Removing carbon *responsibly*

Appendix

25 September 2023

World Business Council *for Sustainable Development*

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Appendix

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Acronyms and abbreviations

AR	afforestation and reforestation
BECCS	bioenergy with carbon capture and storage
BECCS exp.	bioenergy with carbon capture and storage, with agricultural expansion
BECCS no exp.	bioenergy with carbon capture and storage, without agricultural expansion
BECCU	bioenergy carbon capture and utilization
BiCRS	biomass carbon removal and storage
BVCM	beyond value chain mitigation
CCS	carbon capture and storage
CCU	carbon capture and utilization
CDR	carbon dioxide removal/carbon removal/removals
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
°C	degrees Celsius
DAC	direct air capture
DACCS	direct air carbon capture and storage
DACCU	direct air carbon capture and utilization
FLAG	Forest, Land and Agriculture
GHG	greenhouse gas
Gt	gigatonne
IPCC	Intergovernmental Panel on Climate Change
MCDA	multi-criteria decision-analysis
MRV	measurement, reporting and verification
NCS	natural climate solutions
NET	negative-emissions technology
SBTi	Science Based Targets initiative
SCS	soil carbon sequestration
t	metric tonne
TRL	technology readiness level
USD	United States dollar
VCM	voluntary carbon market

Appendix

MCDA framework usefulness and limitations

The multi-criteria decision-analysis (MCDA) framework provides a transparent, quantitative evaluation of key carbon dioxide removal (CDR) attributes and ranks their performance under plausible portfolio preferences.

The selection of the criteria is critical in defining the value of the comparison framework. We selected the nine criteria based on a literature review and reviews by expert groups. The specific evaluation of some aspects can improve with more intuitive metrics, as more accurate data becomes available.

More broadly, the evaluation considers only a global perspective. A more nuanced approach would consider regional or even project-level considerations.

Despite the uncertainties in some areas, the proposed framework delivers a valuable comparative assessment of critical CDR aspects. Experts generally agree on the relative performance of each technology. Hence, policymakers, organizations and other stakeholders can use the framework and its results as a guiding tool to ease the objective assessment of CDR methods.

Performance evaluation summary

Table 1: Overview of evaluation methodologies for all performance aspects

Aspect	Evaluation	Sources	Scale (units)	Normalized score
Technical feasibility	Ordinal data, based on the technology readiness level (TRL)	Evaluation in review (51)	0–9 [-]	0–10, (TRL/9)·10
Economic feasibility	Ordinal data, based on market price estimates to reflect affordability in relation to social cost of carbon	Various sources, including reviews of (7) (2) (59) and available market price data	“Very low” to “very high”	0–10 (scale based on relative prices)
Governance feasibility	Ordinal data, based on ease of measurement, reporting and verification (MRV), social media sentiment (as a proxy for acceptance), and the framework:”Public principles for the good governance of NET’s” (60)	Inputs from reference (60) and reviews from (7) (2) (50) (24) (61)	“Very low” to “very high”	0–10 (in line with IPCC’s scale[a])
Mitigation effect	Ordinal data	Based on evaluation done in review (50) (62)	“Very low” to “very high”	0–10 (in line with IPCC’s scale[a])
Timeliness	Ordinal data, based on (1) time to reach maximum capture capacity and (2) other factors (flexibility, controllability, reversibility)	Authors’ assessment, based on reviews of (7) (2)	“Very low” to “very high”	0–10 [in line with IPCC’s scale[a]]
Durability	Ordinal data, “Temporary”/ “Permanent”, based on storage time	Storage time estimates and classification from (20) (63)	“Very low” to “very high”	0–10 (in line with IPCC’s scale[a])

Aspect	Evaluation	Sources	Scale (units)	Normalized score
Environmental impacts	Ordinal data	Summary of conclusions in reviews (7) (2) (50) (51)	"Highly negative" to "highly positive" (seven levels)	Minimum–maximum scaling
Economic impacts				
Social impacts				

[a] IPCC level of confidence scale used to normalize scores (64) (64)

Feasibility

We calculated the technical feasibility to be directly proportional to the mid-range TRL.

Table 2: Technical feasibility assessment

Option	TRL range (-)[a]	TRL mid-range (-)	Technical feasibility (score)
Afforestation & reforestation	8–9	8.5	9.4
Biochar	6–7	6.5	7.2
BECCS	5–6, 9[b]	7.2	8.0
DACCS saline aq.	6, 9[b]	7.5	8.3
DACCS mineral.	6, 4[b]	5.0	5.5
Enhanced weathering	3–4	3.5	3.9
Soil carbon sequestration	8–9	8.5	9.4

[a] TRL values from (24)

[b] Storage TRL values from (65)

Source: Based on (43)

Table 3: Indicator scale for economic feasibility assessment

Social cost of CO_2 (quantile: USD $/tCO_2$)[a]	Social cost of CO_2 (USD $/tCO_2$)	Performance	Economic feasibility (score)
Q95: 828	828+	Very low	1.0
	736-828	Low	2.0
	644-736	Low	3.0
	552-644	Moderate-low	4.0
	460-552	Moderate	5.0
	368-460	Moderate-high	6.0
	276-368	High	7.0

Social cost of CO_2 (quantile: USD $/tCO_2$)[a]	Social cost of CO_2 (USD $/tCO_2$)	Performance	Economic feasibility (score)
	184-276	High	8.0
	92-184	Very high	9.0
	0-92	Very high	10.0

[a] Quartile social cost of carbon based on Howard & Stern damage function, using a 1.5% discount rate. (53)

Table 4: Economic feasibility assessment

Option	Price range (USD $/tCO_2$)	Approximate price (USD $/tCO_2$)	Economic feasibility (score)
Afforestation & reforestation	5–50[a]	27.5	10.0
Low-temperature biochar	100–114[a]	107.0	9.0
High-temperature biochar	270[b]–565[c]	417.5	6.0
BECCS	N/A	300[e]	7.0
DACCS	320-1800[d]	1060[e]	1.0
Enhanced weathering	200-480[d]	435[e]	6.0
Soil carbon sequestration	0–100[a]	50.0	10.0

[a] (18) estimated cost for a limited potential
[b] (supplier) listed cost for biochar offering with a duration defined as >1,000 years
[c] range end of cost for single purchases made in the past of at least 1,000 tCO_2 from CDR.fyi (35)
[d] range end of cost for single purchases made in the past of at least 100 tCO_2 from CDR.FYI due to limited datapoints (35)
[e] Average market price indicated by Allied Offsets (59)

Table 5: Governance assessment

Option	Score		Key barriers/incentives	Source
Afforestation and reforestation	**6** (med-high)	High MRV, med-high acceptance, and med.-low governance	Deemed acceptable on several fronts including environmental safety, reversibility and locality" (7) (60) but implementation could be challenging due to the large number of actors involved.	(7) (24) (60) and authors' judgement
Biochar	**6** (med-high)	Med.-high MRV, med.-high acceptance, and med.-low governance	Similar implementation challenges as afforestation and reforestation. Supply chain transparency may be a challenge to ensure sustainable biomass sourcing.	(24) and authors' judgement
Bioenergy carbon capture and storage (BECCS) no exp.	**6** (med-high)	High MRV, moderate acceptance, and med-low governance	Public acceptance may be an issue because of facility siting, local air pollution, and feedstock transportation and handling. High transparency and accountability but not as high as for DACCS. Supply chain transparency may be a challenge to ensure sustainable biomass sourcing.	(24) (66) and authors' judgement

Option	Score		Key barriers/incentives	Source
BECCS exp.	**5** (moderate)	Similar as BECCS no exp., but med.-low acceptance)	Similar to BECCS no exp. Additional governance riks arising due to need to ensure land expansion does not have materially negative consequences.	Similar to BECCS no exp.
Direct air carbon capture and storage (DACCS) saline aq.	**8** (very high)	High MRV, med.-high acceptance, and high governance	It is “more ambiguous, being seen as contained, reversible and well understood, but at the same time as aesthetically intrusive, end-of-pipe and technically difficult to scale up”. (61) Still above average perception. Emission reductions are more easily accounted for, tracked and controllable. Among all options, DACCS accountability is the easiest.	(24) (61) and authors’ judgement
DACCS mineral.	**8** (very high)	Med.-high MRV, med.-high acceptance, and high governance	Similar to DACCS saline aq. The rapid mineralization of storage method may increase acceptance compared to storage in saline aquifers, which would take centuries to mineralize the CO_2 (although it would be safe too). Capture MRV is the same but storage MRV for mineralization is at an early development stage.	(24) (61) and authors’ judgement
Enhanced weathering	**6** (med.-high)	Low MRV, high acceptance, and high governance	“While much less is known about perceptions of enhanced weathering, early results suggest more support than opposition”	(7) (60) and authors’ judgement
Enhanced weathering	**6** (med.-high)	Low MRV, high acceptance, and high governance	“While much less is known about perceptions of enhanced weathering, early results suggest more support than opposition”	(7) (60) and authors’ judgement
Soil carbon sequestration	**5** (moderate)	Med-low MRV, med-high acceptance, and moderate governance	Like afforestation and reforestation, it requires incentives to align the interest of multiple stakeholders but transparency and accountability may be lower.	(7) (24) (60) and authors’ judgement

MRV and acceptance evaluations based on (24). MRV is a combination of capture and storage, and acceptance is based on sentiment of tweets between 2010 and 2021.

Climate change effectiveness

Table 6: Effect assessment

Option	Score	Reasoning	Source
Afforestation	**2** (low)	Vulnerable to disturbance; post-AR management essential. (2) (50) “Direct and indirect LUC [land use change], albedo change (boreal: offsetting impact; temperate: neutralized)”. (2) Monoculture plantations over non previously forested land increase vulnerability (high confidence); they can also exacerbate further greenhouse gas (GHG) emissions. (1)	(2) (50)
Reforestation	**4** (low-med)	Similar in vulnerability as afforestation. However, it can contribute to more resilient natural ecosystems.	(2) (50) (25)
Low temperature biochar	**5** (moderate)	(50) “Albedo change partly offsetting mitigation effect, even though likelihood low, as biochar would be buried”. (2) Intermediate risk of reversal (29: a comparative).	(2) (50)

Option	Score	Reasoning	Source
High temperature biochar	**6** (med-high)	(50)"Albedo change partly offsetting mitigation effect, even though likelihood low, as biochar would be buried". (2) More stable than low-temperature biochar.	(2) (50)
BECCS exp.	**7** (high)	"Albedo change, direct and indirect LUC GHG emissions". (2) Very low risk of reversal. (62)	(2) (50)
BECCS no exp.	**8** (high)	Less albedo change, direct and indirect LUC GHG emissions if it relies less than BECCS exp. on dedicated bioenergy crops. Very low risk of reversal. (62)	(62) and authors' assessment
DACCS saline aq.	**8** (high)	Very low risk of reversal. (62)	(62) and authors' assessment
DACCS mineral.	**10** (very high)	Permanent. Negligible risk of reversal. (62)	(62) and authors' assessment
Enhanced weathering	**10** (very high)	Permanent. Negligible risk of reversal. (62)	(62) and authors' assessment
Soil carbon sequestration	3 (low)	Similar to afforestation and reforestation. "Soil sinks saturate and are reversible when the management practice promoting soil carbon sequestration ceases". (2) (50)	(2) (50)

Source: Based on (43)

"Durability" scores of "low" or "very low" score to "temporary" solutions (<1,000 years) because it is necessary to recapture the CO_2. "Permanent" solutions (>100,000 years, the period over which carbon perturbations are removed from the surface carbon cycle (20)) receive the top score of 10.

Table 7: Durability assessment

Option	Storage time* (years)	Score	Further details	Source
Afforestation & reforestation	~10^2 (decades to centuries)	**2** (low)	"Temporary" (2) (20) solution.	(2) (20)
Low temperature biochar	>10^2	**3** (low)	"Temporary" (2) (20) solution. Residence times of biochars depends on soil type, management and environmental conditions	(2) (20)
High temperature biochar	>10^3	**6** (med-high)	Pyrolysis temperatures > 500°C generally led to longer-term (i.e., > 1,000 years) half-lives.	(67) (67)
BECCS	>10^4	**9** (very-high)	"Permanent" (2) (20) solution. "High permanency for adequate geological storage". (2) (20) Potential limits due to co-location of bioenergy production and availability of "permanent" sequestration sites	(2) (20)
DACCS	>10^4	**9** (very high)	"Permanent" (2) (20) solution. "High permanency for adequate geological storage; possible storage limitations but flexible co-location with storage possible". (2) (20)	(7) (2) (20)

Option	Storage time* (years)	Score	Further details	Source
Enhanced weathering	>10^4	**9** (very high)	"Permanent" (2) (20) solution. "Saturation of soil; Residence time from months to geological time scale". (2) (20)	(2) (20)
Soil carbon sequestration	~10^2 (decades to centuries)	**2** (low)	"Temporary" (2) (20) solution	(2) (20)

*All storage time estimates are taken from (20) and are consistent with IPCC, 2022 (1)

Source: Based on (43)

Table 8: Timeliness assessment

Option	Score[a]	Further details [score]	Source
Afforestation and reforestation	1.5	Very slow to reach peak capture capacity; in addition, albedo change can further delay achieving net negative emissions [1]. Low flexibility due to organizational challenges and large land requirements [2].	(7) (68)
Biochar	10.0	It can have an immediate effect. And the increasing market offerings related to biochar suggest it may be possible to have a quick adoption rate.	(63) (63) and authors' assessment
BECCS no exp.	8.0	It can reach the potential of the capacity installed within one year (where biomass is sourced from lands where carbon stocks are stable and increasing). Highly flexible, scalable, and controllable, but flexibility may be limited by dependence on bioenergy demand and availability of storage, and scalability by availability of sustainably sourced biomass (to a lesser extent than AR).	(7) (69)
BECCS exp.	1.0	It can result in high initial land-use change emissions. For this reason, it can become net-negative only after several years of operation.	(7) (69) (52)
DACCS	10.0	Time to reach installed capacity is the shortest among CDR methods [10]. It is more scalable than AR, SCS, biochar, and BECCS as it depends less on biophysical limits. High flexibility of location. It is also more controllable as it is possible to stop it at any time [10].	(7)
Enhanced weathering	3.5	Highly uncertain timeliness of effect because it largely depends on environmental factors [2]. More flexible and scalable than AR, SCS, and biochar as it depends more on technology deployment, but it is not reversible (e.g., once it is implemented, it is not possible to stop, whereas with DACCS and BECCS it is possible to stop) [5].	(2) (51)
Soil carbon sequestration	2.0	Highly uncertain timeliness of effect because of large variation in saturation times and dependence on environmental factors [2]. Low flexibility due to organizational challenges [2].	(7) (2)

[a] Timeliness is the average of two scores: one related to the time to reach the maximum capacity, and another score combining factors related to flexibility and controllability.

Side impacts

The evaluation of side impacts follows a seven-level, bipolar scale (from “highly negative” to “highly positive” impacts), normalized to the common scale from 0 to 10.

Table 9: Net side impact scoring scale

	Negative	Positive
High	0.00	10.00
Moderate	1.67	8.33
Low	3.33	6.67
None/neutral	5.00	5.00

The quantification of the impacts is mostly based on the conclusions of extensive research studies, mainly by the Royal Society, the Royal Academy of Engineering, and the Mercator Research Institute on Global Commons and Climate Change. (7) (2) (50) (51)

Afforestation and reforestation

Environmental: Afforestation, 1.67 (Positive: None. Negative: Medium); Reforestation, 10 (Positive: High. Negative: None)

Positive:

- “Reforestation of previously forested land can help protect and recover biodiversity… and restore hydrological processes, thereby improving water supply and quality… and reducing the risk of soil erosion and floods (high confidence) (25)

Negative:

- Afforesting areas such as savannas and temperate peatlands, which would not naturally be forested, damages biodiversity and increases vulnerability to climate change (high confidence) (25)

Economic: Afforestation, 5 (Positive: Low. Negative: Low); Reforestation, 6.67 (Positive: Medium. Negative: Low)

Positive:

- Can have some positive economic impacts from improved ecosystem services (70)

Negative:

- “Less agricultural exports, higher food prices” (due to large land-use requirement) (2)

Social: Afforestation, 5 (Positive: Low. Negative: Low); Reforestation, 8.33 (Positive: Medium. Negative: None)

Positive:

- “Employment (caveat: low-paid seasonal jobs), local livelihoods” (2)
- Reforestation of previously forested land can help improve climate adaptation. It can “improve water supply and quality” and “reduce the risk of soil erosion and floods (high confidence)” (25)

Negative:

- Can have some negative impacts on food security and energy access (e.g., for people relying on traditional bioenergy in developing countries)

Biochar (low and high temperature)

Environmental: 6.67 (Positive: Medium. Negative: Low)

Positive:

- "Reduced CH4 [methane] and N2O [nitrous oxide] emissions from soils" (2)
- "Improved soil carbon, nutrient and water cycling impacts" (2)

Negative:

- "Down-regulation of plant defence genes may increase plant vulnerability against insects, pathogens, and drought" (2)
- "Long-term effects on soils not yet known" (50)
- "Medium risk of unanticipated environmental effects" (50)

Economic: 6.67 (Positive: Medium. Negative: Low)

Positive:

- "Increased crop yields and reduced drought" (2)

Negative:

- "Competition for biomass resources" (2) and potential rise in food prices

Social: 6.67 (Positive: Low. Negative: None)

Positive:

- By improving soil health and agricultural yields, (29) it could improve food security

BECCS (with and without agricultural expansion)

Environmental: BECCS exp., 0 (Positive: None. Negative: High); BECCS no exp., 3.33 (Positive: None. Negative: Low)

Positive:

- If BECCS replaces current agricultural land, without inducing agricultural expansion elsewhere, it can enhance soil organic carbon and biodiversity, but the benefits would be minimal compared to natural regrowth (e.g., leaving the agricultural land alone). (52)
- Water and nutrients could be sustainably managed to minimise side impacts such as eutrophication and water stress. (52)
- Can make use of waste and residuals or existing markets that might otherwise be burnt or sent to landfill.
- Can improve sustainability of forest or farm management when supply chain adopts strict governance and certification systems.

Negative:

- "Biodiversity loss, deforestation and forest degradation, air pollution CO_2 leakage, impacts of fertiliser use on soil and water" (2)
- "Medium risk of unanticipated environmental effects" (50)

Economic: BECCS exp., 5 (Positive: High. Negative: High); BECCS no exp., 8.33 (Positive: High. Negative: Low)

Positive:

- Energy production side benefits, which is a core aspect distinguishing BECCS from other CDR methods.
- Market opportunities, economic diversification, technology development and transfer (2)
- It could also benefit from economic uses for CO_2 (71)

Negative:

- Potential rise in food prices (2) and competition for biomass resources

Social: BECCS exp., 1.67 (Positive: Low. Negative: High); BECCS no exp., 6.67 (Positive: Medium. Negative: Low)

Positive:

- Energy independence (2) it can influence securing energy access in some countries.

Negative:

- Food security risk, health impacts (7)

DACCS

Environmental: 3.33 (Positive: None. Negative: Low)

Negative:

- Low impacts, assuming renewable energy use and no large impacts from material use
- "CO_2 penalty if high (thermal) energy demand satisfied by fossil fuels; mostly insufficiently studied; material/waste implications not known but cannot be excluded; some spatial requirements" (7)

Economic: 3.33 (Positive: Low. Negative: Medium)

Positive:

- Business opportunities in market niches: improved indoor quality, synfuels production, greenhouse fertilization, industrial use, enhanced oil recovery; however, market demand for CO_2 is very small compared to the CO_2 to be stored. (2) In the future (by 2050), there may be a much larger market for CO_2 at a Gt-scale. (71)

Negative:

- High expected costs are accounted for under economic feasibility
- Competition for energy resources (currently highly valuable)

Social: 6.67 (Positive: Low. Negative: None)

Positive:

- Equality of market opportunities. Thanks to its scalability and flexibility, and the possibility of start-ups taking on the challenge, economic opportunities would be accessible to entrepreneurs and smaller organisations. (66) Hence, social benefits from increased income could reach a larger audience than, for example, BECCS. However, it would not impact more people than other options like SCS, which may directly benefit more people who need it more, for example, farmers in developing countries.

- Health: It can have niche applications for improved indoor quality. (7)
- Although governance issues and social acceptance are better than for other options, which increases DAC's feasibility, it does not provide any added social side benefits.

Negative:

- Competition for energy resources may affect energy access due to increased costs.

Enhanced weathering

Environmental: 3.33 (Positive: Low. Negative: Medium)

Positive:

- "Improved plant nutrition" (2)
- "Improved soil fertility, nutrient and moisture, increase in soil pH, increasing cation exchange capacity in depleted soils" (2)
- "Ocean EW [enhanced weathering] reverses undesirable effects of ocean acidification" (50)

Negative:

- "Ecological impacts of mineral extraction and transport on a massive scale" (2)
- "Direct and indirect land use change if biomass sourced from dedicated crops, potentially heavy metal release depending on the soil characteristics, risks of fine-grained material, changes in soil hydraulic properties" (2)
- Terrestrial enhanced weathering may have few serious side effects, but effects on soil pH, vegetation, etc. need to be established (at levels of application that are effective); ocean enhanced weathering may have adverse side-effects on some marine biota (51)
- "Medium risk of unanticipated environmental effects" (51)

Economic: 6.67 (Positive: Low. Negative: None)

Positive:

- "Increase in crop yields" (2)

Social: 3.33 (Positive: None. Negative: Low)

Negative:

- "Human health impacts associated to fine grained material" (2)

Soil carbon sequestration

Environmental: 6.67 (Positive: Medium. Negative: Low)

Positive:

- "Mostly reduced pollution and improved soil quality" (2)
- "Mostly positive impacts on soil, water and air quality" (2)

Negative:

- "Possible increase in N_2O emissions and N [nitrogen] and P [phosphorus] losses to water due to more N and P substrate for mineralisation" (2)
- "Need for addition of N and P to maintain stoichiometry of soil organic matter" (2)

Economic: 8.33 (Positive: Medium. Negative: None)

Positive:

- "Improved soil resilience and improved agricultural production" (2)

- "Negative cost options" (2)

Social: 10 (Positive: High. Negative: None)

Positive:

- Employment and poverty reduction. Distribution and access to economic benefits: smallholder farmers in developing countries can largely benefit from it. (72)
- It can contribute to more resilient agriculture.

Survey for real stakeholder portfolio preference weighting factors.

We conducted a survey to calculate average stakeholder portfolio preferences. Table 4 in the main report shows the average stakeholder score for each performance category. The data was based on input from 45 stakeholders with expertise or interest in CDR collected during April 2023. Participants represented 12 industry sectors on six continents. Roughly half of the companies were small, with <500 employees, and a quarter were large, with >15,000 employees. The participants were from nine corporate functions, with one-third in strategic management. There were a variety of experience levels, with three-quarters in a management role.

Disclaimer

This publication is released in the name of the World Business Council for Sustainable Development (WBCSD). It is the result of a collaborative effort between WBCSD, South Pole and representatives from companies participating in the WBCSD CCS & Removals workstream.

A wide range of members of the CCS & Removals workstream have reviewed the material, thereby ensuring that the document broadly represents a majority view. It does not mean, however, that every company within the workstream agrees with every word.

This publication has been prepared for general informational purposes only and is not intended to be relied upon as accounting, tax, legal or other professional advice.

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About WBCSD

The World Business Council for Sustainable Development (WBCSD) is a global community of over 225 of the world's leading businesses driving systems transformation for a better world in which 9+ billion people can live well, within planetary boundaries, by mid-century. Together, we transform the systems we work in to limit the impact of the climate crisis, restore nature and tackle inequality.

We accelerate value chain transformation across key sectors and reshape the financial system to reward sustainable leadership and action through a lower cost of capital. Through the exchange of best practices, improving performance, accessing education, forming partnerships, and shaping the policy agenda, we drive progress in businesses and sharpen the accountability of their performance.

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