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Innovations & cost reductions in Direct Ocean Capture

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Executive summary

Given the nascent stage of the carbon dioxide removal (CDR) industry, there is limited data on the cost of specific CDR technologies, making it difficult for policymakers, researchers, and industry to make informed decisions. This paper was developed by Captura Corporation (hereafter referred to as Captura) to contribute to broader industry efforts to understand CDR costs by sharing new insight into its proprietary Direct Ocean Capture process. Through a comparison with prior academic studies, the paper offers a fresh perspective on the potential cost and feasibility of Direct Ocean Capture that can help inform future developments in the field.

The paper outlines Captura's Direct Ocean Capture approach that uses a pH-swing-based process to extract carbon dioxide (CO_2) from seawater. It provides a detailed description of Captura's technology roadmap and proprietary innovations in the key areas of electrodialysis, gas extraction, and energy use, providing performance insights from its research and development (R&D) and pilot program. Improved performance in these areas has enabled Captura to increase the system's energy and CO_2 capture efficiency and decrease capital cost. Further cost improvements are expected over time through 'economies of scale' and learning curves.

The progress and approach described in this paper supports a cost model that projects Captura achieving levelized costs of \$100-\$200 per ton of CO_2 removed. While recognizing that significant uncertainty remains ahead of widespread deployment, this projection is significantly lower than prior academic estimates and is highly competitive with projections for other nascent, high-integrity CDR technologies, such as Direct Air Capture.

Introduction

There is widespread scientific consensus that CDR is essential, alongside rapid and deep emissions reductions, to keep global warming within the 1.5°C or even 2°C threshold.[1] Leading climate assessments, including those from the Intergovernmental Panel on Climate Change[1] and the National Academies of Sciences, Engineering, and Medicine,[2] agree that CDR will need to be deployed at multi-gigaton scale annually by mid-century to achieve net zero emissions and meet Paris Agreement targets.

The ocean is one of the world's largest carbon sinks, holding roughly 50 times more carbon than the atmosphere.[3] It already plays a crucial role in climate mitigation by absorbing almost 30% of anthropogenic CO_2 emissions yearly.[4] This innate capacity to absorb atmospheric CO_2, coupled with the sheer scale of the ocean, means that any ocean-based CDR solutions proven to be viable and safe have the potential to scale to the levels needed.[5]

A range of ocean or marine CDR (mCDR) solutions are under development today that leverage the ocean's natural processes to deliver a net removal of CO_2 from the atmosphere. While noting that many others in academia and industry are also advancing the frontiers of mCDR, this paper explores the advances being made by Captura into a high-potential mCDR approach known as Direct Ocean Capture. This mCDR method extracts CO_2 directly from the ocean, creating capacity for the ocean to absorb additional CO_2 from the atmosphere.

Direct Ocean Capture can be implemented using existing, commercially available equipment and materials, but since many of these products were originally tailored for other functions, such a system would result in a cost point that is not economical in today's markets. This is underscored by existing literature on the topic. The most widely referenced studies on the cost of Direct Ocean Capture attribute high cost projections to systems based solely on commercially obtainable components, and highlight the need for key technological innovations to bring costs down.[6,7]

Since its founding at Caltech in 2021, Captura has advanced a proprietary Direct Ocean Capture technology that addresses these innovation and cost reduction needs, enabling a solution with potential for both economic viability and climate-relevant scalability. This paper explores Captura's technology roadmap to bring costs well below the prior estimates in the near-term, with further cost improvements expected to come through 'economies of scale' and learning curves seen when deploying a new technology at scale. This progress offers a fresh perspective on the feasibility of Direct Ocean Capture and positions it as a promising and highly relevant solution within the broader CDR landscape.

Technology overview

"Direct Ocean Capture" refers to technologies that extract CO_2 directly from the upper ocean where it is approximately 150 times more concentrated volumetrically compared to the air.[8] CO_2-depleted seawater is then returned to the ocean with the regenerated capacity to absorb an equivalent amount of CO_2 from the atmosphere. This absorption occurs due to the natural equilibrium that broadly exists between the atmospheric concentration of CO_2 and its concentration in the surface ocean (explained by Henry's Law).[9] By returning CO_2-depleted seawater to the ocean, the disequilibrium of CO_2 will result in CO_2 being drawn out of the atmosphere and into the ocean to re-equilibrate.

The net result of the process is the removal of CO_2 from the atmosphere via the ocean, without increasing the level of CO_2 in the ocean.

By leveraging the ocean for atmospheric CO_2 removal, Direct Ocean Capture inherently avoids many of the costs associated with technologies that extract CO_2 directly from the ambient air, where it is very dilute at approximately 426 parts per million.[10] Specifically, it eliminates the high capital costs of constructing large air contactors and the ongoing expenses of producing and replacing absorbents. Further, Direct Ocean Capture requires no fresh water or substantial land use, avoiding competition for agricultural resources.

Similar to land-based Direct Air Capture approaches, Direct Ocean Capture delivers the captured CO_2 as a measurable stream of purified gas that subsequently can be either safely and securely stored to deliver CDR or utilized to produce low carbon intensity products. Synthetic fuels, for example, can be produced by combining captured CO_2 with renewably produced hydrogen using gas-to-liquids technology. This delivers a sustainable, high-energy-density liquid fuel with an essentially unlimited feedstock that is well-suited for decarbonizing difficult-to-electrify sectors, such as aviation and maritime.

For deployment, Direct Ocean Capture facilities have the flexibility to be situated both on-shore and off-shore and can integrate into existing ocean-based infrastructure or develop purpose-built platforms. Onshore deployment benefits from synergies with industries that have existing infrastructure for water intake and discharge, such as desalination and thermal power plants, making them prime candidates for co-deployment. Offshore, the energy transition presents an opportunity to repurpose retiring oil and gas platforms and their associated geologic reservoirs for storage. In the long term, the industry envisions the development of standalone ocean-based platforms powered by offshore renewable energy.

The Direct Ocean Capture field is still nascent but quickly growing, with an increasing number of companies developing a variety of processes for this promising mCDR approach. Captura has developed an electrochemical pH-swing-based process that is described in the following section.

Captura process description

Captura's Direct Ocean Capture process has been demonstrated end-to-end at a 100-ton-per-year pilot system, located at AltaSea at the Port of Los Angeles in San Pedro, California (Figure 1.). The process includes the following key steps:

1. A stream of screen-filtered seawater is drawn into the facility.

2. A small fraction of the seawater (~0.5%) is diverted and pre-treated, or softened, to produce softened salt water.

3. The softened water is then passed through a bipolar membrane electrodialysis unit that uses renewable electricity to dissociate the salt and water into their constituent parts, forming acid (hydrochloric acid) and base (sodium hydroxide) streams.

4. The acid stream is added to the original ~99.5% seawater flow, lowering the pH of the seawater from ~8.1 to ~4 inside the system. This causes the majority of the dissolved inorganic carbon that is naturally present in the seawater to convert into dissolved CO_2.

5. The seawater then passes through a gas extraction system that uses a rough vacuum to extract the dissolved CO_2 from the seawater at a target of >90% extraction efficiency. The CO_2 stream is subsequently purified to remove nitrogen and oxygen, and delivered as a measurable stream of gaseous CO_2 that can either be geologically sequestered or utilized.

6. The base stream generated in the electrodialysis unit is then added to the acidified, CO_2-depleted seawater to neutralize the acid and restore its alkalinity. Due to its low CO_2 content, the seawater has a slightly higher pH (less acidic) than ambient conditions and may be diluted with ambient seawater if needed to ensure regulatory compliance.

7. The CO_2-depleted seawater is then released back into the ocean with the regenerated capacity to absorb atmospheric CO_2 at an amount equivalent to what was removed.

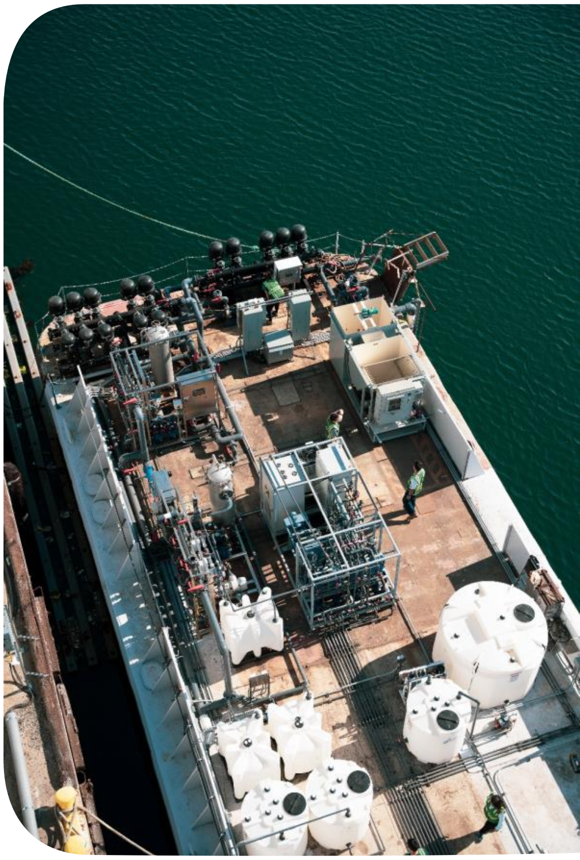

FIGURE 1.

Captura's 100 ton-per-year Direct Ocean Capture pilot system at the Port of Los Angeles

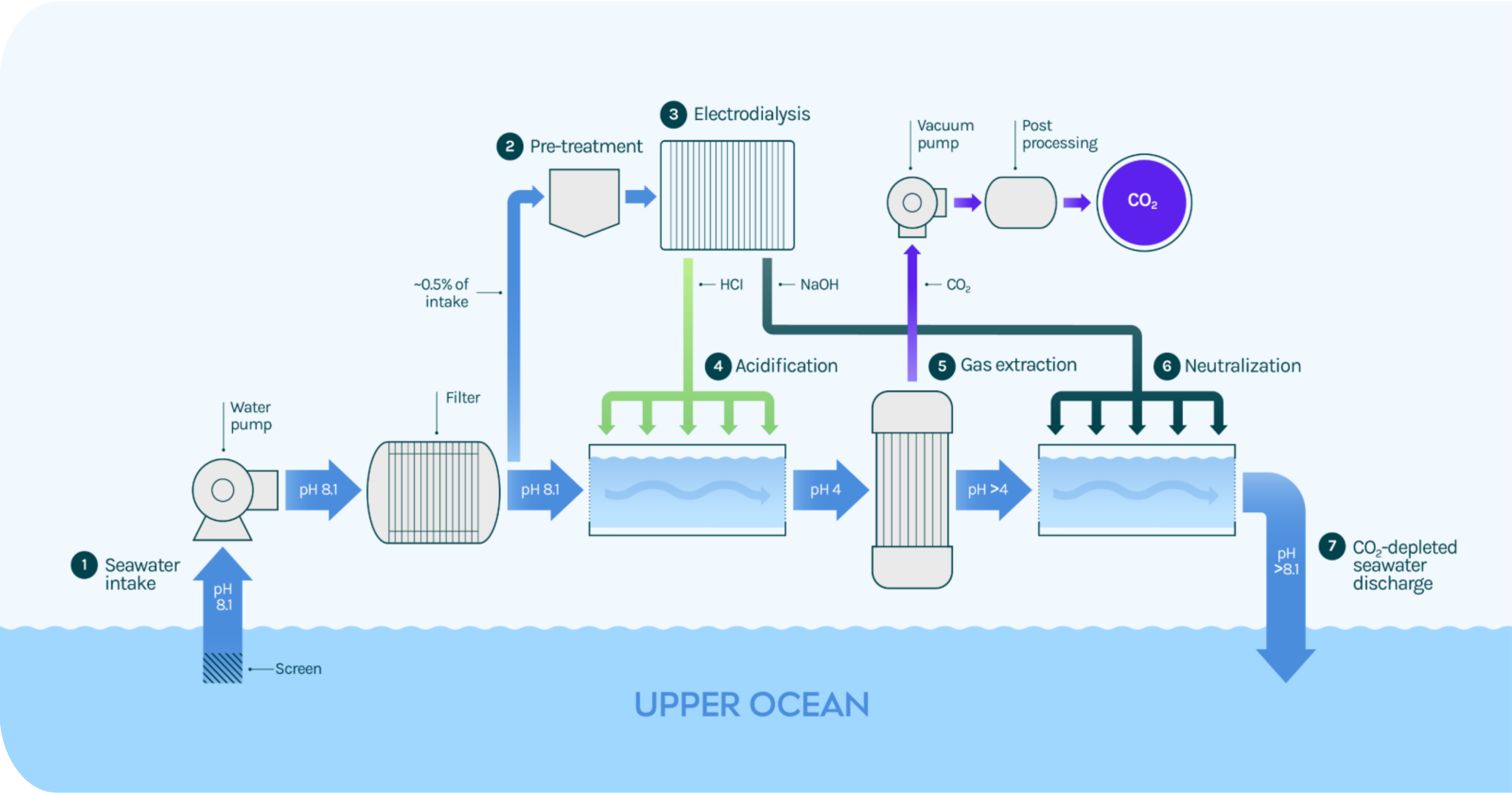

FIGURE 2.

Schematic of the major steps in the Captura Direct Ocean Capture process

These steps collectively create a "closed loop" process that captures CO_2 from the ocean and creates a stream of CO_2-depleted seawater that absorbs atmospheric CO_2 upon discharge. The term "closed loop" means the system doesn't require a constant supply of chemicals to operate, nor does it produce unwanted by-products that need disposal. It also means that no new materials are added to the ocean ecosystem. The process operates using only seawater and renewable electricity as inputs and produces only CO_2 and CO_2-depleted seawater as outputs.

Captura's solution can be implemented with existing commercial electrodialysis and gas extraction systems, combined with off-the-shelf industrial equipment for the rest of the process (water pumping and filtration). However, the commercial electrodialysis and gas extraction technologies available today were designed for other industries, rather than CO_2 extraction, and thus are expensive and energy intensive for this application. From day one, Captura's R&D focus has been on developing and optimizing proprietary membranes and sub-systems for both the electrodialysis and gas extraction steps. Improved performance in these areas increases the system's energy efficiency, decreases the capital cost, and enables higher CO_2 capture efficiency.

Existing literature on cost

Given the nascent stage of the CDR industry, there is very little publicly available data on the cost of individual technologies. The limited data that is available is often fragmented, outdated, or misinterpreted, making it difficult for policymakers, researchers, and industry to make informed decisions. For example, one of the most widely referenced sources for the cost of Direct Ocean Capture, and other CDR approaches, is the publicly available CDR pre-purchase agreements from Frontier Climate. These pre-purchase contract amounts, however, are not representative of actual plant costs; they are calculated by dividing a standard pre-purchase amount by the quantity of CDR each company is willing and able to sell from their project.

Additionally, few academic papers on the feasibility and cost of Direct Ocean Capture exist today. The most thorough estimate of potential costs was published in 2018 in the International Journal of Greenhouse Gas Control in a two-part study by Charles-Francois de Lannoy et al.[6] and Matthew D. Eisaman et al.[7] The papers evaluate a process akin to Captura's (referred to as the 'acid process') using equipment and materials commercially available in 2018. A techno-economic analysis was conducted to project a cost per ton for CO_2 captured from a small-scale plant with a 7,202 metric ton annual capacity and in various plant scenarios.

For a plant co-located with a desalination plant, the papers estimated a best-case cost of $436 per metric ton of CO_2, and for a standalone plant, a best-case cost of $1,839 per ton. The discrepancy is primarily attributed to the costs associated with additional water pumping and pre-treatment in standalone plants, and the additional expense of seawater intake and outfall piping that would be covered by the desalination plant in a co-location scenario.[7]

Eisaman recognized that variations on the technology modelled in 2018, such as improvements to unit processes and creative process optimization, could significantly reduce the cost estimates. He projected the greatest individual cost drivers of the technology to be electrodialysis, gas extraction, and electricity, and notes that "to reduce costs, systems engineering and membrane development for the electrodialysis and gas extraction sub-systems are needed."[7]

Captura technology innovations

Captura, and its research partners at Caltech, have developed a Direct Ocean Capture system that addresses the cost reduction needs highlighted by de Lannoy[6] and Eisaman[7] in 2018. The company's technology combines standard industrial equipment with proprietary innovations in the key areas of electrodialysis, gas extraction, and energy use, optimizing both the process and economic efficiency of Direct Ocean Capture. These technological innovations and significant cost reduction steps are discussed in detail below.

1. Electrodialysis

Electrodialysis is a separation process in which ions are selectively transported through semipermeable polymer membranes under the influence of an applied electric field.[11] It is used widely across a variety of industries including wastewater treatment, desalination, food processing, and chemical recycling.

Captura's Direct Ocean Capture approach utilizes a bipolar membrane electrodialysis technology to dissociate seawater, generating acid and base for the pH swing process. The electrodialysis unit uses a stack of ion exchange membranes, including anion exchange membranes (AEMs), cation exchange membranes (CEMs), and bipolar membranes (BPMs). As explained in subsequent paragraphs, Captura has developed proprietary membranes for all three classes that lower the capital cost of the electrodialysis system and significantly reduce the energy consumption. Furthermore, Captura's R&D team is working on improving the design of the membrane stack itself.

To achieve low capital and operating costs in electrochemical devices, stable operation of the electrodialysis membrane system at high current densities and low voltages is critical.[12] The most pivotal area in which Captura is improving electrodialysis performance is the BPM, which has already demonstrated high performance of operation at ultra-high current density (5,000 A/m^2) and low voltage (close to the thermodynamic limit) while maintaining exceptional stability (>1,000 hours at <10 um/h degradation).[12] This high current density and low voltage operation demonstrated by Captura's BPM allows for equivalent amounts of acid and base to be produced using 5–10 times less membrane area than commercial membranes, with no additional energy use. This exceptional stability also provides confidence that membrane lifetime will be equivalent to, or better than, commercial membranes. Furthermore, results from Captura's R&D labs show that these BPMs can be made using polymer materials that are significantly less expensive per m^2 than current commercially available options.

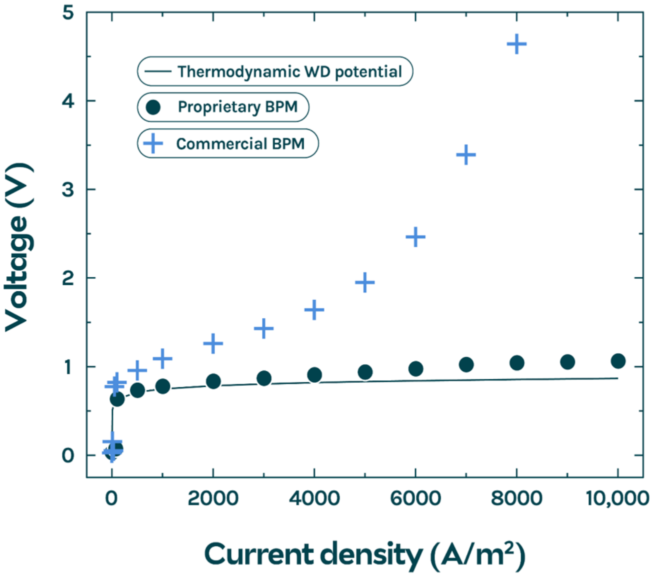

FIGURE 3.

Comparison of the performance of Captura's proprietary BPMs compared to commercial off-the-shelf BPMs. Captura's BPMs perform close to the thermodynamic limit at ultra-high energy efficiency with strong stability. Commercial BPMs begin to lose efficiency dramatically above 1,000 A/m^2 due to material limitations.

Captura is also improving the electrodialysis system by using low cost, highly conductive polymers for the AEM and CEM, further lowering the capital cost as well as the energy cost necessary for operation. De Lannoy highlighted this as a promising area for cost reductions, noting that "one impactful way to improve this negative emissions technology is to develop inexpensive and highly selective AEM and CEM membrane materials that can operate efficiently at higher acid and base concentrations. Because electrodialysis is a small industry today, there may be opportunity for significant improvement in membrane performance and decrease in cost".[6]

The combination of these low cost, high efficiency membranes with an improved overall electrodialysis stack design positions Captura to deliver one of, if not the, lowest production costs of acid and base on the market.

2. Gas extraction

Gas-liquid membrane contactors are devices that can be used in various industrial processes and applications to transfer materials (such as gases or liquids) across a membrane between two phases.[13] Captura's Direct Ocean Capture technology utilizes gas-liquid membrane contactors to isolate and extract dissolved CO_2 from acidified seawater inside the plant. The membrane contactors utilized by Captura, and modelled by de Lannoy[6] and Eisaman[7], use low-cost hollow fiber membranes that are typically used in water filtration, but also have applications in a variety of industries that require gas separation and degassing liquids.

Hollow fiber membranes have many nano pores on the hydrophobic surface that allow gas molecules to pass through but prevent liquid water molecules from penetrating. In Captura's process, the acidified seawater stream flows over the shellside (outside) of the hollow fibers while a vacuum is applied to the lumenside (inside) of the fibers. The dissolved CO_2 is forced through the membrane pores and carried away by a vacuum pump.

Commercial hollow fiber membrane contactors are mostly used in ultra-pure applications, such as the semi-conductor industry, and are therefore not optimized for seawater use cases. Additionally, commercial designs for these modules are limited to smaller scales and higher pressure drops, making them energy-intensive and costly for Direct Ocean Capture.

To optimize the efficiency and cost of membrane contactors for this application, Captura developed a CO_2-selective thin film layer that coats the hollow fiber membranes. The coating layer is made from widely available, inexpensive materials that are mechanically stable and fouling resistant. Captura is also improving the design of the contactor modules, optimizing the fiber dimensions, packing, density, and housing materials, and developing custom operating conditions specifically tailored for Direct Ocean Capture applications.

Collectively, these innovations result in a significant increase in CO_2 removal efficiency, and a decrease in the required membrane surface area. At commercial scales, Captura's proprietary hollow fiber membrane contactors are estimated to be approximately 10% more efficient and one-tenth the cost of commercial modules.

These design changes also result in a major decrease in energy and water pumping needs. At scale, Direct Ocean Capture requires significant quantities of seawater to be moved through the system. Commercial hollow fiber membrane contactors operate at approximately 2 bar pressure drop, whereas Captura's proprietary design allows a significant reduction to less than 0.5 bar. This results in a substantial reduction in pumping energy consumption and opens the possibility of harnessing tidal or ocean current flows to move seawater through standalone systems, potentially eliminating the need for seawater pumping altogether. Eisaman highlighted the major cost improvements this could deliver, noting that "pumping and piping expenses may be avoided in alternate system configurations (floating platforms, ocean currents), bringing the CO_2 cost [of standalone plants] in line with the co-location scenarios, while simultaneously allowing for significantly increased abatement capacity."[7]

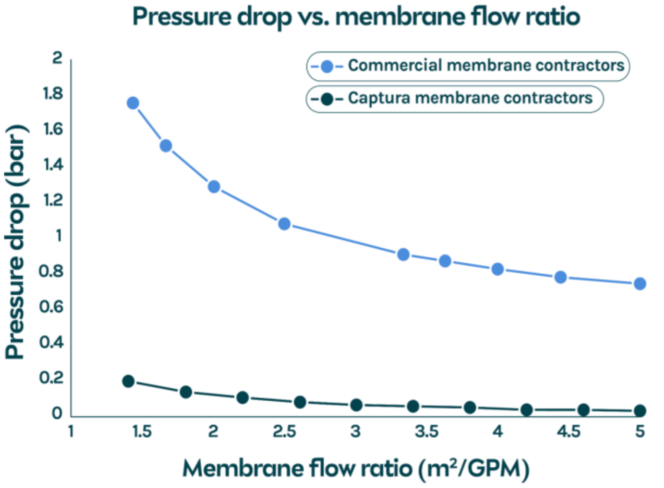

FIGURE 4.

Comparison of pressure drop achieved by Captura's proprietary membrane contactors compared to commercial membrane contactors. Captura's membranes achieve lower pressure drop than commercial membranes, consequently enabling smoother seawater flow. Note: Captura pressure drop is based on simulations.

In addition to the innovations described above, Captura is fielding additional gas extraction process improvements at its 100-ton pilot system, with initial results indicating further performance and cost improvements. Eisaman recognized the potential for major cost reductions in the gas extraction step, stating that "a much less expensive gas removal system, either cheaper membrane contactors or a different system altogether, could significantly reduce the cost of the acid process".[7]

3. Electricity

Captura's process requires no thermal energy and can run entirely on renewable electricity. For overall energy efficiency, Captura's proprietary electrodialysis and gas extraction technologies described above significantly improve the system's energy use, reducing energy usage to approximately 1,800 kWh per ton of CO_2.

Captura's electrodialysis technology further reduces energy costs by creating an opportunity to leverage off-peak renewable electricity. The most energy-intensive part of Captura's process is the electrodialysis, which comprises approximately 60% of energy needs for the whole system. By operating at ultra-high current densities, Captura's proprietary electrodialysis unit can be overbuilt to match location-specific availability of off-peak energy. For example, if off-peak times fall in a six-hour window at a specific plant location, the electrodialysis unit can be overbuilt by a factor of four to run for six hours and produce enough acid and base to feed the rest of the system over 24 hours. In this way, the most energy-intensive equipment operates for a shorter duration and can use off-peak energy pricing. This unique feature also extends the lifetime of the electrodialysis membranes, reducing replacement costs.

Furthermore, Captura's electrodialysis system has a short duty cycle, meaning it can cycle on and off quickly and therefore isn't constrained by intermittent renewable energy supply. Many CDR solutions require continuous, high levels of energy, which limits deployment potential and creates conflict with the use of renewable energy for other decarbonization solutions. Captura's system has a duty cycle of a few minutes, giving it more flexibility to work with the renewable energy sector.

Finally, energy use can be reduced by approximately 10% further in systems that eliminate seawater pumping requirements. De Lannoy found that the dominant electricity consumption in standalone plant configurations came from pumping and pretreatment of seawater.[6] As mentioned above, Captura's membrane contactors significantly reduce pumping needs and create the potential to eliminate it altogether by harnessing tidal or ocean current flows in future systems.

Further cost reductions

Beyond the technological innovations described above, Captura's process utilizes equipment that benefits from either modularity or scalability.

Modular equipment that is not yet fielded at scale (e.g. Captura's electrodialysis and membrane contactors) will benefit from the typical learning curves seen when scaling up a new technology. These accumulated learnings and small process changes will incrementally improve performance and lead to a dramatic reduction in installation costs from first-of-a-kind to n^{th}-of-a-kind plants. For example, based on a study on cell electrolysis learning rates,[14] Captura estimates an 18% learning rate for electrodialysis membrane production, which makes up the majority of electrodialysis costs.

Another significant cost reduction comes from increasing the size of facilities, which enables 'economies of scale' for equipment such as pumping and post processing, comparable to those seen in large chemical or power plants. Here, larger size allows a lower cost per ton of CO_2 captured.

Captura is also exploring alternate Direct Ocean Capture processes with the potential for further cost improvements in the future. Moreover, the electrochemistry sector is witnessing exponential growth, driven by breakthroughs in materials science and a surge in investments in sustainable technologies.[15] This trend opens opportunities for leveraging broader innovations within the industry.

Cost projections

Projecting the cost of a new technology before it is scaled up and widely deployed is inherently uncertain. Acknowledging this, Captura has focused on building a technology roadmap with a clear path to significantly reduce costs in the near term, with potential for further reductions over time as equipment becomes cheaper as deployment expands.

Taken together, the combination of technology evolution, modularity and scalability described above supports a cost model that projects Captura achieving levelized costs of $100-$200 per ton of CO_2 removed. This model incorporates costs for CO_2 capture to sequestration, including initial investment, operational costs, and financing expenses. In an alternate plant configuration in which the captured CO_2 is utilized in low carbon products, this estimate could reduce further as some cost elements, such as sequestration and post-processing, are either avoided or reduced.

While recognizing that substantial uncertainty remains ahead of large-scale deployment, this projection gives an estimate of potential cost for Direct Ocean Capture that is significantly lower than the prior estimates[7] and is highly competitive with projections for other nascent, high-integrity CDR technologies, such as Direct Air Capture.[16]

Conclusion

In summary, Captura is rapidly advancing the state of Direct Ocean Capture technology past what was thought possible just several years ago. Adding Direct Ocean Capture to the existing suite of CDR technologies results in a greater solution-set of tools to tackle climate change and will allow greater decarbonization at lower societal costs.

The U.S. Department of Energy (DOE), through its Carbon Negative Shot Program, has a goal of cultivating a portfolio of approaches that can deliver CDR at gigaton scales for less than $100 per ton by 2032.[17] Direct Ocean Capture complements other high-integrity approaches, like Direct Air Capture, and provides another high-potential solution to help the DOE reach this target.

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