Modular, Intensified Approaches to Carbon Capture and Utilization

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Carbon capture and utilization (CCU) is a key element of carbon recycling and the move toward a circular carbon economy. CCU is the process of capturing and upgrading carbon dioxide and related gaseous sources of waste carbon for use in an application. CCU also includes carbon capture for enhanced oil recovery (EOR) and direct air capture (DAC) of atmospheric CO_2 for transformation to solid, carbon-rich products.

Modular CCU approaches are necessary to capture and utilize CO_2 from distributed sources. Such modular units could be easily transported and numbered up or down to suit variable production volumes. Modular technologies are also crucial to hybrid approaches, known as hub-and-spoke, in which distributed operations work in combination with a centralized station. For example, CO_2 could be captured by a distributed unit and processed at a central utilization facility.

CCU strategies can be tailored to the volume and concentration of the source of carbon dioxide, including:

- medium-to-large volume and high concentration (*e.g.,* waste CO_2 sources from ethanol and ammonia production)
- large volume and medium concentration (*e.g.,* waste streams from fossil fuel combustion at power plants)
- variable volume and very low concentration (*e.g.,* atmospheric air to be processed by DAC).

The characteristics of the source are key to specifying the CCU technology. Concentrated sources of CO_2 require only minimal purification for utilization. Intensified approaches to CO_2 concentration and separation are critical to efficiently obtaining concentrated CO_2 streams. Some of the most promising CO_2 capture approaches are based on intensified separation technologies, including advanced polymer membranes, mineralization processes (CO_2 is captured as a solid or aqueous carbonate material), and electrolysis (carbon is captured as an intermediate, such as CO, from an electrified process).

Carbon can be utilized as pure CO_2 or as a carbon-rich product. Uses of pure carbon dioxide are somewhat limited. For example, EOR involves injecting pressurized CO_2 into mature oil fields to increase well production. However, the distance between the source of CO_2 and the target oil fields represents a challenge. Therefore, EOR may only be attractive when pipelines to transport CO_2 are in place. EOR also has questionable sustainability benefits, as it perpetuates reliance on fossil sources of energy. Pure CO_2 may also be used for carbonated beverages, but the need is limited and the market may resist CO_2 from industrial waste for human consumption.

On the other hand, carbon dioxide can be upgraded into more useful carbon products, but this transformation has critical thermodynamic limitations. As a fully oxidized carbon form, CO_2 is a very stable molecule. External energy sources are needed to react CO_2, such as:

- high temperatures and pressure (*e.g.,* Sabatier methanation reaction)
- electricity (*e.g.,* electrolysis to CO)
- photons (*e.g.,* natural or artificial photosynthesis)
- presence of highly reactive species (*e.g.,* hydrogen in the Sabatier reaction).

To counter this energy need, CCU technologies must use energy from highly efficient low-carbon sources. The fundamental driver of CCU is not simply to reuse CO_2 molecules, but to do so in such a way that sustainably addresses the increasing amounts of CO_2 in the atmosphere. We need to adopt a lifecycle approach that minimizes emissions of carbon and other harmful wastes.

In addition to energy considerations, the selection of the product to be manufactured from CO_2 is a significant decision. It is tempting to target high-volume products currently produced with large associated emissions, but this often brings numerous technical and commercial constraints. Starting with low-volume, high-margin products, such as specialty chemicals, may be a better strategy. A progressive evolution from specialty chemicals to chemical commodities to fuels will likely be the best strategy to achieve sustainable growth and market acceptance of CCU.

It is not enough to create a CCU process for the right product at an appropriate size and location with good efficiency and yield. The process also has to make commercial sense under the current legislative and regulatory environments. Regulatory treatment of CO_2 and its transformation varies globally, and it is subject to changing political choices and pressures from interest groups. Understanding and addressing these policies along with the proper incentives and taxes is essential for the successful deployment of CCU processes.

The RAPID Manufacturing Institute is focusing on modular technologies for capturing and converting waste carbon in the next edition of the new DEPLOY conference series (virtual, Aug. 17–18, 2021, www.aiche.org/rapid/events/2021-08-17/rapid-deploy-modular-technologies-capturing-and-converting-waste-carbon). We look forward to working with attendees to identify novel modular solutions for CCU that are technically and economically attractive, meet market needs, and drive sustainability. CEP