RESEARCH UPDATE

INDUSTRIAL CARBON UTILIZATION

Enabling a Carbon-Neutral Economy

Even under the most ambitious decarbonization pathways, limiting global warming to 2°C will require managing billions of tons per year of carbon dioxide (CO_2) and other greenhouse gases. Despite growing renewable energy generation, decarbonization remains severely constrained by society's deep dependence on fossil fuels, which dominate the energy supply for heavy industry and transportation and serve as essential feedstocks in chemical production. Achieving net-zero emissions will require a range of scalable carbon capture solutions, including capturing gaseous CO_2 from industrial point sources (e.g., cement, steel, pulp-and-paper, and chemical manufacturing), as well as from the atmosphere through direct air capture (DAC), or via the ocean through emerging electrochemical approaches. While carbon capture and storage (CCS) will play an important role in mitigating industrial emissions, industrial carbon utilization (ICU) offers a complementary pathway by converting captured CO_2 from a waste stream into a feedstock for fuels, chemicals, and materials that can displace products that are currently fossil-derived.

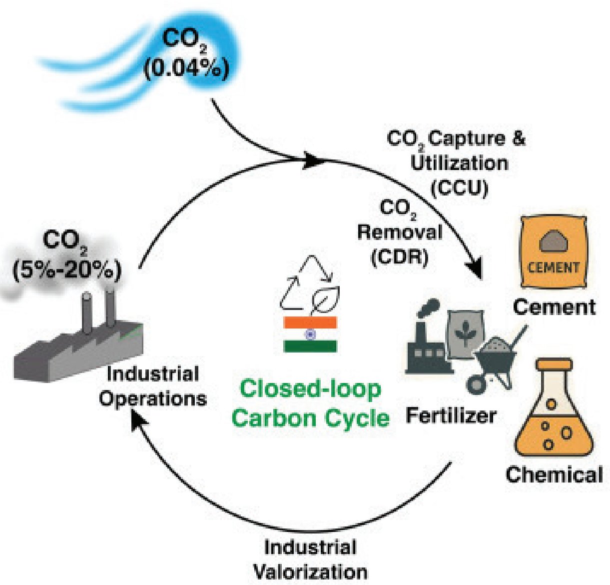
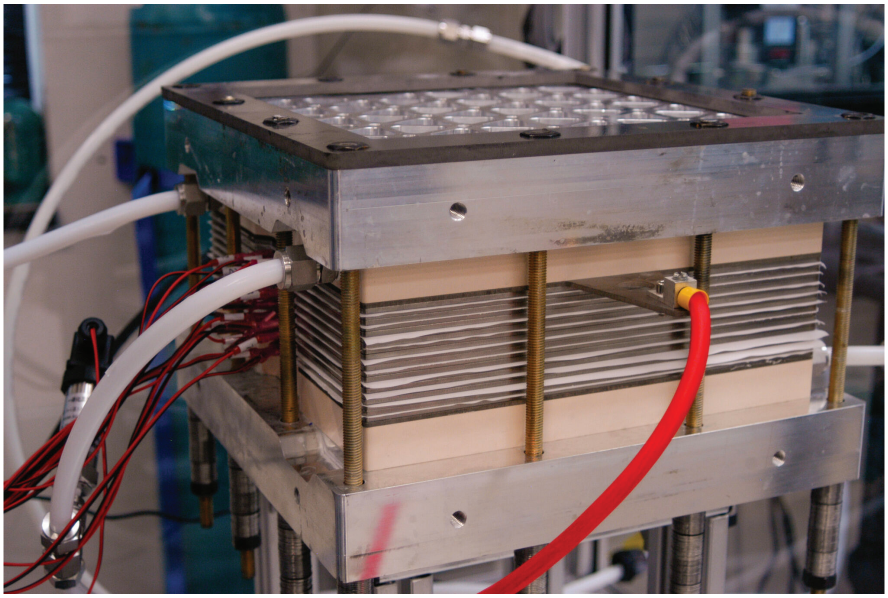


FIGURE 1: Industrial carbon utilization (ICU) strategies convert atmospheric or industrial CO_2 into value-added products, enabling a circular carbon economy. (Dutta et al., *iScience*, October 2025)

TRANSFORMING CARBON WASTE INTO VALUABLE PRODUCTS WITH SUNLIGHT AND ELECTRICITY

Carbon dioxide from both concentrated industrial emissions and diffuse non-point sources represents a valuable feedstock for sustainable chemical manufacturing. In addition to being concentrated, industrial CO_2 emissions are continuous and often co-located with infrastructure, which makes industrial point sources particularly attractive targets for carbon utilization technologies. Non-point sources, including atmospheric CO_2 captured through DAC and aqueous carbon sources, also represent an important opportunity for large-scale carbon management and long-term climate mitigation.

CO_2 is a very stable and unreactive molecule, and thus separating the carbon requires energy in the form of heat, light, or a combination of these with electricity. Using different forms of energy, a variety of CO_2-derived products can be converted to fuels, energy storage, fuel cells, and pharmaceuticals. When powered by sunlight or green hydrogen in combination with renewable electricity, these transformations can reduce greenhouse emissions while displacing fuel use. YCNCC scientists are pioneering renewable-powered ICU pathways that replace conventional heat-driven, fossil-reliant processes with light- and electricity-driven systems. Through electrochemical, photochemical, and electron-driven plasma approaches, Yale researchers are advancing selective CO_2 conversion and greenhouse gas remediation at lab scale with an eye towards developing techno-economically feasible ICU solutions that have the potential to achieve climate-relevant scale in the coming decades.



Kilowatt-scale pilot system for electrochemical CO_2 conversion
Courtesy of Oxylus Energy

LIGHT-POWERED ELECTROCHEMICAL CO_2 CONVERSION TO FUELS

- YCNCC researchers have developed an electrochemical process to convert CO_2 to methanol using water, by immobilizing a cobalt-based catalyst on a heterogeneous carbon support. Methanol is an effective hydrogen carrier because it can store a significant amount of hydrogen in liquid form (about 12.5% by weight); this enables energy storage densities far greater than typical battery systems, while being easy to contain and transport like conventional fuels. This research is being commercialized and scaled by the Connecticut-based startup Oxylus Energy.

- A team of YCNCC scientists is advancing electrocatalytic platforms powered by sunlight to achieve the selective conversion of CO_2 to formate via manganese-based photocathodes. Formate (or formic acid) is a valuable CO_2-derived product with established applications in chemical manufacturing at industrial scale and potential use in fuel-cell technologies. Novel catalysts are essential for achieving selective CO_2 conversion by suppressing competing reactions such as the hydrogen evolution reaction.

- YCNCC researchers are exploring novel carbon separation pathways using renewable electricity to form carbon-carbon bonds that transform CO_2 into long chain carbohydrates such as sugars. These approaches provide a unique route to couple electrochemical CO_2 valorization to carbon-based C_{5+} products relevant to the food, pharmaceutical, and biotechnology industries.

GREENHOUSE GAS REMOVAL AND CO_2 MINERALIZATION

- Hydrofluorocarbons (HFCs) are extremely potent greenhouse gases, with 100-year global warming potentials up to 12,400 times that of CO_2. YCNCC scientists are developing low-temperature plasma to break the strong and chemically inert carbon-fluorine bonds in HFCs. An important aspect of this research is coupling plasma systems with water and oxidants such as CO_2 to enhance the conversion rate of HFCs while ensuring safe and controlled degradation of these harmful compounds.

- Researchers at YCNCC are developing a new sunlight-driven method to remove carbon dioxide from seawater. This strategy uses specially designed photoacids that reversibly change the pH of water when exposed to light, enabling the controlled release of dissolved CO_2 for capture. The approach demonstrates how renewable energy can be harnessed to manage ocean carbon in a practical and sustainable way.

- Alkaline seawater absorbs CO_2 in the form of dissolved inorganic carbon to concentrations nearly 140 times higher than in the atmosphere. A team of YCNCC scientists have developed a flow-based photoelectrochemical CO_2 reduction device that enables sustainable conversion of dissolved carbon in seawater using sunlight as the energy input. The flow-reaction engineering strategy significantly enhances CO product selectivity to 21% over competitive H2 evolution, demonstrating a viable carbon utilization approach for scalable solar fuel production.

CHALLENGES AND IMPACT

Scaling ICU from laboratory research to commercial deployment remains a significant challenge. One key hurdle is developing systems that can capture CO_2 directly from industrial emissions and convert it on-site into useful products. These processes require catalytic platforms that can operate efficiently with impure CO_2 streams commonly found in industrial sources while maintaining high molecular selectivity. Another critical challenge is creating high-value products from CO_2 efficiently and in ways that can compete economically with conventional manufacturing processes. In addition, many CO_2 conversion platforms require substantial energy: To address this, YCNCC researchers are using renewable energy to avoid CO2 emissions inherent to traditional thermochemical routes, as well as constantly pushing for increased efficiency.

YCNCC ICU researchers are seeking to overcome these challenges to transform CO_2 from an industrial waste product into a valuable resource for producing fuels, chemicals, and other materials. In the coming years, YCNCC will continue to invent and develop new ICU methods, as well as advance promising technologies via pilot and demonstration-scale projects with governmental and industrial partners, or direct commercialization as new startups – with a goal of driving real-world mitigation outcomes and climate impact at a decadal timescale.

SELECTED YCNCC PUBLICATIONS FOR REFERENCE:

- Wu, Y., Jiang, Z., Lu, X., et al. (2019). Domino electroreduction of CO_2 to methanol on a molecular catalyst. *Nature, 575*, 639–642. https://doi.org/10.1038/s41586-019-1760-8
- Hong, J., Stewart-Jones, et al. (2025). Photoelectrocatalytic reduction of CO_2 to formate using immobilized molecular catalysts on oxidized porous silicon. *Chem.* https://doi.org/10.1016/j.chempr.2025.102462
- Li, J., Chen, K., Soland, N. E., et al. (2026). Artificial synthesis of carbohydrates from electrochemically fixed carbon dioxide. *Nature Synthesis.* https://doi.org/10.1038/s44160-025-00961-x
- Saha, Meeder, et al. (2024). Enabling light-driven CO_2 removal from seawater using metastable photoacids. *The Journal of Physical Chemistry C.* https://doi.org/10.1021/acs.jpcc.3c08306
- Wang, et al. (2025). Hydrofluorocarbon greenhouse gas mineralization via oxidative low temperature plasma. *ACS Energy Letters.* https://doi.org/10.1021/acsenergylett.5c02595
- Liu, et al. (2025). Solar-driven selective conversion of millimolar dissolved carbon to fuels with molecular flux generation. *Nature Communications.* https://doi.org/10.1038/s41467-025-56106-3