Biological Carbon Capture and Conversion: Establishing a sustainable, engineering biology-enabled economy

A Policy Paper by the Engineering Biology Research Consortium

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The U.S. and global economies must reach net-zero CO_2 emissions by 2050 to avoid the worst effects of climate change, which include routine catastrophic weather and wildfires, extreme equatorial aridity, mass human migration, and coastal destruction. Together, industrial manufacturing, transportation, and electricity generation are responsible for more than 75% of CO_2 emissions in the U.S. While electrification and decarbonization are accelerating across these sectors, new technologies will be needed to capture, convert, and permanently sequester CO_2 at the gigatons-per-year scale. Given that carbon is a major component of essential everyday products, including foods, chemicals, materials, and fuels, we also need to find sustainable alternatives to manufacturing processes that depend on fossil-carbon feedstocks.

Biological carbon capture and conversion is uniquely suited for this grand climate challenge as it has the potential to annually remove 2-10 gigatons of CO_2 emissions,[1,2] while simultaneously converting a portion of that carbon into those essential products. Engineering biology technologies can build off existing biological capabilities of utilizing CO_2 and other renewable or waste carbon sources, and enable the conversion of those feedstocks into the carbon-based materials that are necessary and ubiquitous in modern society. Our climate future depends on moving away from virgin fossil carbons and capturing atmospheric CO_2 and other carbon oxides; herein we explore the ways that engineering biology will allow us to accomplish this.

Engineering biology for carbon capture and conversion

Engineering biological organisms such as plants, algae, archaea, and bacteria has the potential to enable manufacturing of a wide variety of products from CO_2 and other carbon oxides. This can be done through the modification of organisms, or by engineering enzymes and cell-free systems. An advantage of using biological systems is that many of these organisms naturally metabolize CO_2 or other forms of carbon. Thus, rather than having to generate novel pathways and capabilities, engineering advancements can enhance innate biological abilities. Moreover, unlike other non-biological technologies, biological systems are inherently flexible and capable of processing diverse, and sometimes chaotic, input streams, making them prime candidates for capturing atmospheric CO_2 or other carbon emissions.

Using engineering biology to enhance carbon capture, conversion, and sequestration capabilities in biological organisms is an important step towards moving away from linear fossil carbon supply chains towards a circular

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[1] IPCC, 2022: Summary for Policymakers. In: Climate Change 2022: *Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.

[2] International Energy Agency (2021), *Net Zero by 2050, A Roadmap for the Global Energy Sector*

carbon economy. Herein, we refer to *carbon capture* as the process of an organism uptaking atmospheric or other sources of carbon. We refer to *carbon conversion* as the process of converting carbon into an end product, such as food products, chemicals, materials, and fuels. Carbon capture and conversion capabilities can be engineered into a single organism, or split across multiple organisms or steps, whether biological or non-biological, within a system. In conjunction with biological carbon capture and conversion, *carbon sequestration* – wherein carbon is removed from use for long time spans – can help to reduce the total CO_2 in the atmosphere. Engineered organisms could be used to accelerate natural carbon deposition and geologic formation processes in a reversal of petroleum and fossil fuel mining. Even so, the most effective form of sequestration is leaving virgin fossil carbon in the ground. Biological carbon capture and conversion are the most impactful applications of engineering biology for moving away from a fossil carbon-based economy, as they can be direct replacements for processes that use fossil-based feedstocks, making biological sequestration advancements less effective and necessary in the long-term.

Carbon capture can be enhanced in engineered organisms by improving the efficiency of naturally occurring pathways. Often this is achieved by increasing the conversion rate of the enzymes involved in the pathway, or by porting such pathways or enzymes into other organisms to introduce carbon capture capabilities. Though this is an active area of research, gaps persist in the complete understanding of these pathways; many CO_2 fixation pathways, including the most energy efficient Wood-Ljungdahl pathway, are complex and comprise a network of hundreds of enzymes involved for growth and associated energy conversion.[3] Another key carbon capture capability that must be developed is the capture of diffuse and environmental carbon at an industrial scale. Engineered organisms are currently tested primarily in research settings using controlled amounts of CO_2 or methane as input. Improving gas fermentation technology will be crucial to accomplishing this scalability.[4,5]

Engineering biology has made significant advancements in carbon conversion in the last decade; modifications to genes and enzymes, and construction of novel pathways, through DNA editing and protein enhancement techniques, have led to a multitude of compounds that can be biosynthesized. However, these biological production processes are seldomly viable for industrial translation, as they are far more costly than existing petroleum-based chemical production.[6] Dedicated research efforts are addressing this challenge, aiming to improve the titer and yield of biological production processes and thereby improving the process economics. Another key area of development is in consolidating carbon capture and conversion capabilities, such as for the direct use of carbon oxides to produce commodity chemical building blocks, e.g. ethylene and propylene.

Potential products that can be generated from captured and converted carbon span multiple sectors across the bioeconomy. For example, alternative proteins for sustainable meats could be generated from engineered cells that convert CO_2, to simultaneously decrease the carbon emissions and increase the carbon uptake in the food and agriculture sector. To generate replacements for products that are currently petroleum-based, engineered

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[3] Kaster, A.-K., Goenrich, M., Seedorf, H., Liesegang, H., Wollherr, A., Gottschalk, G., & Thauer, R. K. (2011). More Than 200 Genes Required for Methane Formation from H_2 and CO_2 and Energy Conservation Are Present in *Methanothermobacter marburgensis* and *Methanothermobacter thermautotrophicus*. *Archaea, 2011*, e973848.
[4] Köpke, M., & Simpson, S. D. (2020). Pollution to products: Recycling of ‘above ground’ carbon by gas fermentation. *Current Opinion in Biotechnology*, 65, 180–189.
[5] Fackler, N., Heijstra, B. D., Rasor, B. J., Brown, H., Martin, J., Ni, Z., Shebek, K. M., Rosin, R. R., Simpson, S. D., Tyo, K. E., Giannone, R. J., Hettich, R. L., Tschaplinski, T. J., Leang, C., Brown, S. D., Jewett, M. C., & Köpke, M. (2021). Stepping on the Gas to a Circular Economy: Accelerating Development of Carbon-Negative Chemical Production from Gas Fermentation. *Annual Review of Chemical and Biomolecular Engineering*, 12(1), 439–470.
[6] IEA Bioenergy (2020). Bio-Based Chemicals - A 2020 Update. Retrieved from: https://www.ieabioenergy.com/iea-publications/.

biology can be used for producing biobased and biologically synthesized chemicals and materials, such as plastic precursors, adhesives, coatings, textiles, and other specialty chemicals. High-performance biofuels for sustainable aviation, trucking, and oceanic shipping and other forms of bioenergy can be produced from engineered organisms, using renewable feedstocks, thereby reducing the net carbon output in the transportation and energy sectors. Many more potential carbon capture and conversion capabilities that engineering biology can enable are covered in detail in the recent EBRC technical roadmap, *Engineering Biology for Climate & Sustainability*.

Short- and long-term actions towards realizing large-scale, engineering biology carbon solutions

While some engineering biology-driven carbon capture and conversion technologies exist in the commercial space, the majority are still in the research and development pipeline. Continued investment is needed in these research activities, and the technologies they enable, including careful analysis of the techno-economics, the carbon footprint of products and processes, the overall carbon intensity, and potential conversion of side streams. Furthermore, policy and regulations to incentivize and increase the adoption of carbon capture and conversion technologies is needed to secure their place in the bioeconomy, and especially to increase their current and near-term competitiveness with fossil-based feedstocks.

In the short term, while latent engineering biology research and technologies must be bolstered to maturity with sufficient funding and support, we can scale up and deploy the existing, commercially proven biological carbon capture and conversion capabilities. **Support for scaling efforts is needed to bring existing technologies to a large and distributed scale.** The maturity of anaerobic digestion and gas fermentation technologies would make their large-scale deployment an effective short-term action towards reducing CO_2 emissions from industrial processes. Carbon-negative biomanufacturing of chemicals such as acetate, ethanol, acetone, isoprene, and isopropanol through gas fermentation have been demonstrated and scaled up.[7,8] Cost and cost competitiveness is a major barrier to commercializing these technologies. Subsidies and programs to enable biobased and biologically synthesized products could aid in the transition from an economy built on fossil-carbon based products to one where foods, chemicals, materials, and fuels are made from renewable, industrially-captured, or atmospheric carbon sources.

Some of the longer-term actions needed to realize wide implementation of engineering biology carbon solutions include technological advancements, market development, and continued support through investment, policy, and regulations. Engineering biology technology will need to continue the development of: **(1) utilizing diverse recycled, waste, and atmospheric carbon feedstocks**, many of which have low carbon concentrations and contain various impurities, and **(2) increasing the yield, productivity, and diversity of bio-manufactured products**. As more carbon capture and conversion technologies are invented and deployed, suitable markets must be developed for their feedstocks and products. Bio-based feedstock sources, locations, and logistics differ from fossil-based ones. Many biomass feedstocks are available on a seasonal basis, which could lead to fluctuations in bio-based product availability that must be addressed and de-risked. The location of production centers will need to be matched to that of regional feedstock supplies to reduce costs. Supply chain considerations will be critical in the longer term, as engineering biology carbon capture and conversion

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[7] Liew, F.E., Nogle, R., Abdalla, T. et al. (2022) Carbon-negative production of acetone and isopropanol by gas fermentation at industrial pilot scale. *Nat Biotechnol* 40, 335–344.
[8] Aldridge, J., Carr, S., Weber, K.A., & Buan, N.R. (2021) Anaerobic Production of Isoprene by Engineered *Methanosarcina* Species Archaea. *Appl. Environ. Microbiol*. 87, 6.

becomes increasingly integrated into the economy. Overcoming these short- and long-term challenges will help to establish a sustainable and profitable bio-enabled economy, in which CO_2 and other carbon oxides are essential feedstocks, rather than an emission that exacerbates climate change.

Conclusion

Engineering biology has the potential to transform the economy through the carbon capture and conversion that is necessary to mitigate a climate catastrophe, while meeting society's needs for food, chemicals, materials, and fuels. We can capitalize on this promise by supporting the scale up and incentivizing the deployment of existing biological carbon capture and conversion technologies, advancing engineering biology technologies to utilize recycled, waste, and atmospheric carbon, and developing markets for biobased feedstocks and biologically synthesized products. Investment, policy, and regulations that promote engineering biology-enabled carbon capture and conversion are critical to their development, adoption, and widespread implementation.