The Role of Carbon Dioxide Removal in Achieving Carbon Neutrality

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Carbon dioxide removal (CDR) is becoming critical to tackle global emissions

6-16[1] Gt/y Carbon dioxide removal ("CDR") required by **2050**

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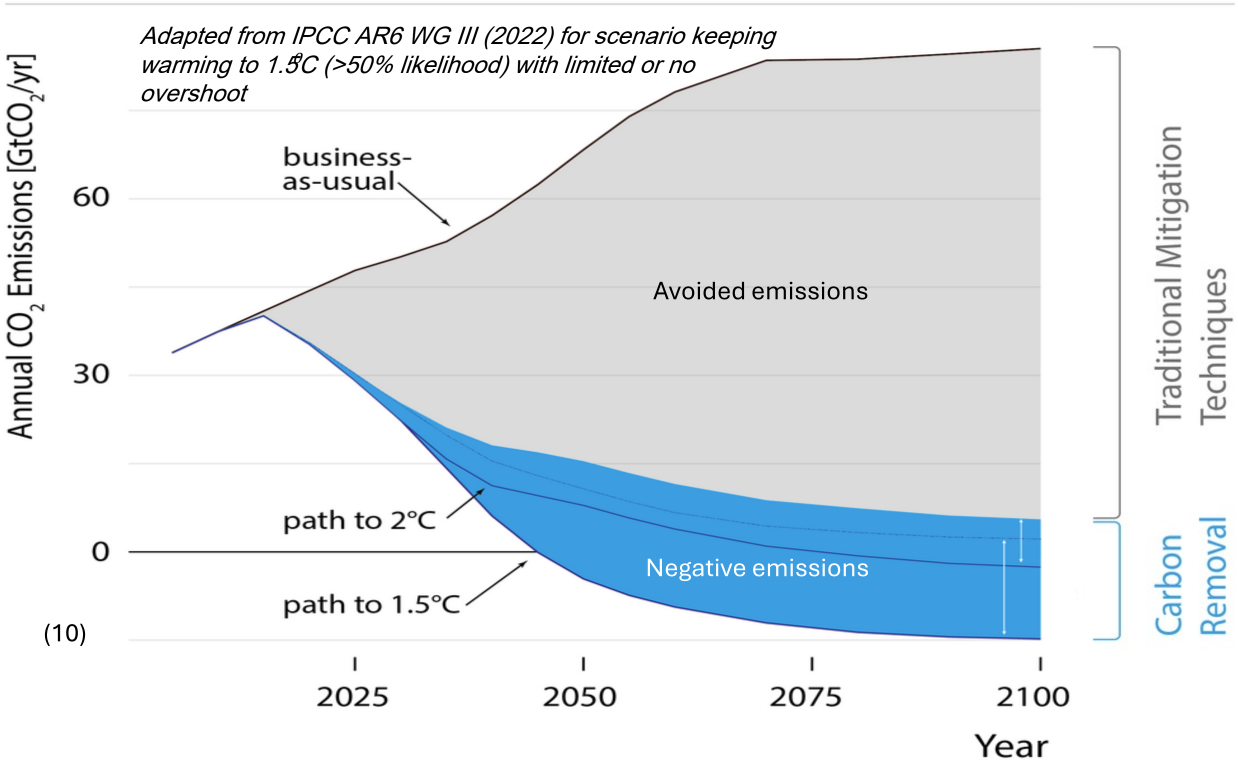
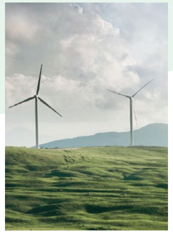
- Net-zero targets require neutralizing residual emissions
- IPCC scenarios show CDR is essential for 1.5°C pathways
- Hard-to-abate sectors (e.g., cement, aviation) depend on CDR
- Without CDR, climate goals become unachievable





Growing shortfall in required carbon reduction (current emissions gap in 2030: ~20-24 Gt/y[2])

Need for removals increases as the world fails to deliver emission reductions

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Sources

1 The state of carbon dioxide removal (2023) for scenario keeping warming to 1.5°C;
2 UNFCCC Secretariat (2023): Technical dialogue of the first global stocktake. Synthesis report by the co-facilitators on the technical dialogue

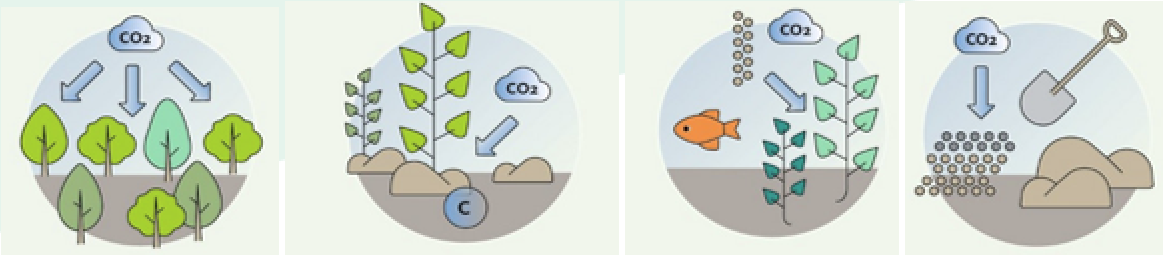
What are Carbon Dioxide Removals: Technology types

- CDRs remove CO_2 from the atmosphere and store it durably
- Different from CCS (point-source capture)
- Includes both nature-based and engineered approaches
- Key attributes: permanence, scalability, and verifiability

CO_2 storage in

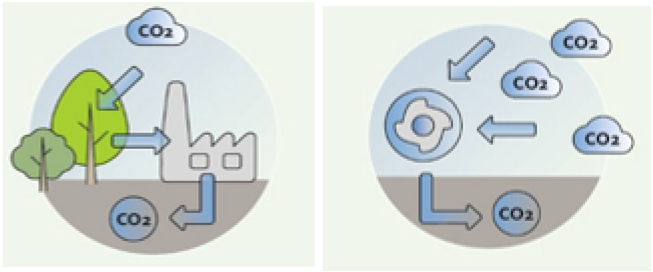
Nature-based
(Afforestation, soil sequestration; ocean fertilization, enhanced weathering, etc.)

Agriculture / forests | Soil | Ocean | Rocks

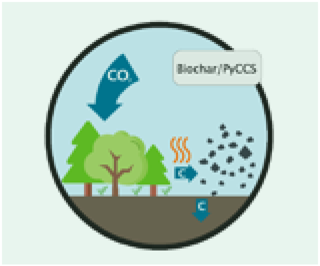


Engineered
(Direct Air Capture, DAC; Bioenergy conversion with CCS, BECCS; and community scale biochar systems)

Geological formations (in combination with CCS)



Biochar



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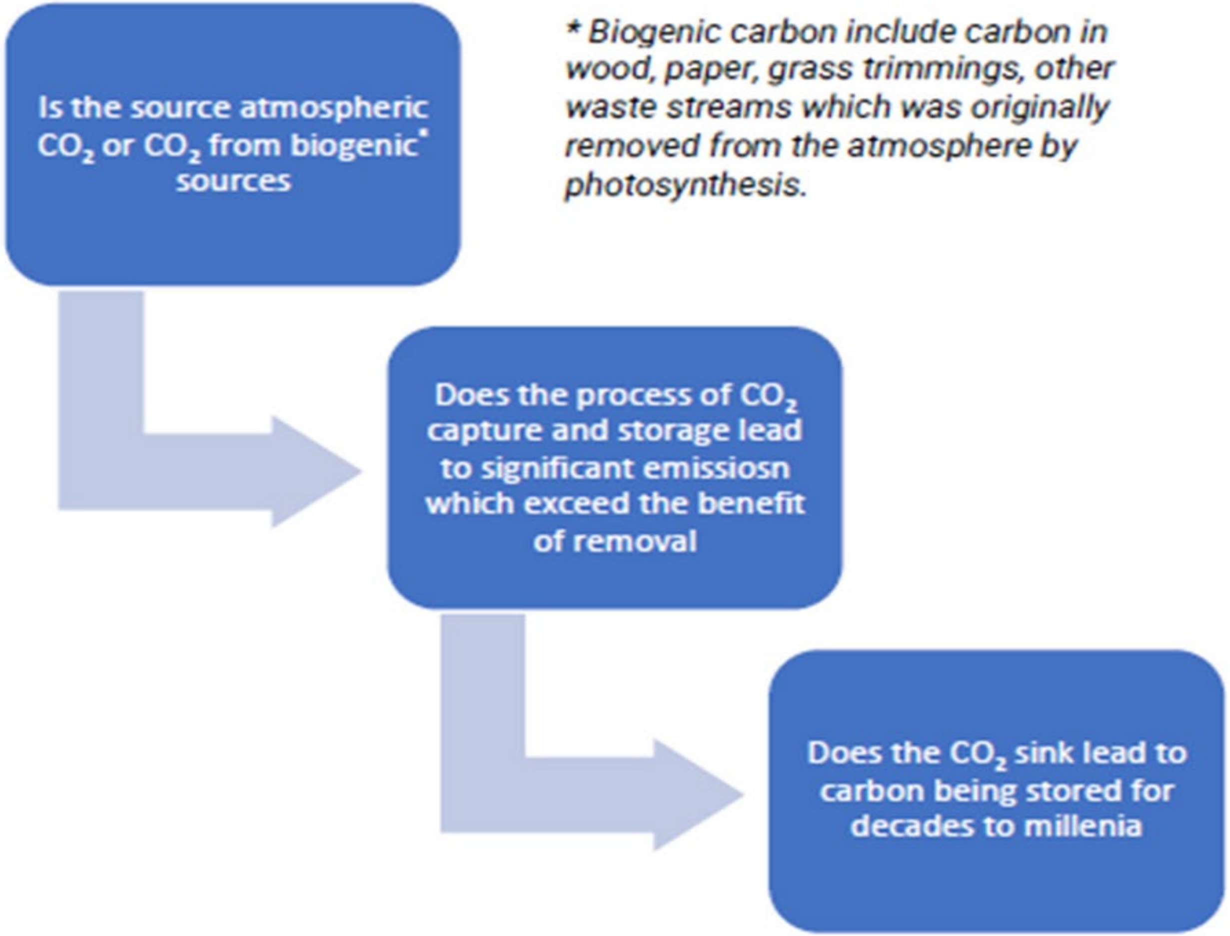
The foundations of credible and lasting CDRs

- A holistic, technology-neutral approach is essential to ensure CDRs are real, effective, and durable.
- Source, sink and process are all essential for the definition of a CDR
- Permanence:
  - Geological storage: 10,000-100,000s of years,
  - Mineralization: 100-1000s of years
  - Biochar: 100-1000 years
  - Nature-based solutions: 10-100 years



CDR in global net -zero pathways

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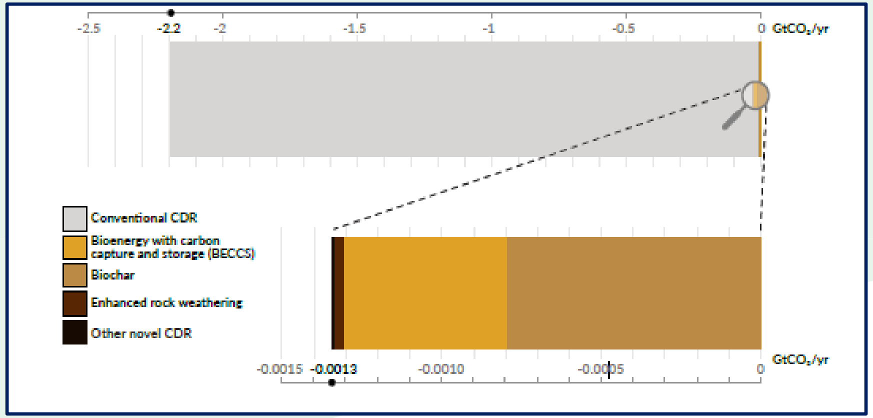
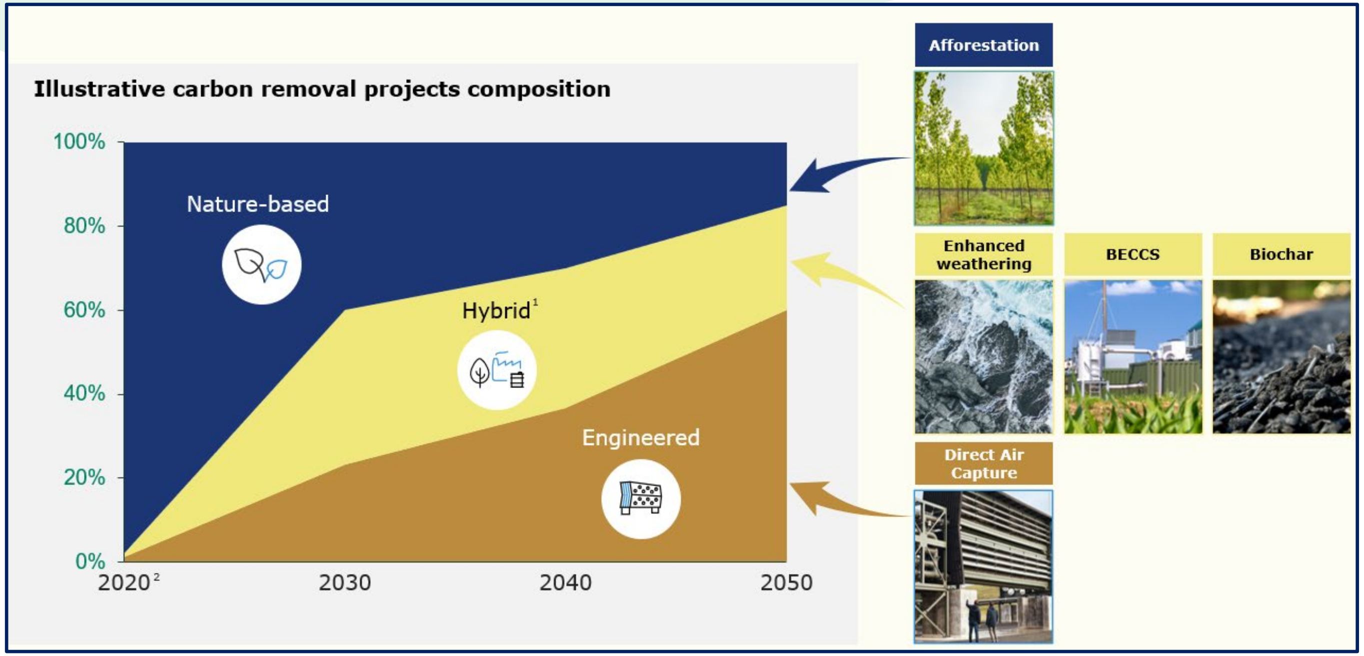
- Currently limited deployment
- IPCC projects 5–16 $GtCO_2$ / year CDR needed by 2050
- IEA Net-Zero Emissions scenario includes engineered CDR
- 65 Mt/y of DAC and 185 Mt/y of BECCS by 2030
- CDR scales rapidly post-2030 to compensate for residuals

Only 7 kt of durable CDRs were delivered in 2020 as per CDR.fyi of which 4 kt were delivered by Charm



Source: *Smith et al., 2024. State of Carbon Dioxide Removals Second Edition.*



Due to scalability, engineered solutions outperform other carbon removal technologies in the long run as costs decline

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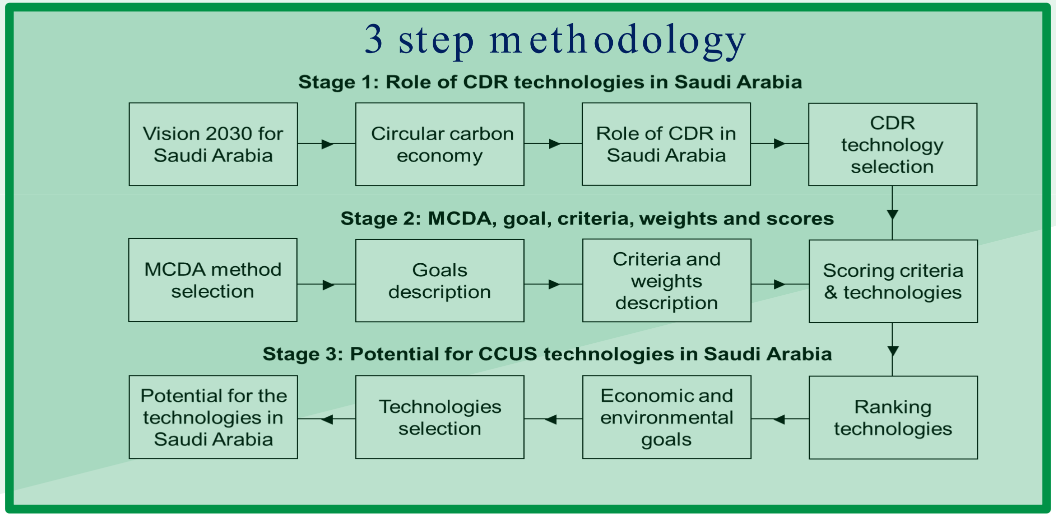
Sources CDR.fyi as of December 2023, World Resources Institute, adapted from McKinsey Sustainability report as of December 2023 "*Carbon Removals: How to scale a new gigaton industry*"

CDR prioritization for Saudi Arabia – A case study

- KAPSARC study applied MCDA to rank CDR options
- 11 combinations of CDRs and storage options
- 8 Criteria including technology maturity, cost, permanence, MRV, alignment with Vision 2030 and co-benefits



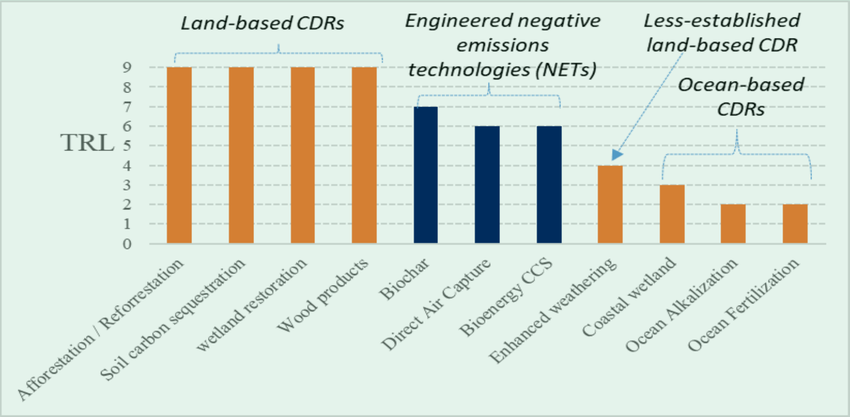
We considered 11 CDR options for analysis	
1	Afforestation (AF)
2	Soil sequestration (SS)
3	Wetland restoration (WR)
4	Wood for timber in construction (WfC)
5	Direct air capture (DAC) with CO_2 geological storage (DACCS)
6	DAC with CO_2 utilization in concrete and brine (DACCU)
7	DAC with mineral carbonation (DACMC)
8	Energy-from-waste with carbon capture and storage (EfW BECCS)
9	Anaerobic digestion of waste with CO_2 utilization (BM BECCU)
10	Biochar (BC)
11	Enhanced weathering (EW)

We applied technical, economic and environmental criteria	
1	Technology readiness level
2	Permanence / durability of CO_2 storage
3	Current costs and potential for cost reduction
4	Environmental and life cycle impacts (impact on air emissions; water emissions; land, water and energy use; ecological impacts)
5	Enabling policy and regulatory framework
6	Monitoring, reporting and verification (MRV)-readiness
7	Suitability of Saudi Arabia
8	Additionality and co-benefits

The impact of each criterion for each of the CDR options is scored as high, medium or low

CDR characterization: Maturity and Global potential

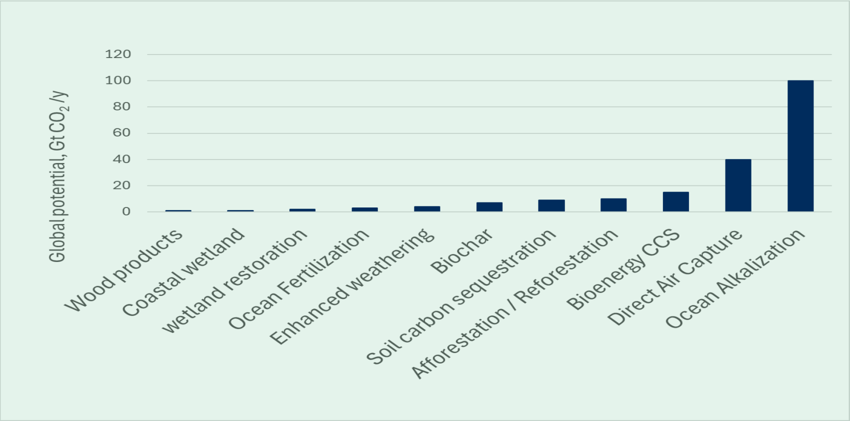
Technology Readiness Level (TRL)



Conventional nature-based CDRs are higher TRL

Novel engineered solutions are in pilot and demonstration phase

Global potential (Gt/y in 2050)



Ocean alkalization, DAC and BECCS provide significant potential

Nature-based alone are not sufficient to achieve CDR targets

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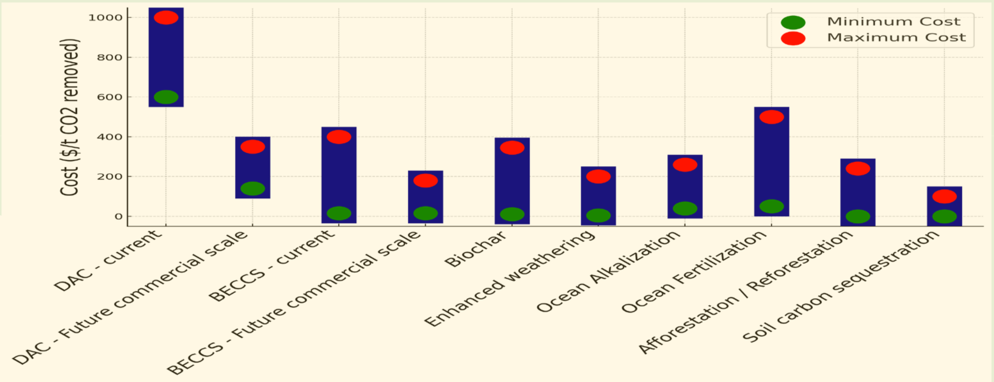
CDR characterization: Costs and MRV readiness

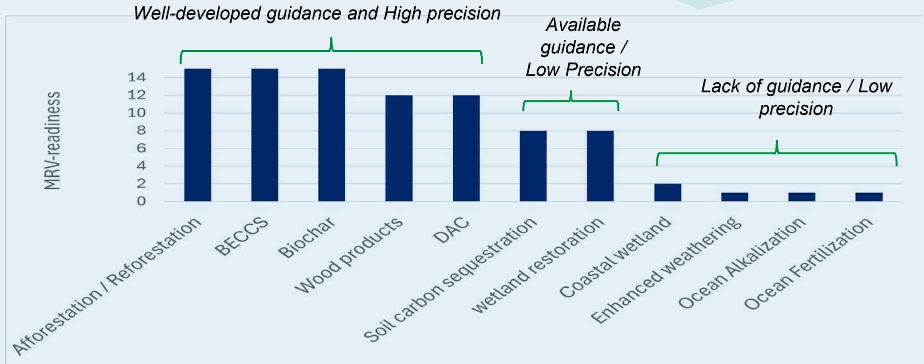
Range of removal costs in literature ($/t CO_2 removed)



Costs are highest for engineered solutions but expected to reduce with time (by learning)

Conventional natured-based solutions are lower in costs

Readiness of monitoring, reporting and verification (MRV) protocols



1-15 is scale defined by KAPSARC

Calculation methodology considers both (i) ***precision of measurement*** and (ii) availability of ***guidance***

Engineered solutions score high in general

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CDR ranking for Saudi Arabia

Engineer CDR solutions are essential for enabling negative emissions in Saudi Arabia

Land and water demand are key barriers for nature-based solutions

EfW with CCS and Biochar offer an immediate opportunity in the next decade

DAC has a longer-term role due to high costs and energy intensity

MRV and permanence challenges need to be addressed

Need for financial incentives, regulatory framework, clear governance

Decision matrix for comparing CDR technologies in Saudi Arabia.

CDR Technology	Technology readiness level (TRL)	CO_2 permanence and durability	Costs in KSA	Environmental impact	Established policies & regulations	MRV guidance & precision	Suitability to Saudi Arabia	Co-benefits to Saudi Arabia	Ranking by group
Afforestation	H	L	L	H	H	H	M	M	4
Wetland restoration	H	L	H	H	H	L	M	H	
Soil carbon sequestration	H	L	H	H	L	L	M	L	
Wood products	H	L	H	H	L	M	L	M	
BECCS (EfW) & permanent storage	M	H	H	M	M	H	H	H	1
BECCS (biomethane) & concrete storage	M	H	H	M	M	H	H	H	
Biochar	H	M	H	H	L	M	M	H	3
DAC & permanent storage	M	H	M	M	M	M	H	H	2
DAC & concrete storage	M	H	M	M	M	M	H	H	
DAC & Mineral carbonation	M	H	M	M	M	M	H	H	
Enhanced weathering	L	H	H	L	L	L	L	L	5

Scoring: H = High; M = Medium; L = Low

Odeh, N., Hunt J., Hejazi M., Wada Y. 2025. Energy Policy, Volume 205, 114698

Summary

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- **Carbon dioxide removal is essential to achieve and sustain net-zero**
- A **diverse portfolio** of CDR solutions, nature-based and engineered, is needed to deliver scalable, permanent removals.
- **Engineered CDRs** like DAC, BECCS, and biochar are scaling rapidly and will be increasingly critical post-2030.
- **Saudi Arabia can lead** by advancing scalable, verifiable CDR solutions aligned with Vision 2030, notably EfW with CCS and biochar in combination with geological storage or mineral carbonation.
- Building a national CDR strategy with **MRV frameworks, pilot projects, and market incentives** will be key to unlocking this potential.

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Thank you

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