New Technology Options to Decarbonize Petrochemical Production

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1 Introduction

The seemingly intractable challenge of producing petrochemicals without damaging climate impacts has been transformed by unexpected innovations in fields like biotechnology, electrochemistry, and artificial intelligence. But capturing the potential will require a much-expanded array of federal programs.

1.1 The Challenge

Petrochemical[*] manufacturing is on track to become the leading end use of fossil fuels in the next three decades and thus a central challenge for reducing greenhouse gas (GHG) emissions. Plastics are cheap, waterproof, durable, lightweight, and easy to shape. Indeed, they are in demand in part because they substitute for more GHG-intensive materials to improve the energy efficiency of cars and other products. At issue is whether society can continue to enjoy the unquestionable benefits of plastics without paying an unacceptable environmental price.

Substitutes are likely to erode fossil fuel use in transportation and electric power, the largest markets today, while global demand for petrochemicals is likely to continue to grow because few substitutes are available. Unlike other manufacturing processes, petrochemical production uses fossil fuels both for production and as a feedstock. More than 60% of the fuel ends up embodied as a part of the product, a fraction that is growing as production becomes more energy efficient.[1] Common strategies for reducing GHG process emissions such as electrification, hydrogen fuel, and carbon capture have no impact on fossil fuel production and transportation or on the GHGs released at the end of a product's life. End-of-life emissions are very poorly understood. Some petrochemical products such as PVCs do not decay and may not release carbon to the atmosphere for thousands of years, while others do so very quickly.

The staggering complexity of petrochemical manufacturing makes it difficult to understand. There are thousands of different products and production systems that are linked in complex ways. These processes involve mind-numbing chemical engineering designs that are difficult for outsiders to penetrate. As a result, the sector often receives

[*] Petroleum is, by definition, a fossil fuel. This discussion will, however, use the word "petrochemical" to refer to the family of chemicals now primarily made from fossil fuels.

minimal coverage in environmental policymaking. That must change if climate goals are to be reached.

Electrification, using hydrogen instead of natural gas, and carbon capture at chemical production facilities are options that may offer practical near-term solutions.[2] But these technologies cannot reduce the carbon embedded in plastics and other products. Nor can they reduce emissions associated with the production and transport of natural gas and other fossil fuel feedstocks used in petrochemical manufacturing.

It would be enormously useful to have other options. One obvious strategy would be finding production methods that do not use fossil fuels at all. It's hard to imagine an innovation as important to our future. A concerted national program to develop fossil-free petrochemical production technologies is urgently needed

1.2 Technical Opportunities

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The technical options fall into three broad categories:

- **Bio-based production:** In principle, petrochemicals made with and from plant materials do not contribute to emissions, because any carbon later released has been taken initially from the atmosphere by the plants themselves. There are, however, serious concerns about the environmental impacts of using food products such as corn as a source for bio-feedstocks. Major improvements are now possible, using engineered microbes and other new technologies that can use grasses, wood, organic waste, and other non-crop biomass resources to produce a variety of petrochemical products.
- **Recycling:** Like biomass, plastic and other petrochemical waste can be used as a feedstock and energy source. Commercial recycling methods achieve 50–75% reductions in carbon emissions but can release significant amounts of toxic materials. Advanced methods for taking plastic molecules apart, and use of products designed for recycling, could all but eliminate emissions. Recycling plastics made without using fossil carbon would eliminate greenhouse gas emissions but wouldn't eliminate local plastic waste.
- **Direct production from CO_2 and water:** Complex organic chemicals can be produced directly from concentrated sources of CO_2 (and potentially from air) and water. Such processes in effect reproduce the ultimate source of both biomass and fossil fuels: photosynthesis. While many technical hurdles remain, this route has the potential to provide the most spectacular breakthrough for abating petrochemical GHG emissions.

The estimates provided in the body of this report suggest that technologies across all three of these categories have the potential to make major contributions to emissions reduction in coming decades. But there is great uncertainty about whether that potential will be realized. The technical advances that are needed to make them affordable depend heavily on policy choices. These technologies are generally too immature at the moment to make credible estimates about their ultimate performance and cost. A full comparison of the real and implicit costs of different approaches to petrochemical production that include all steps from feedstock and fuel extraction to the eventual fate of the embodied carbon depends on future research.

In such comparisons, an important factor to consider is the potential for non-fossil technologies to operate at much smaller scales than today's production systems and to disperse production across many different parts of the country. A smaller scale creates the potential for faster learning as producers learn from each increment and continuously improve operations.

1.3 Headwinds in the United States

Alternatives to fossil-fuel-based production face unique challenges in the United States since natural gas is much cheaper there than in most of the rest of the world. In 2020, natural gas prices in Europe and much of Asia were two to three times more expensive than in the United States. The price of ethylene, a widely used input for plastics and other end products, was four to five times higher. The price gap has only grown since the global energy crisis brought on by Russia's invasion of Ukraine. One result is that investment in research, development, and demonstration (RD&D) of advanced petrochemical production technologies has been far higher abroad.

A second reason for the United States' lagging position is that its policymakers have not forced markets to bear the full environmental costs of investment decisions. Some states impose a carbon price, but many do not, and neither does the federal government. There has been greater consensus at the federal level on investing in climate and energy RD&D. The time has come to extend this work to petrochemical production in a serious way. Technological progress clearly depends on policy decisions.

This report shows that there are a number of ways to make petrochemicals without fossil fuels, that success in doing so would not require prohibitive amounts of rare materials or involve dangerous facilities, and that a commercially competitive process would greatly improve the likelihood of meeting global climate goals. These conclusions justify a large and focused national investment. The final section of this report discusses some options for doing so.

2 Biomass-Based Production

2.1 Some Basics

The evolutionary invention that converts air, water, and dirt to the chemicals of life using the energy of sunlight appeared about three billion years ago. The technology of converting (fermenting) one of these chemical families—sugar—into ethanol has been known for millennia and is the basis for the largest biochemical production system operating today, driven by strict policy mandates in the United States. A new low-carbon, bio-based chemical industry, however, will require three major revolutions: in the biomass feedstocks used, in processing technology, and in end products.

US regulations in the require 10% blends of ethanol with gasoline, creating a huge market. (The Congressional Research Service has prepared a detailed discussion of these regulations.[3]) Virtually all of the ethanol produced today to satisfy this mandate is made from corn in fermentation processes powered by natural gas or other fossil fuels.[4] The use of edible crops like corn as a fossil fuel substitute, however, is problematic over the long term because it risks compromising food supplies. Technologies capable of processing wood, grasses, waste, and other *lignocellulosic* materials could access a much larger resource base. All aggressive programs to meet climate goals show, however, that there will be enormous competition for these resources including production of aviation fuel and electricity.

Lignocellulose contains two types of sugars—cellulose (a sugar with 6 carbon atoms) and hemicellulose (a sugar with 5 carbon atoms). It also contains lignin, a complex material that serves as a binder and many other functions. The fraction of each component depends on the type of biomass.[5]

Bacteria, fungi, and other microorganisms have been decomposing and repurposing lignocellulose for hundreds of millions of years, but it has proven frustratingly difficult to mimic the process in artificial systems.[6] Efforts to shift from corn to lignocellulose feedstocks for ethanol have resulted in repeated commercial failures in spite of major research investments.[7, 8, 9]

The following two basic strategies have been pursued:

- separating the lignocellulose into its components using chemical or biological tools and using engineered microorganisms to convert the resulting sugars. The sugars (but not the lignin) can be upgraded to a variety of petrochemical products using bioengineered microorganisms.[10]
- heating the lignocellulose so that its components break down into hydrogen, carbon dioxide, and other simple molecules, then using industrial chemistry to upgrade these molecules. The products can be upgraded to complex petrochemicals using technologies that are commercially available in refineries.

While current US biomass production concentrates almost exclusively on ethanol, future production is likely to focus on a new range or products—if only because traditional ethanol markets may be severely reduced as personal vehicles are increasingly electrified. Biomass facilities may make plastics or other complex materials onsite or they may make intermediate products (including ethanol, and ethylene) that can be shipped for further refinements.

The environmental impacts of alternative biomass production are complex and discussed in some detail in the Appendix A. In addition to emissions resulting from production, emissions are associated with the production, harvesting, and transportation of crops, and land use impacts associated with conversion to biomass crops.

2.2 Separation and Fermentation

Separating lignocellulosic materials into sugars that can be processed by microorganisms is hard. A range of solutions has been explored including biochemical[11] and thermochemical[12] processes. The processes are costly because they are slow, and the enzymes and other materials needed to carry them out are costly and hard to recover.[13] Synthetic biology can create organisms that can convert the separated sugars into a variety of chemicals.[14] For example, genes for producing ethylene are easily available, since it is essential for fruit ripening and other biological functions.[15] When these genes are inserted into bacteria, the modified organisms produce ethylene.[16]

When the sugars have been separated, lignin remains. A major problem is how to capture the energy embedded in it. Progress in doing so has been limited due to lignin's complex chemistry. If this problem cannot be solved, lignin may simply be burned to provide energy for other parts of the production process.

2.3 Pyrolysis and Gasification

Heating lignocellulose has the advantages of using all of the biomass feedstock, including lignin, and tolerating more diverse feedstock mixtures. This approach also seems to avoid some of the mechanical problems associated with handling bulky biomass materials.

There are two families of technology for heating lignocellulose: pyrolysis and gasification.

Conventional pyrolysis heats lignocellulose to a temperature of 300–700° C. At this temperature, it is converted to a mixture of gases, liquids, and solids called "char". Conventional gasification uses higher temperatures (700–1200° C) and results in gases, including hydrogen and carbon monoxide.[17] A number of commercial gasification systems are now operating, and advanced systems are in development including plasma gasification, hydrocracking, plasma pyrolysis, microwave assisted pyrolysis, and pyrolysis with in-line reforming.[18]

The choice of technology will depend on local circumstances, including the type and volume of feedstocks available and the options for transporting intermediate products to downstream processors. The mix of materials that form the outputs of pyrolysis and gasification becomes the feedstock for petrochemical production. In most cases, hydrogen will need to be added to these outputs for them to be converted into complex chemicals.[19, 20] For the full system to be low-carbon, the added hydrogen would need to come from low-carbon sources.

2.4 The End-Product Revolution

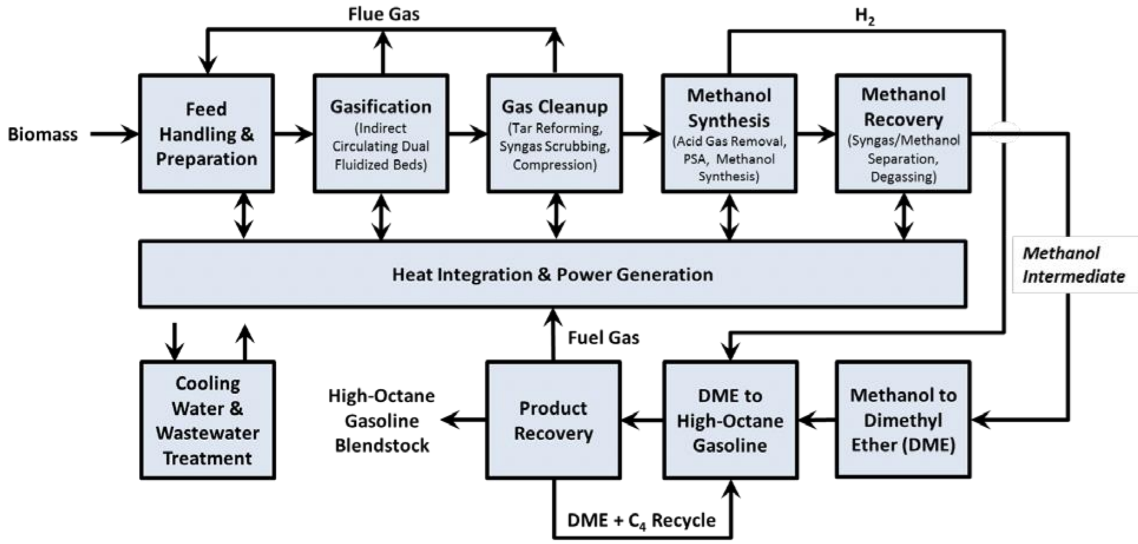
The bio-based chemical industry in the United States is dominated today by production of ethanol, which is used as an additive in gasoline. Change is coming: this market will shrink as cars begin using electricity instead of petroleum-based fuels. The new technologies offer opportunities both for converting corn into a variety of other valuable petrochemical products and for using lignocellulosic feedstocks.

Since there are limits on the distance biomass feedstocks can be economically transported, production plants are likely to be similar in size to today’s corn ethanol facilities. It may be best if these facilities make intermediate products like ethanol, methane, and methanol in relatively small quantities that are then shipped to larger downstream processors where they can be economically converted to more sophisticated petrochemical products. It may, however, be possible to have decentralized facilities produce sophisticated products on their own.[21]

Figure 1 shows a design for a system that integrates new feedstocks, new processes, and new end products. It would make high-octane gasoline through gasification of lignoscellosic materials. In the system shown, biomass is used both as a feedstock and to produce heat, electricity, and hydrogen.[22]

Future configurations of such systems might substitute low-carbon electricity and hydrogen from other sources if they are available at a low cost.

Figure 1: Production of High-Octane Gasoline Blendstock via Syngas Conversion Pathway and Methanol/Dimethyl Ether Intermediates



Source: Tan, Eric, Dan Ruddy, Connor Nash, et al. "High-Octane Gasoline from Lignocellulosic Biomass via Syngas and Methanol/Dimethyl Ether Intermediates: 2019 State of Technology" NREL/TP-5100-76619. National Renewable Energy Laboratory, April 2020, p. 2.

As appealing as this three-part revolution sounds, it will not succeed unless it overcomes three core challenges: (1) limits on the biomass resource for chemical production; (2) high costs; and (3) net environmental impact.

2.4.1 Resource Challenges

Estimates suggest that 150 EJ† of biomass could potentially be available worldwide at prices ranging from $2–20/GJ.[23] About 17EJ of biomass could be available in the United States from farm and forestry waste as well as grasses or trees growing on land that is not suitable for conventional agriculture but has already been disturbed by human activities.[24] Additional resources are available from municipal solid waste, food waste, sludge, manure, and biogas. The huge price range reflects the wide range of costs associated with growing, harvesting, and transporting bulky materials.

It is not clear, however, how much of this resource will be available for petrochemical production since biomass will be in high demand in a low-carbon world. For example, there is high interest in biomass-fueled electricity-generation systems fitted with carbon capture and sequestration (CCS). Such systems create negative emissions. The Intergovernmental Panel on Climate Change assumes enormous quantities of negative emissions from this technology in scenarios designed to prevent global temperatures from increasing above 1.5° C.[25]

† The US consumes a total of about 100 EJ each year.

High demand for biomass may also come from producers of fuel for aircraft, heavy trucks, and other equipment that cannot be easily electrified.

The choice of final product will depend heavily on the price of the biomass resource and the price of potential products, which are highly regional. In the US it is likely that transportation fuels will be a preferred market, at least in the long run, because producing petrochemicals at competitive prices will be challenging. (Gasoline is several times more expensive in the United States than natural gas.[26]) Natural gas prices are significantly higher in Europe and Asia, which may make biomass a more competitive feedstock option there.[27] Ethylene made from fossil resources in Europe and Asia costs up to $1200/tonne, whereas in the United States prices have been closer to $250/tonne.[28] Recent events, of course, may be shrinking this difference.

2.4.2 Economic Challenges

Most economic analysis of petrochemical production from biomass has focused on methane and methanol. These outputs can be used as fuels or piped to refineries as feedstocks for plastics and other products. A number of studies indicate that such bio-based production systems could become competitive by 2030–2050.[29, 30] Industry estimates suggest that the potential future costs of bio-methanol will be $12–42/GJ, compared with current global methanol prices of $10–20/GJ.[31]

More-complex petrochemicals made from biomass may also become competitive in this time frame. An analysis using the GREET model developed by DOE’s Argonne National Laboratory (see Appendix B), shows that both gasification and pyrolysis could produce could gasoline and diesel blend stocks for $3–3.50 per gallon: a price much lower than production from sugars.[32]

Commercial interest in bio-based petrochemical production is growing.[33]

- Worldwide, 540 plants are now producing pipeline-quality methane from biomass.
- Several commercial bio-based pyrolysis projects have been underway in Europe since 2014, although progress has been slow.[34] The Empyro project, for example, has a pyrolysis facility in the Netherlands that converts 5 tons per hour of wood residues into 24,000 tons of bio-oil per year as well as producing process steam and electricity.[35]
- About 2 million tons of bioplastics were manufactured worldwide, about 0.5 percent of total production.[36] About 18 percent of this production was in North America, and about half of it was also biodegradable.[37]
- The Brazil-based Braskem Company has been making 180,000 metric tonnes of polyethylene per year since 2010 using sugar cane as a feedstock.[38]

2.4.3 Environmental Challenges

Environmental concerns about large-scale use of biomass for chemical production arise from GHG emissions caused by planting, fertilizing, transportation, and processing, as well as by the impacts of land use changes on food prices and GHG emissions, among other things.[39]

The net emissions associated with biomass production depend heavily on the feedstock. Products made from corn are particularly problematic. In fact, some recent analyses suggest that ethanol made from corn might have a net positive impact on emissions.[40] The emissions associated with growing and harvesting lignocellulosic materials are far lower. If biomass is combusted to provide energy to make petrochemicals, GHGs emitted as a byproduct do not contribute to net global emissions, because the carbon was previously captured from the atmosphere by plants. However, biomass harvested from forests may cause habitat destruction and may also have been captured more than century ago, complicating the accounting. In the future it might be preferable to use alternative low-carbon energy sources and conserve the biomass. For example, fermentation-based systems might be electrified, since the required temperatures are comparatively low. High-temperature heat pumps might also be used.[41]

3 Recycled Petrochemicals

3.1 Some Basics

Petrochemicals contain many compounds and elements that can, in principle, be recycled. Virtually all recycled plastics today (more than 99%) are processed mechanically: they are ground up and melted down to make fence posts, siding, and similar products. Mechanical recycling requires minimal preprocessing but typically results in products that are less valuable than the ones that were recycled (a phenomenon known as "downcycling").[42]

The variety of pyrolysis and gasification technologies described for breaking down biomass can also be used to deconstruct plastic and other petrochemical waste materials. As with biomass, the gases and liquids produced can then be upgraded to make a wide range of chemical products, usually with the addition of hydrogen from an external source

Advanced chemical-recycling technologies are in development to take the waste inputs apart at a molecular level. The resulting stew of components can be refined into inputs for chemical production. Such technologies may be able to avoid downcycling and yield end products that are fully equivalent to the original materials.

3.2 Pyrolysis and Gasification

Pyrolysis and gasification processes can transform mixed streams of recycled petrochemicals (with limits) into valuable intermediates. At least 12 commercial systems of this type are now in operation around the world.[43] For instance, Nexus Circular, which is partly funded by Shell and Braskem, uses several common plastics as inputs.[44] The process uses a significant amount of energy and operates most efficiently if the waste input streams are pure.

Innovations are under development that can lead to significant improvements. For instance, catalysts can be added to accelerate chemical processes. Contaminant removal (which has proven challenging) and molecular breakdown can be achieved in separate processes (known as pyrolysis with in-line reforming).[45] Hydrocracking and hydrothermal systems add hydrogen and near-critical water to process intransigent materials, such as carbon fiber.[46] Microwave pyrolysis, powered by electricity, may be easier to control than fuel-powered systems.[47,48] Plasma pyrolysis is able to tolerate a wide range of contaminants, including PVC, thin films, multi-layer containers, and hazardous materials, and its requirements for sorting and processing are simpler.[49, 50]

3.3 Depolymerization and Other New Approaches

While tearing plastic into small molecules at high temperatures and reassembling them into new plastic molecules clearly works, it would seem more logical to preserve the more complex components of such plastics as monomers.[51] Several approaches that would do so are in advanced stages of development, including some that can tolerate mixed waste inputs. One approach uses a variety of catalysts, solvents, or enzymes for depolymerization and reassembly into new plastic.[52, 53] Hydrolysis doesn't require catalysts and can manage a range of waste materials.[54] Other systems separate polymers from waste material without breaking them into monomers; the polymers are then purified and reused.[55, 56] Chemical recycling can be made much easier as well if chemicals are designed with disassembly in mind.[57]

There is also growing interest in using biological systems to perform chemical recycling. Ideally, these systems will operate at ambient temperatures with very low environmental impacts. Research teams searching plastic dump sites, sewage sludge, landfills, and other sites have found microorganisms capable of degrading most kinds of plastics. [58] These discoveries might be integrated with synthetic biology, machine learning, and other methods to build advanced systems.[59, 60]

3.4 Challenges

While the processes are different, chemical recycling faces challenges similar to bio-based production from biomass: collection of materials from a large geographic area, keeping costs down, and avoiding environmental impacts.

3.4.1 Collection Challenges

Collection (and separation) costs are driven in part by consumer behavior. They could be reduced if consumers would participate in recycling. But few consumers have done so. As a result, technology developers have been forced to focus on separation technologies sophisticated enough to handle highly mixed waste streams.

Less than 10% of plastic waste is recycled in the United States, while about a sixth is burned to generate electricity and for other purposes.[61] Worldwide, the comparable figures are about 14% recycled and 11% burned, although there are large variations.[62, 63, 64]

Most interest in recycling is driven by a desire to prevent ocean and land pollution, rather than GHG abatement. While burning waste prevents land and ocean pollution, GHG emissions are not averted unless CO_2 can be captured. A major facility that will do so in Oslo is well underway.[65]

It's easy to understand why recycling is so difficult. Waste must be gathered from dispersed sources, recyclable material separated, and then transported to a central processing site. Some recycling systems can tolerate mixed inputs while others require clean streams of a specific plastic type. Plastics usually include dyes and other additives that provide color, flexibility, fire resistance, and other properties, but that complicate recycling. Multi-layered food containers are especially hard to recycle.[66]

Systems that sort mixed waste must sense differences in shape, density, chemical composition, and other characteristics. The processes are expensive to build and operate and can create environmentally damaging side products without careful controls.[67] Transportation logistics alone are daunting. A scenario developed for a German recycler, for example, assumed the following: waste was moved 30 km from household pickup sites to collection points, 80 km from collection points to sorting facilities, 50 km to a chemical recycling facility, and 500 km to a purification facility.[68] Major efforts are underway to reduce the cost and complexity of collection and separation systems.[69]

Despite technical progress, the price of sorted plastics has risen sharply in the past few years. Sorted PET (polyethylene terephthalate), the major component of plastic bottles, costs about $170/tonne and sorted HDPE (High Density Polyethylene) used for many consumer products, costs about $400/tonne.[70] This is two to four times the cost of fossil fuels inputs used to make new plastics in the United States, a significant disadvantage.

3.4.2 Economic Challenges

While a wide range of chemical recycling technologies is being explored, economic and environmental analysis is largely limited to pyrolysis and gasification. A detailed analysis published in 2022 concluded, “there is a lack of quantitative data and scientific/technical literature to support a comparative evaluation of the strengths and weaknesses of CR [chemical recycling] against conventional recycling and energy recovery pathways. The predominant attention today—academic and otherwise—is on technical issues…."[71]

While the business opportunities for chemical recycling are potentially very large—the American Chemistry Council estimates that it could add nearly $10 billion to the US economy—the economics are challenging given current regulatory and economic conditions.[72] The path to profitability is likely to rely heavily on indirect benefits, such as sale of products from waste separation and energy offsets where recycling has replaced fossil-based plastic production.[73, 74]

Commercial investments suggest that at least some pathways are potentially profitable as markets evolve. For example:

- Loop Industries has partnered with PepsiCo to recycle PET containers (bottles).[75]
- APK is using a solvent dissolution process that can convert a variety of packaging materials into new packaging.[76, 77]
- Purecycle Technologies is using a technology licensed from Procter & Gamble to disassemble and recycle polypropylene.[78]
- Carbios is using biological enzymes to recycle PET.[79]
- Polystyvert uses dissolution and purification to recycle polystyrene.[80]

3.4.3 Environmental Challenges

The environmental consequences of chemical recycling are complex. All recycling helps eliminate plastic pollution on land and at sea and the dispersal of microplastics. But recycling processes can release significant amounts of GHGs as well as toxins like chlorine, dioxins, and sulfur oxides.[81]

A number of recent studies have concluded that high-temperature chemical recycling processes like pyrolysis and gasification produce about half the emissions of incineration.[82]

It may be possible to cut CO_2 emissions in half again with advanced technology, but that is still far from zero.[83] Additional emissions reductions may be credited if chemical recycling avoids more GHG-intensive conventional petrochemical production. Logic suggests that emissions from chemical recycling using depolymerization and other low-temperature processes would be much lower, but data are scarce.

4 Direct Production of Petrochemicals from CO_2 and Water Using Advanced Technologies

4.1 Some Basics

Photosynthesis, the evolutionary invention that make it possible for living things to make complex chemicals from simple ingredients at ambient temperatures, begins with two key steps: producing hydrogen from water (H_2O) and taking oxygen away from the carbon in CO_2. This energy-intensive process provides the building blocks for life's incredibly complex biochemistry.

Photosynthesis is reliable and inexpensive, but it isn't particularly efficient. Most crops achieve an efficiency of only about 1 percent.[84] This suggests the tantalizing possibility that natural photosynthesis can be tweaked to become more efficient, or be replicated artificially. A third and final step converts these building block products into carbohydrates and other complex chemicals needed to sustain life. Some of the systems described here produce complex chemicals directly while others produce components (such as hydrogen or CO) that can be sent to other equipment for conversion. Some of these techniques remove CO_2 from the atmosphere, but unless the plastic or other products produced are permanently sequestered, these techniques cannot be considered as carbon sequestration technologies.

Several approaches are being actively explored (listed roughly in order of commercial readiness):

- **Advanced catalysts:** Using commercial catalysts to combine CO_2 with hydrogen to make methane or methanol that can be upgraded to more complex chemicals.
- **Advanced methods:** Novel approaches to producing chemicals from CO_2 and water using electrolytic methods, microorganisms, and fuel cells.
- **"Artificial photosynthesis":** Use sunlight directly to drive a catalytic device that can convert water and CO_2 into complex chemicals.

Most of these systems need fairly high concentrations of CO_2 to be efficient. Input streams with high CO_2 concentrations will be available from CCS systems at industrial and power facilities. Systems that can operate with the highly diluted CO_2 concentrations in air form a research frontier.

4.2 Advanced Catalysts

Given a supply of hydrogen, commercial catalysts can be used to convert CO_2 to methanol and upgrade it to a variety of petrochemical end products. (Similar systems can be used to produce ammonia.) This approach, also known as e-methanol, has gained interest in China and other regions where natural gas is comparatively expensive.[85] It avoids many contaminants that complicate the conventional process, which uses coal as a feedstock. A much more efficient e-methanol production system has been demonstrated at DOE's Pacific Northwest National Laboratory. It uses an aqueous system to capture CO_2 and a catalyst that can combines the captured CO_2 with hydrogen to produce methane for as little as $25/MMBTU (assuming hydrogen costs of $2.1/kg).[86]

A recent survey found 24 "existing or planned facilities and technology providers for e-methanol production."[87]

None were in the United States. They include the following facilities:

- Carbon Recycling International in Iceland, which has been operating at a commercial scale since 2012 using CO_2 from geothermal sources and hydrogen made with geothermal power.[88]
- A 1,000-ton-per-year e-methanol plant operated by the Chinese Dailian Institute of Chemical Physics that uses solar power.[89]

4.3 Advanced Methods

The efficiency of petrochemical production can improved if catalysts can be used to drive electrochemical reactions that split water into its elemental components and remove both oxygen atoms from carbon dioxide, which is much more difficult than removing one.[90]

The following three approaches are being explored within this broad grouping:

- integrated devices
- microorganisms
- solid oxide fuel cells in reverse

4.3.1 Integrated Devices

Integrated devices can be built that use electricity to split water and CO_2 in a single device. A host of practical problems, such as blocked fluid flows, bubbles, and degrading membranes, have slowed progress along this track, but this may be changing. Experimental systems have achieved 50–80% efficiency in converting electricity into ethylene and other commercially valuable products.[91]

Examples include:

- Sunfire's system to produce syngas from captured CO_2 and water using a highly efficient electrolyzer. The syngas can then be upgraded using conventional techniques.[92] Norsk e-fuel is partnering with Sunfire to produce jet fuel using CO_2 captured from the atmosphere.[93]
- Twelve's electrochemical device reduces CO_2 and electrolyzes water, producing syngas that can be upgraded using conventional techniques.[94, 95] The company has recently partnered with the US Air Force to produce jet fuels.[96]

A team from Lawrence Livermore National Laboratory and Stanford University has developed a novel strategy for accelerating progress across all of these approaches. They use sophisticated simulation tools to develop new designs and convert these software designs into functioning hardware using 3D printing and other advanced manufacturing techniques.[97]

4.3.2 Microorganisms

Microorganisms can be used to perform all or part of the process of splitting water and CO_2 and converting the components into complex chemicals. Like advanced biomass systems, they could use sunlight for these purposes, but it appears that much greater efficiencies can be achieved by combining biological and synthetic systems. Engineered microbes can, for example, take hydrogen and CO_2 produced synthetically and combine them to produce complex chemicals. Other hybrid systems use hydrogen produced with electrolysis and send it to an engineered biological organism that combines it with CO_2 to produce methane, methanol, and other products.[98]

These systems can operate with near zero greenhouse gas emissions if the electricity or other fuels used to split water or process CO_2 are produced by renewables or other clean resources. The first systems, however, are likely to use hydrogen and carbon produced by industrial processes, including waste gases and outputs from pyrolysis or gasification of biomass or plastic waste. Anaerobic acetogens, for example, can catalyze syngas into organic acids and alcohols.[99]

A variety of experiments are underway. For example:

- Chemvita is working with Occidental Petroleum on one such system. The companies are investing in facilities that can produce "bioethylene."[100]
- LanzaTech uses proprietary microbes to process a variety of waste gases into chemical products. Its portfolio includes microbes that can take gas mixtures deficient in hydrogen and convert carbon monoxide and water into hydrogen.[101]
- A number of groups have been pursuing the use of microalgae as a production system.[102]

Hybrid systems using both electrochemical and biological systems are also being explored. For example, an electrolyzer developed by Siemens, Covestro, and Evonik converts CO_2 into CO and injects the CO and hydrogen into a bioreactor with two species of clostridia bacteria that produce petrochemicals. A demonstration facility is operating in Marl Germany. [103,104]

4.3.3 Reversed Fuel Cells

A third general approach uses solid oxide fuel cells. Electricity in these cells drives the creation of syngas (H_2 and CO) from water and CO_2. Syngas can serve as a feedstock for biological or chemical engineering methods that produce petrochemicals. These systems in effect reverse the usual function of fuel cells.[105] Research on such systems focuses on increasing efficiency, ensuring that carbon atoms aren't lost, reducing costs, and increasing durability.[106]

The durability of solid oxide systems has been demonstrated in conventional applications (i.e. conversion of fuels to electricity); mid-sized electric generating systems have operated in Japan for 11 years, and more than 50 thousand residential scale units are now in use there.[107] However, early research suggests that reversed-fuel-cell systems will face difficulties competing with catalytic systems, which are easier to manage, more flexible, and can produce a wider variety of useful products including ethylene.[108]

4.4 Artificial Photosynthesis

The final approach is the most ambitious: using sunlight instead of electric power to convert CO_2 and water into useful chemicals.[109, 110] The World Economic Forum listed this technology as one of the "Top Ten Emerging Technologies of 2020."[111] Artificial photosynthesis attempts to modify the way plants operate to increase its efficiency and optimize production of commercially useful chemicals. Natural systems did not evolve in this direction because they faced multiple competing design requirements, such as building structures, defense against predators, and reproduction.

One approach within this general category uses completely synthetic electrochemical cells that are powered entirely by sunlight. Like the reversed fuel cells considered above, these cells split water into hydrogen and combine the hydrogen with CO_2 to produce useful chemicals. The concept is proven, and efficiencies of 10% and higher have been demonstrated.[112,113]

DOE's Office of Science has supported work in this area since at least 2010.[114] Recipients include the Liquid Sunlight Alliance, the Center for Hybrid Approaches in Solar Energy to Liquid Fuels, and the Joint Center for Artificial Photosynthesis.[115, 116, 117] While progress has been made, no commercially viable system has been developed. Areas where improvements are possible include:[118]

- Improving the efficiency of capturing sunlight. Existing plants and algae reflect rather than capture a significant fraction of the available light, such as the infrared.
- Exploiting different colors of sunlight for producing hydrogen and combining hydrogen with concentrated CO_2. Current systems use the same colors of sunlight and therefore compete for the available energy.[119]
- Adapting to full sunlight. Biological systems are designed to operate in low sunlight and cope with full sun by rejecting as much as 80% of the light they receive.
- Avoiding cellular growth. Cellular growth consumes about 30% of the energy produced and respiration another 25%, costs that could be greatly reduced in a synthetic system, particularly if concentrated CO_2 were available.

4.5 Challenges

Direct production of petrochemicals from water and carbon dioxide avoids two of the three major challenges facing other strategies. These systems do not require rare materials. In principle they can be located anywhere that inexpensive electricity and water are available. They promise extremely low emissions and few other environmental impacts. The enormous challenge facing this strategy is cost—particularly for systems that capture carbon from the air rather than relying on CCS facilities.

Some estimates suggest that direct production systems will never be cost-competitive.[120] But a recent analysis concludes that electrocatalytic systems could produce ethylene at $600–$800 per tonne and biocatalytic systems at $1200–$2000 per tonne, which would be competitive in many parts of the world. To achieve these levels would require conversion efficiencies above 60%, electricity prices below $40 per megawatt hour, and a source of pure CO_2 at $30/tonne, all of which seem to be within reach.[121]

Cost estimates for e-methanol also vary enormously, depending on the cost of hydrogen and CO_2. Current production costs appear to range from $800 to $2400 per tonne, with anticipated declines to $250–630/tonne.[122]

Current prices can be as low as $100/tonne in the Middle East up to $300 or more in the United States and Europe. Solid oxide systems for producing gasoline depend on similar factors and currently cost about $8–11/gallon.[123, 124]

5 Integrated Production Challenges

Given their novelty and the colossal scale of investment required, it is far from clear how the new technologies reviewed above will be integrated into new and existing chemical supply chains. Replacing conventional methods for producing plastics and fuels will be a heroic challenge. Locating new facilities next to existing refineries offers many advantages, including access to a variety of chemical feedstocks and well-established sales and distribution networks. In addition, many of the new processes require final steps that are already carried out at refineries.

However, most of the next-generation technologies may be able to operate economically at much smaller scales than current production systems. That, in turn, may allow production to be decentralized and redistributed across geographic regions. The choice of location and scale will depend on the availability of water, concentrated CO_2, and inexpensive electricity and/or hydrogen. Biomass and recycling facility locations will also depend on the availability and cost of these feedstocks. New chemical producers could make distributed production more likely by making products such as methanol or ethanol that are easily transported to refineries or other purchasers.

Distributed production offers several advantages. Many more sites would become viable options. Lower investment cost per plant would reduce the risks faced by investors. Sites could be expanded in a modular fashion, further reducing investment risk. The construction of many relatively small facilities time would allow continuous improvements through learning over time.

The US ethanol industry provides an example of continuous improvement in distributed chemical production. Continuous learning reduced the unit capital costs by a factor of four between 1981 and 2006[125] and industrial processing costs declined by 45% between 1983 and 2005.[126] Continuous learning has also been documented in Brazilian ethanol production as well.[127] Both programs benefited from aggressive public policy creating a strong market.

Another potential advantage of distributed production would be provided by access to variable renewable energy sources, such as wind and solar farms. Advanced chemical production facilities might use power only when it is available or least expensive. They could even provide energy storage if hydrogen (or other chemicals produced on-site) can be converted back to electricity, although the economic challenge of doing so is formidable. The economics of such systems depend on a careful analysis of the fraction of the time the capital equipment is in use.[128]

While there are few examples of plastic and other petrochemical facilities operating at a relatively small scale, a few are emerging. The new Chemetry e-shuttle technology, for example, would allow production of polyvinyl chloride using brine and ethylene that could presumably be produced locally.[129] The first Chemvita facility using microorganisms to process industrial CO_2 waste will be located close to existing refineries, minimizing transportation.[130]

6 Policy Recommendations

Technologies to produce petrochemicals without fossil fuels face a fundamental barrier: the failure of markets to reflect the real cost of GHG emissions.[131] This barrier compounds the challenges caused by risk aversion that face innovators in any sector, even when the potential long-term benefits to society are very large.[132] A wide range of public policies designed to address these issues has been extensively explored, and they are clearly needed to support the technologies discussed here.[133] The discussion in this section will not reprise these general arguments but focus instead on a few focused actions.

Vigorous development efforts are already underway in Europe and Asia. The European Commission has established the ambitious 2030 goal of having "at least 20% of the carbon used in products…from sustainable non-fossil sources."[134] A Euro Prize is being offered for "a fully functional, bench-scale prototype of an artificial photosynthesis based system which can produce a useable synthetic fuel."[135] These technologies are integral parts of Europe's flagship research and innovation policies, Horizon Europe[136] and the ETS Innovation Fund.[137]

6.1 A Major Coordinated Research Program

The baseline policy to initiate a strategy is federal funding and management of a major, coordinated research program. While past federal funding has not been trivial, it falls far short of the amount needed to ensure that these innovations lead to large-scale commercial production on a timeline that would make a significant contribution to climate policy by 2050. In addition, the legacy program is fragmented. The research programs behind it seldom, if ever, gain the attention of senior management. (The large collection of organizations supporting this research is outlined in Appendix B.)

To address this weakness, the White House Office of Science and Technology Policy and Domestic Policy Council should draw on expertise in federal agencies, industry, and academia to develop a coherent plan of action. It should include research, development, and scale-up demonstrations that can be closely aligned with programs designed to fund first-generation commercial investments.

This roadmap should include the following elements:

- A coherent description of the potential technical opportunities;
- A preliminary estimate of the potential contribution to emissions reduction of each major technology as well as potential resource limitations and other constraints;
- A preliminary timeline for key development milestones and commercial production;
- An outline of research, development, and demonstration priorities; and
- A clear assignment of responsibilities to each participating agency and an associated budget recommendation.

The roadmap should revisited annually, summarizing progress and refining priorities

The White House would be responsible for ensuring that priorities are being pursued by the participating agencies and for facilitating communication and cross-fertilization. The work should be conducted as an integral part of a broader program to revitalize American manufacturing.

6.2 Integration with the "Hydrogen Shot"

The US Department of Energy should review its "Hydrogen Shot" program to ensure that it includes the research and commercialization priorities of the interagency road map.[138] Most if not all of the non-fossil petrochemical-production technologies require additional hydrogen to supplement their feedstocks. In addition, many of the systems for direct production of petrochemicals from water and carbon dioxide involve technical issues very similar to those involved in electrolytic hydrogen production. (In fact, some of the systems use electrolytic hydrogen.)

6.3 A Transition Plan for Ethanol Producers

The US Department of Agriculture should develop a transition plan for incumbent ethanol producers. Rapid electrification of the light-duty vehicle fleet will reduce markets for ethanol as a gasoline additive, driving producers to look for new markets. Their most attractive choice may be to shift production to other fuels, but petrochemicals should also be considered. USDA should draw on expertise from DOE and other federal agencies to review the options. Some ethanol producers might be enlisted to test commercial operation of technologies like pyrolysis and gasification.

6.4 Petrochemical Product Labels Based on Life-Cycle Greenhouse Gas Emissions

A robust plan for transitioning the petrochemical industry should enlist consumers as well as producers. Yet, informed choice on environmental grounds among plastics and other products is essentially impossible today. Labels on some plastic products are designed to facilitate recycling, but are "confusing and inconsistent," according to consumer groups.[139, 140]

These labels say nothing about net greenhouse gas emissions, fail to indicate how hazardous the materials are if they are not properly recycled or disposed of, and fail to recognize new plastic production and recycling technologies. Many key tools that could be used to encourage next-generation petrochemical technologies cannot be implemented without an honest accounting of these impacts. These tools include government procurement policies, voluntary commercial purchasing incentives, and standards.

Drawing on expertise throughout the government, the US Environmental Protection Agency should, within one year, produce a life-cycle assessment that can be the basis for consistent labeling of petrochemical products. This report should include net greenhouse gas emissions on a range of time scales (years, decades, centuries) associated with the following:

- feedstock extraction and delivery,
- production, fabrication, transportation, and storage,
- end-states, including disposal in a secure landfill, uncontrolled release to the environment, and recycling.

The complexity of petrochemical production will make precision impossible, but even if these estimates wind up ignoring some secondary issues, they will be better than having no estimate at all.

7 Conclusion

Can we enjoy the enormous benefits of plastics and other petrochemicals while avoiding devastating environmental impacts? The answer is unquestionably yes. There are many ways to produce these materials without using fossil fuels. The core question is not whether advanced petrochemical production technologies are technically feasible but whether they can be made affordable. The answer to this question depends heavily on public policy.

What are needed are policies that shape the terms of competition to account for the full lifecycle environmental impacts of different production systems and that support rapid innovation and commercial development. Policymakers might also focus on encouraging regional diversity in petrochemical production.

Limited availability and intense competition for biomass may limit the contribution of this resource to petrochemical production. The environmental problems associated with recycling petrochemicals made by conventional means will be a major barrier to that approach; these will only be resolved if the recycled materials don't contain fossil carbon to begin with. A practical way to produce petrochemicals materials directly from carbon dioxide and water would be an enormous breakthrough—a true environmental home run—but these technologies face the most daunting development challenges. None of these pathways should be ignored. The stakes are enormous, and deadlines are daunting.

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Appendix A

Environmental Impacts of Biomass Use

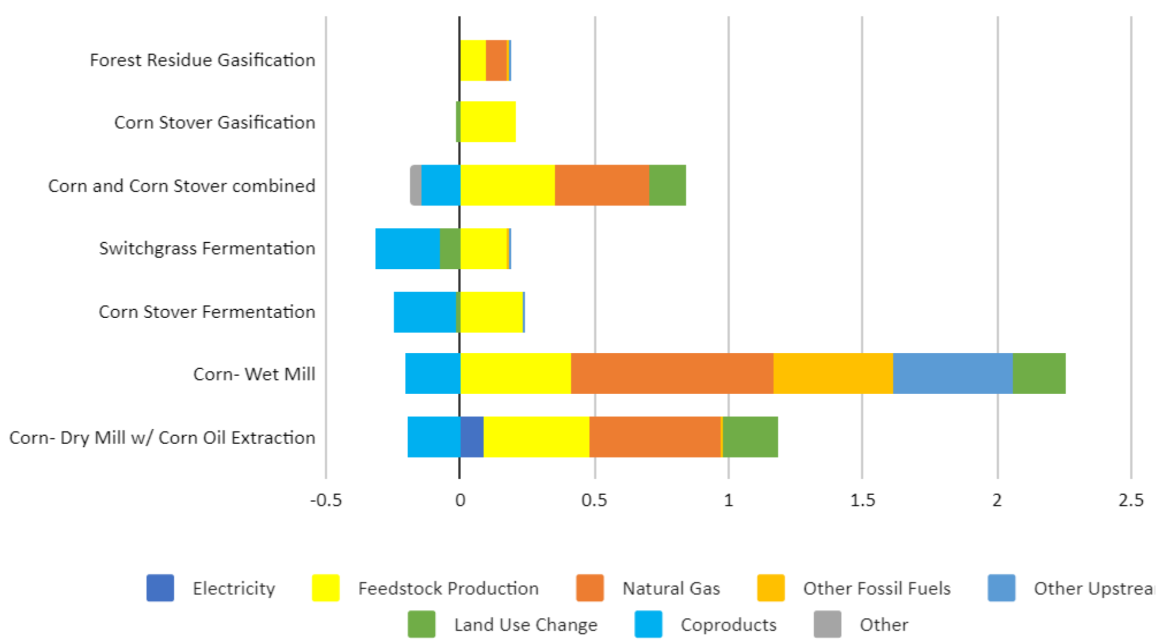
Ryan Murphy

The GREET model (GREET.net) was use to compute the net environmental impacts of a variety of conventional and advanced biomass systems. The following cases were examined:

- Corn fermentation—dry mill with corn oil extraction
- Corn fermentation—wet mill
- Corn stover fermentation
- Switchgrass fermentation
- Corn and corn stover combined fermentation (68% corn, 32% corn stover)
- Corn stover gasification
- Forest residue gasification

The estimates include emissions from production and transportation of the biomass and from the electricity and fuels used in production. The default inputs to each process were eliminated one-by-one to calculate the change in CO_2 emissions associated with that particular input. Electricity and fuel emissions could be eliminated if zero carbon production of these inputs were achieved. The results are shown as total emissions per kg of ethanol produced.

CO_2 per kg of Fuel Produced (Grams)



Appendix B

Advanced Biochemical Production Research and Development in Federal Agencies: A Partial List*

1. White House

- Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe and Secure American Bioeconomy (Executive Order, September 12, 2022)
  - It is the policy of my Administration to coordinate a whole-of-government approach to advance biotechnology and biomanufacturing towards innovative solutions in health, climate change, energy, food security, agriculture, supply chain resilience, and national and economic security. Central to this policy and its outcomes are principles of equity, ethics, safety, and security that enable access to technologies, processes, and products in a manner that benefits all Americans and the global community and that maintains United States technological leadership and economic competitiveness.[1]

2. US Department of Energy

2.1. Energy Efficiency and Renewable Energy

2.1.1. Bioenergy Technologies Office

- Waste to Energy
  - Wet waste, solid waste, and gaseous waste streams are potential high-impact resources for the domestic production of biofuels, bioproduct precursors, heat, and electricity. Wastes represent a significant and underutilized set of feedstocks for renewable fuel and product generation.
- Deconstruction & Fractionation
  - To convert biomass into a biofuel, it must first be deconstructed into its component chemicals. One can generally differentiate between deconstruction processes by the temperature at which they take place….

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* Text directly from US government websites.

- Synthesis & Upgrading
    - Intermediates produced following deconstruction of biomass include bio-oils, gaseous mixtures such as synthetic gas (syngas), sugars, and other chemical building blocks. These intermediates are upgraded using various techniques to produce a finished product. These finished products could be fuels or bioproducts, or they could be stabilized intermediates suitable for finishing in a petroleum refinery or chemical manufacturing plant.
- Bioproduct Production
    - Many products derived from petrochemicals could be supplemented with biomass-derived materials. In some cases, the unique properties of biomass may provide advantages for efficiently producing new biomass-derived chemicals. BETO is supporting research and development of these bio-advantaged products.
- CO_2 Utilization
    - BETO's main strategy for investigating CO_2 utilization occurs first through engineered carbon reduction, where electricity is used to convert CO_2 to reduced carbon intermediates, such as carbon monoxide, formic acid, or methanol. This step can occur through a number of approaches, such as: electrocatalysis, thermocatalysis, bioelectrocatalysis. These intermediates can then be upgraded to fuels and products through a variety of technologies such as gas fermentation and catalytic upgrading.

- Advanced Manufacturing Office
    - Industrial Heat Shot™, a new effort aimed at dramatically reducing the cost, energy use, and carbon emissions associated with the heat used to make everything from food to cement and steel. The latest DOE Energy Earthshots Initiative™, the Industrial Heat Shot™ seeks to develop cost-competitive solutions for industrial heat with at least 85% lower greenhouse gas emissions by 2035.[2]
    - Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment (BOTTLE): Developing new chemical upcycling strategies for today's plastics and redesigning tomorrow's plastics to be recyclable-by-design.
    - The Clean Energy Manufacturing Innovation Institute for Reducing Embodied-energy And Decreasing Emissions (REMADE) in Materials Manufacturing, launched in 2017, is the thirteenth Institute in the Manufacturing USA network. The Institute will focus on early-stage applied research towards innovations that could dramatically reduce the energy required to manufacture key materials and improve overall manufacturing energy efficiency through increased material reuse, recycling, and remanufacturing.

2.1.2. Hydrogen and Fuel Cell Technologies Office

- Hydrogen Shot "seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade."
  - Hydrogen production including thermochemical processes, electrolytic processes, direct-solar water-splitting processes, and biological processes.

2.2. Office of Science

- University and National Laboratory competitive research grants.
  - The Liquid Sunlight Alliance (LiSA), established in 2020 and led by the California Institute of Technology in close partnership with Lawrence Berkeley National Laboratory…. LiSA partner institutions also include the National Renewable Energy Laboratory, SLAC National Accelerator Laboratory, the University of California Irvine, the University of California San Diego, and the University of Oregon.
  - The Center for Hybrid Approaches in Solar Energy to Liquid Fuels (CHASE), established in 2020 and led by the University of North Carolina at Chapel Hill…. CHASE partner institutions are Brookhaven National Laboratory, Yale University, the University of Pennsylvania, North Carolina State University, and Emory University.

2.3. Office of Fossil Energy and Carbon Management

- Carbon dioxide removal (CDR)…refers to approaches that capture carbon dioxide (CO_2) directly from the atmosphere and store it in geological, biobased and ocean reservoirs or in value-added products to create negative emissions….. Carbon Negative Shot is the all-hands-on-deck call for innovation in technologies and approaches that will remove CO_2 from the atmosphere and store it at meaningful scales for less than $100/ net metric ton of CO_2-equivalent (CO_2e).

2.4. ARPA-E

- The ECOSynBio program aims to promote the use of advanced synthetic biology tools to engineer novel biomass conversion platforms and systems. These systems will be designed to use external energy inputs to substantially increase carbon use, versatility, and efficiency while achieving economies of scale for industrial applications. Successful platforms will offer new capacities for the bioeconomy by enabling fully carbon-optimized renewable fuel and chemical synthesis with maximum carbon and resource efficiency.
- In-silico heterogeneous catalyst design for GHG reduction via bulk chemicals.

2.5. Office of Clean Energy Demonstrations

- A mission to deliver clean energy demonstration projects at scale in partnership with the private sector to launch or accelerate market adoption and deployment of technologies, as part of an equitable transition to a decarbonized energy system.

2.6. Carbon Sequestration Challenge

- .. four programs that will help build a commercially viable, just, and responsible carbon dioxide removal industry in the United States…. funded with $3.7 billion from President Biden’s Bipartisan Infrastructure Law
- Direct Air Capture Commercial and Pre-Commercial Prize – DOE’s Office of Fossil Energy and Carbon Management (FECM) is announcing the Direct Air Capture Prize for support and prize awards totaling $115 million to promote diverse approaches to direct air capture.
- Regional Direct Air Capture Hubs – DOE’s Office of Clean Energy Demonstrations (OCED), in partnership with FECM, is announcing the Regional Direct Air Capture Hubs program. DOE will invest $3.5 billion to develop four domestic regional direct air capture hubs, each of which will demonstrate a direct air capture technology or suite of technologies at commercial scale with the potential for capturing at least 1 million metric tons of CO2 annually from the atmosphere and storing that CO2 permanently in a geologic formation or through its conversion into products.
- Carbon Utilization Procurement Grants – FECM will manage the Carbon Utilization Procurement Grants Program, which will provide grants to states, local governments, and public utilities to support the commercialization of technologies that reduce carbon emissions while also procuring and using commercial or industrial products developed from captured carbon emissions.

3. Department of Agriculture

- The Bioproduct Pilot Program, under assistance listing 10.236, will advance development of cost-competitive bioproducts with environmental benefits compared to incumbent products. The program seeks projects that will study the benefits of using materials derived from covered agricultural commodities for production of construction and consumer products.

4. Department of Commerce

- DOC plans to invest an additional $14 million next year at the National Institute of Standards and Technology for biotechnology research programs to develop measurement technologies, standards, and data for the U.S. bioeconomy. This support will catalyze development of capabilities for engineering biology, advance biomanufacturing processes and technologies, and help utilize artificial intelligence to analyze biological data.[3]
- NIIMBL (launched by the Department of Commerce (DOC)) will expand their industry partnerships to enable commercialization across regenerative medicine, industrial biomanufacturing, and biopharmaceuticals. For example, NIIMBL will launch a biomanufacturing initiative that will engage the institute’s 200 partners across industry, academic, non-profit, and Federal agencies to mature biomanufacturing technology

5. Department of Defense

- BioMADE will launch hubs supporting equitable regional development, create jobs nationwide, and enhance American economic competitiveness. BioFabUSA is standing up the BioFab Foundries, a first-of-its-kind U.S. facility that integrates engineering, automation, and computation with biology
- The Department of Defense (DoD) will invest $1 billion in bioindustrial domestic manufacturing infrastructure over 5 years to catalyze the establishment of the domestic bioindustrial manufacturing base that is accessible to U.S. innovators. This support will provide incentives for private- and public-sector partners to expand manufacturing capacity for products important to both commercial and defense supply chains, such as critical chemicals. DoD will invest an additional $200 million to support enhancements to biosecurity and cybersecurity posture for these facilities[4]
- In 2020, Air Force Operational Energy endorsed the carbon transformation company, Twelve, to launch a pilot program to demonstrate that their proprietary technology could convert CO_2 into operationally viable aviation fuel called E-Jet.

6. Sustainable Aviation Fuel Grand Challenge

- The SAF Grand Challenge is the result of DOE, DOT, and USDA launching a government-wide Memorandum of Understanding (MOU) that will attempt to reduce the cost, enhance the sustainability, and expand the production and use of SAF.… Meeting a goal of supplying sufficient SAF to meet 100% of aviation fuel demand by 2050.

Notes

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