Mission Analysis for Marine Renewable Energy To Provide Power for Marine Carbon Dioxide Removal

James Salvador Niffenegger, David Greene, Robert Thresher, and Michael Lawson

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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List of Acronyms

AU	artificial upwelling
Bio-C	biological carbon
BPMED	bipolar membrane electrodialysis
$CaCO_3$	calcium carbonate
CC	carbon capture
CDR	carbon dioxide removal
CS	carbon sequestration
Cl_2	chlorine
CO_2	carbon dioxide
DAC	direct air capture
eChem	electrochemical
eChem mCDR	electrochemical marine carbon dioxide removal
ED	electrodialysis
gBiomass	grams of biomass
$GtCO_2$	gigatons of carbon dioxide
$GtCO_2$/yr	gigatons of carbon dioxide per year
GWh	gigawatt-hour
H_2	hydrogen
kgC	kilograms of carbon
ktC	kilotons of carbon
kWh	kilowatt-hour
kWh/tCO_2	kilowatt-hours per ton of carbon dioxide
mCC	marine carbon capture
mCDR	marine carbon dioxide removal
mCS	marine carbon sequestration
MWh	megawatt-hour
N_2O	nitrous oxide
O_2	oxygen
OTEC	ocean thermal energy conversion
PBR	photobioreactor
pCO_2	partial pressure of CO_2
RO	reverse osmosis
Seq.	sequestration
tC	tons of carbon
tCO_2	tons of carbon dioxide
tDrySeaweed	tons of dry seaweed
tRawSeaweed	tons of raw seaweed
TRL	technology readiness level
TWh	terawatt-hour

Executive Summary

The mission of this project was to provide a preliminary feasibility assessment of powering different marine carbon dioxide removal (mCDR), marine carbon capture (mCC), and marine carbon sequestration (mCS) strategies with marine energy. In this report, carbon capture (CC) refers to methods that can separate or capture carbon dioxide (CO_2) from the air or ocean; carbon sequestration (CS) refers to methods that store CO_2 obtained by capture methods out of the atmosphere for long periods of time; and carbon dioxide removal (CDR) refers to methods that do both. The project found that mCDR powered by marine energy and offshore wind energy available in the United States could meet global CDR scales needed by 2040 and 2050 to limit warming to 1.5°C by 2100 [1, 2]. Note that this preliminary estimate assumes that it is possible to harvest all the marine and offshore wind resources available in the United States with existing technology options, and it does not account for the power needed for monitoring these methods, as these power needs are not yet well defined and require further research. Additionally, these CDR scales will still require emissions reductions [2].

While the focus of this study was the potential of marine-energy-powered mCDR, mCC, and mCS, offshore wind energy was included to better understand the amount of CO_2 that could be removed, captured, or sequestered when these methods are powered by U.S. offshore renewable energy sources, and compare the potential scales that can be achieved using marine versus offshore wind energy. Marine energy alone could still be used to reach CDR scales of about one gigaton per year, which, despite being less than necessary to reach global targets, is still a significant step toward mitigating climate change.

This preliminary feasibility study was split into two parts: (1) the viability of the mCDR, mCC, and mCS methods in general, and (2) their high-level compatibility with marine and offshore wind energy. The viability of the methods was assessed by determining their energy requirements, location specifications, scalabilities, cost, technology readiness levels, and environmental impacts via a literature review along with informed estimates based on information from literature, which largely involved unit conversions (see Section A.2 for more details). Artificial upwelling, deep-ocean storage, electrochemical mCDR and mCC, offshore microalgae cultivation, and seaweed farming and sinking along with their monitoring requirements were investigated because these methods all require power at sea (Figure ES-1). Figure ES-2 shows more details on which methods are mCDR, mCC, or mCS.

The high-level compatibility of the methods with marine and offshore wind energy involved estimating possible mCDR, mCC, and mCS scales that could be achieved using the marine and offshore wind energy available in the United States; note that the scales of mCC and mCS were also investigated because these methods could be used together for mCDR. The energy and location requirements determined in the literature review from part one as well as the resources of marine and offshore wind energy that could be harvested using existing technologies at these locations were used to determine these scales. These calculated scales were limited by the maximum scales reported in literature. The scales that could be reached with the marine and offshore wind energy available to these methods and the fraction of wave, tidal, current, ocean thermal, and river energy available in the locations where the mCDR, mCC, and mCS methods could be performed were recorded as a preliminary approximation of compatibility. These details

highlight not only how effective the mCDR, mCC, and mCS methods could be in the United States but also which types of energy sources they could benefit from the most.

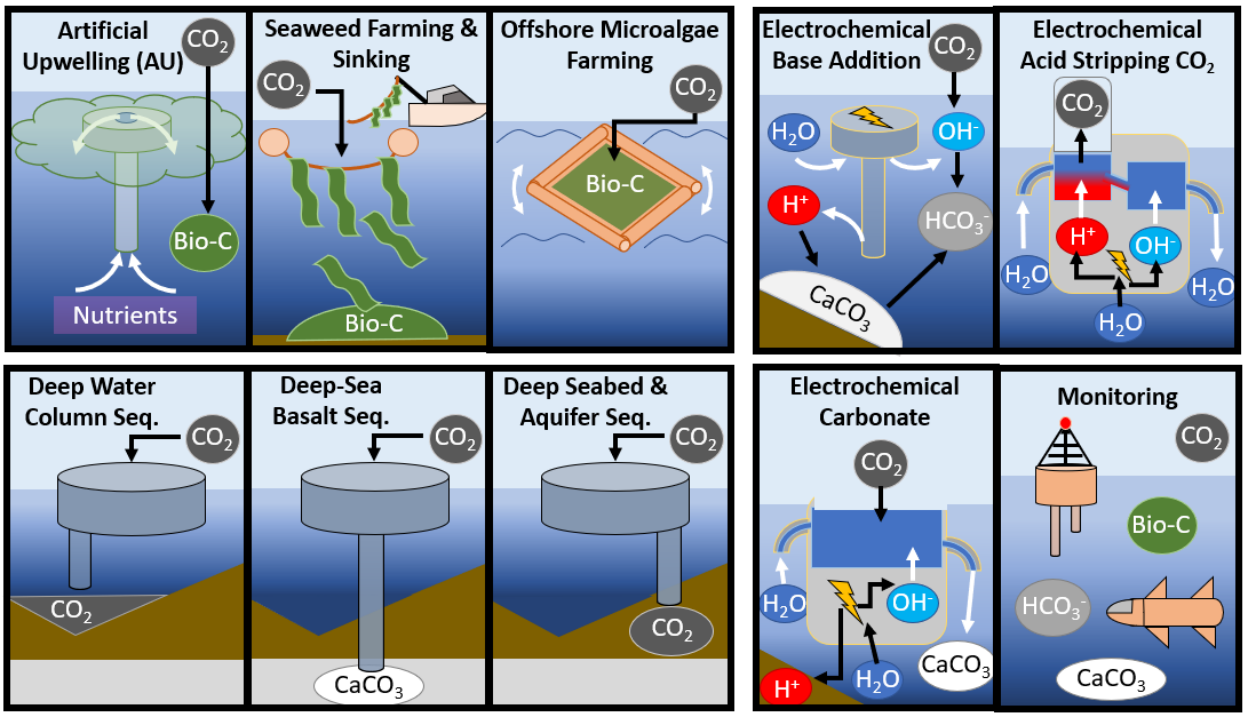

Figure ES-1. Simplified graphics describing the mCDR, mCC, and mCS strategies investigated in this study.

The literature review found that there are clear and significant environmental risks to scaling up biological mCDR and mCC methods such as artificial upwelling and seaweed farming and sinking, whereas certain methods of mCS or deep-sea storage of CO_2, such as injection into self-sealing seabed sediments and subseafloor basalt mineral deposits are currently believed to be environmentally safe, although more research is needed to verify this [3, 4, 5, 6, 7, 8, 9, 10]. Additionally, electrochemical (eChem) mCDR methods such as adding alkalinity to the ocean and carbonate formation were found to have the potential to capture CO_2 at scales above 1 gigaton of CO_2 per year ($GtCO_2$/yr) and sequester it for more than a thousand years [1, 4, 11, 12, 13, 14, 15]. Moreover, offshore microalgae farming is expected to reach a much smaller scale and mainly convert CO_2 into short-lived products as a form of mCC; however, the field could benefit from collaboration with marine energy researchers because they are already using ambient marine energy, mainly wave energy, to improve yields [16, 17, 18].

To identify the most promising forms of mCDR, mCC, and mCS more clearly, thresholds were estimated for longevity of CO_2 storage, possible global scale of CO_2 capture, energy needs, and cost, which are detailed in Section 4.1. Overall, the eChem mCDR and deep-sea sequestration methods were best able to meet the thresholds, especially eChem methods that add alkalinity to the ocean or create carbonates from dissolved inorganic carbon and deep-sea seabed and basalt sequestration. eChem mCC that extracts pure CO_2 from the ocean (referred to as "acid stripping CO_2") and sequestration in deep-sea aquifers were also promising because the pure CO_2 from the relatively energy-efficient eChem mCC method could be sequestered via other methods, and

aquifer sequestration is more developed and has a higher technology readiness level than the other mCS methods.

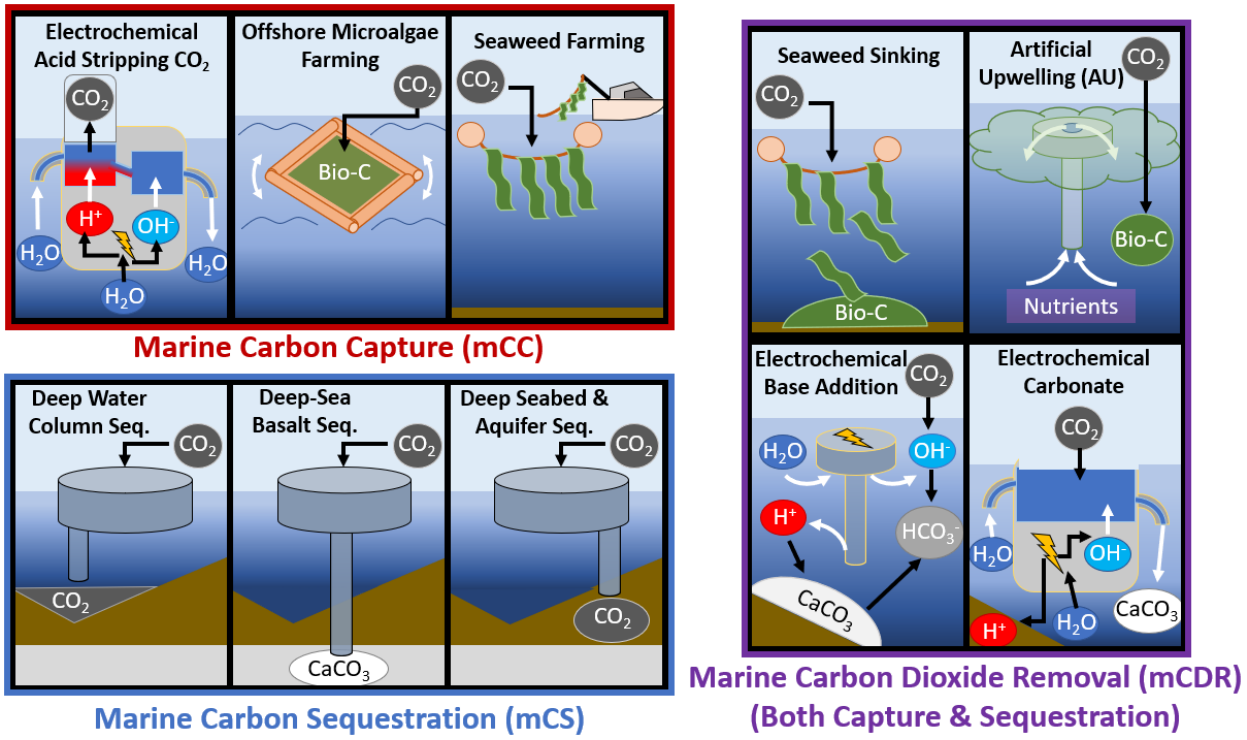

Figure ES-2. Simplified graphics of the methods investigated in this study split by whether they are forms of mCC, mCS, or mCDR.

Note that mCC methods only separate CO_2 from the ocean or atmosphere, mCS methods can store that separated CO_2 for long periods of time, and mCDR methods can do both. mCC and mCS can be combined to perform mCDR.

Additional research found that the eChem mCDR methods, including eChem acid stripping CO_2 using aquifer sequestration as storage, could theoretically scale to capture and sequester 10 $GtCO_2$/yr using U.S. marine and offshore wind energy, which would meet the necessary global CDR targets needed by 2040 and 2050 to limit warming to 1.5°C by 2100. Note that these methods not only were the most promising from the literature review but also had the highest scalabilities when powered by U.S. offshore renewable energy. This is possible even after the offshore renewable energy resources are used to meet coastal energy demand, highlighting the massive level of offshore energy resources that could be utilized to mitigate climate change. These results combined with the findings from the literature review show significant promise in powering mCDR and mCC combined with mCS with marine energy and offshore wind. Additionally, wave energy was found to generally be the most available marine energy source to the majority of the methods except for deep seabed sequestration, which had primarily ocean thermal energy available to it. This indicates that wave energy harvesting systems could be used at scale to power mCC, mCS, and mCDR however more research is needed to validate this.

It should be noted that removing this much CO_2 from the ocean through 2100 will be a massive effort and an extreme change to the environment over a short period of time. Though it is theoretically possible to implement these ocean-based methods to significantly mitigate climate change, the ocean is a challenging place to monitor due to its complex dynamics and vast space.

Therefore, to deploy any of the mCC, mCS, and mCDR technologies described in this report, it will be essential to develop robust ocean environmental monitoring methods and research programs that span prototype deployments to small-scale pilot projects to global-scale deployment to identify and remediate undesirable outcomes. Currently anticipated monitoring requirements are listed in Table 2.

Though there will be significant challenges in implementing offshore renewable-energy-powered mCC, mCS, and mCDR, the findings from this report indicate that these technologies can enable significant progress toward mitigating climate change. Therefore, the compatibility between these technologies and offshore renewable energy must be assessed further through additional research that more closely examines how these technologies could be integrated with each other.

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1 Introduction

To limit warming to 1.5°C by 2100, carbon capture and storage technologies must remove 1.5 gigatons of carbon dioxide ($GtCO_2$) per year by 2040, 3–7 $GtCO_2$ per year by 2050, and 15 $GtCO_2$ per year by 2100, according to the Intergovernmental Panel on Climate Change [1, 2, 19]. Increasing capture up to just 1.5 $GtCO_2$ per year would involve a 35-fold increase in the current amount of carbon dioxide removal (CDR) being done globally [19]. Note that in this report carbon capture (CC) refers to methods that separate CO_2 from the atmosphere or ocean, carbon storage or sequestration (CS) refers to methods that store the already captured CO_2 for long periods of time, and CDR refers to methods that do both. Expanding CDR offshore could assist in scaling global removal efforts high enough to mitigate climate change due to the ocean's massive potential for CO_2 storage and its vast amount of space, which will reduce competition for space on land [20]. Additionally, offshore renewable energy, like marine energy, can be used to power this offshore or marine CDR (mCDR) to improve its carbon removal efficiency by avoiding additional emissions from fossil fuel energy sources [20]. mCDR includes a diverse array of strategies to capture and sequester CO_2, ranging from biological methods that promote an increase in photosynthetic ocean biomass to electrochemical methods that focus on reducing ocean acidification or extracting CO_2 directly from the ocean to sequestration strategies that inject captured CO_2 into the deep ocean [1, 4]. Note that some of these technologies are used just for marine carbon capture or sequestration and are referred to as mCC and mCS, respectively. The strategies in this field, though at early stages of development, could reach gigaton scales of CO_2 removal by moving offshore, making them prime candidates for integration with marine and other offshore energy technologies, such as offshore wind.

As a result, mCDR, mCC, and mCS represent an up-and-coming blue economy industry. These methods can integrate with marine aquaculture via seaweed and offshore microalgae farming and with seawater desalination via electrochemical (eChem) mCDR and mCC. The methods can also promote economic activity beyond carbon credits, such as creating hydrogen from eChem mCDR and mCC strategies that use electrolysis; synthetic fuel production from eChem mCC methods that extract pure CO_2 from the ocean; and biofuels, bioplastics, fertilizers, and other high-value products from seaweed and offshore microalgae farming [4, 14, 15, 21, 22]. Marine energy, mCDR, mCC, and mCS are all in early stages of development and could be co-developed as integrated systems dedicated to CDR. The in-situ power provided by marine energy, and other offshore energy sources such as offshore wind, would eliminate the need for expensive electrical cables from the shore, which will greatly reduce deployment costs and expand the possible areas for deployment. This co-development could enable higher scales of CDR and energy production.

However, not all mCDR strategies have power needs that can be directly met with marine energy or other offshore energy sources. Some require transporting and dumping alkaline minerals, iron, or other materials obtained on shore into the ocean to remove CO_2 [1]. Because these methods require power just to transport materials to and from shore, and because electric cargo ships that are large enough to be used for gigaton-scale CDR are still in early development, these methods were not investigated in detail and were considered out of scope for this study. Note that these methods and marine ecosystem restoration could use marine energy or other offshore energy sources for monitoring; however, analyzing and comparing the energy requirements of these monitoring strategies could not be normalized by tons of CO_2 without making significant

assumptions, especially because the literature sources do not indicate how many sensors are required for different capture scales. Additionally, system monitoring is a widespread research challenge shared by all mCDR, mCC, and mCS methods, and there is little to no consensus for how to accurately monitor methods that release biological matter, minerals, or chemicals into the ocean due to the complexity of ocean flows and the small concentrations of these additives relative to the volume of the ocean [1, 4]. Therefore, these methods were determined to be out of scope for this analysis.

The mCDR, mCC, and mCS methods selected for this study were chosen because they can use power from marine energy and other offshore energy sources to capture, sequester, or utilize CO_2. Artificial upwelling, eChem mCDR and mCC, deep-sea storage, and seaweed sinking require mechanical energy for pumping, whereas offshore microalgae farming requires mechanical energy for mixing nutrients in its culture media [3, 9, 11, 15, 16, 17, 18, 22, 23, 24] [25, 26, 27, 28, 29, 30, 31, 32]. In contrast, electrical energy is necessary to operate the electrochemical systems used by eChem mCDR and mCC methods and in seaweed nurseries and facilities that convert biomass to fuels and other products created from seaweed farming [4, 11, 15, 25, 26, 28, 33, 34].

The overall goal for this investigation was to provide a preliminary feasibility assessment of powering the different mCDR, mCC, and mCS methods investigated in this study (shown in Figure ES-2) with marine energy. This feasibility study was divided into two parts: (1) explore the viability of the mCDR, mCC, and mCS methods in general, and (2) investigate their high-level compatibility with marine and offshore wind energy. Note that while the focus of this report is on marine energy, offshore wind energy was investigated as well for comparison and to better understand the total CDR, CC, and CS scales that can be reached using U.S.-based offshore energy to power these methods.

Part one involved conducting a literature review of the mCDR, mCC, and mCS methods investigated in this study to understand factors that impact the overall scalability and safety of these strategies. This included finding or estimating their energy requirements, anticipated full scales, the length of time that CO_2 is stored, the cost of the strategies per ton of CO_2, their technology readiness level (TRL), location requirements, environmental risks, and monitoring requirements. Note that all estimates used were informed by literature, largely involved unit conversion, and are described in Section A.2. Part two involved estimating mCDR, mCC, and mCS scales using the offshore marine and wind energy resources that could be harvested by existing technologies in U.S. waters that meet the strategies' location requirements. The proportions of the different types of marine energy available to the mCDR, mCC, and mCS methods within their suitable locations were also recorded to indicate which individual types of marine energy are most appropriate for each method.

2 Summary of mCDR, mCC, and mCS Strategies

This study uncovered details for the original categories of mCDR, mCC, and mCS: artificial upwelling, deep-sea storage, electrochemical mCDR and mCC, seaweed farming and sinking, and offshore microalgae farming. It also uncovered subcategories within these methods. These subcategories were significantly distinct from one another, and therefore the results for the subcategories are shown in the figures and tables in Section 4 in place of the generic categories.

2.1 Artificial Upwelling (mCDR)

Artificial upwelling (AU) is an mCDR method that pumps nutrient-rich, deep seawater upward to shallow waters to provide enough nutrients to cause algae blooms (Figure 1). The idea is that the additional carbon stored in the new biomass will eventually sink into the deep ocean for storage [4]. However, AU can also release CO_2 into the atmosphere due to the dissolved inorganic carbon that is also pumped to the surface from the deeper waters. AU only results in overall CDR if the nutrients provided by the upwelling encourage enough phytoplankton growth to offset the CO_2 released from the upwelled dissolved inorganic carbon [4]. Therefore, AU can result in net removal or release of CO_2 from the ocean, which depends on a variety of factors, such as season, location, and local biogeochemistry [3]. At scale, AU is limited to absorbing less than 1 $GtCO_2$/yr into the ocean while releasing about 3 $GtCO_2$/yr that will need to be vacuumed and stored to avoid release into the atmosphere. However, at this level of capture, AU is likely to disrupt the global ocean thermocline cycle and cause additional warming [3, 4]. At smaller scales, AU can still harm local and downstream ecosystems, especially those that are sensitive to eutrophication (see Table 1) [4, 35].

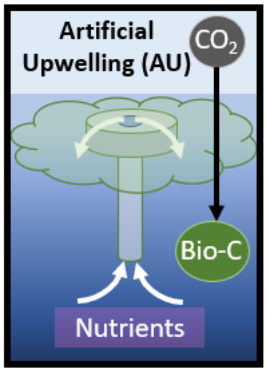

Figure 1. Graphic describing artificial upwelling (AU) as an mCDR method.

The image is a simple description of AU as a mCDR method that brings nutrient rich deep-ocean water to shallow waters to cause algae blooms, which capture and convert CO_2 into biological carbon or biomass.

AU has been most successful in enhancing aquaculture of seaweed and shellfish in enclosed areas such as bays or fjords [23, 24]. AU can be powered directly with electricity or use wave energy for pumping [36]. This analysis found that while it has been assumed that AU removes CO_2, CDR has generally been approximated by measuring concentrations of chlorophyll a and analyzing the increase in microalgae growth and photosynthesis [24, 35]. One study, however, was able to show an increase in seaweed growth due to AU, more clearly demonstrating CDR by this method, but more work is necessary to further validate AU's potential [23]. Monitoring this method has largely been considered a significant challenge because of the need to measure changes in carbon flux in the deep ocean caused by AU as opposed to natural changes (see Table 2) [3, 4]. AU can use a

variety of methods to raise nutrient-rich deep-ocean water to enable algal blooms that can remove CO_2; however, the processes are similar enough that no subcategories were necessary for AU [4, 35].

2.2 Deep-Ocean Storage (mCS)

Deep-ocean storage is an mCS category that focuses on pumping CO_2 that has already been captured by other CC methods and storing it in or beneath the deep ocean (Figure 2). CO_2 deposited above the seafloor via "water column sequestration" from moving ships or fixed injection sites is generally done so as a liquid at a depth where it is denser than seawater. The CO_2 fluid will sink to the seafloor, forming lakes of CO_2, and will be kept there for up to 1,000 years, depending on its depth and location (refer to Table 1) [30, 37]. However, this method is dangerous for marine life and can cause chronic health issues and acute mortality (Table 1) [30].

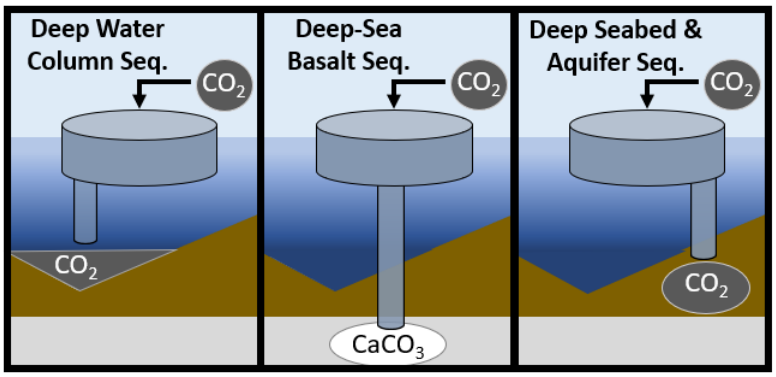

Figure 2. Graphic describing deep-ocean storage/deep-sea sequestration as mCS methods.

The image is a simple description of the deep-sea sequestration methods explored in this report. Water column sequestration deposits CO_2 above the seafloor where it turns into a liquid due to the immense pressure of the deep sea. Basalt sequestration involves injecting CO_2 into subseafloor mineral reservoirs that convert the gas into solid carbonate. Finally, seabed and aquifer sequestration involve injecting CO_2 into ocean sediments or pore spaces where it remains buried as a liquid due to the extreme pressure at depth. Note that none of these methods capture CO_2 from the atmosphere but can be used to increase the time that the gas is separated from the atmosphere after it is captured by other methods.

Alternatively, through "seabed sequestration," CO_2 can be injected into self-sealing deep-sea sediments that have very low biological activity, and these sediments can safely sequester the greenhouse gas for more than 100,000 years, so long as there are no faults or fractures in the seabed [38, 39, 40].

CO_2 can also be injected in non-self-sealing sediments or saline aquifers, referred to as "aquifer sequestration," which is currently being done at megaton scales and is safe so long as there are no cracks in the aquifer [31]. The gas can alternatively be inserted into basalt formations, which convert the CO_2 into stable carbonate minerals enabling permanent storage, referred to as "basalt sequestration" [9, 41]. Energy is required to compress and inject the CO_2 into these reservoirs [9, 30, 38, 39].

2.3 Electrochemical mCDR and mCC

Electrochemical mCDR and mCC cover a variety of methods that use seawater and electrochemistry either to separate pure CO_2 from the ocean for use or storage (eChem mCC) or to sequester CO_2 into the ocean by forming alkaline inorganic carbon, such as bicarbonate or

carbonate (eChem mCDR) (Figure 3) [4]. Generally, these strategies use electrodialysis, which makes acidic and basic solutions from seawater, or electrolysis, which also creates acid and base but generates valuable hydrogen (H_2) and toxic chlorine gas (Cl_2) [4]. However, in electrolysis the Cl_2 can be avoided while still producing H_2 by desalinating some of the seawater entering the system [21]. The energy and financial costs of eChem mCDR and mCC can be reduced by incorporating it into existing infrastructure, such as desalination plants, and selling the H_2 that is produced in the process [14].

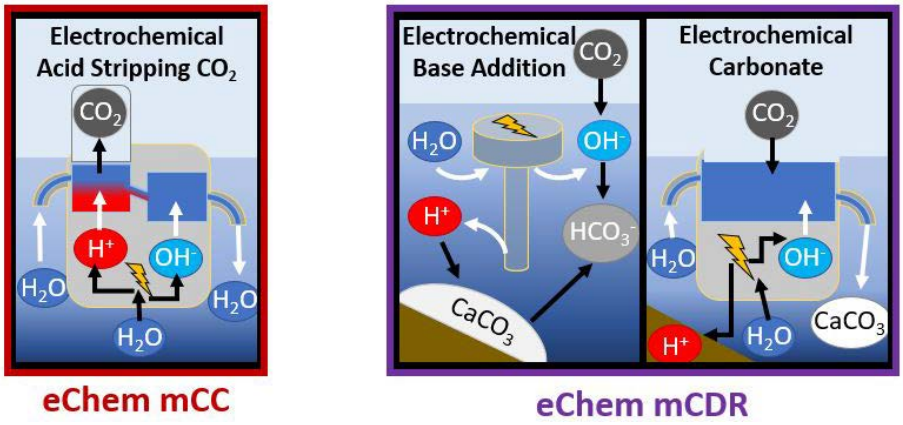

Figure 3. Graphic describing electrochemical mCC and mCDR methods.

The image is a simple description of the electrochemical mCC and mCDR (eChem mCC and mCDR) methods explored in this report, all of which use electrochemistry to create acidic and basic solutions from seawater but use them in different ways. Acid stripping CO_2 is an eChem mCC method that involves bringing some seawater into an enclosed chamber where the acid is added to it. As a result, the CO_2 bubbles out, similar to bubbles in soda or sparkling water and is vacuumed into a storage container. The acidic seawater is then neutralized with the basic solution before being returned to the ocean. Base addition is an eChem mCDR method that directly adds the basic solution to the ocean, which can reduce ocean acidity and draw more atmospheric CO_2 into the ocean as bicarbonate. The excess acid can then be injected underground, sold as a product, or, as shown in the figure, be injected into the deep ocean to dissolve carbonates, which will neutralize the waste product and turn into more bicarbonate. Carbonate formation is an eChem mCDR method that also primarily uses the basic solution but adds enough in an enclosed space to create mineral carbonates from the dissolved CO_2 in seawater. The excess acid can be dealt with in the same way as it is in base addition.

Pure CO_2 can be obtained from seawater through the eChem mCC method referred to as "acid stripping CO_2," in which seawater is moved into a chamber where it is acidified, causing its dissolved CO_2 to bubble out. The gas is then vacuumed into a storage system and the acidified seawater is then mixed with a basic solution to return it to a neutral pH to avoid harming the local environment once it is released back into the ocean [4]. The extracted CO_2 can then be converted into fuels and sold or sequestered using mCS methods such as deep-ocean storage. This type of eChem mCC is sometimes referred to as a form of direct ocean capture [1].

CO_2 stored in seawater, even in the deep sea, will eventually return to the atmosphere unless the alkalinity of the ocean is increased [37]. This can be done through "base addition," in which the alkaline solution made from the eChem mCDR method is added directly to seawater (in dilute concentrations to avoid environmental impacts) to create bicarbonate ions that store CO_2 up to 100,000 years [4]. However, the unused acidic solution needs to be neutralized. This can be done by pumping the acid into rock formations or by mining and transporting the minerals, usually silicates, to the eChem mCDR system [4, 12, 13, 42]. Alternatively, the dilute acidic solution can be pumped into the deep ocean where carbonate deposits on the seafloor will dissolve to form

bicarbonate ions and buffer the changes in pH, but the risks of this method need to be studied further [11]. This type of eChem mCDR is a form of ocean alkalinity enhancement, a term that also includes methods that add alkaline minerals to the ocean [4].

In "carbonate production," enough concentrated basic solution is added to seawater to create carbonates that can store CO_2 for up to 100 million years [4, 15]. While this eChem mCDR method also has an acid disposal issue, the acid can be used to convert the carbonates back into CO_2, which can then be sequestered by other means or converted into a product [14]. This eChem mCC method is referred to as "base stripping CO_2," but not enough sources proposed and discussed this method for it to be included in the key analysis in Section 4 [14].

2.4 Offshore Microalgae Cultivation (mCC)

Microalgae cultivation has typically been done onshore in large ponds to produce biofuels, animal feed, bioplastics, and high-value chemicals such as pharmaceutical compounds. Recently, researchers have investigated using offshore floating photobioreactors (PBRs) to reduce the financial and energy costs for growing microalgae (see Figure 4) [22]. Floating PBRs save money by using the ocean for free temperature regulation because it has quadruple the heat capacity of air, meaning that no cooling system is required. PBRs also require nutrients, which can be directly absorbed from the surrounding waters via specialized membranes [22]. Additionally, these systems can use wave energy to simply rock themselves back and forth, mixing their internal microalgae solution, which prevents cell sedimentation and enhances the distribution of nutrients, pH, temperature, dissolved CO_2, and light—all critical to ensuring adequate yields [16, 22]. Offshore microalgae farming was separated into two subcategories, "open" and "closed," which refer to whether the algal culture could capture CO_2 in the air due to bicarbonates in its media ("open") or if the culture received a concentrated gas stream of CO_2 delivered into its enclosed bioreactor ("closed") [16, 22, 43]. Not enough data were available on these subcategories, however, to split up the offshore microalgae farming category in the key results in Section 4 [16, 22, 43].

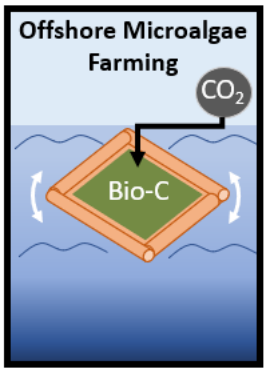

Figure 4. Graphic describing offshore microalgae farming as an mCC method.

The image is a simple description of offshore microalgae farming, in which ocean waves are used to mix algae media to encourage algae growth and capture CO_2.

Floating PBRs are typically closed and minimally interact with their marine environment, meaning that during normal operation they do not disrupt ecosystems or directly harm marine life to the extent that AU, deep-ocean storage, and seaweed cultivation and sinking can (see Table 1). Though some designs can extract nutrients from their environment, which could also harm local ecosystems, this is not the case for all systems [22]. However, all these devices can cause

significant harm if they are damaged and release their algal cultures and nutrient solutions (see Table 1). Another limiting factor of offshore microalgae cultivation is that since they are an mCC method, CO_2 is not sequestered by the operation of this method, and carbon storage is limited to the lifetime of the product that is produced from the algae, such as biofuel or bioplastic, which is typically short (see Figure A-2) [4, 22].

2.5 Seaweed Cultivation and Sinking (mCC and mCDR)

Seaweed can be grown in the ocean for two different purposes: to be converted into products (a form of mCC) or sunk to the deep ocean to ensure sequestration (a form of mCDR) (see Figure 5). Generally, the former is referred to as "seaweed farming," and the latter is called ocean afforestation, or in this report "seaweed sinking" [4]. Seaweed can be converted into a variety of products like those made from microalgae [4]. Energy is required for powering nurseries to grow the seaweed initially before it is placed into the ocean, converting the seaweed into biofuels, and sinking it to the deep ocean [32, 34].

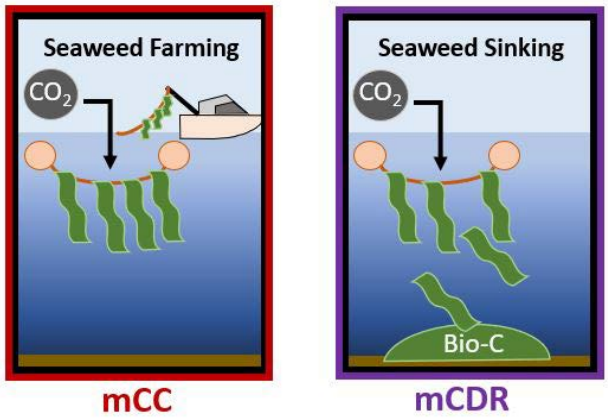

Figure 5. Graphic describing seaweed farming and sinking as mCC and mCDR methods, respectively.

The image is a simple description of seaweed farming and sinking, where CO_2 is absorbed by the growing macroalgae but is only stored for significant periods of time if the biomass is sunk to the deep sea.

Unlike microalgae cultivation, seaweed is grown in the open environment and can sequester CO_2 during its growth by forming and shedding recalcitrant tissue. The tissue cannot be quickly digested by microbes, meaning that more of the carbon can reach the deep ocean and be stored [4]. The main hurdle for expanding seaweed production is that the crop requires adequate space, sunlight, and nutrients. While nutrients are available near shore, there is not enough space for achieving large-scale CO_2 capture. Offshore, there is enough space and sunlight, but not enough nutrients [4]. As a result, some groups have proposed using AU to provide enough nutrients to enhance seaweed growth offshore [23].

Although growing seaweed can sequester some carbon, a significantly higher proportion can be stored for much longer if the crop is quickly sunk to deep water, which is why seaweed farming alone is an mCC method and seaweed sinking is an mCDR method. Generally, most of the carbon in the seaweed can be stored for 100 years if it is released at a 1-km depth [4]. The speed of sinking is important because if it is sunk slowly, microbes will begin digesting or remineralizing the carbon into CO_2 that will be released to the atmosphere on a faster time scale [4]. Despite its benefits, this

mCDR strategy will likely harm sea life and disrupt the balance of food chains in the deep and shallow oceans (see Table 1) [6]. Another challenge posed by this approach is accurately monitoring the biomass at depth. However, sinking seaweed can also be used to mitigate certain environmental issues such as reducing the amount of methane and toxins released by rotting seaweed. This has been a significant issue in the Caribbean where massive seaweed blooms have occurred yearly since the 2010s. The fumes from this rotting biomass are harming the vital tourism industry of the region [32].

3 Methods

The information obtained in the first part of this study was obtained by conducting a literature review of journal articles, reports, and news about the mCDR, mCC, and mCS methods of interest to find details about their energy needs, their full scales, the length of time that they store CO_2, their cost per ton of CO_2, and their TRL, location requirements, environmental risks, and monitoring requirements. Note that estimations, informed by the literature, were necessary for certain data points. For example, when values for the energy required per ton of CO_2 captured for an mCDR method were not provided by available literature, estimates were made using information provided by the source itself and similar sources, if necessary. Generally, this involved unit conversion, and the steps used to make each estimate that was not directly provided from literature can be found in Section A.2.

Initially, reports from sources such as the Energy Futures Initiative and the Climateworks Foundation were used to get a background understanding about all mCDR, mCC, and mCS methods in general [1, 20]. From this initial investigation, the five categories of mCDR, mCC, and mCS investigated in the study were chosen based on their clear power needs that could be provided by marine or other offshore renewable energy sources, as opposed to other methods that largely require offshore power just for monitoring [1, 4, 22, 30]. Although monitoring could be powered by marine energy, data on energy requirements for monitoring systems were not recorded because the data could not be normalized by the weight of CO_2 captured, removed, or sequestered without making large assumptions about how monitoring systems scale with greater levels of mCDR, mCC, or mCS (no sources indicated how monitoring requirements increase with increasing scale). Additionally, monitoring these strategies is an active area of research with little to no consensus for how to accurately monitor methods that release biological matter, minerals, or chemicals into the ocean because of the complexity of ocean flows and the small concentrations of these additives relative to the volume of the ocean [1, 4]. As a result, those methods were out of scope; however, details on the monitoring requirements for the mCDR, mCC, and mCS strategies of interest are included in this report in Table 2. Once the mCDR, mCC, and mCS strategies were investigated in more detail, it became clear that many of these methods had subcategories within them. This increased the amount of research necessary to fully understand the potential scalabilities and risks of the viable strategies.

The second part of this study assessed the high-level compatibility of these methods with marine energy. This involved estimating the scales of mCDR, mCC, and mCS that could be achieved using the offshore renewable energy available in the United States that could be harvested using existing technologies. The energy and location requirements, determined in the literature review, and the technical resources of marine and offshore wind energy available in these locations were used to determine these scales, which were limited by the maximum scales reported in literature (see Section A.3 for more detail). Note that offshore wind was included in this analysis, despite not being the focus, to compare its potential to power these technologies with that of marine energy and to better understand the full scale mCDR, mCC, and mCS potential using U.S. offshore renewable energy.

As a preliminary approximation of compatibility, these calculated scales and the fraction of wave, tidal, current, ocean thermal, river, and wind energy available in the locations where the mCDR methods could be performed were recorded (see Section A.3 for more detail). Where the scales

indicate the overall carbon capture possible from deploying and powering these mCDR methods in the United States and the fractions of marine energy indicate which energy sources are most appropriate for the different forms of mCDR. Note that the river energy from coastal states was included in this analysis because certain mCDR methods, such as eChem carbonate formation, can benefit from being conducted near river deltas at the interface between freshwater and saltwater (see Table 1) [15]. Additionally, because these rivers are in coastal areas, it was assumed that they would either flow into the ocean or be close enough to the coast to reasonably provide power for mCDR. Note that this is an approximation, and logistical challenges may reduce the level of river energy available to mCDR. Offshore wind energy, from both fixed-bottom and floating wind turbines, was included in the analysis to understand the overall scales of mCDR powered by offshore renewable energy possible in the United States; however, the focus of the overall study is on using marine energy (see Section A.3 and Table A-7 for more detail). The results of this study are detailed in Section 4.

Information on the different strategies of mCDR were recorded in an Excel spreadsheet containing notes on the technologies used, form of energy required, amount of energy needed, location requirements, TRL, consistency of power required, full-scale capabilities, cost, environmental impacts, mobility of the systems, longevity of CO_2 storage, additional benefits of the method, whether or not the use of marine energy was considered, and the monitoring needs of the methods, in addition to any estimations made that were necessary to determine this information (see Section A.2). These notes were then cleaned up in a separate Excel file to better organize the information, and custom Python code was written to create the figures used in this study. The box-and-whisker plots in Figures 13 to 15 and the figures in the appendix (Figures A-1 to A-5) include details on the maximum, minimum, upper and lower quartiles, median, and outliers from the recorded and estimated data from literature. The 2D rectangular plots in Figures 6 to 9 used the data points closest to the upper and lower quartile cutoffs or the edges of the box plots in the appendix (see Figures A-1 to A-3). Figures 7 to 9 specifically used the upper and lower quartiles from the total energy needs for the mCDR, mCC, and mCS methods as detailed in Table A-2. Meanwhile, the determination of the level of risk for these strategies at scale in Figures 6 to 9 was based on the information from literature, which is further shown in Table 1. The graphics in Figures ES-1, 1–5, and 12 were made in PowerPoint.

4 Results

4.1 Key Results From Part One: Most Promising Subcategories Based on Longevity, Scale, and Energy Needs

To simplify the results of this analysis and highlight the categories and subcategories that have the highest potential to scale to reach the necessary levels of CDR for climate change mitigation, thresholds were created for the mCDR, mCC, and mCS methods investigated in this report. These thresholds varied for the different forms of climate change mitigation. All three had scale and energy requirement thresholds, and the mCDR and mCS thresholds also had a longevity of CO_2 storage threshold since both sequester CO_2, whereas mCC does not. Generally, the CDR necessary for climate change mitigation is on a scale of gigatons of CO_2; therefore, the threshold was set to a minimum of 1 $GtCO_2$/yr [1, 4, 19]. Note that this was the threshold for all the mCDR, mCC, and mCS methods since the mCC and mCS methods could be paired together to become mCDR methods. The sequestration time threshold for the mCDR and mCS methods was set to a minimum of 1,000 years because this is generally considered to be near-permanent sequestration [1, 4]. Meanwhile the energy requirement thresholds varied between the mCDR, mCC, and mCS methods. The energy requirement threshold for mCC was set to a maximum of 2,450 kilowatt-hours per ton of CO_2 (kWh/tCO_2), which is the upper quartile of energy needed by direct air capture, a more developed form of onshore CC and therefore a suitable comparison (see Section A.1 and Figure A-3 for more details) [9, 25]. Meanwhile, the threshold for the mCS methods was set to a maximum of 480.5 kWh/tCO_2, which is the upper quartile of energy needed by onshore basalt sequestration, a more developed form of CS being used by the company Carbfix to sequester about 4,000 tCO_2/yr (see Section A.1 and Figure A-3 for more details) [44, 45]. Since mCDR involves both capture and sequestration, the threshold was set to the sum of the thresholds for mCC and mCS or 2,930.5 kWh/tCO_2.

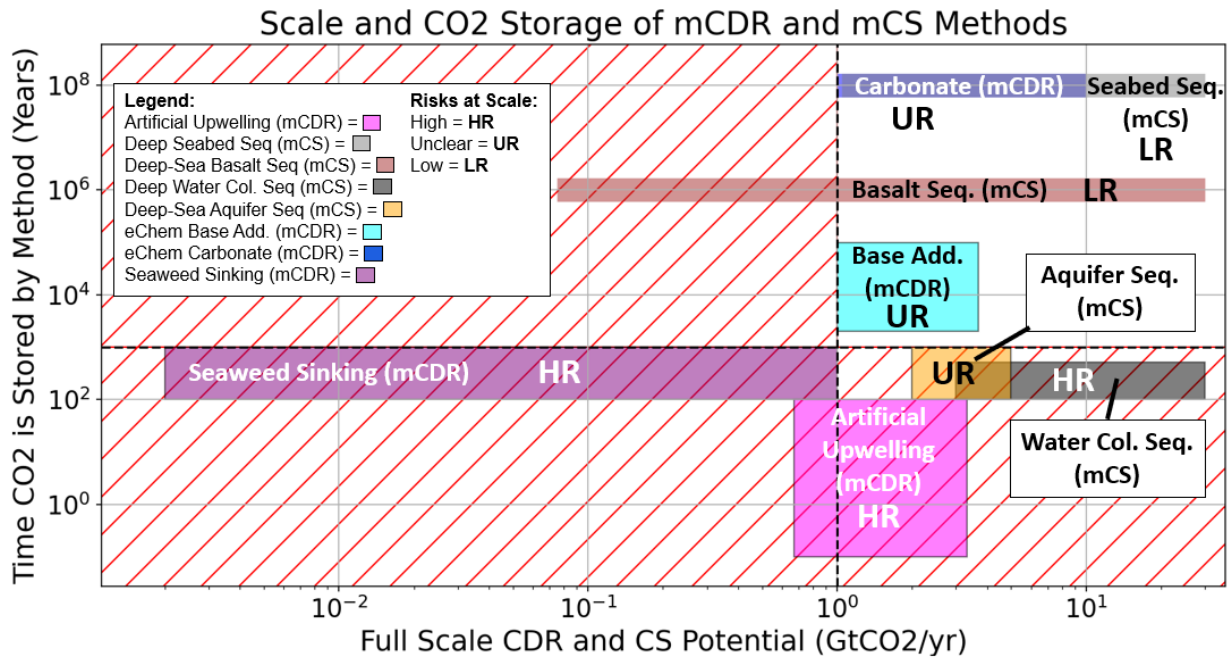

Figure 6. Comparison between the full-scale removal or sequestration potential and longevity of CO_2 storage enabled by the types of mCDR and mCS investigated in this study.

The boxes in the figure represent the upper and lower quartile estimates and/or references found for the considered subcategories (see Figure A-1 and Figure A-2 and Sections A.2, A.4, and A.5 for more details on the ranges for scale and sequestration time). Note that the red hash lines cover the regions that fail to meet the thresholds of interest. Additionally, the level of environmental risks at scale for the methods are included in this figure, which are described further in Table 1.

Overall, the eChem and deep-sea storage subcategories were found to be the most promising. Specifically, base addition, carbonate production, seabed sequestration, and basalt sequestration passed all three of their thresholds (see Figures 6, 7, and 9). Note that basalt and seabed sequestration are considered to be low risk at scale since studies reported a low likelihood of CO_2 leakage and other negative environmental impacts due to these methods; however, more research is needed to validate these claims [9, 10, 38, 39]. Meanwhile, it is unclear what the environmental impacts will be of base addition and carbonate production. Generally, they are considered safe, and base addition can reverse ocean acidification, but it is unclear what the effects of these methods will be on biological systems, as they have yet to be field-tested [4, 46]. Acid stripping CO_2 is also a promising method for mCC, as it was the only mCC method that passed the two thresholds in Figure 8. Therefore, acid stripping CO_2 could be combined with promising mCS methods such as seabed or basalt sequestration, to become a promising mCDR method that passes all three thresholds [21, 25, 26].

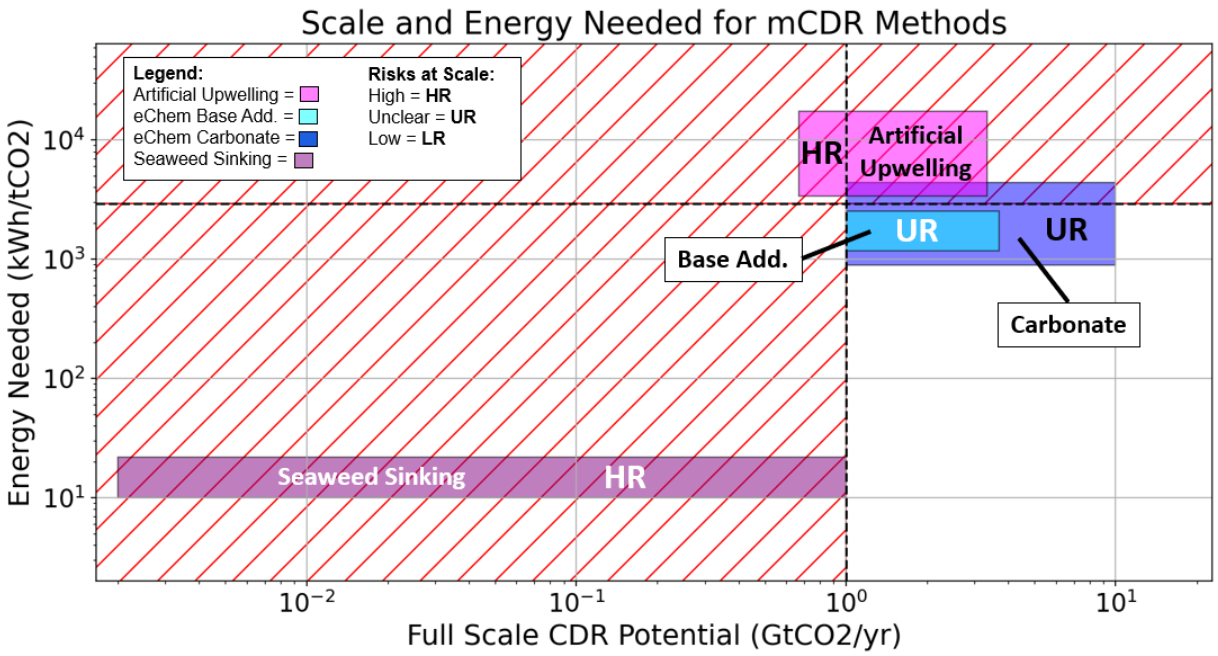

Figure 7. Comparison between the full-scale CDR potential and energy by the types of mCDR investigated in this study.

The boxes represent the upper and lower quartile estimates and/or references found for the subcategories, where the energy is the total energy required for the mCDR methods (see Figure A-1, Figure A-3, and Sections A.2, A.4, and A.6 for more details on the ranges for scale and energy, and Table A-2 for the energy values used for this figure). Note that the red hash lines cover the regions that fail to meet the thresholds of interest. Additionally, the environmental risks at scale for the methods are included in this figure and are described further in Table 1.

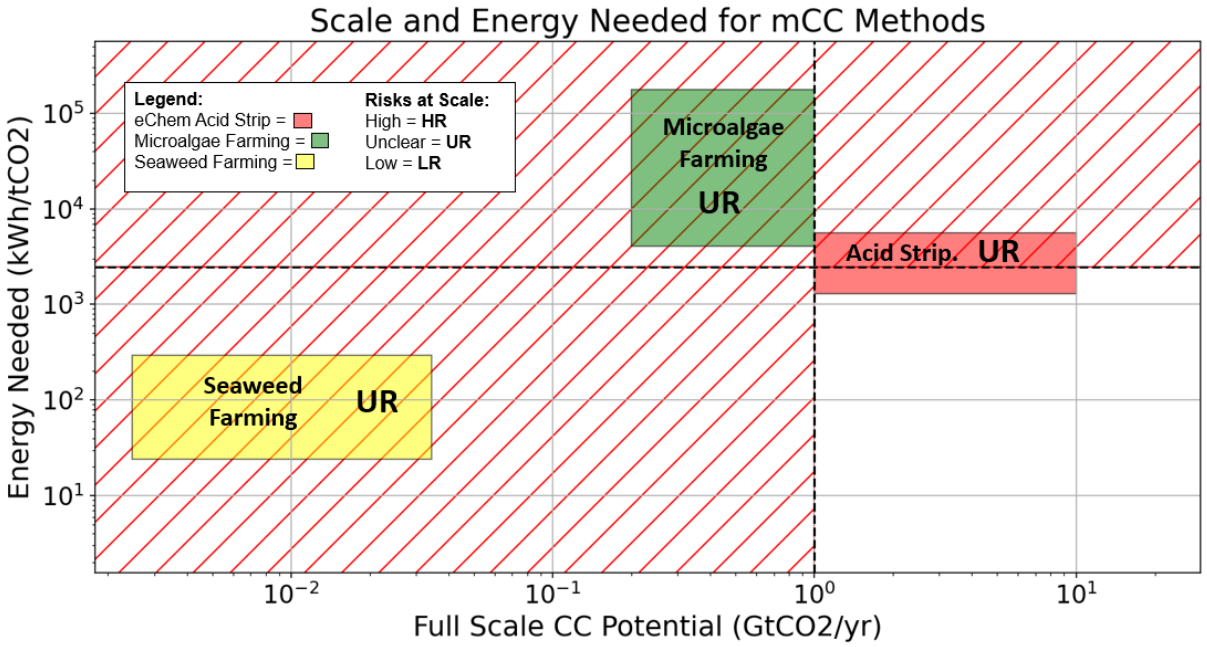

Figure 8. Comparison between the full-scale CC potential and energy by the types of mCC investigated in this study.

The boxes represent the upper and lower quartile estimates and or references found for the subcategories, where the energy is the total energy required for the mCC methods (see Figure A-1, Figure A-3, and Sections A.2, A.4, and A.6 for more details on the ranges for scale and energy, and Table A-2 for the energy values used for this figure). Note that the red hash lines cover the regions that fail to meet the thresholds of interest. Additionally, the environmental risks at scale for the methods are included in this figure and are described further in Table 1.

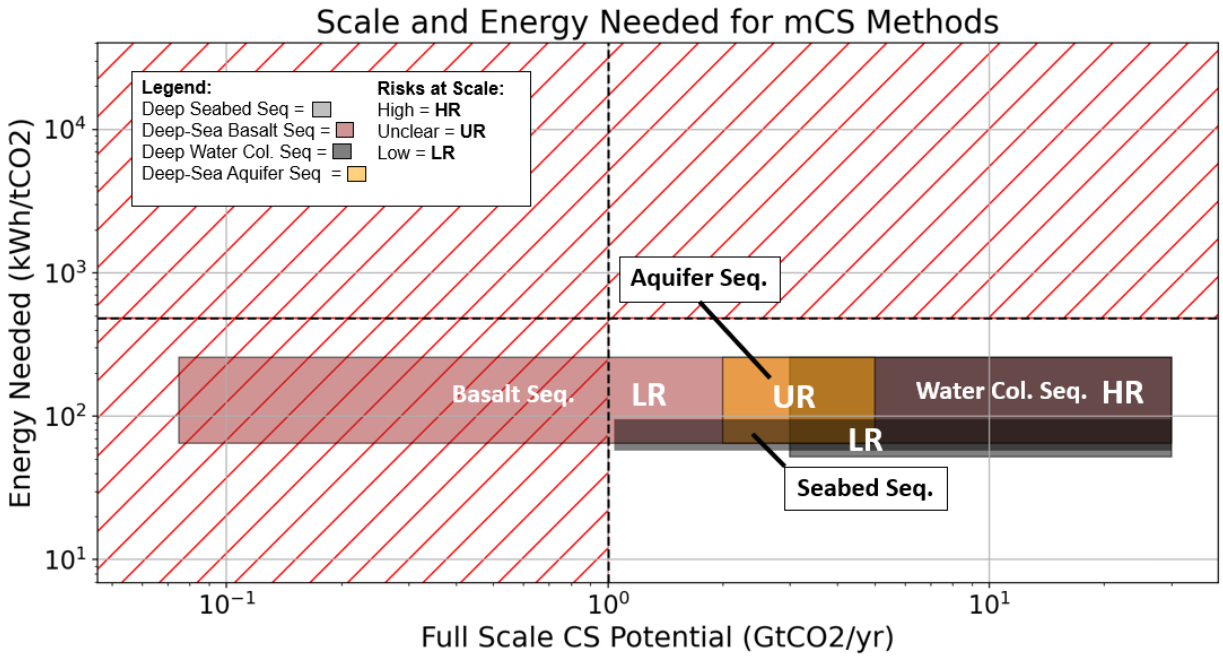

Figure 9. Comparison between the full-scale CS potential and energy by the types of mCS investigated in this study.

The boxes represent the upper and lower quartile estimates and or references found for the subcategories, where the energy is the total energy required for the mCS methods (see Figure A-1, Figure A-3, and Sections A.2, A.4, and A.6 for more details on the ranges for scale and energy, and Table A-2 for the energy values used for this figure). Note that the red hash lines cover the regions that fail to meet the thresholds of interest. Additionally, the environmental risks at scale for the methods are included in this figure and are described further in Table 1.

An additional finding of note from Figures 6, 7, and 8 is that the biological methods of mCDR and mCC met very few of the thresholds. AU and seaweed sinking were considered to be difficult to control and monitor and likely to disrupt global ecosystems and food chains at scale, giving them a high risk level [3, 4, 6, 8]. This resulted in a lower scale for these biological mCDR methods, which was also the case for seaweed farming because it can also disrupt global ecosystems above the scale range shown in Figure 8; however, the risks at the scale shown in this figure are unclear [7]. Meanwhile, the potential scale for offshore microalgae farming was not well defined in literature; therefore, estimates were made using data from offshore and onshore microalgae efforts (see Figure 8, Figure A-1, and Sections A.1 and A.2) [1, 47, 48]. Despite being able to use energy in their ambient environment, floating PBRs used in offshore microalgae farming achieve a low amount of CDR; consequently, they have the highest energy requirement per ton of CO_2 captured of the mCC methods examined in this report (see Figure 8 and Figure A-3) [3]. Additionally, the sequestration time was low for biological mCDR methods due to the speed of CO_2 remineralization in the deep ocean for sunken biological carbon [4]. Overall, AU and microalgae cultivation largely did not reach their energy thresholds due to low CO_2 uptake despite low power use (see Section A.2 and Figure A-3) [16, 17, 18, 23]. Alternatively, seaweed farming and sinking have very low energy requirements, which are lower per ton of CO_2 than the other mCC and mCDR methods described in this report (see Figures 7, 8, and A-3).

Additionally, aquifer and water column sequestration did not meet the longevity requirements due to higher likelihoods of CO_2 release, and water column sequestration was considered hazardous

since studies have shown the above-seafloor CO_2 injections to cause acute and chronic health issues for wildlife (see Figure 6 and Table 1) [30, 31]. However, aquifer sequestration is still promising, despite not surpassing the longevity threshold, since it is more technologically developed and has a higher TRL than the other sequestration methods (see Figures 6, 9, and 15) [31].

4.2 Key Results From Part Two: Achievable Scales Using U.S. Offshore Renewable Energy

Part two of this study focused on approximating compatibility between the mCDR, mCC, and mCS strategies investigated in this report and offshore renewable energy sources (such as wave, tidal, current, ocean thermal energy conversion (OTEC), river, and wind). To accomplish this, estimates for the median energy requirements and potential scales of the mCDR, mCC, and mCS subcategories were combined with the technical resources, or the renewable energy that could be harvested within U.S. waters with existing technologies, in the locations where these methods could be performed. Note the location specifications for the subcategories are described in Table 1, and the values for the technical resources were obtained from past NREL reports, all of which are detailed in Section A.3 [49, 50]. Note that the analysis and graphs in Figures 10 and 11 considered the energy left over after the 2019 energy demands of coastal communities are met, so the energy considered would solely be used for mCDR, mCC, or mCS. While the energy demand in these communities will likely increase over time, this energy demand is already very small (3,539 terawatt-hours per year [TWh/yr]) compared with the technical energy resources of offshore wind and marine energy (25,941 TWh/yr) (see Table A-8). Even if this energy demand increases by 50% by 2050 as anticipated, all of the methods except for AU can still reach their full scales and match the results shown in Figure 10 [51] (see Section A.3 for more details). Further increases in energy demand could be met with onshore renewable energy production. The energy available in the specified locations was divided by the median energy needs for removal, capture, or sequestration (see Tables A-3, A-6, A-7, A-8, and A-9) to determine the potential scales of CDR, CC, or CS achievable using all the available offshore energy after onshore electricity demand is met (see Table A-11). To make these scale estimates more realistic, they were limited to being at most equal to the median full scales of the methods (see Table A-4). The median scales used in this section for the deep-sea sequestration methods were limited to regional estimates due to the fixed geological reservoirs where they can be performed, whereas the mCDR and mCC methods used global estimates because it was assumed that the sequestered carbon from the mCDR methods will likely flow outside of U.S. waters and the mCC methods could use a variety of storage options (see Table A-4). The results of this analysis are shown in Figure 10. Note that this figure includes the results from all the methods investigated in this report to highlight the limited scalability of the less promising subcategories. The mCC and mCS results have been included on the same graph as the mCDR results to show the potential for these methods to contribute to CDR, where if the scales of an mCC and an mCS method are similar, they could be used together as a method of mCDR. For instance, eChem acid stripping CO_2 and deep-sea aquifer sequestration can both reach scales of 3 $GtCO_2$/yr, meaning that they could potentially pair well for mCDR (see Figure 10).

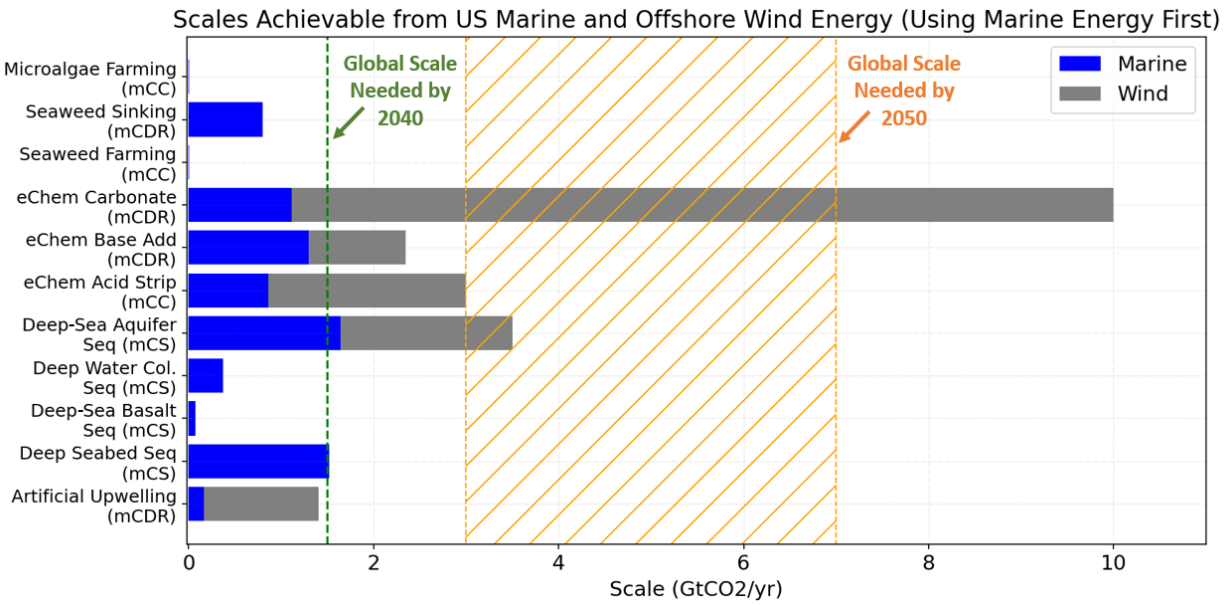

Figure 10. Theoretically achievable scales of mCDR, mCC, and mCS using the marine energy available in their appropriate U.S. locations followed by using offshore wind energy.

The bar graph shows the calculated scales when all the marine energy available to the methods according to their location requirements detailed in Table 1 and Section A.3 is used prior to the offshore wind available. If the median theoretical scale of these methods could not be met by all the marine energy available to them, then the available offshore wind energy would be used to meet the rest of the demand (see Section A.3 for more details). Note the estimates for offshore wind include energy from both fixed-bottom and floating wind turbines (see Table A-7 for more details). The global scales needed by 2040 and 2050 to limit warming to 1.5°C by 2100 are shown [1, 2, 19].

Overall, the biological methods of microalgae farming, seaweed farming, seaweed sinking, and AU are either limited to below 1 $GtCO_2$/yr or require a significant amount of energy to reach gigaton scales. In contrast, the eChem methods can reach 1 to 10 $GtCO_2$/yr scales when using solely marine energy and using marine and offshore wind energy, respectively. As shown in Figure 11, there is enough offshore energy available, accounting for 2019 coastal demand, to implement the eChem mCDR methods to remove about 10 $GtCO_2$/yr, including eChem acid stripping CO_2 with aquifer sequestration. This level of CDR is about the global rate of 3 to 7 $GtCO_2$/yr required by 2050 and close to the rate of 15 $GtCO_2$/yr required by 2100 to limit warming to 1.5°C by 2100, according to the Intergovernmental Panel on Climate Change [1, 2, 19]. These results are very promising and highlight the large amount of offshore energy resources that, even if also used to meet current and future coastal electricity needs, can still be used to substantially mitigate climate change.

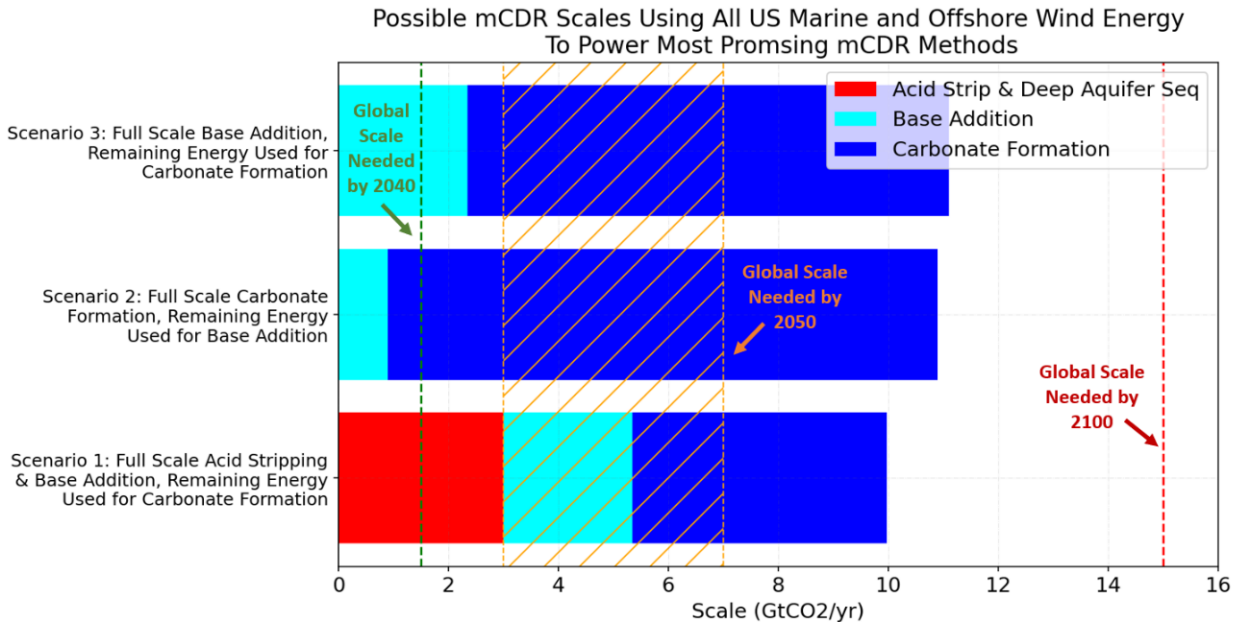

Figure 11. Different scenarios that use all the marine and offshore energy available to power the electrochemical mCDR methods, which were found to be the most promising forms of mCDR from the literature review.

The bar graph shows the calculated scales of eChem mCDR when all the marine and offshore wind energy available to these methods according to their location requirements detailed in Table 1 and Section A.3 are used to power them. The scenarios differ due to the different median full scales and energy needs of the three types of electrochemical mCDR. Note that the power needs of acid stripping included those of aquifer sequestration since it is the most developed mCS method, and because acid stripping is an mCC method, it captures pure CO_2 but does not sequester it on its own. Together, these methods become an mCDR method. See Section A.3 for more details. Additionally, the scales needed by 2040, 2050, and 2100 to limit warming to 1.5°C by 2100 are shown [1, 2, 19].

The compatibility between the mCDR subcategories and offshore renewable energy sources is largely based on those available in their optimal locations, which are detailed in Tables 1 and A-9. Overall, most of the energy available offshore comes from offshore wind energy, with the only exception being offshore microalgae cultivation, which relies on the rocking motion from ocean waves to mix its culture media. The proportions of the forms of marine energy available in the relevant regions for these mCDR, mCC, and mCS methods are detailed in Figure 12. Generally, the largest proportion of marine energy available was made up of wave energy, besides OTEC for deep-seabed sequestration, which is anticipated to be done on the East Coast and the Gulf of Mexico (see Tables 1 and A-9). These results generally indicate that wave energy is the most compatible form of marine energy for the mCDR methods except for OTEC, which is best for deep-seabed sequestration. Note that though marine energy is the focus of this report, there is also substantial potential to use offshore wind to power mCDR.

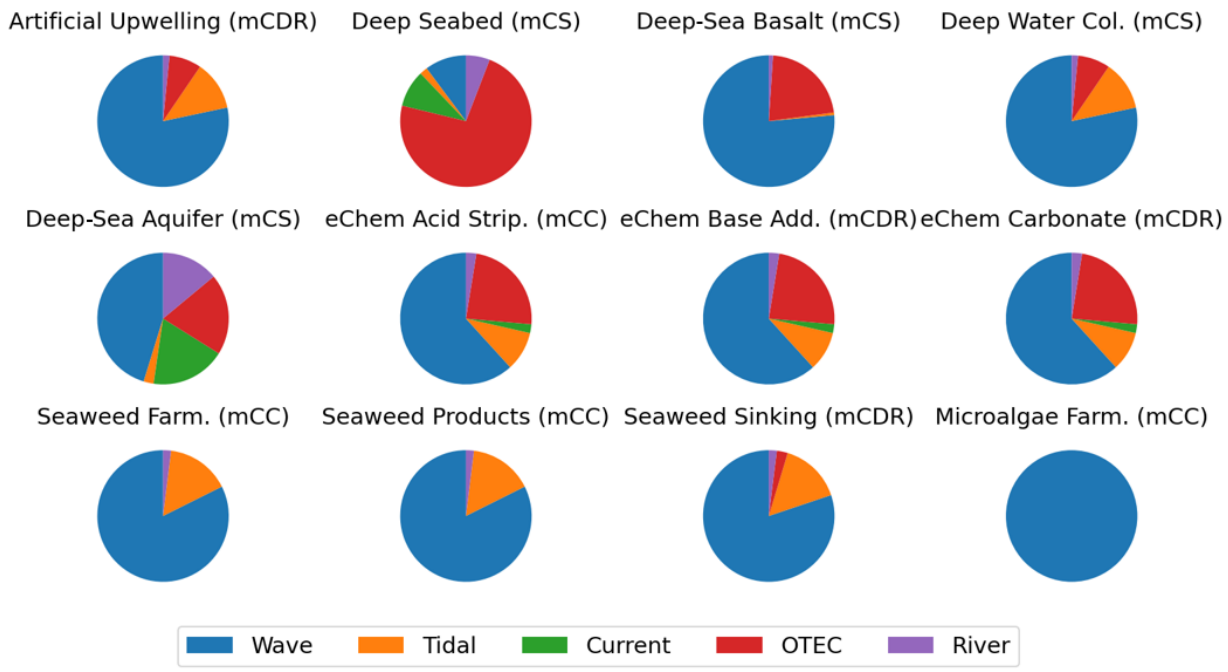

Figure 12. Proportions of marine energy available in the locations where the mCDR, mCC, and mCS methods are most effective according to the literature review.

Note, seaweed farming was also split into two categories for growing seaweed ("seaweed farming") and making products from seaweed ("seaweed products") due to their different energy needs; however, because the full scales of these categories are identical, only seaweed farming is included in Figure 10 (see Section A.3). Note in this case, the seaweed products subcategory is considered an mCC strategy due to its generally short storage time (see Section A.1 and Figure A-2), but it can also be referred to as a form of "carbon utilization."

The estimations made in this section used the total technical resources available in each state or region where the method could be implemented and are therefore likely overestimates but nonetheless good preliminary indications of which mCDR, mCC, and mCS methods are the most promising (see Section A.3 for more details).

The results from the analysis done in this section largely corroborate the findings from Section 4.1—that eChem mCDR and deep-sea sequestration minus water column sequestration are the most promising methods. Notably in this section, aquifer sequestration was shown to have significant promise and scalability, despite not meeting all its thresholds in Section 4.1.

4.3 Additional Findings From Part One: Cost and Technology Readiness Level

The literature review also found details on the costs and TRLs of the mCDR, mCC, and mCS methods, which have been included in this section to initially demonstrate their potential feasibility. To better contextualize the costs of these methods, a maximum threshold of $\$100/tCO_2$ was included for the mCDR methods in the box-and-whisker plot in Figure 13, since this is a common CDR cost goal in the industry and the target for the U.S. Department of Energy's Carbon Negative Shot [52]. The cost target for the mCS methods was set to $\$25/tCO_2$ since this is the upper range of costs for more developed onshore CS methods, adjusted for inflation from 2012 to 2022 dollars using the consumer price index inflation calculator from the U.S. Bureau of Labor

Statistics [31, 53]. The cost target for the mCC methods was simply the target for the mCDR methods with the mCS methods subtracted, or \$75/tCO$_2$. The median TRLs for these methods were also included to further contextualize these ranges, see Sections A.1, A.2, A.7, and A.8 and Figure A-5 for more details on how the TRLs were determined. The box-and-whisker plots show the maximum, minimum, outliers, median, and upper and lower quartiles for the estimated and referenced costs. Note that the costs shown here are based on the various processes' use of conventional energy; any potential for energy cost reductions by using marine energy have not been explored in this study but should be explored in future work.

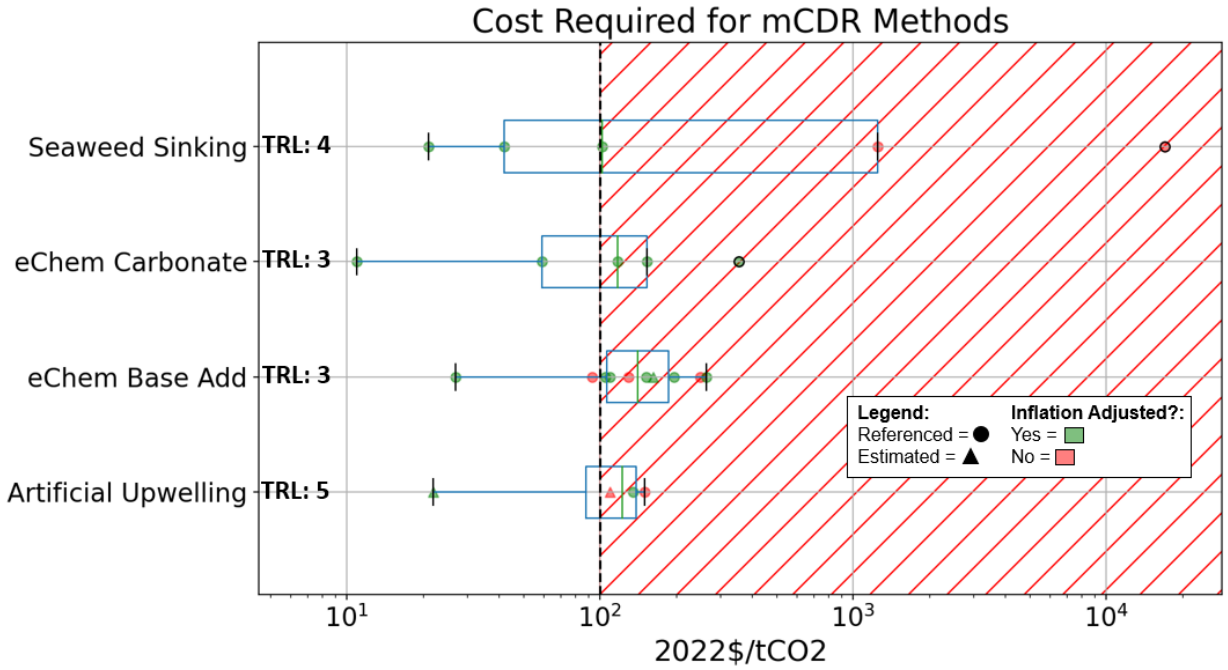

Figure 13. Costs in 2022 dollars required for the types of mCDR investigated and the median TRLs.

A more detailed version of this graph is shown in Figure A-4, and estimations used are explained in Section A.2. The red hash lines refer to the costs above the threshold of \$100/tCO$_2$. Costs were converted to 2022 dollars using the consumer price index inflation calculator from the U.S. Bureau of Labor Statistics [53]. The calculations for the TRLs are detailed in Sections A.1 and A.2, and the medians are shown in Figure A-5.

The costs for the mCDR methods, as shown in Figure 13, were generally below \$200/tCO$_2$; however, few met the target of being below \$100/tCO$_2$. Seaweed sinking had the lowest median cost reported in literature, but as highlighted in Figures 6 and 7 and Table 1, this method also comes with significant environmental risks such as disrupting deep-sea food chains and inducing hypoxia [6, 8]. Additionally, the median cost of seaweed sinking, \$102/tCO$_2$, was the upper limit cost of sinking seaweed from the massive blooms in the Caribbean [32]. When the seaweed needs to be grown for sinking, the median cost becomes \$1,257/tCO$_2$, which is the minimum cost for growing seaweed near shore and sinking it offshore at scale [6]. Meanwhile, the median costs for eChem carbonate formation, eChem base addition, and artificial upwelling were \$118/tCO$_2$, \$141.50/tCO$_2$, and \$122.50/tCO$_2$, respectively. Though the eChem mCDR costs are above \$100/tCO$_2$, they are relatively close to the target despite having a lower TRL than the other mCDR methods. Note that the cost estimates near or below \$100/tCO$_2$ for these eChem mCDR methods accounted for cost savings from selling and or using the H$_2$ produced in their electrolysis processes

[15, 42, 54]. As these promising mCDR methods are further developed and scaled, their price may generally become less than $100/tCO2.

The costs of the mCC methods, as shown in Figure 14, were generally much greater than their $75/tCO2 cost threshold, with only very few reported costs from seaweed farming and eChem acid stripping CO2 meeting these targets. The median CC costs for offshore microalgae farming, seaweed farming, and eChem acid stripping CO2 were $1,028/tCO2, $627/tCO2, and $731/tCO2, respectively. Since these methods also need to be paired with sequestration methods to become CDR methods, these costs will need to be reduced to ensure their scalability as CDR methods. This is especially true for eChem acid stripping CO2, which passed all its thresholds in Section 4.1. However, this mCC method is still at an early TRL, meaning that future innovation could improve its cost. Note that most of the costs below the median for this eChem mCC method were for cases where it was combined with existing infrastructure such as desalination or seawater cooling; therefore, initial deployments could benefit from partnering with these industries [14, 25].

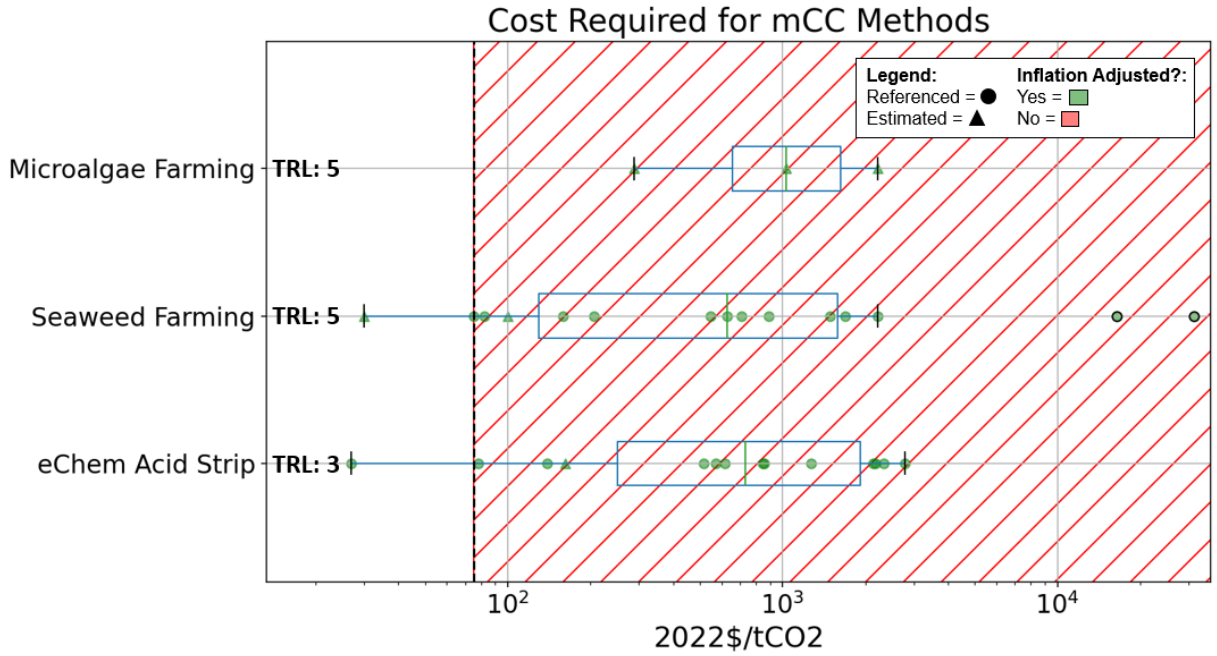

Figure 14. Costs in 2022 dollars required for the types of mCC investigated and the median TRLs.

A more detailed version of this graph is shown in Figure A-4, and estimations used are explained in Section A.2. The red hash lines refer to the costs above the threshold of $75/tCO2. Costs were converted to 2022 dollars using the consumer price index inflation calculator from the U.S. Bureau of Labor Statistics [53]. The calculations for the TRLs are detailed in Sections A.1 and A.2, and the medians are shown in Figure A-5.

The costs of the mCS methods, as shown in Figure 15, were generally above the $25/tCO2 threshold, but close to the target. Basalt sequestration had a median cost below $25/tCO2, $11/tCO2, but not much cost data on this method could be found in the literature, and it has a relatively low TRL, so this cost may change as the technology matures. Deep-sea water column sequestration also had a median cost below the target, at $22/tCO2, but this method is largely considered to be environmentally hazardous since it can kill deep-sea marine life and increase ocean acidification (Figures 6 and 9 and Table 1) [30]. The median costs of deep-sea aquifer and seabed sequestration were $34/tCO2 and $43.50/tCO2, respectively. Aquifer sequestration has a high TRL value and is close to the threshold, and as this technology scales, its cost may meet the

target. Deep-seabed sequestration likely had the highest median cost due to its much lower TRL value compared to the other mCS methods.

Overall, among the most promising methods from Section 4.1, eChem base addition, carbonate formation, acid stripping CO_2, and deep-sea basalt, aquifer, and seabed sequestration, only the median cost of deep-sea basalt sequestration passed its respective threshold. Aquifer sequestration and eChem carbonate formation were close to their targets; however, the median costs of deep-seabed sequestration and eChem base and acid stripping CO_2 were nearly 2, 1.5, and 10 times their targets, respectively. Therefore, further research and development is essential to reduce the costs of these methods and enable them to reach their full scales.

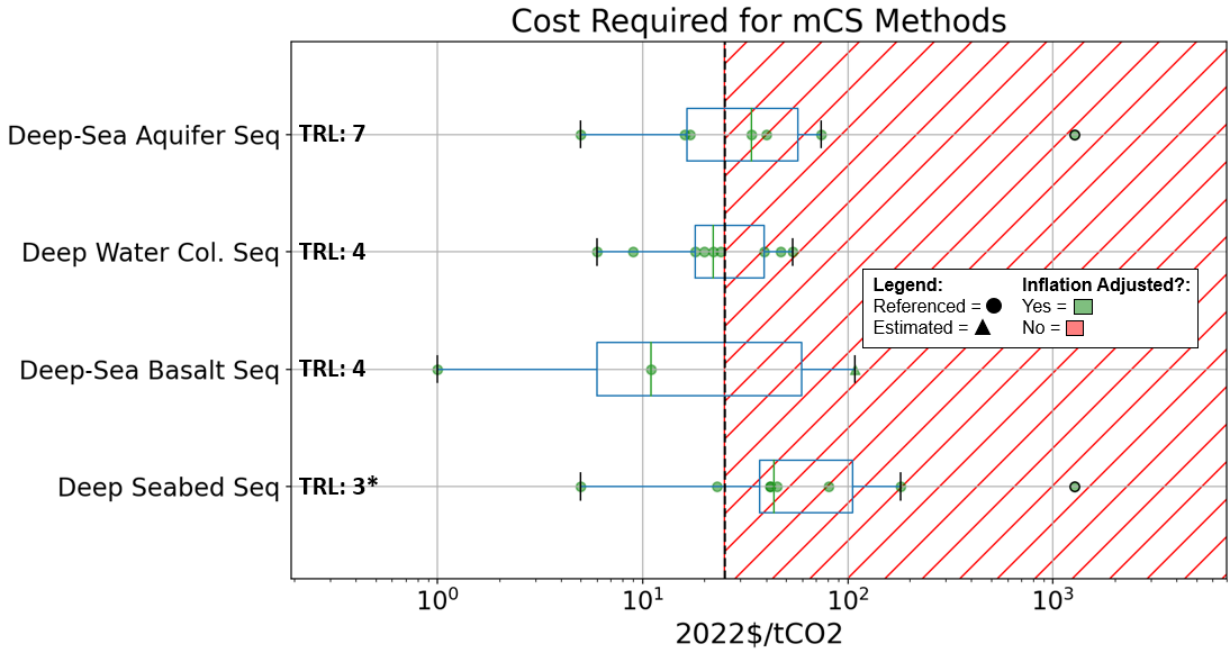

Figure 15. Costs in 2022 dollars required for the types of mCS investigated and the median TRLs.

A more detailed version of this graph is shown in Figure A-4, and estimations used are explained in Section A.2. The red hash lines refer to the costs above the threshold of \$25/tCO_2. Note that the TRL calculation for deep-seabed sequestration excluded a multitude of conceptual papers from the late 1990s to create a more up-to-date estimate. Costs were converted to 2022 dollars using the consumer price index inflation calculator from the U.S. Bureau of Labor Statistics [53]. The calculations for the TRLs are detailed in Sections A.1 and A.2, and the medians are shown in Figure A-5.

4.4 Additional Findings From Part One: Location Requirements and Environmental Risks

The location requirements and environmental risks for the mCDR, mCC, and mCS categories and subcategories are shown below in Table 1. The sources found in this study included global and regional maps, such as that of the U.S. Exclusive Economic Zone, highlighting the ideal locations for the types of mCDR, mCC, and mCS investigated in this study (see Figure A-6 through Figure A-14). These maps were used along with a marine energy resource assessment comparison to determine specific compatibilities between individual mCDR, mCC, and mCS methods and marine energy technologies (see Section A.3 for more details). The environmental risks detailed in this

section are summaries of the findings from literature that were used to determine the risk levels for the methods in Figures 6, 7, 8, 9 and A-1.

Table 1. mCDR, mCC, and mCS Location Requirements and Environmental Risks

Method	Location Requirements	Environmental Risks
Artificial Upwelling (mCDR)	Can either remove or release CO_2 depending on location, season, and biogeochemical factors; generally, site > 3 nautical miles from coast; can limit environmental risks by siting in enclosed bays or fjords [4, 24].	Ecological risks are high since AU can disrupt the ocean thermocline and cause more warming, increase ocean acidification, disturb upper and lower ocean ecosystems, cause hypoxia, release greenhouse gasses, and reduce precipitation [4]. Also need to carefully monitor AU in coastal regions where impacts of eutrophication and imbalanced macro-nutrients are non-negligible [35].
Deep-Sea Water Column Sequestration (mCS)	Sequestration times of CO_2 released above the seafloor depend on location and depth: in the U.S. the waters around the West Coast, Alaska, and Hawaii have the longest times, reaching up to 1,000 years at 3 km [37].	Formation of CO_2 lakes in the deep ocean if CO_2 is deposited close to the seafloor, killing most organisms under the lake and those that wander into it; unclear how deep-sea organisms will react to overall changes in CO_2 concentrations, but they are likely sensitive to these changes and could die from chronic exposure; also increases ocean acidification [30].
Deep-Sea Basalt Sequestration (mCS)	Must be conducted in areas with reactive minerals such as basalt, which can be found throughout the ocean floor; however, the best locations are near mid-ocean ridges where the basalts are warmer, more reactive with CO_2, and buried underneath enough sediment (ex. > 200 m) to be unweathered. In the U.S. this includes ridges off the coasts of Oregon and Washington [9, 41].	There is a minimal risk of post-injection leakage or environmental damage; also mitigates the risks of induced earthquakes since the increase in pressure in these reservoirs is unlikely to cause faulting due to their massive size and the seawater that fills their pores [9].
Deep-Seabed Sequestration (mCS)	Requires permeable marine sands at depths of at least 3 km with sediments that are a few hundred meters thick. The sands need to be permeable enough to inject CO_2 at high rates and not near steep slopes since landslides can release the CO_2 or in locations with high-salinity pore waters that are denser than CO_2 since they can also release the CO_2 [10, 38]. Ideal locations include the Atlantic Coast and the Gulf of Mexico, especially off the coast of North Carolina where sediments are closer to the coast [38, 39].	CO_2 may be released if there are faults or fractures in the sediment or excessive injection overpressure or changes in pressure or temperature [40]. However, with proper site selection and injection, the CO_2 should remain safely stored, requiring less significant monitoring than land storage. The biological impacts are considered minimal due to the low biological activity in these sediment depths, and the very low CO_2 dissolution will limit local pH changes [10, 55].
Deep-Sea Aquifer Sequestration (mCS)	The Gulf of Mexico is a good basin for undersea aquifers, and it already has extensive infrastructure from the oil and gas industry. There is also significant potential in the Atlantic and Pacific Outer	Sites must be carefully selected to avoid risks of leakages, which can harm offshore life. Additionally, the injected CO_2 stream can contain hazardous substances such as mercury or can

Method	Location Requirements	Environmental Risks
	Continental Shelves [31]. However, it is necessary to ensure that the area is free of transmissive faults or fractures and can be injected with CO_2 without creating or propagating fractures [31].	mobilize substances in the subsurface that could react with groundwater to make hazardous substances like sulfuric acid [31].
eChem Acid Stripping CO_2 (mCC)	Most cost-effective when paired with existing pumping systems (e.g., desalination), can have flexible placement close to population centers, and could be combined with aquaculture and other marine activities, but may be initially limited to be near the coast due to the need to transport captured CO_2 to shore [4, 14, 26].	Methods that use electrolysis to produce H_2 from seawater as part of their eChem process generally produce toxic Cl_2 gas, which needs to be carefully stored along with the wastewater made by the process. Low dissolved inorganic carbon levels in the effluent seawater could be harmful for autotrophic organisms, but more research is necessary [4].
eChem Base Addition (mCDR)	Benefits from being sited with existing pumping systems such as desalination. Environmental risks can be mitigated by siting systems in semi-enclosed locations (e.g., bays) or areas with high surface currents [4, 11, 56]. Methods that neutralize acid with deep-sea carbonates can be sited offshore (the best regions for this strategy are in the North Pacific) [11]. This neutralization could also be done with methods that neutralize the acid with silicate minerals, but they would require specialized infrastructure and proximity to mineral resources [42].	Similar risks of Cl_2 gas disposal for methods using electrolysis in addition to neutralization and disposal of unused acidic solution; in terms of adding alkalinity to seawater, need to avoid drastic pH changes, but this process can reduce ocean acidification and improve coral growth. Overall, more research is needed on these potential impacts [4, 56]. Methods that involve using minerals such as silicate to neutralize the acid also have environmental impacts due to mining and adding the unused acid to the deep ocean for neutralization requires further study [11, 42, 54].
eChem Carbonate Production (mCDR)	Can benefit from being combined with desalination plants onshore; risks of cation depletion can be mitigated by siting the systems near river deltas at the interface between fresh and saltwater since rivers have a higher cation concentration and can replenish the lost ions; siting offshore can lower pumping requirements [15].	Similar risks for Cl_2 gas production for electrolysis methods; additionally reducing the concentration of calcium and magnesium ions due to the carbonate production can increase seawater acidity [4, 15].
Offshore Microalgae Farming (mCC)	Need sunlight and moderate waves, can be deployed on any body of water but likely best to be operated in ocean bays to reduce risk of damage from storms and likely need to be near shore to enable harvesting; ideal temperatures in the U.S. include southern California, the Gulf Coast, Puerto Rico, and the South Atlantic coast [16, 22, 57].	Risks are minimal during normal operation, but if the floating systems are destroyed, they can release algae and nutrients into the local environment and cause eutrophication and hypoxia. The released microalgae may also outcompete or transfer genes with native species causing unknown impacts [16, 22].
Seaweed Farming (mCC) & Seaweed	Temperate waters preferred since they are more nutrient-rich than tropical ones; strong currents support nutrient replacement and CO_2 absorption but if currents and waves are too strong, the	Risks from growing seaweed for products or for sinking: Displacing plankton communities and reducing their CDR in addition to spreading invasive species and entangling marine life (note that risks

Method	Location Requirements	Environmental Risks
Sinking (mCDR)	seaweed can be damaged. Seaweed must be sunk to > 1 km for sequestration; regions in the North Pacific are considered to have longer sequestration times. Meanwhile, excess rotting seaweed from algal blooms needs to be removed or sunk in the Caribbean Sea [6, 32, 37, 58].	scale with the amount of seaweed grown); but can promote habitat creation and minimize risks by using local endemic species [6, 4, 7, 8]. Risks from sinking: Impacts to deep-sea ecosystems unclear but will likely greatly disrupt food chains and cause hypoxia in the deep sea; ecological risks are high and the concept is considered unethical by some, but risks can be mitigated by sinking seaweed in already hypoxic regions [6, 8].

4.5 Additional Findings From Part One: Monitoring Requirements

Monitoring mCDR, mCC, and mCS methods will require either sensors inside of the systems, such as pH or CO_2 sensors inside an eChem mCDR or mCC device, or mobile autonomous surface or underwater vehicles equipped with sensors needed to detect environmental damage and verify CO_2 capture and sequestration (see Figure 16) [4]. While equipment exists that can be used to monitor some aspects of CO_2 sequestration in the ocean, such as total alkalinity, pH, partial pressure of CO_2 (pCO_2), and dissolved inorganic carbon, there are no standardized, reliable ways to measure sequestration from biological methods such as AU and seaweed cultivation and sinking, nor are there clear, consistent methods of assessing environmental damages from these methods [4]. More details are shown in Table 2.

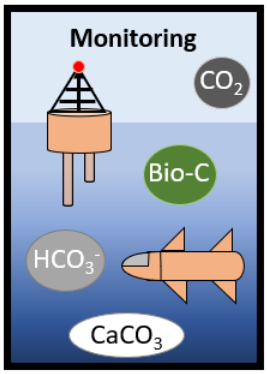

Figure 16. Graphic describing mCDR, mCC, and mCS monitoring needs.

The image is a simple description of the types of carbon needed to be monitored such as atmospheric CO_2, dissolved bicarbonate, solid carbonate, and biological carbon, and of the simplified floating monitoring stations or undersea drones that could be used to monitor them.

Table 2. Monitoring Needs for the mCDR, mCC, and mCS Strategies Investigated

Method	Monitoring Requirements
Artificial Upwelling (mCDR)	Need to monitor over thousands of square kilometers with measurements over months or years [35, 59]. Need to measure or detect released gases (N_2O, methane, CO_2), ocean levels of dissolved inorganic carbon, oxygen (O_2), pH, temperature, nutrients (phosphate, nitrate, nitrite, and silicate), chlorophyll a, carbon flux into the deep ocean, species of plankton and their size, salinity, particulate organic carbon (POC), water currents (speed and direction), and ecosystem changes such as harmful algae blooms [4, 24, 35, 59]. Although there is no effective method for monitoring all these factors over the necessary time periods, volumes of water, or small concentrations, methods such as sediment traps, gliders, and instrumented profiling floats have been used previously [4, 35, 59]. Monitoring needs are expected to greatly increase deployment costs [59].
Deep-Sea Water Column Sequestration (mCS)	In terms of near-field monitoring: Ocean pH and current profiles at a high enough temporal scale can evaluate the rate of CO_2 release, local CO_2 accumulation, and net transport from the site; undersea video cameras can be used to monitor the point of release to observe the CO_2 flow; acoustic techniques such as sonar can be used to monitor the flow of liquid CO_2; CO_2 injection and the formation of a CO_2 lake can be verified and the quality and loss rate can be determined by a combination of acoustic, pH, and velocity measurements done by tethered or autonomous underwater vehicles [30]. Far-field monitoring requires monitoring the distributions of injected CO_2 and pH changes using shipboard measurements via ship surveys every 2 to 5 years and modeling; however, it will be difficult or even impossible to measure changes in CO_2 very far from the injection site [30]. Additionally, need to monitor the health of wildlife in the deep sea via process studies, long-term surveys of biogeochemical tracers and deep-sea biota, and ocean bottom studies [30]. Costs of monitoring and verification are expected to be high since they would involve deploying and maintaining a large array of sensors in the ocean, which are still in development [30].
Deep-Sea Basalt Sequestration (mCS)	Need better monitoring methods of the mineralization and estimation of CO_2 fixation at scale [41]. One group was able to monitor their injection in real time using NEPTUNE, an active cabled network for observation and monitoring [60].
Deep-Seabed Sequestration (mCS)	Monitoring needs are considered to be minimal, but this will require verification and further study [10]. Overall, it will be necessary to evaluate the minerology of the target sediments and the pressure and temperature at the location, and to assess leakages of CO_2 [38]. Leakages can be monitored over the short and long term using both manned and autonomous submersibles and tools from institutions such as the Woods Hole Oceanographic Institution's Deep Submergence Lab, which has experience with surveying methane hydrates in sediments along the U.S. Atlantic continental margin and could use this experience for monitoring this form of mCS [61].
Deep-Sea Aquifer Sequestration (mCS)	Similar to seabed sequestration, it is necessary to identify and evaluate potential leaks of CO_2 which can be done in a similar manner [31].
eChem Acid Stripping CO_2 (mCC)	Sensors are contained within the system itself to evaluate the solution flow rates, pH, dissolved organic carbon, dissolved inorganic carbon, pressure in the compartments, and CO_2 flow rate as it is vacuumed from the seawater, this includes a H_2 and Cl_2 gas sensor if electrolysis is used [21, 28, 33]. May require

Method	Monitoring Requirements
	monitoring the effects of low dissolved inorganic carbon levels from the effluent seawater on autotrophic organisms [4].
eChem Base Addition (mCDR)	Need to assess the spatial and temporal dynamics of ocean pH, dissolved inorganic carbon, total alkalinity, and pCO_2 [1, 4, 11]. Due to indirect CO_2 capture from alkalinity addition, may need to verify capture via direct measurements, which can substantially increase monitoring costs [4]. Additionally, can monitor biogeochemistry and carbonate saturation state [11, 62]. Surface moorings (ex. PRAWLERs), fixed observatories, profiling floats, gliders, and autonomous surface vehicles (ex. Saildrones) can be used for monitoring these parameters [4, 63, 64]. To assess potential impacts on wildlife nutrient concentrations, temperature, salinity, and dissolved O_2 can be monitored as well [56]. Also require a H_2 and Cl_2 gas sensor if electrolysis is used [4].
eChem Carbonate Production (mCDR)	Lower needs for monitoring because producing solid carbonates has a lower risk of CO_2 release [15]. Uses internal sensors to assess pH, dissolved organic carbon, dissolved inorganic carbon, and solution flow rates, in addition to calcium and magnesium ion concentrations [28, 65]. Also require a H_2 and Cl_2 gas sensor if electrolysis is used [4]. May require monitoring environmental levels of acidity and ion concentrations of calcium and magnesium to minimize risks [4, 15].
Offshore Microalgae Farming (mCC)	Monitoring techniques are needed that can distinguish the differences between the cultured microalgae and nutrient salts to those in the environment, to detect leakages and mitigate environmental impacts if the floating bioreactors are destroyed [16]. Can additionally measure factors within the bioreactors such as pH, cell size, chlorophyll a and b, dissolved O_2, temperature, sunlight exposure, and nutrient concentration [17, 18, 43, 66, 67, 68].
Seaweed Farming (mCC) & Seaweed Sinking (mCDR)	It will be necessary to monitor phytoplankton communities to determine the extent of their displacement due to increased seaweed growth [6]. Additional aspects to monitor while the seaweed is growing include temperature, salinity, turbidity, nitrogen levels, growth rate of seaweed, water clarity, nutrient levels, dissolved O_2, genetic diversity, nutrient and carbon absorption, and sugar content [4, 69]. eDNA, depth, dissolved inorganic carbon, currents, and dissolved organic carbon can be monitored to track sequestered carbon in the sunk biomass to record its fate and possible carbon leakage after sinking. Note that it will be easier to monitor sunk seaweed as opposed to the shed particulate organic carbon from seaweed farming [4, 6, 8]. These parameters can be monitored by autonomous surface, aerial, and underwater vehicles and by moored buoys with sensors [4, 69]. Note that verifying changes due to seaweed sinking rather than from other sources will be incredibly challenging due to the large volumes and timespans that need to be evaluated, in addition to assessing the impact on deep-sea ecology and migration of sunken seaweed that flow outside of intended sink zones [32, 70].

5 Conclusion

The goal of this project was to better understand the feasibility of using U.S. marine energy to power mCDR, mCC, and mCS strategies to reach scales that could mitigate climate change. This preliminary analysis involved two parts. The first involved a literature review and estimations informed by literature that assessed the feasibility of these methods in general, without considering how they would be powered. The second involved using the amount of energy that could be harvested by existing marine and offshore wind energy technologies in the locations where these methods could be performed in the United States to approximate the scales that could be achieved by powering these methods with offshore energy and to initially assess their compatibility with different forms of marine energy. Although this analysis was extensive, it is important to keep in mind that this field has a multitude of early-stage technologies and concepts that are still under development, and new technologies that do not fit into these categories may be developed in the coming years.

Part one primarily involved evaluating and estimating the anticipated mCDR, mCC, and mCS methods' full-scale potential, longevity of CO_2 storage (for the mCDR and mCS methods), energy needs, costs, TRLs, location requirements, environmental risks, and monitoring needs. The most promising mCDR, mCC, and mCS methods were those with potential scales above 1 $GtCO_2$/yr, energy needs below the upper quartile of those from onshore CDR, CC, and CS methods, and CO_2 storage times of 1,000 years for the mCDR and mCS methods. The storage time of the mCC methods depended on what CS method they would be combined with or whether or not the captured CO_2 was turned into products (see Section 4.1 for more details). By these standards, the most promising mCDR methods were eChem base addition and carbonate formation; the most promising mCC method was eChem acid stripping CO_2; and the most promising mCS methods were deep-sea basalt and seabed sequestration. Aquifer sequestration is also promising, despite not meeting longevity requirements, because it is already being done in pilot projects at megaton scales, meaning that it has a higher TRL and could be a good near-term partner for offshore renewable energy developers interested in using their technologies to power mCS to sequester CO_2 captured by eChem acid stripping CO_2 or other CC methods [31].

While cost and TRL information was recorded for all the methods identified in the first part of this study, this was not included in the key results in Section 4.1 because these values will change once the methods are integrated with marine or other forms of offshore renewable energy. However, the information was kept in Section 4.3 to highlight the current state of the technologies. Among the methods that passed the thresholds from Section 4.1, only deep-sea basalt sequestration passed its cost threshold, but cost information for this mCS method was limited, and more research is necessary to clarify its potential costs. Generally, the other methods were close to their cost thresholds, except for eChem acid stripping CO_2, whose median cost was nearly 10 times greater than its target. The lowest cost estimates for the eChem methods generally were minimized by selling and or using H_2 produced in their electrolysis processes or pairing with existing infrastructure from other industries such as desalination or seawater cooling [14, 15, 25, 42, 54]. More research is required to better understand how integrating these methods with offshore renewable energy will impact their costs.

The second part of the study assessed how marine energy and other forms of offshore renewable energy, like offshore wind, can be used to power these technologies to enable large-scale mCDR,

mCC, and mCS. For instance, eChem mCDR methods (including eChem acid stripping combined with deep-sea aquifer sequestration) could use U.S. offshore marine and wind energy resources (that can be harvested by existing technologies) to remove 10 $GtCO_2$/yr, which could be used to reach global removal targets needed by 2050 and assist in reaching those needed by 2100 to limit warming to 1.5°C by 2100 (see Figure 11) [1, 19]. Marine energy alone could still be used to reach 1 $GtCO_2$/yr CDR scales with the eChem mCDR methods, which is still a significant step toward global capture targets (see Figure 10). This highlights the potential global impacts of combining these technologies together. Among the marine energy sources considered, wave energy generally had the highest resources available to the methods, except for deep-seabed sequestration, which had a majority of OTEC available to it in its appropriate locations (see Figure 12). This preliminary measure of compatibility will need to be verified with future studies that examine how specific technologies can be integrated with one another. This would include studies that assess how the methods can handle variable energy from renewable sources and oceanic conditions and how the timing of offshore renewable energy development will impact possible deployments of these technologies. Additionally, this massive deployment will likely be heavily impacted by costs and public support.

Despite the other mCDR, mCC, and mCS methods not reaching all the performance thresholds set in this study, they still have their own benefits. Seaweed and microalgae farming can be used to make carbon-neutral biofuels and food among other products, AU can support aquaculture, and seaweed sinking could be used in regions such as the Caribbean where a seaweed bloom is causing environmental, health, and financial strife [4, 22, 23, 32]. Additionally, marine energy could be used to protect offshore seaweed farms or floating microalgae bioreactors from harsh sea states, which has been proposed for an offshore seaweed farm using an overtopping wave energy converter array [58].

However, it is important to recognize that removing 10 $GtCO_2$/yr from the oceans through 2100 would represent an extreme change to the current situation over a short period of time, especially since the currently available CO_2 inventory in the Earth's atmosphere has been dictated by hundreds of millions of years of gas partitioning pathways between the troposphere and the combined terrestrial and ocean sinks. The scientific community understands the terrestrial carbon pathways and cycle dynamics from the benefit of firsthand experience spanning many years of experience and study and has verified terrestrial models to guide us. In contrast, the oceans are largely an unknown environment. Not only are they uninhabitable, the shear vastness and complexity/dynamics renders many terrestrial monitoring tools inadequate for observing changes in the ocean. This difficulty in observing the marine environment also renders ocean computational models less verifiable and thus less reliable in predicting the outcome of major changes to the ocean's chemical composition and biological response. As described in Tables 1 and 2, the environmental risks and monitoring needs of these methods can be substantial and are generally not well understood. So, the deployment of mCDR, mCC, and mCS in the open ocean at the scale envisioned in this report would need to be accompanied by an ocean environmental monitoring and research program that spans prototype deployments to small-scale pilot projects up through global-scale deployment to identify and remediate undesirable outcomes.

Despite these challenges, the current study has indicated that certain mCDR, mCC, and mCS strategies, specifically the eChem mCDR methods (including eChem acid stripping CO_2 combined with CS) described in this work, have the potential to reach large enough scales needed to achieve

global CDR targets. More work is necessary to understand the compatibilities of these strategies with specific forms of marine energy and other offshore renewable energy sources, which is highly encouraged due to the promising results of this study.

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Appendix A. Supplementary Data

A.1 Supplementary Figures of mCDR, mCC, and mCS Attributes Independent of Marine Energy

The following section provides more details on the results of the literature review and estimations to determine the full-scale potential, longevity of CO_2 storage, energy required to capture and/or sequester CO_2, cost, and TRL of the mCDR, mCC, and mCS methods explored in this report.

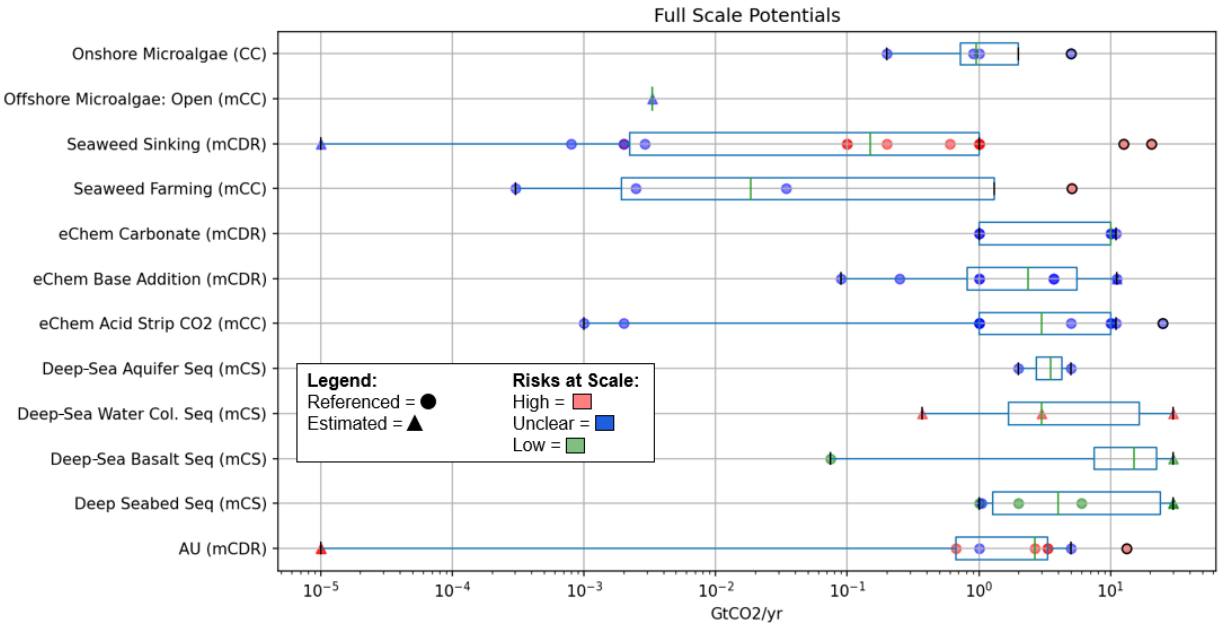

Figure A-1. Full-scale potential of mCDR, mCC, and mCS methods.

Figure A-1 shows the full-scale referenced and estimated values found in this report. Note that the estimates for seaweed sinking and AU at 10^{-5} $GtCO_2$/yr refer to how these methods may release CO_2 rather than sequester it [4, 5, 70]. Additionally, the scales of seaweed sinking below 10^{-2} $GtCO_2$/yr refer to efforts in the Caribbean to sink rotting excess seaweed that harm the local tourism economy [32, 70]. The estimate for offshore open microalgae's scale was roughly determined by assuming that 1 $GtCO_2$ could someday be made into bicarbonate for the cultures used by this method globally (see Section A.2) [48]. Due to this rough estimate, data points from onshore microalgae cultivation were used as additional estimates for the potential scale of offshore microalgae farming and are shown in the graphs in Figure 6 and 7. Generally, above 0.1 $GtCO_2$/yr scales of seaweed sinking were considered to be hazardous due to the massive increase in seaweed cultivation required and the massive amount of sunk organic matter that would disrupt deep-sea ecology causing deoxygenation, acidification, and eutrophication (see Table 1) [4, 6, 7]. Note that sinking all the seaweed being cultivated globally presently would only remove 0.002 $GtCO_2$/yr [7]. These risks are similar for seaweed farming, though the main concerns are over-competition with other photosynthetic biomass, entangling marine life, and disease risks [7]. The lower estimates for acid stripping CO_2 and base addition via electrochemical methods are based on converting global desalination efforts into these forms of eChem mCC and mCDR, respectively [4, 13]. Generally, all scales of injecting CO_2 into the water column and AU are considered hazardous, whereas all scales of subseafloor CO_2 injection (in the seabed and basalt reservoirs) are considered to be low risk due to the low biological activity at the depths in the seabed where these

methods would be implemented and the low risks of leakages [3, 4, 5, 9, 10, 38, 39]. Though multiple papers in seabed and basalt sequestration considered their global scales to be unlimited, the maximum estimated scale possible was set equal to the maximum estimate for water column CO_2 injection since this was the largest numerical value determined [4, 9, 10, 38]. The scales of aquifer, seabed, and basalt sequestration below 10 $GtCO_2$/yr were limited to regional locations, such as the United States Exclusive Economic Zone [9, 10, 31, 38, 39].

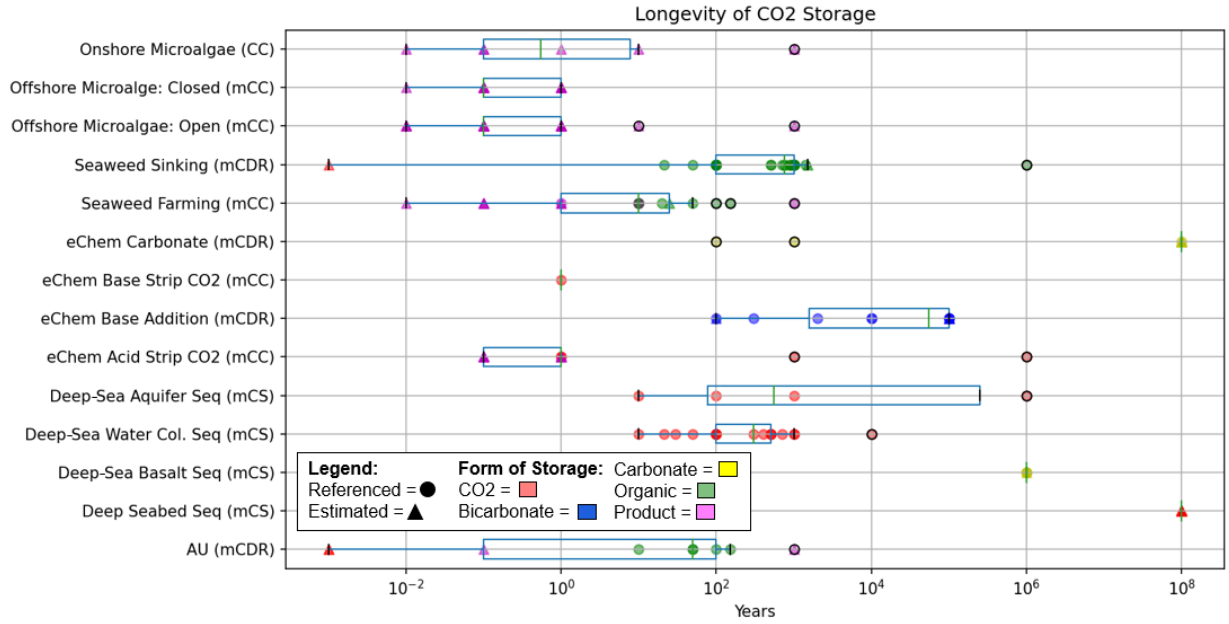

Figure A-2. Longevity of CO_2 storage by the mCDR, mCC, and mCS methods.

Figure A-2 shows the referenced and estimated values for the longevity of CO_2 storage found in this report. The length of time that CO_2 could be kept out of the atmosphere by these methods was largely dependent on the form that this CO_2 took because of the strategy. Like the estimations for scale in Figure A-1, for the cases where CO_2 would be released into the atmosphere rather than stored by the method, the value was estimated to be 0.001 years and the form is listed as CO_2. Microalgae and seaweed farming generally resulted in converting CO_2 into products since they are mCC methods. The estimates for the lifetimes of these products were informed by Rose, who considered biofuels to last from months to years, food to last from days to months, building materials that last decades, and biochar to last about 1,000 years [71]. Since AU can be used to improve seaweed growth that can later be used for biofuel or biochar, these estimates were used for this category as well [23, 71]. The organic category of storage refers to the biomass grown that absorbed CO_2 and was then sunk by the method. Estimates for seaweed sinking varied depending on the location the biomass was sunk at, and the organic data points for seaweed farming are representative of the recalcitrant carbon or fibrous tissue that falls from seaweed as it grows and can sequester some CO_2 [4, 6, 7, 37, 70, 72]. AU and seaweed farming were also considered to be methods that enhance upper ocean productivity and therefore the biological pump, so estimates from Siegel et al. were included for these categories [37]. Carbonates were generally considered to be permanent or stable for periods on the order of hundreds of millions of years by electrochemical methods [4, 14, 15, 28, 65, 73, 74]. However, for carbonates created during basalt sequestration, the longevity is on the order of millions of years [9, 60, 75]. eChem mCC methods such as acid and base stripping remove CO_2 from the ocean itself, and after a year the ocean

equilibrates with the atmosphere [14, 28]. The CO_2 captured can be used as synthetic fuel, in which case the estimate used for biofuel from Rose was used for this category, or sequestered via deep-sea storage, which is represented by the two outliers above 10 years for eChem acid stripping CO_2 [21, 26, 71, 74]. Generally, bicarbonate can store CO_2 in the ocean for about 100,000 years at most; however, this estimate can be as low as a few hundred years, which is especially the case for the method that also injects acid into the ocean where the longevity of storage increases the deeper the acid is injected into the ocean [4, 11, 12, 42, 46, 54, 64, 74]. In deep-ocean storage, CO_2 is typically stored as a liquid or a hydrate due to the intense pressures of the deep sea, but longevity of this CO_2 varies with location and depth [10, 30, 31, 37, 76]. Seabed sequestration was generally considered to be permanent, so long as the sediment was not fractured; therefore, the 100-million-year estimate, which was the maximum found in this study across all categories, was used for this subcategory [10, 38, 39, 40, 76, 77]. The details of these estimations and assumptions are in Section A.2.

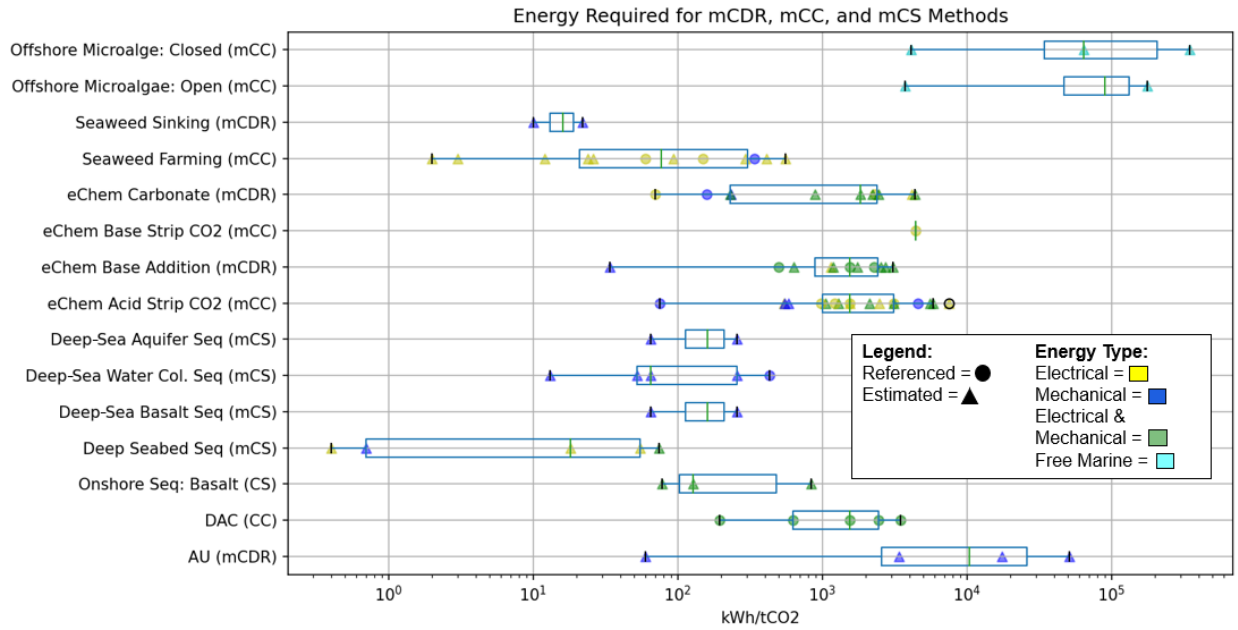

Figure A-3. Energy required for the mCDR, mCC, and mCS methods normalized by tons of CO_2.

Figure A-3 shows the referenced and estimated values of the energy needs found in this report. Direct air capture (DAC) and onshore basalt sequestration were included in the graph for comparison since they are more developed forms of CC and CS and can therefore be used as benchmarks for the mCC and mCS methods. The sum of their energy requirements can also be used as a benchmark for the mCDR methods [9, 13, 25]. These thresholds were used in Figures 7, 8, and 9. Note that besides DAC and some of the eChem mCDR and mCC methods, this normalized energy was largely not referenced in the literature. As a result, estimations were made using assumptions for the mass of CO_2 absorbed by a mass of biomass for the biological methods or unit conversions for the eChem strategies. The details of these estimations and assumptions are in Section A.2 and Table A-2. The energy types included in this graph include electrical, mechanical, electrical and mechanical, and free marine. The free marine energy type refers to how offshore microalgae methods can use waves—and for one device, currents as well—to mix their algal cultures, which improves yields [16, 17, 18, 22, 48]. These bioreactors do not need a marine energy device to provide power for them since they only require the shaking that is induced by

ambient marine energy [16, 17, 18, 22, 48]. However, the estimations for the energy they require per ton of CO_2 were included as a way of understanding the efficiency of these methods at capturing CO_2. The mechanical energy for seaweed sinking refers to energy needed to pump the seaweed to depth [32]. The electrical energy for seaweed farming refers to the energy needs for converting seaweed into biofuel or high-value products such as alginate or drying it so it can be used for feed or powering nurseries [29, 34, 78]. The mechanical energy can be used to recycle nutrients [29]. Generally the mechanical energy used for the eChem strategies was used for pretreating and pumping seawater through the systems, and the electrical energy was used to power the electrochemical processes [4, 11, 15, 25, 26, 28, 33]. However, some of the papers on the eChem methods and seabed sequestration listed the energy required for their entire systems, which included the electrical and mechanical energy requirements—this is represented by the "electrical and mechanical" energy type, and estimates for this group are in Section A.2 and specifically in Table A-2 [12, 13, 28, 42, 54, 65, 73]. The mechanical energy for the deep-sea sequestration strategies references the energy needed to compress and pump the CO_2 to depth and varied largely with the distance needed to pump the CO_2 from the capture site to the injection site [9, 27, 29, 30, 31]. Generally, the energy needed for deep-sea sequestration is solely mechanical; however, seabed sequestration can involve using "CO_2 torpedoes" or frozen blocks of CO_2 or metal containers with liquid CO_2 [27, 61]. Freezing the CO_2 into these forms also requires electrical energy, and the lowest estimate for that subcategory includes the energy needs for auxiliary power on an injection platform that could conduct this type of seabed sequestration [27]. AU has not been thoroughly proven to remove CO_2; most estimates for its capture efficiency have been extrapolated by the increase in signs of photosynthesis such as higher concentrations of chlorophyll a in the surrounding waters [3, 4, 24]. The estimates for this category were largely informed by the proposed increase in biomass due to the mechanical or pumping energy provided by the AU devices. However, in one study AU was used to improve seaweed growth, and seaweed farms were compared with and without AU [23]. That study resulted in an estimate of about 17,500 kWh/tCO_2 which was on a similar scale as some of the other estimates for the category.

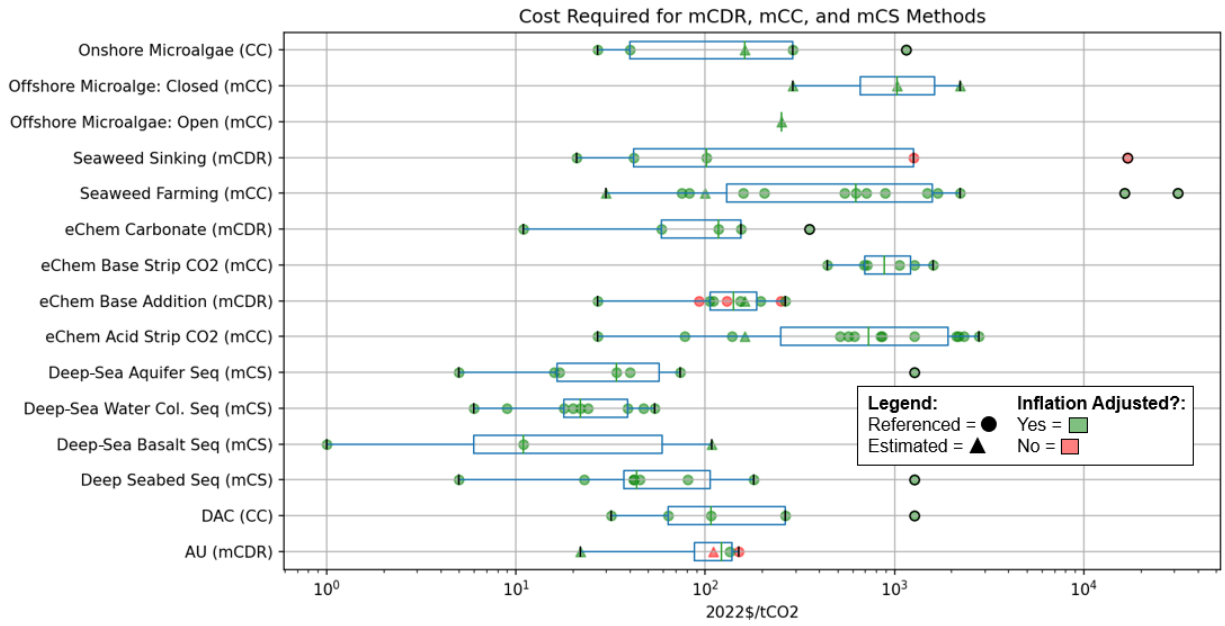

Figure A-4. Cost required per ton of CO_2 captured by the mCDR, mCC, and mCS strategies in 2022 dollars.

Figure A-4 shows the referenced and estimated values of the cost of the mCDR, mCC, and mCS methods found in this report. Since most of the reported costs for these methods were from papers prior to 2022, the costs were adjusted for inflation using the U.S. Bureau of Labor Statistics Consumer Price Index Inflation Calculator. The tool enables the user to input the cost of an item for a given month and year and adjust the price for inflation [53]. For consistency, December was chosen as the month for both 2022 and the years of the costs needed to be adjusted. The estimates used for the costs were mostly done in cases where the source said that the cost of capture was greater or less than a certain value, in which case rough estimates were made to illustrate this information in the graph [1, 4, 41]. For the biological methods, sometimes the cost would be in terms of the mass of the biomass produced, so the assumptions for the mass of CO_2 absorbed per mass of biomass that were applied in the energy estimations were used for these estimates as well [79, 80, 81]. The details of these estimations and assumptions are in Section A.2. Generally, the costs for the biological methods varied with the species cultivated and the location [6, 7]. The costs for eChem mCDR and mCC strategies varied depending on if H_2 was produced and sold or if the system could be integrated into existing infrastructure such as desalination plants, which would lower the overall cost of capture [14, 15, 42, 54]. The costs of deep-sea sequestration tended to vary with the distance from the CO_2 capture site to the injection site [30]. The cost estimates for subseafloor basalt sequestration included a very rough estimate since one of the sources claimed that it would be much greater than \$50/tCO_2. Without context for what the cost could be, it was assumed to be roughly \$100/tCO_2 [41]. DAC was included in this figure to compare the current costs for this more developed form of onshore CDR with the mCDR strategies [9, 25]. The cost estimates for AU were from review papers that made rough estimates themselves [1, 4].

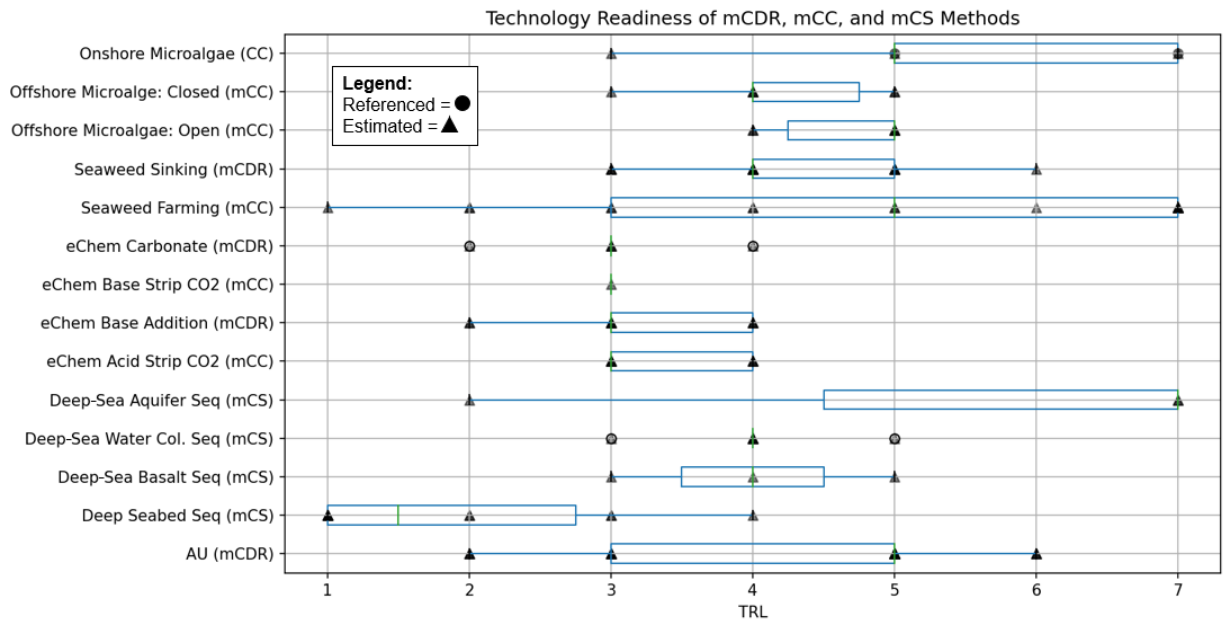

Figure A-5. The technology readiness levels (TRLs) of the mCDR, mCC, and mCS strategies.

Figure A-5 shows the referenced and estimated values of TRLs found in this report. The framework for determining the TRL for each study was modified from that used in the Australian Renewable Energy Agency's report on the TRLs for Renewable Energy Sectors and the DOE's Technology Readiness Assessment Guide [82, 83]. Generally the methodology was that TRL 1 represented a conceptual idea, TRL 2 was for preliminary modeling studies, TRL 3 was for preliminary experimental studies and/or large-scale and/or global models informed by experimental data, TRL 4 was for experimental studies done on larger scales, TRL 5 was for preliminary field testing, TRL 6 was for larger-scale field testing, and TRL 7 was for systems that were operational at or near scale and to refer to small industries such as seaweed farming (which is small in comparison to the scale needed to reach significant CO_2 capture) [1, 4, 72, 82]. Note that these TRL estimates come from sources that span a range of years. The main reason why the seabed sequestration category has multiple sources at TRL 1 is because they are mostly from the late 1990s when this concept was in its earliest stages [27, 55, 76, 77]. Onshore microalgae cultivation is generally at a higher TRL than offshore because offshore microalgae farming is a much newer concept [22]. Seaweed sinking is still largely at an experimental validation stage, but there has been some field testing [32]. The large range for seaweed farming reflects that while there is a small industry for this field, there are still efforts investigating how to scale it up further to increase its CO_2 capture potential at varying TRLs, such as using robotic harvesting, which is only at a conceptual stage [1, 4, 29, 72, 79, 84]. Generally, the eChem mCDR and mCC strategies were at TRL 3 due to their preliminary experimental tests or global modeling; however, some used large enough volumes of seawater and brine to be considered at TRL 4 [1, 14, 21, 25, 26, 28, 33, 42, 54]. While no examples of field tests were found, there were experimental studies assessing the environmental impacts of base addition to the ocean [56, 85]. Deep-sea sequestration in undersea aquifers is currently being done at megaton scales of CO_2, so generally it is at TRL 7, but there are still modeling studies being done to assess how to scale these operations [31, 39]. Other deep-sea sequestration methods are generally at TRL 4 since more environmental and experimental studies are needed before deploying them [9, 30, 38, 39, 40, 41, 60]. AU has largely involved modeling studies and short-lived field deployments with varying levels of success [1, 4, 5, 23, 24, 35, 36, 37, 59, 86] [87, 88].

A.2 Estimations for mCDR, mCC, and mCS Attributes Independent of Marine Energy

This section describes every estimation made in this report to determine attributes about the mCDR, mCC, and mCS methods alone without considering marine energy or other offshore energy sources. These attributes include the energy required, anticipated full scale, cost, longevity of CO_2 storage, and TRL: their values and how they were determined are shown in the table below.

Table A-1. Estimations for Figures 6, 7, and 11 and A-1 to A-5

Method	Source	Estimate For?	Estimate Value	Process
Microalgae: Offshore Open (mCC)	[16]	Energy/tCO_2	3.73–176 MWh/ tCO_2	Between 1.6 to 2 grams of CO_2 is captured per gram of microalgae produced [68] 1 gBiomass ~ 1.8 gCO_2 Max productivity was 18.9 gBiomass/m^2 per day [16] 18.9 gBiomass/m^2 per day = 34.02 gCO_2/m^2 per day or 1.42 $gCO_2/m^2/h$ 53 to 2,500 W/m^3 is required for photobioreactors (PBRs) that do not use wave energy [16] A 10 m^2 size of the author's system would have a volume of 1,000 L or 1 m^3, meaning it would need 53–2,500 W for mixing or 5.3–250 W/m^2 [16] 5.3–250 W/m^2 / 1.42 $gCO_2/m^2/h$ = 3.73–176 Wh/gCO_2 = 3.73–176 MWh/tCO_2 (assuming max productivity)
eChem Base Addition (mCDR)	[11]	Energy/tCO_2	Bipolar membrane electrodialysis (BPMED): 1,146 kWh/tCO_2 Pump: 34 kWh/tCO_2	BPMED: 180 kJ/mol [11] Pump: 5.4 kJ/mol (requires 3% of electrodialysis (ED) energy) [11] 1 kJ = 0.00028 kWh 1 tCO2 = 22,730 mol CO_2 BPMED: 1,146 kWh/tCO_2 Pump: 34 kWh/tCO_2
AU (mCDR)	[3]	Energy/tCO_2	3,400–51,000 kWh/tCO_2	Power required is from 200 W to 3 kW [3] Generally on order of kW for depths of about 400 to 1,200 m [3] System sequestered a partial pressure of 40 micro-atmospheres of CO_2 [3] Using an online partial pressure calculator with input of about 4 Pa the concentration of CO_2 (using Henry's Law) is 1.34×10^{-6} mols/L [89]

Method	Source	Estimate For?	Estimate Value	Process
				The flow rate of the pump is 1,000 m^3 per hour or 1,000,000 L/h or 1.34 mols CO_2/h [3] 59 g of CO_2/ h or 59×10^{-6} tCO_2/h divided by the required power is: 3,400 to 51,000 kWh/tCO_2
AU (mCDR)	[24]	Energy/tCO_2	60 kWh/tCO_2	Pump requires 60 kW and primary production increased by 6,600 kgC/d due to AU [24] 1 kgC/d × 365 d/yr × 1 tC/1000 kgC × 3.67 tCO_2/tC = 1.3396 tCO_2/yr Continuous operation so 1,440 kWh in a day from the 60 kW pump [24] 1,440 kWh to capture 6.6 tC or 24.2 tCO_2 or 60 kWh/tCO_2
eChem Acid Stripping CO_2 (mCC)	[33]	Energy/tCO_2	1,540.2 kWh/tCO_2	242 kJ/mol CO_2 stripped required (only for electrodes, not including pump and vacuum) [33] 1 kJ = 0.00028 kWh 1 tCO_2 = 22,730 mol CO_2 1,540.2 kWh/tCO_2
eChem Acid Stripping CO_2 (mCC)	[28]	Energy/tCO_2	Total: 3,131 kWh/tCO_2 BPMED: 2,485 kWh/tCO_2 Pumps: 550 kWh/tCO_2	7,202 tCO_2/yr removed using 22.55 GWh/yr (not including pretreatment and filtering since assumed to be done by reverse osmosis (RO) plant) [28] They estimated CO_2 capture at 20 kmol CO_2/h since it matches flow rate of typical midsized desal plant [28] 1 GWh = 1,000,000 kWh 3,131 kWh/ tCO_2 17.9 GWh/yr required for BPMED or 2,485 kWh/tCO_2 [28] 3.96 GWh/yr required for pumps or 550 kWh/tCO_2 [28]
eChem Carbonate Production (mCDR)	[28]	Energy/tCO_2	Total: 4,386 kWh/tCO_2 BPMED: 4,151 kWh/tCO_2 Pumps: 233.7 kWh/tCO_2	7,202 tCO_2/yr removed using 31.59 GWh/yr (not including pretreatment and filtering since assumed to be done by RO plant) [28] 1 GWh = 1,000,000 kWh 4,386 kWh/tCO_2 total 29.9 GWh/yr required for BPMED or 4,151 kWh/tCO_2 [28] 1.68 GWh/yr required for pumps or 233.7 kWh/tCO_2 [28]

Method	Source	Estimate For?	Estimate Value	Process
eChem Base Addition (mCDR)	[12]	Energy/tCO_2	636.44–2,545.76 kWh/tCO_2	100–400 kJ/mol CO_2 required [12] 1 kJ = 0.00028 kWh 1 tCO_2 = 22,730 mol CO_2 636.44 to 2,545.76 kWh/tCO_2
eChem Acid Stripping CO_2 (mCC)	[26]	Energy/tCO_2	RO and electrolysis to make H_2: 7,500 kWh/tCO_2 BPMED: 1,540 kWh/tCO_2 Pumping: 583 kWh/tCO_2 MeOH Production: 542 kWh/tCO_2	2.4 tCO_2/h removed by floating solar island [26] 18 MW for RO and electrolysis to make H_2 7.5 MWh/tCO_2 for RO and electrolysis to make H_2 3.7 MW for ED cells [26] 1.54 MWh/tCO_2 for ED cells 1.4 MW for pumping [26] 583 kWh/tCO_2 for pumping 1.3 MW for MeOH production [26] 542 kWh/tCO_2 for MeOH production
eChem Base Addition (mCDR)	[42]	Energy/tCO_2	2,711–3,061 kWh/tCO_2 (experimental) 1,744 kWh/tCO_2 (scaled: efficiency increased from ~30% to ~>50%)	426–481 kJ/mol CO_2 (experimental) [42] 1 kJ = 0.00028 kWh 1 tCO_2 = 22,730 mol CO_2 2,711–3,061 kWh/tCO_2 (experimental) < 274 kJ/mol CO_2 (scaled efficiency increasing from ~30% to ~>50%) [42] 1,744 kWh/tCO_2 (scaled: efficiency increased from ~30% to ~>50%)
eChem Carbonate Production (mCDR)	[65]	Energy/tCO_2	2,024 +/- 185 kWh/tCO_2	318 +/- 29 kJ/mol $CaCO_3$ precipitated [65] Assuming 1:1 ratio for CO_2 and $CaCO_3$ [65] 318 +/- 29 kJ/mol CO_2 (captured since pH increases overall) [65] 1 kJ = 0.00028 kWh 1 tCO_2 = 22,730 mol CO_2 2,024 +/- 185 kWh/tCO_2
eChem Carbonate Production (mCDR)	[73]	Energy/tCO_2	890 kWh/tCO_2	0.89 kWh/$kgCO_2$ fixed [73] 1,000 kg = 1 t 890 kWh/tCO_2 fixed
AU (mCDR)	[23]	Energy/tCO_2	17,476 kWh/tCO_2	Large scale estimate: 14.8 ktC additional CO_2 capture by the AU enhancing seaweed growth over 442 km^2 area [23] 33.5 tC/km^2

Method	Source	Estimate For?	Estimate Value	Process
				Experimental area = 70 m × 120 m = 8400 m^2 or 0.0084 km^2 [23] 0.2814 tC captured 1tC = 3.67 tCO_2 1.03 tCO_2 captured Energy/ Power = 60 kW each day [23] Length of operations = 5 months = 150 days [23] Worked continuously for 2 hours every day [23] 300 hours of operation Total energy = 18,000 kWh 17,476 kWh/tCO_2
Seaweed Sinking (mCDR)	[32]	Energy/tCO_2	9.87–22.05 kWh/tCO_2	Used the paper's equation for FC_{pump} (below eq 8) & their values for the parameters in that equation [32] FC_{pump} = 8.06 L diesel/tDrySeaweed They estimated that sinking seaweed would reduce CO_2 emissions from decomposition by 1.36 to 3.03 tCO_2/tDrySeaweed [32] Assuming 10.6 kWh/L diesel and diesel efficiency of 35% [32, 90] 8.06 L diesel/tDrySeaweed × 10.6kWh/L diesel × 1 tDrySeaweed/1.36–3.03tCO_2 × 35% = 9.87–22.05 kWh/tCO_2
Seaweed Farming (mCC)	[34]	Energy/tCO_2	26.4 kWh/tCO_2 for powering seaweed nursery lab 554 kWh/tCO_2 to make biogas 412 kWh/tCO_2 to make biogas and bioethanol	30 kWh of electricity needed per ton of dry seaweed in laboratory seaweed nursery (illumination and pumping) [34] 1.14 tCO_2/tDrySeaweed [34] 26.4 kWh/tCO_2 absorbed For processing into biogas: total energy consumption = 630 kWh/tDrySeaweed [34] 554 kWh/tCO_2 absorbed For making biogas and bioethanol 469 kWh/tDrySeaweed [34] 412.5 kWh/tCO_2 absorbed
Seaweed Farming (mCC)	[78]	Energy/tCO_2	Drying seaweed for food production: 2.06–12.3 kWh/tCO_2	Used the energy estimates from tables 9.2–9.4 divided by the tons of raw seaweed considered (4.5 tons) [78] Drying seaweed for food production:

Method	Source	Estimate For?	Estimate Value	Process
			Producing biofuel: 2.7–23.8 kWh/tCO_2 Producing alginate: 92.6–292.9 kWh/tCO_2	21.1–130 kWh/tRawSeaweed [78] Producing biofuel: 27.6–244 kWh/tRawSeaweed [78] Producing alginate: 947.55–2,996 kWh/tRawSeaweed [78] tRawSeaweed = ~9 × tDrySeaweed [91] Drying seaweed for food production: 2.34–14 kWh/tDrySeaweed Producing biofuel: 3.1–27.1 kWh/tDrySeaweed Producing alginate: 105.3–333 kWh/tDrySeaweed 1.14 tCO_2/tDrySeaweed [34] Drying seaweed for food production: 2.06–12.3 kWh/tCO_2 Producing biofuel: 2.7–23.8 kWh/tCO_2 Producing alginate: 92.6–292.9 kWh/tCO_2
Microalgae: Offshore Closed (mCC)	[18]	Energy/tCO_2	348 MWh/tCO_2	The minimum power is equivalent to the minimum force multiplied by the minimum velocity of the rotating bioreactor [18] $P_{min} = F_{min} \times v_{min}$ F_{min} = 34.68 N [18] v_{min} = 0.81 m/s [18] P_{min} = 28.1 W Biomass productivity = 3.1 g/m^2/d = 0.13 g/m^2/h = 0.2325 gCO_2/m^2/h [18] Between 1.6 and 2 grams of CO_2 is captured per gram of microalgae produced [68] Avg 1.8 gCO_2 = 1 gBiomass Area = 0.3478 m^2 [18] 0.081 gCO_2/h 348 Wh/gCO_2 348 MWh/tCO_2
Microalgae: Offshore Closed (mCC)	[17]	Energy/tCO_2	4.1–64.52 MWh/tCO_2	Power input = 57.6–903.3 W/m^3 = 0.0576–0.9033 W/L [17] Biomass productivity = 0.187 g/L/day = 0.0078 g/L/h [17]

Method	Source	Estimate For?	Estimate Value	Process
				Between 1.6 and 2 grams of CO_2 is captured per gram of microalgae produced [68] Avg 1.8 gCO_2 = 1 gBiomass 0.014 gCO_2/L/h 4.1–64.52 Wh/gCO_2 4.1–64.52 MWh/tCO_2
Deep-Sea Aquifer Sequestration (mCS)	[31]	Energy/tCO_2	65–257 kWh/tCO_2	Cost of service is \$1.10–4.36/tCO_2 per 75 mi or 121 km depending on pipe diameter (smallest cost is the largest diameter (ID: 39.4 in) and vice versa (ID: 12 in for smallest diameter)) [31] Calculated energy using the detail that the cost of service is based on energy costs of \$0.07/kWh [31] 15.7–62.3 kWh/tCO_2 per 75 mi or 121 km Assuming the max distance from CO_2 capture to injection site is 500 km [30]
Deep-Sea Basalt Sequestration (mCS)	[9]	Energy/tCO_2	65–257 kWh/tCO_2	Used same estimate as was used for undersea aquifers [31]
Deep-Sea Water Column Sequestration (mCS)	[30]	Energy/tCO_2	For 100 km: 13–51.5 kWh/tCO_2 For 500 km: 65–257 kWh/tCO_2	Used similar estimate as was used for undersea aquifers (included new estimate for the 100 km distance) [30, 31]
Deep-Sea Seabed Sequestration (mCS)	[27]	Energy/tCO_2	Freezing liquid CO_2: ~55 kWh/tCO_2 Thrusters for marine platform: 18.3 kWh/tCO_2 Pumping: 0.7 kWh/tCO_2 Aux equip and living quarters: 0.4 kWh/tCO_2	Making one 540-ton penetrator (which is 64% solid CO_2 and 36% liquid CO_2) per hour would take 30 MW [27] ~55 kWh/tCO_2 Freezing CO_2 takes 86 kW per ton of liquid CO_2 (penetrator = 64% solid CO_2) so 55 kWh/tCO_2 [27] Need 10 MW to power self-positioning thrusters for marine platform (1/3 of energy as freezing CO_2) [27] 200 kW for pumping fluids to platform reservoirs, 50 kW to pump liquid CO_2 from storage buoyancy reservoirs and distributing it throughout the production plant, 200 kW for the auxiliary equipment and living quarters [27] Thrusters = 55/3 = 18.3 kWh/tCO_2

Method	Source	Estimate For?	Estimate Value	Process
				Pumping = 0.25/30 × 55 = 0.7 kWh/tCO_2 Auxiliary equipment & living quarters = 0.2/30 × 55 = 0.37 kWh/tCO_2
Deep-Sea Water Column Sequestration (mCS)	[30]	Full Scale	0.37 $GtCO_2$/yr 3 $GtCO_2$/yr 30 $GtCO_2$/yr	Injecting 0.37 $GtCO_2$/yr for 100 years would reduce pH by < 0.3 over 0.01% of ocean volume, but if 10% of excess CO_2 (avg. 3 $GtCO_2$/yr) was stored in the ocean by 2100, there would be significant changes in pH (reduction of > 0.5 pH) over ~1% of the ocean volume (or reduction of < 1.5 pH in 0.01% of ocean), 100% of excess CO_2 stored in the ocean via this method (avg 30 $GtCO_2$/yr) results in a reduction of 2 pH in 0.1% of ocean to < 1.5 pH in 1% of ocean [30] Note that the total for excess emissions is based on how the authors anticipate 18,000 $GtCO_2$ of emissions from the year 1850 to 2450, with a maximum of 90 $GtCO_2$/yr in 2150 if 100% of emissions are pumped into deep-sea, or an average of 30 $GtCO_2$/yr taken from Figure 9 of Kheshgi et al. (this average assumes that the profile of emission rate is symmetric) [30, 92] Since moderate pH changes (0.1–0.3) are expected to cause long-term chronic issues for deep-sea fauna injecting 0.37 $GtCO_2$/yr for 100 years would create these conditions in < 1% of the total ocean volume (but changes of 0.2–0.4 pH will likely happen anyway if atmospheric CO_2 concentrations reach 550 ppm) [30]. Injecting ~3 $GtCO_2$/yr (10% of anticipated) would create these hazardous conditions in ~1–10% of the ocean and injecting ~30 $GtCO_2$/yr (100% of anticipated) would create these changes (0.3 pH) in most of the ocean [30]. Overall, a scale of 0.1–1 $GtCO_2$/yr is relatively safe since it would impact < 1% to 1–10% of sea.
Microalgae: Offshore Open (mCC)	[48]	Full Scale	0.0033 $GtCO_2$/yr	Average biomass productivity appears to stay constant as system scales from 1 m^2 to 10 m^2 (6.6 gBiomass/m^2/d) [48]

Method	Source	Estimate For?	Estimate Value	Process
				6.6 gBiomass × 1.8 gCO_2/gBiomass [22, 68] = 11.88 $gCO_2/m^2/d$ 365 days in 1 year 4,336 $gCO_2/m^2/yr$ = 4.3 $tCO_2/m^2/yr$ 1 km^2 = 1,000,000 m^2 4.3 $MtCO_2/yr/km^2$ 1 $GtCO_2$ = 1,000 $MtCO_2$ 1,000 L volume for their 10 m^2 system and assuming that ratio is consistent in 1 km^2 there is 100,000,000 L [48] Bicarbonate is necessary for these algal cultures and the bicarbonate concentration with the highest productivity is 0.3 mol/L which translates to 30,000,000 mol/km^2 [48] The area needed to capture 1 $GtCO_2$/yr would be ~233 km^2 and would require 7 Gmol of bicarbonate which could be made from 300 $GtCO_2$, assuming a 1:1 CO_2 to bicarbonate ratio Note that the bicarbonate regenerates itself through this method so theoretically it would only need to be supplied once [48] Assuming 1 $GtCO_2$ can be converted into bicarbonate for this method then the maximum scale is limited to 3.3 $MtCO_2$/yr
Microalgae: Offshore Open & Closed (mCC)	[80]	Cost/tCO_2 (Prior to Inflation Adjustment)	Open (Using Bicarbonate): \$254/tCO_2 Closed (Using CO_2): \$890/tCO_2	Using bicarbonate: microalgae production cost is \$0.4/kgMicroalgae [80] or \$0.22/$kgCO_2$ since 1.8 gCO_2 = 1 gMicroalgae [22, 68] or ~\$220/tCO_2 Using CO_2: \$1.60/kgMicroalgae or ~\$890/tCO_2 [80]
Microalgae: Offshore Closed (mCC)	[81]	Cost/tCO_2 (Prior to Inflation Adjustment)	\$289–2,221/tCO_2	The authors' system had a cost of \$0.42/kgDryCell vs \$3.19/kgDryCell cost for the most expensive other system they listed [81] Therefore, the cost range for these methods is \$0.23-1.77/$kgCO_2$, since 1 kgDryCell = 1.8 $kgCO_2$ [81]
Seaweed Farming (mCDR)	[79]	Cost/tCO_2 (Prior to Inflation Adjustment)	\$26–100/tCO_2	The cost for this method was \$30 to hundreds of dollars per ton of dry seaweed depending on the ability of the smart towing system to bring the seaweed to nutrient rich water, smart

Method	Source	Estimate For?	Estimate Value	Process
				monitoring systems, and the level of yield [79] Given that 1.14 tCO_2/tDrySeaweed [34] = ~\$26–100/tCO_2 (for simplicity the hundreds of dollars were set to a hundred)
AU (mCDR)	[4]	Cost/tCO_2 (Prior to Inflation Adjustment)	\$110–150/tCO_2	Range was > \$100–150/tCO_2 and it was assumed that the minimum value was about \$110/tCO_2 [4]
AU (mCDR)	[1]	Cost/tCO_2 (Prior to Inflation Adjustment)	\$20–125/tCO_2	Range was < \$25–125/tCO_2 and it was assumed that the minimum value was about \$20/tCO_2 [1]
Deep-Sea Basalt Sequestration (mCS)	[41]	Cost/tCO_2 (Prior to Inflation Adjustment)	\$100/tCO_2	Stated to be much greater than \$50/tCO_2 so it was assumed to be \$100/tCO_2 [41]
eChem Acid Stripping CO_2 (mCC)	[1]	Cost/tCO_2 (Prior to Inflation Adjustment)	\$25–150/tCO_2	Range was \$25 to > \$125/tCO_2 and it was assumed that the maximum value was \$150/tCO_2 [1]
eChem Base Addition (mCDR)	[1]	Cost/tCO_2 (Prior to Inflation Adjustment)	\$25–150/tCO_2	Range was \$25 to > \$125/tCO_2 and it was assumed that the maximum value was \$150/tCO_2 [1]
Microalgae: Onshore (mCC)	[1]	Cost/tCO_2 (Prior to Inflation Adjustment)	\$25–150/tCO_2	Range was \$25 to > \$125/tCO_2 and it was assumed that the maximum value was \$150/tCO_2 [1]
AU (mCDR)	[4]	Full Scale	0.00001 $GtCO_2$/yr	Since full scale can cause outgassing or release of CO_2, but 0 or negative numbers cannot be included on a log scale like the one used in Figure A-1, this estimate was used [4]
AU (mCDR)	[5]	Full Scale	0.00001 $GtCO_2$/yr	Found that AU could release 9.62 $MtCO_2$/yr into the air over 100 years if done regionally in Alaska [5]. Since 0 or negative numbers cannot be included on a log scale like the one used in Figure A-1 this estimate was used [5]
Deep-Seabed Sequestration (mCS)	[10]	Full Scale	30 $GtCO_2$/yr	Considered to be unlimited by the authors so to represent this the largest estimated scale (which was determined to be 30 $GtCO_2$/yr for

Method	Source	Estimate For?	Estimate Value	Process
				water column CO_2 injection) was used [10, 30, 92]
Deep-Seabed Sequestration (mCS)	[38]	Full Scale	30 $GtCO_2$/yr	Considered to be unlimited by the authors, so to represent this the largest estimated scale (which was determined to be 30 $GtCO_2$/yr for water column CO_2 injection) was used [30, 38, 92]
Deep-Sea Basalt Sequestration (mCS)	[9]	Full Scale	30 $GtCO_2$/yr	Considered to be unlimited by the authors so to represent this the largest estimated scale (which was determined to be 30 $GtCO_2$/yr for water column CO_2 injection) was used [9, 30, 92]
eChem Base Addition (mCDR)	[1]	Full Scale	11.1 $GtCO_2$/yr	The source lists the scale at > 5 so the next highest estimate or reference above 5 for this method was used [1, 11]
Seaweed Farming (mCC) & Sinking (mCDR) in General	[1]	Full Scale	5.1 $GtCO_2$/yr	The source lists the scale at > 5 so the next highest estimate or reference above 5 for this method was used [1, 7]
Seaweed Sinking (mCDR)	[70]	Full Scale	0.00001 $GtCO_2$/yr	CO_2 could be released overall due to an increase in growth of calcifying organisms or from taking nutrients from phytoplankton [70]. Since 0 or negative numbers cannot be included on a log scale like the one used in Figure A-1 this estimate was used
Seaweed Farming (mCC)	[71]	Longevity of CO_2 Storage	Building materials, textiles, and packaging: 10 years Biochar: 10–1,000 years Food: 0.01–0.1 years Biofuel: 0.1–1 years	Rose estimated the longevity of different products made of seaweed: [71] For building materials, textiles, and packaging this estimate was for decades which for this analysis was set to 10 years For biochar the storage time was from decades to thousands of years which was set to 10–1,000 years for this analysis Food was considered to store carbon on a time scale from days to months which was approximated to be 0.01 to 0.1 years since 1/365 = 0.003 and 3/365 ~ 0.01 and 1/12 = 0.08 Biofuel was considered to have a longevity from months to years so the estimated range was 0.1–1 years

Method	Source	Estimate For?	Estimate Value	Process
AU (mCDR)	[5]	Longevity of CO_2 Storage	0.001 years	CO_2 could be released overall and since 0 or negative numbers cannot be included on a log scale like the one used in Figure A-2 this estimate was used [5]. 0.001 years was specifically chosen because it was a factor of 10 lower than the lowest estimate which was determined from Rose's work [71]
AU (mCDR)	[4]	Longevity of CO_2 Storage	0.001 years	Since CO_2 could be released overall and since 0 or negative numbers cannot be included on a log scale like the one used in Figure A-2 this estimate was used [4]; 0.001 years was specifically chosen because it was a factor of 10 lower than the lowest estimate which was determined from Rose's work [71]
AU (mCDR)	[23]	Longevity of CO_2 Storage	0.1–1,000 years	Since the seaweed grown due to AU would be converted into biofuel and biochar the minimum and maximum of both ranges from Rose, respectively, were used for the sequestration range [23, 71]
Deep-Seabed Sequestration (mCS)	[10]	Longevity of CO_2 Storage	100,000,000 years	Considered to be permanent so used the highest estimate for CO_2 storage out of all the methods [4, 10]
Deep-Seabed Sequestration (mCS)	[38]	Longevity of CO_2 Storage	100,000,000 years	Considered to be permanent so used the highest estimate for CO_2 storage out of all the methods [4, 38]
Deep-Seabed Sequestration (mCS)	[39]	Longevity of CO_2 Storage	100,000,000 years	Considered to be permanent so used the highest estimate for CO_2 storage out of all the methods [4, 39]
Deep-Seabed Sequestration (mCS)	[40]	Longevity of CO_2 Storage	100,000,000 years	Considered to be permanent so used the highest estimate for CO_2 storage out of all the methods [4, 40]
Deep-Seabed Sequestration (mCS)	[76]	Longevity of CO_2 Storage	100,000,000 years	Considered to be permanent so used the highest estimate for CO_2 storage out of all the methods [4, 76]
Deep-Seabed Sequestration (mCS)	[77]	Longevity of CO_2 Storage	100,000,000 years	Considered to be permanent so used the highest estimate for CO_2 storage out of all the methods [4, 77]
Deep-Sea Basalt Sequestration (mCS)	[41]	Longevity of CO_2 Storage	1,000 years	Considered to be long term so used the estimate from Goldberg et al. since this also involves CO_2 storage as carbonate in basalt reservoirs [9, 41]

Method	Source	Estimate For?	Estimate Value	Process
eChem Acid Stripping CO_2 (mCDR)	[33]	Longevity of CO_2 Storage	0.1–1 years	Since the CO_2 would be converted into fuel used the same estimate as for biofuel from Rose [33, 71]
eChem Acid Stripping CO_2 (mCDR)	[25]	Longevity of CO_2 Storage	0.1–1 years	Since the CO_2 would be converted into fuel used the same estimate as for biofuel from Rose [25, 71]
eChem Acid Stripping CO_2 (mCDR)	[26]	Longevity of CO_2 Storage	0.1–1 years	Since the CO_2 would be converted into fuel used the same estimate as for biofuel from Rose [26, 71]
eChem Acid Stripping CO_2 (mCDR)	[21]	Longevity of CO_2 Storage	0.1–1 years	Since the CO_2 would be converted into fuel used the same estimate as for biofuel from Rose [21, 71]
eChem Base Addition (mCDR)	[11]	Longevity of CO_2 Storage	100,000 years	When using acid pumping at > 3km depth ~40% of CO_2 is considered permanently sequestered, which since the end form is bicarbonate the max estimate for bicarbonate storage was used [4, 11]
eChem Base Addition (mCDR)	[11]	Longevity of CO_2 Storage	100 years	With shallow acid pumping (< 2km depth) the carbon is retained for only a few hundred years [11]
eChem Base Addition (mCDR)	[54]	Longevity of CO_2 Storage	100,000 years	Create bicarbonate which has a lifespan of about 100,000 years [4, 54]
eChem Base Addition (mCDR)	[42]	Longevity of CO_2 Storage	100,000 years	Create bicarbonate which has a lifespan of about 100,000 years [4, 42]
eChem Carbonate Production (mCDR)	[28]	Longevity of CO_2 Storage	100,000,000 years	Form carbonates which are considered to have permanent storage or a lifetime of 100,000,000 years [4, 28]
eChem Carbonate Production (mCDR)	[14]	Longevity of CO_2 Storage	100,000,000 years	Form carbonates which are considered to have permanent storage or a lifetime of 100,000,000 years [4, 14]
eChem Carbonate Production (mCDR)	[65]	Longevity of CO_2 Storage	100,000,000 years	Form carbonates which are considered to have permanent storage or a lifetime of 100,000,000 years [4, 65]
eChem Carbonate Production (mCDR)	[73]	Longevity of CO_2 Storage	100,000,000 years	Form carbonates which are considered to have permanent storage or a lifetime of 100,000,000 years [4, 73]

Method	Source	Estimate For?	Estimate Value	Process
eChem Carbonate Production (mCDR)	[15]	Longevity of CO_2 Storage	100,000,000 years	Form carbonates which are considered to have permanent storage or a lifetime of 100,000,000 years [4, 15]
eChem Carbonate Production (mCDR)	[93]	Longevity of CO_2 Storage	100,000,000 years	Form carbonates which are considered to have permanent storage or a lifetime of 100,000,000 years [4, 93]
Seaweed Farming (mCC)	[4]	Longevity of CO_2 Storage	1–10 years	CO_2 is sequestered by the products made from the seaweed which is ≤ 10 years at best and assumed the lowest is 1 year [4]
Seaweed Farming (mCC)	[34]	Longevity of CO_2 Storage	0.1–1 years	Used biofuel estimate from Rose [71]
Seaweed Farming (mCC)	[70]	Longevity of CO_2 Storage	20–25 years	Source stated that only 2% of dissolved organic carbon is not remineralized for ≥ 20 years, used 25 years to represent the upper limit since none was provided [70]
Seaweed Sinking (mCDR)	[70]	Longevity of CO_2 Storage	1,400–1,500 years	Sinking seaweed in the North Pacific can trap CO_2 for > 1,400 years, assumed the upper limit was 1,500 years since none was provided [70]
Seaweed Sinking (mCDR)	[70]	Longevity of CO_2 Storage	0.001 years	Since CO_2 could be released overall and since 0 or negative numbers cannot be included on a log scale like the one used in Figure A-2 this estimate was used [70]. 0.001 years was specifically chosen because it was a factor of 10 lower than the lowest estimate which was determined from Rose's work [71]
Seaweed Sinking (mCDR)	[94]	Longevity of CO_2 Storage	750–800 years	Sinking seaweed below 2.1 km results in a median sequestration time of > 750 years across major parts of the North Pacific, assumed the upper limit was 800 years since none was given [94]
Microalgae: Generic (mCC)	[95]	Longevity of CO_2 Storage	Food: 0.01–0.1 years Biofuel: 0.1–1 years	Used food and biofuel estimate from Rose [71]
Microalgae: Offshore Closed (mCC)	[66]	Longevity of CO_2 Storage	0.1–1 years	Used biofuel estimate from Rose [71]

Method	Source	Estimate For?	Estimate Value	Process
Microalgae: Offshore Closed (mCC)	[81]	Longevity of CO_2 Storage	Food: 0.01–0.1 years Biofuel: 0.1–1 years	Used food and biofuel estimate from Rose [71]
Microalgae: Offshore Closed (mCC)	[43]	Longevity of CO_2 Storage	0.1–1 years	Used biofuel estimate from Rose [71]
Microalgae: Offshore Closed (mCC)	[17]	Longevity of CO_2 Storage	0.1–1 years	Used biofuel estimate from Rose [71]
Microalgae: Offshore Open (mCC)	[16]	Longevity of CO_2 Storage	Biofuel: 0.1–1 years Biochar: 10–1,000 years	Used biofuel and biochar estimates from Rose [71]
Microalgae: Offshore Open (mCC)	[96]	Longevity of CO_2 Storage	Food: 0.01–0.1 years Biofuel: 0.1–1 years	Used food and biofuel estimate from Rose [71]
Microalgae: Offshore Open (mCC)	[48]	Longevity of CO_2 Storage	0.1–1 years	Used biofuel estimate from Rose [71]
Microalgae: Offshore Open (mCC)	[80]	Longevity of CO_2 Storage	0.01–0.1 years	Used food estimate from Rose [71]
Microalgae: Offshore Open (mCC)	[57]	Longevity of CO_2 Storage	0.1–1 years	Used biofuel estimate from Rose [71]
Microalgae: Offshore Open (mCC)	[97]	Longevity of CO_2 Storage	Food: 0.01–0.1 years Biofuel: 0.1–1 years	Used food and biofuel estimate from Rose [71]
Microalgae: Onshore (CC)	[98]	Longevity of CO_2 Storage	0.1–1 years	Used biofuel estimate from Rose [71]
Microalgae: Onshore (CC)	[47]	Longevity of CO_2 Storage	0.01–0.1 years	Longevity considered to be on a weeks to months scale but has high likelihood of release so a similar estimate as was used for food from Rose [47, 71]
Microalgae: Onshore (CC)	[68]	Longevity of CO_2 Storage	10–1,000 years	Used biochar estimate from Rose [71]

Method	Source	Estimate For?	Estimate Value	Process
AU (mCDR)	[35]	TRL	5	Described an air bubble type AU that was field tested [35]
AU (mCDR)	[35]	TRL	5	Described air lift AUs that were field tested (2 lake trials and 1 sea trial) [35]
AU (mCDR)	[23]	TRL	6	5 month long experimental deployment that measured increase in seaweed growth [23]
AU (mCDR)	[36]	TRL	5	Described experimental field testing for airlift pump AU [36]
AU (mCDR)	[86]	TRL	3	Model based on experimental deployment [86]
AU (mCDR)	[35]	TRL	5	Field testing of brackish uplift AU described [35]
AU (mCDR)	[99]	TRL	3	Experimental and modeling study [99]
AU (mCDR)	[36]	TRL	5	Experimental field testing of current powered AU [36]
AU (mCDR)	[35]	TRL	6	Electric pump AU that operated for more than 2 years without serious damage [35]
AU (mCDR)	[37]	TRL	3	Global ocean model of longevity of CO_2 sequestration from methods including AU [37]
AU (mCDR)	[1]	TRL	5	TRL considered to be moderate due to short term field experiments assessing pumping mechanisms (wave vs perpetual salt fountain, etc.) and efficacy of upwelling nutrients and resulting local productivity increases [1]
AU (mCDR)	[3]	TRL	5	TRL considered to be low since a range of AU systems have been proposed but few have reported to be successful at raising deep water levels to the euphotic layer in sea trials, especially for long term operations [3]
AU (mCDR)	[59]	TRL	5	AU devices need to be more robust to survive in the ocean, so far one device was able to enhance primary production over 30 days Others have not been deployed long enough to show expected biological and biogeochemical results and environmental impacts

Method	Source	Estimate For?	Estimate Value	Process
				Limited field testing leaves the TRL at 5 [59]
AU (mCDR)	[5]	TRL	2	Modeling study with no time estimate for deployment [5]
AU (mCDR)	[87]	TRL	5	Mentions field deployments in Norway and China (Aoshan Bay) that could benefit from their model and experiments to improve injection efficiency [87]
AU (mCDR)	[88]	TRL	5	Lab and field experiments described [88]
AU (mCDR)	[24]	TRL	6	Large scale AU experiment in isolated marine environment [24]
AU (mCDR)	[4]	TRL	5	Small-scale field tests (deployments less than a week and impact an area no larger than tens of kilometers) Need systems to be robust in the open ocean over timescales needed for CDR (longer than months) [4]
AU (mCDR)	[36]	TRL	5	Hybrid powered AU experimental field testing described [36]
AU (mCDR)	[36]	TRL	2	Ocean thermal energy AU theoretical study described [36]
AU (mCDR)	[35]	TRL	5	Perpetual salt fountain powered AU field test described [35]
AU (mCDR)	[36]	TRL	5	Perpetual salt fountain powered AU field test described [36]
AU (mCDR)	[35]	TRL	5	Wave powered AU field test described [35]
AU (mCDR)	[100]	TRL	3	Described experimental tests and validated models (not yet tested with random waves) for AU system [100]
AU (mCDR)	[101]	TRL	2	Theoretical study [101]
AU (mCDR)	[102]	TRL	3	Experimental and modeling study [102]
AU (mCDR)	[36]	TRL	5	Experimental field testing of wave powered AU system [36]
Deep-Seabed Sequestration (mCS)	[10]	TRL	3	Low TRL since this is just a modeling study [10]
Deep-Seabed Sequestration (mCS)	[38]	TRL	2	Modeling study [38]

Method	Source	Estimate For?	Estimate Value	Process
Deep-Seabed Sequestration (mCS)	[39]	TRL	2	Modeling study [39]
Deep-Seabed Sequestration (mCS)	[40]	TRL	3	Modeling study based on theoretical, experimental, and numerical studies [40]
Deep-Seabed Sequestration (mCS)	[30]	TRL	4	Described small-scale experiment conducted off the coast of California with a dry ice and CO_2 slurry (8 cm initial diameter ice sank 50 m) [30]
Deep-Seabed Sequestration (mCS)	[76]	TRL	1	Concept but claimed to be feasible with present engineering capabilities [76]
Deep-Seabed Sequestration (mCS)	[27]	TRL	1	Conceptual injection plant based on prior modeling and experimental work [27]
Deep-Seabed Sequestration (mCS)	[55]	TRL	1	Conceptual idea supported by experimental and modeling work [55]
Deep-Seabed Sequestration (mCS)	[77]	TRL	1	Conceptual idea supported by experimental and modeling work [77]
Deep-Seabed Sequestration (mCS)	[61]	TRL	1	Conceptual idea supported by experimental, modeling, and considerable published field work [61]
Deep-Sea Basalt Sequestration (mCS)	[41]	TRL	4	The TRL is low since the technology has not yet been tested in the deep ocean but onshore injection into basalt formations has been done by the company Carbfix in Iceland [41] There is a pre-feasibility project for Cascadia basin in the U.S. Northwest aim to capture 2.5 $MtCO_2$/yr from point sources on land for 20 years and pump it 200 mi of the Pacific Coast (investigating monitoring and site characterization) [41]
Deep-Sea Basalt Sequestration (mCS)	[9]	TRL	3	Includes experiments for DAC and models for wind resources and geological storage [9]
Deep-Sea Basalt Sequestration (mCS)	[60]	TRL	5	Described an already conducted pilot project in Wallula, WA (they injected 1 kiloton of liquid CO_2 into permeable layered basalt flow tops) to

Method	Source	Estimate For?	Estimate Value	Process
				demonstrate that the mineralization does occur [60] They also have done lab experiments [60]
Deep-Sea Aquifer Sequestration (mCS)	[31]	TRL	7	CO_2 pipelines and injecting gas into geological media are mature technologies [31] Existing offshore CO_2 storage projects: Sleipner in Norway: storing 1 $MtCO_2$/yr in sandstone 1.1 km below the sea surface sealed with shales and mudstones started in 1996 and longest running commercial-scale CO_2 storage project in the world [31]
Deep-Sea Aquifer Sequestration (mCS)	[31]	TRL	7	Other project described: Snohvit in Barents Sea: storing 0.7 $MtCO_2$/yr in sandstone 2.6 km below the seabed [31]
Deep-Sea Aquifer Sequestration (mCS)	[39]	TRL	2	Describes modeling study including non-self-sealing sediments [39]
Deep-Sea Water Column Sequestration (mCS)	[30]	TRL	4–5	Generally, describes lab experiments, small scale in situ experiments (<100 L CO_2), and modeling. No larger scale in situ experiments have been done, same for making CO_2 lakes (on the scale of 10 liters of CO_2) [30] Large scale experiments (< 60 tCO_2 and 5.4 tCO_2) have been put forward but not granted permits by governing bodies (ex. U.S. (HI) and Norway) [30]
Deep-Sea Water Column Sequestration (mCS)	[30]	TRL	4	Describes in situ experiments concerning the sensitivity of deep and shallow-living marine biota to elevated carbon dioxide levels which have been limited in scope [30]
Deep-Sea Water Column Sequestration (mCS)	[30]	TRL	4	Describes additional in situ experiments [30]
Deep-Sea Water Column Sequestration (mCS)	[37]	TRL	3	Global ocean model of longevity of CO_2 sequestration from methods including CO_2 injection into the water column [37]

Method	Source	Estimate For?	Estimate Value	Process
Deep-Sea Water Column Sequestration (mCS)	[31]	TRL	4	Ocean storage (direct injection to the water column/ formation of CO_2 lakes) has not been demonstrated at a large scale (some theoretical, lab, and modeling studies) [31]
eChem Acid Stripping CO_2 (mCC)	[1]	TRL	4	TRL is moderate since the method has been modeled, prototyped, and analyzed from a techno-economic perspective [1]
eChem Acid Stripping CO_2 (mCC)	[33]	TRL	3	Described experimental prototype that stripped CO_2 from synthetic seawater and desalination brine waste [33]
eChem Acid Stripping CO_2 (mCC)	[28]	TRL	4	Custom built system that tested process with larger volume of artificial seawater (1,000 L tank flows on order of L/min) [28]
eChem Acid Stripping CO_2 (mCC)	[14]	TRL	3	Lab scale system testing [14]
eChem Acid Stripping CO_2 (mCC)	[25]	TRL	3	Proof of concept experimental testing with synthetic oceanwater [25]
eChem Acid Stripping CO_2 (mCC)	[26]	TRL	3	Theoretical study based on experimental work [26]
eChem Acid Stripping CO_2 (mCC)	[21]	TRL	4	Experimental study using real seawater along with a reverse osmosis unit [21]
eChem Base Addition (mCDR)	[1]	TRL	3	Low TRL according to the source so it was assumed to be the same as the other estimates for this category [1]
eChem Base Addition (mCDR)	[56]	TRL	4	Environmental field test of alkalinity addition [56]
eChem Base Addition (mCDR)	[85]	TRL	4	Field test of environmental impacts of alkaline addition to seawater (added 2,000 L of dilute solution) [85]
eChem Base Addition (mCDR)	[64]	TRL	4	Proposal for experimental and field testing with a focus on environmental impacts and monitoring [64]
eChem Base Addition (mCDR)	[11]	TRL	2	Modeling study [11]

Method	Source	Estimate For?	Estimate Value	Process
eChem Base Addition (mCDR)	[54]	TRL	3	Experimental work using seawater and theoretical full-scale forecasting [54]
eChem Base Addition (mCDR)	[42]	TRL	3	Experimental work using seawater and theoretical full-scale forecasting [42]
eChem Base Addition (mCDR)	[12]	TRL	2	Theoretical study [12]
eChem Base Addition (mCDR)	[13]	TRL	3	Theoretical study based on experimental work [13]
eChem Base Addition (mCDR)	[14]	TRL	3	Lab scale system testing [14]
eChem Carbonate Production (mCDR)	[28]	TRL	4	Custom built system that tested process with larger volume of artificial seawater (1,000 L tank flows on an order of L/min) [28]
eChem Carbonate Production (mCDR)	[65]	TRL	3	Benchtop experiment using real seawater [65]
eChem Carbonate Production (mCDR)	[73]	TRL	3	Experimental tests with CO_2 gas aerated into seawater [73]
eChem Carbonate Production (mCDR)	[15]	TRL	2	Modeling study [15]
eChem Carbonate Production (mCDR)	[93]	TRL	3	Benchtop experiments [93]
Seaweed Farming (mCC)	[4]	TRL	7	Existing farms are already up to a few thousand hectares in size but need to reach a higher scale [4]
Seaweed Farming (mCC)	[84]	TRL	5	First field test [84]
Seaweed Farming	[72]	TRL	7	Market sector that needs to grow to reach full scale capture potential

Method	Source	Estimate For?	Estimate Value	Process
(mCC)				(most of the offshore technology is early stage) [72]
Seaweed Farming (mCC)	[29]	TRL	2	Concept for large scale seaweed farming [29]
Seaweed Farming (mCC)	[103]	TRL	5	Overall need more field tests for both cultivation and sinking: Need to do 1 km^2 scale field tests in a variety of locations with a variety of species. A multitude of field tests are necessary to understand the efficacy and risks of this method [103]
Seaweed Farming (mCC)	[58]	TRL	4	Planned project to combine overtopping wave energy converter array with offshore seaweed cultivation [58]
Seaweed Farming (mCC)	[6]	TRL	7	Offshore seaweed aquaculture production is negligible. Still need to verify viability with more modeling and field tests [6]
Seaweed Farming (mCC)	[94]	TRL	7	There is growth in the sector, but more development is necessary [94]
Seaweed Farming (mCC)	[7]	TRL	7	There is not much large-scale strategic use of seaweed farming for explicit carbon offsetting [7]
Seaweed Farming (mCC)	[79]	TRL	2	Preliminary concept study with some modeling but a plan to do a field deployment [79]
Seaweed Farming (mCC)	[72]	TRL	1	Robotic seaweed harvesting is conceptual [72]
Seaweed Farming (mCC)	[69]	TRL	7	Industry in the U.S. is small but growing. There are both commercial and developing monitoring devices for this field [69]
Seaweed Farming (mCC)	[34]	TRL	3	LCA based on experimental work, literature, and professional contacts [34]
Seaweed Farming (mCC)	[78]	TRL	3	Proposal described [78]
Seaweed Farming (mCC)	[71]	TRL	6	Review of LCAs that mostly focused on biofuel production [71]

Method	Source	Estimate For?	Estimate Value	Process
Seaweed Sinking (mCDR)	[4]	TRL	4	Methods of conveyance of biomass to the deep ocean are still in early development [4]
Seaweed Sinking (mCDR)	[70]	TRL	3	Scale up analysis for macroalgae / seaweed sinking using data from a natural event (seaweed bloom) [70]
Seaweed Sinking (mCDR)	[94]	TRL	4	Describes a group called Pull to Refresh. They are mainly growing seaweed in an experimental tank and testing their control system using a small boat on a lake [94]
Seaweed Sinking (mCDR)	[94]	TRL	4	Describes a group called Running Tide who has done field testing in the North Atlantic to determine where and how types of kelp grow under a variety of conditions but they have yet to test sinking [94]
Seaweed Sinking (mCDR)	[104]	TRL	4–5	Proposal for experimental and field testing (focus on environmental impacts and monitoring) [104]. Already done preliminary coastal field tests, plan to do offshore field tests [104]
Seaweed Sinking (mCDR)	[105]	TRL	5	Describes projects in Preparation: Prototype scale pilot experiment (by Running Tide) Kg-scale sinking experiments (by Oceanwise/ Ocean Networks Canada) Sinking ~30 bales of Sargassum (1 m^3 each) [planned for Nov 2022] (by Seafields) [105] Describes ongoing project: kg-scale Sargassum sinking experiments (by Fearless Fund) [105]
Seaweed Sinking (mCDR)	[105]	TRL	5	Describes additional ongoing project: Ton-scale measurements of detrital flux falling from deep water platforms during growth and sinking to seafloor (by the Climate Foundation) [105]
Seaweed Sinking (mCDR)	[105]	TRL	5	Describes ongoing ton scale sinking experiments [started in July 2022] (by UC Santa Barbra) [105]
Seaweed Sinking (mCDR)	[105]	TRL	5	Describes ongoing project in deep-sea burial (NIWA, New Zealand) [105]

Method	Source	Estimate For?	Estimate Value	Process
Seaweed Sinking (mCDR)	[6]	TRL	4	Few startups considering seaweed sinking but they are early-stage ventures and still need to verify viability with more modeling and field tests [6]
Seaweed Sinking (mCDR)	[94]	TRL	4	Experts in the field believe that not enough is known about the environmental impacts to implement seaweed growing and sinking concepts [94]
Seaweed Sinking (mCDR)	[37]	TRL	3	Global ocean model of longevity of CO_2 sequestration including methods of seaweed sinking [37]
Seaweed Sinking (mCDR)	[8]	TRL	3	Modeling study [8]
Seaweed Sinking (mCDR)	[32]	TRL	6	Developed pilot system of open ocean seaweed collection device and pump to sink the biomass to depth [32]
Microalgae: Offshore Closed (mCC)	[18]	TRL	5	Designed, constructed, and tested device in a controlled environment (unidirectional flowing pond) [18]
Microalgae: Offshore Closed (mCC)	[66]	TRL	5	Field tested in a controlled environment (area with unidirectional wave direction) [66]
Microalgae: Offshore Closed (mCC)	[81]	TRL	4	Outdoor semi-continuous study [81]
Microalgae: Offshore Closed (mCC)	[67]	TRL	4	Outdoor experiment [67]
Microalgae: Offshore Closed (mCC)	[43]	TRL	4	Tested 110 L PBR in seawater tank, considered as a small-scale experimental study and requires larger scale testing to understand the environmental impacts and actual costs for at scale operation [43]
Microalgae: Offshore Closed (mCC)	[17]	TRL	3	Tested wave PBR in controlled lab setting (on shaker Table) [17]

Method	Source	Estimate For?	Estimate Value	Process
Microalgae: Offshore Generic (CC)	[22]	TRL	4–5	Floating PBRs are still an early-stage concept (account for only 2% of the literature about microalgae cultivation). Generally they are used for lab-scale or coastal applications. Need more studies on dynamics of the floating structures, flow effect on microalgae culture due to external motions, biofouling, and effect of varying wave conditions on mixing culture. Need better modeling methods for partially filled containers and their sloshing dynamics. Additionally need studies on the environmental impacts of full-scale deployment and using wave energy for mixing [22].
Microalgae: Offshore Open (mCC)	[16]	TRL	5	TRL is low they did experimental work and field testing, but this is a new concept [16]
Microalgae: Offshore Open (mCC)	[96]	TRL	5	Experimental study with small-scale field tests [96]
Microalgae: Offshore Open (mCC)	[48]	TRL	5	Field tested 1,000 L and 100 L system for 1 month and conducted experimental testing on how microalgae could manage long periods of low mixing due to calm seas [48]
Microalgae: Offshore Open (mCC)	[80]	TRL	5	Field tested 1,000 L and 100 L system for 1 month and experimental testing on microalgae prior to field testing [80]
Microalgae: Offshore Open (mCC)	[57]	TRL	4	Wave tank testing this is the first time for a floating PBR that they know of [57]
Microalgae: Offshore Open (mCC)	[97]	TRL	4	Experimental examination of using bicarbonate for microalgae cultivation [97]
Microalgae: Onshore (CC)	[1]	TRL	5–7	TRL is considered moderate which according to Hepburn et al. is 5–7 [1, 47]
Microalgae: Onshore (CC)	[68]	TRL	3	Lab and pilot studies for capturing CO_2 using microalgae described [68]

Method	Source	Estimate For?	Estimate Value	Process
Onshore Basalt CO_2 Storage (CS)	[44]	Energy /tCO_2	Pilot: 833 kWh/tCO_2 Full: 128 kWh/tCO_2 Max: 77.6 kWh/tCO_2	Source describes three scales of CS anticipated by the company Carbfix's systems. The pilot scale stores 2099 tCO_2/yr and requires 200 kW. The full scale stores 57,000 tCO_2/yr and requires 830 kW. The highest possible scale stores 400,000 tCO_2/yr and requires 3,547 kW [44]. Assuming these plants run 24/7: Converting to tCO_2/hr where there are 24 hr/day * 365 day/yr = 8,760 hr/yr Pilot: 0.24 tCO_2/hr Full: 6.5 tCO_2/hr Max: 45.7 tCO_2/hr The energy needs are: Pilot: 200 kW / 0.24 tCO_2/hr = 833 kWh/tCO_2 Full: 830 kW / 6.5 tCO_2/hr = 128 kWh/tCO_2 Max: 3,547 kW / 45.7 tCO_2/hr = 77.6 kWh/tCO_2

A.3 Estimations Used to Determine mCDR, mCC, and mCS Scales Using U.S. Marine and Offshore Wind

Determining the scales that can be achieved with the mCDR, mCC, and mCS methods investigated in this report powered by U.S. marine and offshore wind technical resources required calculating the median energy needs and full scales first. Note that the estimates described in Section A.2 were largely unit conversions from values reported from literature. Table A-2 lists the total energy values required for the mCDR, mCC, and mCS methods rather than those for subsystem needs, which are included in Section A.2 and in Section A.6. The final two columns of Table A-2 clarify if the total is from an existing entry or a sum of multiple and what those entries are. The median total energy needs used for determining the achievable mCDR, mCC, and mCS scales using U.S. offshore renewable energy resources were determined from Table A-2 and are listed in Table A-3.

The median full scales are listed in Table A-4, note that the deep-sea sequestration method scales are based on the regional values from Section A.4 since only regional geological reservoirs can be accessed within the United States, whereas it was assumed that global scales could be used for the other methods since ocean currents could mitigate potential environmental risks by distributing captured carbon or added chemicals outside of U.S. waters. Note that the regional estimates for deep-sea aquifer and seabed sequestration were for the United States [10, 31, 38, 39, 61]. However, the regional estimate for water column sequestration was the minimum global estimate calculated

since no regional estimates were found for this sequestration method [30]. Additionally, the regional estimate for basalt sequestration is for a basalt formation in the Indian Ocean, far outside U.S. waters [9]. The lack of U.S. regional estimates for these methods is indicative of the need for further research into these sequestration methods; however, given that the estimates in this report are largely preliminary, these sequestration methods were included in this section nonetheless.

The total energy required to reach the full scales possible within U.S. waters was determined by multiplying the median energy requirements in Table A-3 with the median full scales in Table A-4 and is listed for each method in Table A-5.

The marine energy available in different offshore regions of the United States is listed in Table A-6, including the amount of wave, tidal, ocean current, ocean thermal, and river energy available [49]. Meanwhile, finding the offshore wind energy available in offshore regions of the United States required data from multiple sources, as shown in Table A-7. The source used for the continental United States considered siting constraints and included resources with wind speeds below 7 m/s [106]. However, the sources for Hawaii and Alaska did not include resources with these low wind speeds [50, 107]. Additionally, the offshore wind energy produced in the U.S. territories of Puerto Rico and the U.S. Virgin Islands was not directly referenced and needed to be estimated using relevant data from literature [108, 109]. Note that the regions along the East Coast (North Atlantic/New England, Mid-Atlantic, and South Atlantic) are not identical between the marine and offshore wind energy sources (see Tables A-6 and A-7) since they include different states. However, since this is a preliminary estimation and the locations where mCDR, mCC, and mCS can be performed do not cover all the waters in these regions (see Figure A-6 to A-14), the East Coast regions for the marine and offshore wind technical resources were not adjusted to match each other. To highlight the massive amount of excess offshore renewable energy in the United States that could be used for mCDR, mCC, and mCS, the coastal demand from 2019 was subtracted from the total marine and offshore wind energy available in the considered regions, as shown in Table A-8.

The regions considered to be appropriate or ideal for the mCDR, mCC, and mCS methods are listed in Table A-9, along with the sources used to determine them. Additionally, Figures A-6 to A-14 have been included to show maps from these sources that highlight areas were these methods store CO_2 the longest, have a higher capacity for storage, or have the necessary nutrients and temperatures. Note that Figure A-11 shows ideal locations for a certain types of eChem base addition where the excess acid produced is pumped to the deep ocean [11]. This is not representative of all forms of eChem mCDR and mCC or even eChem base addition, which generally do not have distinct location requirements, besides initially benefiting from being co-located with desalination plants or located nearshore. However, these methods could eventually move further offshore at higher costs [4, 14, 15, 26, 42]. Since the eChem mCDR and mCC methods are not constrained to or do not especially benefit from specific offshore regions like the other methods, the resources available throughout the offshore United States were considered for all the eChem mCDR and mCC methods, as detailed in Table A-9.

The scales achievable from using marine energy, without meeting coastal demand, are listed in Table A-10. These values were determined by using the location information from Table A-9, the marine energy available in the regions considered in Table A-6, the median energy values in Table A-3, and the full scales that could be achieved by these methods in Table A-4. The scales

achievable using the total excess marine and offshore wind energy after meeting coastal energy demand are listed in Table A-11. The results from these tables were used to make Figure 10 to 10.

If the energy demand described in Table A-8 increases by 50% by 2050, all methods but AU can still reach their full scales [51]. This was determined via the same methodology used for finding the scales in Table A-11.

Table A-2. Total Energy Values for mCDR, mCC, and mCS Strategies

Method	Source	Total Energy (kWh/tCO_2)	Sum of Existing Entries?	Entries Summed
AU (mCDR)	[23]	17,476	No	N/A
AU (mCDR)	[24]	60	No	N/A
AU (mCDR)	[3]	3,400	No	N/A
AU (mCDR)	[3]	51,000	No	N/A
Deep-Seabed Sequestration (mCS)	[27]	74.1	Yes	Freezing liquid CO_2: ~55 kWh/tCO_2 Thrusters for marine platform: 18.3 kWh/tCO_2 Pumping: 0.7 kWh/tCO_2 Aux equip and living quarters: 0.4 kWh/tCO_2
Deep-Sea Basalt Sequestration (mCS)	[9]	65	No	N/A
Deep-Sea Basalt Sequestration (mCS)	[9]	257	No	N/A
Deep-Sea Water Column Sequestration (mCS)	[29]	430	No	N/A
Deep-Sea Water Column Sequestration (mCS)	[30]	65	No	N/A
Deep-Sea Water Column Sequestration (mCS)	[30]	257	No	N/A
Deep-Sea Water Column Sequestration (mCS)	[30]	13	No	N/A
Deep-Sea Water Column Sequestration (mCS)	[30]	52	No	N/A

Method	Source	Total Energy (kWh/tCO_2)	Sum of Existing Entries?	Entries Summed
Deep-Sea Aquifer Sequestration (mCS)	[31]	65	No	N/A
Deep-Sea Aquifer Sequestration (mCS)	[31]	257	No	N/A
eChem Acid Stripping CO_2 (mCC)	[28]	3,131	No	N/A
eChem Acid Stripping CO_2 (mCC)	[25]	5,580	Yes	eChem System: 980 kWh/tCO_2 Pumping and Pretreatment: 4600 kWh/tCO_2
eChem Acid Stripping CO_2 (mCC)	[25]	1,295	Yes	eChem System: 1,220 kWh/tCO_2 Pumping and Pretreatment: 75 kWh/tCO_2
eChem Acid Stripping CO_2 (mCC)	[25]	1,055	Yes	eChem System: 980 kWh/tCO_2 Pumping and Pretreatment: 75 kWh/tCO_2
eChem Acid Stripping CO_2 (mCC)	[25]	5,820	Yes	eChem System: 1,220 kWh/tCO_2 Pumping and Pretreatment: 4,600 kWh/tCO_2
eChem Acid Stripping CO_2 (mCC)	[26]	2,123	Yes	eChem System: 1,540 kWh/tCO_2 Pumping: 583 kWh/ tCO_2
eChem Base Addition (mCDR)	[11]	1,180	Yes	eChem System: 1,146 kWh/tCO_2 Pumping: 34 kWh/tCO_2
eChem Base Addition (mCDR)	[54]	2,273	No	N/A

Method	Source	Total Energy (kWh/tCO_2)	Sum of Existing Entries?	Entries Summed
eChem Base Addition (mCDR)	[42]	1,774	No	N/A
eChem Base Addition (mCDR)	[42]	2,711	No	N/A
eChem Base Addition (mCDR)	[42]	3,061	No	N/A
eChem Base Addition (mCDR)	[12]	636	No	N/A
eChem Base Addition (mCDR)	[12]	2,546	No	N/A
eChem Base Addition (mCDR)	[13]	500	No	N/A
eChem Base Addition (mCDR)	[13]	1,556	No	N/A
eChem Carbonate Production (mCDR)	[28]	4,386	No	N/A
eChem Carbonate Production (mCDR)	[65]	1,839	No	N/A
eChem Carbonate Production (mCDR)	[65]	2,209	No	N/A
eChem Carbonate Production (mCDR)	[73]	890	No	N/A
eChem Carbonate Production (mCDR)	[15]	229	Yes	eChem System: 70 kWh/tCO_2 Pumping and Handling Onshore: 159 kWh/tCO_2
eChem Carbonate Production (mCDR)	[15]	2,459	Yes	eChem System: 2,300 kWh/tCO_2 Pumping and Handling Onshore: 159 kWh/tCO_2
Seaweed Farming: Growing (mCC)	[34]	26	No	N/A

Method	Source	Total Energy (kWh/tCO_2)	Sum of Existing Entries?	Entries Summed
Seaweed Farming: Growing (mCC)	[29]	60	No	N/A
Seaweed Farming: Growing (mCC)	[29]	340	No	N/A
Seaweed Farming: Products (mCC)	[34]	554	No	N/A
Seaweed Farming: Products (mCC)	[34]	412	No	N/A
Seaweed Farming: Products (mCC)	[78]	2	No	N/A
Seaweed Farming: Products (mCC)	[78]	12	No	N/A
Seaweed Farming: Products (mCC)	[78]	3	No	N/A
Seaweed Farming: Products (mCC)	[78]	24	No	N/A
Seaweed Farming: Products (mCC)	[78]	93	No	N/A
Seaweed Farming: Products (mCC)	[78]	293	No	N/A
Seaweed Sinking (mCDR)	[32]	10	No	N/A
Seaweed Sinking (mCDR)	[32]	22	No	N/A
Microalgae Farming (mCC)	[18]	348,000	No	N/A
Microalgae Farming (mCC)	[17]	4,100	No	N/A
Microalgae Farming (mCC)	[17]	64,520	No	N/A

Method	Source	Total Energy (kWh/tCO_2)	Sum of Existing Entries?	Entries Summed
Microalgae Farming (mCC)	[16]	3,730	No	N/A
Microalgae Farming (mCC)	[16]	176,000	No	N/A

Table A-3. Total Energy Requirement Medians

Method	Median Total Energy (kWh/tCO_2)
AU (mCDR)	10,438
Deep-Seabed Sequestration (mCS)	74.1
Deep-Sea Basalt Sequestration (mCS)	161
Deep-Sea Water Column Sequestration (mCS)	65
Deep-Sea Aquifer Sequestration (mCS)	161
eChem Acid Stripping CO_2 (mCC)	2,627
eChem Base Addition (mCDR)	1,744
eChem Carbonate Production (mCDR)	2,024
Seaweed Farming: Growing (mCC)	60
Seaweed Farming: Products (mCC)	93
Seaweed Sinking (mCDR)	16
Microalgae Farming (mCC)	64,520

Table A-4. Full-Scale Medians

Method	Regional or Global?	Median Full Scale ($GtCO_2$/yr)
AU (mCDR)	Global	3
Deep-Seabed Sequestration (mCS)	Regional	1.52
Deep-Sea Basalt Sequestration (mCS)	Regional	0.075
Deep-Sea Water Column Sequestration (mCS)	Regional	0.37
Deep-Sea Aquifer Sequestration (mCS)	Regional	3.5
eChem Acid Stripping CO_2 (mCC)	Global	3
eChem Base Addition (mCDR)	Global	2.35
eChem Carbonate Production (mCDR)	Global	10
Seaweed Farming: Growing (mCC)	Global	0.00248
Seaweed Farming: Products (mCC)	Global	0.00248
Seaweed Sinking (mCDR)	Global	0.8
Microalgae Farming (mCC)	Global	0.9

Table A-5. Energy Needed To Reach Full Scale

Method	Energy To Reach Full Scale (TWh/yr)
AU (mCDR)	31,314
Deep-Seabed Sequestration (mCS)	112.6
Deep-Sea Basalt Sequestration (mCS)	12.1
Deep-Sea Water Column Sequestration (mCS)	24.1
Deep-Sea Aquifer Sequestration (mCS)	563.5
eChem Acid Stripping CO_2 (mCC)	7,881
eChem Base Addition (mCDR)	4,098
eChem Carbonate Production (mCDR)	20,240
Seaweed Farming: Growing (mCC)	0.15
Seaweed Farming: Products (mCC)	0.23
Seaweed Sinking (mCDR)	12.8
Microalgae Farming (mCC)	58,068

Table A-6. Technical Resources of Marine Energy in the United States [49]

Locations	Total Marine Energy (TWh/yr)	Wave (TWh/yr)	Tidal (TWh/yr)	Ocean Current (TWh/yr)	Ocean Thermal (TWh/yr)	River (TWh/yr)
U.S. (total excluding inland states)	2,259	1,400	220	49	540	58
East Coast (Maine to Florida)	460	55	10	49	340	0.67
Alaska	1,100	890	210	0	0	21
West Coast (Washington to California)	250	240	4.1	0	0	6.7
Hawaii	390	250	0	0	140	0
Gulf Coast (Texas to Florida)	84	0	0.37	0	53	31
Caribbean (Puerto Rico and U.S. Virgin Islands)	38	0	0	0	38	0
Southeast (North Carolina to Florida)	74	22	3	49	0	0
New England (Maine to Connecticut)	24	21	3.3	0	0	0
Mid-Atlantic (New York to Virginia)	16	12	3.8	0	0	0
Oregon	95	93	0.21	0	0	2.2
Washington	12	5.4	3	0	0	4
California	140	140	0.89	0	0	0.55

Table A-7. Technical Resources of Offshore Wind Energy in the United States

Locations	Source	Total Offshore Wind (TWh/yr)	Estimation Method
California	[106]	348	Sum of floating and fixed-bottom wind energy technical resources (338 and 10 TWh/yr, respectively)
Gulf of Mexico (Texas to Florida)	[106]	4,075	Sum of floating and fixed-bottom wind energy technical resources (2,289 and 1,786 TWh/yr, respectively)
Mid Atlantic (Delaware to North Carolina)	[106]	1,191	Sum of floating and fixed-bottom wind energy technical resources (607 and 584 TWh/yr, respectively)
North Atlantic (Maine to New Jersey)	[106]	2,924	Sum of floating and fixed-bottom wind energy technical resources (1,843 and 1,081 TWh/yr, respectively)
Oregon	[106]	549	Sum of floating and fixed-bottom wind energy technical resources (544 and 5 TWh/yr, respectively)
South Atlantic (South Carolina to Florida)	[106]	2,172	Sum of floating and fixed-bottom wind energy technical resources (1,628 and 544 TWh/yr, respectively)
Washington	[106]	204	Sum of floating and fixed-bottom wind energy technical resources (188 and 16 TWh/yr, respectively)
Hawaii	[50]	157	Value from Table G-1 in source
Alaska	[107]	12,087	N/A
Puerto Rico	[108]	132	The net capacity factor mean for offshore wind energy is 0.37 which is multiplied by 8.76 (the conversion factor from GW to TWh/yr) which is then multiplied by 40.76 GW technical capacity
U.S. Virgin Islands	[109]	0.00675	Based on planned capacity for 2025
Total for all U.S. Regions	N/A	23,682	Sum of entries above

Table A-8. Marine and Offshore Wind Energy Available in the United States After Meeting Demand

Locations	Electricity Generation/ Demand Source	2019 Regional Electricity Generation/ Demand (TWh)	Total Offshore Energy (TWh/yr)	Excess Energy Available (TWh/yr)
California	[49]	201.8	488	286.2
Oregon	[49]	62.3	644	581.7
Washington	[49]	106.5	216	109.5
West Coast	[49]	370.5	1,351	980.5
New England/ North Atlantic	[49]	97.7	2,948	2,850.3
Mid Atlantic	[49]	344	1,207	863
South Atlantic	[49]	482.8	2,246	1,763.2
East Coast	[49]	924.5	6,747	5,822.5
Gulf of Mexico	[49]	914.8	4,159	3,244.2
Alaska	[49]	6.1	13,187	13,180.9
Hawaii	[49]	9.7	547	537.3
Puerto Rico and U.S. Virgin Islands	[49]	18	170	152.1
Total Coastal U.S.	[49]	3,538.7	25,941	22,402

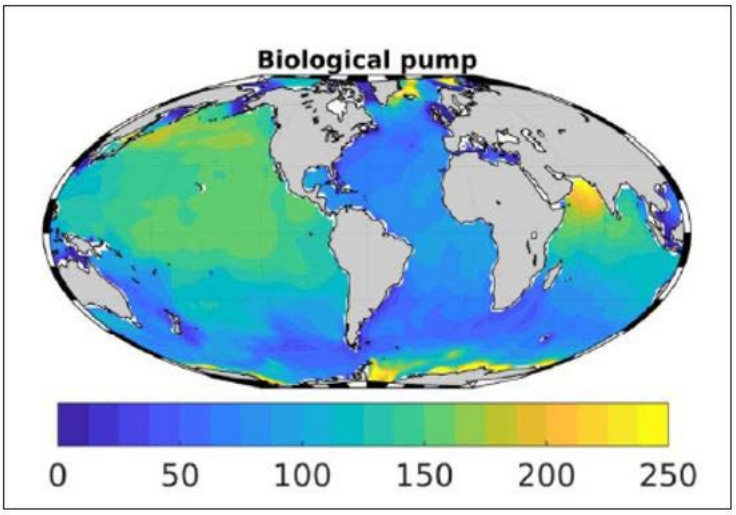

Figure A-6. Map describing ideal locations for AU.

The ideal locations for AU were determined using the map from Siegel et al., where the scale shows the years that carbon can be stored in the ocean from biological pumps like those used for AU [37].

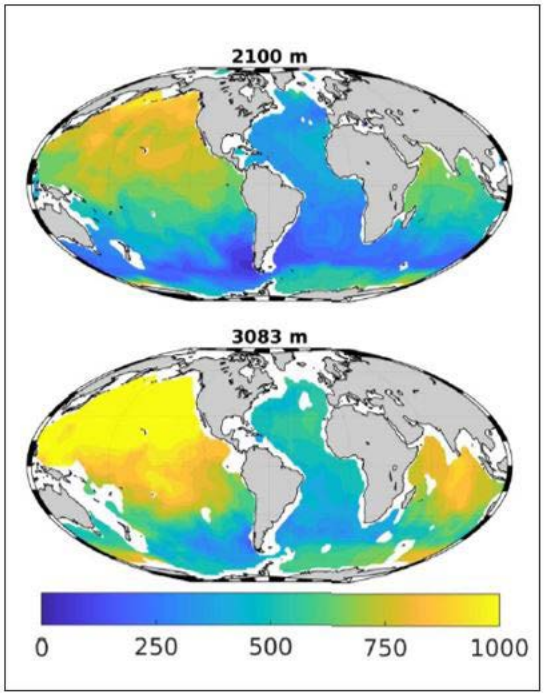

Figure A-7. Maps describing ideal locations for water column sequestration and seaweed sinking.

The ideal locations for deep-sea water column sequestration and seaweed sinking were determined using the maps from Siegel et. al., where the scale shows the years that carbon can be stored in the deep ocean at depths of 2,100 and 3,083 m respectively in the figures [37].

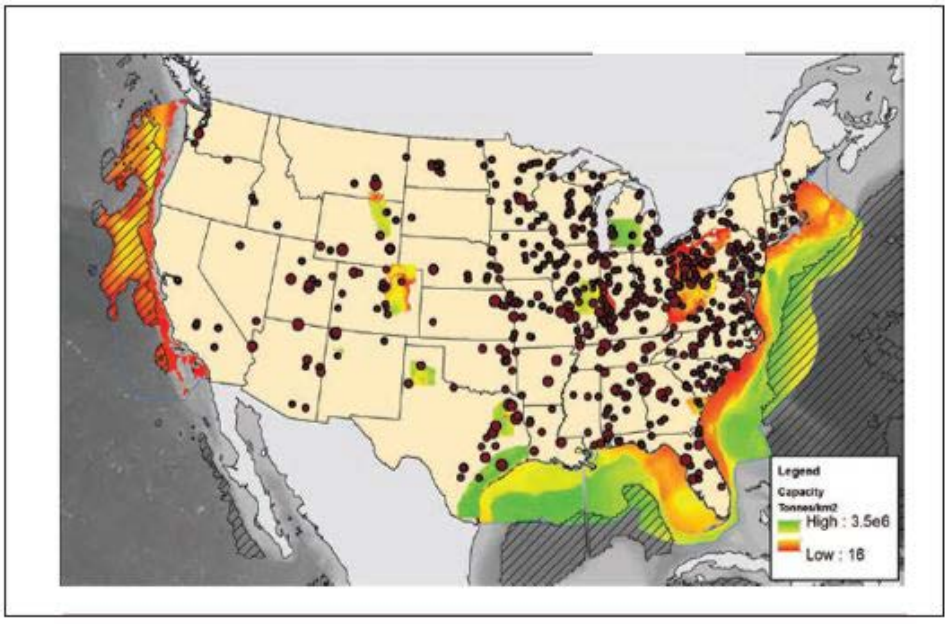

Figure A-8. Map describing ideal locations for seabed sequestration.

The ideal locations for deep-seabed sequestration were determined using the map from Eccles and Pratson, where the scale shows the capacity for these sediments to store CO_2 in terms of tonnes per square kilometer; green represents high capacity while red shows low capacity [39].

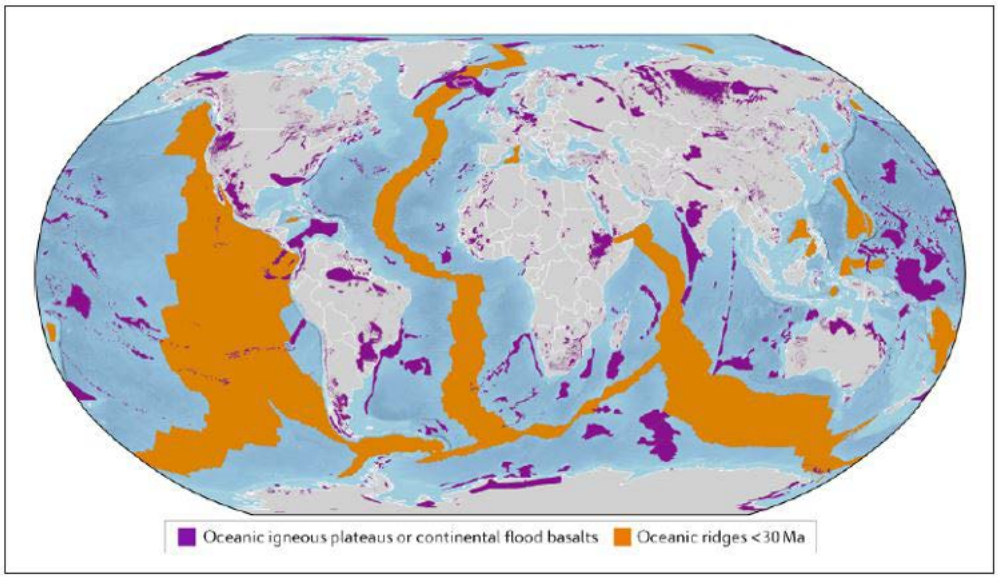

Figure A-9. Map describing ideal locations for basalt sequestration.

The ideal locations for deep-sea basalt sequestration were determined using the map from the Energy Futures Initiative and Snaebjornsdottir, where the purple regions show oceanic igneous plateaus or continental flood basalts and the orange regions show oceanic ridges that are younger than 30 million years old, all of which are regions where basalt sequestration could be undertaken [41, 110].

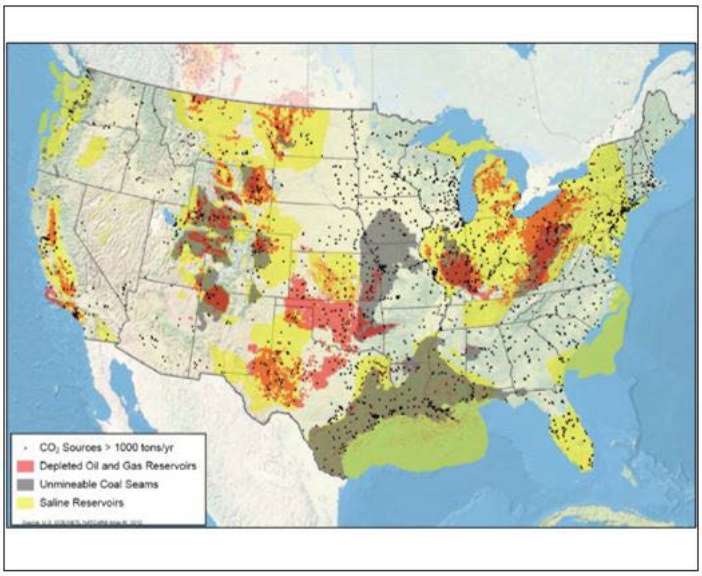

Figure A-10. Map describing ideal locations for aquifer sequestration.

The ideal locations for deep-sea aquifer sequestration were determined using the map from Vidas et al., where the yellow regions show saline reservoirs that could be used for aquifer sequestration [31].

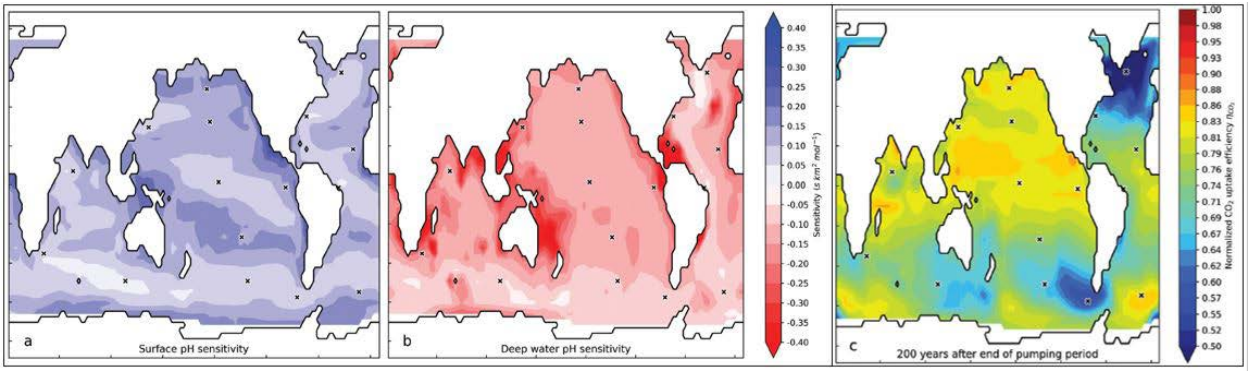

Figure A-11. Maps describing ideal locations for eChem base addition where the excess acid is pumped to deep waters.

The maps show the ideal locations for eChem base addition when the excess acid is pumped to depth. The left figure shows the sensitivity of surface waters to changes to increases in pH while the center figure shows the sensitivity of deep-sea waters to increases in acidity or decreases in pH. The figure on the right shows the normalized CO_2 uptake efficiency of ocean waters 200 years after the eChem mCDR method is used [11]. Note that this is not representative of all eChem mCDR and mCC methods or even all types of eChem base addition, and all the other types of eChem mCDR and mCC do not have significant location requirements.

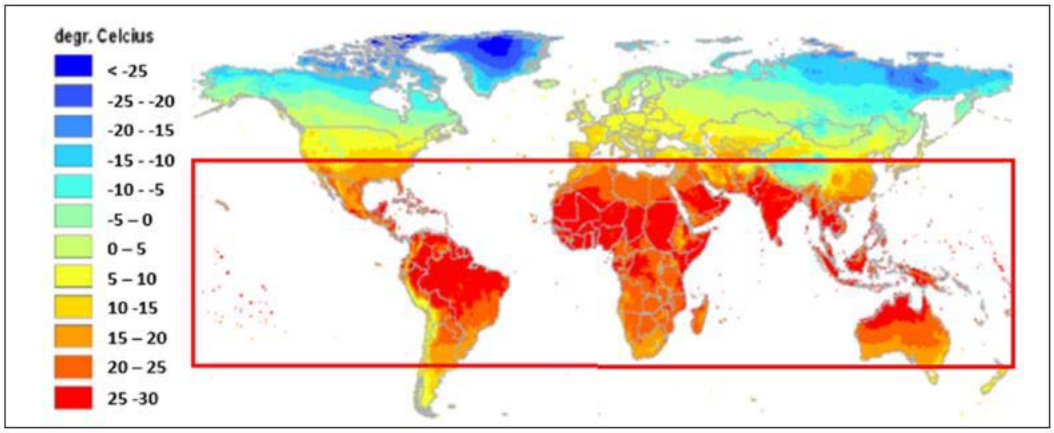

Figure A-12. Map describing ideal locations for offshore microalgae cultivation.

The ideal locations for offshore microalgae cultivation were determined using this map, where the red box shows regions of the world with ideal temperatures for microalgae cultivation [22].

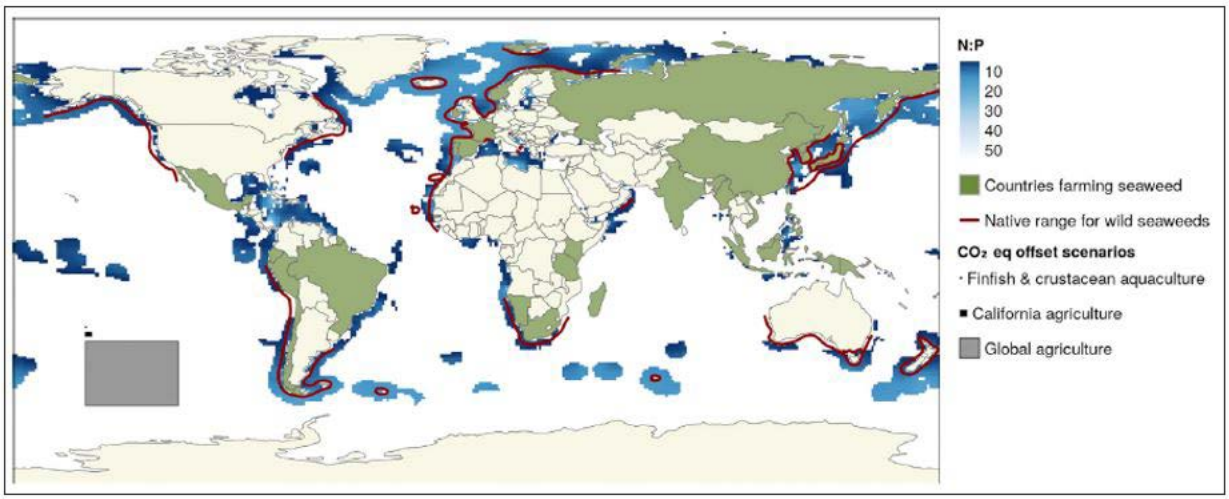

Figure A-13. Map describing ideal locations for seaweed farming and sinking.

The ideal locations for seaweed farming and sinking were determined using the map, where the blue regions are areas with ideal ratios of nitrogen to phosphorus for growing seaweed and the red regions represent native ranges for wild seaweeds [7].

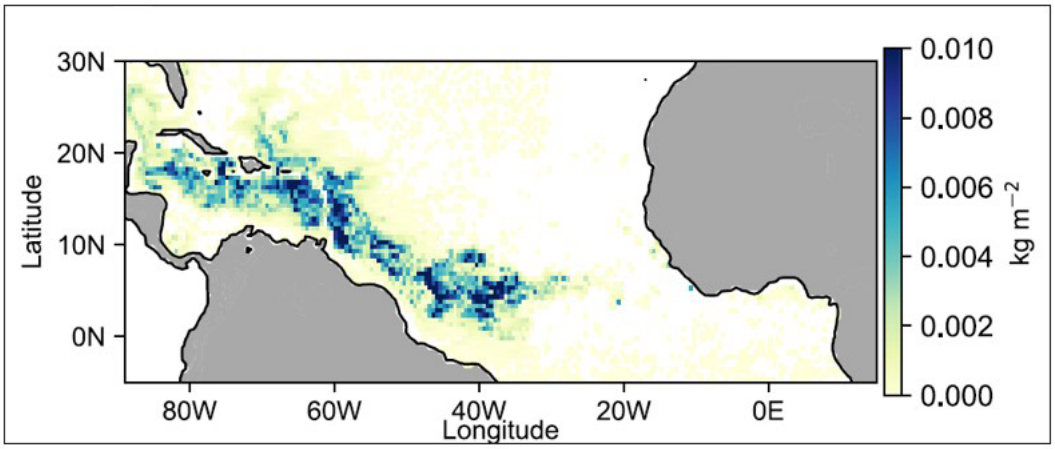

Figure A-14. Map describing ideal locations for seaweed sinking in the Caribbean.

The ideal locations for seaweed sinking in the Caribbean were determined using the map, which shows the concentration of seaweed blooms in the region in terms of biomass weight per unit area [70].

Table A-9. Relevant Regions for the mCDR, mCC, and mCS Methods

Method	Sources	Regions Considered To Be Ideal/ Appropriate for the Methods
AU (mCDR)	[37]	West Coast, Hawaii, and Alaska
Deep-Seabed Sequestration (mCS)	[38, 39]	East Coast and Gulf Coast
Deep-Sea Basalt Sequestration (mCS)	[9, 41, 110]	Washington, Oregon, and Hawaii
Deep-Sea Water Column Sequestration (mCS)	[37]	West Coast, Hawaii, and Alaska
Deep-Sea Aquifer Sequestration (mCS)	[31]	Gulf Coat, Southeast, Oregon, and Washington
eChem Acid Stripping CO_2 (mCC)	[4, 14, 26]	All
eChem Base Addition (mCDR)	[4, 11, 42, 56]	All
eChem Carbonate Production (mCDR)	[15]	All
Seaweed Farming: Growing (mCC)	[6, 7, 37, 58]	Alaska, West Coast, Mid-Atlantic, and New England/ North Atlantic
Seaweed Farming: Products (mCC)	[6, 7, 37, 58]	Alaska, West Coast, Mid-Atlantic, and New England/ North Atlantic
Seaweed Sinking (mCDR)	[6, 32, 37]	Alaska, West Coast, and Caribbean
Microalgae Farming (mCC)	[16, 22, 57]	Gulf Coast, Caribbean, Southeast, and Hawaii (Note only wave energy can be used for this type of mCC)

Table A-10. Scales of mCDR, mCC, and mCS Achievable With Marine Energy

Method	Total Marine Energy Available in Relevant Locations (TWh/yr)	Scale Achievable ($GtCO_2$/yr)	Percentage of Full Scale Achievable ($GtCO_2$/yr)	Percent of Marine Energy Needed To Reach Full Scale
AU (mCDR)	1,740	0.167	5.56%	N/A
Deep-Seabed Sequestration (mCS)	544	1.52	100%	20.7%
Deep-Sea Basalt Sequestration (mCS)	497	0.075	100%	2.43%
Deep-Sea Water Column Sequestration (mCS)	1,740	0.37	100%	1.38%
Deep-Sea Aquifer Sequestration (mCS)	265	1.65	47%	N/A
eChem Acid Stripping CO_2 (mCC)	2,259	0.86	28.7%	N/A
eChem Base Addition (mCDR)	2,259	1.3	55.1%	N/A
eChem Carbonate Production (mCDR)	2,259	1.12	11.2%	N/A
Seaweed Farming: Growing (mCC)	1,390	0.00248	100%	0.011%
Seaweed Farming: Products (mCC)	1,390	0.00248	100%	0.017%
Seaweed Sinking (mCDR)	1,388	0.8	100%	0.922%
Microalgae Farming (mCC)	272	0.004	0.47%	N/A

Table A-11. Scales Achievable With Excess Marine and Offshore Wind Energy

Method	Total Excess Energy Available in Relevant Locations (TWh/yr)	Scale Achievable ($GtCO_2$/yr)	Percentage of Full Scale Achievable ($GtCO_2$/yr)	Percent of Excess Energy Needed To Reach Full Scale
AU (mCDR)	14,699	1.41	46.9%	N/A
Deep-Seabed Sequestration (mCS)	9,067	1.52	100%	0.16%
Deep-Sea Basalt Sequestration (mCS)	1,229	0.075	100%	0.98%
Deep-Sea Water Column Sequestration (mCS)	14,699	0.37	100%	0.16%
Deep-Sea Aquifer Sequestration (mCS)	5,699	3.5	100%	9.89%
eChem Acid Stripping CO_2 (mCC)	22,402	3	100%	35.2%
eChem Base Addition (mCDR)	22,402	2.35	100%	18.3%
eChem Carbonate Production (mCDR)	22,402	10	100%	90.4%
Seaweed Farming: Growing (mCC)	17,875	0.00248	100%	0.001%
Seaweed Farming: Products (mCC)	17,875	0.00248	100%	0.001%
Seaweed Sinking (mCDR)	14,314	0.8	100%	0.09%
Microalgae Farming (mCC)	272	0.004	0.47%	N/A

A.4 Data Used in Supplementary Figure 1

Note that the determination of environmental risks for these methods at scale was based on whether these sources referenced the hazards outlined in Table 1. If they mentioned the high-risk environmental impacts, then the risk would be listed as high. If they mentioned that the risks were limited, then the risk would be low. Finally, if the source mentioned that more research is necessary to understand the potential risks of the mCDR, mCC, or mCS strategy or no mention of environmental impacts was included then the risk would be listed as unclear. The regional range refers to scales limited to a single location such as the U.S. Exclusive Economic Zone or the region of seaweed bloom in the Caribbean Sea [32, 38].

Table A-12. Data for Figure A-1

Method	Source	$GtCO_2/yr$	Range	Likelihood of Negative Impacts on Global Ecosystems?	Estimated or Referenced
AU (mCDR)	[3]	0.67	Global	High	Referenced
AU (mCDR)	[3]	3.33	Global	High	Referenced
AU (mCDR)	[3]	2.67	Global	High	Referenced
AU (mCDR)	[4]	0.00001	Global	High	Estimated
AU (mCDR)	[4]	13.3	Global	High	Referenced
AU (mCDR)	[4]	3.33	Global	High	Referenced
AU (mCDR)	[5]	0.00001	Regional	High	Estimated
AU (mCDR)	[1]	1	Global	Unclear	Referenced
AU (mCDR)	[1]	5	Global	Unclear	Referenced
Deep-Seabed Sequestration (mCS)	[10]	6	Regional	Low	Referenced
Deep-Seabed Sequestration (mCS)	[10]	30	Global	Low	Estimated
Deep-Seabed Sequestration (mCS)	[38]	1	Regional	Low	Referenced
Deep-Seabed Sequestration (mCS)	[38]	30	Global	Low	Estimated
Deep-Seabed Sequestration (mCS)	[39]	2	Regional	Low	Referenced
Deep-Seabed Sequestration (mCS)	[61]	1.04	Regional	Unclear	Referenced
Deep-Sea Basalt Sequestration (mCS)	[9]	0.075	Regional	Low	Referenced
Deep-Sea Basalt Sequestration (mCS)	[9]	30	Global	Low	Estimated
Deep-Sea Aquifer	[39]	2	Regional	Unclear	Referenced

Method	Source	$GtCO_2/yr$	Range	Likelihood of Negative Impacts on Global Ecosystems?	Estimated or Referenced
Sequestration (mCS)					
Deep-Sea Aquifer Sequestration (mCS)	[31]	5	Regional	Unclear	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	0.37	Global	High	Estimated
Deep-Sea Water Column Sequestration (mCS)	[30]	3	Global	High	Estimated
Deep-Sea Water Column Sequestration (mCS)	[30]	30	Global	High	Estimated
eChem Acid Stripping CO_2 (mCC)	[1]	1	Global	Unclear	Referenced
eChem Acid Stripping CO_2 (mCC)	[1]	5	Global	Unclear	Referenced
eChem Acid Stripping CO_2 (mCC)	[4]	0.001	Global	Unclear	Referenced
eChem Acid Stripping CO_2 (mCC)	[4]	0.002	Global	Unclear	Referenced
eChem Acid Stripping CO_2 (mCC)	[14]	10	Global	Unclear	Referenced
eChem Acid Stripping CO_2 (mCC)	[14]	11	Global	Unclear	Referenced
eChem Acid Stripping CO_2 (mCC)	[28]	1	Global	Unclear	Referenced
eChem Acid Stripping CO_2 (mCC)	[62]	10	Global	Unclear	Referenced

Method	Source	$GtCO_2/yr$	Range	Likelihood of Negative Impacts on Global Ecosystems?	Estimated or Referenced
eChem Acid Stripping CO_2 (mCC)	[62]	1	Global	Unclear	Referenced
eChem Acid Stripping CO_2 (mCC)	[62]	25	Global	Unclear	Referenced
eChem Base Addition (mCDR)	[1]	1	Global	Unclear	Referenced
eChem Base Addition (mCDR)	[1]	11.1	Global	Unclear	Estimated
eChem Base Addition (mCDR)	[4]	0.09	Global	Unclear	Referenced
eChem Base Addition (mCDR)	[11]	3.7	Global	Unclear	Referenced
eChem Base Addition (mCDR)	[11]	11.1	Global	Unclear	Referenced
eChem Base Addition (mCDR)	[12]	3.7	Global	Unclear	Referenced
eChem Base Addition (mCDR)	[13]	0.25	Global	Unclear	Referenced
eChem Base Addition (mCDR)	[13]	1	Global	Unclear	Referenced
eChem Carbonate Production (mCDR)	[14]	10	Global	Unclear	Referenced
eChem Carbonate Production (mCDR)	[14]	11	Global	Unclear	Referenced
eChem Carbonate Production (mCDR)	[65]	1	Global	Unclear	Referenced

Method	Source	$GtCO_2/yr$	Range	Likelihood of Negative Impacts on Global Ecosystems?	Estimated or Referenced
eChem Carbonate Production (mCDR)	[28]	1	Global	Unclear	Referenced
eChem Carbonate Production (mCDR)	[15]	10	Global	Unclear	Referenced
Seaweed Farming (mCC) and Sinking (mCDR): Generic	[1]	1	Global	Unclear	Referenced
Seaweed Farming (mCC) and Sinking (mCDR): Generic	[1]	5.1	Global	Unclear	Estimated
Seaweed Farming (mCC)	[111]	0.00248	Global	Unclear	Referenced
Seaweed Farming (mCC)	[7]	0.000303	Global	Unclear	Referenced
Seaweed Farming (mCC)	[7]	5.1	Global	High	Referenced
Seaweed Farming (mCC)	[7]	0.0344	Regional	Unclear	Referenced
Seaweed Sinking (mCDR)	[4]	0.6	Global	High	Referenced
Seaweed Sinking (mCDR)	[4]	0.2	Global	High	Referenced
Seaweed Sinking (mCDR)	[4]	1	Global	High	Referenced
Seaweed Sinking (mCDR)	[4]	0.1	Global	High	Referenced

Method	Source	$GtCO_2/yr$	Range	Likelihood of Negative Impacts on Global Ecosystems?	Estimated or Referenced
Seaweed Sinking (mCDR)	[6]	1	Global	High	Referenced
Seaweed Sinking (mCDR)	[94]	0.1	Global	High	Referenced
Seaweed Sinking (mCDR)	[94]	1	Global	High	Referenced
Seaweed Sinking (mCDR)	[7]	0.002	Global	High	Referenced
Seaweed Sinking (mCDR)	[8]	12.5	Global	High	Referenced
Seaweed Sinking (mCDR)	[8]	20.5	Global	High	Referenced
Seaweed Sinking (mCDR)	[32]	0.0008	Regional	Unclear	Referenced
Seaweed Sinking (mCDR)	[32]	0.002	Regional	Unclear	Referenced
Seaweed Sinking (mCDR)	[70]	0.00001	Regional	Unclear	Estimated
Seaweed Sinking (mCDR)	[70]	0.0029	Regional	Unclear	Referenced
Microalgae: Offshore Open (mCC)	[48]	0.0033	Global	Unclear	Estimated
Microalgae: Onshore (CC)	[1]	1	Global	Unclear	Referenced
Microalgae: Onshore (CC)	[1]	5	Global	Unclear	Referenced
Microalgae: Onshore (CC)	[47]	0.2	Global	Unclear	Referenced
Microalgae: Onshore (CC)	[47]	0.9	Global	Unclear	Referenced

A.5 Data Used in Supplementary Figure 2

Table A-13. Data for Figure A-2

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
AU (mCDR)	[37]	10	Organic	Referenced
AU (mCDR)	[37]	50	Organic	Referenced
AU (mCDR)	[37]	100	Organic	Referenced
AU (mCDR)	[37]	150	Organic	Referenced
AU (mCDR)	[4]	50	Organic	Referenced
AU (mCDR)	[4]	0.001	CO_2	Estimated
AU (mCDR)	[5]	0.001	CO_2	Estimated
AU (mCDR)	[23]	0.1	Product	Estimated
AU (mCDR)	[23]	1,000	Product	Estimated
Deep-Seabed Sequestration (mCS)	[10]	100,000,000	CO_2	Estimated
Deep-Seabed Sequestration (mCS)	[38]	100,000,000	CO_2	Estimated
Deep-Seabed Sequestration (mCS)	[39]	100,000,000	CO_2	Estimated
Deep-Seabed Sequestration (mCS)	[40]	100,000,000	CO_2	Estimated
Deep-Seabed Sequestration (mCS)	[76]	100,000,000	CO_2	Estimated
Deep-Seabed Sequestration (mCS)	[77]	100,000,000	CO_2	Estimated
Deep-Sea Basalt Sequestration (mCS)	[41]	1,000,000	Carbonate	Estimated
Deep-Sea Basalt Sequestration (mCS)	[75]	1,000,000	Carbonate	Referenced
Deep-Sea Basalt Sequestration (mCS)	[9]	1,000,000	Carbonate	Referenced
Deep-Sea Basalt Sequestration (mCS)	[60]	1,000,000	Carbonate	Referenced

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
Deep-Sea Aquifer Sequestration (mCS)	[31]	10	CO_2	Referenced
Deep-Sea Aquifer Sequestration (mCS)	[31]	100	CO_2	Referenced
Deep-Sea Aquifer Sequestration (mCS)	[31]	1,000	CO_2	Referenced
Deep-Sea Aquifer Sequestration (mCS)	[31]	1,000,000	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[37]	21	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[37]	508	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[37]	50	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[37]	500	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[37]	1,000	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[37]	100	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	300	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	700	CO_2	Referenced
Deep-Sea Water Column	[30]	1,000	CO_2	Referenced

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
Sequestration (mCS)				
Deep-Sea Water Column Sequestration (mCS)	[30]	30	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	400	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	10,000	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	100	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	500	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[10]	100	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[76]	10	CO_2	Referenced
Deep-Sea Water Column Sequestration (mCS)	[76]	100	CO_2	Referenced
eChem Acid Stripping CO_2 (mCC)	[74]	1,000	CO_2	Referenced
eChem Acid Stripping CO_2 (mCC)	[74]	1,000,000	CO_2	Referenced
eChem Acid Stripping CO_2 (mCC)	[33]	0.1	Product	Estimated
eChem Acid Stripping CO_2 (mCC)	[33]	1	Product	Estimated

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
eChem Acid Stripping CO_2 (mCC)	[28]	1	CO_2	Referenced
eChem Acid Stripping CO_2 (mCC)	[14]	1	CO_2	Referenced
eChem Acid Stripping CO_2 (mCC)	[25]	0.1	Product	Estimated
eChem Acid Stripping CO_2 (mCC)	[25]	1	Product	Estimated
eChem Acid Stripping CO_2 (mCC)	[26]	0.1	Product	Estimated
eChem Acid Stripping CO_2 (mCC)	[26]	1	Product	Estimated
eChem Acid Stripping CO_2 (mCC)	[21]	0.1	Product	Estimated
eChem Acid Stripping CO_2 (mCC)	[21]	1	Product	Estimated
eChem Base Addition (mCDR)	[74]	10,000	Bicarbonate	Referenced
eChem Base Addition (mCDR)	[4]	100,000	Bicarbonate	Referenced
eChem Base Addition (mCDR)	[46]	100,000	Bicarbonate	Referenced
eChem Base Addition (mCDR)	[64]	10,000	Bicarbonate	Referenced
eChem Base Addition (mCDR)	[64]	100,000	Bicarbonate	Referenced
eChem Base Addition (mCDR)	[11]	300	Bicarbonate	Referenced
eChem Base Addition (mCDR)	[11]	2,000	Bicarbonate	Referenced
eChem Base Addition (mCDR)	[11]	100,000	Bicarbonate	Estimated

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
eChem Base Addition (mCDR)	[11]	100	Bicarbonate	Estimated
eChem Base Addition (mCDR)	[54]	100,000	Bicarbonate	Estimated
eChem Base Addition (mCDR)	[42]	100,000	Bicarbonate	Estimated
eChem Base Addition (mCDR)	[12]	100	Bicarbonate	Referenced
eChem Base Stripping CO_2 (mCC)	[14]	1	CO_2	Referenced
eChem Carbonate Production (mCDR)	[74]	100	Carbonate	Referenced
eChem Carbonate Production (mCDR)	[74]	1,000	Carbonate	Referenced
eChem Carbonate Production (mCDR)	[4]	100,000,000	Carbonate	Referenced
eChem Carbonate Production (mCDR)	[28]	100,000,000	Carbonate	Estimated
eChem Carbonate Production (mCDR)	[14]	100,000,000	Carbonate	Estimated
eChem Carbonate Production (mCDR)	[65]	100,000,000	Carbonate	Estimated
eChem Carbonate Production (mCDR)	[73]	100,000,000	Carbonate	Estimated
eChem Carbonate Production (mCDR)	[15]	100,000,000	Carbonate	Estimated
eChem Carbonate Production (mCDR)	[93]	100,000,000	Carbonate	Estimated
Seaweed Farming (mCC)	[4]	1	Product	Estimated
Seaweed Farming (mCC)	[4]	10	Product	Referenced
Seaweed Farming (mCC)	[34]	0.1	Product	Estimated

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
Seaweed Farming (mCC)	[34]	1	Product	Estimated
Seaweed Farming (mCC)	[70]	20	Organic	Referenced
Seaweed Farming (mCC)	[70]	25	Organic	Estimated
Seaweed Farming (mCC)	[71]	10	Product	Referenced
Seaweed Farming (mCC)	[71]	10	Product	Referenced
Seaweed Farming (mCC)	[71]	1,000	Product	Referenced
Seaweed Farming (mCC)	[71]	0.01	Product	Estimated
Seaweed Farming (mCC)	[71]	0.1	Product	Estimated
Seaweed Farming (mCC)	[71]	0.1	Product	Estimated
Seaweed Farming (mCC)	[71]	1	Product	Referenced
Seaweed Farming (mCC)	[37]	10	Organic	Referenced
Seaweed Farming (mCC)	[37]	50	Organic	Referenced
Seaweed Farming (mCC)	[37]	100	Organic	Referenced
Seaweed Farming (mCC)	[37]	150	Organic	Referenced
Seaweed Sinking (mCDR)	[4]	100	Organic	Referenced
Seaweed Sinking (mCDR)	[4]	1,000	Organic	Referenced
Seaweed Sinking (mCDR)	[70]	0.001	CO_2	Estimated
Seaweed Sinking (mCDR)	[70]	700	Organic	Referenced
Seaweed Sinking (mCDR)	[70]	900	Organic	Referenced
Seaweed Sinking (mCDR)	[70]	1,400	Organic	Referenced
Seaweed Sinking (mCDR)	[70]	1,500	Organic	Estimated

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
Seaweed Sinking (mCDR)	[94]	750	Organic	Referenced
Seaweed Sinking (mCDR)	[94]	800	Organic	Estimated
Seaweed Sinking (mCDR)	[112]	1,000	Organic	Referenced
Seaweed Sinking (mCDR)	[72]	100	Organic	Referenced
Seaweed Sinking (mCDR)	[72]	1,000	Organic	Referenced
Seaweed Sinking (mCDR)	[104]	100	Organic	Referenced
Seaweed Sinking (mCDR)	[104]	1,000	Organic	Referenced
Seaweed Sinking (mCDR)	[6]	100	Organic	Referenced
Seaweed Sinking (mCDR)	[7]	100	Organic	Referenced
Seaweed Sinking (mCDR)	[7]	1,000	Organic	Referenced
Seaweed Sinking (mCDR)	[7]	1,000,000	Organic	Referenced
Seaweed Sinking (mCDR)	[37]	21	Organic	Referenced
Seaweed Sinking (mCDR)	[37]	508	Organic	Referenced
Seaweed Sinking (mCDR)	[37]	50	Organic	Referenced
Seaweed Sinking (mCDR)	[37]	500	Organic	Referenced
Seaweed Sinking (mCDR)	[37]	1,000	Organic	Referenced
Seaweed Sinking (mCDR)	[37]	100	Organic	Referenced
Seaweed Sinking (mCDR)	[8]	900	Organic	Referenced
Microalgae: Generic (mCC)	[95]	0.1	Product	Estimated
Microalgae: Generic (mCC)	[95]	1	Product	Estimated

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
Microalgae: Generic (mCC)	[95]	0.01	Product	Estimated
Microalgae: Generic (mCC)	[95]	0.1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[66]	0.1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[66]	1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[81]	0.1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[81]	1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[81]	0.01	Product	Estimated
Microalgae: Offshore Closed (mCC)	[81]	0.1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[43]	0.1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[43]	1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[17]	0.1	Product	Estimated
Microalgae: Offshore Closed (mCC)	[17]	1	Product	Estimated
Microalgae: Offshore Open (mCC)	[16]	0.1	Product	Estimated
Microalgae: Offshore Open (mCC)	[16]	1	Product	Estimated
Microalgae: Offshore Open (mCC)	[16]	10	Product	Estimated

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
Microalgae: Offshore Open (mCC)	[16]	1,000	Product	Estimated
Microalgae: Offshore Open (mCC)	[96]	0.1	Product	Estimated
Microalgae: Offshore Open (mCC)	[96]	1	Product	Estimated
Microalgae: Offshore Open (mCC)	[96]	0.01	Product	Estimated
Microalgae: Offshore Open (mCC)	[96]	0.1	Product	Estimated
Microalgae: Offshore Open (mCC)	[48]	0.1	Product	Estimated
Microalgae: Offshore Open (mCC)	[48]	1	Product	Estimated
Microalgae: Offshore Open (mCC)	[80]	0.01	Product	Estimated
Microalgae: Offshore Open (mCC)	[80]	0.1	Product	Estimated
Microalgae: Offshore Open (mCC)	[57]	0.1	Product	Estimated
Microalgae: Offshore Open (mCC)	[57]	1	Product	Estimated
Microalgae: Offshore Open (mCC)	[97]	0.1	Product	Estimated
Microalgae: Offshore Open (mCC)	[97]	1	Product	Estimated
Microalgae: Offshore Open (mCC)	[97]	0.01	Product	Estimated
Microalgae: Offshore Open (mCC)	[97]	0.1	Product	Estimated

Method	Source	Years of Storage	Form of storage	Estimated or Referenced
Microalgae: Onshore (CC)	[98]	0.1	Product	Estimated
Microalgae: Onshore (CC)	[98]	1	Product	Estimated
Microalgae: Onshore (CC)	[47]	0.01	Product	Estimated
Microalgae: Onshore (CC)	[47]	0.1	Product	Estimated
Microalgae: Onshore (CC)	[68]	10	Product	Estimated
Microalgae: Onshore (CC)	[68]	1,000	Product	Estimated

A.6 Data Used in Supplementary Figure 3

Table A-14. Data for Figure A-3

Method	Source	Energy (kWh/tCO_2)	Energy Type	Estimated or Referenced?
AU (mCDR)	[23]	17,476	Mechanical	Estimated
AU (mCDR)	[24]	60	Mechanical	Estimated
AU (mCDR)	[3]	3,400	Mechanical	Estimated
AU (mCDR)	[3]	51,000	Mechanical	Estimated
DAC (CC)	[9]	630	Electrical & Mechanical	Referenced
DAC (CC)	[13]	194	Electrical & Mechanical	Referenced
DAC (CC)	[13]	3,472	Electrical & Mechanical	Referenced
DAC (CC)	[25]	1,540	Electrical & Mechanical	Referenced
DAC (CC)	[25]	2,450	Electrical & Mechanical	Referenced
Deep-Seabed Sequestration (mCS)	[27]	55	Electrical	Estimated
Deep-Seabed Sequestration (mCS)	[27]	18	Electrical	Estimated
Deep-Seabed Sequestration (mCS)	[27]	0.4	Electrical	Estimated
Deep-Seabed Sequestration (mCS)	[27]	0.7	Mechanical	Estimated

Method	Source	Energy (kWh/tCO_2)	Energy Type	Estimated or Referenced?
Deep-Seabed Sequestration (mCS)	[27]	74.1	Electrical & Mechanical	Estimated
Deep-Sea Basalt Sequestration (mCS)	[9]	65	Mechanical	Estimated
Deep-Sea Basalt Sequestration (mCS)	[9]	257	Mechanical	Estimated
Deep-Sea Water Column Sequestration (mCS)	[29]	430	Mechanical	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	65	Mechanical	Estimated
Deep-Sea Water Column Sequestration (mCS)	[30]	257	Mechanical	Estimated
Deep-Sea Water Column Sequestration (mCS)	[30]	13	Mechanical	Estimated
Deep-Sea Water Column Sequestration (mCS)	[30]	52	Mechanical	Estimated
Deep-Sea Aquifer Sequestration (mCS)	[31]	65	Mechanical	Estimated
Deep-Sea Aquifer Sequestration (mCS)	[31]	257	Mechanical	Estimated
eChem Acid Stripping CO_2 (mCC)	[33]	1,540	Electrical	Referenced
eChem Acid Stripping CO_2 (mCC)	[25]	5,580	Electrical & Mechanical	Estimated
eChem Acid Stripping CO_2 (mCC)	[25]	1,295	Electrical & Mechanical	Estimated
eChem Acid Stripping CO_2 (mCC)	[25]	1,055	Electrical & Mechanical	Estimated
eChem Acid Stripping CO_2 (mCC)	[25]	5,820	Electrical & Mechanical	Estimated
eChem Acid Stripping CO_2 (mCC)	[26]	2,123	Electrical & Mechanical	Estimated
eChem Acid Stripping CO_2 (mCC)	[28]	2,485	Electrical	Estimated
eChem Acid Stripping CO_2 (mCC)	[25]	980	Electrical	Referenced
eChem Acid Stripping CO_2 (mCC)	[25]	1,220	Electrical	Referenced
eChem Acid Stripping CO_2 (mCC)	[4]	3,100	Electrical	Referenced
eChem Acid Stripping CO_2 (mCC)	[26]	1,540	Electrical	Estimated

Method	Source	Energy (kWh/tCO_2)	Energy Type	Estimated or Referenced?
eChem Acid Stripping CO_2 (mCC)	[26]	7,500	Electrical	Estimated
eChem Acid Stripping CO_2 (mCC)	[26]	542	Electrical	Estimated
eChem Acid Stripping CO_2 (mCC)	[28]	550	Mechanical	Estimated
eChem Acid Stripping CO_2 (mCC)	[25]	4,600	Mechanical	Referenced
eChem Acid Stripping CO_2 (mCC)	[25]	75	Mechanical	Referenced
eChem Acid Stripping CO_2 (mCC)	[26]	583	Mechanical	Estimated
eChem Acid Stripping CO_2 (mCC)	[28]	3,131	Electrical & Mechanical	Estimated
eChem Base Addition (mCDR)	[11]	1,146	Electrical	Estimated
eChem Base Addition (mCDR)	[11]	34	Mechanical	Estimated
eChem Base Addition (mCDR)	[11]	1,180	Electrical & Mechanical	Estimated
eChem Base Addition (mCDR)	[54]	2,273	Electrical & Mechanical	Referenced
eChem Base Addition (mCDR)	[42]	1,744	Electrical & Mechanical	Estimated
eChem Base Addition (mCDR)	[42]	2,711	Electrical & Mechanical	Estimated
eChem Base Addition (mCDR)	[42]	3,061	Electrical & Mechanical	Estimated
eChem Base Addition (mCDR)	[12]	636	Electrical & Mechanical	Estimated
eChem Base Addition (mCDR)	[12]	2,546	Electrical & Mechanical	Estimated
eChem Base Addition (mCDR)	[13]	500	Electrical & Mechanical	Estimated
eChem Base Addition (mCDR)	[13]	1,556	Electrical & Mechanical	Estimated
eChem Base Stripping CO_2 (mCC)	[4]	4,400	Electrical	Referenced
eChem Carbonate Production (mCDR)	[28]	4,151	Electrical	Estimated
eChem Carbonate Production (mCDR)	[15]	70	Electrical	Referenced
eChem Carbonate Production (mCDR)	[15]	2,300	Electrical	Referenced

Method	Source	Energy (kWh/tCO_2)	Energy Type	Estimated or Referenced?
eChem Carbonate Production (mCDR)	[28]	234	Mechanical	Estimated
eChem Carbonate Production (mCDR)	[15]	159	Mechanical	Referenced
eChem Carbonate Production (mCDR)	[28]	4,386	Electrical & Mechanical	Estimated
eChem Carbonate Production (mCDR)	[65]	1,839	Electrical & Mechanical	Estimated
eChem Carbonate Production (mCDR)	[65]	2,209	Electrical & Mechanical	Estimated
eChem Carbonate Production (mCDR)	[15]	229	Electrical & Mechanical	Estimated
eChem Carbonate Production (mCDR)	[15]	2,459	Electrical & Mechanical	Estimated
eChem Carbonate Production (mCDR)	[73]	890	Electrical & Mechanical	Estimated
Seaweed Farming (mCC)	[34]	26	Electrical	Estimated
Seaweed Farming (mCC)	[29]	60	Electrical	Referenced
Seaweed Farming (mCC)	[34]	554	Electrical	Estimated
Seaweed Farming (mCC)	[34]	412	Electrical	Estimated
Seaweed Farming (mCC)	[29]	150	Electrical	Referenced
Seaweed Farming (mCC)	[78]	2	Electrical	Estimated
Seaweed Farming (mCC)	[78]	12	Electrical	Estimated
Seaweed Farming (mCC)	[78]	3	Electrical	Estimated
Seaweed Farming (mCC)	[78]	24	Electrical	Estimated
Seaweed Farming (mCC)	[78]	93	Electrical	Estimated
Seaweed Farming (mCC)	[78]	293	Electrical	Estimated
Seaweed Farming (mCC)	[29]	340	Mechanical	Referenced
Seaweed Sinking (mCDR)	[32]	10	Mechanical	Estimated
Seaweed Sinking (mCDR)	[32]	22	Mechanical	Estimated
Microalgae: Offshore Closed (mCC)	[18]	348,000	Free Marine	Estimated
Microalgae: Offshore Closed (mCC)	[17]	4,100	Free Marine	Estimated
Microalgae: Offshore Closed (mCC)	[17]	64,520	Free Marine	Estimated
Microalgae: Offshore Open (mCC)	[16]	3,730	Free Marine	Estimated

Method	Source	Energy (kWh/tCO_2)	Energy Type	Estimated or Referenced?
Microalgae: Offshore Open (mCC)	[16]	176,000	Free Marine	Estimated
Onshore Seq: Basalt (CC)	[44]	77.6	Electrical & Mechanical	Estimated
Onshore Seq: Basalt (CC)	[44]	128	Electrical & Mechanical	Estimated
Onshore Seq: Basalt (CC)	[44]	833	Electrical & Mechanical	Estimated

A.7 Data Used in Supplementary Figure 4

Table A-15. Data for Figure A-4

Method	Source	2022$/$tCO_2$	Inflation Adjusted?	Estimated or Referenced
AU (mCDR)	[4]	110	No	Estimated
AU (mCDR)	[4]	150	No	Referenced
AU (mCDR)	[1]	22	Yes	Estimated
AU (mCDR)	[1]	135	Yes	Referenced
DAC (CC)	[9]	32	Yes	Referenced
DAC (CC)	[9]	1,274	Yes	Referenced
DAC (CC)	[9]	64	Yes	Referenced
DAC (CC)	[25]	107	Yes	Referenced
DAC (CC)	[25]	264	Yes	Referenced
Deep-Seabed Sequestration (mCS)	[77]	42	Yes	Referenced
Deep-Seabed Sequestration (mCS)	[39]	5	Yes	Referenced
Deep-Seabed Sequestration (mCS)	[39]	1,274	Yes	Referenced
Deep-Seabed Sequestration (mCS)	[39]	181	Yes	Referenced
Deep-Seabed Sequestration (mCS)	[39]	23	Yes	Referenced
Deep-Seabed Sequestration (mCS)	[39]	45	Yes	Referenced
Deep-Seabed Sequestration (mCS)	[77]	81	Yes	Referenced
Deep-Seabed Sequestration (mCS)	[77]	42	Yes	Referenced
Deep-Sea Basalt Sequestration (mCS)	[9]	1	Yes	Referenced
Deep-Sea Basalt Sequestration (mCS)	[9]	11	Yes	Referenced
Deep-Sea Basalt Sequestration (mCS)	[41]	108	Yes	Estimated
Deep-Sea Aquifer Sequestration (mCS)	[39]	5	Yes	Referenced

Method	Source	2022$/tCO$_2$	Inflation Adjusted?	Estimated or Referenced
Deep-Sea Aquifer Sequestration (mCS)	[39]	1,274	Yes	Referenced
Deep-Sea Aquifer Sequestration (mCS)	[39]	74	Yes	Referenced
Deep-Sea Aquifer Sequestration (mCS)	[39]	17	Yes	Referenced
Deep-Sea Aquifer Sequestration (mCS)	[39]	40	Yes	Referenced
Deep-Sea Aquifer Sequestration (mCS)	[31]	16	Yes	Referenced
Deep-Sea Aquifer Sequestration (mCS)	[77]	34	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[77]	54	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	18	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	20	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	22	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	24	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	9	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[30]	47	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[113]	34	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[31]	6	Yes	Referenced
Deep-Sea Water Column Sequestration (mCS)	[31]	39	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[1]	27	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[1]	162	Yes	Estimated
eChem Acid Stripping CO_2 (mCC)	[14]	515	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[14]	847	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[14]	859	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[14]	1,271	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[14]	2,173	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[14]	2,782	Yes	Referenced

Method	Source	2022$/tCO$_2$	Inflation Adjusted?	Estimated or Referenced
eChem Acid Stripping CO_2 (mCC)	[25]	570	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[25]	615	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[25]	2,131	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[25]	2,336	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[62]	78	Yes	Referenced
eChem Acid Stripping CO_2 (mCC)	[62]	139	Yes	Referenced
eChem Base Addition (mCDR)	[1]	27	Yes	Referenced
eChem Base Addition (mCDR)	[1]	162	Yes	Estimated
eChem Base Addition (mCDR)	[11]	130	No	Referenced
eChem Base Addition (mCDR)	[11]	250	No	Referenced
eChem Base Addition (mCDR)	[11]	93	No	Referenced
eChem Base Addition (mCDR)	[54]	264	Yes	Referenced
eChem Base Addition (mCDR)	[54]	105	Yes	Referenced
eChem Base Addition (mCDR)	[42]	196	Yes	Referenced
eChem Base Addition (mCDR)	[42]	153	Yes	Referenced
eChem Base Addition (mCDR)	[42]	110	Yes	Referenced
eChem Base Stripping CO_2 (mCC)	[14]	441	Yes	Referenced
eChem Base Stripping CO_2 (mCC)	[14]	714	Yes	Referenced
eChem Base Stripping CO_2 (mCC)	[14]	689	Yes	Referenced
eChem Base Stripping CO_2 (mCC)	[14]	1,062	Yes	Referenced
eChem Base Stripping CO_2 (mCC)	[14]	1,271	Yes	Referenced
eChem Base Stripping CO_2 (mCC)	[14]	1,594	Yes	Referenced
eChem Carbonate Production (mCDR)	[14]	118	Yes	Referenced
eChem Carbonate Production (mCDR)	[14]	354	Yes	Referenced
eChem Carbonate Production (mCDR)	[15]	154	Yes	Referenced
eChem Carbonate Production (mCDR)	[15]	59	Yes	Referenced
eChem Carbonate Production (mCDR)	[15]	11	Yes	Referenced
Seaweed Farming (mCC)	[72]	75	Yes	Referenced

Method	Source	2022$/tCO$_2$	Inflation Adjusted?	Estimated or Referenced
Seaweed Farming (mCC)	[72]	159	Yes	Referenced
Seaweed Farming (mCC)	[7]	82	Yes	Referenced
Seaweed Farming (mCC)	[7]	627	Yes	Referenced
Seaweed Farming (mCC)	[7]	31,441	Yes	Referenced
Seaweed Farming (mCC)	[7]	206	Yes	Referenced
Seaweed Farming (mCC)	[7]	545	Yes	Referenced
Seaweed Farming (mCC)	[7]	889	Yes	Referenced
Seaweed Farming (mCC)	[7]	1,685	Yes	Referenced
Seaweed Farming (mCC)	[7]	708	Yes	Referenced
Seaweed Farming (mCC)	[7]	16,426	Yes	Referenced
Seaweed Farming (mCC)	[7]	1,491	Yes	Referenced
Seaweed Farming (mCC)	[7]	2,222	Yes	Referenced
Seaweed Farming (mCC)	[79]	30	Yes	Estimated
Seaweed Farming (mCC)	[79]	100	Yes	Estimated
Seaweed Sinking (mCDR)	[29]	21	Yes	Referenced
Seaweed Sinking (mCDR)	[29]	12	Yes	Referenced
Seaweed Sinking (mCDR)	[29]	9	Yes	Referenced
Seaweed Sinking (mCDR)	[6]	17,048	No	Referenced
Seaweed Sinking (mCDR)	[6]	1,257	No	Referenced
Seaweed Sinking (mCDR)	[32]	42	Yes	Referenced
Seaweed Sinking (mCDR)	[32]	102	Yes	Referenced
Microalgae: Offshore Closed (mCC)	[80]	1,028	Yes	Estimated
Microalgae: Offshore Closed (mCC)	[81]	289	Yes	Estimated
Microalgae: Offshore Closed (mCC)	[81]	2,221	Yes	Estimated
Microalgae: Offshore Open (mCC)	[80]	254	Yes	Estimated
Microalgae: Onshore (CC)	[1]	27	Yes	Referenced
Microalgae: Onshore (CC)	[1]	162	Yes	Estimated
Microalgae: Onshore (CC)	[98]	40	Yes	Referenced
Microalgae: Onshore (CC)	[47]	289	Yes	Referenced
Microalgae: Onshore (CC)	[47]	1,154	Yes	Referenced

A.8 Data Used in Supplementary Figure 5

Table A-16. Data for Figure A-5

Method	Source	TRL	Estimated or Referenced?
AU (mCDR)	[35]	5	Estimated
AU (mCDR)	[35]	5	Estimated
AU (mCDR)	[23]	6	Estimated
AU (mCDR)	[36]	5	Estimated
AU (mCDR)	[86]	3	Estimated
AU (mCDR)	[35]	5	Estimated
AU (mCDR)	[99]	3	Estimated
AU (mCDR)	[36]	5	Estimated
AU (mCDR)	[35]	6	Estimated
AU (mCDR)	[37]	3	Estimated
AU (mCDR)	[1]	5	Estimated
AU (mCDR)	[3]	5	Estimated
AU (mCDR)	[59]	5	Estimated
AU (mCDR)	[5]	2	Estimated
AU (mCDR)	[87]	5	Estimated
AU (mCDR)	[88]	5	Estimated
AU (mCDR)	[24]	6	Estimated
AU (mCDR)	[4]	5	Estimated
AU (mCDR)	[36]	5	Estimated
AU (mCDR)	[36]	2	Estimated
AU (mCDR)	[35]	5	Estimated
AU (mCDR)	[36]	5	Estimated
AU (mCDR)	[35]	5	Estimated
AU (mCDR)	[100]	3	Estimated
AU (mCDR)	[101]	2	Estimated
AU (mCDR)	[102]	3	Estimated
AU (mCDR)	[36]	5	Estimated
Deep-Seabed Sequestration (mCS)	[10]	3	Estimated
Deep-Seabed Sequestration (mCS)	[38]	2	Estimated
Deep-Seabed Sequestration (mCS)	[39]	2	Estimated
Deep-Seabed Sequestration (mCS)	[40]	3	Estimated
Deep-Seabed Sequestration (mCS)	[30]	4	Estimated
Deep-Seabed Sequestration (mCS)	[76]	1	Estimated

Method	Source	TRL	Estimated or Referenced?
Deep-Seabed Sequestration (mCS)	[27]	1	Estimated
Deep-Seabed Sequestration (mCS)	[55]	1	Estimated
Deep-Seabed Sequestration (mCS)	[77]	1	Estimated
Deep-Seabed Sequestration (mCS)	[61]	1	Estimated
Deep-Sea Basalt Sequestration (mCS)	[41]	4	Estimated
Deep-Sea Basalt Sequestration (mCS)	[9]	3	Estimated
Deep-Sea Basalt Sequestration (mCS)	[60]	5	Estimated
Deep-Sea Aquifer Sequestration (mCS)	[31]	7	Estimated
Deep-Sea Aquifer Sequestration (mCS)	[31]	7	Estimated
Deep-Sea Aquifer Sequestration (mCS)	[39]	2	Estimated
Deep-Sea Water Column Sequestration (mCS)	[30]	4–5	Estimated
Deep-Sea Water Column Sequestration (mCS)	[30]	4	Estimated
Deep-Sea Water Column Sequestration (mCS)	[30]	4	Estimated
Deep-Sea Water Column Sequestration (mCS)	[37]	3	Estimated
Deep-Sea Water Column Sequestration (mCS)	[31]	4	Estimated
eChem Acid Stripping CO_2 (mCC)	[1]	4	Estimated
eChem Acid Stripping CO_2 (mCC)	[33]	3	Estimated
eChem Acid Stripping CO_2 (mCC)	[28]	4	Estimated
eChem Acid Stripping CO_2 (mCC)	[14]	3	Estimated
eChem Acid Stripping CO_2 (mCC)	[25]	3	Estimated
eChem Acid Stripping CO_2 (mCC)	[26]	3	Estimated
eChem Acid Stripping CO_2 (mCC)	[21]	4	Estimated
eChem Base Addition (mCDR)	[1]	3	Estimated
eChem Base Addition (mCDR)	[56]	4	Estimated
eChem Base Addition (mCDR)	[85]	4	Estimated
eChem Base Addition (mCDR)	[64]	4	Estimated
eChem Base Addition (mCDR)	[11]	2	Estimated
eChem Base Addition (mCDR)	[54]	3	Estimated
eChem Base Addition (mCDR)	[42]	3	Estimated
eChem Base Addition (mCDR)	[12]	2	Estimated
eChem Base Addition (mCDR)	[13]	3	Estimated
eChem Base Stripping CO_2 (mCC)	[14]	3	Estimated

Method	Source	TRL	Estimated or Referenced?
eChem Carbonate Production (mCDR)	[28]	4	Estimated
eChem Carbonate Production (mCDR)	[65]	3	Estimated
eChem Carbonate Production (mCDR)	[73]	3	Estimated
eChem Carbonate Production (mCDR)	[15]	2	Estimated
eChem Carbonate Production (mCDR)	[93]	3	Estimated
Seaweed Farming (mCC)	[4]	7	Estimated
Seaweed Farming (mCC)	[84]	5	Estimated
Seaweed Farming (mCC)	[72]	7	Estimated
Seaweed Farming (mCC)	[29]	2	Estimated
Seaweed Farming (mCC)	[103]	5	Estimated
Seaweed Farming (mCC)	[58]	4	Estimated
Seaweed Farming (mCC)	[6]	7	Estimated
Seaweed Farming (mCC)	[94]	7	Estimated
Seaweed Farming (mCC)	[7]	7	Estimated
Seaweed Farming (mCC)	[79]	2	Estimated
Seaweed Farming (mCC)	[72]	1	Estimated
Seaweed Farming (mCC)	[69]	7	Estimated
Seaweed Farming (mCC)	[34]	3	Estimated
Seaweed Farming (mCC)	[78]	3	Estimated
Seaweed Farming (mCC)	[71]	6	Estimated
Seaweed Sinking (mCDR)	[4]	4	Estimated
Seaweed Sinking (mCDR)	[70]	3	Estimated
Seaweed Sinking (mCDR)	[94]	4	Estimated
Seaweed Sinking (mCDR)	[94]	4	Estimated
Seaweed Sinking (mCDR)	[104]	4–5	Estimated
Seaweed Sinking (mCDR)	[105]	5	Estimated
Seaweed Sinking (mCDR)	[105]	5	Estimated
Seaweed Sinking (mCDR)	[105]	5	Estimated
Seaweed Sinking (mCDR)	[105]	5	Estimated
Seaweed Sinking (mCDR)	[6]	4	Estimated
Seaweed Sinking (mCDR)	[94]	4	Estimated
Seaweed Sinking (mCDR)	[37]	3	Estimated
Seaweed Sinking (mCDR)	[8]	3	Estimated
Seaweed Sinking (mCDR)	[32]	6	Estimated
Microalgae: Offshore Closed (mCC)	[18]	5	Estimated

Method	Source	TRL	Estimated or Referenced?
Microalgae: Offshore Closed (mCC)	[66]	5	Estimated
Microalgae: Offshore Closed (mCC)	[81]	4	Estimated
Microalgae: Offshore Closed (mCC)	[67]	4	Estimated
Microalgae: Offshore Closed (mCC)	[43]	4	Estimated
Microalgae: Offshore Closed (mCC)	[17]	3	Estimated
Microalgae: Offshore Generic (mCC)	[22]	4–5	Estimated
Microalgae: Offshore Open (mCC)	[16]	5	Estimated
Microalgae: Offshore Open (mCC)	[96]	5	Estimated
Microalgae: Offshore Open (mCC)	[48]	5	Estimated
Microalgae: Offshore Open (mCC)	[80]	5	Estimated
Microalgae: Offshore Open (mCC)	[57]	4	Estimated
Microalgae: Offshore Open (mCC)	[97]	4	Estimated
Microalgae: Onshore (CC)	[1]	5–7	Estimated
Microalgae: Onshore (CC)	[68]	3	Estimated
Microalgae: Onshore (CC)	[47]	5–7	Referenced