Electrochemical Carbon Capture: A Scalable Path to Decarbonization

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Abstract

As the climate emergency continues, researchers project that slowing down global warming will require removing nearly 20 billion metric tons of CO_2 annually [3]. Current carbon removal technologies, such as direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS), are inefficient, energy-intensive, and difficult to scale [1]. Due to these challenges, researchers are exploring alternatives, and one promising approach is electrochemical carbon capture with Porous Solid Electrolyte (PSE) reactors. PSE reactor captures pure CO_2 in a dissolved water solution (bicarbonate form) by simply consuming electricity, without heat or chemicals, while simultaneously recovering the sorbents with low energy consumption of 50-118 kJ/mol CO_2 [5]. The stable long-term operation of the modular reaction reactor could be potentially scalable for wider deployment, following economic analysis, policy analysis, and process analysis to observe its strengths and weaknesses and determine the direction for global adoption [5]. The future of electrochemical CO_2 capture is a bright one, not lit by combustion but rather by green and sustainable technologies.

Introduction

Atmospheric CO2 levels have now topped 420 parts per million, a threshold closely associated with intensified global warming. At this stage, incremental emissions reductions will not suffice, as the scale of removal needed is a staggering 20 billion metric tons of CO2 per year to prevent global temperatures from increasing to a level of habitability [3]. Traditional approaches like Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS) are conceptually sufficient, but in practice, their advantages are weighed down by massive energy demands, high capital costs, and daunting questions around scaling up [1]. Electrochemical carbon capture is emerging as a promising alternative. Instead of using heat or a chemical sorbent, this technology leverages electricity to extract CO2 from carbonate or bicarbonate solutions. Another notable invention is the Porous Solid Electrolyte (PSE) reactor. This system achieves high-purity CO_2 output with impressive energy efficiency, making it a strong candidate for integration into industrial carbon management.

Among the current technologies promoted for carbon removal, Direct Air Capture (DAC) is unique in that it removes CO_2 directly from ambient air. The carbon capture process for DAC uses chemical sorbents or liquid solvents to capture carbon, but, since ambient air is only about 420 ppm CO_2, there are energy-intensive processes to condense and release the gas. As of 2023, DAC has reported the cost of $400 to $1,000 per ton of CO2 captured [1]. The main limitation is that it takes a large amount of thermal energy to regenerate the chemical sorbents, which adds complexity and costs. A dominant technology, however, is Bioenergy with Carbon Capture and Storage (BECCS). In BECCS, CO2 is captured from its emissions by biomass

burning or biomass process, which could make it possible to achieve net negative emissions. The enormous downside is the need for immense amounts of biomass. This raises serious concerns about land use, biodiversity, logistics, and supply chain issues.

Electrochemical Carbon Capture and PSE Reactors

The electrochemical carbon capture method uses a Porous Solid Electrolyte (PSE) reactor, a modular device that releases CO2 from a bicarbonate solution via a highly efficient, energy-efficient process. The PSE reactor has a three-chamber module drive design in which electrodes are separated by a porous, solid electrolyte layer, thus allowing ions to transfer, without a liquid electrolyte solution, minimizing the overall complexity of the system and maintenance[5]. CO2 captured from the atmosphere is generally stored in water as bicarbonate or carbonate ions. The PSE reactor uses electromagnetic techniques to retrieve the dissolved ions and produce pure CO2 gas and alkaline absorbent solution. The redox reactions occur through hydrogen evolution at the cathode and hydrogen oxidation at the anode, causing CO2 to be released without any external heat or chemical additives [5]. The energy consumption for the process is highly efficient, using 50-118 kJ/mol of energy per captured CO2, which is considerably less than current technologies.

Advantages of PSE Reactors

There are many critical advantages to this reactor design. First, removing thermal energy inputs and additional chemicals reduces environmental risk and reduces operational complexity. Second, combining the regeneration of absorbents with the breaking of the CO2 stream provides for continuous operation, as well as improved throughput and reliability of the system over time [5]. Third, low energy input allows the technology to be categorized as one of the most efficient ways to capture carbon, increasing economic viability. Moreover, PSE reactors can be designed to be modular and scalable, which allows for the potential for a decentralized approach that would allow for pairing with renewable energy sources and location in places without centralized infrastructure. For example, a small PSE reactor could be paired with a solar farm to capture carbon locally. This modularity and scalability contrast with the centralized framework of DAC and BECCS reactors and open more potential for implementation in a variety of contexts.[6]

Limitations and Challenges

In spite of those advantages, there are multiple barriers that prevent the broader adoption of PSE-based carbon capture technologies. These include high material and manufacturing costs for specialist membranes and electrodes that are used in the reactor. The technology is still at a relatively immature readiness level, as most studies have focused on small-scale laboratory demonstrations rather than pilot or commercial plants [6]. Furthermore, policy and market issues are also limiting factors. While there are some government subsidies available related to carbon removal, such as tax credits, they are not yet extensive or stable enough to mobilize large-scale

investment and deployment. There will also need to be more robust regulations and financial instruments in place for electrochemical capture to be considered economically viable compared to conventional technologies [2].

Economic and Policy Considerations

To realise the full potential of the PSE technology, several activities should be pursued cooperatively. Through national and international commercial deployment, the reactors could create value streams with renewable electricity and hydrogen production, enabling carbon-neutral operation. Also, with relative seawater bicarbonate as the feedstock, they could provide options for decentralized and scalable carbon capture in the coastal communities. Importantly, policies regarding carbon pricing and credit systems need to align with carbon removal technologies for early adoption and recouping investments. As the carbon removal market develops, clear monitoring, reporting, and verification (MRV) standards are essential to establish credibility and transparency, and they ultimately will help to elevate the bar on public trust.

Conclusion

The PSE reactor is a breakthrough for carbon capture technology. High-purity CO2 regeneration from the atmosphere, a low-input energy system that operates without chemicals, ultimately addresses many of the disadvantages of current DAC and BECCS technologies. Yet the economic and technological hurdles are quite significant, and the funding community. If this initiative scales successfully, PSE reactors can become a meaningful part of the global carbon removal solution, contributing to climate stabilization and ultimately paving the way for a sustainable, low-carbon world. The approach of electrochemical carbon capture with PSE reactors provides a viable and cost-effective alternative to conventional carbon removal technologies. PSE technology could be poised to play a central role in global decarbonization programs, as it represents a relatively flat energy profile and simple production stream. Scaling up PSE technology can only be achieved by overcoming both cost and technology readiness challenges through deliberate innovation, pilot projects, and supportive policies. Given the seriousness of the climate crisis, now is the time to invest in novel solutions like PSE reactors before the window to stabilize our climate closes.

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