Deployment potential of direct air capture and BECCS technologies – considerations for MRV

Dr Mai Bui

Centre for Environmental Policy, Imperial College London
Centre for Process Systems Engineering, Imperial College London
m.bui@imperial.ac.uk

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Measurement, Reporting and Verification (MRV)

MRV is needed in the near-term to provide transparency and accountability around carbon removal claims.

In the long-term, MRV is essential to enable the inclusion of CDR into national inventories so that carbon removals can be counted towards nationally determined contributions (NDCs) of countries.

Type of MRV	Objective of MRV
National	Quantify GHG emissions and removals for a national GHG inventory; based on guidance from IPCC
Policy	Quantify the GHG impact of certain policies
Organization	Quantify entity or organizational level emissions for reporting under emissions trading schemes or to report for corporate/ organizational GHG inventories
Project	Quantify GHG reductions or carbon removed associated with a specific project.

Source: Lebling, K., Riedl, D. and Leslie-Bole, H., (2024). High Quality Carbon Removal Requires Credible and Consistent MRV — Government Oversight Can Help, World Resources Institute. https://www.wri.org/technical-perspectives/measurement-reporting-verification-of-carbon-removal

Measurement, Reporting and Verification (MRV)
Key principles

MEASUREMENT

Direct accounting of removals and impacts

The best MRV protocols directly measure all variables associated with the project including removals and impacts to human health and ecosystems.

MONITORING

Traceability over time

After measuring the removal of CO_2 from the atmosphere, monitoring stored carbon and ongoing health and ecosystem impacts is needed to establish durability and safety. Even after a project ends, impacts persist.

REPORTING

Data transparency

How project information is made available to stakeholders is just as important as measurement and monitoring of the initial collection of data. Without data transparency and accessibility, there is no accountability.

VERIFICATION

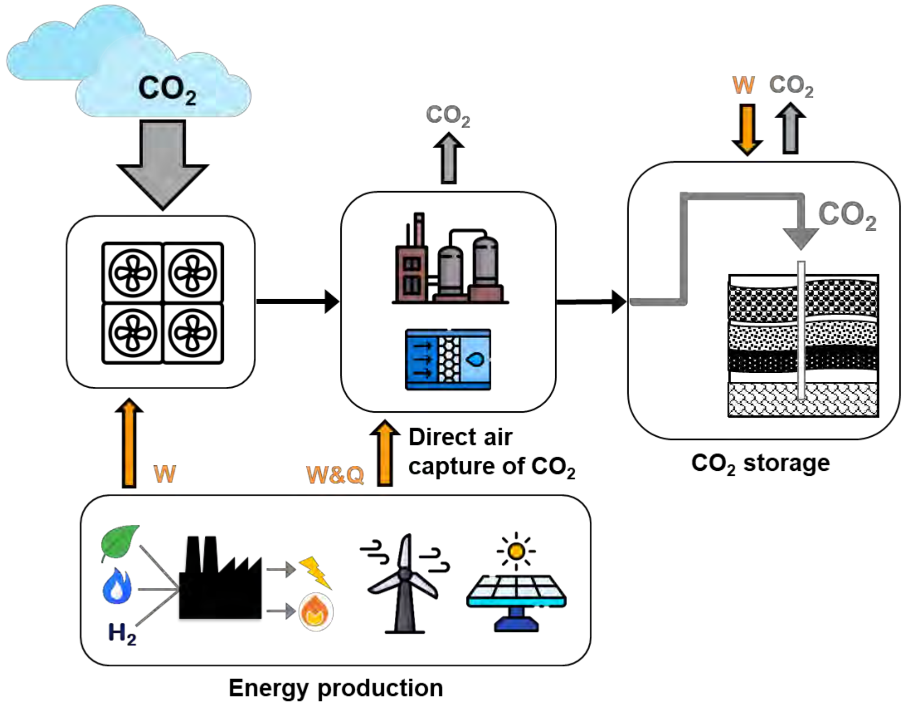
Appropriate incentive structure

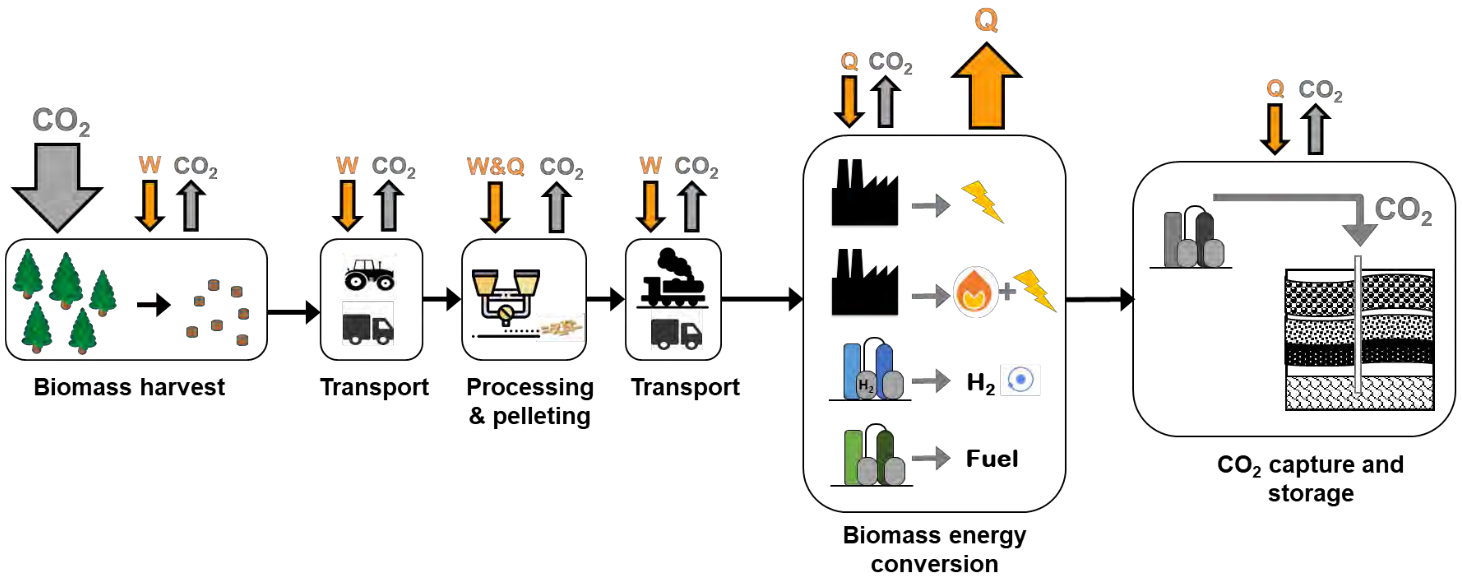
Verification of removals must take place within a financial incentive structure that minimizes fraud and maximizes public benefit.

Carbon180, 2024. High-Accountability MRV. https://carbon180.org/initiative/high-accountability-mrv/

Direct air capture with CO_2 storage (DACCS)

Bioenergy with carbon capture & storage (BECCS)

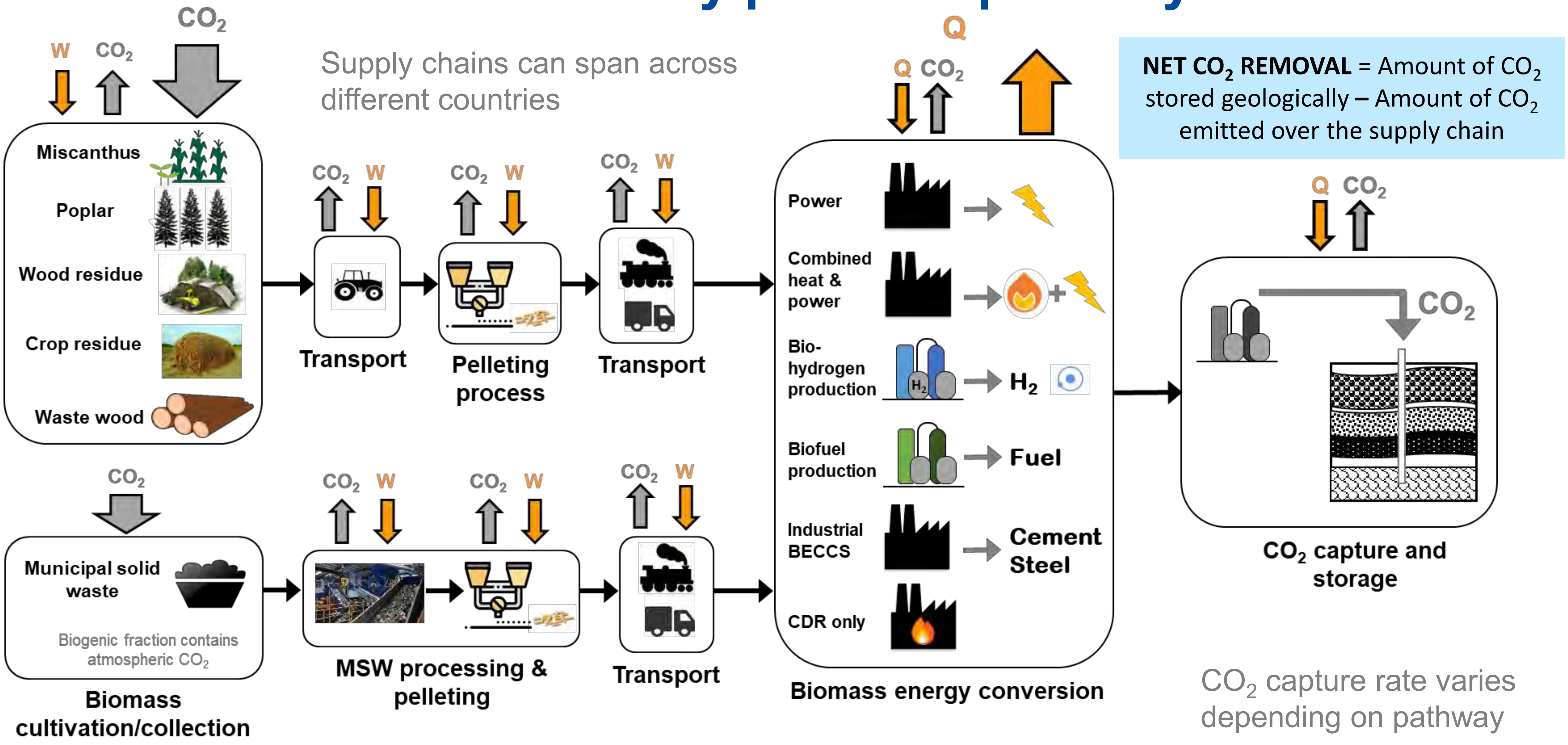




- Unlike BECCS, DACS consumes energy.
- Different archetypes requires different energy sources, e.g., electricity, low/high temperature heat.
- Deployment depends on availability of low carbon energy sources and CO_2 sequestration potential.

- Bioenergy product can be used to decarbonise other sectors.
- Different technology archetypes and CO_2 capture rates.
- CDR potential can vary with biomass feedstock type, biomass availability, and LCA emissions of the supply chain.
- Deployment also depends on CO_2 sequestration potential.

BECCS… many possible pathways

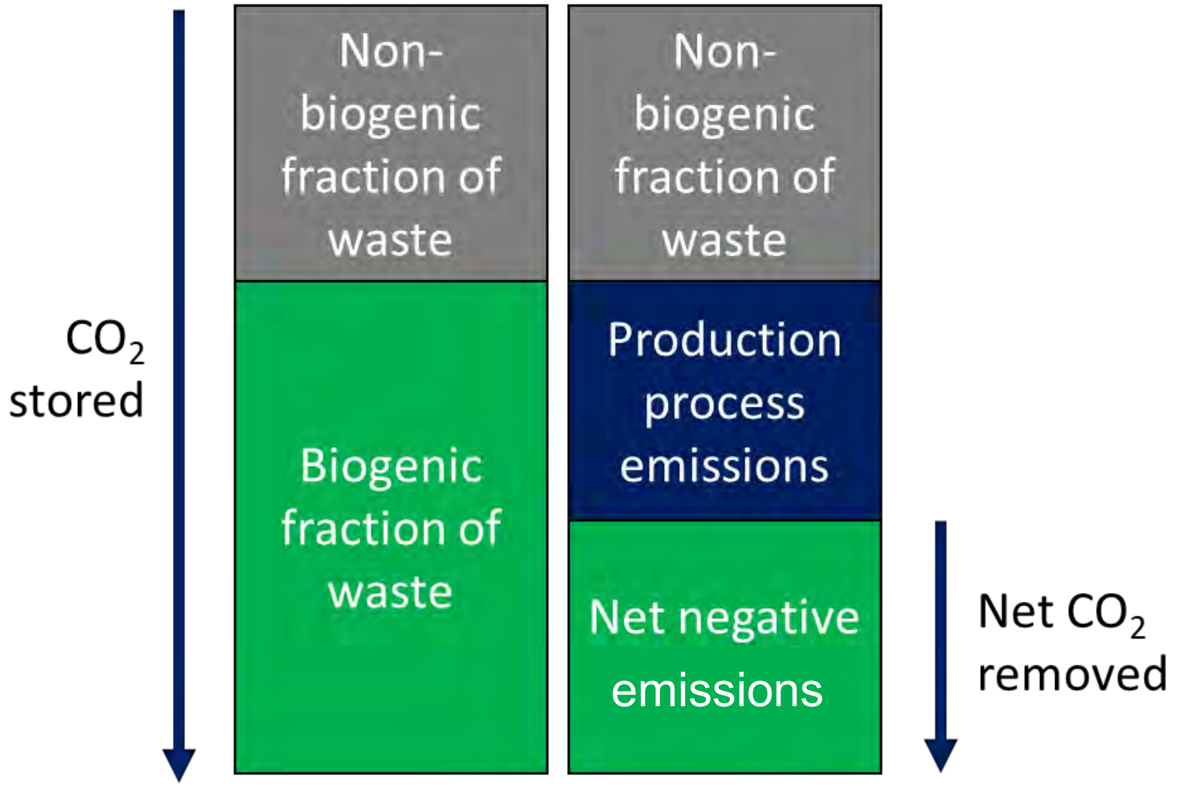


Pathway	Inputs for biomass conversion with CCS	Efficiency (%)	CO_2 capture rate (%)
BECCS power plant	Biomass, electricity, heat, water	15–37%$_{HHV}$ Pulverised fuel + CCS	90–99%
		38–42%$_{HHV}$ Pulverised fuel + improved CCS	90–99%
		28–30%$_{HHV}$ Oxy-combustion	90–99%
		34–36%$_{HHV}$ IGCC	90–95%
BECCS combined heat & power (CHP)	Biomass, electricity, heat, water	Electrical efficiency 10–36% Heat efficiency 29%	90–99%
BECCS to hydrogen	Biomass, electricity, heat, water	30–40%$_{HHV}$ Gasification with CCS	56–98%
		54–70%$_{LHV}$ Gasification with CCS (using new gasification configurations)	
		10–15% Fermentation processes (excluding CCS)	–
BECCS to bioethanol	Biomass, electricity, heat, water	24–44%$_{LHV}$ Fermentation	10–15% (CCS on fermentation)
		–	64–74% (CCS on fermentation & auxiliary boiler)
BECCS to biodiesel	Biomass, electricity, heat, water	42–43% Gasification and Fischer-Tropsch	51–56% (CCS on gasification) 64% (CCS on gasification & auxiliary boiler)
BECCS in pulp & paper	Biomass, electricity, heat, water	–	63–79% (CCS on the recovery boiler)

M. Fajardy (2022), Chapter 5 BECCS, GGR Book, RSC. https://pubs.rsc.org/en/content/ebook/978-1-83916-199-5

Carbon accounting of waste-to-energy BECCS example

NET CO_2 REMOVAL = Amount of CO_2 stored geologically – Amount of CO_2 emitted over the supply chain



Not to scale, for illustrative purposes only

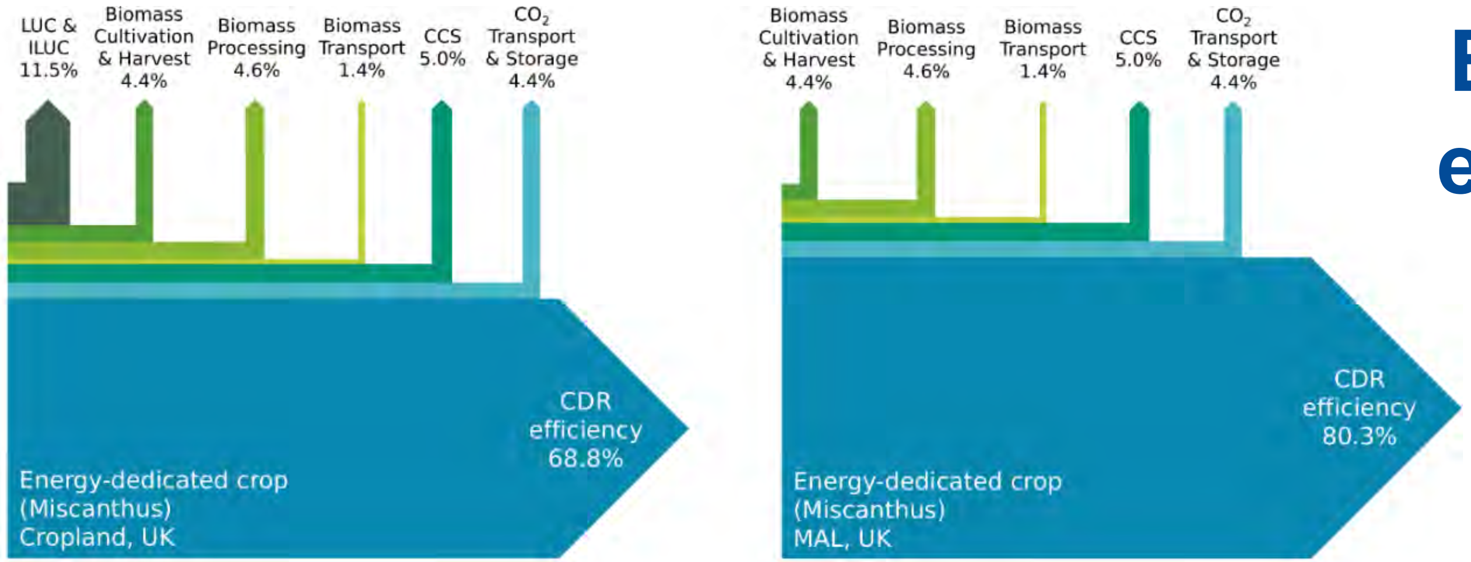
A net-negative process needs to store more biogenic CO_2 than the production process GHG emissions.

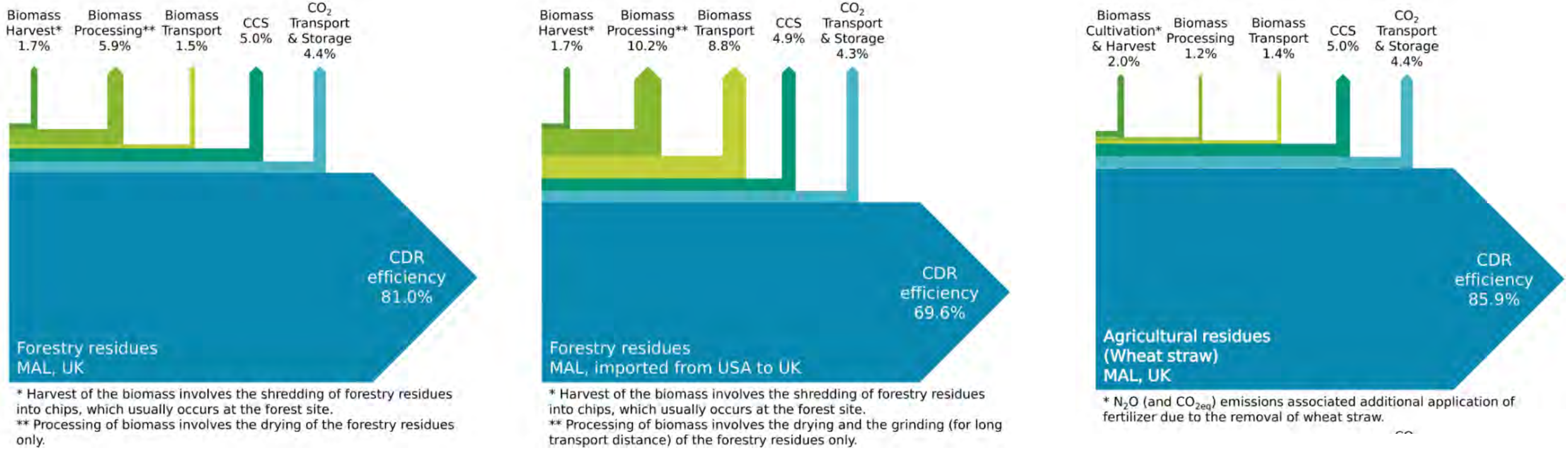
The ability to achieve net CO_2 removal for waste-to-energy BECCS plants will depend on the biogenic fraction.

The supply chain across different CDR approaches vary significantly…

BECCS CO_2 removal efficiency varies with biomass feedstock

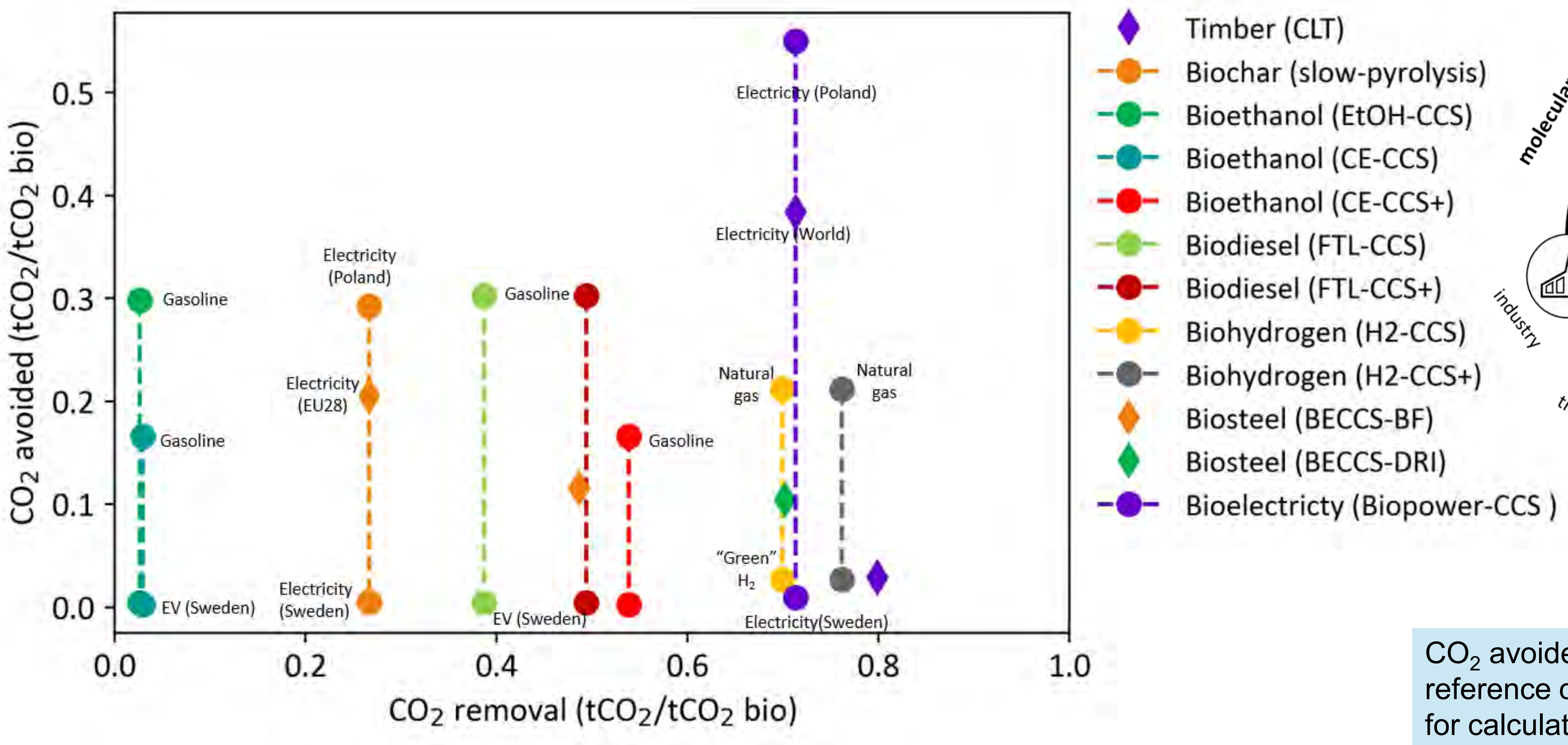
Using cropland for biomass cultivation can contribute a significant level of emission from LUC and ILUC

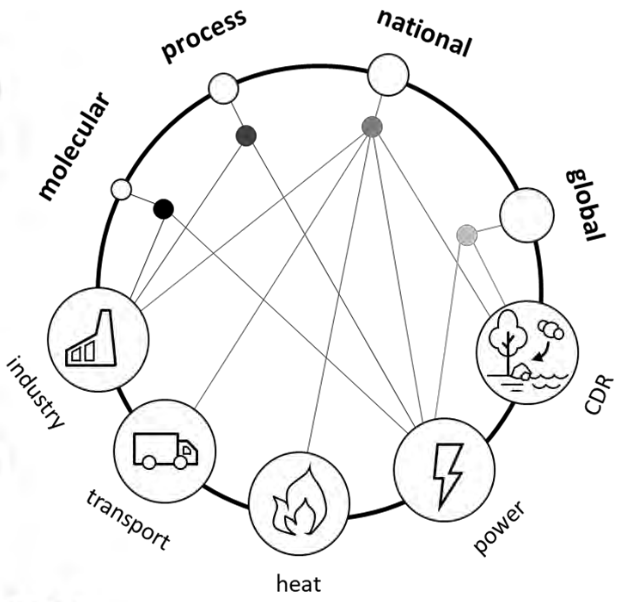




Chiquier, S., Patrizio, P., Bui, M., Sunny, N., Mac Dowell, N., (2022). A comparative analysis of the efficiency, timing, and permanence of CO_2 removal pathways. Energy & Environmental Science.15, 4389-4403. https://doi.org/10.1039/D2EE01021F

BECCS CO_2 removal potential will depend on the pathway – could help decarbonise other sectors



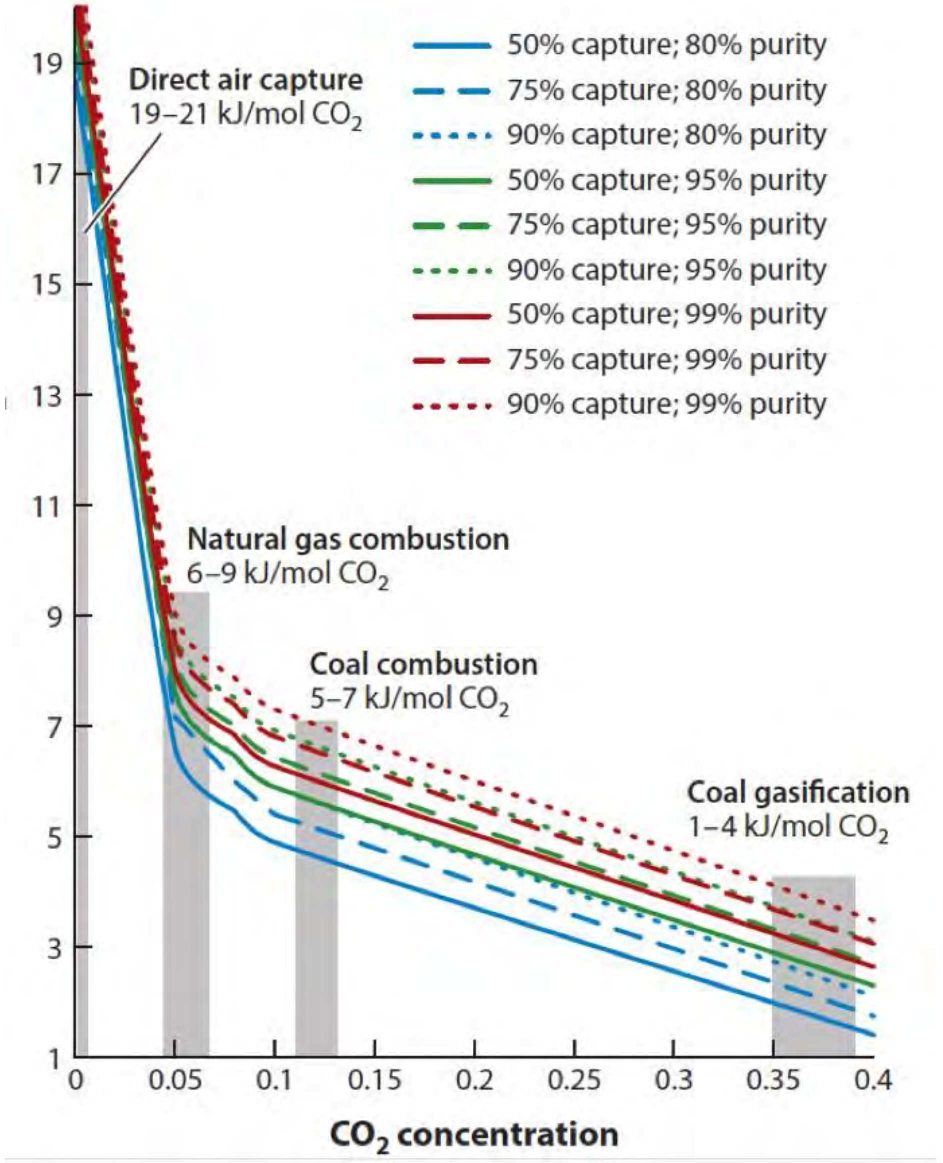


CO_2 avoided highly dependent on the reference case (i.e. counterfactual) used for calculation.

Patrizio, P., Fajardy, M., Bui, M. & Mac Dowell, N. (2021). iScience, 102765. https://doi.org/10.1016/j.isci.2021.102765

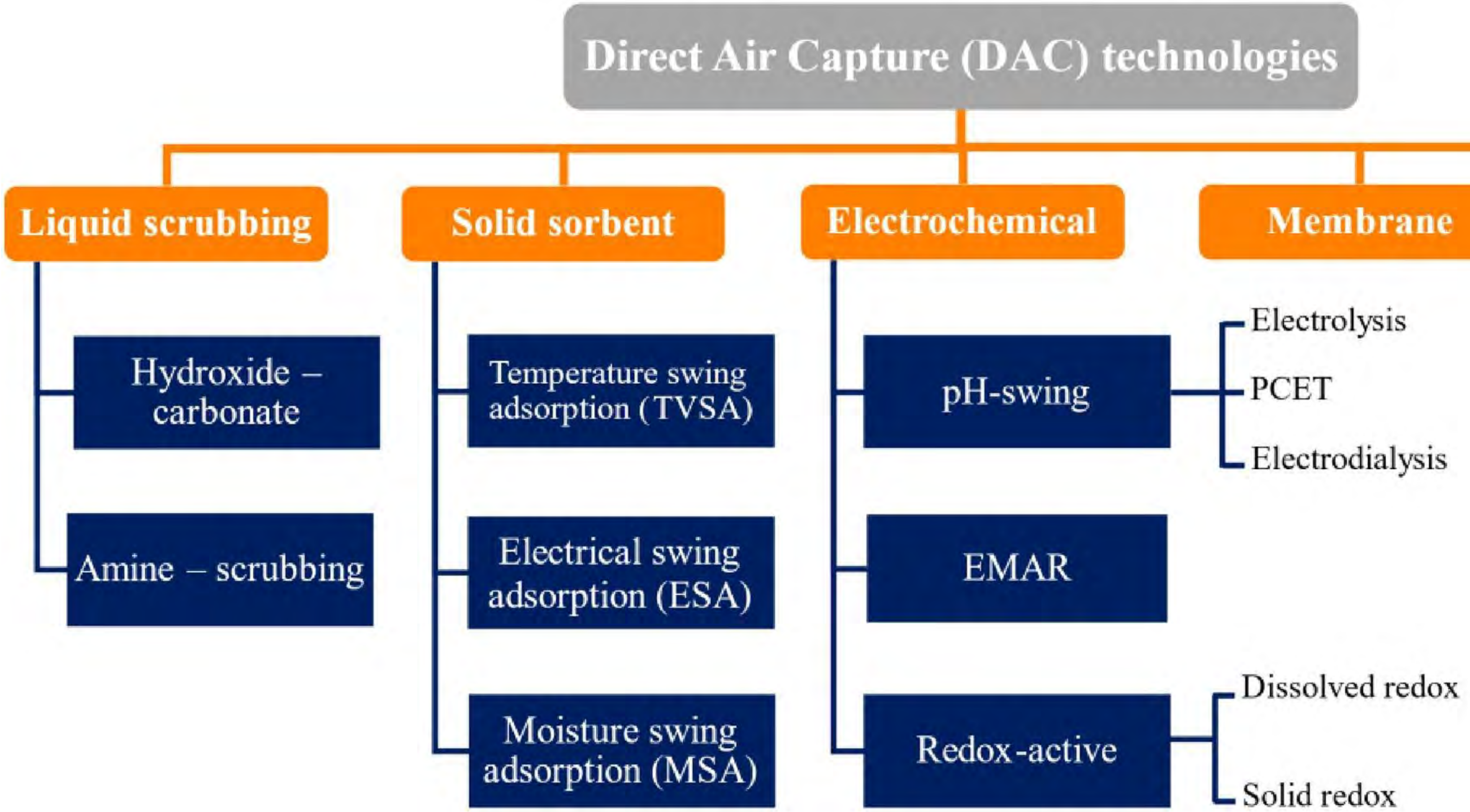
Direct air capture of CO_2

- Technical and economic challenges due to dilute concentrations of atmospheric CO_2.
- Requires sorbent with much higher affinity to CO_2, approx. 2 orders of magnitude greater than conventional amine-based capture.
- Sorbent regeneration is much more challenging and requires a significant amount of energy.
- Treating vast volumes of air in order to capture a meaningful amount of CO_2, e.g., capture of 1 $MtCO_2$ per year necessitates the processing of 80 000 m^3/s of air.



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

Direct air capture technology archetypes



PCET = proton-coupled-electron-transfer

EMAR = Electro-mediated-amine-regeneration

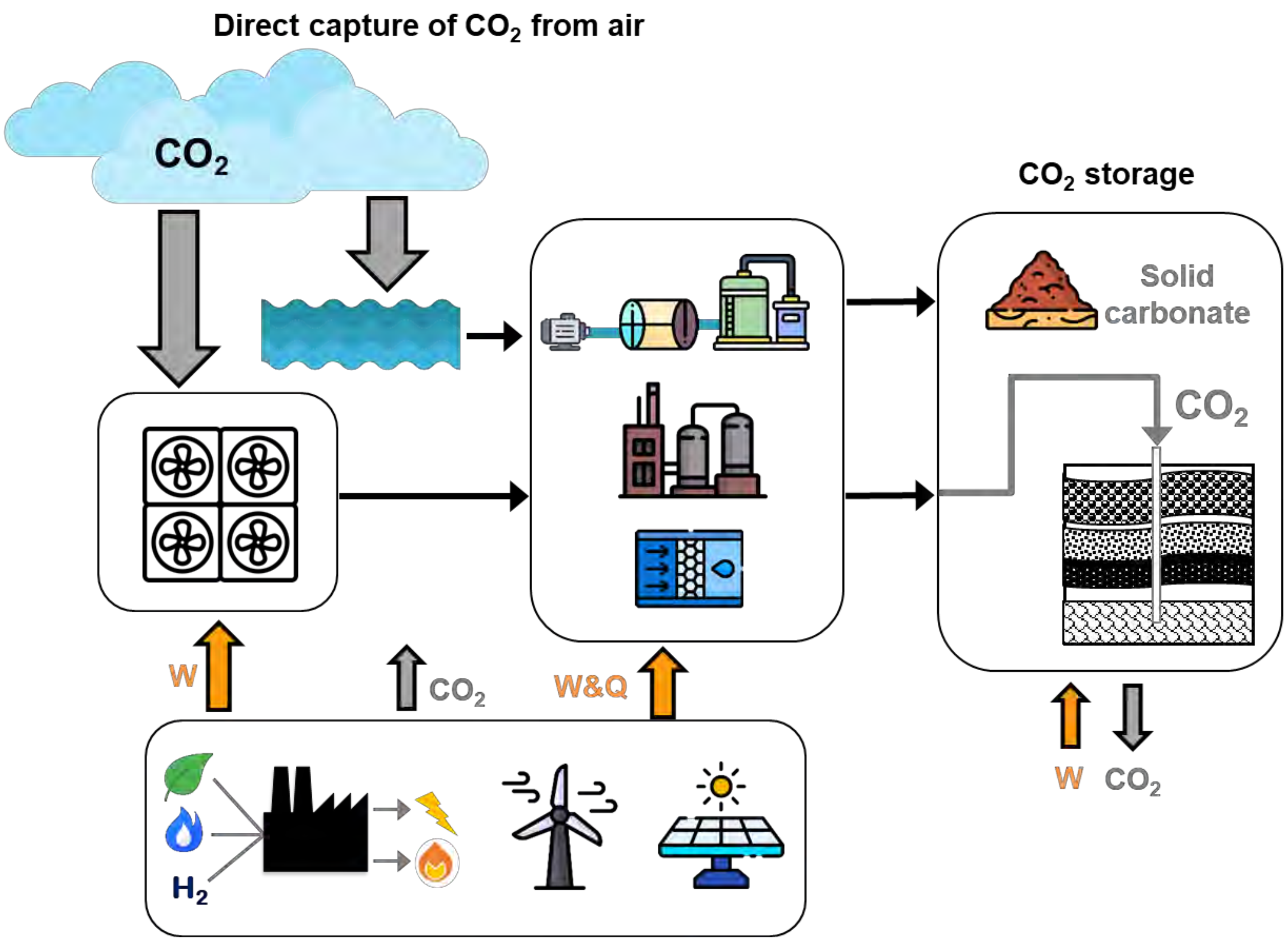
Bouaboula, H., Chaouki, J., Belmabkhout, Y., Zaabout, A., (2024). Comparative review of Direct air capture technologies: From technical, commercial, economic, and environmental aspects, Chemical Engineering Journal, 484, 149411. https://doi.org/10.1016/j.cej.2024.149411

Direct air capture technology archetypes

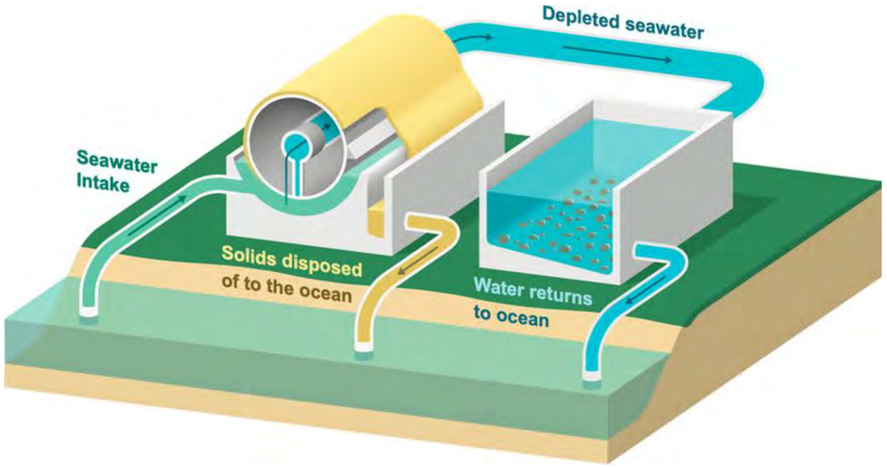
DAC technology	Operation mode	Process configuration	TRL	Regeneration/cycling conditions		Sorbents/materials used	SEC		Water usage (t_{H2O}/t_{CO2})	CO_2 purity (%)	Specific land use [b] ($km^2/MtCO_2/year$)
				Temperature (°C)	Pressure (bar)		Heat (GJ_{th}/tCO_2)	Electricity[a] (GJ_e/tCO_2)			
Hydroxide-carbonate	Continuous	Non-modular	6 – 7	300 (slaker)900 (calciner)	Ambient	Hydroxides	5.25 – 8.8	0.82 – 1.52	1 – 7	94.7 – 97.1	0.4 – 1.5
Amine	Continuous	Non-modular	3 – 4	120 – 150	Ambient	Amines	10.7 – 48.28	0.76 – 0.8	2.5 – 13	97	0.05 – 0.1
Amino-acid	Continuous	Non-modular	3–4	60–120	Ambient	Amino-acids	5.18 – 8.2	N/A	N/A	N/A	N/A
Electrolysis	Continuous	Non-modular	1 – 4	Ambient	Ambient	Hydroxides	None	4.37 – 9.14	0.614[c]	75	N/A
BPMED	Continuous	Non-modular	2 – 4	Ambient	Ambient	Hydroxides	None	3.4 – 28.7[d]	0.409[c]	95	N/A
PCET	Continuous	Non-modular	1 – 3	Ambient	Ambient	Hydroxides	None	0.45 – 1.68	N/A	N/A	N/A
TVSA	Batch	Modular	6 – 7	80 – 130	Vacuum	Amine-functionalized sorbents	4 – 11.8	0.4 – 1.4	−2 to −0.8[d]	94 – 99	1.2 – 1.7
MSA	Batch	Modular	3 – 5	40 – 50	0.1	Ion-exchange resin	None [e]	0.65	4.91 – 15.14	Up to 3 mol %	0.136
ESA	Batch	Modular	1 – 2	80 – 130	Ambient	Physical/chemical sorbents	None	N/A	None	N/A	N/A
Redox	Batch	Modular	4 – 5	Ambient	Ambient	Redox-active sorbents	None	0.9 – 2.04	N/A	100	0.02
Membrane	Continuous	Modular	2 – 4	Ambient	Pressure difference	None	None	64.8	None	< 40 (in 4 stages)	N/A
Cryogenic	Continuous	Non-modular	1 – 3	− 78 to −140	High pressure	None	None	50 – 102	None	99.99	N/A

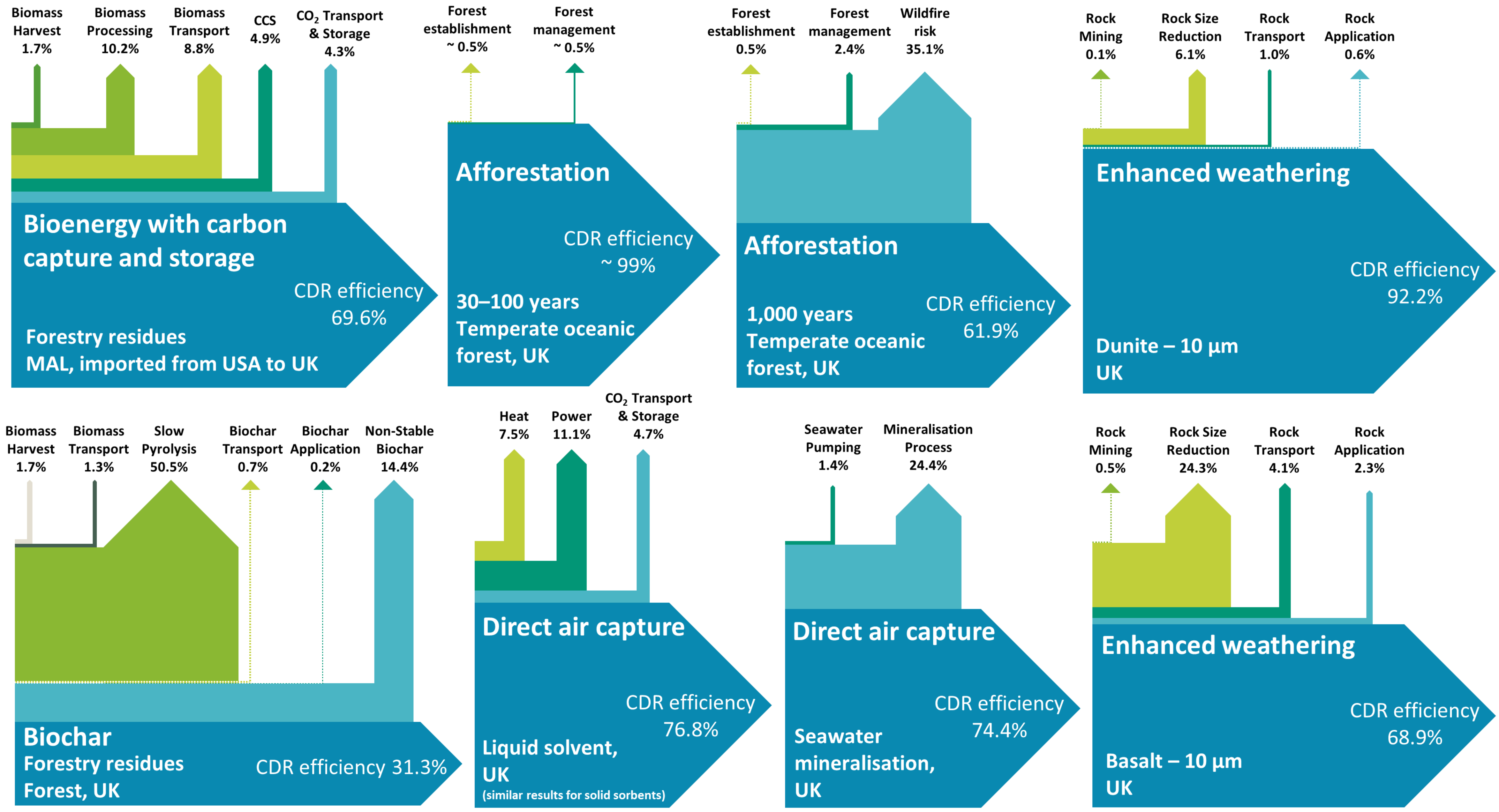
Bouaboula, H., Chaouki, J., Belmabkhout, Y., Zaabout, A., (2024). Comparative review of Direct air capture technologies: From technical, commercial, economic, and environmental aspects, Chemical Engineering Journal, 484, 149411. https://doi.org/10.1016/j.cej.2024.149411

MRV of direct air capture



Easy to monitor flows and carbon intensity of the input streams. This makes MRV of DAC easier compared to other CDR approaches.





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BECCS & DACS: Measurement, Reporting & Verification

	MEASUREMENT *Direct accounting of removals and impacts*	MONITORING *Traceability over time*	REPORTING *Data transparency*	VERIFICATION *Appropriate incentive structure*
	The best MRV protocols directly measure all variables associated with the project including removals and impacts to human health and ecosystems.	After measuring the removal of CO_2 from the atmosphere, monitoring stored carbon and ongoing health and ecosystem impacts is needed to establish durability and safety. Even after a project ends, impacts persist.	How project information is made available to stakeholders is just as important as measurement and monitoring of the initial collection of data. Without data transparency and accessibility, there is no accountability.	Verification of removals must take place within a financial incentive structure that minimizes fraud and maximizes public benefit.
BECCS	Measurement is possible but challenges due to supply chains spanning across different countries, e.g., biomass grown in US for a BECCS process in Europe.	Monitoring of the full BECCS value chain will require sourcing data from different operators – issues with timeliness and reliability of data. Monitoring stored CO_2 is over long timescales.	Very challenging to gain trust in the data around biomass sustainability, especially for projects using biomass from multiple suppliers. Complex supply chains make it difficult to report in a transparent way.	Standards and protocols for BECCS MRV and biomass sustainability do exist. Many challenges with trust and is highly scrutinised. Need to ensure measures are in place prevent fraud.
DACS	Input and output streams (e.g., material & energy) are easily measured and tend to be within the local area.	High traceability at the DAC plant and CO_2 transport network. Monitoring stored CO_2 is over long timescales.	Able to provide relatively high data transparency (i.e., measurement precision and time resolution of data).	If DAC system uses grid electricity, possible challenges for electricity grids with insufficient carbon intensity data.

Carbon180, 2024. High-Accountability MRV. https://carbon180.org/initiative/high-accountability-mrv/

Takeaway messages

- Most BECCS & DACS technologies are commercially available.
- Deployment of both will rely on the development of large-scale CO_2 transport and storage infrastructure. Supply chains and scale up take time to evolve…
- Both require water. Solid sorbent based DACS may have a net output of water.

Bioenergy with carbon capture & storage (BECCS)

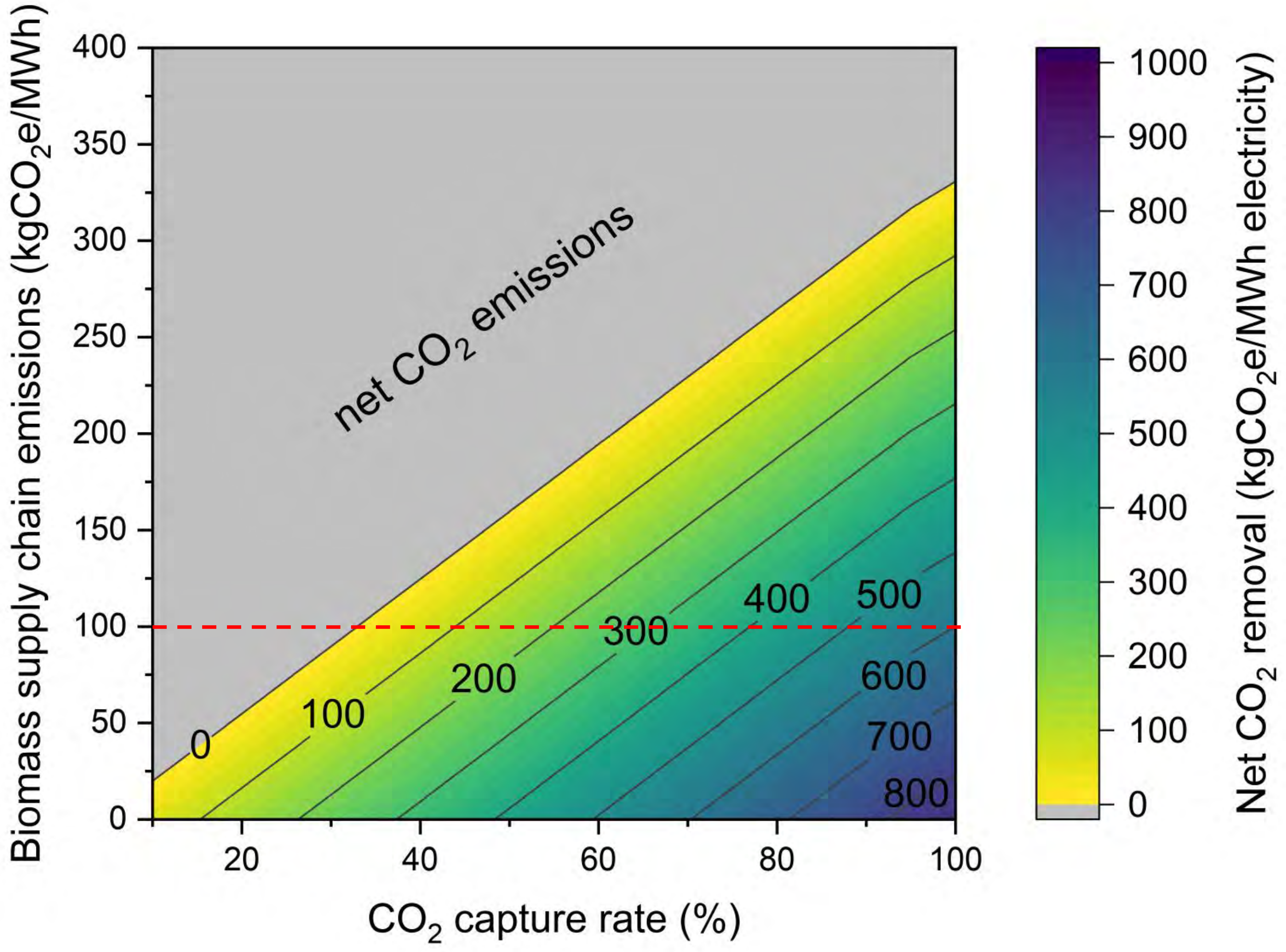
- BECCS can provide energy – there are a range of different BECCS pathways.
- Maximising the CO_2 removal efficiency of BECCS requires low supply chain emissions and high CO_2 capture rates.
- MRV across the full BECCS value chain is challenging: (i) Sourcing data from different operators (e.g., biomass producer, processing/pelleting facility), (ii) sections of the value chain can span across different countries. Thus, MRV data communication and providing transparency may be difficult, especially in terms of gaining/maintaining trust in the data.

Direct air capture with CO_2 storage (DACCS)

- Many technology archetypes – all require significant amounts of low-carbon intensity energy.
- Large-scale DACS deployment will require major expansion of low-carbon energy infrastructure.
- Input and output streams (e.g., material & energy) are easily measured and tend to be within the local area – makes MRV easier compared to other CDR approaches.
- Should mostly be able to provide relatively high data transparency (i.e., measurement precision and time resolution of data) for the full DACS value chain.

Extra slides

Maximising CO_2 removal



To maximise the net CO_2 removal, use biomass with a low carbon footprint and higher CO_2 capture rates.

The Drax average for biomass supply chain GHG emissions is shown with the horizontal dotted line at 100 $kgCO_2eq/MWh$.

Need to capture at least 35% or more to achieve net CO_2 removal.

Data sources: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021
https://www.drax.com/wp-content/uploads/2022/03/ESGXSupplement_v41_Single_Pages.pdf

Current status of CDR

The coloured circles indicate the current progress towards target levels required for wider adoption of the technology.

CDR methods are at different stages of development and vary in performance.

Some key characteristics to consider include technology readiness level (TRL); scalability; ease of monitoring, reporting and verification (MRV), potential side effects, social acceptance, permanence, and cost.

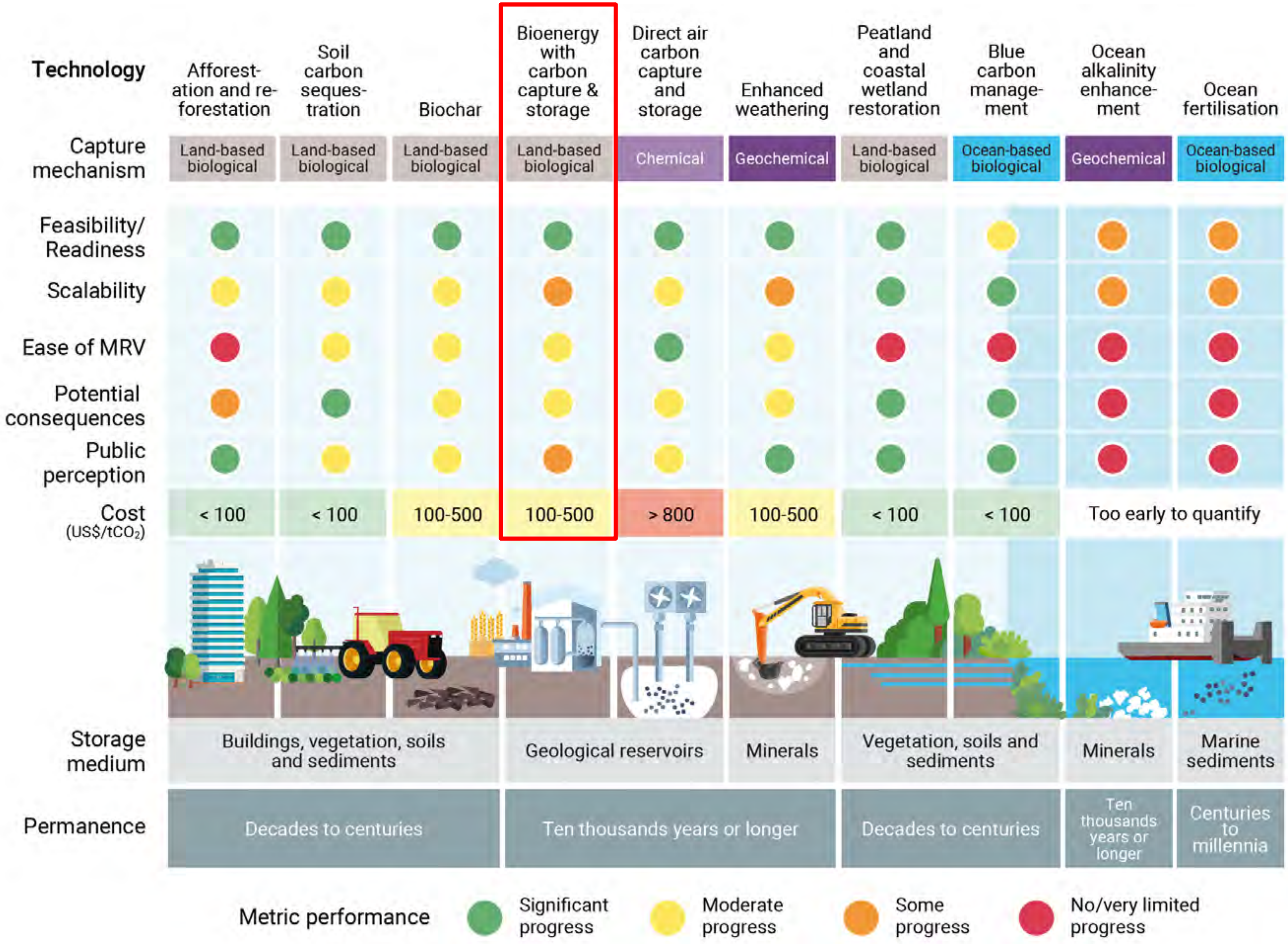
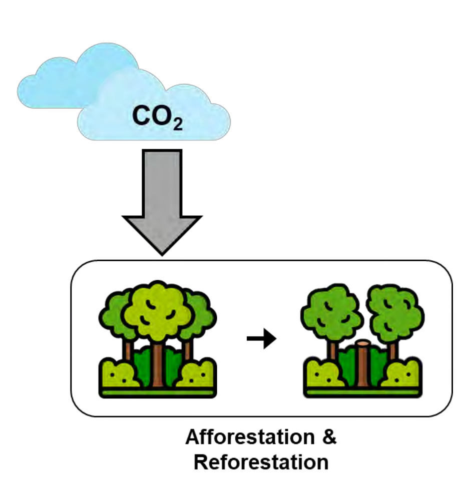


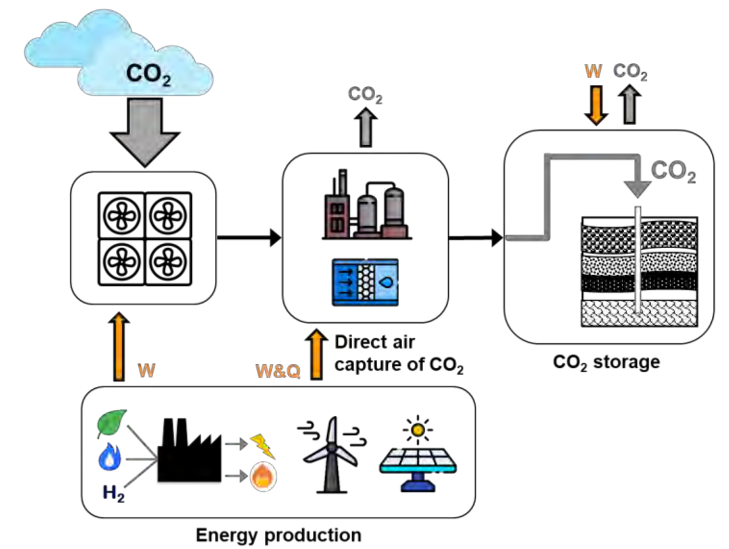
Figure Source: Oliver Geden, Matthew Gidden, Mai Bui, Mercedes Bustamante, (2023). Chapter 7 of the United Nations Environment Programme (UNEP) Emissions Gap Report 2023 “Broken Record Temperatures hit new highs, yet world fails to cut emissions (again)” https://www.unep.org/resources/emissions-gap-report-2023

Ref: M. Pisciotta, J. Davids, J. Wilcox (2022), Chapter 2, Greenhouse Gas Removal Technologies. Bui & Mac Dowell (eds). DOI: https://doi.org/10.1039/9781839165245

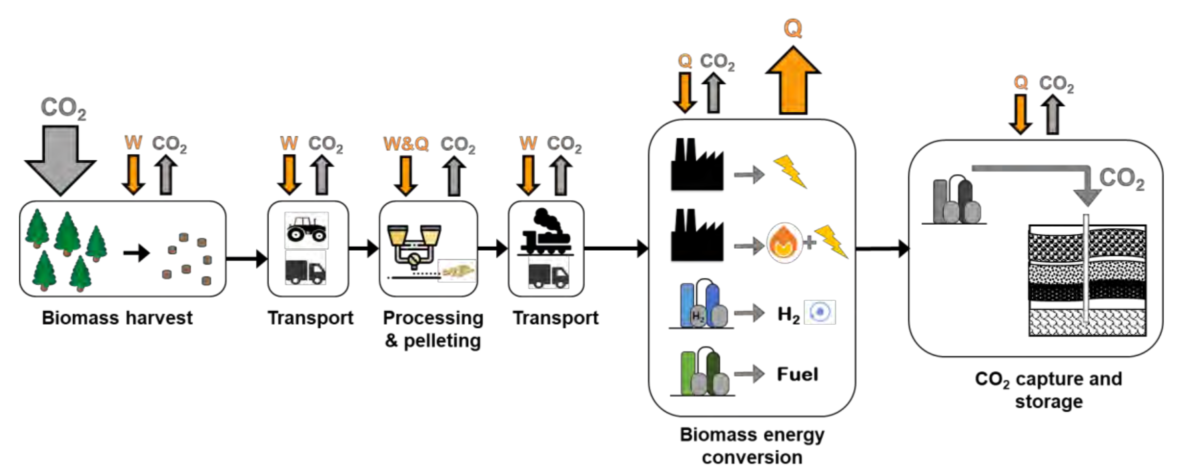
Afforestation (AR)



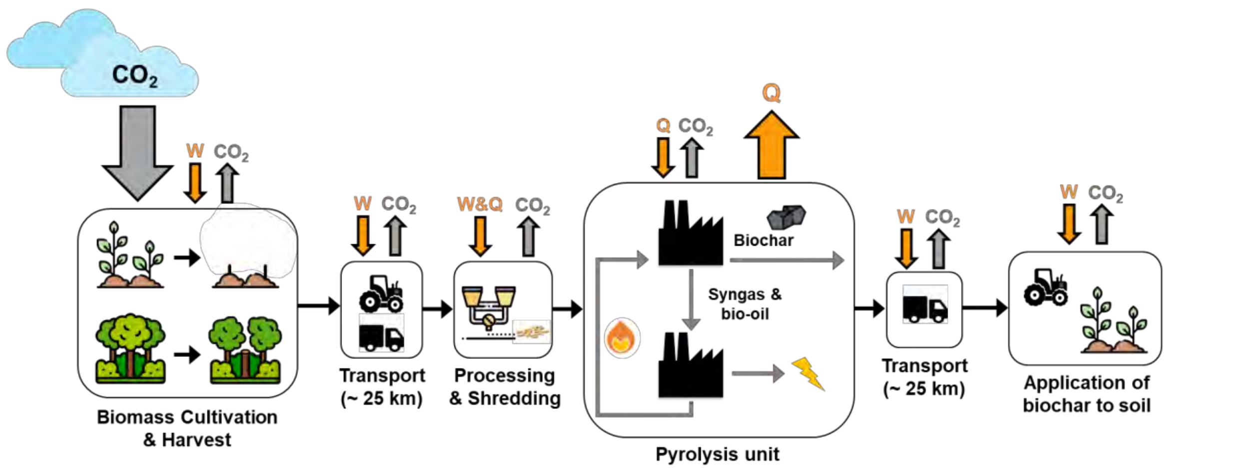
Direct air capture with CO_2 storage (DACCS)



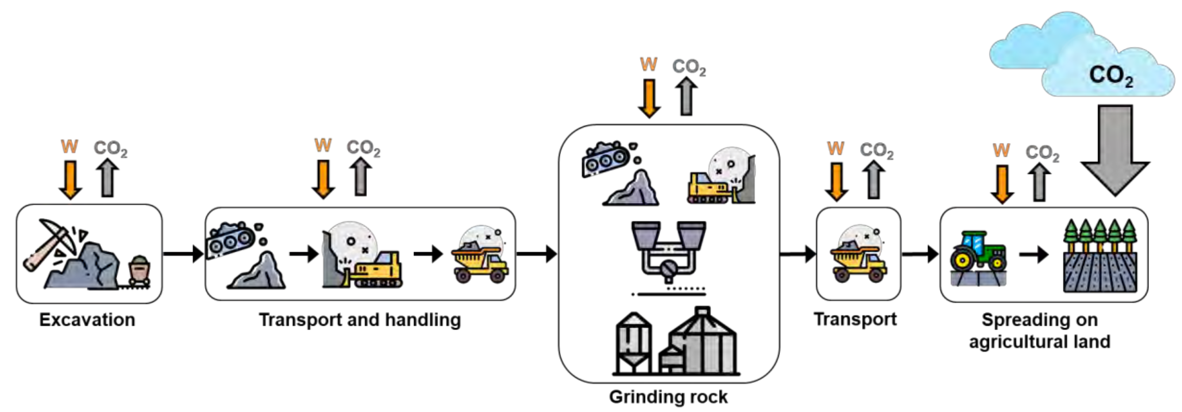
Bioenergy with carbon capture & storage (BECCS)



Biochar

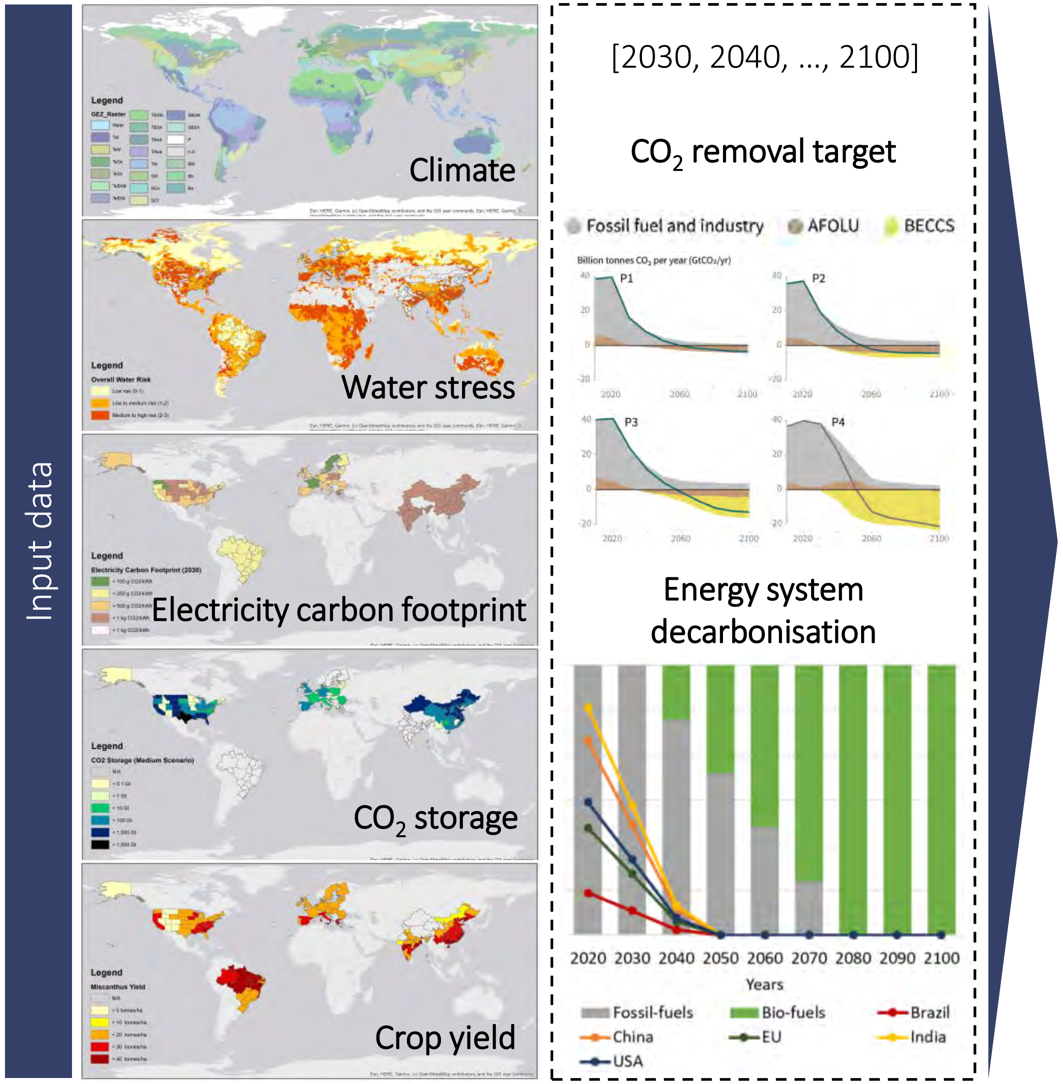


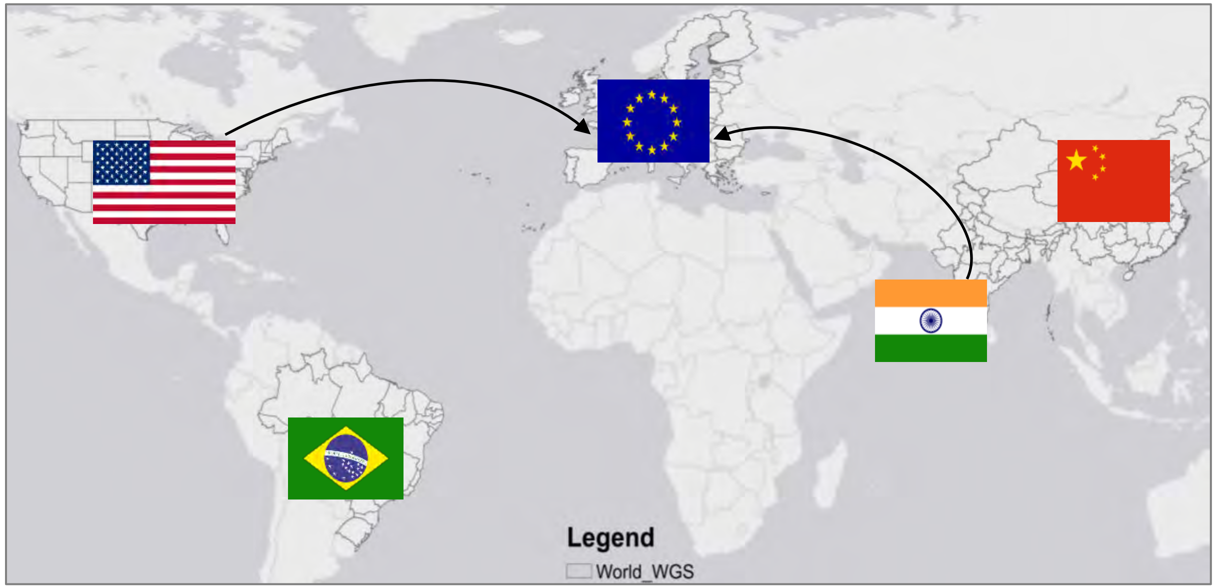
Enhanced Rock Weathering (EW)

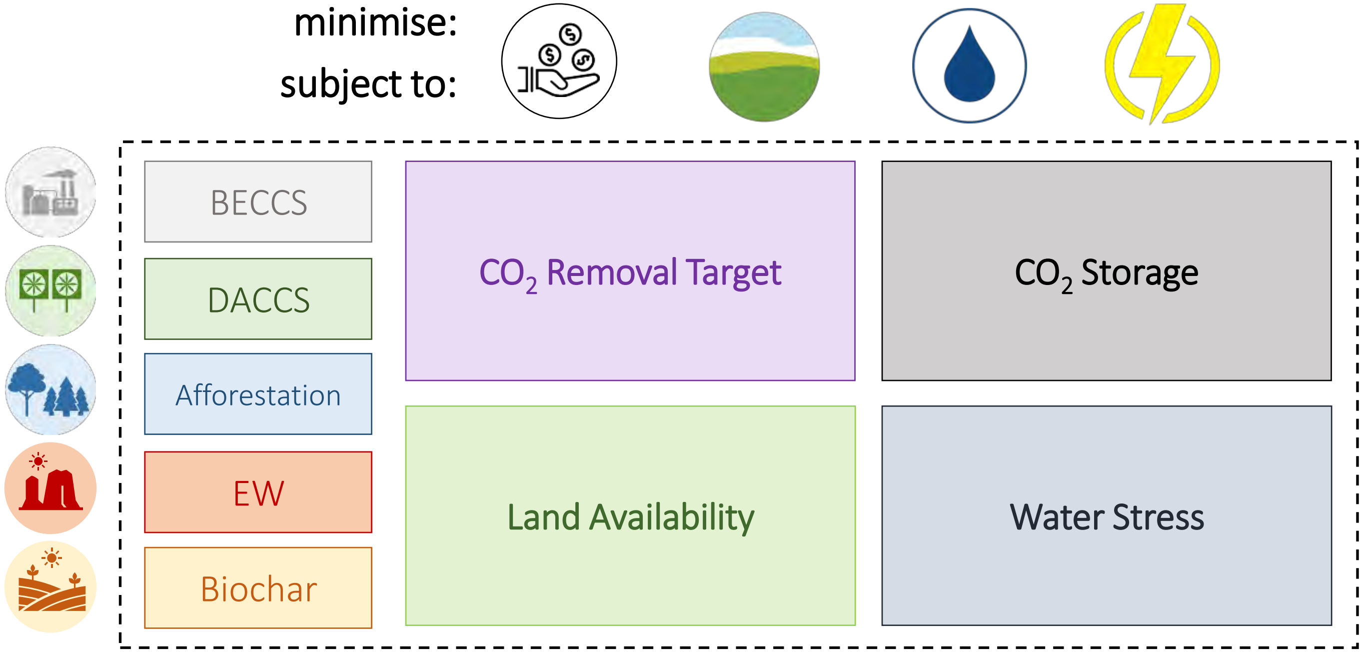


Modelling & Optimisation of Negative Emissions Technologies (MONET) – Global analysis

Spatial Temporal







Fajardy, M. & Mac Dowell, N. (2017). Energy and Environmental Science, 10 (6), 1389-1426.
Fajardy, M. & Mac Dowell, N. (2018). Energy & Environmental Science, 11 (6), 1581-1594.
Fajardy, M., Chiquier, S. & Mac Dowell, N. (2018). Energy & Environmental Science. 11, 3408-3430.