CO2} per year necessitates the processing of 80 000 $m^3\ s^{-1}$ of air.

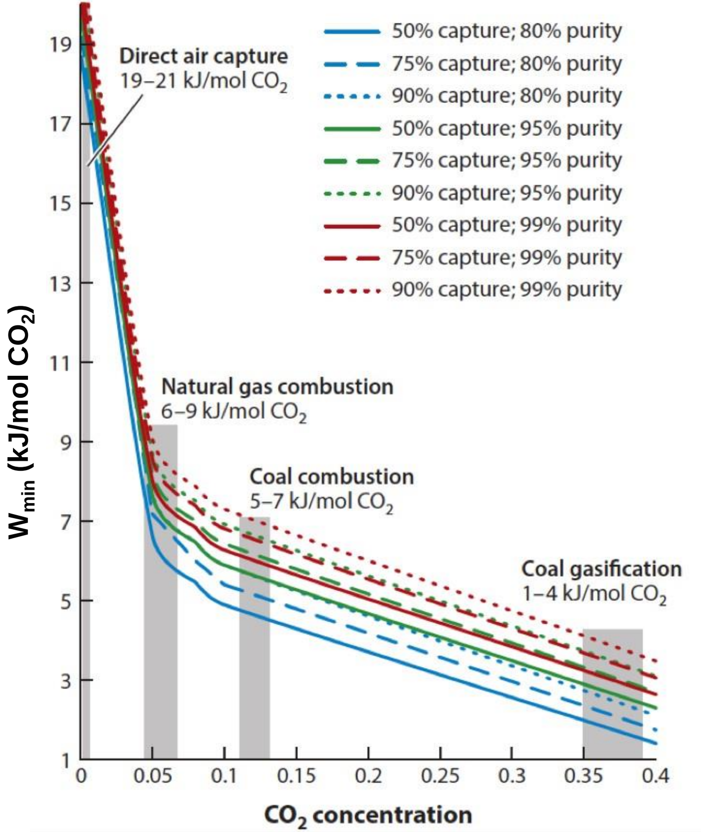

Figure: J. Wilcox, et al., Annu. Rev. Chem. Biomol. Eng., 2014, 5, 479–505

Industrial CCS

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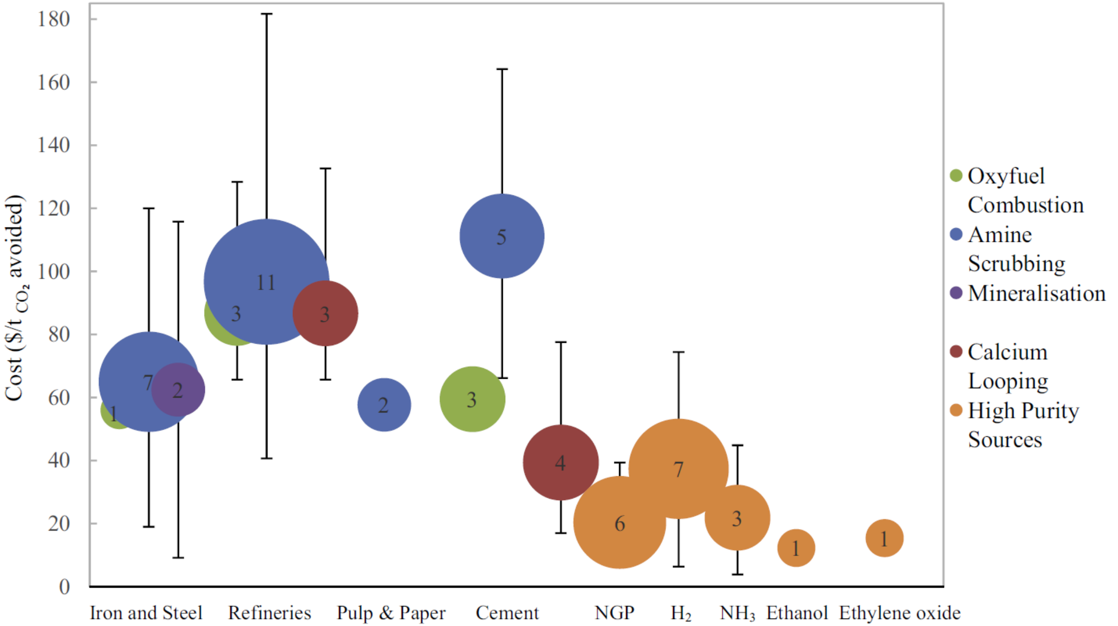
Industrial processes contribute 25% of the global CO_2 emissions.

Industry	Carbon intensity
Steel	1.8 t_{CO2}/t_{steel}
Cement	0.6–1 t_{CO2}/t_{cement}
Refining*	0.04–0.06 t_{CO2}/barrel crude

Industrial decarbonisation: Challenges

- Industries tend to be energy intensive & depend on using fossil fuels.
- No obvious alternative to CCS (power sector has renewables).
- International nature of industry.



* Average refinery emissions intensity.
Ref: CBE–UCS Final Report, Oil Refinery CO_2 Performance Measurement, 2011.

Fig: Leeson, D., et al., International Journal of Greenhouse Gas Control, 61, 71–84, 2017.

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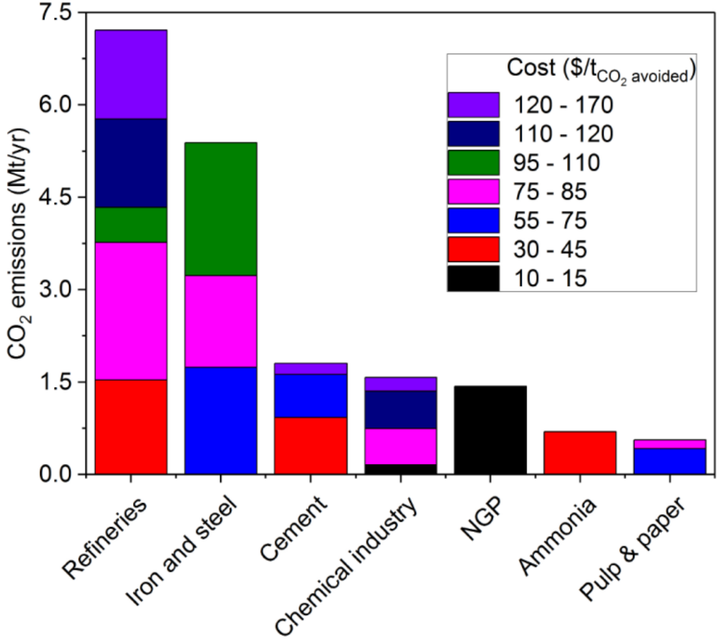
Industrial decarbonisation: Challenges

- Industries tend to be energy intensive & depend on using fossil fuels.
- No obvious alternative to CCS (power sector has renewables).
- International nature of industry.
- Multiple sources of CO_2 emissions within the process with varied concentration.



Within the range of product prices (particularly oil), the end-use sectors could possibly afford to pay for decarbonisation.

Industrial symbiosis, e.g. waste heat recovery, may reduce cost

* Average refinery emissions intensity.
Ref: CBE–UCS Final Report, Oil Refinery CO_2 Performance Measurement, 2011.

Fig: Leeson, D., et al., International Journal of Greenhouse Gas Control, 61, 71–84, 2017.

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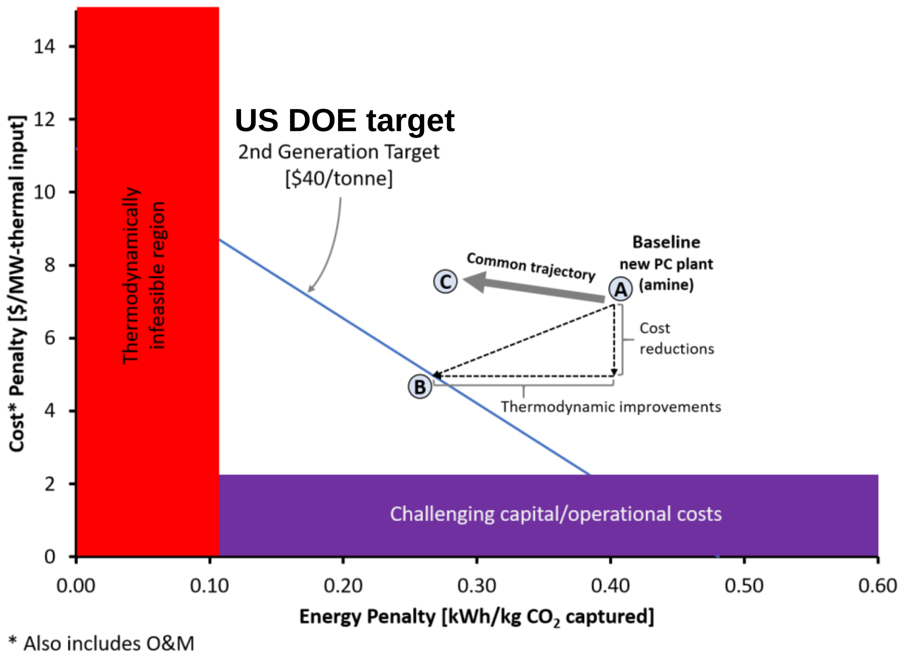
Technology improvement & cost reduction



CCS community focuses on reducing the cost to capture CO_2, whereas the CO_2-emitting facility will prioritise minimising the cost of their low carbon product (e.g., electricity).

R&D initiatives aimed towards “improving” CCS should take a whole systems approach.

Focus on reducing the cost per unit of decarbonised product (e.g., steel, cement, power) and how the decarbonised process will compete in the market.

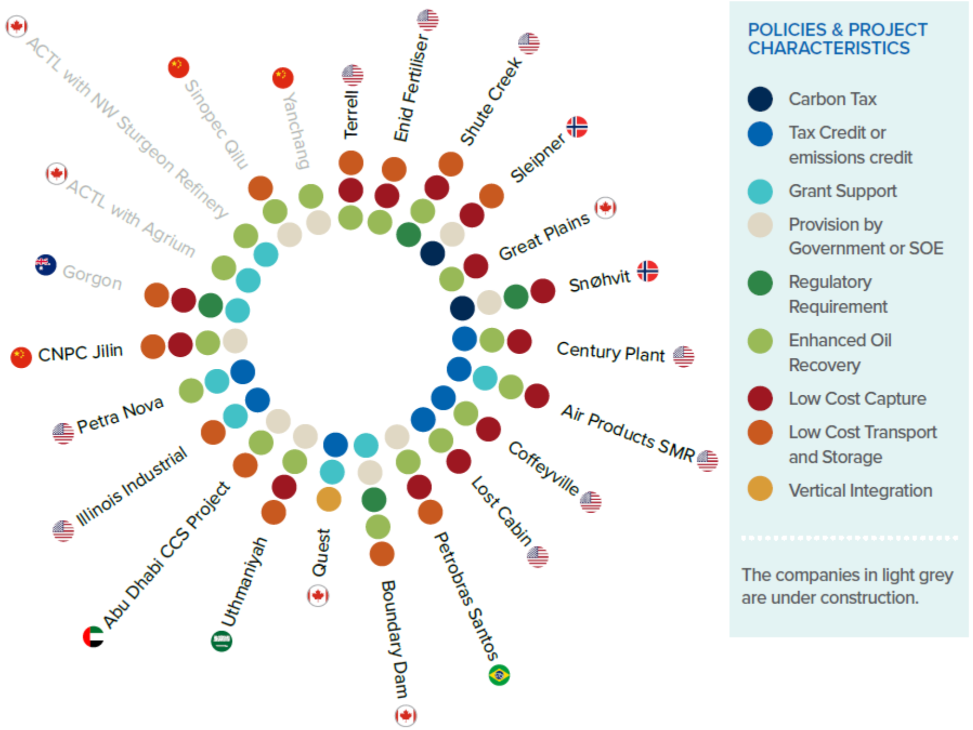
Distinct from focussing on minimising the cost of capturing CO_2.

Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

There is a lack of a proven models for the commercialisation of CCS (distinct to the CO_2-EOR industry – more straightforward).

Policy considerations

Overcoming the barriers to investment for CCS



Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

Policy considerations

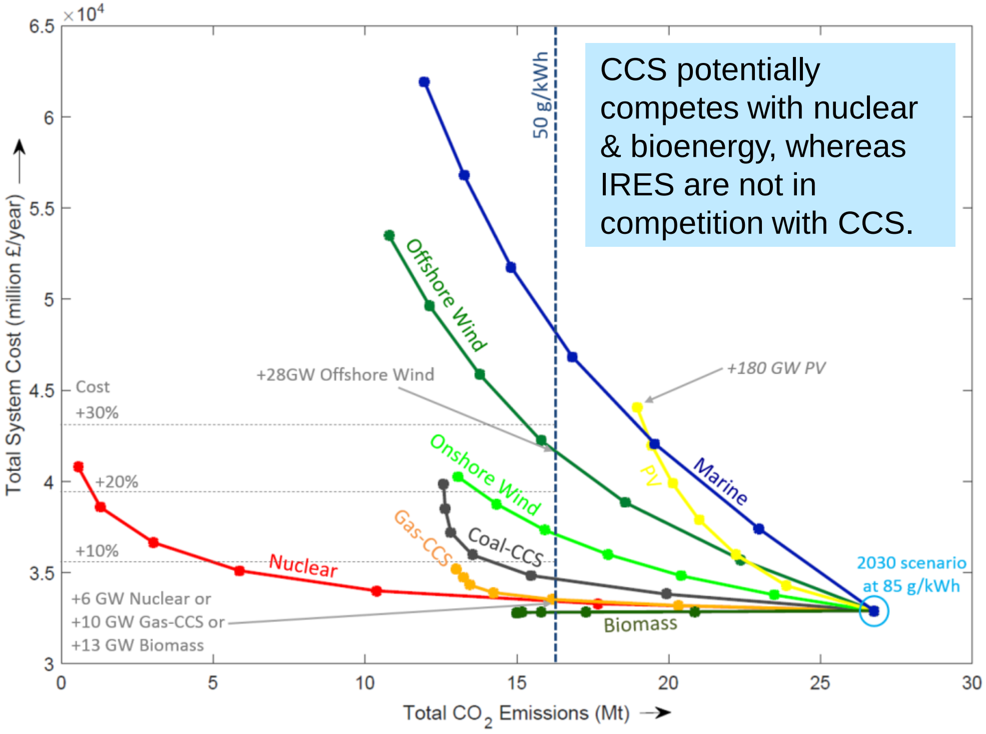
There is a lack of a proven models for the commercialisation of CCS (distinct to the CO_2-EOR industry – more straightforward).

Decarbonisation targets in terms of a percentage of renewable energy puts CCS at a disadvantage from a policy perspective.

Instead, policy could define low carbon energy targets. For example: (i) carbon intensity of grid 50 g/kWh, or (ii) X% of power needs to come from low carbon energy by a given date.

Enables individual states flexibility to achieve goals in a locally optimal manner.

As the energy system becomes more diverse, not all energy technologies provide the same services.



LCOE not the best metric of technology “value”. An alternative metric is the “system value” – considers the effect of adding the technology on the whole energy system (holistic approach).

IRES = intermittent renewable energy sources

Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

Carbon capture & storage: the way forward

The technical elements of CCS are well-understood and the financial/commercial models are becoming increasingly clear.

Large-scale deployment CCS is needed for deep decarbonisation. There is substantial evidence of the economy-wide GDP and employment benefits associated with CCS deployment.

However, public acceptability & understanding of the impact on the political economy are at an early stage.

Some governments provide generous subsidies to low-carbon technologies such as offshore wind and nuclear power (similar scale as what would be required for CCS).

Unlike nuclear power or onshore wind, there are no strong opponents, but neither are there advocates willing to lobby strongly.

CCS provides a litmus test for how serious governments take the challenge of meeting ambitious climate targets.

The needed shifts in incentives and regulations will mean change in the interests/political will (and the economics), eventually large-scale deployment of CCS will follow.