RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue





Cite this: *RSC Sustainability*, 2025, **3**, 1424

# Carbon removal efficiency and energy requirement of engineered carbon removal technologies

Daniel L. Sanchez, *[abc] Peter Psarras,[ad] Hannah K. Murnen[b] and Barclay Rogers[b]

Received 5th September 2024
Accepted 2nd January 2025

DOI: 10.1039/d4su00552j

rsc.li/rscsus

To ensure carbon negativity, processes that achieve carbon dioxide removal (CDR) from the atmosphere must consider lifecycle emissions and energy requirements across the entire system. We conduct a harmonized lifecycle greenhouse gas assessment to compare the carbon removal efficiency and total energy required for twelve engineered carbon removal technologies. The goal of this comparison is to enable the assessment of diverse engineered carbon removal approaches on a consistent basis. Biomass-based CDR approaches generally maintain higher carbon removal efficiency than direct air capture (DAC) and, to a lesser extent, enhanced rock weathering (ERW) due to the high concentration of carbon within the biomass and the relatively low energy requirements for processing the biomass for removal. Nevertheless, there is high variance in CDR approaches, as some biomass conversion processes (*e.g.*, pyrolysis for biochar or gasification for fuels) exhibit high, yet variable, carbon losses, while DAC and ERW can utilize low-carbon energy inputs for more efficient removal. Regarding energy use, ERW and biomass-based approaches generally require less energy than DAC today, but biomass approaches again exhibit more variation. Displacement of products, when included, increases the total climate benefits of biomass used for bioenergy with carbon capture and storage (BECCS) and biochar. These two measures are intuitive metrics to guide allocation of scarce resources amongst potentially competing uses of biomass and low-carbon energy.

### Sustainability spotlight

Processes that generate carbon dioxide removal (CDR) from the atmosphere are core to Sustainable Development Goals of climate action, affordable and clean energy, and life on land. We assess 12 engineered CDR approaches on two metrics, net carbon removal efficiency and net energy requirement, to guide allocation of scarce resources amongst potentially competing uses of resources including biomass and low-carbon energy. These metrics can help ensure the efficient and prudent use of land and clean energy for climate action.

## Introduction

Innovation in engineered carbon dioxide removal (CDR) is proceeding rapidly, with numerous technologies being explored in both commercial and academic contexts. In the past several years, startup companies and academics have proposed what appear to be relatively simple processes that may be cheaper, more efficient, or less resource-intensive than other prominent CDR approaches. For instance, several biomass carbon removal and storage (BiCRS) technologies, such as biomass sinking or sludge sequestration, intend to both preserve a larger fraction of the biogenic carbon contained in biomass and use less process energy, when compared to prominently studied technologies such as biomass energy with carbon capture and sequestration (BECCS).[1] Developing intuitive metrics can help guide allocation of scarce resources amongst potentially competing uses of biomass and low-carbon energy. These metrics can help ensure the efficient and prudent use of resources including biomass and clean energy for climate action.

Since CDR approaches are designed to lower atmospheric $CO_2$, it is important to monitor both the flux of carbon into the techno- or biosphere, as well as the flux of carbon back to the atmosphere over the process lifecycle. The net flux of carbon, defined as the carbon removal efficiency, can be thought of as a measure of process efficiency, and reflects the fraction of carbon that is removed from the atmosphere from that which is captured either directly from the air, in the case of direct air capture (DAC) and enhanced rock weathering (ERW), or *via* photosynthesis in the case of biomass CDR approaches. There are numerous ways to reduce the carbon removal efficiency, such as process emissions, supply chain losses, or inefficient carbon conversion to long-lived products. For instance, it is

[a]Carbon Direct, USA. E-mail: sanchezd@berkeley.edu
[b]Graphyte, USA
[c]University of California-Berkeley, USA
[d]University of Pennsylvania, USA

 

likely in the near term that energy-consuming CDR processes will use carbon-intensive energy, such as grid electricity or natural gas. These factors are also unevenly distributed across the various emerging CDR landscape. For instance Chiquier *et al.*[2] report that BECCS has relatively high carbon removal efficiency absent significant land use change, biochar has lower efficiency, and the efficiency of DAC and ERW are largely dependent on their energy use.

Existing literature has primarily compared biomass, DAC, or ERW approaches separately,[3,4] likely due to the very different nature of the pathways and therefore the different nature of the types of concerns and resources required to carry out the pathways. For instance, Patrizio *et al.* estimate the net carbon removal and avoidance for biomass-based CDR, focusing on the transport, power, construction, and iron and steel sectors in Europe.[5] They do not consider DAC, ERW, and some novel biomass CDR approaches, nor do they estimate energy requirements for engineered CDR. Similarly, several authors have examined the best use of biomass in the context of climate change mitigation.[6,7] These authors emphasize both the carbon storage and substitution benefits of biomass utilization. However, they do not provide consistent metrics, nor do they consider non-biomass CDR approaches.

To date, a systematic comparison of CDR approaches, including new market entrants, has not yet been performed. This analysis considers multiple different biomass carbon removal approaches including approaches ranging from marine sinking of biomass to encapsulation and burial of biomass, as well as other biomass-based CDR, ERW, and DAC. Four ‘‘minimum qualifications’’ are adopted here for determining whether a technology results in carbon dioxide removal:[8]

1. Physical greenhouse gases are removed from the atmosphere. In the case of biomass based approaches, this can be met using waste biomass that has collected $CO_2$ from air during it's growth and would otherwise decompose and send the carbon back into the atmosphere in the form of $CO_2$ or $CH_4$.

2. The removed gases are stored out of the atmosphere in a manner that is demonstrably permanent.

3. Upstream and downstream greenhouse gas emissions associated with the removal and storage process, such as biomass origin, energy use, gas fate, and co-product fate, are comprehensively estimated and included in the emission balance.

4. The total quantity of atmospheric greenhouse gases removed and permanently stored is greater than the total quantity of greenhouse gases emitted to the atmosphere.

We evaluate two metrics, carbon removal efficiency and total energy required, across 12 engineered carbon removal technologies. These metrics are an output from the lifecycle assessment (LCA), a quantification tool largely viewed as a necessary component of any CDR claim. The goal of this analysis is to determine which removal processes retain the largest amount of carbon while also understanding the energy (and other resources) required to execute, or produced alongside, the removal. Notionally, processes that are both highly carbon efficient and avoid high resource consumption are likely to incur less barriers to scale and may prove the least impactful to the environment. Total land use for these projects is inversely proportional to carbon removal efficiency.

An additional challenge is that many CDR approaches offer co-products (and related co-benefits) outside of (and in addition to or *in lieu* of) durable carbon removals. This is a largely complicating feature of many CDR approaches because in addition to the need for a comprehensive and scientifically robust assessment of all benefits, it necessitates a comparison amongst benefits generated, *e.g.*, weighing durable carbon removal against electricity generation, other co-product generation, or extended ecosystem co-benefits like nutrient cycling. Some of these co-benefits can be assessed through LCA to yield similar comparative impacts such as GHG abatement or reductions in other impact categories. However, many of these approaches rely on complicated counterfactual scenarios, and other benefits yield no comparable life cycle impacts which makes their comparison subjective. We exclude these displacement benefits in our base definition of carbon removal efficiency but consider them as a sensitivity scenario.

In addition to carbon removal efficiency, it is important to assess the total energy required for CDR. Provision of process energy to remove $CO_2$ from the atmosphere reduces net carbon removal. DAC, for instance, requires both heat and power.[9] Numerous energy sources have been proposed for DAC, including renewable electricity, natural gas, and biomass, with and without CCS.[10,11] Many project developers contend that renewable carbon-free energy will be utilized for processes, thus reducing the amount of carbon emitted for a given pathway. However, renewable energy is already a scarce resource and is likely to become even scarcer as we work collectively to decarbonize a wide variety of industrial processes. For example, it is estimated we will need to expand the global electricity supply by nearly 4× by 2050 while converting all of it to renewable generation to meet the needs of decarbonizing processes.[12] This dramatic increase does not include additional electricity requirements for scaling carbon removal pathways.

It is also important to understand other finite resource requirements across engineered removal approaches. Biomass wastes and residues, for instance, have been popularized in several reports as a resource to meet carbon removal goals while avoiding unwanted upstream emission penalties like indirect and direct land use changes.[13,14] BECCS uses these biomass resources to create energy and sequester $CO_2$. In contrast, BiCRS emphasizes a more expansive role for biomass in CDR beyond cogeneration of energy.[15] Acknowledgement of this potential conflict has been embodied in such positions as the Aines Principle, which recognizes the competing economic value of CDR *versus* energy generation.[16] To date, this techno-economic principle does not have an analog in LCA. This study attempts to place these considerations in full view for comparison.

## Methods

The goal of this study is to rigorously compare a variety of engineered CDR approaches on a consistent set of metrics to assess the carbon removal efficiency and energy requirements against any additional co-benefits. The scope of this study includes a cradle-to-storage LCA that evaluates each technology's efficacy at achieving durable carbon removal against their respective life cycle emissions of both direct (on-site) and indirect (supply chain) greenhouse gases, using global warming potentials (GWPs) from the 5th IPCC assessment report. Non-GHG impact categories (*e.g.*, acidification, eutrophication, particulate matter formation, *etc.*) are not included in this analysis.

While the technologies under study were intentionally selected to represent pathways with a strong likelihood of achieving durable carbon removal, it is important to note that reversal of carbon storage has been excluded from this analysis due to insufficient data. First, the likelihood of reversal of each pathway is not universally agreed upon, nor is the time frame in which the reversal might occur. Secondly, the type and form of reversal is important. In the case of biomass methods, there is the potential for reversal in the form of methane, which would have a much greater impact than release of $CO_2$. The risk associated with these reversals is also inherently linked to execution of each pathway and thus outside this analysis. Finally, the energy required for monitoring is not included in the analysis. Along with an analysis of reversal risk, energy for monitoring could be a useful addition to this framework in the future.

We have created a framework with consistent system boundaries, emissions factors and transportation distances across approaches (Fig. 1). We consider the same project location of Arkansas, United States, for all cases for the purposes of electricity carbon intensity. Where possible, we have utilized data associated with delivered carbon removal credits, such as reports from CDR registries. When such data was unavailable, we relied on publicly available analyses of the approaches.

The functional unit is defined as one net tonne of $CO_2$ durably removed from the atmosphere. Reversals over time are not considered in the assessment. The net carbon dioxide removal efficiency for biomass CDR is calculated as follows:

$$\text{CDR efficiency}_{\text{biomass}} = (\text{CO}_2 \text{ stored in products} - \text{GHG emissions})/(\text{CO}_2 \text{ originating in biomass})$$

For non-biomass CDR approaches, $CO_2$ stored in products is considered equivalent to $CO_2$ originating from the atmosphere:

$$\text{CDR efficiency}_{\text{DAC or ERW}} = 1 - (\text{GHG emissions}/\text{CO}_2 \text{ sourced from atmosphere})$$

Finally, we consider a sensitivity case for energy-producing biomass conversion processes that displace fossil-intensive sources of energy. We only consider displacement for three scenarios: BECCS (power), BECCS (fuel), and biochar field application, which produces bio-oil as a co-product. We do not consider carbon storage in short-lived products.

We define total energy requirement as the energy input required for the entire set of actions to durably store the carbon. This includes all heat energy which could be supplied through fossil fuels or through the burning of biomass as well as electrical energy. We calculate the internal energy for pyrolysis and torrefaction based on Seoherman *et al.* 2023 & Yang *et al.* 2013.[17,18] These results do not include energy for transportation of materials.

$$\text{Total energy requirement} = \sum(\text{electric energy} + \text{thermal/diesel energy})/(\text{CDR efficiency})$$

We consider twelve approaches in this analysis, which were chosen due to their existing or planned deployment in the voluntary carbon market:

Enhanced Rock Weathering (ERW) – basalt or olivine rocks are ground up to provide enhanced surface area for weathering of the material. The ground up rock is spread over an area (most typically an agricultural field) where $CO_2$ from the air can react with the mineral elements to form carbonic acid or bicarbonate

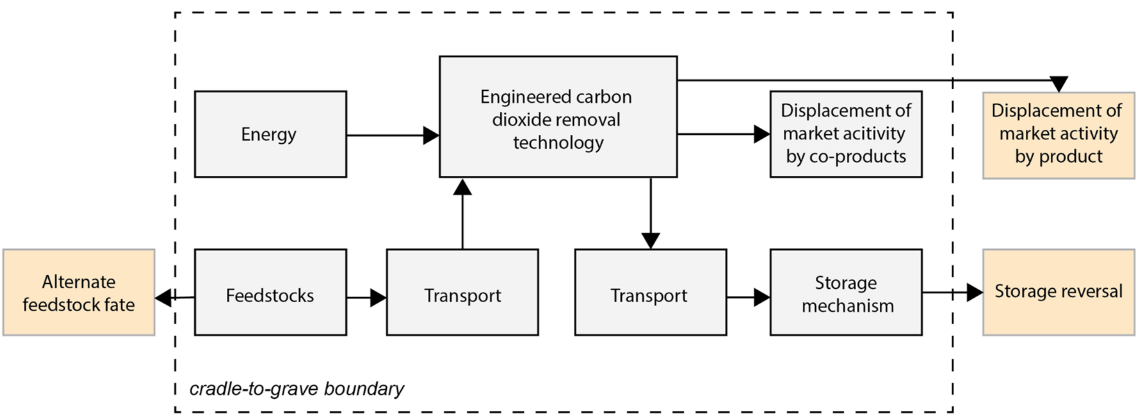


Fig. 1 System boundary for estimating the net carbon removal efficiency of engineered carbon removal technologies. This system is meant to be generic across the different removal pathways. The different boxes will take different forms depending on the removal pathway. For example, feedstocks in the case of ERW systems include any rock that needs to be crushed and transported. For BICRS pathways, feedstocks are biomass. In the case of DAC systems, the feedstocks are not required as air is the main recurring input. The transport represents whatever transport is required; in the case of DAC, this represents transportation of $CO_2$ in a pipeline prior to sequestration.

 

which is then washed into the waterways and eventually permanently stored within ocean waters. In analyzing this method, we have utilized the work done by Moosdorf *et al.*, but updated assumptions about the transportation associated with getting the ground rock to the deployment site.[19] We have leveraged publicly available data from specific deployments that include rock extraction and grinding in Norway and transportation to deployment sites in Mississippi, United States.[20] ERW with basalts has been proposed by Lithos, while ERW with olivine has been proposed by Eion. We report scenarios for basalts and olivine separately.

Sequestration of biomass sludge[21] – in this approach, minimally processed organic wastes are injected underground as a slurry where the geology of the injection space traps any evolved $CO_2$ or $CH_4$. This approach has been proposed by Vaulted Deep and the delivered credits are documented by Isometric. Storage takes place in a Class V storage well under EPA's underground injection control program. For this approach, a carbon content of 10% has been used to reflect the slurried nature of this waste where the solids content is relatively low.

Sinking of biomass into anoxic marine environments[22] – biomass from terrestrial applications is transported into marine environments where it is sunk into the ocean. The marine environment is anoxic, preventing the decomposition of the biomass. This approach has been proposed by Rewind Earth for the Black Sea.

Carbon casting – biomass is aggregated, dried to halt microbial decomposition and then encapsulated in a polymer to prevent re-entry of water. The encapsulated biomass is then stored in a purpose-built site below ground. This approach has been proposed by Graphyte in Arkansas, United States. Data was shared directly from the company. Similar methods have also been suggested by Yablonovitch and Deckman although they focused on using salt to maintain the dry conditions rather than encapsulation.[23]

Biochar production[24] – biomass is aggregated and pyrolyzed to transform the raw biomass into a more stable, carbon-rich material. Pyrolysis occurs at 500 °C. This carbon-rich material is then distributed into agricultural settings as a soil amendment. Bio-oil is also produced as a co-product. This approach has been proposed by Carbofex, amongst others, and delivered credits are documented by Carbonfuture and Puro.earth.

Torrefied biomass production and burial[18] – this is a variation on biochar production, where torrefied biomass is buried after production. Torrefaction occurs at 400 °C. This approach has been proposed by Carba.

Bio-oil sequestration[25,26] – biomass is aggregated and pyrolyzed to transform the raw biomass into bio-oil, a carbon-rich liquid. Pyrolysis occurs at 600 °C. Bio-oil is injected into a Class V storage well under EPA's underground injection control program. This approach has been proposed by Charm Industrial.

Bioenergy with carbon capture and sequestration (BECCS) for power[27] – biomass is aggregated and combusted to produce electricity. 90% of produced $CO_2$ is captured using an amine capture system, compressed, and stored underground in a deep geologic formation. For the United States, storage occurs in a Class VI well under EPA's underground injection control program. This approach has been proposed by Ørsted, amongst others.

Bioenergy with carbon capture and sequestration (BECCS) for fuels[28] – biomass is aggregated, gasified, and chemically transformed into a mixture of diesel fuel and naphtha. Byproduct $CO_2$ is captured, compressed and stored underground. This approach has been proposed by Strategic Biofuels, amongst others.

DAC (solid absorbent)[29] – $CO_2$ is captured from ambient air using small, modular contactors containing an amine-functionalized sorbent supported on silica. A temperature-vacuum swing approach is modeled, where steam is generated on site and used to desorb the sorbent surface. The $CO_2/H_2O$ mixture is then dehydrated and the purified $CO_2$ is compressed for geologic storage. Thermal and electric power demands are estimated from literature and public disclosure. This approach has been proposed by Climeworks, amongst others.

Table 1 List of modeling assumptions

| | |
|---|---|
| Biomass sources | Lignocellulosic biomass, biomass sludge |
| Biomass carbon content | 50 wt% for lignocellulosic biomass, 10% for biomass sludge |
| Carbon uptake in minerals | 0.57 $tCO_2/t$ olivine; 0.20 $tCO_2/t$ basalt |
| Transportation distance (upstream and downstream) | 50 miles |
| Solid material loss | 3% |
| Upstream natural gas leakage factor | 2.1% |
| Transportation/machinery fuel | Conventional diesel |
| eGRID subregion | SRSO (SERC South) |
| Baseline scenario | Electricity: grid electricity<br>Thermal: unabated natural gas |
| Sensitivity 1 | Electricity: 100% renewable energy blend (*via* power purchase agreement)<br>Thermal: unabated natural gas |
| Sensitivity 2 | Electricity: 100% renewable energy blend (*via* power purchase agreement)<br>Thermal: natural gas with CCS |
| Sensitivity 3 (DAC only) | +33% energy requirement to account for the relationship between ambient conditions and DAC performance in a sub-ideal location |

Table 2 Carbon removal efficiency and total energy (per gross tonne removed) for the technologies under consideration. Bold values represent the most likely scenario implementation of each technology. Total Energy estimates do not include co-products

| | Carbon removal efficiency | | | | | | |
|---|---|---|---|---|---|---|---|
| Technology | Baseline scenario | Sensitivity 1 | Sensitivity 2 (sensitivity 3 – DAC only | Total energy (GJ/$tCO_2$) | Commercial example | Status | Limitations to scaling |
| Carbon casting | 0.877 | 0.936 | 0.962 | 0.946 | Graphyte | Credits issued | Biomass supply |
| Torrified biomass burial | 0.734 | 0.756 | 0.756 | 1.392 | Carba | In development | Biomass supply |
| Biochar field applied | 0.194 | 0.217 | 0.217 | 5.913 | Carbofex | Credits issued | Logistics for field application |
| Marine biomass sinking | 0.962 | 0.962 | 0.962 | 0.376 | Rewind | Demonstration | Logistics, monitoring of reversals |
| Sludge sequestration | 0.951 | 0.963 | 0.963 | 0.137 | Vaulted | Credits issued | Waste sludge supply close to sequestration site, geologically appropriate sequestration sites |
| Bio-oil sequestration | 0.601 | 0.613 | 0.613 | 2.295 | Charm Industrial | Credits issued | Biomass supply, geologically appropriate sequestration sites |
| BECCS – power | 0.870 | 0.878 | 0.878 | 2.468 | Ørsted | Credits issued | Biomass supply, large capex projects, logistics for $CO_2$ transport and storage (class VI well permits) |
| BECCS – fuels | 0.553 | 0.568 | 0.568 | 2.518 | Strategic Biofuels | Credits issued | Biomass supply, large capex projects, logistics for $CO_2$ transport and storage (class VI well permits) |
| DAC – solid | 0.061 | 0.238 | 0.826 (0.777) | 11.940[a] | Climeworks | Credits issued | Renewable power, logistics for $CO_2$ transport and storage (class VI well permits) |
| DAC – liquid | 0.154 | 0.374 | 0.851 (0.809) | 10.300[a] | 1PointFive | Credits issued | Renewable power, logistics for $CO_2$ transport and storage (class VI well permits) |
| ERW – basalt | 0.823 | 0.868 | 0.868 | 0.716 | Lithos | Credits issued | Rock sourcing and crushing, logistics for application, MRV |
| ERW – olivine | 0.912 | 0.924 | 0.924 | 0.214 | Eion | Credits issued | Rock sourcing and crushing, logistics for application, MRV |

[a] Per sensitivity 3, the energy requirement for DAC is increased by +33% to account for sub-optimal ambient conditions.

DAC (liquid absorbent)[30,31] – $CO_2$ is captured from ambient air using larger contactors where the aqueous alkaline solution (*e.g.*, 1 M KOH(aq)) makes cross-contact with ambient air in a packed structure. The resulting aqueous carbonate solution is reacted with slaked lime to yield solid $CaCO_3$ and regenerate the solvent. This carbonate is then sized and calcined in an oxy-fired kiln to yield a pure stream of $CO_2$ and lime at around 900 C. Natural gas is used to heat the klin in a near-pure oxygen environment and, due to the nature of kiln and capture step, these emissions are intrinsically co-captured with the ambient $CO_2$ from the solid carbonate for conditioning and storage. This approach has been proposed by 1PointFive (formerly Carbon Engineering).

Both DAC technologies are sensitive to ambient conditions, namely temperature and relative humidity, which can impact the amount of energy required, as described elsewhere.[32–35]

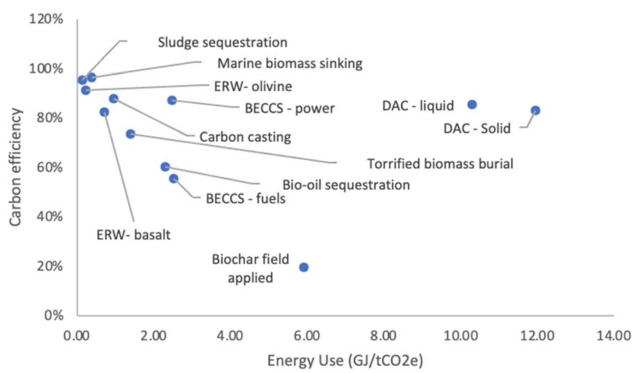


Fig. 2 Scatter plot of energy use and carbon efficiency in baseline scenario. Ideal CDR technologies have low energy use and high carbon removal efficiency.

While DAC companies are likely to seek out regions that lend to more efficient performance at scale, we have included an additional sensitivity case to demonstrate DAC net carbon efficiency in a less-than-ideal climate (*e.g.*, arid regions with lower average temperatures or greater variability in ambient temperature and relative humidities).

Assumptions are listed below in Table 1. These assumptions were fixed in an attempt to make the comparison as apples-to-apples as possible; however, there are a few important caveats to understand about the fixed assumptions, as well as the nominal values chosen for variable assumptions in the baseline scenario. These will be explored in the discussion section.

For external power required, we consider three scenarios. In our baseline, electricity is sourced from the local eGRID subregion (SRSO, or Southeastern Electric Reliability Council South) and heat is sourced from unabated natural gas. In our 1st sensitivity scenario, electricity is provided by renewable electricity and heat is sourced from unabated natural gas. In our 2nd sensitivity scenario, electricity is provided by renewable electricity and heat is sourced from natural gas with carbon capture and storage.

## Results

Table 2 lists each CDR approach and the two metrics assessed in this work. In addition, a commercial example for each approach is shared. These are not the only commercial examples of these approaches, but are meant to be representative of the approach type. The values within the table cover all three scenarios, with bold values representing the most likely implementation of each type of approach based on the authors' judgment. For example, in the case of "biochar field applied", we assume that

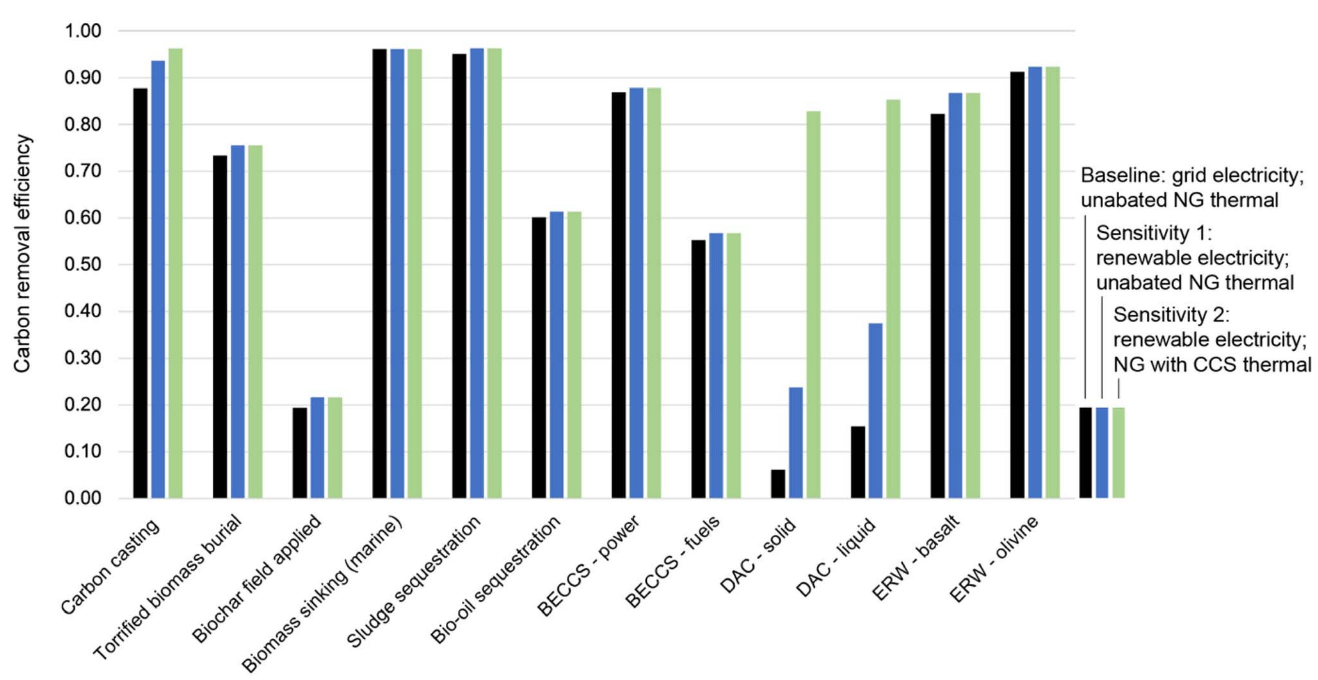


Fig. 3 Carbon removal efficiency for baseline and sensitivity scenarios.

most of the energy required for the conversion of biomass into biochar is coming from the thermal combustion of the biomass, reducing the carbon efficiency. In the case of the DAC approaches, we have assumed that the majority of the energy is supplied utilizing co-developed renewable energy generation.

The scatter plot in Fig. 2 shows all examined methods and places them according to their carbon efficiency and their energy use in their most likely embodiment. DAC processes require much more energy than other technologies. This is due to the very low concentration of $CO_2$ in the atmosphere and therefore the relatively high energy requirements to capture and store that $CO_2$. Interestingly, many of the most energy and carbon efficient approaches are biomass-based or open systems such as ERW or biomass sinking in the ocean. Rather than storing carbon in a closed chamber (*i.e.*, a geologic reservoir or engineered burial site), these open systems work to influence the natural environment to uptake more carbon and store it in natural environments (*e.g.*, minerals within water). This passive uptake is one reason while ERW is relatively carbon efficient and low energy use.

Fig. 3 shows the carbon removal efficiency of each method across all three scenarios. Most of the approaches are relatively insensitive to energy sourcing, as illustrated by the small range of carbon removal efficiencies observed over these scenarios. One key exception is DAC, which relies heavily on low-carbon energy sourcing to achieve comparable carbon removal efficiency. We consider one final sensitivity to illustrate the impact of ambient conditions on DAC performance and the consequential impact to net carbon removed. Because DAC performance falls off in less ideal climates (colder, drier regions), less $CO_2$ is captured per energy input and this increases the overall energy intensity of $CO_2$ removed. In this case, an increase in energy requirement of +33% over baseline, where baseline is taken from literature and assumed to reflect ideal climatic conditions for optimal performance, the net carbon removal decreases from 83 to 77% for solid sorbent DAC, and 85 to 81% for solvent DAC.

Ambient conditions can also influence the rate at which broadcast minerals uptake $CO_2$, however this is not expected to have a significant impact on the net carbon removal. Likewise, different geographies could have varying availability of reactive minerals, which are known to have variable alkalinity content based on mineral composition; this is addressed in the two separate ERW systems, though much more abundant materials – with even lower alkalinity content – may be considered.[36]

Geography can also influence biomass feedstock availability, where feedstocks with higher carbon content and lower moisture content are preferred. Processes like bio-oil sequestration or biochar get most of their process energy from burning of biomass itself, making them less sensitive to the carbon intensity of electricity or heat. However, the use of biomass as an energy source in these processes invariably reduces the amount of carbon available for permanent removal. A key example of this is field-applied biochar: the low reactor carbon yield (25% as modeled here) is driven in part due to biomass conversion into thermal energy, but also due to the loss of carbon into other products. Both of these conditions have implications on the net carbon removal (and, by extension, the net carbon abatement potential). First, use of biomass for thermal energy reduces the need for other forms of thermal energy like fossil fuels with their noted climate impacts, but also renewable energy that might be used for other emission reductions. Secondly, the creation of co-products enables market displacement of other products. The impact of market displacement on total emission abatement potential is shown in Fig. 4.

Displacement of products, when included, increases the total climate benefits of biomass used for BECCS and biochar.

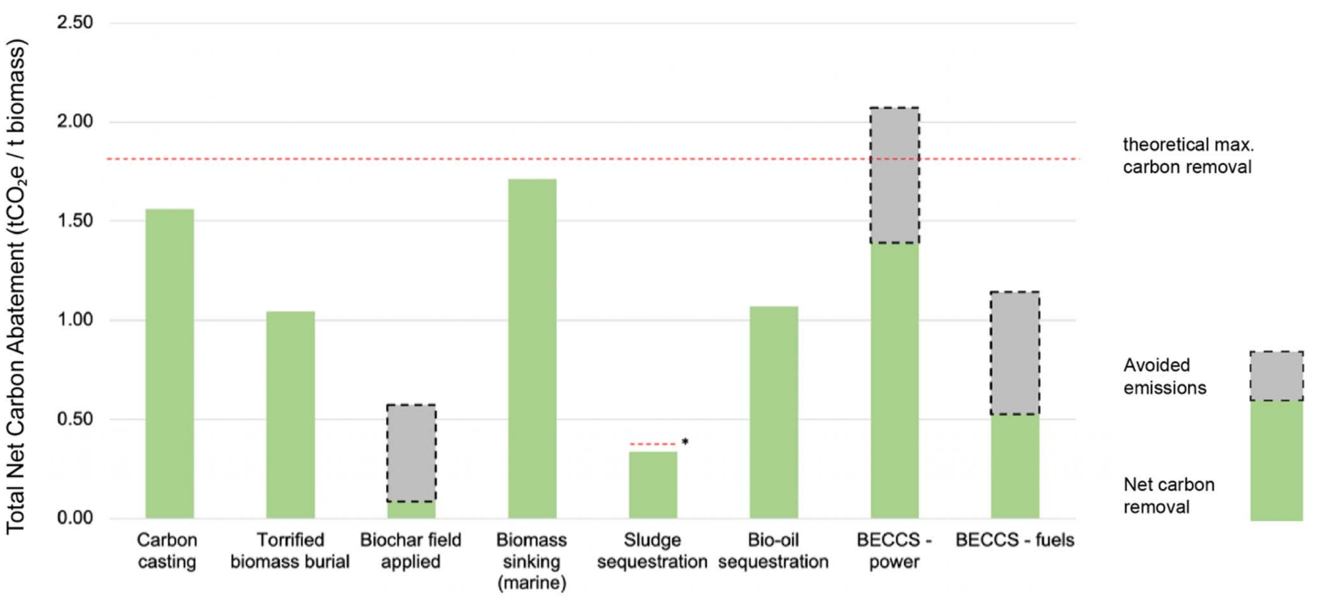


Fig. 4 Total net carbon abatement on a per tonne waste biomass basis (50 wt% C, except sludge sequestration). Gray bars represent avoided emissions. Theoretical maximum for carbon removal denoted by dashed line (*sludge sequestration is calculated at a lower wt% C as indicated in methods).

 

Results are reported on a per tonne waste biomass basis to illustrate the carbon abatement potential of one tonne of waste biomass over a number of technologies. The theoretical maximum for carbon removal as modeled in this study can be calculated as follows:

$$N_{\max} = \%\text{wt C} \times \frac{44}{12}$$

At 50 wt% carbon, a tonne of waste biomass can yield a maximum of *ca.* 1.83 tonnes of carbon dioxide (equivalent) removal. Many carbon removal technologies approach this maximum yet fall short due to emission losses due to process energy consumption and inefficiencies. Interestingly, the inclusion of displaced emissions in the case of BECCS power yields greater carbon abatement than the theoretical maximum for carbon removal from biomass alone. This is due to the greater emission impact of displaced power generation. For other co-product technologies, like bio-oil from pyrolysis or BECCS to various fuel products, the resulting market displacement effects add to the total carbon abatement but do not approach the total carbon abatement potential of other approaches. Excluded from this analysis are any additional, induced carbon emission impacts from market displacement by the main product, *e.g.*, fertilizer displacement from use of biochar as a soil amendment. The authors recognize that while these impacts may be important, it is too challenging to assess the actual induced effects due to large variability in soil conditions, soil type and crop systems.

## Discussion and conclusion

Several trends emerge from an examination of results. Biomass-based CDR approaches generally maintain higher carbon removal efficiency than DAC and, to a lesser extent, ERW, due to the high concentration of carbon within the biomass and the relatively low energy requirements for processing the biomass for removal. Nevertheless, there is high variance in CDR approaches, as some biomass conversion processes (*e.g.* pyrolysis for biochar or gasification for fuels) exhibit high carbon losses, while DAC and ERW can utilize low-carbon energy inputs for more efficient removal. Regarding energy use, ERW and biomass-based approaches require less energy than DAC, but biomass again exhibits more variation. In an energy-constrained world, these details matter. Consider that while most DAC projects consume north of 10 GJ per tonne of $CO_2$ net removed, many of the biomass approaches require less than 3 GJ of energy per tonne removed, with ERW, carbon casting, sludge sequestration and marine sinking of biomass requiring less than 1 GJ of energy.

The source of energy inputs for each CDR approach is also important for carbon removal efficiency. For example, carbon casting as conceived of here utilizes fossil energy for the drying, densification and encapsulation of biomass. Utilization of renewable energy for those steps would improve the carbon efficiency of that approach. Similarly, DAC approaches can be deployed using dedicated renewable generation which significantly improves the carbon efficiency of the removal. Finally, significant land use change will reduce the carbon removal efficiency on biomass-based approaches, as explored elsewhere.[2]

Displacement of products, when included, increases the total climate benefits of biomass used for bioenergy with carbon capture and storage (BECCS) and biochar. BECCS produces energy that can be utilized for other processes, potentially displacing the use of fossil energy for those processes. Similarly, bio-oil produced in the production of biochar could be utilized for the displacement of fossil fuels. However, it is also important to think about the total resource requirements for those types of displacements and whether there are alternative pathways that could make sense for the same displacement. In the case of BECCS, the parasitic load required to capture the resulting emissions from the generated power may make it more advantageous to utilize that biomass for carbon removal directly and utilize renewable energy in the form of solar or wind generation to produce the power needed to displace fossil emissions. This could inform a project developer about how to prioritize development of a BECCS plant as opposed to a solar installation and utilization of the biomass for carbon removal. Further, the loss in carbon removal potential in this – or any – pathway will require further deployment of CDR to reach an equivalent carbon removal target. Because of the vast disparity in outcomes and resource needs outlined above, the choice of CDR strategy makes a difference. For example, BECCS-power yields *ca.* 0.32 $t\text{CO}_2\text{e}$ less carbon removal per tonne biomass processed than the highest carbon removal efficiency BiCRS options, albeit while yielding roughly 1.45 MW h of low carbon power to the grid for each biomass tonne. If this 0.32 $t\text{CO}_2\text{e}$ is compensated with an electrified DAC project, for example, the additional low carbon energy consumption would be approximately twice that yielded to the grid from the BECCS-project.

Biomass waste and residues are a vast and useful, yet finite, resource that has emerged as a central part of envisioned carbon removal.[37–39] Still, the question of the “best” use of this resource remains hotly debated. Any fixed unit of waste biomass has an intrinsic maximum of $CO_2$ equivalent storage and this is directly related to the carbon content of the biomass feedstock. When the goal is net carbon removal, technologies with low energy consumption, minimal processing, and minimal losses due to conversion or other means, maximize this potential. Further, it is evident that extraction of biomass co-products, whether deliberately or as an unavoidable byproduct, invariably reduces the amount of carbon removal that a unit of biomass can deliver. While it is clear that these technologies deliver less carbon removal per unit biomass, the total carbon abatement potential of a BiCRS approach is dependent on the market displacement of any coproduct(s): *i.e.*, there is no support for an axiom suggesting that co-products make any pathway superior or inferior to any other with respect to greenhouse gas abatement.

There remain many intangible and less quantifiable benefits that make these pathways very challenging to compare on an apples-to-apples basis; therefore, the authors suggest that the results reported within are not taken out of this important context. Impacts like nutrient cycling, biodiversity support and further market displacement of carbon intensive products can have tangible benefits that make these pathways valuable in any climate mitigation strategy. Further, degradation or other reversal mechanisms are not included in this study, which could favor technologies like ERW and DAC that have perhaps a more straightforward path to verifiable durability. More scholarship is required to understand if there are additional, unwanted tradeoffs associated with the balance of engineering and reversal risk, particularly on newer technologies with less mature MRV protocols.

While this work has focused on two consistent metrics of carbon efficiency and energy requirement, there are numerous other considerations for evaluating a carbon removal approach or project. In particular, it is important to consider commercial and technical feasibility of deployment. Feasibility includes all aspects required to execute on projects including permitting pathways, co-development of renewable energy projects, pipeline or other transportation requirements, and sustainable sourcing and transportation of biomass. In addition, this analysis does not consider the cost of deployment or the maturity of MRV protocols to ensure that these projects adhere to principles of high quality. Finally, it is important to note that these results are presented in a static context and do not consider the consequential evolution of CDR technologies with respect to MRV maturity, energy and resource intensity, nor the evolution of supporting markets, especially with respect to grid decarbonization and economic leakage in waste biomass procurement.

This study used LCA to compare several emerging and established CDR technologies to assess their efficacy in achieving net carbon removal. Our results produce several conclusions:

• Technologies with low energy consumption, minimal processing, and minimal losses due to conversion or other means, best preserve the intrinsic carbon removal potential in biomass and thus yield the highest net carbon removal efficiencies.

• Production of multiple products invariably lowers the amount of carbon removal potential on a per tonne feedstock basis, but the effect on total carbon abatement potential is inconclusive and depends heavily on the market displacement effects of the co-products.

• Details surrounding resource intensity, especially with respect to specific energy and feedstock consumption matter: both energy and biomass exist in constrained markets and the evolution of those markets will invariably shift the value proposition of each respective technical approach.

## Data availability

The data analysis scripts of this article are available in the interactive notebook "Public Carbon Removal Data" at **https://docs.google.com/spreadsheets/d/1PXusblh94THP0rBWkzD6rsC5KnhaapNf/edit?usp=sharing&ouid=100113676912118968489&rtpof=true&sd=true**.

## Conflicts of interest

Barclay Rogers is the founder and Chief Executive Officer, and Hannah K. Murnen is the Chief Technical Officer, of Graphyte, a company focused on developing engineered carbon removal technologies. Daniel L. Sanchez is a science advisor to Graphyte. Peter Psarras is an employee of Carbon Direct, a company dedicated to scaling high-quality carbon removal solutions. Daniel L. Sanchez also works for Carbon Direct as a Principal Scientist. Carbon Direct and Graphyte maintain a commercial relationship involving the sale of Graphyte's carbon removal credits from the Loblolly Project by Carbon Direct.

## Acknowledgements

We thank Sinead Crotty for her valuable comments on a prior draft of this manuscript.

## References

1 S. E. Strand and B. Gregory, Ocean Sequestration of Crop Residue Carbon: Recycling Fossil Fuel Carbon Back to Deep Sediments, *Environ. Sci. Technol.*, 2009, **43**(4), 1000–1007, DOI: **10.1021/es8015556**.

2 S. Chiquier, *et al.*, A Comparative Analysis of the Efficiency, Timing, and Permanence of $CO_2$ Removal Pathways, *Energy Environ. Sci.*, 2022, **15**(10), 4389–4403, DOI: **10.1039/D2EE01021F**.

3 F. Sabatino, *et al.*, A Comparative Energy and Costs Assessment and Optimization for Direct Air Capture Technologies, *Joule*, 2021, **5**(8), 2047–2076, DOI: **10.1016/j.joule.2021.05.023**.

4 J. Strefler, *et al.*, Potential and Costs of Carbon Dioxide Removal by Enhanced Weathering of Rocks, *Environ. Res. Lett.*, 2018, **13**(3), 034010, DOI: **10.1088/1748-9326/aaa9c4**.

5 P. Patrizio, *et al.*, $CO_2$ Mitigation or Removal: The Optimal Uses of Biomass in Energy System Decarbonization, *iScience*, 2021, **24**(7), 102765, DOI: **10.1016/j.isci.2021.102765**.

6 R. A. Metzger, *et al.*, To Bury or to Burn: Optimum Use of Crop Residues to Reduce Atmospheric $CO_2$, *Clim. Change*, 2002, **54**(3), 369–374, DOI: **10.1023/A:1016136202309**.

7 D. W. Keith and J. S. Rhodes, Bury, burn or both: a two-for-one deal on biomass carbon and energy, *Clim. Change*, 2002, **54**(3), 375.

8 S. E. Tanzer and A. Ramírez, When Are Negative Emissions Negative Emissions?, *Energy Environ. Sci.*, 2019, **12**(4), 1210–1218, DOI: **10.1039/C8EE03338B**.

9 N. McQueen, *et al.*, Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States, *Environ. Sci. Technol.*, 2020, **54**(12), 7542–7551, DOI: **10.1021/acs.est.0c00476**.

10 D. W. Keith and J. S. Rhodes, Bury, burn or both: a two-for-one deal on biomass carbon and energy, *Clim. Change*, 2002, **54**(3), 375.

11 W. J. Sagues, *et al.*, Enhanced Carbon Dioxide Removal from Coupled Direct Air Capture–Bioenergy Systems, *Sustainable*

 

*Energy Fuels*, 2019, **3**(11), 3135–3146, DOI: 10.1039/C9SE00384C.

12 *Material and Resource Requirements for the Energy Transition*, Energy Transitions Commission, 2023, https://www.energy-transitions.org/new-report-scale-up-of-critical-materials-and-resources-required-for-energy-transition/.

13 M. H. Langholtz, *et al.*, *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy*, EERE Publication and Product Library, DOE/EE-1440, Washington, D.C. (United States), 2016, DOI: 10.2172/1271651.

14 J. Pett-Ridge, *et al.*, *Roads to Removal: Options for Carbon Dioxide Removal in the United States*, Lawrence Livermore National Laboratory (LLNL), LLNL-TR-852901, Livermore, CA (United States), 2023, DOI: 10.2172/2301853.

15 D. Sandalow, *et al.*, *Biomass Carbon Removal and Storage (BiRCS) Roadmap*, Lawrence Livermore National Lab. (LLNL), LLNL-TR-815200, Livermore, CA (United States), 2021, DOI: 10.2172/1763937.

16 C. M. Woodall and F. M. Colin, Assessing the Optimal Uses of Biomass: Carbon and Energy Price Conditions for the Aines Principle to Apply, *Front. Clim.*, 2022, **4**, DOI: 10.3389/fclim.2022.993230.

17 H. Yang, *et al.*, Estimation of Enthalpy of Bio-Oil Vapor and Heat Required for Pyrolysis of Biomass, *Energy Fuels*, 2013, **27**(5), 2675–2686, DOI: 10.1021/ef400199z.

18 J. K. Soeherman, *et al.*, Overcoming the Entropy Penalty of Direct Air Capture for Efficient Gigatonne Removal of Carbon Dioxide, *ACS Eng. Au*, 2023, **3**(2), 114–127, DOI: 10.1021/acsengineeringau.2c00043.

19 N. Moosdorf, *et al.*, Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering, *Environ. Sci. Technol.*, 2014, **48**(9), 4809–4816, DOI: 10.1021/es4052022.

20 *Lithos Carbon Stripe Carbon Removal Purchase Application*, Frontier Climate, 2022, https://github.com/frontierclimate/carbon-removal-source-materials/blob/main/Project%20Applications/2022%20Spring%5BLithos%20Carbon%5D%20Stripe%20Carbon%20Removal%20Purchase%20Application.pdf.

21 *Suppliers — Isometric*, https://registry.isometric.com/suppliers, Accessed 30 July 2024.

22 S. E. Strand and B. Gregory, Ocean Sequestration of Crop Residue Carbon: Recycling Fossil Fuel Carbon Back to Deep Sediments, *Environ. Sci. Technol.*, 2009, **43**(4), 1000–1007, DOI: 10.1021/es8015556.

23 E. Yablonovitch and H. W. Deckman, Scalable, Economical, and Stable Sequestration of Agricultural Fixed Carbon, *Proc. Natl. Acad. Sci. U. S. A.*, 2023, **120**(16), e2217695120, DOI: 10.1073/pnas.2217695120.

24 EcoBio, *LCA Report – Carbofex's Biochar Product*, 2023, https://carbofex.fi/wp-content/uploads/2023/05/Ecobio-LCA_Carbofex-Biochar-2023-v5.pdf.

25 S. Jones, *et al.*, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway*, National Renewable Energy Lab. (NREL), PNNL-23053, NREL/TP-5100-61178, Golden, CO (United States), 2013, DOI: 10.2172/1126275.

26 P. Reinhardt, *Carbon Removal: Putting Oil Back Underground*, 2021, https://ww2.arb.ca.gov/sites/default/files/2021-08/charm_presentation_sp_engineeredcarbonremoval_august2021.pdf.

27 K. Buchheit, E. Lewis, K. Mahbubani and D. Carlson, *Technoeconomic and Life Cycle Analysis of Bio-Energy with Carbon Capture and Storage (BECCS) Baseline*, National Energy Technology Laboratory, Pittsburgh, 2021.

28 T. G. Kreutz, *et al.*, Techno-Economic Prospects for Producing Fischer-Tropsch Jet Fuel and Electricity from Lignite and Woody Biomass with $CO_2$ Capture for EOR, *Appl. Energy*, 2020, **279**, 115841, DOI: 10.1016/j.apenergy.2020.115841.

29 J. Young, *et al.*, The Cost of Direct Air Capture and Storage Can Be Reduced *via* Strategic Deployment but Is Unlikely to Fall below Stated Cost Targets, *One Earth*, 2023, **6**(7), 899–917, DOI: 10.1016/j.oneear.2023.06.004.

30 J. Valentine and A. Zoelle, *Direct Air Capture Case Studies: Solvent System*, National Energy Technology Laboratory, DOE/NETL-2021/2864, 2022, https://www.netl.doe.gov/projects/files/DirectAirCaptureCaseStudiesSolventSystem_083122.pdf.

31 National Academies of Sciences, Engineering, and Medicine, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, National Academies Press, 2019.

32 B.-G. J. Brooks, *et al.*, The performance of solvent-based direct air capture across geospatial and temporal climate regimes, *Front. Clim.*, 2024, **6**, 1394728.

33 J. F. Wiegner, *et al.*, Optimal design and operation of solid sorbent direct air capture processes at varying ambient conditions, *Ind. Eng. Chem. Res.*, 2022, **61**(34), 12649–12667.

34 M. Sendi, *et al.*, Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment, *One Earth*, 2022, **5**(10), 1153–1164.

35 K. An, A. Farooqui and S. T. McCoy, The impact of climate on solvent-based direct air capture systems, *Appl. Energy*, 2022, **325**, 119895.

36 C. M. Woodall, *et al.*, Utilization of mineral carbonation products: current state and potential, *Greenhouse Gases:Sci. Technol.*, 2019, **9**(6), 1096–1113.

37 D. Sandalow, *et al.*, *Biomass Carbon Removal and Storage (BiRCS) Roadmap*, Lawrence Livermore National Lab. (LLNL), LLNL-TR-815200, Livermore, CA (United States), 2021, DOI: 10.2172/1763937.

38 S. E. Baker, *et al.*, *Getting to Neutral: Options for Negative Carbon Emissions in California*, Lawrence Livermore National Lab. (LLNL), LLNL-TR-796100, Livermore, CA (United States), 2020, DOI: 10.2172/1597217.

39 J. Pett-Ridge, *et al.*, *Roads to Removal: Options for Carbon Dioxide Removal in the United States*, Lawrence Livermore National Laboratory (LLNL), LLNL-TR-852901, Livermore, CA (United States), 2023, DOI: 10.2172/2301853.