BIOTECH SOLUTIONS FOR CLIMATE REPORT

Examining biotechnology's contributions to addressing the climate crisis

Matt Carr | Green Capitol, LLC

Tristan Brown | State University of New York, College of Environmental Sciences and Forestry

Colin Murphy | University of California, Davis, Policy Institute for Energy, Environment, and the Economy

Biotechnology Innovation Organization

TABLE OF CONTENTS

INTRODUCTION

"CLIMATE CHANGE IS ONE OF THE GREATEST PUBLIC POLICY CHALLENGES FACING THIS GENERATION."

The rapid accumulation of anthropogenic carbon dioxide in the atmosphere is already altering natural climate[1] and biological systems, resulting in abnormally destructive wildfires, storms, rainfall patterns and the spread of infectious disease. It is increasingly clear that the historical, fossil fuel-based models of carbon, energy and material cycling through the economy are incompatible with maintaining a hospitable environment. Humanity will need to bring every tool it has to bear on this critical challenge. New approaches are required at almost every level of the economy. Biotechnology has the potential to be a transformative asset in this struggle.

Biotechnology is technology based on biology. Biotechnology applications touch most aspects of modern life, from agriculture to manufacturing to medicine. In the context of climate change, biotechnology offers solutions in four key categories:

- Producing sustainable biomass feedstock
- Empowering sustainable production
- Developing lower carbon products
- Enhancing carbon sequestration

Biotechnology offers vital contributions to near-term greenhouse gas (GHG) reductions and revolutionary tools to combat climate change in the longer term. Policies supporting the development and deployment of biotech climate solutions should be part of any government effort to address climate change. This report reviews the current contributions of biotechnology to greenhouse gas (GHG) reductions and identifies the emerging biotech solutions with the greatest potential to avert, and reverse, catastrophic climate change. We focus on four main areas:

Producing Sustainable Biomass Feedstock. For most of human existence, our lives were based on the products of renewable biomass – plants and other living material. In the past 150 years, much of our economy has come to depend on petroleum and other non-renewable resources. The environmental consequences of this transition from renewable resources to non-renewable resources are well documented[2]. Biotechnology has developed more sustainable, biobased alternatives for many products, including fuels, polymers, and other chemicals. The U.S consumed over 7.5 billion barrels of petroleum in 2019[3], some of which was turned into plastic; as much as 35 million tons of plastic ended up in waste streams annually in recent years.[3,4] More sustainable options have been developed over recent decades, but ultimately they still require a material input. Biobased alternatives offer the potential for significantly reduced carbon footprints and environmental benefits compared to the traditional systems they displace, and these alternatives depend on broad availability of sustainable biomass feedstock. At present, there are concerns that not enough biomass will be sustainably available to meet growing demand. Biotechnology is rapidly reducing the carbon footprint of feedstock production by enabling new, sustainable ways to produce usable biomass, improving yields on existing crops, developing scalable, low-input production systems, and finding new ways to utilize biomass that would otherwise be waste.

Empowering Sustainable Production. Manufacturing is a major greenhouse gas emitter, from industrial boilers, chemical production, and the release of high-warming-potential gases like methane or fluorinated hydrocarbons. Biotech empowers a variety of options to reduce emissions from these processes, by reducing the need for energy inputs, facilitating more efficient material processing, or replacing high-warming-potential gases. Biotechnology has also enabled renewable natural gas systems that can displace the fossil-based methane today, simply by switching the source of the gas. The U.S. manufacturing sector is responsible for 22% of total GHG emissions[5], and while no single technology or solution can single-handedly solve the problem, biotech enables opportunities for lower-emission production across many sectors.

Developing Lower-Carbon Products. As awareness of the climate crisis expands, consumers are increasingly demanding lower-carbon options and more sustainable replacements for existing products.[6] This means finding low-emission alternatives that provide the same level of performance, durability and cost-effectiveness as mature fossil-based systems. Biotechnology allows for the production of low-carbon consumer products through the substitution of biomass or other recycled carbon feedstocks and by enabling more efficient, biologically based production, satisfying an increasingly important market segment while reducing emissions at the same time.

Enhancing Carbon Sequestration. While there is a lot of uncertainty about what a sustainable future may look like, several features are common across all likely scenarios. One of these is the deployment of massive amounts of carbon capture and sequestration (CCS), which converts carbon to a form that does not contribute to climate change or stores it underground. CCS cannot be the sole or even the primary solution to climate change, but it will make a critical contribution. Biotechnology has a key role in advancing CCS techniques, making it more scalable, reliable and cost-effective.

1 http://www.ipcc.ch/site/assets/uploads/2018/02/TAR-03.pdf

2 http://www.pnas.org/content/116/15/7192

3 http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MTTUPUS1&f=A

4 https://www.statista.com/statistics/1097290/us-plastic-waste-generation/

5 http://cfpub.epa.gov/ghgdata/inventoryexplorer/

6 http://www.carbontrust.com/news-and-events/news/research-reveals--consumer-demand-for-climate-change-labelling

2 TECHNOLOGIES

IN THIS SECTION, WE REVIEW BIOTECHNOLOGY APPLICATIONS TO CLIMATE MITIGATION IN FOUR BROAD CATEGORIES: PRODUCTS; AGRICULTURAL INPUTS AND CLIMATE SERVICES; NEW BIOTECH TOOLS AND BIO-INDUSTRIAL MANUFACTURING; AND PLANT AND ANIMAL BIOTECHNOLOGIES.

2.1 PRODUCTS

2.1.1 ADVANCED BIOFUELS

Liquid biofuels were one of the earliest biotechnology products to be deployed at scale in the U.S. for the purpose of achieving greenhouse gas (GHG) emission reductions. In the early 21st century, production mostly took the form of the 1st-generation biofuels ethanol and biodiesel, derived from feedstocks such as corn and vegetable oils. Concerns about competition for these feedstocks with the food and animal feed sectors prompted the development of 2nd-generation liquid biofuels that are produced from low-carbon-intensity (CI) feedstocks, such as lignocellulosic biomass.

Existing 1st-generation biofuels pathways rely heavily on the fermentation of starch-rich feedstocks to ethanol and, to a lesser but still substantial extent, the transesterification or hydrotreating of vegetable oils to biodiesel or renewable diesel, respectively. Fermentation is one of the oldest examples of biotechnology, having been mastered by humans thousands of years ago for the purpose of producing alcoholic beverages. Glucose is easily fermented by the microorganism Saccharomyces cerevisiae to yield a diluted form of ethanol known in the industry as “beer”. Distillation of this intermediate produces a high-proof ethanol that is then blended with gasoline for use in motor vehicles. Most gasoline in the U.S. today contains 10% ethanol, with 15% blends increasingly available.[7]

Advances in biotechnology have enabled U.S. ethanol producers to achieve substantial efficiency improvements in recent decades that have enabled the volume of 1st-generation ethanol obtained from a bushel of corn to increase by more than 10% between 1982 and 2014.[8] Milling improvements based on improved knowledge of corn kernel composition increased conversion efficiency, reducing the amount of corn required.[9] Likewise, a better understanding of yeast biology led to ethanol yield optimization via temperature-controlled fermentation.[10] And advanced fractionation techniques have allowed for greater yield of co-products, such as distillers dry grains (DDGS), a key animal feed ingredient. Together these advances have improved the process economics and sustainability of the pathway by reducing costs and waste. The EPA estimates them to have resulted in reductions to ethanol’s carbon intensity in excess of 10%.[11] A shift to more sustainable growing practices, driven by a desire to capture the compliance value of low-carbon programs such as the California Low Carbon Fuel Standard (LCFS), is further reducing the carbon intensity of 1st-generation fuels. And the prospect of deploying carbon capture technology at ethanol plants, detailed in section 2.2.2, could reduce the carbon footprint of 1st-generation ethanol by an additional 40%.[12]

Biotechnology has also made a wide range of low-carbon intensity feedstocks available for utilization by biofuel producers. Glucose is a fundamental building block of plants, and plants possess multiple defense mechanisms to protect themselves from yeast and other microorganisms that consume glucose. Plants’ glucose content takes the form of the polysaccharide cellulose that is not digestible by most living things (one notable exception being termites). Other simple sugars such as arabinose and xylose comprise a second type of major polysaccharide that plants contain, hemicellulose. Plants are further protected by a third compound with antimicrobial properties, lignin, that is cross-linked with cellulose and hemicellulose to protect them against attack by microorganisms. These traits allow plants to thrive in the wild but have also posed a major hurdle to their use as a 2nd-generation biofuel feedstock by inhibiting their conversion to ethanol via fermentation.

Recent progress in the development of biocatalysts and engineered microorganisms has made possible the production of ethanol from 2nd-generation feedstocks such as grasses, shrubs, and other dedicated energy crops. The enzymatic hydrolysis pathway employs biocatalysts to break cellulose and hemicellulose down to glucose and other constituent sugars. The glucose is converted to fuel ethanol in the same manner as corn glucose. Microorganisms that are naturally able to ferment glucose have been engineered to make them capable of also fermenting simple sugars derived from hemicellulose to ethanol, improving both yields and efficiencies of lignocellulosic biofuel production.

An early commercial application of this pathway utilizes the lignocellulose that is found in small quantities in corn kernels to produce ethanol. Biotech companies POET, Syngenta, and Enogen, among others, have begun adding corn kernel fiber conversion units to 1st-generation ethanol plants, potentially increasing ethanol yield per bushel of corn by nearly 10%.[13]

The full potential of cellulosic biofuel to mitigate climate change will depend on broad deployment of cellulosic technology to agricultural residues, municipal solid waste (MSW), and dedicated energy crops. An initial wave of cellulosic ethanol biorefinery construction occurred following the 2009 implementation of the federal Renewable Fuel Standard (RFS) program. Leading 1st-generation ethanol producers such as POET, LLC, have partnered with leading biotech innovators to build first-of-a-kind cellulosic biofuel plants in the U.S., Europe, and South America, but low oil prices, policy obstacles, and technology challenges have limited global production volumes.

Advances in biotechnology have expanded the supply of feedstocks available to biodiesel and renewable diesel, two of the major success stories in sustainable transportation. Biodiesel (BD) is produced via the transesterification process in which lipid feedstocks are reacted with methanol to yield a fatty acid methyl ester (FAME) that can be blended into conventional diesel, without needing any modification to the engine. Renewable diesel (RD) is made by hydrotreating the same kind of lipid feedstocks, in a process very similar to parts of conventional oil refining; it has performance characteristics like those of diesel fuel, passes the same product specifications and can be used in any diesel engine at any concentration. Historically most U.S. BD and RD have been produced from soybean oil.[14] The need for new feedstocks has grown over the last decade, however, as production has expanded and policies such as California's Low Carbon Fuel Standard (LCFS) have incentivized the use of 2nd-generation low-carbon intensity feedstocks. Some of these newer feedstocks are waste products that are not as easily converted to biodiesel as 1st-generation feedstocks. Biocatalysts have been developed that improve the conversion efficiencies and performance characteristics of biodiesel that is yielded from waste feedstocks,[15] allowing for more of them to be converted to low-carbon transportation fuel.

Biotechnology has also enabled the production of novel low-carbon fuels that complement existing ethanol and biodiesel production. First-generation biofuels have a limited ability to widely displace existing fossil fuels due to infrastructure compatibility hurdles. The U.S. only allows ethanol blends of up to 15% by volume with gasoline in non-flex fuel vehicles[16] and most diesel engine warranties only cover biodiesel blends of up to 20% by volume.[17] Moreover, neither is capable of displacing specialized fossil fuels such as aviation fuel. Technological advances have yielded a new category of "drop-in biofuels" -- so named for their ability to utilize the existing refined fuels infrastructure -- that have an even greater decarbonization potential.

Biobutanol (butanol derived from biomass) was one of the first biofuels to gain attention for its drop-in properties, as it chemically behaves more like a hydrocarbon than ethanol does. While actually an intermediate to renewable hydrocarbons (see below), biobutanol's high energy equivalence ratio compared to ethanol and ability to be blended with gasoline at rates of up to 16% by volume allow it to displace correspondingly larger volumes of gasoline.[18] Biobutanol is produced via fermentation from the same simple sugars as in ethanol production. Some biofuel producers have genetically modified ethanol yeast to instead produce isobutanol. There are also pathways that utilize bacteria for the conversion rather than yeast. Biobutanol can also be produced via engineered microorganisms from the carbohydrates in some microalgae strains that remain after lipids have been extracted, allowing for microalgae to serve as a simultaneous feedstock for both biobutanol and biomass-based diesel.[19]

More recently, biobutanol has attracted interest as a key step towards production of the renewable hydrocarbon fuels isooctane and sustainable aviation fuel SAF). Unlike biobutanol, which is an alcohol, biobased isooctane and SAF are hydrocarbons with performance characteristics that are very similar to their fossil counterparts (isooctane is an important blending component in gasoline). They are true drop-in biofuels in that they can be used in the same quantities as the fossil fuels that they displace before encountering infrastructure constraints.

Biotechnology has also enabled the production of SAF directly from biomass via fermentation. Historically the conversion of biomass to hydrocarbons via fermentation has been limited by the presence of oxygen in biomass that has caused microorganisms to favor oxygen-containing products (e.g., ethanol, butanol). Metabolic engineering has been employed to improve the yield of the specific hydrocarbon, kerosene, that comprises a common form of aviation fuel by increasing the selectivity of fermenting microorganisms.[20] The microorganisms are able to convert sugars derived from a variety of feedstock types to SAF.[21] Hydrocarbons have hydrophilic properties, allowing those produced in this manner to avoid the need for the energy-intensive distillation step that is required when producing fuel alcohols.

Biofuels currently supply approximately 12% of U.S. on-road transportation fuel.[22] Ethanol and biodiesel currently comprise the large majority of U.S. biofuels consumption. Production of 2nd-generation biofuels is expected to increase rapidly during the early 2020s, however, as the new feedstocks and pathways made possible by biotechnology breakthroughs are commercialized (see Figure 1).[23] A combination of factors is responsible for this development. First, the COVID-19 pandemic has seriously disrupted demand for fossil fuels in the U.S. transportation sector, in turn limiting demand for biofuels such as ethanol that have restrictive

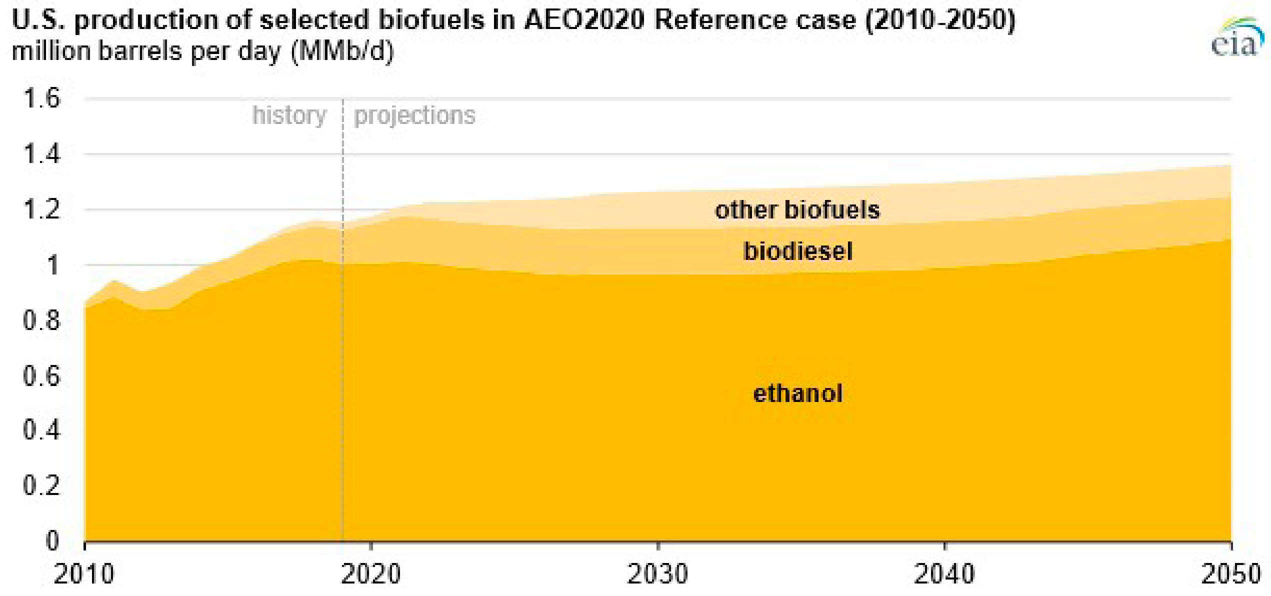


Figure 1: Estimated U.S. biofuel production volumes by type of fuel, 2010-2050. Source: U.S. Energy Information Administration

blend limits. Second, policies such as the federal revised Renewable Fuel Standard (RFS2), the California Low Carbon Fuel Standard (LCFS) and the Oregon Clean Fuels Program incentivize 2nd-generation biofuels, with their lower carbon intensities, over 1st-generation biofuels (and both over fossil fuels). Third, whereas the last decade's rapid growth in 1st-generation biofuels production has slowed due to supply constraints, 2nd-generation feedstocks remain underutilized.[24]

The carbon intensities of biofuels vary widely depending on feedstock(s), conversion processes, and the geographic length of the supply chain. California publishes detailed carbon intensities of the biofuels that participate in its LCFS for both broad biofuel categories as well as individual producers. Ethanol, which has historically been the primary source of biofuels under the LCFS by volume, has achieved average GHG emission reductions compared to gasoline of between 32% and 41% in recent years.[26] Ethanol from waste, or dedicated energy crop feedstocks, have achieved GHG reductions of up to 80% with current technology.[27] Continued improvements in feedstock production, conversion efficiency, and co-products are expected to yield pathways with negative carbon scores.[28]

Similarly, biodiesel has achieved average GHG emission reductions compared to diesel fuel of between 69% and 74% over the same period, although individual reduction values range from as low as 50% to over 90% depending on the feedstock used.[29] In both cases, California reports the lowest carbon intensities for those biofuels that are produced from waste feedstocks, illustrating the value that biotechnology has provided by helping to make such feedstocks usable by biofuels producers.

Biobutanol from lignocellulosic biomass has yet to achieve commercial-scale production volumes and does not have published LCFS carbon intensity values as a result. Independent life cycle assessments estimate a GHG emission reduction for the biofuel compared to gasoline of approximately 66%, which is comparable to ethanol from lignocellulosic biomass.[30] Likewise, SAF from biobutanol is estimated to achieve GHG emission reductions compared to petroleum aviation fuel of between 60% and 75% depending on the choice of feedstock and conversion inputs.[31]

GHG emissions are not the only form of air pollution that the use of biofuels reduces. Emissions of criteria pollutants such as carbon monoxide, particulate matter, and sulfur dioxide have a direct impact on human health, causing air pollution to be one of the main risk factors causing non-communicable diseases globally.[32] The combustion of commonly used biofuels in both blended and unblended forms has been found to reduce many, if not all, of the criteria pollutants that are emitted by the combustion of petroleum fuels.[33,34]

7 https://www.eia.gov/todayinenergy/detail.php?id=40095

8 https://www.eia.gov/todayinenergy/detail.php?id=21212

9 https://agresearchmag.ars.usda.gov/ar/archive/2004/jul/corn0704.pdf

10 http://www.sciencedirect.com/topics/engineering/fermentation-temperature

11 http://www.tandfonline.com/doi/full/10.1080/17597269.2018.1546488

12 http://www.pnas.org/content/pnas/early/2018/04/18/1719695115.full.pdf

13 http://illinoisrfa.org/wp-content/uploads/2019/02/Short-Version-CKF--EthanolTechnologies-final-1.pdf

14 Unnasch. S.and D. Parida (2021) GHG Reductions from the RFS2–A 2020Update. Life Cycle Associates Report LCA.LCA.6145.213.2021 Prepared for Renewable Fuels Association. https://ethanolrfa.org/wp-content/uploads/2021/02/LCA_-_RFS2-GHG-Update_2020.pdf

15 http://www.biodieselmagazine.com/articles/9481/commercializing--enzymatic-biodiesel-production

16 http://www.epa.gov/renewable-fuel-standard-program/final-rulemaking-modifications-fuel-regulations-provide-flexibility

17 http://www.biodiesel.org/using-biodiesel/oem-information

18 http://afdc.energy.gov/fuels/emerging_biobutanol.html

19 Sabarathinam S.. et al., Recent developments and strategies in genome engineering and integrated fermentation approaches for biobutanol production from microalgae. Fuel, 285, 2021, 119052, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2020.119052. https://www.sciencedirect.com/science/article/pii/S0016236120320482

20 Straathof AJJ, Cuellar MC. Microbial Hydrocarbon Formation from Biomass. Adv Biochem Eng Biotechnol. 2019;166:411-425. doi: 10.1007/10_2016_62. PMID: 28707104. http://pubmed.ncbi.nlm.nih.gov/28707104/

21 http://www.etipbioenergy.eu/images/ETIP_Bioenergy_Factsheet_Aviation_Biofuels.pdf

22 http://www.govinfo.gov/content/pkg/FR-2020-02-06/pdf/2020-00431.pdf

23 http://www.eia.gov/todayinenergy/detail.php?id=43096

24 http://www.energy.gov/eere/bioenergy/2016-billion-ton-report

25 http://www.eia.gov/todayinenergy/detail.php?id=43096

26 http://ww3.arb.ca.gov/fuels/lcfs/lrtqsummaries.htm

27 http://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

28 Kim S, Zhang X, Reddy AD, Dale BE, Thelen KD, Jones CD, Izaurralde RC, Runge T, Maravelias C. Carbon-Negative Biofuel Production. Environ Sci Technol. 2020 Sep 1;54(17):10797-10807. doi: 10.1021/acs.est.0c01097. Epub 2020 Aug 19. PMID: 32786588. http://pubmed.ncbi.nlm.nih.gov/32786588/

29 http://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

30 Tao, L., Tan, E.C.D., McCormick, R., Zhang, M., Aden, A., He, X. and Zigler, B.T. (2014), Techno‐economic analysis and life‐cycle assessment of cellulosic isobutanol and comparison with cellulosic ethanol and n‐butanol. Biofuels, Bioprod. Bioref., 8: 30-48. http://doi.org/10.1002/bbb.1431 https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1431

31 de Jong, S., Antonissen, K., Hoefnagels, R. et al. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. Biotechnol Biofuels 10, 64 (2017). https://doi.org/10.1186/s13068-017-0739-7. http://link.springer.com/article/10.1186/s13068-017-0739-7

32 Pruss-Ustun A, van Deventer E, Mudu P, Campbell-Lendrum D, Vickers C, Ivanov I et al. Environmental risks and non-communicable diseases BMJ 2019; 364 :l265 doi:10.1136/bmj.l265. http://www.bmj.com/content/364/bmj.l265

33 Sakai, S. and Rothamer, D. Impact of ethanol blending on particulate emissions from a spark-ignition direct-injection engine, Fuel, 236, 2019, 1548-1558, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2018.09.037. http://www.sciencedirect.com/science/article/pii/S0016236118315746.

34 MILLER, C. A. Characterizing Emissions from the Combustion of Biofuels. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-08/069, 2008. http://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=191572.

GEVO CASE STUDY

Gevo is an advanced renewable fuel producer that converts renewable energy to energy-dense liquid hydrocarbons by transforming renewable energy into low-carbon transportation fuels. This next generation of renewable premium gasoline, jet fuel and diesel fuel has the potential to achieve net zero carbon emissions, addressing the market need of reducing GHG emissions with sustainable alternatives while continuing to utilize current infrastructure and vehicles.

The company originally converted an existing dry-mill corn ethanol facility to a commercial-sized scaled up facility in Luverne, Minnesota. The converted facility utilizes corn starch as feedstock. While corn-based biofuels have not historically been credited with large reductions to carbon intensity relative to gasoline, Gevo employs an integrated approach to carbon intensity reductions that maximizes the environmental and sustainability potentials from agricultural systems, while creating innovative solutions to convert the feedstocks into energy-dense hydrocarbons.

In January 2021, Gevo announced a new project, planned for construction at Lake Preston, South Dakota, to be named "Net-Zero 1." Gevo expects that Net-Zero 1 would have the capability to produce liquid hydrocarbons that when burned have a net-zero greenhouse gas footprint.[35] Net-Zero 1 is expected to have a capacity of 45million gallons per year of hydrocarbons for gasoline and jet fuel and will produce more than 350 million pounds per year of high-protein feed products for use in the food chain. In addition to feed and fuel, the facility will produce enough renewable natural gas to be self-sufficient for production process needs. The facility will also generate renewable electricity with a combined heat and power system and integrate additional renewable power production utilizing wind energy.

Gevo's integrated approach utilizes decarbonization practices across the entire supply chain. It begins by working with the farmers who employ best farming practices that maximize soil carbon sequestration and minimize GHG emissions during the planting, growing, and harvesting stages.[36] The partnership with farmers involves the active tracking and monitoring of the feedstock suppliers to ensure that best practices are encouraged and in the future can be incentivized for the purpose of consistently minimizing feedstock carbon intensity.

Gevo also conducts experimental trials to identify additional feedstock decarbonization routes such as the use of manure in place of nitrogen fertilizer application, enhanced soil carbon sequestration via reduced soil tillage practices, and improved crop yields via microbial soil solutions. The company estimates that its corn feedstock has a carbon intensity that is at least 50% lower than the U.S. average.[37]

Because of the low-carbon-footprint feedstocks, the sustainable agricultural practices used to produce feedstock, and the use of renewable energy for the production processes – much of which is expected to be generated on site – the hydrocarbon fuel products produced at Net-Zero 1 have the potential to achieve net-zero greenhouse gas emissions, as measured across the whole of the life cycle, based on Argonne National Laboratory's GREET model. The GREET model takes into account emissions and impacts "cradle to cradle" for renewable resource based fuels, including inputs and generation of raw materials, agriculture practices, chemicals used in production processes of both feedstocks and products, energy sources used in production and transportation, and end fate of products.

Gevo's Luverne facility also makes extensive use of other sources of renewable energy to reduce the carbon intensity of its production process. The production of biofuels such as isobutanol from corn uses process heat and electricity that have historically been obtained from fossil fuels, such as coal and natural gas. And Gevo has installed wind turbines to generate renewable electricity. Minnesota has abundant access to low-cost wind power and Gevo pays "about the same" price for electricity as it did prior to the installation of the wind capacity.[38] In 2019, Gevo announced its intention to utilize renewable natural gas that is produced from dairy manure in place of the fossil natural gas it used to produce process heat in the past.[39] In both cases, Gevo has been able to take advantage of local renewable energy resources that are supplied directly to the Luverne facility via transmission line and natural gas pipeline.

35 http://investors.gevo.com/news/net-zero-1-project

36 http://www.iscc-system.org/wp-content/uploads/2017/02/Sustainable-Aviation-Fuel.pdf

37 http://www.iscc-system.org/wp-content/uploads/2017/02/Sustainable-Aviation-Fuel.pdf

38 http://gevo.com/about-gevo/our-plants/wind-project/

39 http://biomassmagazine.com/articles/16395/gevo-discusses-plans--for-hydrocarbon-rng-production

2.1.2 RENEWABLE CHEMICALS AND BIOBASED PRODUCTS/ MATERIALS

Fossil-derived chemicals and products are a key future driver of petroleum consumption.[40] The chemicals sector (known as petrochemicals when derived from fossil feedstocks) accounts for a wide variety of common products, including plastics, synthetic rubber, solvents, fertilizers, pharmaceuticals, additives, explosives, and adhesives.[41] They differ from fossil fuels in that their consumption does not normally cause GHG emissions via combustion. They are still produced from fossil fuels, though, especially petroleum and natural gas, and their production incurs both direct and indirect emissions. By one estimate the petrochemicals sector generates 18% of direct industrial GHG emissions, and its production capacity is growing rapidly.[42] The sector is also, due to its reliance on fossil fuels, an important source of other forms of pollution that have a detrimental impact on human health, especially in disadvantaged communities.[43] Moreover, many fossil-derived products such as plastics are resistant to degradation and end their useful lives either in landfills or in natural environments as litter.

Biotechnology's contributions to efforts to mitigate the damage caused by fossil chemicals and products generally fall into one of two broad categories: (1) the replacement of these fossil-derived products by non-fossil products, and (2) the replacement of degradation-resistant materials with biodegradable materials. A substantial amount of overlap exists between the two categories due to the novel production pathways and product types that have been developed by the biotechnology industry. The ability of biomass to replace a wide variety of fossil products has greatly benefited from recent biotechnology advances that have enabled the manufacture of products from both categories.[44]

The petrochemical industry is expected to become a primary driver of demand for fossil fuels by 2030.[45] Many advances have been made in the production of the same chemicals and products from biomass or recycled feedstocks rather than fossil feedstocks. One early biobased chemical was developed as an extension of biofuels production, allowing it to utilize existing production capacity. Ethanol obtained from corn and sugarcane, but potentially from lignocellulosic biomass in the future, is easily dehydrated to yield a biobased version of the plastics precursor ethylene.[46] Plastics comprise most of the fossil chemicals market,[47] giving biobased plastics an important role to play in its decarbonization.

Biotechnology companies have also developed biobased versions of synthetic fibers that are used by the textile industry. Polyester, which is widely employed in the manufacture of textiles and bottles, is usually produced from natural gas and/or petroleum feedstocks. Its building blocks can instead be obtained either from ethanol, as in the production of biobased plastics, or from hydrocarbons that are directly converted from biomass feedstocks.[48,49] In both pathways the resulting fibers are the same as those that are currently produced from fossil feedstocks, making them drop-in biobased products.

Growing concerns over the longevity of plastic waste in the environment have also prompted the development of biodegradable plastics that are capable of decomposing over short timeframes compared to those of traditional plastics. The most common of these are polylactic acid (PLA) and polyhydroxyalkanoates (PHA). PLA is derived from plant sugars that are naturally fermented by bacteria to yield lactic acid. This lactic acid is then chemically converted to PLA for use as a biobased plastic.[50] PHA is produced via the fermentation of plant sugars (although vegetable oils and even wastewater can also be used) by a different type of bacteria under very specific conditions that promote PHA synthesis.[51] Biobased plastics made from both PLA and PHA are biodegradable under higher-temperature conditions such as those found in industrial composters.

Biotechnology breakthroughs have also been made in the replacement of lesser known but equally important fossil products. Lubricants made from petroleum are in common use throughout the industrial and transportation sectors and, while they represent a small share of a typical refinery's product mix, they are a critical input for many applications (e.g., engine oil). Plant sugars can be fermented by bacteria to yield a chemical that is capable of conversion to biobased versions of the synthetic lubricants that are normally obtained from petroleum.[52] In a similar application biodiesel, which has a high lubricity, is blended with petroleum-derived ultra-low sulfur diesel fuel to improve the latter's low lubricity.[53] Finally, novel medicines and medical treatments are being developed through biotechnology, including those that are personalized to individual patients.[54]

Renewable chemicals and materials provide climate benefits through twin advantages. First, by leveraging biological production platforms, biobased products are frequently less energy-intensive to produce than their petrochemical counterparts. For example, BASF Corporation has developed a biobased home insulation product that results in 66% fewer GHG emissions than its fossil-based alternative.[55] But, perhaps most significantly, whether produced from biomass or waste gases, biobased products are built from carbon that would otherwise reside in the atmosphere, and thus serve as a vital pathway for atmospheric carbon removal.

The direct recycling of GHG emissions, both biogenic and fossil in origin, to create chemicals and fuels has emerged as a notable pathway over the last decade. Landfills and animal waste lagoons are sources of biogenic emissions of the potent GHG methane. Methane is the primary component of natural gas, however, making biogenic methane when captured a potential biobased chemicals feedstock. Biogas captured from landfills and agricultural anaerobic digesters is also directly utilized as fuel for natural gas-powered vehicles.[56] The use of biogas in both applications has especially large climate benefits because it eliminates a source of methane emissions while simultaneously displacing demand for a fossil feedstock (biogas combustion converts methane to the comparatively weaker GHG carbon dioxide).

Finally, biotechnology advances have also enabled fossil GHG emissions to be captured and recycled via a pathway known as carbon capture and utilization (CCU), thereby reducing demand for fossil fuels and the resulting emissions without requiring biomass (see Section 2.2.2). One novel process developed by carbon recycling pioneer LanzaTech utilizes engineered microorganisms to ferment emissions captured from industrial facilities such as steel mills to either fuels or chemicals, depending on the choice of microorganism.[57] While the resulting products are not of biological origin, their climate benefits are substantial and comparable to those of biobased products in that both partially eliminate the need for fossil fuel extraction and serve as sinks for carbon that would otherwise be emitted to the atmosphere.

Like biofuels, the market for biobased chemicals has been constrained by persistent low natural gas and petroleum prices for much of the last decade. The lack of mandates or other policy mechanisms in the U.S. that internalize biotechnology products' climate benefits have made it still more difficult for biobased pathways to compete with fossil pathways. That said, a growing interest by many manufacturers and their consumers in reducing their climate impacts in service of ESG goals has supported an expansion of the U.S. biobased products industry despite these hurdles. One recent analysis estimated the industry's size to be $459 billion in terms of valued added to the U.S. economy in 2016, up from $393 billion in 2014 and $353 billion in 2012.[58] These bioproducts were estimated to displace 9.4 million barrels of petroleum equivalents in 2016. While still smaller than the fossil products sector – the U.S. chemicals industry alone achieved $765 billion in sales in 2017[59] - the U.S. biobased products industry is expected to grow rapidly as state governments and corporations increasingly act to minimize plastic waste, methane emissions, and other forms of pollution.[60]

Biodegradable biobased products have the potential to substantially contribute to climate change mitigation efforts due to their ability to achieve net carbon sequestration under certain production conditions. A life cycle analysis of the biodegradable bioplastic PHB calculated negative GHG emissions for the product when produced from either corn or biogas, with the greatest amount of carbon sequestration occurring when the PHB is produced from existing PHB that has degraded to biogas.[61] A separate analysis of PHA production determined that the bioplastic has a carbon intensity that is 80% lower than that of fossil-derived plastics even before taking into account the PHA's ability to be recycled following biodegradation.[62] Biobased PLA for use in water bottles has likewise been found to have a substantially lower carbon intensity than fossil-derived plastic.[63] Finally, a comparison of multiple chemicals and fuels pathways determined that products derived from recycled carbon dioxide achieved carbon intensity reductions compared to conventional fossil products despite ultimately being derived from fossil feedstocks.[64]

Biobased products such as renewable chemicals historically have not received as much attention from policymakers as biofuels, due to the lack of direct emissions resulting from their use. That is changing, however, as policymakers in states such as California and New York have implemented economywide restrictions on GHG emissions. In addition to disincentivizing the use of fossil feedstocks in energy-intensive manufacturing processes, such policies also encourage entities such as steel mills and refineries to develop new revenue streams via the implementation of CCU technologies.[65] Biotechnology provides a wide range of options for reducing the carbon intensities of many of the biobased chemicals and products upon which the U.S. economy relies.

40 http://www.nytimes.com/2018/10/04/climate/climate-change-plastics.html

41 http://www.sciencedirect.com/book/9780128001585/project-finance--for-the-international-petroleum-industry

42 Tayeb, B. Ghg emissions from new petrochemical plants: background information paper for the elaboration of technical notes and guidelines for IDB projects. IDB Technical Note; Inter-American Development Bank, 2013. http://publications.iadb.org/publications/english/document/Greenhouse-Gas-Emissions-from-New-Petrochemical-Plants-Background--Information-Paper-for-the-Elaboration-of-Technical-Notes-and-Guidelines-for-IDB-Projects.pdf

43 http://www.businessinsider.com/louisiana-cancer-alley-photos-oil-refineries-chemicals-pollution-2019-11

44 Isikgor, FH., Becer, CR. Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers. DOI: 10.1039/C5PY00263J (Review Article) Polym. Chem., 2015, 6, 4497-4559. http://pubs.rsc.org/ko/content/articlehtml/2015/py/c5py00263j

45 IEA (2018), The Future of Petrochemicals, IEA, Paris. http://www.iea.org/reports/the-future-of-petrochemicals.

46 http://www.icis.com/explore/resources/news/2019/11/08/10441869/brazil-braskem-mulls-new-renewable-ethylene-pe-capacity

47 http://www.usitc.gov/publications/332/working_papers/using_waste_carbon_feedstocks_to_produce_chemicals_0.pdf

48 http://www.ncfap.org/documents/biofuels_aviation/Huber%20George%20Biofuels%20Review.pdf

49 Masuo, S., Zhou, S., Kaneko, T. et al. Bacterial fermentation platform for producing artificial aromatic amines. Sci Rep 6, 25764 (2016). http://doi.org/10.1038/srep25764. http://www.nature.com/articles/srep25764

50 Rajeev Mehta, Vineet Kumar, Haripada Bhunia & S. N. Upadhyay (2005) Synthesis of Poly(Lactic Acid): A Review, Journal of Macromolecular Science, Part C, 45:4, 325-349, DOI: 10.1080/15321790500304148. http://www.tandfonline.com/doi/abs/10.1080/15321790500304148

51 Jingnan Lu, Ryan C. Tappel & Christopher T. Nomura (2009) Mini-Review: Biosynthesis of Poly(hydroxyalkanoates), Polymer Reviews, 49:3, 226-248, DOI: 10.1080/15583720903048243. http://www.tandfonline.com/doi/abs/10.1080/15583720903048243?journalCode=lmsc20

52 Balakrishnan, M. et al. Pathways for fuels and lubricants from biomass. Proceedings of the National Academy of Sciences Jun 2015, 112 (25) 7645-7649; DOI: 10.1073/pnas.1508274112. http://www.pnas.org/content/112/25/7645.short.

53 hM.A. Hazrat, M.G. Rasul, M.M.K. Khan, Lubricity Improvement of the Ultra-low Sulfur Diesel Fuel with the Biodiesel, Energy Procedia, Volume 75, 2015, Pages 111-117, ISSN 1876-6102, http://doi.org/10.1016/j.egypro.2015.07.619. http://www.sciencedirect.com/science/article/pii/S1876610215013879

54 http://www.mckinsey.com/industries/pharmaceuticals-and-medical--products/our-insights/the-bio-revolution-innovations-transforming-economies-societies-and-our-lives

55 http://www.basf.com/ca/en/who-we-are/sustainability/we-produce--safely-and-efficiently/energy-and-climate-protection/our-climate-protection-solutions.html (See Neopor® BMB).

56 http://www.greencarcongress.com/2019/12/20191229-lcfs.html

57 http://www.usitc.gov/publications/332/working_papers/using_waste_carbon_feedstocks_to_produce_chemicals_0.pdf

58 http://www.biopreferred.gov/BPResources/files/BiobasedProductsEconomicAnalysis2018.pdf

59 http://www.selectusa.gov/chemical-industry-united-states

60 http://www.usda.gov/sites/default/files/documents/usda-bioindicators-jan-2020.pdf

61 Environ. Sci. Technol. 2012, 46, 18, 9822–9829, July 9, 2012. http://pubs.acs.org/doi/full/10.1021/es204541w

62 Environ. Sci. Technol. 2008, 42, 18, 6961–6966. August 16, 2008. http://pubs.acs.org/doi/abs/10.1021/es7032235.

63 Papong, S. et al. Comparative assessment of the environmental profile of PLA and PET drinking water bottles from a life cycle perspective, Journal of Cleaner Production, 65, 2014, 539-550, ISSN 0959-6526, http://www.sciencedirect.com/science/article/abs/pii/S0959652613006331.

64 http://www.iea.org/reports/putting-co2-to-use

65 http://www.cdp.net/en/articles/media/steel-sector-faces-significant--losses-from-future-climate-regulation

DANIMER SCIENTIFIC CASE STUDY

Biobased PHA is Danimer Scientific's primary bioplastics product. The company manufactures the polyester at a commercial facility in Winchester, Kentucky, by feeding a bacterium with inexpensive vegetable oil feedstock derived from agricultural oilseed crops such as canola, and soy. In addition to directly displacing the fossil fuels used in the manufacture of conventional plastics, Danimer Scientific's production pathway also provides indirect environmental benefits.

Danimer Scientific obtains vegetable oils via the crushing of oilseeds. The crushing process yields protein-rich byproducts that are employed as a natural fertilizer and livestock feed. The vegetable oils are consumed by soil bacteria that biosynthesize the PHA in a bioreactor. The PHA is then separated from the bioreactor medium, purified, and dried in preparation for conversion to various plastic resins, blending with other biopolymers such as PLA, or bonding with materials such as paper.[66]

Danimer Scientific's biobased PHA possesses performance parameters that are comparable to those of many fossil plastics and are capable of use in many of the same applications, including food preservation and storage and conversion to multiple types of finished resins. Unlike fossil plastics, however, PHA utilizes only renewable feedstocks and is biodegradable. This latter characteristic is an important advantage over fossil plastics at a time of growing concern over landfilling and the widespread presence of non-biodegradable plastic waste in many ecosystems.

66 http://danimerscientific.com/pha-beginning-of-life/

GENOMATICA CASE STUDY

Genomatica has commercialized a more sustainable, biobased technology to make a key ingredient used in apparel, spandex, footwear, and plastics used in electronics and automotive parts. Millions of tons per year of this ingredient, 1,4-butanediol (BDO), are currently produced from fossil-derived feedstocks, resulting in many millions of tons per year of greenhouse gas emissions. By contrast, Genomatica's GENO BDOTM process uses renewable feedstocks – the sugars that come from locally-grown crops such as corn and sugarcane – along with engineered microorganisms and fermentation. The products made with Genomatica's ingredient have 56% lower carbon intensity[67], and their renewable content is traceable – meaning customers know that the carbon actually came from plants. Genomatica's technology also avoids the use of toxic compounds like formaldehyde, common to fossil processes.

Genomatica's technology has been proven at industrial scale since 2012. Italy-based plastics manufacturer Novamont started production of biobased BDO at a 30,000 ton per year capacity plant in 2016, built with Genomatica's licensed technology. Novamont's BDO has been used in compostable produce bags, mulch film and coffee capsules. BASF has also licensed Genomatica's BDO technology. The Novamont plant is the world's first commercial scale plant to make a widely-used intermediate chemical biologically. Genomatica has received repeated recognition for its innovations, including three EPA Green Chemistry awards, the Kirkpatrick award and ICIS Innovation awards.

67 http://www.brontidebg.com/wp-content/uploads/2020/10/Genomatica-Sustainability-and-Social-Responsibility-2019.pdf

2.1.3 FOOD AND FEED INGREDIENTS

According to the 2019 U.N. IPCC Special Report on Climate Change and Land, the global food system – including the land and resources to raise animals and grow crops, plus processing, packaging, and transportation – is responsible for up to 19.1 $GtCO_2eq$ annually, or 37% of total net GHG emissions.[68] The report finds that changes in both production and consumption are needed to meet global emissions reduction objectives. Biotechnology offers the potential for substantial emissions reductions at every stage of the food system, including potentially transformative solutions in food and feed ingredients.

Animal products account for the largest segment of food sector emissions. According to the FAO, livestock production accounts for approximately 7.1 $GtCO_2eq$ annually, or 15% of global GHG emissions, and consumes roughly one quarter of available land worldwide, with meat production expected to increase 19%, and dairy production 33%, from 2017 levels by 2030.[69] Solutions that reduce dependence on animals offer the greatest potential for emissions reductions from the food sector. But, given the growing global demand for meat and other animal products, sustainable near-term solutions are also needed for animal agriculture. Biotechnology is playing a leading role in the development of both new low-carbon product choices and technologies to reduce the carbon footprint of animal agriculture.

Plant-Based Proteins and Food Products

A recent analysis found that if Americans opted for nutritionally equivalent plant-based products for their meat (beef, chicken and pork) consumption choices, U.S. GHG emissions would be reduced by 280 million metric tons annually – roughly equivalent to the total emissions of the state of Ohio.[70] Consumer concerns with the carbon footprint of animal agriculture – along with health and animal welfare considerations – are driving strong growth in plant-based proteins and food product choices. Many of the leading options leverage biotechnology.

Impossible Foods, the fourth fastest growing brand in the U.S. in 2019,[71] uses engineered yeast to add heme, an iron-containing molecule found in blood, to its plant-based products to produce a meaty flavor. As of September 2020, Impossible Foods burgers were in 11,000 supermarkets and on the menu of a growing list of national and regional restaurant chains.[72] A 2019 lifecycle analysis of Impossible Foods' burger found a 89% reduction in carbon footprint and 96% reduction in land use versus traditional beef burgers.[73]

Perfect Day Foods is bringing a similar approach to milk, cheese and ice cream, using genetically engineered microbes to produce animal-free dairy products.[74] Given the high carbon intensity of dairy products (nearly 12 kilograms of carbon dioxide are produced for every kilogram of butter, for example)[75] plant-based dairy has the potential to have an outsized impact.

Motif FoodWorks, a spinoff of biotech leader Ginkgo Bioworks, is employing synthetic biology to develop fermentation-based ingredients to enhance the taste and texture of plant-based meat and dairy options. Motif is expected to launch its first commercial product — an ingredient to improve the flavor of beef substitutes – in 2021.[76]

One of the more novel applications of biotechnology is cultured meat products. New Age Meats is one of several companies working to produce cultured meat, an engineered tissue produced in laboratories by microorganisms that induce and feed the growth of animal muscle cells in a bioreactor. Unlike plant-based approaches, cultured meat is a drop-in option for applications in which specific meat attributes are desired. Cultured meat production is an energy-intensive process that requires more energy than poultry production and almost as much energy as pork production (albeit less than sheep or cattle production). But cultured meat's lack of methane production and ability to utilize low-carbon energy sources is projected to reduce GHG emissions up to 96% compared to traditional meat products.[77] Cultured meat production also utilizes a small fraction of the land required by livestock production, potentially resulting in lower indirect GHG emissions from land-use change. Cultured meat's consumer acceptance is currently limited by its high production costs and novelty, although this is expected to change as the product moves toward commercialization.[78]

Feed and Feed Ingredients

Roughly half of animal agriculture emissions result from land use, production and processing of animal feed.[79] Biotechnology is being harnessed to address feed-related emissions from multiple angles, from development of new, low-carbon feed options and lower-carbon approaches to feed production to ingredients that reduce feed waste.

In addition to developing biotech options for animal products, biotech innovation is also being deployed to develop new, low-carbon animal feeds. NouriTech, a joint venture between biotech start-up Calysta and Cargill, is among a growing list of companies using microorganisms to convert methane and other heat-trapping waste gases into single-cell proteins or other ingredients for animal feed. In addition to recycling GHGs that would otherwise be emitted directly to the atmosphere, this process, known as gas fermentation, does not require the use of arable land, avoiding the largest source of GHG emissions associated with feed production. A lifecycle analysis of NouriTech's FeedKind fish feed protein found GHG emissions up to 30 percent lower than conventional fish meal, depending on the source of methane used.[80] Several biotech businesses are also developing feed ingredients using algae. Similar benefits are anticipated.

Reducing Emissions from Animals

Another leading source of GHGs from agriculture are emissions from the animals themselves. Roughly 40% of all animal agriculture emissions is attributable to methane from enteric fermentation in the digestive system of ruminant animals, for example.[81] Biotech solutions are being developed to address emissions from cattle, swine, poultry, and other animals.

Cattle are the leading source of animal emissions, due to the large numbers of cattle grown globally and their high levels of enteric methane production. Microbial feed additives have the potential to dramatically reduce enteric methane emissions from ruminant livestock by disrupting the methane production process. One ester additive suppresses the enzyme that causes methane production in the digestive tracts of cattle, reducing methane emissions by 30% or more.[82] A study in peer review of microbial feed additives developed by biotech start-up Locus Fermentation Solutions found reduction in methane levels of up to 78%.[83] And recent studies have found methane reductions of up to 99% using certain species of algae.[84,85] Feed additives based on extracts of garlic and citrus have also produced strong results.[86] All three additives are being developed for the market. Finally, two other feed additives that are already on the market, one a yeast culture[87] and the other a blend of essential oils,[88] reduce dairy cow methane emissions indirectly by increasing the efficiency of milk production, thereby reducing the number of methane-emitting dairy cows needed to produce a certain volume of milk.

Biotech enzymes from Novozymes and others have also been introduced into pig and chicken feed to improve nutrient uptake, reduce waste, and substantially reduce carbon footprint.[89]

Emissions of methane and nitrous oxide from manure is another significant source of GHGs, accounting for 10 percent of emissions from animal agriculture.[90] As mentioned previously, biotechnology has a key role in reducing these emissions as well. The use of anaerobic digestion in animal agriculture has the potential to reduce U.S. GHG emissions by 151 $MTCO_2$ eq. annually by 2050 using current technology.[91] Considerable research and development is also underway to utilize biotechnology to improve the efficiency of anaerobic digestion through optimization of the microbes and microbial communities used.[92]

Open manure lagoons are capable of both reducing existing methane emissions and displacing fossil fuels when converted to enclosed anaerobic digesters. These systems capture the lagoons' methane emissions in the form of biogas that can be used to displace fossil fuels such as natural gas as a source of heat and/or electricity. The combustion of the biogas converts the methane into the less-potent GHG carbon dioxide. (One ton of methane has 84 times the global warming potential over 20 years of a ton of carbon dioxide.)[93] This capability, when combined with fossil fuel displacement, can result in carbon intensity values for biogas that are very negative despite not involving net carbon sequestration. Biogas that is produced from dairy manure and injected into natural gas pipelines for use as transportation fuel in compressed natural gas vehicles under California's LCFS has received certified carbon intensities that are almost 4 times lower than that of gasoline, for example.[94] One estimate calculated that up to 3% of total U.S. electricity consumption could be met by biogas produced in manure lagoons and captured for use with microturbines.[95]

Increased demand for animal protein will cause the livestock sector's contribution to global GHG emissions to increase in the years ahead. The use of biotechnology to limit the climate change impacts of livestock production is at a comparatively early stage of development due to a lack of low-carbon incentivizes, such as those that have existed in the U.S. power and transportation sectors since the turn of the century. Biotechnology has the potential to drive both near-term and long-term GHG emission reductions in the livestock sector, however. Feed additives and the use of enclosed anaerobic digesters can reduce near-term emissions.

Food and Feed Waste

Waste from food and feed production and delivery is also a significant source of GHG emissions. Nearly a third of all food produced is wasted annually. This food waste had a carbon footprint of 3.3 $GtCO_2eq$ in 2007, representing 7 percent of total global GHG emissions, according to the FAO.[96] Biotech solutions are available or under development to reduce food waste at multiple stages of the food and feed system.

The use of enzymes in bread and other baked goods has significantly enhanced product shelf life and reduced waste.[97] Organic acids and other products of industrial biotechnology have been developed by BASF and others to reduce spoilage of animal feeds.[98] Other biotech innovators are developing biobased antimicrobial coatings to reduce spoilage and inhibit pathogens in fruits and vegetables.[99] Others still are focusing on the use of biosensors to optimize produce ripeness to minimize spoilage. [100,101]

Food Ingredients

Biotechnology is also reducing the carbon footprint of a variety of food ingredients. The plant-based sweetener, stevia, for example has shown an 82% reduction in carbon footprint compared with beet sugar and a 64% reduction compared with cane sugar.[102] But the most desirable compounds of the stevia leaf are present in very low concentrations, limiting its market. Biotech leaders Evolva and DSM have developed pathways to produce those key stevia compounds through fermentation. Both have formed partnerships with Cargill and began production of fermentation-based stevia at commercial scale in 2019. Cargill's initial lifecycle assessment suggests the fermentation-based stevia has an even lower carbon footprint than the plant-based extract.[103] Nearly 200 million tons of sugar are produced globally each year.[104] With a carbon footprint of 241 kg CO_2e per ton of sugar,[105] the sugar sector accounts for roughly 48 MTCO2 annually.

BIOTECHNOLOGY	APPLICATIONS IN FOOD AND FEED WASTE
ORGANIC ACIDS	REDUCE SPOILAGE IN ANIMAL FEEDS
BIOBASED COATINGS	REDUCE SPOILAGE AND INHIBIT PATHOGENS IN FRUITS AND VEGETABLES
BIOSENSORS	OPTIMIZE RIPENESS TO MINIMIZE SPOILAGE
PLANT GENETIC ENGINEERING	DEVELOP FOOD VARIETIES WITH LESS SPOILAGE
ANIMAL GENETIC ENGINEERING	DEVELOP FARMED ANIMALS THAT REQUIRE LESS FOOD

As another example, vanillin, one of the most widely used synthetic food ingredients, was traditionally produced through a carbon- and energy-intensive process using coal tar. New biotech routes now allow for purer production without reliance on extraction or processing of fossil fuels.[106]

Food Processing

Biotech enzymes are also being used to dramatically lower the carbon footprint of food processing. The most significant example is the use of enzymes in meat processing. By eliminating energy-intensive traditional processing steps, industry-wide integration of enzymatic processes for meat processing would result in over 100 MTCO2e annually, according to the World Wildlife Fund. Smaller, but significant, reductions would result from adoption of enzymatic processing in fish and dairy processing, and beer and wine production. WWF estimated the total potential reductions from enzyme applications in the food sector at 114 to 166 MTCO2e annually.[107]

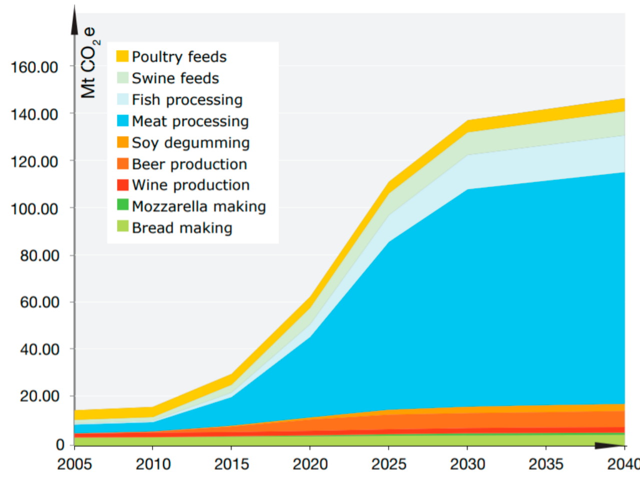


Figure 2. Potential GHG reductions from applications of biotechnology in the food industry. Source: Figure 5, https://wwfeu.awsassets.panda.org/downloads/wwf_biotech_technical_report.pdf

68 http://www.ipcc.ch/srccl/chapter/summary-for-policymakers/

69 http://www.fao.org/ag/againfo/resources/en/publications/tackling_climate_change/index.htm

70 Eshel, G., Stainier, P., Shepon, A. et al. Environmentally Optimal, Nutritionally Sound, Protein and Energy Conserving Plant Based Alternatives to U.S. Meat. Sci Rep 9, 10345 (2019). http://doi.org/10.1038/s41598-019-46590-1. https://www.nature.com/articles/s41598-019-46590-1

71 http://morningconsult.com/wp-content/uploads/2019/12/Morning--Consult_Fastest-Growing-Brands-2019-Report_FINAL.pdf

72 http://impossiblefoods.com/media/news-releases/2020/09/impossible-foods-quickly-expands-to-canadas-favorite-restaurant-chains

73 http://impossiblefoods.com/mission/lca-update-2019/

74 http://www.perfectdayfoods.com/

75 http://www.nrdc.org/sites/default/files/10-common-climate-damaging-foods-infographic.pdf

76 http://techcrunch.com/2020/10/01/motif-foodworks-preps-commer-

cial-production-for-its-first-ingredient-improving-the-flavor-of-beef--substitutes/

77 Environ. Sci. Technol. 2011, 45, 14, 6117–6123, June 17, 2011. http://pubs.acs.org/doi/full/10.1021/es200130u

78 Christopher Bryant, Julie Barnett, Consumer acceptance of cultured meat: A systematic review, Meat Science, 143,2018, Pages 8-17, ISSN 0309-1740, https://doi.org/10.1016/j.meatsci.2018.04.008. http://www.sciencedirect.com/science/article/abs/pii/S0309174017314602

79 http://www.fao.org/ag/againfo/resources/en/publications/tackling_climate_change/index.htm

80 http://www.carbontrust.com/resources/assessment-of-environmental-footprint-of-feedkind-protein

81 http://www.fao.org/ag/againfo/resources/en/publications/tackling_climate_change/index.htm

82 Proceedings of the National Academy of Sciences Aug 2015, 112 (34) 10663-10668; DOI: 10.1073/pnas.1504124112. http://www.pnas.org/content/112/34/10663

83 http://locusfs.com/leading-california-university-finds-78-percent-reduction-in-livestock-methane-emissions-with-direct-fed-microbials-from--locus-fermentation-solutions/

84 http://www.biorxiv.org/content/10.1101/2020.07.15.204958v1.abstract

85 http://www.sciencedirect.com/science/article/abs/pii/S0959652619321559

86 http://www.ncbi.nlm.nih.gov/pmc/articles/PMC7200514/

87 http://www.sciencedirect.com/science/article/abs/pii/S108074461530139X

88 http://www.mdpi.com/2076-2615/10/4/620

89 http://biosolutions.novozymes.com/animal-health-nutrition/en/insights/whitepaper/making-feed-more-sustainable

90 http://www.fao.org/ag/againfo/resources/en/publications/tackling_climate_change/index.htm

91 http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3155279/

92 http://www.ncbi.nlm.nih.gov/pmc/articles/PMC7198183/

93 http://www.epa.gov/ghgemissions/understanding-global-warming-potentials

94 http://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified--carbon-intensities

95 http://iopscience.iop.org/article/10.1088/1748-9326/3/3/034002/meta

96 http://www.fao.org/3/i3347e/i3347e.pdf

97 http://wwfeu.awsassets.panda.org/downloads/wwf_biotech_technical_report.pdf

98 http://www.basf.com/us/en/who-we-are/sustainability/we-drive-sustainable-solutions/sustainable-solution-steering/examples/organic-acids-luprosil-amasil.html

99 https://www.foodnavigator.com/Article/2019/10/21/A-new-tool-in--the-fight-against-food-waste-Milekons-is-highly-effective-environmentally-friendly-and-versatile

100 Neethirajan S, Ragavan V, Weng X, Chand R. Biosensors for Sustainable Food Engineering: Challenges and Perspectives. Biosensors. 2018; 8(1):23. https://doi.org/10.3390/bios8010023

101 https://penntoday.upenn.edu/news/strella-biotechnologys-biosensors-minimize-food-waste-one-apple-time

102 https://journals.lww.com/nutritiontodayonline/Fulltext/2015/05000/Stevia,_Nature_s_Zero_Calorie_Sustainable.7.aspx

103 https://www.cargill.com/food-beverage/na/eversweet-faqs

104 https://apps.fas.usda.gov/psdonline/circulars/sugar.pdf

105 https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-5-3#:~:text=According%20to%20our%20calculations%2C%20241,a%20ton%20of%20sugarcane%20processed).

106 https://www.forbes.com/sites/johncumbers/2019/10/30/better-than--nature-fermenting-vanilla/#2e35b85636c3

107 https://wwfeu.awsassets.panda.org/downloads/wwf_biotech_technical_report.pdf

VERAMARIS CASE STUDY

Fish are among the lowest carbon intensity sources of meat.[108] As global demand for animal products continues to grow, and with most of the world's wild fish stocks at, or beyond, sustainable harvest levels,[109] aquaculture – farmed fish and other seafood – will play a key role in mitigating the impact of meat consumption on the climate.

Salmon aquaculture is the fastest-growing food production system in the world.[110] Salmon's popularity and relatively low carbon intensity make it an attractive option to displace some of the projected growth in the consumption of beef and other higher carbon intensity meats. The growth of salmon aquaculture is currently limited by the availability of the marine omega-3 oils EPA and DHA, key components of salmon diets. Marine omega-3 oils have, until recently, been derived almost exclusively from wild-caught oily fish, such as anchovy and menhaden, whose wild stocks are limited and increasingly threatened by climate change.[111]

Veramaris, a joint venture between biotech leaders DSM and Evonik Industries, has eliminated this supply chain and sustainability barrier by developing a biotech approach to marine omega-3 oil production. Veramaris identified marine algae that produce EPA and DHA naturally, and recently began commercial production of algae-based omega-3 oils at a $200 million facility in Blair, Nebraska.[112] The facility can produce omega-3 oils equivalent to 1.2 million tons of wild-caught fish, enough to supply 15 percent of salmon farming industry demand,[113] and has brought jobs and economic development to a region hit hard by low commodity prices and recent trade disputes.

By sourcing omega-3 oils from locally grown algae, Veramaris also dramatically shortens the feed supply chain, reducing emissions associated with the harvesting, processing, and transport of fish oil.

108 http://www.nature.com/articles/s41598-020-68231-8

109 http://www.veramaris.com/why-we-do-it-detail.html#sustainable-growth

110 http://www.worldwildlife.org/industries/farmed-salmon

111 http://insideclimatenews.org/news/27092019/ocean-fish-diet-climate-change-impact-food-ipcc-report-cryosphere

112 http://www.feednavigator.com/Article/2019/07/15/New-Veramaris--facility-will-help-it-expand-into-new-markets

113 http://www.veramaris.com/press-releases-detail/veramaris-opens--us200m-facility-for-epa-dha-omega-3-algal-oil-to-support-sustainable--growth-in-aquaculture.html

2.2 AGRICULTURE INPUTS AND CLIMATE SERVICES

2.2.1 AGRICULTURAL BIOLOGICAL

Modern agriculture is an energy-intensive process. In addition to the need to fuel heavy machinery, many farming practices release carbon dioxide from both biogenic and fossil sources that would otherwise remain stably sequestered. Intensive tilling practices expose soil carbon to the atmosphere, allowing it to react with oxygen to form carbon dioxide. Nitrogen fertilizers increase the sequestration potential and minimize the land footprint of crops, but they are derived from fossil fuels such as natural gas and generate the potent GHG nitrous oxide. Advances in crop science and technology can mitigate some of these unwanted environmental effects. No-till agriculture using herbicide-resistant crops limits soil disruption and reduces the amount of soil carbon that is released to the atmosphere as carbon dioxide. The development of crop varieties with added or improved nitrogen-fixing capabilities allows for more efficient use of nitrogen fertilizer when combined with crop rotation practices.[114] And the engineering of commonly used crops to give them resistance to environmental threats such as drought and pests enhances their carbon sequestration potential while minimizing indirect GHG emissions from deforestation.

One of the fastest growing, and most promising, applications of biotechnology is in agricultural biologicals. Soil microorganisms play a key role in plant growth, enabling efficient access to nutrients and protecting against pests and diseases. Ag biologicals leverages biotechnology to improve soil microbes and enhance these natural processes. A major area of focus for ag biologicals companies is increasing plant uptake of nitrogen to allow for more efficient use of synthetic nitrogen fertilizer. Synthetic nitrogen fertilizer is a significant source of climate-warming gases. It is energy intensive to produce, and a substantial fraction of the nitrogen in fertilizer becomes nitrous oxide (N2O) a greenhouse gas 298 times more potent than carbon dioxide. Joyn Bio, a joint venture between the synthetic biology company, Ginkgo Bioworks, and Bayer, is engineering microbes to enable cereal crops like corn, wheat, and rice to convert nitrogen from the air into a form they can use to grow, allowing for more efficient use of synthetic fertilizers for many of the world's leading crops.

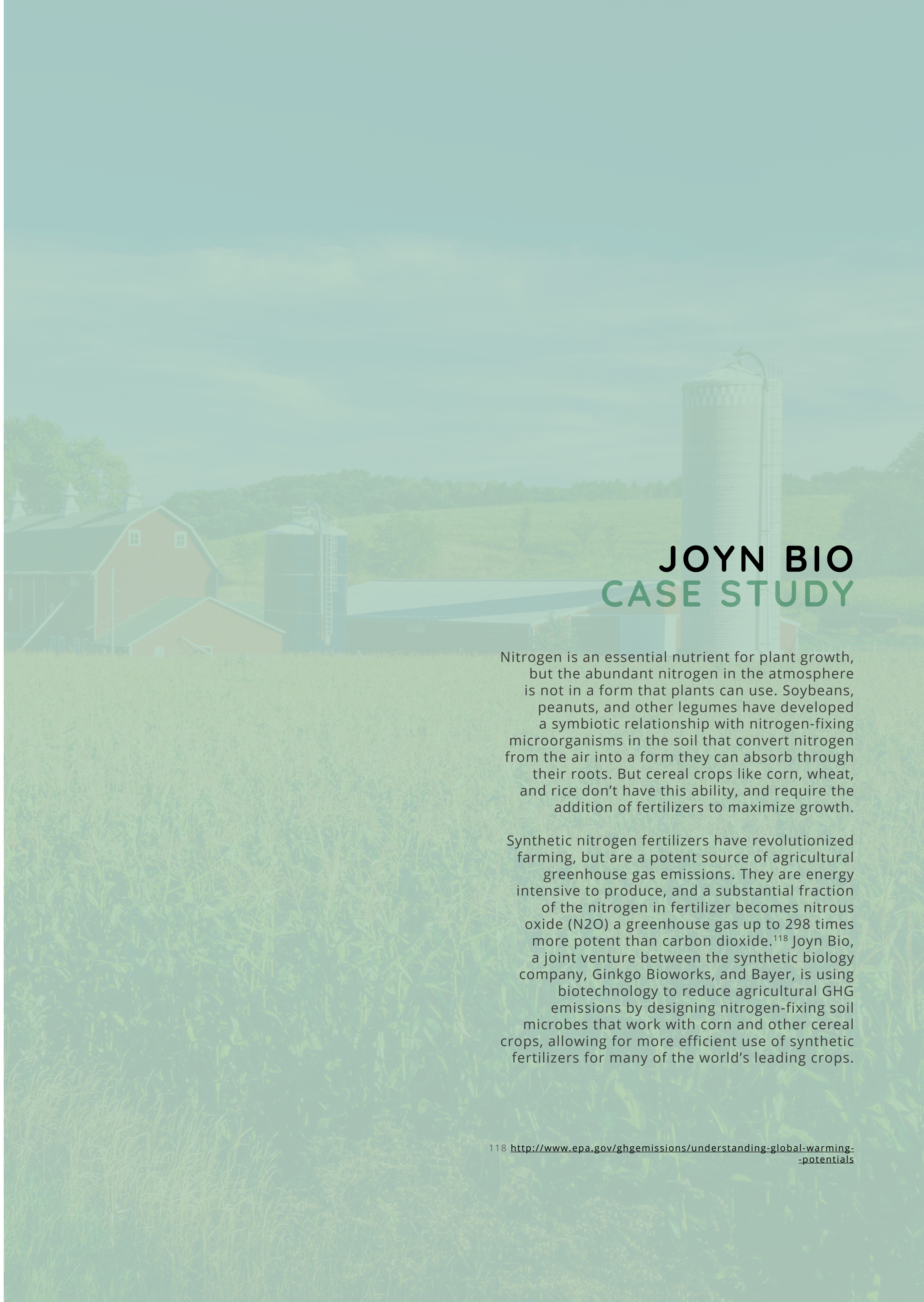
Other biotech researchers and businesses are developing nitrogen- and carbon-fixing bacteria or algae to build soil carbon and enhance the absorption of atmospheric nitrogen by soils.[115,116] And biotech innovators such as Vestaron are developing safer, more sustainable crop protection tools, such as biological peptides, to provide crops with greater resiliency to plant stress induced by climate change.[117]

114 http://news.wisc.edu/corn-that-acquires-its-own-nitrogen-identified--reducing-need-for-fertilizer/

115 http://www.frontiersin.org/articles/10.3389/fmicb.2019.01146/full

116 http://usea.org/sites/default/files/event-/USEA%20Tech%20Briefing_Matt%20Carr_Algae%20for%20Carbon%20Capture%20&%20Use_March_2018.pdf

117 Iriti M, Vitalini S. Sustainable Crop Protection, Global Climate Change, Food Security and Safety—Plant Immunity at the Crossroads. Vaccines. 2020; 8(1):42. http://doi.org/10.3390/vaccines8010042. https://www.mdpi.com/2076-393X/8/1/42



JOYN BIO CASE STUDY

Nitrogen is an essential nutrient for plant growth, but the abundant nitrogen in the atmosphere is not in a form that plants can use. Soybeans, peanuts, and other legumes have developed a symbiotic relationship with nitrogen-fixing microorganisms in the soil that convert nitrogen from the air into a form they can absorb through their roots. But cereal crops like corn, wheat, and rice don't have this ability, and require the addition of fertilizers to maximize growth.

Synthetic nitrogen fertilizers have revolutionized farming, but are a potent source of agricultural greenhouse gas emissions. They are energy intensive to produce, and a substantial fraction of the nitrogen in fertilizer becomes nitrous oxide (N2O) a greenhouse gas up to 298 times more potent than carbon dioxide.[118] Joyn Bio, a joint venture between the synthetic biology company, Ginkgo Bioworks, and Bayer, is using biotechnology to reduce agricultural GHG emissions by designing nitrogen-fixing soil microbes that work with corn and other cereal crops, allowing for more efficient use of synthetic fertilizers for many of the world's leading crops.

118 http://www.epa.gov/ghgemissions/understanding-global-warming--potentials

2.2.2 BIOLOGICAL CARBON CAPTURE, USE AND STORAGE

Biomass is one of America's major, albeit transitory, carbon sinks. All forms of biomass that employ photosynthesis capture atmospheric carbon dioxide and convert it to carbon-based compounds such as sugars, starch, and lignocellulose. The carbon content of this biomass remains sequestered until the biomass is either consumed or decomposes, at which time much of it is oxidized and released back to the atmosphere as carbon dioxide. Some of the carbon content, such as that contained in a plant's roots, is sequestered for much longer time periods in the form of below-ground biomass. It is for this reason that the afforestation/reforestation of marginal land can result in the formation of new carbon sinks and the long-term removal of carbon dioxide from the atmosphere.

Carbon that is sequestered as below-ground biomass can remain in that state so long as the surrounding soil is not disrupted. The length of time that biomass's above-ground carbon content remains sequestered depends on how the biomass is utilized. The combustion of biomass, whether in its natural form or following conversion to biofuel, results in the oxidation and release of its carbon content as carbon dioxide. While carbon-neutral in the sense that the released biogenic carbon had been captured from the atmosphere during the growing season, traditional combustion prevents the carbon from being either sequestered or reused prior to the completion of another growing season.

A variety of biotechnologies have been developed that either capture and sequester or recycle atmospheric carbon dioxide. Many of these processes are closely related to the biobased products covered in Section 2.1 because of the ability of biomass to capture atmospheric carbon dioxide before being converted to different fuels and products. The technologies in question impact every stage of the biomass supply chain, from growth/production to conversion and ultimately end-of-life disposal.

Carbon capture and storage (CCS) technologies enable carbon dioxide emissions from fossil power plants or industrial facilities, such as cement or steel, to be captured at the facility and stored underground. A variety of approaches have been developed to absorb carbon dioxide from flue gases, or to remove carbon prior to combustion.[119] CCS can also be deployed at facilities utilizing biomass as feedstock. The process is largely the same as that employed at some fossil fuel facilities but, whereas fossil energy carbon capture and sequestration (FECCS) processes reduce the GHG emissions of fossil fuels, biomass energy carbon capture and sequestration (BECCS) processes actually reverse past emissions. The biomass captures atmospheric carbon dioxide during its growth phase and is then combusted, yielding both energy and carbon dioxide. The bioenergy displaces fossil energy and the carbon dioxide is either sequestered in underground caverns as a gas or converted to a degradation-resistant solid such as biochar. BECCS is therefore a carbon-negative process in that it results in more carbon dioxide being sequestered than emitted. Biotechnology advances that increase the growth rate, growth potential, and harvest efficiency of biomass that is used as BECCS feedstock all enhance the process's carbon sequestration capability.

BECCS technology can also be deployed to achieve negative carbon results at any industrial facility using biomass as a feedstock. Perhaps the most intriguing application of BECCS is its potential use at ethanol plants and other biorefineries. One third of the carbon in the biomass feedstock used to produce ethanol is released in the form of carbon dioxide during the fermentation process. Using BECCS to capture this CO2 reduces the carbon intensity of ethanol by 40%.[120] Biorefineries represent an extremely attractive option for deploying BECCS because the product of fermentation is a nearly pure (99%) stream of CO2, requiring little or no separation from other gases. As a result, biorefinery BECCS is among the lowest-cost carbon capture opportunities available, at an estimated cost of under $30 per ton of CO2 compared to $60-$120 per ton at fossil power plants or traditional industrial facilities.[121] The world's first ethanol BECCS project is now in operation in Decatur, Illinois, capturing and storing 1 MTCO2eq per year that would otherwise have been emitted to the atmosphere.[122]

In addition to its role in providing biomass feedstocks for BECCS, biotechnology is increasingly seen as a key enabling technology for carbon capture itself. The U.S. Department of Energy (DOE) has invested over $150 million since 2015 in the development of algae and other microbial systems for carbon capture as an alternative – or complimentary – approach to chemistry-based approaches to CO2 extraction from flue gases.[123] Microbial systems have several significant advantage over thermochemical approaches to carbon capture. Typical thermochemical CCS systems are highly energy intensive. Roughly 30% of captured carbon is offset by the additional fossil fuel combustion required to separate, compress, and transport the captured carbon.[124] Microbial systems can dramatically reduce this "parasitic load." Algae and other microbes extract CO2 or other target gases biologically, via photosynthesis or other natural energy pathways, eliminating the energy inputs required for separation. Microbial systems can even operate efficiently at the relatively low CO2 concentrations found in flue gases from natural gas or coal-fired power plants, and can be deployed economically at relatively small scale to address emissions from smaller power plants and industrial facilities that cannot support traditional CCS systems. Microbial systems also convert the captured carbon into a usable solid or liquid form directly, eliminating the substantial energy inputs required to compress captured CO2 for transport, or for use in enhanced oil recovery. As such, *microbial carbon capture systems applied to biomass energy or other biorefinery systems offer one of the most carbon-negative climate solutions available.*

DOE in its 2016 Billion Ton Report found that *suitable land and other infrastructure exists to deploy algae-based carbon capture systems at more than 500 power plants and ethanol facilities in the U.S. These systems would have a potential to capture more than 200 MT CO2 annually.*[125]

Biomass and carbon capture can then be combined with the carbon dioxide recycling technologies discussed in Section 2.1 to produce negative-carbon products from captured biogenic carbon. The biomass energy carbon capture and utilization (BECCU) process displaces both fossil energy consumption and fossil fuel emissions. As with BECCS, BECCU uses biogenic carbon to generate energy via combustion, displacing fossil fuels in the process. The resulting carbon dioxide is captured but, instead of being sequestered, is converted into yet another fuel or product that displaces additional fossil fuels. BECCU can still be carbon-negative, either because it displaces more carbon dioxide emissions from fossil fuels than it emits when the utilization takes the form of conversion to biofuels or biodegradable products, or because the utilization takes the form of conversion to non-biodegradable products.[126] In the latter case, carbon sequestration still occurs, but in a long-lifetime product, rather than geologic storage.

BECCS and BECCU are not widely employed in the U.S. at present due to a relative lack of economic or policy incentives for the capture of carbon dioxide. Those CCS projects that do exist in North America involve fossil rather than biogenic sources of carbon.[127] That said, climate scientists increasingly believe that the two technologies will need to be widely utilized if catastrophic climate change is to be avoided. The UN's Intergovernmental Panel on Climate Change (IPCC) has concluded that keeping the atmospheric carbon dioxide level below 450 ppm by 2100, as is necessary if catastrophic climate change is to be avoided, will require the "availability and widespread deployment of BECCS and afforestation."[128] The primary hurdle facing BECCS/BECCU commercialization is one of economics rather than technology: carbon capture is economically unattractive at a time when the cost of emissions is lower than the cost of capture.[129] The technical feasibility of capture and sequestration is especially well-established for those technologies that rely upon natural processes such as the building of soil carbon via afforestation/reforestation or the planting of certain dedicated energy crops. BECCU also offers an advantage over BECCS in the absence of a high emissions cost due to its production of higher-value products such as fuels or chemicals; BECCS, by contrast, produces lower-value products such as heat and electricity.[130]

The ability of BECCS to achieve net-negative carbon emissions and their magnitude depend on several different factors involving the different stages of the supply chain. A comparison of multiple biomass feedstocks combusted in a power plant equipped with CCS technology determined that while growth of the three feedstocks considered (Miscanthus, switchgrass, and willow) all have the potential to achieve net sequestration, the actual amount of sequestration that occurs is determined by biomass transportation distances, carbon capture rates, and especially land-use change (e.g., what type of land that the biomass feedstock is grown on).[131] The analysis calculated that the amount of carbon dioxide ultimately sequestered on average while generating one megawatt hour of electricity via BECCS with Miscanthus and switchgrass is equal to the average amount emitted by U.S. power plants to generate an equal amount of electricity.

BECCU has also been found to achieve low-to-negative carbon intensities. A life cycle assessment that compared the carbon intensities of ethanol produced from steel mill waste gases found its carbon footprint to be at least 60% lower than that of gasoline.[132] Dedicated energy crops such as Miscanthus and willow grown for the purpose of electricity generation have been found to achieve net-negative emissions of carbon dioxide due to the combined effects of soil carbon sequestration and the displacement of fossil fuels.[133] A different analysis found emissions via afforestation/reforestation to also be negative even if the forest is harvested and utilized as wood products such as sawtimber, as these constitute a different form of BECCU.[134]

The carbon dioxide reduction and sequestration potential of BECCS/BECCU technologies is very sensitive to land-use change. For example, the largest amount of sequestration occurs when dedicated energy crop growth or afforestation/reforestation occurs on abandoned or marginal croplands that have previously had their soil carbon depleted. On the other hand, the conversion of grassland to these uses results in a reduced sequestration potential, while the conversion of productive cropland can have the lowest sequestration potential of all if the resulting decrease in the supply of the crop causes the conversion of land such as forest to cropland somewhere else. Biotechnology provides several methods for mitigating these unintended consequences through advances in plant and crop science that are described in more detail in Section 2.4.1.

119 http://www.c2es.org/content/carbon-capture/

120 http://www.pnas.org/content/pnas/early/2018/04/18/1719695115.full.pdf

121 http://www.pnas.org/content/pnas/early/2018/04/18/1719695115.full.pdf

122 http://www.energy.gov/fe/articles/doe-announces-major-milestone--reached-illinois-industrial-ccs-project

123 http://algaebiomass.org/blog/10655/2020-will-see-record-federal--funding-algae-rd/

124 http://www.reuters.com/article/us-carboncapture-economics-kemp/carbon-captures-energy-penalty-problem-kemp-idUSKCN0HW0TZ20141007

125 http://algaebiomass.org/blog/9541/doe-2016-billion-ton-report-ample-resources-for-algae-production-in-the-u-s/

126 http://www.slideshare.net/UKCCSRC/richard-murphy-cardiffbasep14

127 http://fas.org/sgp/crs/misc/R44902.pdf

128 http://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_summary-for-policymakers.pdf

129 http://www.sciencedirect.com/science/article/abs/pii/S0959652614009536

130 http://www.sciencedirect.com/science/article/abs/pii/S136403211730014X

131 http://pubs.rsc.org/en/content/articlelanding/ee/2017/c7ee00465f

132 http://pubs.acs.org/doi/abs/10.1021/acs.iecr.5b03215

133 http://www.sciencedirect.com/science/article/pii/S0961953409002402

134 http://link.springer.com/article/10.1007/s11367-013-0629-6

LANZATECH CASE STUDY

LanzaTech is unique for its ability to make low carbon fuels and chemicals from a variety of waste-based feedstocks, including industrial emissions, unsorted, unrecyclable municipal solid waste, and agricultural or forestry wastes and residues. The company utilizes a naturally occurring bacteria originally isolated from rabbit droppings. As part of its natural biology, the bacteria ferments gases containing carbon dioxide, carbon monoxide, and/or hydrogen into ethanol. This ethanol can be used directly as a fuel to displace gasoline or as a chemical in consumer products.[135] Additionally, ethanol can be upgraded to make consumer goods from polyethylene[136] or PET, and to make sustainable aviation fuel (SAF) via the LanzaJet Alcohol-to-Jet pathway,[137] to displace fossil fuel demand in the aviation sector. The opportunities for LanzaTech's technologies to utilize waste carbon to produce multiple low carbon fuels and chemicals has expanded over the last decade as its technology has been licensed worldwide.

The LanzaTech pathway differs from conventional ethanol production in that it feeds its microorganisms with a gas stream rather than a liquid sugar substrate. While carbon is the most important ingredient in this gas stream, the microorganisms are capable of fermenting gases produced from a variety of industrial processes and feedstocks. The gases are captured and compressed before being delivered to a bioreactor where fermentation to ethanol occurs. The ethanol is then recovered from the bioreactor and stored for future use either in that form or following subsequent upgrading to a hydrocarbon fuel.

The first commercial-scale facility to utilize LanzaTech's pathway is a steel mill located near Beijing, China. Waste gases produced at the mill are captured and fermented to ethanol at a rate of 16 million gallons per year. The company estimates that the recycling of the mill's GHG emissions in this manner is the equivalent of removing 80,000 cars from the road annually.[138] The success of the technology at such a large scale has resulted in plans to apply it to other types of industrial facilities, including a petroleum refinery in India that will achieve an annual ethanol yield of 11 million gallons, a steel mill in Belgium that will achieve an annual ethanol yield of 21 million gallons, and a smelter in South Africa that will achieve an annual ethanol yield of 17 million gallons.

Beyond recycled carbon fuels, LanzaTech's platform can make second generation biofuels through gasification of biomass wastes and residues. LanzaTech is developing a project to convert locally available agricultural residues to approximately 5.3 million gallons per year of fuel grade ethanol in India, using commercially proven gasification technology and LanzaTech's commercially proven gas fermentation platform. The integrated technology will have the flexibility to process a wide range of biomass feedstocks enabling rapid replication at other locations.

A by-product of the project will be a nutrient rich biochar. Biochar can be a useful soil supplement to enrich soil organic carbon and other nutrients. In 2018, LanzaTech launched a new company, LanzaJet to accelerate the commercialization of SAF production. The LanzaJet process can use any source of sustainable ethanol for jet fuel production, including, but not limited to, ethanol made from recycled pollution, the core application of LanzaTech's carbon recycling platform.

Commercialization of this process, called Alcohol-to-Jet (AtJ) has been years in the making, starting with the partnership between LanzaTech and the U.S Energy Department's Pacific Northwest National Laboratory (PNNL). PNNL developed a unique catalytic process to upgrade ethanol to alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK) which LanzaTech took from the laboratory to pilot scale. SAF produced via the company's pathway has already been employed in two commercial flights to demonstrate its ability to displace fossil aviation fuel.[139] LanzaTech estimates that SAF produced using its technology achieves a 70% reduction to carbon intensity compared to fossil aviation fuel.

135 http://www.cnbc.com/2018/07/27/lanzatech-turns-carbon-waste-into-ethanol-to-one-day-power-planes-cars.html

136 http://www.lanzatech.com/2018/10/04/virgin-atlantic-lanzatech-celebrate-revolutionary-sustainable-fuel-project-takes-flight/

137 http://www.lanzatech.com/2019/11/22/lanzatech-moves-forward--on-sustainable-aviation-scale-up-in-the-usa-and-japan/

138 http://www.cnbc.com/2018/07/27/lanzatech-turns-carbon-waste-into-ethanol-to-one-day-power-planes-cars.html

139 http://www.lanzatech.com/2018/10/04/virgin-atlantic-lanzatech-celebrate-revolutionary-sustainable-fuel-project-takes-flight/

2.3 NEW BIOTECH TOOLS AND BIO-INDUSTRIAL MANUFACTURING

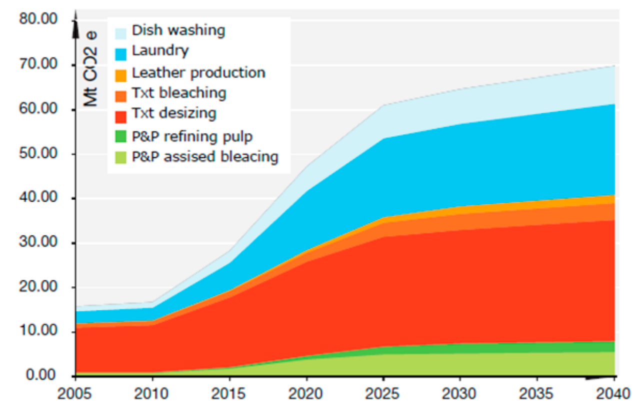
2.3.1 NEW BIOTECH TOOLS

Rapid advances in the fundamental tools of biotechnology increasingly are enabling biotech solutions in manufacturing sectors beyond food, fuels and chemicals. These developments offer the potential for transformative climate solutions in applications beyond manufacturing as well.

Biotech tools for manipulating DNA have been in use for decades. Many of the most important contributions of biotechnology – vaccines and therapies, biotech crops, and modern industrial biotechnology – were made possible by this first generation of genetic engineering tools. But the past decade has seen a wave of new biotech tool innovation with transformative potential. In synthetic biology, scientists insert synthesized pieces of DNA into an organism's genome to alter the characteristics or function of the organism. In genome editing, scientists use tools to make more precise changes to the organism's own DNA to achieve the same outcome.[137] These and other new biotech tools have dramatically increased the speed and reduced the cost of genetic engineering applications and are being deployed to tackle a range of global challenges, including climate change.[138]

2.3.2 APPLICATIONS OF BIO-MANUFACTURING IN TRADITIONAL INDUSTRIES

Some of industrial biotechnology's earliest uses were in the application of enzymes to improve efficiency and reduce energy use in traditional industries. The introduction of enzymes for pulp and paper bleaching, for example, reduced energy consumption 40% versus traditional bleaching, and a shift to fermentation-based production of riboflavin (vitamin B2) in the early 2000's reduced associated CO2 emissions 80% compared to the traditional chemical manufacturing route.[139] Applications of enzymes in textile processing, such as pretreatment, bleaching and desizing, save approximately 10 $MTCO_2e$ annually today. Full adoption of these technologies would triple these reductions. The widespread use of enzymes in laundry and dishwasher detergent could save an additional 30 $MTCO_2e$ annually by 2040 by allowing for cold-water washing of laundry and more efficient dishwashing. Full market penetration of biotech applications in these traditional industries is estimated to save 65 $MTCO_2e$ annually by 2030.[140] While these GHG are incremental relative to the global challenge of climate change, they represent near-term opportunities that will be essential to reducing near-term emissions.



GHG reduction potential from applications of biotechnology to traditional industries. Source: Figure 7, https://wwfeu.awsassets.panda.org/downloads/wwf_biotech_technical_report.pdf

2.3.3 NEW MARKETS AND NOVEL APPLICATIONS

With the emergence of synthetic biology and the ability to tailor microbes to specific industrial tasks, industrial biotechnology solutions are moving into an ever-expanding range of applications. A rapidly growing number of companies, such as Gingko Bioworks, Arzeda, and Twist Biosciences, are providing organism design and DNA synthesis services, using synthetic-biology and other modern biotechnology tools to optimize manufacturing pathways. SynBio companies raised over $1 billion in investment in the second quarter of 2019 alone.[141]

One intriguing potential application of these new biotech tools is in biological data storage, the storage of data on strands of DNA instead of semiconductors or magnetic devices. DNA is roughly a million times denser than conventional hard-disk storage. Testing is now underway with computers that store data by synthesizing strands of DNA. A shift to biological data storage would eliminate the need for mining and production of silicon or precious metals. More significantly, it could dramatically reduce the need for massive data storage facilities.[142] Energy consumption by data storage facilities already accounts for 2% of global GHG emissions, and is projected to surge to 14% of global emissions by 2040.[143] DARPA, the Defense Department's Advanced Research Projects Agency, is investing $15 million in work by Microsoft, Twist Bioscience, and others to develop DNA storage.[144] A collaboration between the University of Washington and Microsoft successfully demonstrated their fully-automated end-to-end DNA storage process in 2019.[145]

Biology-based parallel computing – in which bio-molecules are used to test a large number of solutions to a problem simultaneously – is also being evaluated as another potential application of biotechnology. A proof of concept experiment at McGill University yielded a solution to a complex mathematical problem with less than 0.1% of the energy required to solve the problem with traditional computing.[146]

Synthetic biology is also being deployed to accelerate the development of solutions to the COVID-19 pandemic.

In addition to applications in manufacturing, synthetic biology has the potential to provide transformative solutions for carbon dioxide removal from the atmosphere and oceans.[147]

Synthetic biology could be applied to enhance photosynthetic efficiency of trees, or reduce respiration from soil microbes, to shift natural carbon cycles towards carbon removal. Even small improvements in these natural carbon cycles could have profound impacts, given that 120 GTCO2e is removed from the atmosphere by terrestrial photosynthesis.[148] As discussed in section 2.2.2, deployment of microbial systems for carbon capture has the potential to further draw down atmospheric carbon concentrations.

137 http://www.genome.gov/about-genomics/policy-issues/Synthetic--Biology

138 http://www.genome.gov/about-genomics/fact-sheets/Sequencing--Human-Genome-cost

139 http://www.bio.org/sites/default/files/legacy/bioorg/docs/files/CleanerExecSumm.pdf

140 http://wwfeu.awsassets.panda.org/downloads/wwf_biotech_technical_report.pdf

141 http://synbiobeta.com/these-37-synthetic-biology-companies-raised-1-2b-this-quarter/

142 http://www.scientificamerican.com/article/dna-data-storage-is-closer-than-you-think/

143 http://www.sciencedirect.com/science/article/abs/pii/S095965261733233X?via%3Dihub

144 http://www.wired.com/story/darpa-wants-to-build-an-image-search--engine-out-of-dna/

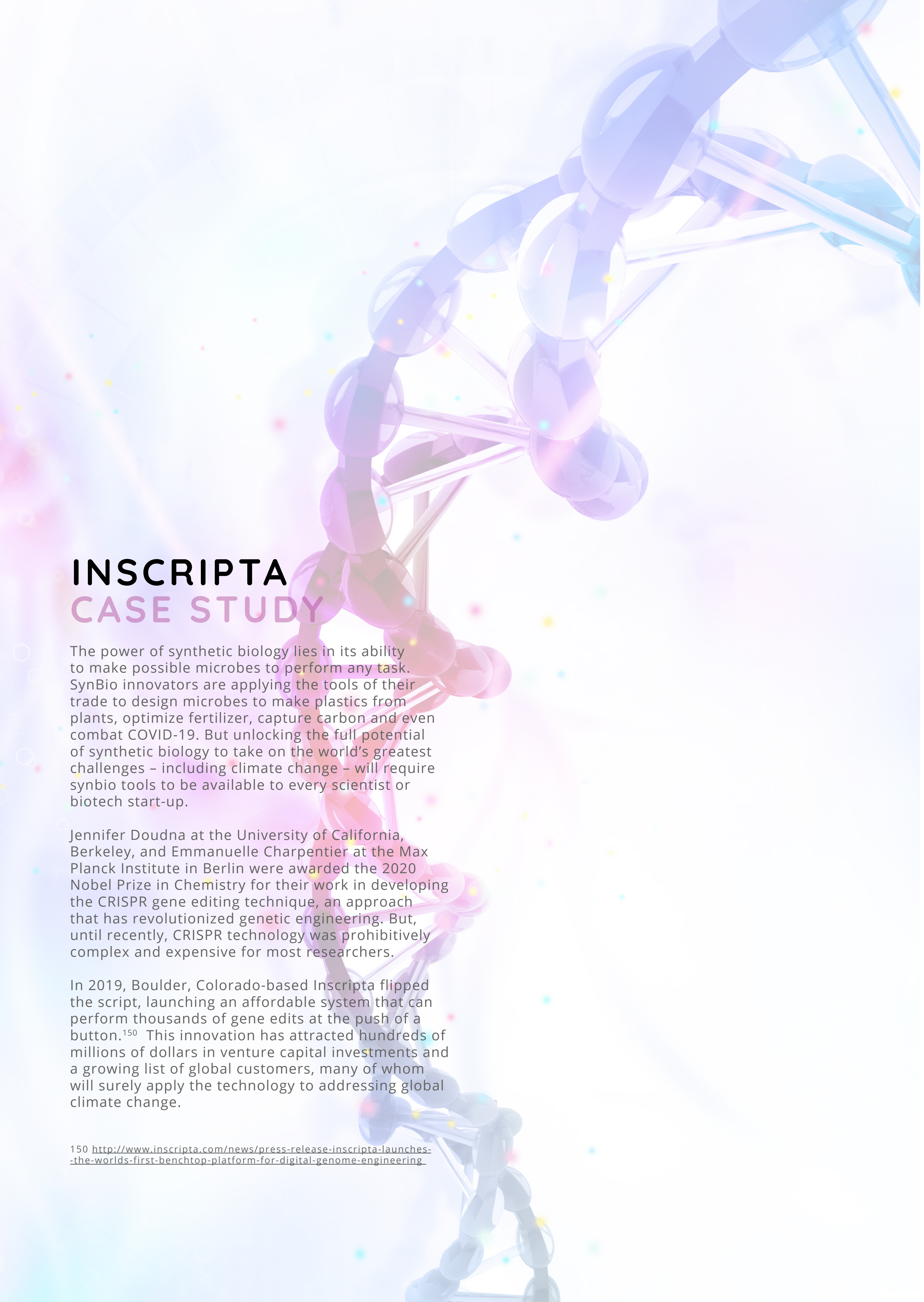
145 http://news.microsoft.com/innovation-stories/hello-data-dna-storage/

146 Nicolau, DV, et al. Parallel computing with molecular motors. Proceedings of the National Academy of Sciences Mar 2016, 113 (10) 2591-2596; DOI: 10.1073/pnas.1510825113. https://www.pnas.org/content/113/10/2591.abstract

147 http://www.wsj.com/articles/companies-rush-to-shore-up-covid--19-testing-ahead-of-flu-season-11598788800

148 DeLisi, C. The role of synthetic biology in climate change mitigation. Biol Direct 14, 14 (2019). https://doi.org/10.1186/s13062-019-0247-8. http://biologydirect.biomedcentral.com/articles/10.1186/s13062-019-0247-8

149 Hu, G. et al. Engineering Microorganisms for Enhanced CO2 Sequestration. Trends in Biotechnology 37(5), 532-547, May 2019. https://doi.org/10.1016/j.tibtech.2018.10.008. http://www.cell.com/trends/biotechnology/fulltext/S0167-7799(18)30304-4



INSCRIPTA CASE STUDY

The power of synthetic biology lies in its ability to make possible microbes to perform any task. SynBio innovators are applying the tools of their trade to design microbes to make plastics from plants, optimize fertilizer, capture carbon and even combat COVID-19. But unlocking the full potential of synthetic biology to take on the world's greatest challenges – including climate change – will require synbio tools to be available to every scientist or biotech start-up.

Jennifer Doudna at the University of California, Berkeley, and Emmanuelle Charpentier at the Max Planck Institute in Berlin were awarded the 2020 Nobel Prize in Chemistry for their work in developing the CRISPR gene editing technique, an approach that has revolutionized genetic engineering. But, until recently, CRISPR technology was prohibitively complex and expensive for most researchers.

In 2019, Boulder, Colorado-based Inscripta flipped the script, launching an affordable system that can perform thousands of gene edits at the push of a button.[150] This innovation has attracted hundreds of millions of dollars in venture capital investments and a growing list of global customers, many of whom will surely apply the technology to addressing global climate change.

150 http://www.inscripta.com/news/press-release-inscripta-launches--the-worlds-first-benchtop-platform-for-digital-genome-engineering

2.4 PLANT AND ANIMAL BIOTECHNOLOGY

2.4.1 PLANT BIOTECHNOLOGY AND GENE EDITING

Biomass has a critical role to play in efforts to mitigate climate change. As described in Sections 2.1 and 2.2, biomass can replace a wide variety of fossil fuels and products, reducing or even sequestering carbon dioxide emissions in the process. At the same time, though, biomass can contribute to climate change if it is used unsustainably, and it will need to adapt to unprecedented growing conditions as the planet continues to warm. Biotechnology is providing important advantages on both counts, enhancing the amount of biomass that can be sustainably harvested while also improving the climate resiliency of many important crops and other plants.

Genetically modified organisms (GMO) have been used since the 1990s to make important crops such as grains and oilseeds resistant to common threats including drought and pests. These past breakthroughs mitigated climate change by reducing the amount of land required by the agriculture sector. Yields of corn per acre in the U.S. increased by approximately 60% between 1991 and 2019[151] while those of soybeans increased by almost 50% over the same period.[152] There were fewer acres of cropland in production in the U.S. in 2012 than there were in 1945,[153] despite the large increases to the U.S. and world populations that occurred over that time, due to this improved productivity.

It is important that these productivity increases continue to be made in the coming decades if agriculture's contributions to climate change are to be limited. The continued growth of the global population will create additional demand for crops at a time when growing seasons and conditions are expected to become more uncertain due to climate change.[154] Future food crop shortages, whether due to increased demand from population growth or crop failures caused by extreme weather, would potentially contribute to climate change by encouraging the conversion of carbon sinks such as grassland and forests to cropland, thereby releasing carbon dioxide sequestered in the biomass and soil to the atmosphere. Likewise, improvements to the resiliency of dedicated energy crops during extreme weather events will improve both climate and energy security by enabling their utilization as low-carbon bioenergy and bioproduct feedstocks to increase.

Biotechnology is also enabling the expansion of existing bioenergy pathways. The U.S. is currently undergoing a rapid increase to its renewable diesel production capacity that will result in additional demand for lipid feedstocks.[155] Work is underway to utilize fast-growing and/or resilient undomesticated biomass such as Jatropha and microalgae as biofuels feedstocks. Both forms of biomass can grow on marginal lands while limiting the disturbance of existing carbon sinks. However, their utilization as bioenergy has historically been constrained by poor crop yields outside of the laboratory. Cell engineering has enabled the necessary yields for commercial production to be achieved in microalgae,[156] and research is actively underway to improve Jatropha as a feedstock.[157] Biotechnology is also being utilized to expand the supply of lipid feedstocks by enabling the conversion of waste products, as is described in Section 1.1.1.

The development of the CRISPR gene editing technique over the last decade has already led to notable breakthroughs in the effort to mitigate climate change. In addition to microalgae,[158] multiple strains of bacteria, yeast, and filamentous fungi have been modified via the CRISPR technique to increase the yields and types of products produced via fermentation.[159] The CRISPR technique has also been employed with dedicated energy crops such as Miscanthus, poplar, switchgrass, and willow to refine specific traits that improve both resiliency and yields, although the higher complexity of these forms of biomass and regulatory uncertainty about their possible status as genetically modified organisms have slowed progress.[160] Finally, CRISPR gene editing has also been employed to improve the resiliency and carbon efficiency of 1st-generation bioenergy feedstocks such as corn[161] and soybeans under the types of extreme weather conditions that are expected to occur with growing frequency as a result of climate change.[162]

Biotechnology is also being used to develop plant varieties, including apples and potatoes, that extend shelf life and avoid cosmetic issues, such as browning or spotting, that cause consumers to throw away food.[163]

Biotechnology has enabled major improvements to the yields, land-use efficiency, and resiliency of important U.S. bioenergy feedstocks in recent decades. Continued biotechnology advances will need to occur in the near future if these improvements are to be maintained, let alone expanded upon. Climate change is expected to result in extreme weather events that are greater in frequency, magnitude, and duration, and these will threaten production of both the feedstocks that have contributed heavily to U.S. bioenergy and bioproducts to date as well as the plant biomass that slows the rate of atmospheric GHG concentration increase. The development of the CRISPR gene editing technique, along with continued advances in more traditional genetic engineering processes, will do much to enhance the ability of biomass to mitigate fossil fuel consumption and GHG emissions.

2.4.2 ANIMAL BIOTECHNOLOGY

In addition to the on-farm applications addressed in previous sections, biotechnology is also being leveraged to improve the carbon efficiency of animal agriculture through genetic engineering of the animals themselves. The biotech AquaBounty salmon, for example, requires 25% less feed than traditional Atlantic salmon. The combination of lower inputs and a closed-loop, land-based production system that can be deployed much closer to U.S. customers is estimated to result in a carbon footprint that is 96% lower than traditional farmed salmon.[164]

Biotech tools are also being used to improve fertility, increase production efficiency, and reduce disease in cattle, swine and other animals, further reducing waste in animal production. Scientists in the U.S. are employing genomic tools to improve the ability of cattle to tolerate higher temperatures while maintaining their growth.[165] Heat stress, which is an increasing problem in the livestock sector due to climate change, limits the production of animal protein, and heat-tolerant cattle will be better able to maintain their production efficiency as temperatures increase. The genetic sequencing of dairy cattle has likewise led to efforts to improve the efficiency of milk production via genetic engineering.[166] Livestock are a major source of the potent greenhouse gas methane, causing improvements to the efficiency of protein and milk production to have an outsized impact on GHG emissions.

151 http://www.nass.usda.gov/Charts_and_Maps/Field_Crops/cornyld.php

152 http://www.nass.usda.gov/Charts_and_Maps/Field_Crops/soyyld.php

153 http://www.ers.usda.gov/webdocs/DataFiles/52096/Cropland_19452012_by_state.xls?v=26.3

154 http://www.fao.org/3/I9553EN/i9553en.pdf

155 http://www.fuelsinstitute.org/getattachment/Research/Biomass-Based-Diesel-A-Market-and-Performance-Anal/Biomass-Based-Diesel_Executive-Summary.pdf?lang=en-US

156 Ajjawi, I., Verruto, J., Aqui, M. et al. Lipid production in Nannochloropsis gaditana is doubled by decreasing expression of a single transcriptional regulator. Nat Biotechnol 35, 647–652 (2017). http://doi.org/10.1038/nbt.3865. http://www.nature.com/articles/nbt.3865

157 S.A. Ceasar, S. Ignacimuthu, Applications of biotechnology and biochemical engineering for the improvement of Jatropha and Biodiesel: A review, Renewable and Sustainable Energy Reviews, 15(9), 2011, 5176-5185, ISSN 1364-0321, http://doi.org/10.1016/j.rser.2011.07.039. http://www.sciencedirect.com/science/article/abs/pii/S1364032111002796

158 Shin, SE., Lim, JM., Koh, H. et al. CRISPR/Cas9-induced knockout and knock-in mutations in Chlamydomonas reinhardtii. Sci Rep 6, 27810 (2016). http://doi.org/10.1038/srep27810. https://www.nature.com/articles/srep27810

159 Paul D. Donohoue, Rodolphe Barrangou, Andrew P. May, Advances in Industrial Biotechnology Using CRISPR-Cas Systems, Trends in Biotechnology, 36(2), 2018, 134-146, ISSN 0167-7799, https://doi.org/10.1016/j.tibtech.2017.07.007. http://www.sciencedirect.com/science/article/abs/pii/S0167779917301877

160 http://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12566

161 http://onlinelibrary.wiley.com/doi/full/10.1111/pbi.12603

162 Doane Chilcoat, Zhan-Bin Liu, Jeffry Sander, Chapter Two - Use of CRISPR/Cas9 for Crop Improvement in Maize and Soybean, Editor(s): Donald P. Weeks, Bing Yang, Progress in Molecular Biology and Translational Science, Academic Press, Volume 149, 2017, 27-46, ISSN 1877-1173, ISBN 9780128117439, https://doi.org/10.1016/bs.pmbts.2017.04.005. http://www.sciencedirect.com/science/article/pii/S1877117317300650

163 http://www.forbes.com/sites/gmoanswers/2016/11/18/gmos-help-reduce-food-waste/#710a513943bc

164 http://aquabounty.com/sustainable/

165 http://www.digitaltrends.com/cool-tech/genetic-engineer-heat-resistant-cows/

166 http://www.wpr.org/how-we-produce-more-milk-fewer-cows

3 CLIMATE IMPACT ANALYSIS

3.1 ISSUES IN LCA FOR BIOTECHNOLOGY

Successfully mitigating the impacts of climate change will involve simultaneous transformational shifts across technology, policy and business. Effectively planning, managing and evaluating these shifts will require an equally profound shift in how we track and account for carbon. Life Cycle Analysis (LCA) is widely regarded as the most appropriate and effective way of evaluating the carbon impacts of products and processes in the complex, modern economy. LCA is an analytical technique in which all inputs, outputs and impacts of a product or process are tracked and accounted for through its full life cycle. This includes the materials used to make things, the energy and associated emissions from transporting and processing them, and what happens at the end of a product's useful life. LCA is especially important and complex when biological systems are involved, since they introduce a significant degree of uncertainty; external conditions, pathogens, or changes in surrounding ecosystems can all impact the productivity of any organism.

There are three main approaches to LCA: attributional LCA, consequential LCA and economic input-output (EIO) LCA. Attributional LCA focuses on the direct actions taken by a producer in order to make a product; all of the energy or materials consumed during production would be captured by an attributional LCA, for example. Consequential LCA, in contrast, focuses on comparing the world with the product in question to a hypothetical world without it; it not only captures all the materials used in production, but also how the product and its supply chains affect markets or other products. EIO LCA uses the flow of money through systems to estimate environmental impacts. For example, an EIO-LCA may use the average carbon emissions per dollar of revenue in the petrochemical industry to estimate the impacts of petrochemical inputs to other products. The accuracy of EIO LCA suffers because its impact-per-dollar estimates are, by necessity, industry averages or abstract estimates. It is best used for high level, market-wide estimates rather than evaluating individual products or services. Attributional LCA is simpler than consequential, especially for most manufacturing processes, but consequential LCA is widely viewed as a more accurate technique because it can account for indirect effects, such as those that occur because of changes in commodity prices or disrupted supply chains. Attributional LCA would overlook the impact of new strains of crop on agricultural markets, for example, whereas consequential approaches may be able to account for these.

The science of LCA has rapidly evolved over recent decades; however, a number of critical challenges remain pertaining to LCA in biotech:

Lack of Data on Critical Inputs or Processes - Like most modeling techniques, the results of an LCA are only as good as the input data. In many cases, critical elements needed to understand the impacts of a product or process are unavailable, due to insufficient fundamental research, protections on proprietary information, or changes in technology. One common example is that many biotechnological manufacturing systems use enzymes or catalysts. Data on the energy or materials used to make these inputs is typically considered proprietary business information, which renders many LCAs on biotech products uncertain, at best. In other instances, the only source of data on an industrial practice is extrapolated from textbooks or older research on the subject, often overlooking recent technological developments in the field.

Inadequate tracking of existing markets or systems - Consequential LCA's value derives largely from its ability to assess indirect effects. A common example of an indirect effect is Indirect Land Use Change (ILUC), which occurs when a system uses an agricultural product as its input, such as a biofuel made from soybean oil. While the biofuel itself may release little carbon during its production or use, the gallons of soybean oil which went into the biofuel would have otherwise been consumed elsewhere, such as in food products, animal feed or cosmetics. Those previous consumers must now find alternative sources of vegetable oil on the open market, driving up prices, which may result in clearing land to grow more oilseed crops. This land clearance is ILUC, the acres being cleared may not be used to produce biofuel, but they are cleared because of biofuel. Consequential LCA often requires tracking markets, land use, or behavior over a long period of time in order to establish "normal" behavior in that system; at present these data are often not collected, or are proprietary.

Multiple LCA Methods - LCA is at its heart a scientific exercise, but parts of it require subjective judgment, like decisions about how to define system boundaries or allocate impacts between multiple products. There may be multiple valid answers to these judgment questions. For example, in the U.S. almost all ethanol production takes in corn and produces ethanol as well as the solids left behind after processing, which are typically sold as a high-protein animal feed known as "distiller's grains". The question for LCA practitioners is how much of the energy used in the process is assigned to the ethanol product vs. the distiller's grains. There are several methods for doing this, such as assigning based on the relative mass, energy content or monetary value of each product, but there is no objectively right or wrong answer about which method should be selected; it's a judgment call. When true objectivity may be impossible to attain, consensus can be a reasonable substitute. Government, industry and academic stakeholders can mutually agree on answers to questions like this to ensure that at the very least, LCAs can be made on the basis of similar assumptions, so that they can be effectively compared against each other.

Ultimately, the analytical tools which support LCA will need to evolve in parallel with the biotech industry as it rises to meet the challenge of climate change. Industry groups can help support the continued development of LCA data by supporting basic research, agreeing to make more data on inputs and outputs from manufacturing available to researchers, and continuing to support and publish LCA studies of their products. Luckily, LCA shares a common characteristic of many sciences: as knowledge accumulates, future studies become easier and more powerful. Groups of companies that use similar processes to make a common product can aggregate their data together to publish industry averages for energy or materials use, thereby protecting their proprietary business information while improving analysts' ability to research. LCA data developed for one study is often used in subsequent ones; students who study real-world examples emerge better prepared to contribute in real-world work; and as more studies are published and critiqued, consensus emerges. While successfully mitigating climate change will require significant new investments in cleaner technologies and production systems, complementary investments must occur in evaluation and analysis of these systems to ensure that the LCA tools necessary to inform the next decades' decisions evolve as well.

Keys to Maximizing Biotech's Potential to Reduce GHG Emissions

- GHG accounting needs to be based on life cycle analysis, and include indirect effects such as ILUC. Industry groups can help by making data available to regulators and researchers; IP can be protected by aggregating or anonymizing the data.
- Most biotech solutions will require massive amounts of feedstock, finding ways to produce this more efficiently will always be useful.
- Using waste biomass to produce energy can make a real difference, but keeping organic carbon in solid form as long as possible maximizes GHG benefits.
- Biofuels may not be zero-carbon, but they can be very low carbon and the scale of transportation means making them sustainable and scalable is critically important.
- Carbon capture and sequestration will be necessary for success, but as a complement to reducing emissions, not a replacement.

3.2 GHG MITIGATION POTENTIAL ON NATIONAL (U.S.) SCALE

3.2.1 PRODUCING SUSTAINABLE BIOMASS FEEDSTOCK

Biomass is one key to decarbonizing the U.S. economy because it leverages the capacity of photosynthesis to remove carbon from the atmosphere and convert it to carbohydrates, which can be utilized for their embodied energy, carbon, or both. In theory, biomass can be a carbon-neutral resource, but in practice the situation is much more complex. Growing biomass, especially at commercial scales, typically requires fertilizer and other inputs which have associated emissions. Depending on how the land being used for biomass is treated, there may be additional sources, or sinks, of carbon in the soil. Understanding the emissions impacts of biomass across its full life cycle requires understanding the ecosystems, carbon and nutrient cycles at play where it's grown. Given the potential for biomass production to result in significant and unexpected emissions of carbon, a risk-averse approach is prudent, but the immense potential of biofuels, bioenergy and bioproducts argues in favor of utilizing these resources where available. While there is significant uncertainty around the emissions associated with any source of biomass, there are a few useful rules of thumb:

1. **Biomass can be low-carbon but is almost never zero-carbon.** While the carbon embodied in plant matter was taken from the atmosphere, and therefore has a minimal on climate change, there are numerous sources of climate-forcing emissions from fertilizer, irrigation, transport, processing and changes in the soil.
2. **Bio-based products can reduce GHG emissions when substituted for high-carbon ones, especially those relying on fossil fuels.** GHG reductions are realized when low-carbon bio-based products displace higher-carbon ones. Without that displacement, there is minimal environmental benefit. Substitution, by itself, is no guarantee of benefit, a few bio-based products are more carbon-intensive than their fossil equivalents.
3. **Alternative uses and indirect effects must be considered.** Accurately assessing biomass carbon emissions typically requires considering indirect effects like ILUC, as well as what would have happened in absence of the biomass production. A cultivation system may increase soil carbon, but should only be credited for these increases if this increase is greater than what would have happened otherwise.
4. **The labels "waste" and "residue" can be misleading.** In theory, wastes or residues have no value, and cause emissions from their use. In truth, many of these materials are used in some fashion, sometimes by sustainable bio-product systems, sometimes more traditionally, as animal bedding or returned to the soil; these uses must be considered.

Climate policy has largely overlooked emissions from agriculture to date, in part because of the complexity of the system and concern about financial impacts on farmers and rural communities. With new focus on sustainable and regenerative agriculture, however, a window of opportunity is opening to achieve a win-win scenario for agricultural producers: utilize the latest science to find opportunities to use agriculture as a tool to reduce emissions, and reward farmers for the carbon benefits they provide.

Agriculture in the U.S. emitted GHGs equivalent to about 658.6 million metric tons of carbon dioxide in 2018, roughly 10% of the U.S. total.[170] About 94% of this was emitted from agricultural soils or livestock (direct or "enteric" emissions from animals as well as manure management). Additional emissions come from the production of ammonia, which is a primary input for most fertilizers. With continued population growth as well as the emergence of the bioeconomy, the agricultural sector will be called upon to produce even more food, fodder, fiber and feedstock. Meeting this challenge while reducing emissions will require the rapid deployment of advanced biotechnology in several critical areas including:

Optimizing fertilizer use through new crop strains or increased nitrogen fixation.

Nitrogen is often a limiting factor in agricultural yields. The "Green Revolution," which massively increased agricultural production and allowed rapid population growth during the 20th Century, was largely facilitated by the development of the Haber Process for producing ammonia from natural gas. Ammonia production supports 50-75% of global fertilizer production and is responsible for more than 1% of global GHG emissions.[171] Removing biomass from fields, whether it's crops for consumption or residues for bioenergy, takes some of that nitrogen along with it, which must be replaced. Biotech can improve plants' efficiency at utilizing nitrogen, or adding genes from nitrogen-fixing organisms to allow them to produce their own. Using modern biotechnological tools to optimize the use of synthetic fertilizers allows growers to consume less of them, which could help U.S. farmers cut back on 15-20 million metric tons of carbon associated with its production, about as much as fueling 3-4 million cars for a year.[172]

Reducing nitrous oxide emissions from soil

Nitrogen fertilizers enhance plant growth, but many soil microbes convert fertilizer nitrogen to nitrous oxide (N2O), a greenhouse gas up to 298 times more potent than carbon dioxide. In 2017, nitrous oxide emissions from agricultural soil accounted for 266 million metric tons of carbon dioxide equivalent in the U.S. Relatively low-tech interventions, such as using less volatile fertilizers and applying them more efficiently could reduce nitrous oxide emissions by 30-100 million metric tons annually.[173] Analyses of chemical inhibitors indicate a potential to cut nitrous oxide emissions by over 40%, and there are promising lines of research which would integrate production of these inhibitors into a plant's root system.[174] By combining all of these approaches, nitrous oxide emissions could be reduced, by well over 150 million metric tons of carbon equivalent, or as much as shutting down 32 U.S. coal power plants for a year.

Enhancing soil carbon retention through expanded root growth

Despite its mundane appearance, soil is a complex and dynamic environment, in which carbon and nutrients enter and leave through multiple avenues and cycle through plants, animals, microbes and fungi. There are several promising approaches by which the soil carbon system could be encouraged to retain more carbon in solid form, rather than being decomposed and released to the atmosphere. Root growth is a major pathway for soil carbon accumulation, as plants take carbon from the atmosphere and convert it to solid plant matter, moving it underground as roots grow. Engineering crops to have larger and deeper root systems expands this pathway and could sequester carbon by 200 to 600 million metric tons per year if widely deployed, though this number is highly uncertain due to the relative immaturity of this technology.[175]

Reducing methane emissions from livestock

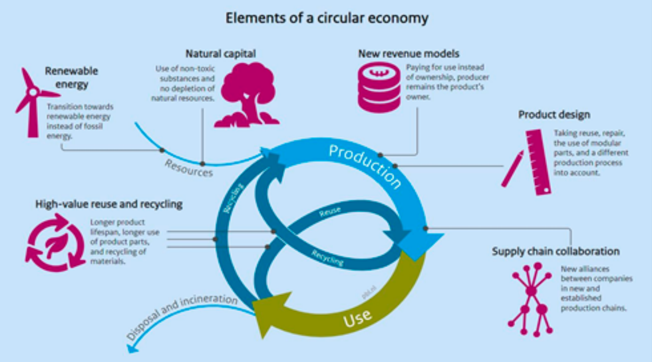
As population and incomes increase globally, so does the consumption of meat and dairy products. This leads to an increase in livestock numbers and the associated emissions. Livestock, especially cattle, are a major source of methane, from enteric sources (i.e. burps) as well as from decomposing manure. Several novel feed additives have been proposed which may be able to reduce the amount of methane emitted without negatively affecting animal health or reducing yields. DSM has announced a cattle feed supplement that claims to reduce methane emissions by 30%,[176] while other compounds under investigation - often derived from red seaweed - may be able to provide 80% reductions or greater in methane emissions.[177,178] While numerous technological and policy hurdles remain, widespread deployment of feed technologies like these could reduce emissions from livestock production by 50 - 140 million metric tons, or roughly one to three times the annual emissions from the state of Oregon.

3.2.2 EMPOWERING SUSTAINABLE PRODUCTION

Empowering Sustainable Production

Modern economies produce a staggering amount of things. From millions of printed silicon microcircuits in electronics to billions of tons of concrete and steel, production of physical objects is a hallmark of human society. As we seek to limit the damage caused by climate change, a new focus on sustainability must enter the conversation about how we make things. Luckily, advances in technology have presented a number of opportunities to do just this, by developing more efficient and lower-emission alternatives to traditional industrial techniques. Biotechnology can continue this process by leveraging the affinity biological processes have for working within a circular economy.

Green is the New Black



Elements of a circular economy. Source: PBL NETHERLANDS.[179]

Traditionally, once materials were extracted, their life was a one-way trip that ended in a landfill. As industries become more aware of the need to reduce emissions, it is becoming clear that reuse and recycling of materials and energy is an essential tool for sustainability. Biotechnology is well-positioned to succeed in a sustainable circular economy because it is built on a foundation of biological carbon cycling. Working with natural systems which have evolved to capture and re-use carbon and nutrients, biotechnology firms can expand these processes to commercial scale, replacing energy- and emission-intensive extractive industries with low-impact circular ones.

Turning Carbon into Products

U.S. industry emits over 800 million metric tons of carbon per year from the combustion of fossil fuels; at present almost all of this goes into the atmosphere, representing over one-eighth of national emissions. Numerous projects have already sought to demonstrate the feasibility of capturing this carbon and sequestering it underground, or using it for enhanced oil production, but a number of innovative processes are emerging to use the carbon as a raw material for other products, including polymers, carbon fiber, chemicals, nanomaterials or fuels using a variety of methods. Conventional carbon capture systems can typically pull 80-90% of the carbon dioxide out of exhaust from combustion systems,[180] which means that there is a potential resource of hundreds of millions of tons of carbon dioxide which could potentially be used to make new products. The limiting factor will probably be the availability of processes to utilize the carbon and markets for the resulting products.

Bioplastics have been one of the first large-scale applications of biotechnology for the purpose of improving industrial sustainability. Dozens of alternative biobased polymers have entered the market, demonstrating the capacity to replace fossil carbon in a variety of applications and, in many cases, offering more sustainable recycling or reuse options than traditional equivalents. Around 1% of U.S. GHG emissions come from producing plastics. Switching from fossil-based plastics to corn-based biopolymers could reduce emissions by 0.6kg – 1.4kg of CO_2 per kilogram of plastic.[181] Widely applied, this could reduce emissions from plastic production by about 25%, totaling 16 million metric tons of CO_2 per year. Switching from corn to cellulosic feedstocks, like switchgrass, miscanthus, or corn stover could double the emission benefits.[183]

Organic Waste Utilization

Researchers and policy makers are becoming increasingly aware of the need to more efficiently use materials in industry. This is particularly true of organic waste, like food scraps, agricultural residue and un-recyclable wood products, because they not only require fertilizer and other inputs to make those materials, but as they decompose, also emit carbon dioxide or, worse, methane. Anaerobic digestion (AD) is a well-understood technology for converting organic waste into energy, while recovering nutrients that can be returned to the soil. When decomposition happens in the absence of oxygen, microbes convert organic waste into biogas -- a mixture of methane, carbon dioxide, water vapor and other trace components. This can be cleaned up to yield Renewable Natural Gas (RNG), which is mostly methane and functionally equivalent to fossil natural gas. AD produces not only this valuable product, but also solid digestate, which is very similar to compost and can be used as a beneficial soil amendment. By capturing the methane which would otherwise have been released into the atmosphere, AD further reduces the GHG footprint of organic waste disposal; in some cases the effect of preventing uncontrolled releases of methane can be so great that the resulting RNG is effectively carbon-negative, when evaluated by LCA.[180] Widespread deployment of RNG systems at landfills, wastewater treatment plants, livestock yards and other organic waste hotspots could displace enough fossil natural gas to offset 40-75 million metric tons of carbon dioxide emissions. Using agricultural residue or wood waste could add another 12-40 million metric tons, though these resources may have other competing uses in a low-carbon economy.[184]

Cleaner Buildings

There are opportunities to build sustainable, circular material cycles into more than just consumer products. Carbon can be pulled out of the atmosphere and used to make the very buildings, roads, and cities we live in. Wood, long thought of as a traditional building material, is enjoying new attention as a low-carbon solution for future construction. Since wood pulls carbon from the air as it grows, it represents a very stable and durable removal mechanism for atmospheric carbon, which will remain sequestered as long as the wood remains solid. Engineered wood products, including cross-laminated timber, fiber or polymer reinforced products, or wood composites can provide strength and durability previously thought possible only from metal. A recent study of engineered wood products found that they can reduce GHG emissions by 20% when substituted for fabricated metal, 25% for concrete and 50% for iron or steel. Engineered wood has been used to build several multi-story demonstration buildings to show that high-rise construction is possible without conventional materials. A five-story wood building stores about 26 lb of carbon per square foot.[185] With over 350 million square feet of multifamily housing constructed in the U.S. in 2019, the potential carbon savings could be substantial.[186]

Another opportunity to find uses for carbon dioxide is in cement, which is currently one of the largest sources of greenhouse gas emissions in the world and was responsible for over 40 million tons of emissions in the U.S.[187] Researchers have been investigating alternative formulations of cement, which utilize carbon dioxide during production or absorb it from the air as it cures. By integrating these techniques with renewable energy to power the process, it is possible to end up with carbon-neutral concrete turning some infrastructure projects into net carbon sinks.

3.2.3 DEVELOPING LOWER-CARBON PRODUCTS

If humanity is to successfully avoid the worst impacts of climate change, it will have to find lower-carbon substitutes for many of its most important products. No product exemplifies this challenge better than transportation fuel. The ready availability of reliable, high-speed transportation is a foundational element of life in the U.S.; it is the lifeblood of modern supply chains and personal lifestyle. The U.S. is by far the biggest consumer of oil in the world, consuming almost 20 million barrels of crude oil per day, and processing it through more than 130 refineries into a wide range of fuels and petrochemical products, most importantly gasoline and diesel.[188] The emissions from vehicle tailpipes, plus the production and refining of petroleum total over 1,900 million metric tons of carbon dioxide equivalent each year, almost 30% of the U.S. total or about as much as Germany and Japan, combined.[189]

Neither the U.S. nor any other nation can halt climate change while depending on petroleum to fuel its transportation system. There is no single solution to this problem, a full portfolio of tools is needed. Light-duty vehicles, like cars, trucks, and SUVs consume the majority of petroleum in the U.S.; there is consensus within the transportation research community that replacing these with battery electric vehicles, charged on a grid dominated by renewables or other carbon-free sources, will by the primary way of reducing these emissions, with mass transit and other measures also playing a role. Many of the medium and heavy duty vehicles, like box trucks, delivery vans and some tractor-trailers will also be powered by electricity from batteries, or possibly hydrogen fuel cells.[190] There are some types of transportation, however, for which energy-dense liquid fuels will be much harder to replace. Aviation is the biggest of these; the U.S. consumed over 18 billion gallons of jet fuel in 2019,[191] and while the industry will take some time to recover from the ravages of COVID-19, commercial air travel will continue to factor in global transportation. Some marine applications, long-haul trucking, military operations, backup and emergency power, and specialized vehicles may also need liquid fuels. The U.S. currently consumes around 15 billion gallons of ethanol per year, and around 2.5 billion gallons of biomass-based diesel substitutes including biodiesel and renewable diesel. The vast majority of ethanol is made from corn, while around ▯ of U.S. biomass-based diesel is made from soybean or canola oil, with the rest coming from waste oil or byproducts.[192]

Most of the biofuels currently used in the U.S. reduce carbon emissions when they displace petroleum fuels. Typical corn ethanol emits about 30% less carbon than gasoline, when the full life cycle of both products are considered, and typical biodiesel or renewable diesel from soybean oil reduces carbon by 40-50% over the full life cycle.[193] With domestic consumption of these fuels measured in the billions of gallons each year, these emission reductions represent millions of tons of avoided carbon. *The use of biofuels is estimated to have reduced U.S. transportation sector GHG emissions by 980 MMT CO2 from 2009-2020.[194] This is equivalent to taking roughly 16 million vehicles off the road, or 19 coal-fired power plants offline, for that 13-year period.[195]*

First-generation biofuels alone cannot meet the challenge of near-complete decarbonization by mid-century, but have achieved critical near-term reductions as other low-carbon transportation solutions are being developed; and they form an important technological foundation for the next generation of low-carbon fuels. The biotech industry can leverage its capacity to innovate to help advance biofuels in two main ways, reducing emissions from current production and developing zero, or near-zero carbon fuels.

Reducing Emissions From Existing Fuels

The U.S. fuel ethanol industry operates around 200 production facilities spread across the U.S., representing tens of billions of dollars in capital investment and thousands of jobs.[196] While corn-based ethanol may struggle to achieve the very low carbon levels needed in the long-term future, it has a critical role to play over the next few decades. As long as there is petroleum-based gasoline being consumed in the world, there will be value in producing a substitute that is 30% less carbon intensive; and the evidence suggests that the industry can reduce emissions even further. Driven in large part by the adoption of carbon intensity standards like California's LCFS, the ethanol industry has improved the efficiency of its facilities and found new ways to recover valuable co-products. Doubling down on these processes can continue to reduce emissions.

Improved efficiency of ethanol production facilities has reduced the energy inputs needed per gallon of output by a few percent per year,[197] and the industry has begun to utilize cellulosic processing technology to convert the previously indigestible corn kernel fiber into ethanol, increasing the yield from each bushel of corn by 3-4%. Improved crop yields and strains optimized for fuel production also help reduce the emissions associated with each unit of fuel. Incremental improvements like these seldom grab headlines, but on the scale of U.S. ethanol production, they add up. Each 1% improvement in average carbon intensity, across the entire U.S. ethanol industry results in around *800,000 metric tons* of avoided carbon dioxide emissions each year.[198] Similarly, there are opportunities to improve the efficiency of biodiesel and renewable diesel production, the latter of which anticipates almost a six-fold increase in U.S. production capacity over the next five years.[199] More efficient catalysts and purification systems can reduce the need for energy or reagent inputs, driving GHG emissions down even further. If the U.S. renewable diesel industry grows as anticipated, each 1% improvement in efficiency yields around *170,000 metric tons* of avoided emissions each year.[200]

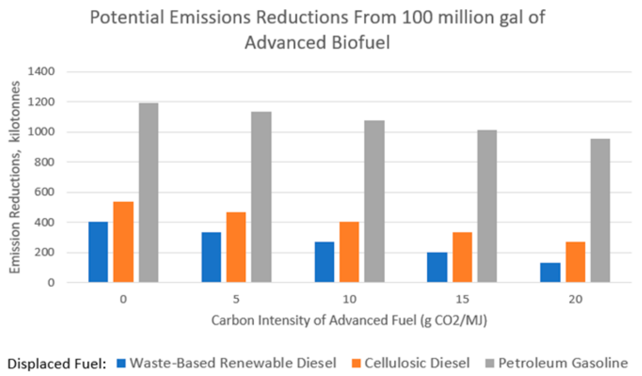


Figure 2: Each 100 million gallons of advanced, low carbon biofuel has the potential to displace as much as one million tonnes of carbon, if it displaces petroleum fuels, or over 200,000 tonnes if it displaces current-generation biofuels. Source: California Air Resources Board.

Developing Zero or Near-Zero Carbon Fuels

Decarbonizing transportation will require a new generation of fuels. Cellulosic biofuels, which use inedible plant matter as their feedstock, offer the potential for much deeper reductions in carbon emissions.[201] Cellulosic biofuels have been on the horizon for many years, but technological and supply chain challenges sank several early projects. A new wave of cellulosic production facilities, promising 60-80% lower emissions than conventional fuels are under development and if early projects are successful, could be the start of a new, multi-billion gallon per year industry. One key difference between the first wave of cellulosic production facilities and this one is that rather than breaking down cellulose into sugars and fermenting them into ethanol like you would with starch, these facilities use heat to convert biomass into a gas, or light oils, then process those into finished fuels. There are numerous opportunities to further refine the process, however, by making more selective and durable catalysts, or providing feedstock which improves yields, is more easily handled or requires less pre-treatment.

Algae or other microbes may offer the greatest potential to deliver fuels that approach or achieve carbon neutrality. Algae can be grown using wastewater or even exhaust gas as their primary source of nutrients and can be tailored to produce highly desirable oils or carbohydrates at extremely high theoretical yields. Attempts to scale these systems up have run into problems with pathogens, competition from wild microbes and finding efficient methods to separate desired products from water and cell mass. If algal fuels, or other advanced synthetic fuels could be commercialized, they offer the potential for billions of gallons of a product that is compatible with existing vehicles and infrastructure. Figure 2, shows the potential emissions reductions from 100 million gallons of a hypothetical advanced fuel, at various carbon intensities.[202] Depending on what it displaces, the *emissions benefits could be a few hundred thousand to over one million metric tons each year*

3.2.4 ENHANCING CARBON SEQUESTRATION

Enhancing Carbon Sequestration

Drastically reducing carbon emissions is necessary if humanity is to avoid the worst effects of climate change, but more will be needed. Almost every model of a successful stabilization of temperatures includes a large amount of carbon dioxide removal from the atmosphere, through enhanced plant growth and CCS. Figure 3 shows results from the IPCC 5th assessment report regarding global carbon emissions trajectories that preserve a hospitable climate. Each line represents one simulation of the future in which average temperature increase is kept below 1.5°C (the graph for a 2°C outcome looks quite similar). In every case, net emissions must not only be reduced to zero, but the world will need to rapidly remove carbon from the atmosphere over the second half of this century.[203] Biotech can provide crucial tools to help this effort.

It is difficult to estimate how much of an impact carbon capture might have on the climate system of the future; in some ways the sky is really the limit since

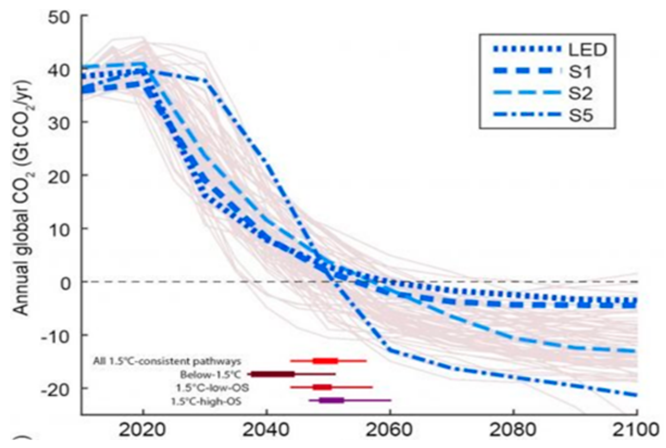


Figure 3: Source: IPCC 5th Assessment Report

there is certainly no shortage of carbon dioxide in the atmosphere to remove. Accelerated R&D and rapid deployment of demonstration projects will be necessary to identify and prove the capabilities of the many technological options which could contribute.

Bioenergy with Carbon Capture and Sequestration (BECCS)

Many of the most promising concepts for scalable carbon sequestration rely on photosynthesis to do the actual capturing of carbon dioxide, which can then be used or stored. One of the most promising is BECCS, which uses the biomass from plants to produce fuels or energy, storing carbon along the way. There are many proposed models for BECCS, from burning biomass in conventional power plants and capturing carbon from the exhaust, to gasification systems which leave behind carbon-dense biochar that can be used as a carbon-sequestering soil amendment. The energy or fuels produced by these systems would also help displace fossil fuels, providing a double climate benefit. A recent analysis estimated that, by 2040, BECCS could cost effectively remove over *700 million metric tons of carbon per year,*[204] or more than half the emissions from all U.S. coal power plants, though doing so would require a massive amount of sustainable biomass feedstock to be produced.

Sequestration in Natural and Working Lands

Natural ecosystems have been sequestering carbon for millennia without human assistance and should not be overlooked as a method of removing carbon from the atmosphere. The main mechanism of sequestration is through the growth of roots in the soil, accumulation of fallen organic matter, or the accumulation of organic matter at the bottom of oxygen-poor bodies of water. Most biomass decomposes or is consumed by animals but some, especially the hard-to-digest fibrous parts of plants composed of lignin and cellulose, remains in solid form for decades or more and is integrated into soil. Human encroachment on natural lands and climate change are affecting most natural ecosystems, often disrupting this process; but careful intervention, through things like managed replanting, selective breeding for sequestration potential, soil amendments such as compost or biochar, selective harvest and prescribed fire can increase the rate of carbon sequestration and build healthy, resilient ecosystems. The National Academies concluded that enhanced management of forests could sequester anywhere from a few hundred pounds to over a ton of carbon per hectare annually;[205] widely deployed this could result in sequestration of *100 million metric tons of carbon per year, with an additional 150 million metric tons possible through expanding forested areas,* this would be like taking 20 to 50 million cars off the road.

Enhanced Weathering

While the majority of carbon removal from the atmosphere is done by plants, it is not the only mechanism. Certain types of mineral like olivine, serpentine and basalt will react with carbon dioxide to form stable carbonate minerals in a process known as "weathering". This mechanism has been largely responsible for mitigation of high atmospheric CO2 concentrations in prehistoric times. Unfortunately, it is naturally quite slow, suited for geological rather than human time scales; but there are ways that it might be accelerated and scaled to help address the climate crisis. Olivine and serpentine are often found in discarded mine tailings or asbestos formations; basalt can often be found in geologically active areas, where geothermal power plants may be active. By managing air flow, moisture and pH levels in these sites, the rate of carbon uptake could be substantially increased. Adding catalysts, or microbial agents could increase the potential even further.

Direct Air Capture

Most carbon capture systems rely on natural processes to remove carbon from the atmosphere, but new innovative approaches may offer the opportunity to cut out the intermediate step. Several processes are being tested that use chemical solvents, such as amine or carbonate solutions, to absorb CO2 from the atmosphere, and release it into a containment system, resulting in pure CO2 that can then be sequestered underground or used to make products. Since CO2 is only a few hundred parts per million in the atmosphere, this process requires a lot of surface area and usually uses heat to regenerate the solvent solution. This can make these systems bulky and energy-intensive. By developing more effective and durable solvents, or lower-energy regeneration processes, these systems could be made cheaper and more scalable. The upper limit of potential for these systems depends on how optimistic one is about the rate at which they will improve their energy and cost efficiency. Studies have projected the impact of direct air capture at anywhere from a few hundred million tons to more than half of today's global CO2 emissions.[206]

170 http://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf

171 Green Chem., 2020,22, 5751-5761. https://doi.org/10.1039/D0GC02301A. http://pubs.rsc.org/en/content/articlelanding/2020/gc/d0gc02301a#!divAbstract

172 Estimate based on EPA GHG emission inventory. Quantification is imprecise because emissions from energy consumption during ammonia production are aggregated with multiple other uses.

173 http://ec.europa.eu/environment/enveco/climate_change/pdf/nitrous_oxide_emissions.pdf

174 Norton Jeanette, Ouyang Yang, Controls and Adaptive Management of Nitrification in Agricultural Soils, Frontiers in Microbiology, 10, 2019, DOI.10.3389/fmicb.2019.01931, ISSN=1664-302X. http://www.frontiersin.org/articles/10.3389/fmicb.2019.01931/full

175 http://arpa-e.energy.gov/sites/default/files/documents/files/Revised_Final_Report_to_ARPA_Bounding_Analysis.pdf

176 http://www.dsm.com/corporate/markets/animal-feed/minimizing-methane-from-cattle.html

177 Roque BM, Venegas M, Kinley RD, de Nys R, Duarte TL, Yang X, et al. (2021) Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 percent in beef steers. PLoS ONE 16(3): e0247820. https://doi.org/10.1371/journal.pone.0247820. http://www.biorxiv.org/content/10.1101/2020.07.15.204958v1.abstract

178 Breanna M. Roque, Joan K. Salwen, Rob Kinley, Ermias Kebreab, Inclusion of Asparagopsis armata in lactating dairy cows' diet reduces enteric methane emission by over 50 percent, Journal of Cleaner Production, 234, 2019, 132-138, ISSN 0959-6526 https://doi.org/10.1016/j.jclepro.2019.06.193 http://www.sciencedirect.com/science/article/abs/pii/S0959652619321559

179 http://themasites.pbl.nl/o/circular-economy/

180 http://doi.org/10.1155/2014/828131. https://www.hindawi.com/journals/tswj/2014/828131/

181 Environ. Sci. Technol. 2016, 50, 6, 2846–2858. https://doi.org/10.1021/acs.est.5b05589. http://pubs.acs.org/doi/10.1021/acs.est.5b05589

182 Daniel Posen et al 2017 Environ. Res. Lett. 12 034024. http://iopscience.iop.org/article/10.1088/1748-9326/aa60a7. It should be noted that this study found greater GHG benefits from plastic production using renewable energy than feedstock conversion, however these are not mutually exclusive.

183 http://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

184 http://gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/

185 http://www.pik-potsdam.de/en/news/latest-news/buildings-can-become-a-global-co2-sink-if-made-out-of-wood-instead-of-cement-and-steel

186 http://www.census.gov/construction/chars/highlights.html

187 http://www3.epa.gov/ttnchie1/conference/ei13/ghg/hanle.pdf

188 http://www.eia.gov/petroleum/refinerycapacity/

189 https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-invntory-2020-main-text.pdf

190 http://www.caletc.com/assets/files/ICF-Truck-Report_Final_December-2019.pdf

191 http://www.transtats.bts.gov/fuel.asp?pn=1

192 http://www.eia.gov/biofuels/update/

193 Based on CARB default values under the LCFS. It should be noted that the GHG reductions from current biofuels are uncertain and the subject of considerable debate, the values presented here are conservative estimates. http://ww2.arb.ca.gov/resources/documents/substitute-pathways-and-default-blend-levels-lcfs-reporting-specific-fuel

194 Unnasch. S.and D. Parida (2021) GHG Reductions from the RFS2–A 2020Update. Life Cycle Associates Report LCA.LCA.6145.213.2021 Prepared for Renewable Fuels Association. http://ethanolrfa.org/wp-content/uploads/2021/02/LCA_-_RFS2-GHG-Update_2020.pdf.

195 http://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

196 http://www.eia.gov/petroleum/ethanolcapacity/

197 Flugge, M.; Lewandrowski, J.; Rosenfeld, J.; Boland, C.; Hendrickson, T.; Jaglo, K.; Kolansky, S.; Moffroid, K.; Riley-Gilbert, M.; andPape, D., "A Life-Cycle Analysis of the Greenhouse Gas Emissions of Corn-Based Ethanol" (2017).Publications from USDA-ARS /UNL Faculty. 1617.http://digitalcommons.unl.edu/usdaarsfacpub/1617. https://www.researchgate.net/profile/Marybeth_Riley-Gilbert2/publication/312621455_A_Life-Cycle_Analysis_of_the_Greenhouse_Gas_Emissions_of_Corn-Based_Ethanol/links/5894ba9e4585158bf6e95397/A-Life-Cycle-Analysis-of-the-Greenhouse-Gas-Emissions-of-Corn-Based-Ethanol.pdf

198 Based on an assumed 15 billion gallon ethanol industry and 68 g CO2e/MJ average carbon intensity for finished ethanol, a value representative of typical Midwest corn ethanol production.

199 http://adi-analytics.com/2020/02/10/regulations-to-drive-u-s-renewable-diesel-capacity-growth-through-2025/

200 Based on an assumed 2.5 billion gallon per year renewable diesel industry and 54 g/MJ carbon intensity for finished renewable diesel, a value representative of current soybean oil based production.

201 Murphy, Colin W., and Alissa Kendall. "Life Cycle Analysis of Biochemical Cellulosic Ethanol under Multiple Scenarios." GCB Bioenergy, vol. 7, no. 5, May 2015, pp. 1019–1033, doi:10.1111/gcbb.12204. http://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12204.

202 Based on typical carbon intensities of fuels under the LCFS as reported in: http://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/current-pathways_all.xlsx

203 Source: IPCC Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development, Figure 2.5. http://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf

204 http://www.ornl.gov/news/bioenergy-carbon-capture-combo-could-cost-effectively-mitigate-carbon-dioxide

205 http://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda

206 Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). http://doi.org/10.1038/s41467-019-10842-5. https://www.nature.com/articles/s41467-019-10842-5

4

BARRIERS TO ADOPTION AND POLICY PROPOSALS

4.1. FINANCING BARRIERS

Biofuels and bioproducts have historically faced a major commercialization hurdle in the form of access to financing. Biotechnology products that are intended to reduce GHG emissions must necessarily compete with fossil fuels that supply a well-established refining and petrochemicals production infrastructure. Whereas this fossil infrastructure is often decades old and has often been fully paid off by its owners, biotechnology products require investment in either new infrastructure or large-scale retrofits of existing infrastructure. These investments can be very expensive, with one review of announced commercial-scale cellulosic biofuel projects finding capital costs to be approximately $11/gallon of installed production capacity.[207] With the exception of large, established companies, few new producers have ready access to this amount of capital, necessitating that they access the capital markets through lenders and/or investors.

Private sources of capital generally require a demonstration that a biotechnology project can achieve certain levels of profitability in the form of a "hurdle rate" before providing access to financing. Biobased fuels and products compete with fossil fuels and products for market share, and the market value of the former operates as a function of the latter as a result. On occasion this has been advantageous for biotechnology products, such as when fossil fuel prices rose sharply in 2007-08. The steady decline of fossil fuel prices that has occurred over the last decade in response to increased unconventional production of natural gas and petroleum in the U.S. has made it more difficult for biotechnology products to obtain the necessary hurdle rates for financing, however, even as climate change has become an important concern for American consumers.[208] Likewise, the immediate financial incentive to make investments in energy efficiency and other marginal reductions to GHG emissions is limited when energy costs are low.

A challenge faced by biofuels and bioproducts is that many of the advantages that they offer over fossil fuels are not reflected in their market value. For example, in addition to the GHG emissions reductions discussed above, many biotechnology products achieve low levels of other types of pollution such as particulate matter emissions, sulfur emissions, water contamination, and toxic waste production compared to fossil fuels. These reduced impacts on human health and the environment have a clear monetary benefit in the form of reduced spending on medical services, environmental remediation, recovery from extreme weather events, etc.[209] Moreover, biotechnology provides the ability to reduce GHG emissions and other forms of pollution across a variety of economic sectors, including agriculture, manufacturing, and transportation. Such benefits are not reflected in the market value of the biotechnology products, however, placing them at a competitive price disadvantage to fossil fuels.

Governments have sometimes enacted policies that cause the benefits of biofuels and bioproducts to be reflected on the marketplace, either by subsidizing those biotechnology products that have reduced impacts on human health and the environment or by increasing the cost of fossil fuels (see Section 4.3). Some, such as California's LCFS, have prompted rapid growth in the use of biofuels by subsidizing biofuels, especially those from 2nd-generation feedstocks, based on the degree to which they reduce transportation GHG emissions.[210] The LCFS recently expanded to provide support for CCS; when combined with Federal 45Q tax credits, this can offer over $150/tonne of total incentive for project developers.[211,212] Government incentives in the U.S. have not always been sufficient to make biotechnology products competitive with inexpensive fossil fuels, though: one recent analysis calculated that new cellulosic biorefineries would struggle to be financially viable despite the presence of supporting federal policies because of the low fossil fuel prices that have prevailed since 2014.[213] Producers of biotechnology non-fuel products, for which government support mechanisms are fewer, have also faced high hurdles to private financing.

Some producers of U.S. biofuels and bioproducts have been able to obtain public financing in the form of loans, loan guarantees, and grants from the federal and state governments. The U.S. Department of Agriculture offers loan guarantees of up to $250 million for the building of capacity for the production of specific biotechnology products including advanced biofuels and biobased chemicals.[214] The loan guarantee program was started in 2008 to enable financing of advanced biofuels and was expanded in 2014 to cover other bioproducts as well. The loan guarantee reduces the barriers to obtaining private financing by having the U.S. government backstop qualifying loans to producers. While this backstop does not guarantee private financing for the facility, it substantially reduces the producer's financing hurdle rate by reducing the risk of default on any loan covered by the guarantee. Several states operate their own direct loan and loan guarantee programs for biorefineries, albeit on a smaller scale.[215]

Grants are another public finance mechanism that has supported the commercialization of biotechnology. Unlike direct loans and loan guarantees, grants are one-time awards of financing that are not repaid. The awards generally involve smaller amounts of financing than are provided via direct loans and loan guarantees, and they have often been used to support R&D or make improvements to existing facilities rather than to build a new commercial-scale facility. One example is the Value Added Producer Grants program administered by the U.S. Department of Agriculture, which "helps agricultural producers enter into value-added activities related to the processing and marketing of new products.[216] Other grants indirectly support the establishment and commercialization of biofuels by being directed toward the upgrading of infrastructure that is downstream of production facilities and improving consumer access.

The private and public capital that has been invested into biobased fuels and products has spurred the commercialization of low-carbon technologies since the turn of the century. Investments have fallen far short of what is necessary to avert catastrophic climate change, however, reflecting the major hurdles to financing that still exist within the biotechnology industry. The IPCC estimates that $2.4 trillion in annual investment is needed globally in the energy sector alone until 2035 to limit temperatures to no more than 1.5°C above pre-industrial levels.[217] This number is larger still if the decarbonization of non-energy sectors such as agriculture and materials are accounted for. Actual global low-carbon energy investment in 2019 was only $0.6 trillion, or 25% of what is needed.[218] Additional policy mechanisms will be required to rapidly reduce existing hurdles to the financing of biobased projects. Governments will also need to reduce the regulatory barriers that these projects face, as unfavorable regulatory environments increase the financial risks that they bear and their hurdles to financing.

4.2. REGULATORY BARRIERS

The biotechnology industry plays an important role in developing and commercializing novel products that are not always directly compatible with the existing infrastructure in the sectors into which they are introduced. Moreover, many of these products are manufactured using technologies such as gene editing that are closely regulated by national governments. These factors have resulted in the formation of multiple regulatory barriers that hinder the adoption of low-carbon biofuels and bioproducts and constrain the biotechnology industry's ability to reduce emissions of GHGs and other pollutants.

Biotechnology Regulation

GMOs have had a long and contentious regulatory history in the U.S. Since 1986, biotech products in the U.S. have been regulated under the Coordinated Framework for the Regulation of Biotechnology (Coordinated Framework).[219] The framework has been updated several times since its introduction, including a comprehensive revision in May 2020, known as the Sustainable, Ecological, Consistent, Uniform, Responsible, Efficient (SECURE) rule, or Part 340 rule, which significantly streamlined and modernized the regulatory framework.[220] While U.S. regulators and consumers are relatively accepting of GMO products, societal opposition to the use of GMOs in the agriculture sector in particular has, on occasion, prompted a cautious response to new GMO products by regulators that has slowed the introduction of biotech products to the market.

Regulations in other regions, such as Europe, are more hostile,[221] hampering the ability of the U.S. biotechnology market's products to make an outsized contribution to global GHG emission reductions. For example, as discussed in Section 1.4, GMO food crops have enhanced resiliency under the types of extreme weather conditions that are becoming more common as the climate changes, thereby reducing the amount of land required by agriculture and reducing the incentive to increase GHG emissions via land-use change.

Studies have found that Americans, including those residing in states with large agricultural sectors, have concerns about the production of bioenergy from GMO feedstocks as well.[222] Some 2nd-generation bioenergy feedstocks have attracted opposition due to their use of fast-growing and potentially invasive forms of biomass. These feedstocks, especially those that have been genetically engineered to expand rapidly, have prompted concerns that they could expand into and damage the surrounding ecosystem.[223] Notably, though, biotechnology has also provided a means of potentially overcoming this barrier. In one recent research breakthrough, microalgae grown as a biofuels feedstock has been genetically engineered to be unable to survive outside of the production facility, thereby preventing its uncontrolled growth.[224]

Genetically engineering microorganisms used in the production of fuels, chemicals and other products are also subject to federal regulation, but their place in the Coordinated Framework has long been unclear, and GE microbes were not clearly addressed in the SECURE rule. This regulatory uncertainty is likely to present a significant barrier to the development and commercialization of biotech climate innovation.

Regulation of Fuels and Products

A second major regulatory barrier is posed by conflicting state policies on certain biotechnology products. While the U.S. has a comparatively more integrated common market than the European Union, individual state governments sometimes have policies in place that discourage the introduction of biotechnology products into entire regions, let alone individual markets. This situation can prevent the adoption of products that have interstate supply chains. One example that is already occurring involves the transport of renewable diesel through existing refined fuels pipelines. Renewable diesel is a drop-in biofuel that can utilize cost-effective distribution infrastructure such as the refined fuels pipelines that connect refineries to multiple states' markets (e.g., the Colonial Pipeline in the Southeastern U.S.). Many states require that the biofuels content of fuels retailed within their borders be stated on a fuel pump label, but this is not easily known if the renewable diesel is being pipelined in a blended form with diesel fuel. The result is that having even a single state on an interstate pipeline with strict pump labeling requirements can discourage the movement of a drop-in biofuel such as renewable diesel through it. The biofuel must instead be transported by rail, ship, or truck, all of which are more expensive and polluting options than pipeline.[225]

Biotechnology products that are not compatible with unmodified existing infrastructure often face a heightened regulatory barrier. U.S. ethanol consumption has historically been constrained by the so-called "ethanol blend wall", which refers to the maximum blend that can be used in existing infrastructure. Ethanol is a hydrophilic fuel that is miscible with water, and this trait prevents its movement through pipelines at any blend rate and use in unmodified engines above specific blend rates due to the potential for water contamination. Ethanol blends for use in unmodified engines were limited to 10% by volume (E10) until 2011, when the U.S. government began to allow blends of up to 15% by volume (E15) during certain seasons of the year.[226] The unrestricted sale of E15 was not permitted until 2019.[227] The blend limits apply to ethanol whether produced from corn or lignocellulosic biomass, and the blend wall sharply constrained fuel ethanol demand from all feedstocks beginning in 2013 as a result.[228]

The U.S. government has also used regulatory changes to restrain demand for all biofuels since 2017. National biofuels demand over the last decade has been driven by the revised Renewable Fuel Standard (RFS2), which mandates the annual consumption of specific volumes of different types of biofuels. Petroleum refiners are tasked with ensuring that sufficient quantities of biofuels are blended with refined fuels to comply with the mandate, and a refiner's individual blending quota is determined by its market share. Between 2017 and 2019 the federal government greatly increased the number of hardship waivers that it awarded to refiners, reducing their blending quotas and overall demand for biofuels under the mandate.[229] One analysis calculates that the increased number of hardship waivers awarded caused demand for advanced biofuels under the mandate to be up to one billion gallons lower per year, and that the amount of the annual reduction has equaled as much as 50% of U.S. production.[230]

Regulatory barriers can be particularly high for truly novel biotechnology products due to a lack of suitable regulatory frameworks. Cultured meat, for example, has been identified as one product for which existing U.S. regulations are inadequate due to the existence of myriad production techniques and the potential for genetic modification as part of the production process.[231] Regulatory uncertainty is as much of a barrier as adverse regulation is, inasmuch as both discourage financiers from providing the capital necessary for commercialization. The lack of an adequate regulatory framework also raises the possibility that adverse regulation could result from a regulatory rulemaking process.

The future growth of the U.S. biotechnology industry will be heavily affected by existing and potential regulatory barriers. One recent analysis estimated that 50% of the total economic impact of biotechnology over the next decade "could hinge on consumer, societal, and regulatory acceptance" of the industry's products.[232] The analysis further calculated that this amount increases to 70% over the next two decades. This has important implications for the ability of biotechnology to provide climate solutions given that early emissions reductions are more valuable than later reductions. The continued presence of regulatory hurdles is an especially pressing issue given the major shortfall of decarbonization investments (see Section 4.1).

4.3. POLICY PROPOSALS

The growing recognition by many U.S. policymakers that existing efforts to decarbonize the country's economy are falling short of its commitments under the 2015 Paris Climate Agreement has led to the unveiling of a variety of climate policy proposals at the federal, state, and local levels of government. These proposals fall into two broad categories: the first category focuses on the decarbonization of individual sectors while the second category instead takes an economy-wide approach. The sector-based proposals are similar to policies already in place in states such as California, whereas the economy-wide proposals are more novel and less well established. An aggressive combination of sector-based and economy-wide policies is needed to rapidly realize the full potential of biotechnology to combat climate change.

4.3.1 DECARBONIZING TRANSPORTATION

The first two decades of the 21st century saw the introduction of several policies to reduce the carbon intensity and GHG emissions of the transportation sector. Some, such as federal RFS2 and California LCFS, were successfully implemented and have resulted in the partial decarbonization of the on-road transportation sectors in their respective jurisdictions through the increased use of biofuels. But regulatory implementation of these policies has, particularly in the case of RFS2, limited their impact. *Barriers to the full implementation of existing federal renewable fuels policies should be removed and aggressive follow-on transportation sector climate policies adopted to achieve the maximum near-term and longer-term GHG reductions.*

Renewable Fuel Standard

The continued presence of the RFS2 as the centerpiece of U.S. transportation sector decarbonization efforts has had an important impact on the development of intermediate-term GHG emission reduction strategies, with cumulative reductions of 980 MMT CO2 since RFS2 was enacted.[233] But a series of EPA regulatory actions has substantially limited the program's climate gains. The agency has repeatedly reduced RFS volume obligations and has issued a growing number of small refinery waivers, further reducing the market for biofuels in the U.S.[234]

EPA has taken some steps to expand U.S. biofuels markets. The ongoing effort to expand the volume of ethanol permitted by the ethanol blend wall is one example of this trend (see Section 3.2). Following on earlier efforts to ease restrictions on E15 consumption, in 2020 the Trump Administration announced that the federal government would not block the use of E15 in fuel pumps that were compatible with E10 (although state governments are still able to do so).[235] The complete replacement of E10 consumption by E15 would increase the amount of fuel ethanol consumed in the U.S. by 50%. While the magnitude of the associated transportation sector emissions reduction would depend on the feedstocks being used, any increase to E15 consumption would contribute to the sector's decarbonization. *Additional actions to expand U.S. biofuel markets and establish greater RFS program certainty are needed to maximize near-term climate gains.*

Low Carbon Fuel Standard

The success of California's LCFS and a lack of federal action on climate policy after 2016 has prompted similar policies to be proposed in other states. Oregon adopted a LCFS under its Oregon Clean Fuels Program that mandates a 10% reduction to the carbon intensity of its transportation sector from 2015 levels by 2025.[236] Efforts to implement a statewide LCFS in neighboring Washington are ongoing despite the failure of an earlier attempt.[237] Similar regional initiatives have been proposed in the Midwest[238] and East Coast,[239] although legislative action on these proposals has yet to occur.

Efforts to implement a national LCFS date to 2007, when then-U.S. senator Barack Obama introduced a bill to require future reductions to the carbon intensity of the U.S. transportation sector.[240] While that proposal was ultimately discarded in favor of legislation that created the RFS2, the U.S. House Select Committee on the Climate Crisis recently recommended that the RFS2 be transformed into a national LCFS.[241] That recommendation also included a provision to expand the remit of the RFS2 to include shipping and aviation fuels, in addition to on-road transportation fuels, as part of the transformation. The success of California's LCFS and steps by other states to adopt similar programs suggests *the time has come for a federal low-carbon fuel standard.*

Other Fuel Policies

In addition to market-driving programs such as the RFS and LCFS, ongoing federal and state investments in the improvement of existing biofuels and the development of next-generation biofuels are recommended to achieve the greatest near-term climate benefit. *Robust federal investment in biofuel research and development at the U.S. Department of Energy and USDA and long-term tax credits or other incentives for private-sector biofuel research and development and facility construction are recommended to help drive additional private sector investment in low-carbon fuels.*

4.3.2 DECARBONIZING INDUSTRY

Policy has historically favored the production of biofuels over other forms of biobased products. Renewable chemicals and other non-fuel biobased products that achieve GHG emission reductions, such as those described in Section 2, will need to be supported if sectors outside of transportation are also to be successfully decarbonized. Several potential mechanisms exist for achieving this result, some of which build upon existing policy frameworks and others that employ more novel approaches.

Renewable Chemical and Biobased Product Programs

The U.S. government operates two important Farm Bill Energy Title programs, the BioPreferred Program and the Biofinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program, that support the commercial development of renewable chemical and biobased product manufacturers. These producers continue to face substantial hurdles to commercialization due to the lack of an even playing field with producers of competing products from fossil fuels.

The BioPreferred Program, originally authorized under the 2002 farm bill and reauthorized and expanded under the 2018 farm bill, includes a federal biobased product procurement preference program and a voluntary USDA labelling program for biobased products.[242] These programs have significantly increased both consumer awareness and market demand for biobased products. The 2018 farm bill provided increased funding for BioPreferred and, among other provisions, directed USDA and the Department of Commerce to develop North American Industry Classification System (NAICS) codes for renewable chemicals and biobased products.[243] The 2020 National Academies of Science report on "Safeguarding the Bioeconomy" cites the lack of an industry classification system for biotech products as a significant roadblock to investment and broader adoption, and recommends a series of actions to fill this gap.[244]

The Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program (BAP) provides loan guarantees for the development, construction, and retrofitting of commercial-scale biorefineries.[245] The 2018 farm significantly expanded and streamlined the BAP loan program.

The Commerce Department and USDA should move swiftly to implement biobased product classification systems, and Congress should fully fund BioPreferred and the BAP loan program.

Tax Policy

Tax policy has been a vital early driver of biofuel and other renewable energy development. Several recent policy proposals seek to provide a similar push to non-fuel biobased products. A proposed change to federal tax law would enable producers of biobased products to utilize the Master Limited Partnership pass-through tax structure that is widely employed by fossil fuel producers to improve access to capital and reduce tax burdens.[246] Such an expansion has been employed in the past in the U.S. to support the development of renewable electricity and biofuels logistics infrastructure, making its absence in the biobased products sector particularly notable. Federal legislation to expand existing business-related and investment tax credits to include renewable chemicals production has also attracted bipartisan support in Congress,[247] although it has yet to become law.

U.S. tax policy should be updated to extend renewable energy tax incentives to renewable chemicals and biobased products.

4.3.3 DECARBONIZING AGRICULTURE

One of the most important mechanisms available to leverage biotechnology for climate mitigation is agriculture policy. As discussed in section 2, the carbon intensity of industrial products is highly dependent on the carbon intensity of feedstocks. Substitution of biobased feedstocks for fossil feedstocks is an essential step, but the greatest gains are achieved when climate objectives are integrated into the production of the feedstocks themselves, internalizing the environmental benefits that are provided by producers of biobased products, especially those that operate within the agricultural sector.

One such proposal would expand Farm Bill programs such as the Conservation Stewardship Program, which encourages producers to undertake conservation activities on working lands,[248] to include practices that decrease the carbon intensity of agricultural production while increasing crop yields. Likewise, the existing section 45Q tax credit for certain CC&S technologies could be expanded to encompass the building of soil carbon in the U.S. agriculture sector.

The agriculture sector faces high barriers of entry to voluntary carbon credit programs that prevent their full carbon sequestration potential from being recognized. Federal legislation such as the Growing Climate Solutions Act of 2020 has been introduced as a means of enabling the private sector to overcome these hurdles,[249] but federal agencies could also provide additional support by expanding existing agricultural conservation programs and creating agricultural sequestration certification programs.

Congress and the White House should move swiftly to implement programs to reward farmers for reducing the carbon footprint of feedstock production and for capturing and sequestering carbon.

4.3.4 NEGATIVE-CARBON TECHNOLOGIES

To achieve agreed upon climate mitigation objectives, a major focus of climate policy must be investment in negative-carbon technologies. This will require policies that drive carbon capture, use and storage throughout the economy, including in agriculture and manufacturing. This should include sector-specific programs in each of these areas. *Climate policy should drive investment in agricultural biologicals, plant biotechnology and other biotechnologies to increase soil carbon sequestration and should reward microbial carbon capture and other biotechnologies for carbon removal and recycling.* Provisions for biological carbon capture and use in the section 45Q tax credit provide a template for inclusion of these technologies in future climate policy.

4.3.5 ECONOMY-WIDE CLIMATE PROGRAMS

The U.S. transportation and power sectors have been the primary focus of policymakers due to their large share of total U.S. GHG emissions (28% and 27%, respectively, in 2018).[250] Several states have adopted more ambitious long-term policies that require the full decarbonization of their economies by 2050, however, and the remaining sectors (industry, commercial/residential, and agriculture) will need to achieve future carbon intensity reductions greater than those that have been achieved by the power and transportation sectors to date if these policies are to be successful.

The first such state policy to be implemented was California's Global Warming Solutions Act of 2006, which mandated an economywide emission reduction of 80% by 2050.[251] In 2018 California's governor issued an executive order that changed this target to 100% on a net basis by 2045. [252] Equally ambitious is the New York Climate Leadership and Community Protection Act (CLCPA). Passed in 2019, the CLCPA requires that the state's economywide emissions by reduced by 100% by 2050,[253] although up to 15% of the reduction can take the form of offsets such as those described in Section 2.2. Colorado, Connecticut, Maine, Massachusetts, Minnesota, Nevada, Rhode Island, and Washington also all have statutory targets requiring statewide GHG emission reductions of at least 80% by 2050.[254]

A notable aspect of the deep economywide decarbonization targets is that they will likely require the widespread deployment of carbon-negative technologies and non-fuel bioproducts in order to be successful. Policy language referring to "net zero" emissions targets or, in the case of New York, explicit carbon offset thresholds reflects the recognition of this probable outcome by policymakers. Existing state decarbonization requirements also identify varying degrees of decarbonization difficulty for different economic sectors. New York's statutory target, for example, imposes an absolute zero-emission target on its power sector by 2040 through language that explicitly excludes the use of carbon offsets by that sector. The reason for this distinction is the expectation that zero-emission technologies such as solar PV and wind will enable an absolute zero requirement to be achieved. Those sectors such as transportation and manufacturing that utilize more energy-intensive systems, by contrast, will need to rely upon biomass and biotechnology to achieve net-zero emissions, sometimes via carbon-negative technologies, while supplying close substitutes for the fossil fuels and products that modern economies rely upon.

Existing government efforts in the U.S. to incentivize decarbonization have largely been limited to the transportation sector, whereas the implementation of performance-based decarbonization standards in manufacturing would enable the broad scope of biotechnology's benefits to be recognized by the market. Such standards include, but are not limited to, financing R&D, promoting alternatives to non-fuel fossil products, supporting and expanding sustainable procurement policies, and incentivizing the development of green manufacturing and sustainable agriculture practices.

Recent years have seen only limited action at the federal level to encourage the utilization of biotechnology's decarbonization potential. Several states have adopted more ambitious long-term economywide decarbonization targets, however. While the policy mechanisms to achieve these targets have yet to be established, their success will likely depend on the extent to which the policies properly value the decarbonization, including net carbon sequestration, abilities of both fuel and non-fuel biotechnology pathways. *The economywide scope of these decarbonization targets will require the adoption of policies that reflect the ability of biotechnology products to achieve decarbonization across all major sectors of the U.S. economy.*

207 Brown, T.R. and Brown, R.C. (2013), A review of cellulosic biofuel commercialscale projects in the United States. Biofuels, Bioprod. Bioref., 7: 235-245. http://doi.org/10.1002/bbb.1387. https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1387

208 http://www.pewresearch.org/science/2019/11/25/u-s-public-views--on-climate-and-energy/

209 Deryugina, Tatyana, Garth Heutel, Nolan H. Miller, David Molitor, and Julian Reif. 2019. "The Mortality and Medical Costs of Air Pollution: Evidence from Changes in Wind Direction." American Economic Review, 109 (12): 4178-4219. DOI: 10.1257/aer.20180279. http://www.aeaweb.org/articles?id=10.1257/aer.20180279.

210 http://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

211 http://www.energy.gov/sites/prod/files/2019/10/f67/Internal%20Revenue%20Code%20Tax%20Fact%20Sheet.pdf

212 http://ww3.arb.ca.gov/regact/2018/lcfs18/15dayattb2.pdf

213 Brown, T.R. (2019), Why the cellulosic biofuels mandate fell short: a markets and policy perspective. Biofuels, Bioprod. Bioref., 13: 889-898. https://doi.org/10.1002/bbb.1987. http://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1987

214 https://www.rd.usda.gov/programs-services/biorefinery-renewable--chemical-and-biobased-product-manufacturing-assistance

215 https://www.usda.gov/sites/default/files/documents/usda-bioindicators-jan-2020.pdf

216 https://www.rd.usda.gov/programs-services/value-added-producer--grants

217 https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

218 https://www.iea.org/reports/world-energy-investment-2020/key-findings

219 https://usbiotechnologyregulation.mrp.usda.gov/biotechnologygov/about/about

220 https://www.aphis.usda.gov/aphis/ourfocus/biotechnology/biotech--rule-revision/secure-rule/secure-about/340_2017_perdue_biotechreg

221 Shahla Wunderlich, Kelsey A Gatto, Consumer Perception of Genetically Modified Organisms and Sources of Information, Advances in Nutrition, Volume 6, Issue 6, November 2015, Pages 842–851, https://doi.org/10.3945/an.115.008870. http://academic.oup.com/advances/article/6/6/842/4555145

222 Ashlie B. Delshad, Leigh Raymond, Vanessa Sawicki, Duane T. Wegener, Public attitudes toward political and technological options for biofuels, Energy Policy, 38(7), 2010, 3414-3425, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2010.02.015. http://www.sciencedirect.com/science/article/pii/S0301421510000960.

223 http://www.wsj.com/articles/BL-EB-6592

224 http://phys.org/news/2018-11-biocontainment-strategy-gmos.html

225 http://www.fuelsinstitute.org/Research/Reports/Biomass-Based-Diesel-A-Market-and-Performance-Anal

226 http://afdc.energy.gov/fuels/ethanol_e15.html

227 http://www.reuters.com/article/us-usa-biofuels-ethanol/trump-lifts--curbs-on-e15-gasoline-to-help-farmers-angering-big-oil-idUSKCN1T11BN

228 http://www.usda.gov/sites/default/files/documents/MARKET_EFFECTS_AND_WELFARE_IMPACTS_OF_THE_RENEWABLE_FUEL_STANDARD.pdf

229 http://www.epa.gov/fuels-registration-reporting-and-compliance--help/rfs-small-refinery-exemptions

230 Irwin, S. "Small Refinery Exemptions and Biomass-Based Diesel Demand Destruction." farmdoc daily (9):45, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, March 14, 2019. http://farmdocdaily.illinois.edu/2019/03/small-refinery-exemptions-and-biomass-based-diesel-demand-destruction.html

231 Neil Stephens, Lucy Di Silvio, Illtud Dunsford, Marianne Ellis, Abigail Glencross, Alexandra Sexton, Bringing cultured meat to market: Technical, socio-political, and regulatory challenges in cellular agriculture, Trends in Food Science & Technology, 78, 2018, 155-166, ISSN 0924-2244, http://doi.org/10.1016/j.tifs.2018.04.010. https://www.sciencedirect.com/science/article/pii/S0924224417303400#sec5

232 http://www.mckinsey.com/industries/pharmaceuticals-and-medical--products/our-insights/the-bio-revolution-innovations-transforming-economies-societies-and-our-lives#

233 http://ethanolrfa.org/wp-content/uploads/2021/02/LCA_-_RFS2-GHG--Update_2020.pdf

234 http://www.bio.org/press-release/ending-unjustified-rfs-waivers--will-put-america-more-sustainable-path

235 http://www.dtnpf.com/agriculture/web/ag/blogs/ag-policy-blog/blog--post/2020/09/12/trump-announces-e15-fuel-can-go-e10

236 http://www.oregon.gov/deq/ghgp/cfp/Pages/default.aspx

237 http://www.seattletimes.com/seattle-news/gov-jay-inslees-low-carbon-fuel-standard-faces-tough-road-ahead-in-washington-state/

238 http://www.governorsbiofuelscoalition.org/groups-exploring-potential-midwest-lcfs-collaborative/

239 http://www.transportationandclimate.org/content/tci-declaration--intent

240 http://www.congress.gov/bill/110th-congress/senate-bill/1324

241 http://climatecrisis.house.gov/sites/climatecrisis.house.gov/files/Climate%20Crisis%20Action%20Plan.pdf

242 http://www.biopreferred.gov/BioPreferred/faces/pages/AboutBio-Preferred.xhtml

243 http://www.soybiobased.org/update-of-usda-biopreferred-program/

244 http://www.nap.edu/resource/25525/interactive/

245 http://www.rd.usda.gov/sites/default/files/fact-sheet/508_RD_FS_RBS_Biorefinery.pdf

246http://www.bio.org/sites/default/files/2020-01/Final-BIO%20Comments-House%20Committee%20on%20Climate%20Crisis%20RFI-12-20-19.pdf

247 http://pascrell.house.gov/news/documentsingle.aspx?DocumentID=4548

248 http://www.federalregister.gov/documents/2019/11/12/2019-24367/conservation-stewardship-program-csp-interim-rule

249 http://www.congress.gov/bill/116th-congress/house-bill/7393/all-info

250 http://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

251 http://ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming--solutions-act-2006

252 http://www.ca.gov/archive/gov39/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf

253 http://climate.ny.gov/-/media/CLCPA/Files/CLCPA-Fact-Sheet.pdf

254 http://www.c2es.org/document/greenhouse-gas-emissions-targets/

SUMMARY AND CONCLUSION

"CLIMATE CHANGE WILL AFFECT EVERY PERSON, NATION, INDUSTRY, AND CULTURE ON EARTH."

Avoiding its worst effects will require an equally universal response. The biotechnology industry is uniquely positioned to play a leading role in the effort to reduce emissions, adapt to new climate conditions, and address the needs of the 21st century and beyond. In this report, three key themes have emerged. These themes should guide policymakers – and the biotech industry itself – if we are to achieve the full potential of biotechnology to address climate change.

Biotechnology is an essential climate mitigation tool. Biotech has already delivered vital climate solutions and holds the potential to provide transformative climate technologies across a broad spectrum of industrial sectors.

Biotech can achieve at least 3 billion tons of CO2 equivalent mitigation annually by 2030 using existing technologies. The biotechnologies with the greatest potential impact include:

- Biotech solutions have the potential to reduce agriculture sector GHG emissions by nearly 1 billion metric tons (1 gigaton) annually – or the equivalent of GHG emissions from more than 100 million U.S. homes. This includes reducing nitrous oxide emissions from agriculture by over 150 million metric tons of carbon equivalent and enhancing soil carbon sequestration by up to 600 million metric tons per year through a combination of agriculture biotechnology and agricultural biologicals.

- The transition to next-generation biofuels enabled by biotechnology will double the per-gallon emissions reductions of biofuels versus petroleum. Doubling biofuel use through broad adoption of next-generation biofuels in aviation and other transportation sectors would increase the contribution of biofuels to U.S. transportation sector GHG emissions reductions from 980 million tons over the past thirteen years to over 1.8 billion tons for the decade 2020-2030, a reduction equivalent to taking more than 45 coal-fired power plants offline.

- Broad adoption of algal and microbial feed ingredients that reduce enteric methane emissions from ruminant animals can avoid the equivalent of up to 140 million metric tons of carbon annually.

- Broad adoption of anaerobic digestion for animal waste would reduce U.S. GHG emissions by over 150 million metric tons annually using current technology.

- Bioenergy with Carbon Capture and Sequestration (BECCS) could cost-effectively remove over 700 million metric tons of carbon per year, or more than half the emissions from all U.S. coal power plants.

- Suitable land and other infrastructure exists to deploy algae-based carbon capture systems at more than 500 power plants and ethanol facilities in the U.S. These systems would have a potential to capture more than 200 million tons of CO2 annually.

Emerging biotechnologies could have transformative GHG benefits in a range of industrial sectors. Among the most promising applications are:

- Biobased plastics and polymers, such as PLA, PHA, and BDO have achieved lifecycle GHG reductions of up to 80% versus their petroleum-based counterparts. A rapidly growing list of new biobased chemical building blocks is now in development.
- Plant-based and cultured meats are providing new consumer choices and up to 89% lower lifecycle emissions for a global food sector responsible for more than a third of total GHG emissions.
- Biology-based parallel computing and DNA data storage have the potential to cut the energy and carbon footprints of computing and data storage – sectors expected to account for 14% or more of global GHG emissions by 2040 – by 99% or more versus current technology.

Biotechnology offers vital contributions to near-term GHG reductions and revolutionary tools to combat climate change in the longer term. To successfully address the challenge of climate change, humanity will need to predominantly decarbonize the global economy by mid-century and begin significantly drawing down concentrations of atmospheric carbon shortly thereafter. The struggle against climate change must be viewed as a multi-decade process, which needs to begin immediately. A ton of carbon emissions avoided now matters more than a ton avoided next year, but every step needs to be evaluated from the perspective of maintaining a trajectory towards success.

An aggressive combination of sector-based and economy-wide policies is needed to rapidly realize the full potential of biotechnology to combat climate change. The future growth of the U.S. biotechnology industry will be heavily affected by both existing and potential regulatory barriers, and by the degree to which governments invest in the development and deployment of biotech solutions. Biotechnology is a vital component of the national and global infrastructure needed to combat catastrophic climate change. The economywide scope of this challenge will require the adoption of policies that reflect the ability of biotechnology products to achieve decarbonization across all major sectors of the U.S. economy. Biotechnology companies will need to speak up not only to ensure that new policy provides opportunities for success, but to make it clear that prosperity is not threatened by sustainability. There is ample evidence that reducing emissions is, in fact, essential in supporting a thriving economy.

The biotechnology industry has a tremendous opportunity to build upon decades of success, and provide critical tools and expertise for the decades to come. Like every other industry, change will be profound and lasting, but if any industry can demonstrate that change can be an opportunity for growth, it is this one.