U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

BIOENERGY TECHNOLOGIES OFFICE

Multi-Year Program Plan

2023

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Letter from the Director

March 2023

I am proud to present the new Multi-Year Program Plan (MYPP) for the U.S. Department of Energy's (DOE) Bioenergy Technologies Office (BETO). BETO, within DOE's Office of Energy Efficiency and Renewable Energy, works with national laboratories, universities, and industry partners to develop and demonstrate resilient and reliable clean energy technologies that convert renewable carbon resources into fuels and products. Our focus is on enabling the widespread adoption of bioenergy technologies that can offer equitable and affordable solutions to contribute to the decarbonization of the transportation, industrial, and agricultural sectors, and provide for environmental equity in both rural and urban settings by promoting job creation and economic growth.

With the advances made in electrification, especially for light-duty vehicles, BETO has shifted its focus to low-carbon and net-zero-carbon fuels for the aviation, marine, rail, and heavy-duty long-haul freight industries, where there are fewer options to reduce their carbon impact. BETO's MYPP provides an overview of the current state and the future potential of bioenergy industries, and the role our office plays in strategically de-risking technologies to accelerate market adoption. BETO has historically focused on broadly applicable applied R&D to address technology challenges and uncertainties, significantly reducing the cost of a variety of technologies. BETO is increasing its focus on partnering with industry to take on the subsequent technology scale-up and demonstration, enabling commercialization to follow.

I would like to thank BETO's public and private stakeholders, including the scientific research community, trade and professional associations, the investment and financial community, industrial entities, governmental and environmental organizations, and the general public. You help identify the technical challenges so BETO can prioritize efforts and shape an effective research, development, and demonstration portfolio. Finally, I want to thank the BETO staff and all our partners, without whom none of our work would be possible.

Sincerely,

Valerie Reed
Director, Bioenergy Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Contents

Acronyms and Abbreviations

AMMTO	Advanced Materials and Manufacturing Technologies Office
BETO	Bioenergy Technologies Office
CI	carbon intensity
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DAC	direct air capture
DMA	Data, Modeling, and Analysis
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
GHG	greenhouse gas
H_2	hydrogen
HEFA	hydroprocessed esters and fatty acids
IBR	integrated biorefinery
LCA	life cycle assessment
MSW	municipal solid waste
MYPP	Multi-Year Program Plan
PDU	process development unit
RCR	Renewable Carbon Resources
RD&D	research, development, and demonstration
SAF	sustainable aviation fuels
SDI	Systems Development and Integration
TEA	techno-economic analysis
TRL	technology readiness level
USDA	U.S. Department of Agriculture

Executive Summary

The United States has the potential to reduce carbon dioxide (CO_2) emissions by 450 million metric tons per year by converting renewable carbon resources[1] into bioenergy and renewable chemicals and materials.[2] These emissions are equivalent to a quarter of current total U.S. transportation sector greenhouse gas (GHG) emissions, and more than three times the GHG emissions from the U.S. commercial aviation sector.[3] By leveraging more than 1 billion tons[4] of sustainable, domestic biomass and waste resources available each year, the United States could produce 60 billion gallons[5] of low-carbon biofuels for jets, ships, rail, and heavy-duty vehicles and 75 billion kilowatt-hours of renewable electricity.[6] If instead of bioenergy, the entire billion-ton resource was devoted to production of renewable hydrocarbon-based chemicals and materials, internal analysis estimates that over 200 million metric tons could be produced per year.

Because of the ability to draw down atmospheric CO_2 and harness the energy of the sun to produce basic carbon building blocks, biomass is a renewable carbon resource with potential for wide application across industries. Renewable carbon resources can displace their finite carbon resource counterparts (e.g., petroleum and coal) in many of the products Americans use every day, such as gasoline, plastics, and industrial chemicals. Bioenergy (which includes both biofuels and biopower) and renewable chemicals and materials (also referred to as bioproducts) are essential to efforts to decarbonize[7] the transportation and industrial sectors and can contribute to decarbonization of adjacent sectors of the economy, such as the agricultural and power sectors. In addition to reducing GHGs across economic sectors, bioenergy and bioproduct development can support increased economic activity across the entire supply chain—reducing waste streams in our communities, creating new jobs in the farms and forests of rural America, and contributing to growth in the nation's construction and manufacturing industries. Investing in new bioenergy technologies helps secure our national competitive advantage and enables private sector opportunities in the renewable energy field. Because biomass and wastes are available in all regions of the country, the Bioenergy

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[1] Renewable carbon resources are carbon-based resources that are regularly regenerated, either via photosynthesis (e.g., plants and algae) or through regular generation of carbon-based waste (e.g., the nonrecycled portion of municipal solid waste, biosolids, sludges, plastics, and CO_2 and industrial waste gases).

[2] J. N. Rogers, B. Stokes, J. Dunn, H. Cai, M. Wu, Z. Haq, and H. Baumes, "An Assessment of the Potential Products and Economic and Environmental Impacts Resulting from a Billion Ton Bioeconomy," *Biofuels, Bioproducts, and Biorefining* 11, no. 1 (2017): 110–128, https://doi.org/10.1002/bbb.1728.

[3] U.S. Environmental Protection Agency, "Fast Facts – U.S. Transportation Sector Greenhouse Gas Emissions 1990-2018," Office of Transportation and Air Quality, EPA-420-F-20-037 (2020), https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100ZK4P.pdf.

[4] U.S. Department of Energy, edited by M. H. Langholtz, B. J. Stokes, and L. M. Eaton, *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*, Oak Ridge, TN: Oak Ridge National Laboratory, ORNL/TM-2016/160 (2016), https://www.energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf.

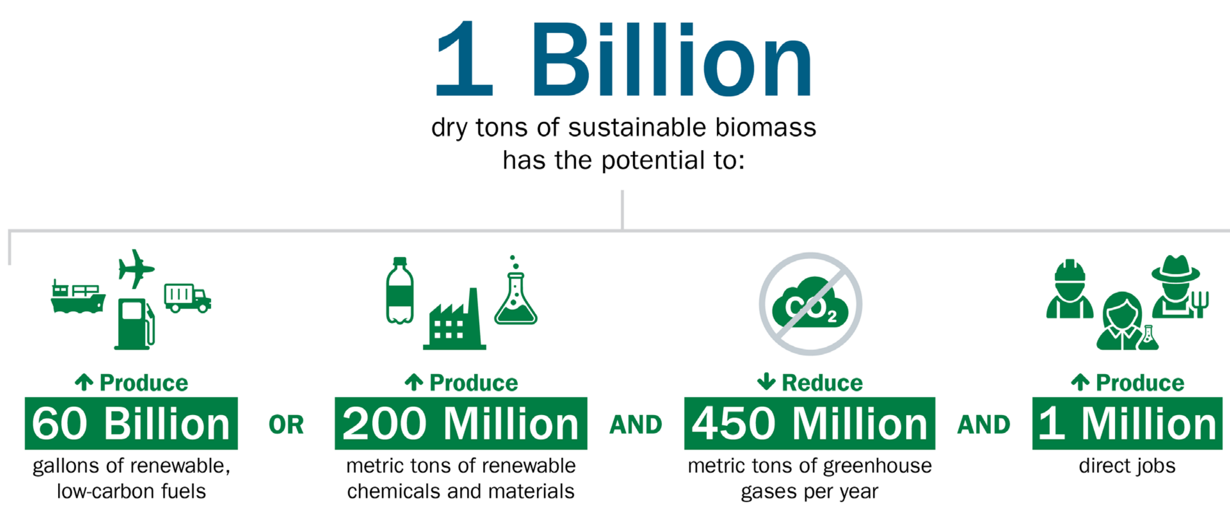
[5] U.S. Department of Energy, U.S. Department of Transportation, U.S. Environmental Protection Agency, and U.S. Department of Housing and Urban Development. 2023. *The U.S. National Blueprint for Transportation Decarbonization: A Joint Strategy to Transform Transportation*. DOE/EE-2674. https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf.

[6] Rogers et al. (2017).

[7] Decarbonization is the reduction or elimination of CO_2 emissions (and other GHG emissions that can be expressed in carbon equivalents) from a process such as manufacturing or the production of energy. See DOE's plan for industrial decarbonization in the 2022 *Industrial Decarbonization Roadmap* at https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

Technologies Office (BETO) works to ensure the growing bioenergy industry also focuses on equitable and just distribution of benefits across the United States.

BETO is a technology development office within the Office of Energy Efficiency and Renewable Energy at the U.S. Department of Energy, under the Sustainable Transportation Pillar. This Multi-Year Program Plan (MYPP) sets forth BETO's mission, goals, and strategic approach. It identifies BETO's research, development, and demonstration (RD&D) plans and crosscutting activities supported by the office, and outlines why these undertakings are important to meeting the energy and sustainability challenges facing the nation. BETO's organizational structure supports identifying and developing broadly impactful renewable carbon resources and conversion technologies, integrated processes, and innovative end uses. The MYPP details how each subprogram in BETO's organizational structure supports the office's overall strategic and performance goals through RD&D strategies. The RD&D strategies described in this MYPP bring in new innovations while de-risking technologies across the supply chain to enable sustainable and affordable domestic energy, create U.S. jobs and economic opportunities, reduce GHG emissions from multiple sectors of our economy, and increase participation of and benefits to a diverse set of energy system users, partners, and workforce. This MYPP is intended for use as an operational guide to help BETO manage and coordinate its activities, as well as a resource to help communicate its mission and goals to stakeholders and the public.



Section 1: Bioenergy Technologies Office Overview

The Bioenergy Technologies Office (BETO) within the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) supports the research, development, and demonstration (RD&D) of technologies aimed at mobilizing domestic renewable carbon resources for the reduction of greenhouse gas (GHG) emissions across the U.S. economy. Renewable carbon resources are carbon-based resources that are regularly regenerated, either via photosynthesis (e.g., plants and algae) or through regular generation of carbon-based waste (e.g., the nonrecycled portion of municipal solid waste [MSW], biosolids, sludges, plastics, and carbon dioxide [CO_2] and industrial waste gases[8]) (see Figure 1-1). This is in contrast to finite carbon resources, such as petroleum and coal, which take millennia to regenerate.

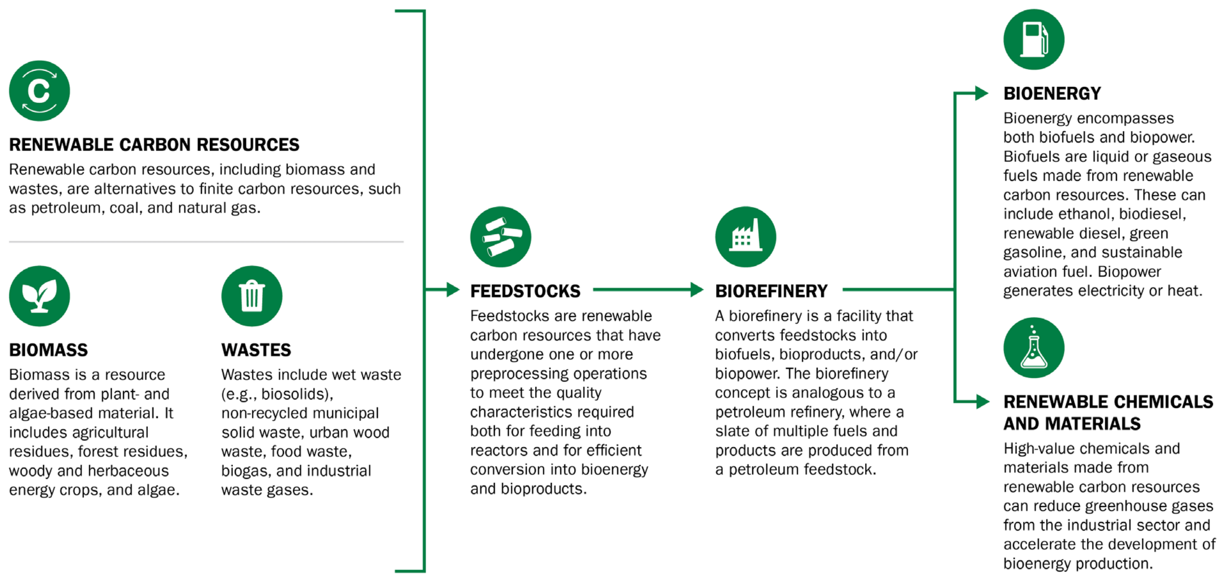


Figure 1-1. Bioenergy terms and their relation

BETO technologies convert renewable carbon resources into the fuels and products in the market today through a biorefinery (see Figure 1-2). In this way, renewable carbon resources are a key contributor to decarbonizing both the transportation and industrial sectors, while contributing to decarbonizing related sectors, including agriculture. For the transportation sector, biofuels provide an energy-dense petroleum alternative in the form of a drop-in replacement fuel especially for aircraft, marine vessels, diesel trucks, rail, off-road, and other difficult-to-electrify vehicles. They also

[8] Waste gases that are generated from the use of petroleum or coal and captured to be utilized can be included here as a means of "alternative" carbon until fossil fuels are phased out.

provide low-carbon fuels (e.g., ethanol and biodiesel) for the legacy vehicle fleet. Liquid transportation fuels made from renewable carbon resources are advantageous because they are largely compatible with existing fuel delivery, blending, and dispensing infrastructure. Improving overall system efficiency and sustainability across the bioenergy supply chain can drive continuous reductions in GHG emissions. For example, improving the life cycle emissions from commercial biofuels will reduce emissions from the legacy combustion vehicle fleet much in the same way that increasing deployment of renewable power generation (such as solar and wind) can drive further GHG reduction in electric vehicles. BETO partners with federal agencies across the transportation sector, as described in *The U.S. National Blueprint for Transportation Decarbonization*.[9]

In the industrial sector, petroleum is used to make a range of chemicals and products, such as plastics, fertilizers, and lubricants. Many products derived from petrochemicals can be supplemented or displaced with bio-derived chemicals or materials. In some cases, the unique properties of biomass even provide material and performance advantages over petroleum-derived counterparts, such as making plastics more recyclable. BETO's coordination with other DOE offices working in this sector is described in the *Industrial Decarbonization Roadmap*.[10]

Mobilizing renewable carbon resources can also contribute to reducing the carbon impact of the agricultural sector through practices such as diverting organic agricultural waste toward bioenergy applications, producing alternative proteins, and improving soil carbon management through the application of biochar from renewable resources.

[9] U.S. Department of Energy et al., *The U.S. National Blueprint for Transportation Decarbonization* (2023).
[10] U.S. Department of Energy, *Industrial Decarbonization Roadmap*, (2022), https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

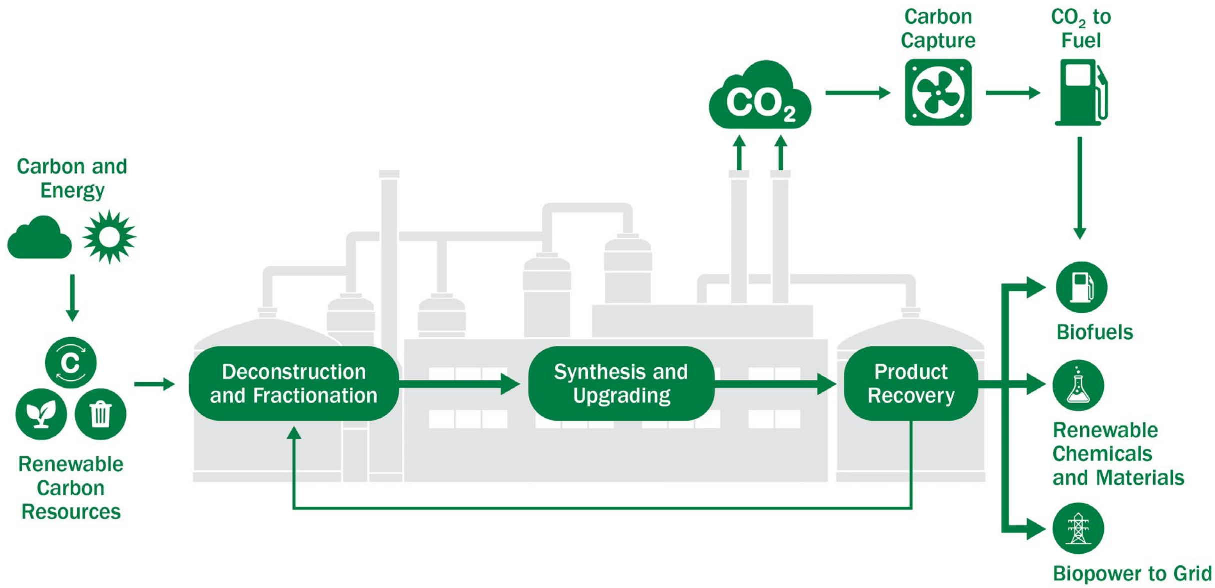


Figure 1-2. Pathway of BETO technologies

In recognition of the urgency of finding low-emission solutions for hard-to-decarbonize modes of transportation, including aviation, marine, and heavy-duty long-haul transport, BETO prioritizes work on the scale-up of biofuels that can meet those needs in the near term. However, BETO balances these priorities along with investments in technologies that have longer-term potential, such as algae-based fuels and products. BETO also pursues additional beneficial uses of biomass that will have positive impacts sooner, such as making carbon-negative electricity and clean hydrogen.[11]

Leveraging renewable carbon resources for diverse applications can lower domestic GHGs, as well as support other environmental and social benefits. Practices such as double cropping, growing biomass on marginal land, and producing bioenergy from residues and waste can help address food security concerns,[12,13] improve carbon management and other environmental indicators in the agriculture and forestry sectors,[14,15] and increase overall system efficiency. Sustainability is a key research focus at BETO, ensuring renewable carbon resources are procured via methods that preserve or improve the environment. This research includes analysis of direct and indirect land use change, GHG emissions, biodiversity, resource conservation, wildlife habitat, fire mitigation, food

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[11] Hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide equivalent (CO_2e) produced at the site of production per kilogram of hydrogen produced. https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-production-standard.pdf.

[12] H.Y. Leong, C.K. Chang, K.S. Khoo, et al., "Waste biorefinery towards a sustainable circular bioeconomy: a solution to global issues," *Biotechnol. Biofuels* 14, 87 (2021), https://doi.org/10.1186/s13068-021-01939-5.

[13] Q. Feng, I. Chaubey, R. Cibin, et al., "Perennial biomass production from marginal land in the Upper Mississippi River Basin," *Land Degrad. Dev.* 29: 1748–1755 (2018), https://doi.org/10.1002/ldr.2971.

[14] C. Zumpf, J. Cacho, N. Grasse, J. Quinn, J. Hampton-Marcell, A. Armstrong, P. Campbell, M. C. Negri, and D.K. Lee, "Influence of shrub willow buffers strategically integrated in an Illinois corn-soybean field on soil health and microbial community composition," *Science of The Total Environment*, 772, 145674 (2021), https://doi.org/10.1016/j.scitotenv.2021.145674.

[15] J. A.F. Kreig, H. Ssegane, I. Chaubey, M. C. Negri, and H. I. Jager, "Designing bioenergy landscapes to protect water quality," *Biomass and Bioenergy* 128, 105327 (2019), https://doi.org/10.1016/j.biombioe.2019.105327.

security, social well-being, water availability, and water, soil, and air quality. All GHG accounting conducted by BETO and project partners measures the entire life cycle of emissions, including those associated with both direct and indirect land use change. For bioenergy pathways, the system boundary of life cycle assessment (LCA) runs from the farm gate (including planting and harvesting) through to the finished fuel (including burning the fuel itself). BETO's analyses utilize real-world data and experience, in close coordination with U.S. Department of Agriculture (USDA) and project partners. The growth of bioenergy production both nationally and globally has raised concerns about potential adverse effects on environmental, economic, and social conditions. BETO carefully considers these concerns and works closely with several international groups to implement sustainability standards and promote responsible practices across the bioenergy supply chain.[16,17] These efforts are building consensus among key partners on sustainability criteria to enable responsible industry practices worldwide.

1.1 Scope of Effort

BETO works with a broad range of public and private stakeholders including the scientific research community, trade and professional associations, the investment and financial community, industrial entities, government and environmental organizations, and the public to identify challenges and define strategies to effectively de-risk technologies through RD&D investments. To evaluate and prioritize RD&D opportunities across the wide range of potential renewable carbon resources, conversion technologies, and fuel and product options, BETO conducts rigorous analyses on potential economic and GHG impacts. BETO also works with industry partners to identify priority RD&D needs. The most promising technologies are funded through competitive solicitations, both open and directed toward national laboratory partners, and managed by four subprogram areas:

Renewable Carbon Resources (RCR) focuses on RD&D to lower the cost, improve the quality, and increase the types and quantities of renewable carbon resources available for conversion to bioenergy and renewable chemicals and materials. This includes improving the efficiency and reliability of production, harvesting or collection, storage, preprocessing, and transportation, and identifying the key quality and operational factors for conversion performance while ensuring sustainable practices. (For subprogram details, see Section 2.4.)

[16] V. H. Dale, R. A. Efroymson, K. L. Kline, and M. S. Davitt, "A Framework for Selecting Indicators of Bioenergy Sustainability," *Biofuels, Bioproducts, and Biorefining* 9, no. 4 (2015): 435–446, https://doi.org/10.1002/bbb.1562.

[17] H.M. Junginger, T. Mai-Moulin, V. Daioglou, U. Fritsche, R. Guisson, C. Hennig, D. Thrän, et al., "The future of biomass and bioenergy deployment and trade: a synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade," *Biofuels, Bioprod. Bioref.* 13: 247–266 (2019), https://doi.org/10.1002/bbb.1993.

Conversion R&D focuses on R&D to reduce the costs of deconstructing renewable carbon resources into intermediate products (such as sugars, intermediate chemicals, bio-oils, or gaseous mixtures) and of upgrading those intermediates into bioenergy and renewable chemicals and materials. Conversion R&D also develops improved tools and methods for faster and less costly conversion technology development. (For subprogram details, see Section 2.5.)

Systems Development and Integration (SDI) focuses on RD&D to reduce technical uncertainty and operational risk of bioenergy systems for subsequent industry deployment. SDI performs systems research to combine technology components, unit operations, or subsystems developed by the other subprograms into integrated processes. These integrated processes are tested at various engineering scales to identify further R&D needs or to verify readiness for industry-led scale-up toward commercialization. (For subprogram details, see Section 2.6.)

Data, Modeling, and Analysis (DMA) focuses on tracking technology progress and identifying opportunities and challenges related to the economic and environmental impacts of bioenergy systems. Activities include conducting research into the long-term environmental and social viability of bioenergy systems and on the equitable distribution of benefits. (For subprogram details, see Section 2.7.)

While these subprograms are focused on addressing a range of technical, operational, and logistical priorities across the supply chain (as further detailed in Section 2), the key challenges addressed by BETO RD&D include:

Availability of Renewable Carbon Resources: There are a variety of technical, operational, and economic uncertainties in the availability of reliable, cost-effective, and sustainable biomass and waste resources. Mobilizing large volumes of previously untapped renewable carbon resources sustainably may require significant changes to existing agricultural and forestry practices and waste management, as well as deploying new supply chains for other renewable carbon streams. These resources must be mobilized in a way that lowers GHGs compared to petroleum counterparts, while ensuring limited environmental impacts.

Cost of Production: The distributed nature of biomass and waste streams requires greater conversion efficiency at smaller scales compared to petroleum refineries. This drives research in process integration, systems efficiencies, and advanced technologies to cost-effectively convert renewable carbon resources into desirable products.

Risk of Financing: Obtaining traditional financing is a challenge for bioenergy technologies. For investors to gain confidence in a technology, processes must function efficiently and reliably. Investors need assurance that operational performance can be scaled up and transferred from smaller to larger scales.

BETO's RD&D successes enable private industry to subsequently commercially deploy technologies in integrated biorefineries (IBRs) that can produce multiple product streams or bolt-on technologies to bring additional revenues to existing sites. Like biorefineries that currently produce ethanol from starch along with other products such as dry distillers grain, IBRs take advantage of diverse biomass and waste components to produce multiple products that maximize value and minimize waste. BETO works with industrial entities, including the petroleum refinery industry, to develop solutions that leverage existing infrastructure when possible.

1.2 Congressional Authorization

BETO derives its primary authorization from the Energy Policy Act (EPAct) of 2005, Section 932 Bioenergy Program, as amended by the Energy Independence and Security Act of 2007.[18] Congress provides additional direction to BETO through committee and conference reports that accompany appropriations bills and acts. To effectively steward taxpayer dollars, BETO establishes strategies and plans that represent a balanced portfolio that incorporates full congressional direction to BETO and DOE.

[18] U.S. Code. 42 USC 16232: Bioenergy Program. https://uscode.house.gov/view.xhtml?req=(title:42%20section:16232%20edition:prelim).

1.3 BETO Mission and Goals

BETO's mission is to develop and demonstrate technologies to accelerate reduction of GHG emissions through the cost-effective, sustainable use of biomass and waste feedstocks across the U.S. economy.

BETO's strategic goals are to:

- Decarbonize the transportation sector through RD&D to produce cost-effective, sustainable aviation and other strategic fuels.
- Decarbonize the industrial sector through RD&D to produce cost-effective and sustainable chemicals, materials, and processes utilizing biomass and waste resources.
- Develop cost-effective, sustainable biomass and waste utilization technologies and innovative approaches contributing to the decarbonization of the agricultural sector, generating carbon-negative power, developing carbon drawdown strategies, or other beneficial uses.

EERE MISSION

EERE's mission is to accelerate the research, development, demonstration, and deployment of technologies and solutions to equitably transition America to net-zero greenhouse gas emissions economy-wide by no later than 2050, and ensure the clean energy economy benefits all Americans, creating good paying jobs for the American people—especially workers and communities impacted by the energy transition and those historically underserved by the energy system and overburdened by pollution.

To measure progress toward these strategic goals, BETO has set key performance goals to achieve by the year 2030 (see Figure 1-3 for how the performance goals align to the strategic goals):

- Enable delivery, preprocessing, and deconstruction of sufficient volumes of biomass and waste feedstocks to biofuel intermediates that can meet industry-relevant cost and performance requirements, with a focus on sustainable aviation fuels (SAF) capable of >70% reduction in GHG emissions relative to petroleum.
- Support scale-up of multiple high-volume, cost-effective biofuel production pathways with a focus on SAF capable of >70% GHG reduction by enabling the construction and operation of at least four demonstration-scale integrated biorefineries.

- Along with industrial and federal partners, support 3 billion gallons of domestic SAF production and use, consistent with a trajectory to ultimately producing 35 billion gallons by 2050.

- Enable commercial production of >10 renewable chemicals and materials with >70% GHG reduction relative to relevant petroleum-derived counterparts, supporting >1 million metric tons/yr CO_2e emissions reductions.

- Enable at least one cost-effective and recyclable bio-based plastic that mitigates ≥50% GHG emissions relative to virgin resin or plastic intermediates.

- Demonstrate more than three place-based strategies for climate-smart agriculture, waste management, environmental remediation, or other beneficial uses of renewable carbon resources.

MISSION	**Develop and demonstrate technologies to accelerate reduction of GHG emissions through the cost-effective, sustainable use of biomass and waste feedstocks across the U.S. economy.**		
	Decarbonize Transportation	**Decarbonize Industry**	**Decarbonize Communities**
BETO Strategic Goals	Decarbonize the transportation sector through RD&D to produce cost-effective, sustainable aviation and other strategic fuels.	Decarbonize the industrial sector through RD&D to produce cost-effective and sustainable chemicals, materials, and processes utilizing biomass and waste resources.	Develop cost-effective, sustainable biomass and waste utilization technologies and innovative approaches contributing to the decarbonization of the agricultural sector, generating carbon-negative power, developing carbon drawdown strategies, or other beneficial uses.
BETO Performance Goals	• By 2030, enable delivery, preprocessing, and deconstruction of sufficient volumes of biomass and waste feedstocks to biofuel intermediates that can meet industry-relevant cost and performance requirements, with a focus on sustainable aviation fuels (SAF) capable of >70% reduction in GHG emissions relative to petroleum. • By 2030, support scale-up of multiple, high-volume, cost-effective biofuel production pathways with a focus on SAF capable of >70% GHG reduction by enabling the construction and operation of at least four demonstration-scale integrated biorefineries. • By 2030, along with industrial and federal partners, support 3 billion gallons of domestic SAF production and use, consistent with a trajectory to ultimately producing 35 billion gallons by 2050.	• By 2030, enable commercial production of >10 renewable chemicals and materials with >70% GHG reduction relative to relevant petroleum-derived counterparts, supporting >1 million metric tons/yr CO_2e emissions reductions. • By 2030, enable at least one cost-effective and recyclable bio-based plastic that mitigates ≥ 50% GHG emissions relative to virgin resin or plastic intermediates.	• By 2030, demonstrate more than three place-based strategies for climate smart agriculture, waste management, environmental remediation, or other beneficial uses of renewable carbon resources.

Figure 1-3. BETO mission and goals

Section 2: BETO Technology RD&D Plan

BETO focuses on applied R&D, analysis, and the subsequent integration of viable technologies at pre-pilot through demonstration scales. BETO's technology RD&D plan addresses technical challenges and opportunities to support the emerging bioenergy and renewable chemicals and materials industries through strategic federal support. BETO prioritizes technologies based on both the degree of life cycle GHG reduction potential and viability of market penetration. With increasing market interest in sustainable aviation and marine fuels as a means of decarbonizing difficult-to-electrify modes of transportation, BETO emphasizes these priority biofuels throughout its program.

Near- to midterm BETO RD&D is focused on developing technologies using renewable carbon resources that are available and reliable. Near-term emphasis for SAF production are low-GHG corn ethanol (used for the alcohol-to-jet process) and fats, oils, and greases due to the maturity of their supply and logistics as feedstocks. Midterm resources include nonrecycled MSW, biosolids, and industrial waste gases and CO_2, and in the midterm to longer term, high-impact agricultural and forestry residues and purpose-grown energy crops, including algae.

BETO's bench-scale applied R&D includes development, testing, and verification of feedstock and conversion technologies. Later-stage RD&D includes performing systems research and verifying integrated processes at increasing engineering scales. "Engineering scale" is the range of development steps beyond laboratory- or bench-scale activities that integrates the major components and subsystems, tests and demonstrates the operational performance, and facilitates the design and optimization of pre-pilot-, pilot-, and/or demonstration-scale systems in increasingly relevant and realistic environments. Demonstration-scale projects help to de-risk technologies for commercial investors, thereby supporting the development of a bio-based industry.

2.1 BETO RD&D Strategic Approach

BETO's RD&D efforts are managed by four subprogram areas tied to the biomass-to-bioenergy supply chain, from mobilizing renewable carbon resources through conversion into bioenergy and renewable chemicals and materials at increasing scales. DOE national laboratories, universities and other research institutions, and private companies leverage BETO funding to conduct key efforts per subprogram area.

To meet BETO strategic and performance goals, subprograms systematically prioritize RD&D across a range of emerging scientific breakthroughs and technology readiness levels (TRLs).[19] This strategy

[19] https://www.directives.doe.gov/terms_definitions/technology-readiness-level

supports a diverse portfolio while developing promising and widely applicable technologies, testing technologies as integrated processes, and verifying integrated process performance at increasing engineering scales. Sections 2.4–2.7 describe in detail the priority RD&D strategies per subprogram and the activities conducted by each to advance their strategies. These strategies and activities are listed for reference in the Appendix.

Subprograms Working Together: An Example Case

The four BETO subprograms work together to deliver bioenergy technologies at increasing scales and integration. One example of a complete bioenergy technology pathway is the conversion of corn stover to ethanol via enzymatic hydrolysis and fermentation and then further upgrading through the alcohol-to-jet process to produce SAF blendstocks. In addition to upgrading the sugar stream to fuels in this process, the lignin fraction can be isolated and either burned for fuel or upgraded into additional products such as adipic acid—a key precursor for nylon. For this pathway, the BETO subprograms work on multiple activities, including:

- RCR supports RD&D to determine and evaluate the critical quality characteristics necessary for successful processing of corn stover into conversion-ready and cost-effective feedstocks.
- Conversion R&D supports research to lower pretreatment costs, increase separations efficiency, and develop catalysts to upgrade biointermediates to aviation fuel.
- DMA supports techno-economic analysis (TEA) and LCA to evaluate the cost-effectiveness and GHG impacts of the pathway.
- SDI partners with commercial companies ready to pilot the full process.

2.2 RD&D Portfolio Management

To execute on RD&D strategies, subprograms solicit project performers through competitive funding opportunity announcements as well as merit reviews of national laboratory project proposals. At the beginning of each project, funding award recipients submit a project management plan detailing their approach to reaching project objectives and overcoming technical challenges. Project management plans are updated annually based on technical progress and the results of milestone verification reviews. BETO regularly assesses progress, approaches, and decisions by monitoring and evaluating portfolio- and project-level performance. Biennially, BETO conducts a formal peer review of the portfolio whereby external experts evaluate project objectives, approach, success, and relevance to subprogram objectives. Additionally, many of the projects in the portfolio, particularly larger research consortia, benefit from review, input, and guidance from technical advisory boards. These performance assessment activities provide avenues for input from other government agencies, industry representatives, stakeholders, and independent subject matter experts on program effectiveness and progress toward BETO's mission and goals.

BETO manages its portfolio using a four-phase, structured systems approach illustrated in Figure 2-1 that includes:

- Strategy and goals
- Program plans and activities
- Project solicitations and project plans
- Performance assessment.

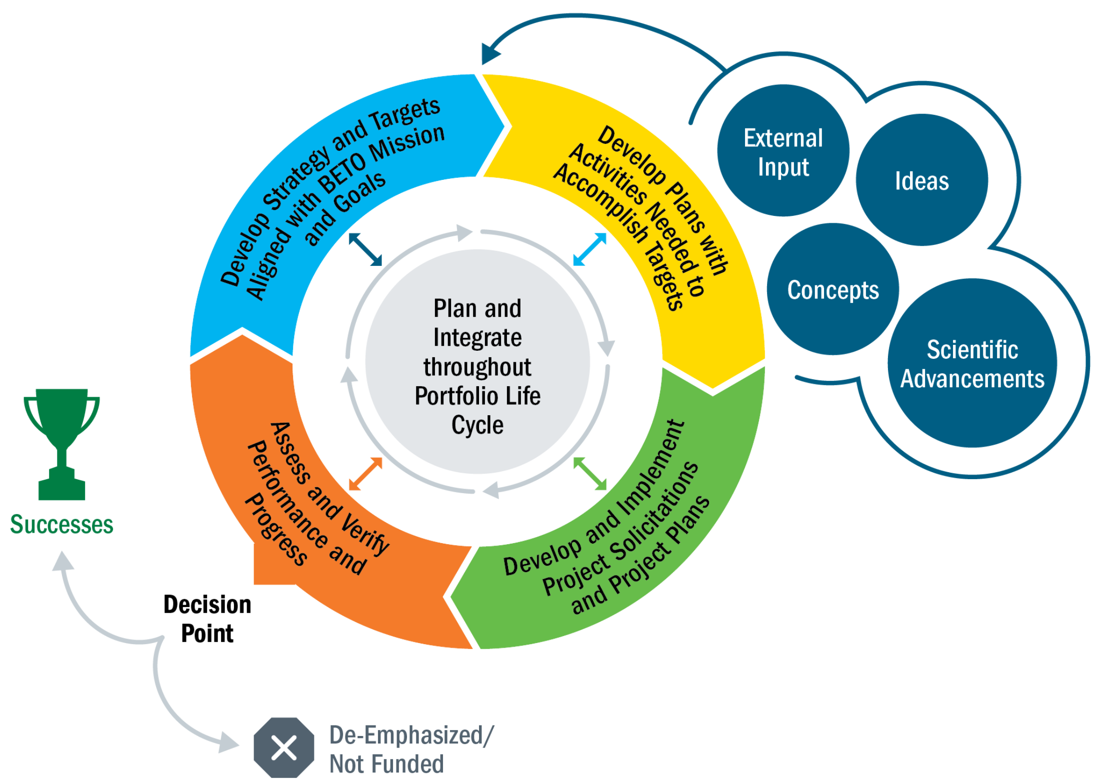

Figure 2-1. BETO's portfolio management approach

2.3 Programmatic and Crosscutting Strategic Approach

To best prioritize and direct taxpayer dollars and advance the mission of the office, BETO carries out the following programmatic and crosscutting strategies:

- **Work with industry partners to identify priority RD&D needs:** BETO regularly creates forums for industry engagement and input including hosting workshops, listening sessions, and working group meetings; meeting with key stakeholders and industry representatives; participating in industry conferences; publishing public requests for information; site visits; and other relationship fostering opportunities.

- **Leverage data and modeling to understand and quantify environmental and economic effects of emerging biofuel and bioproduct technologies:** BETO funds analysis across the program to ensure bioenergy technologies are sustainable both economically and environmentally. These efforts are coordinated by the DMA subprogram but are inherently crosscutting and frequently incorporated into individual RD&D project plans.

- **Support workforce development activities:** A knowledgeable and well-trained workforce is essential for meeting future energy demands, and a growing bioenergy industry has the potential to create opportunities for individuals with a wide range of skills and training. BETO is advancing American energy security and economic development through the development of tools and information on the careers, education, and training opportunities available to meet the needs of a growing bioenergy workforce.

- **Build diversity, equity, and inclusion into hiring and funding decisions, project plans, and community engagement:** Through staff trainings, inclusive hiring practices, and targeted outreach strategies, BETO actively works to increase the inclusion of traditionally underrepresented groups. BETO continuously broadens its pool of participants by funding nontraditional, emerging, and historically underfunded investigators.

- **Ensure projects are advancing energy, environmental, and climate justice:** Communities of color and low-income communities have incurred disproportionate environmental and health impacts due to pollution from our nation's energy system and our waste management and disposal practices. The technologies and approaches to preprocessing, logistics, and conversion of biomass and wastes are fundamentally "place-based" and have implications for the communities in which this infrastructure is ultimately sited. Analysis and models can support communities and industries in designing the most beneficial and least harmful technologies, products, and services possible to ensure a just clean energy transition.

- **Conduct strategic communications:** BETO's strategic communications efforts share BETO's key messages and accomplishments with a range of audiences, helping to increase awareness of and support for its research, initiatives, and technologies. This outreach supports the development of partnerships and increases the applicant pool for competitive funding opportunities. Communications efforts are key to enhancing government accountability by transparently sharing with the public the technical progress BETO is making toward its goals and providing clear, consistent, and accurate information about bioenergy.

- **Coordinate with international and interagency efforts:** Coordination with other DOE offices and government agencies involved in bioenergy development helps optimize federal investments, leverages limited resources, avoids duplication, and ensures a consistent message to stakeholders toward meeting national energy goals. Created by the Biomass Research and Development Act of 2000, the Biomass Research and Development Board is an interagency collaboration co-chaired by USDA and DOE that coordinates R&D activities concerning bioenergy and renewable chemicals and materials to maximize the benefits of federal efforts. In addition to partnerships through the Biomass Research and Development Board, BETO coordinates and partners with other program offices within EERE on relevant R&D, including the Hydrogen and Fuel Cell Technologies Office on the use of low-carbon-intensity hydrogen to enhance biofuel production, and the Advanced Materials and Manufacturing Technologies Office (AMMTO) on the production of renewable chemicals and materials. BETO also collaborates with DOE's Office of Science, Office of Fossil Energy and Carbon Management, Advanced Research Projects Agency–Energy program, Loan Programs Office, and the Energy Information Administration, as well as DOE national laboratories, to support the government's energy, research, and analysis goals.

Federal Agencies Working Together:
Sustainable Aviation Fuel Interagency Grand Challenge

The Sustainable Aviation Fuel Grand Challenge is the result of DOE, the U.S. Department of Transportation, USDA, and other federal government agencies working together to develop a comprehensive strategy for scaling up new technologies to produce SAF on a commercial scale. BETO participates in the interagency SAF Grand Challenge and the tasks needed to achieve its goals to:

- Achieve a minimum of a 50% reduction in life cycle GHG emissions compared to conventional jet fuel.
- Ensure sufficient SAF supply to meet 100% of aviation fuel demand by 2050, which is currently projected to be around 35 billion gallons per year.
- Ensure 3 billion gallons of U.S. SAF supply by 2030.
- Integrate Grand Challenge actions with the overall Net-Zero Aviation by 2050 decarbonization strategy that includes operational and efficiency improvements.

The SAF Grand Challenge and the increased production of SAF will play a critical role in a broader set of actions by the U.S. government and the private sector to reduce the aviation sector's emissions in a manner consistent with the goal of net-zero emissions for the U.S. economy, and to put the aviation sector on a pathway to full decarbonization by 2050.

2.4 Renewable Carbon Resources RD&D

The RCR subprogram focuses on facilitating the availability of renewable carbon resources for conversion into bioenergy and renewable chemicals and materials. The RCR subprogram develops strategies and supports technology development to reduce the cost, improve the quality, increase the quantity, and maximize the environmental benefits of using renewable carbon resources. Examples of these resources include:

- Agricultural residues (e.g., corn stover—corn stalks, cobs, and leaves).
- Forestry residues (e.g., logging residues, forest thinning).
- Purpose-grown energy crops.
    - Algae (e.g., microalgae, macroalgae, cyanobacteria).

  - Herbaceous crops (e.g., switchgrass, miscanthus, energy cane, sweet sorghum, high-biomass sorghum).
  - Short-rotation woody crops (e.g., hybrid poplars, shrub willows).
  - Overwintering secondary crops (e.g., carinata, pennycress).
- Waste streams (e.g., the nonrecycled organic portion of MSW, biosolids, sludges, plastics, CO_2 and industrial waste gases).
- Resources from ecosystem restoration or maintenance (e.g., harmful algal blooms, invasive species, salvaged material from natural disasters, fire mitigation).
- Commodity crops (e.g., corn, grain sorghum, oilseed crops).

Each of these resources has unique considerations related to quality, logistics, siting, sustainability, regulations, and economics. The RCR subprogram aims to optimize the use of each resource, taking into account numerous sustainability indicators including direct and indirect land use change, GHG emissions, biodiversity, resource conservation, wildlife habitat, fire mitigation, food security, social well-being, water availability, and water, soil, and air quality. Mobilizing this wide range of carbon resources most responsibly and most efficiently takes close coordination with stakeholders and many other federal offices and agencies. Broadly, the RCR subprogram coordinates with USDA on agricultural and forestry resources, DOE's Office of Fossil Energy and Carbon Management on CO_2 and industrial waste gases, and more than 10 offices on algal resources primarily through the Biomass Research and Development Board.

In total, it is estimated that in the future, the United States has the potential to sustainably produce over 1 billion tons of biomass and wastes for biofuel, bioproduct, or biopower applications, enough to displace approximately 30% of U.S. petroleum consumption[20] or meet the U.S. governmentwide goal to produce 35 billion gallons of SAF by 2050.[21]

The RCR subprogram supports both applied R&D projects and pilot-scale projects on the production, harvesting/collection, supply logistics, storage, and preprocessing of biomass and wastes to feedstocks. Feedstocks are renewable carbon resources that have undergone one or more preprocessing operations to meet the quality characteristics required for both feeding into reactors and efficient conversion into bioenergy and renewable chemicals and materials. RCR RD&D efforts are designed to maximize supply chain system efficiencies and identify the key feedstock quality and

[20] U.S. Department of Energy, *2016 Billion-Ton Report*.
[21] U.S. Department of Energy, "Memorandum of Understanding: Sustainable Aviation Fuel Grand Challenge," Sept. 8, 2021, https://www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21_0.pdf.

performance factors affecting biorefineries. In addition to increasing the efficiency of current conventional supply chain systems, the RCR subprogram supports the development of innovative advanced supply chain systems that will be required to mobilize the entire billion tons of biomass and waste streams.

RCR Strategic Objective

The RCR RD&D subprogram's strategic objective is to develop technologies to mobilize renewable carbon resources to enable the production of bioenergy and renewable chemicals and materials.

RCR Support of the BETO Performance Goals

RCR supports the BETO performance goal to enable delivery, preprocessing, and deconstruction of biomass- and waste-derived feedstocks to biofuels that can meet industry-relevant cost and performance requirements, with a focus on SAF capable of >70% reduction in GHG emissions relative to petroleum through development of feedstocks that meet the quantity and quality requirements to be converted to SAF. This requires close coordination with the Conversion R&D subprogram to develop conversion-ready feedstocks for a variety of conversion pathways to SAF.

RCR supports the BETO performance goal to demonstrate over three place-based strategies for climate-smart agriculture, waste management, environmental remediation, or other beneficial uses of renewable carbon resource through RD&D to reduce the carbon intensity (CI) of feedstock production, increase soil carbon storage in bioenergy applications, use algae to treat wastewater, and use energy crops for phytoremediation.

As shown in Figure 2-2, RCR coordinates closely with each of the other subprograms in support of BETO's additional performance goals:

- RCR coordinates with SDI in support of BETO's goal to enable the construction and operation of at least four demonstration-scale integrated biorefineries by supporting the development of pilot-scale advanced feedstock supply systems.

- RCR coordinates with Conversion R&D in support of BETO's goal to enable >10 commercial renewable chemicals and materials by supporting research focused on creating algal products and on identifying products that can be produced from the low-quality fractions of biomass and wastes that cannot be used for fuel.

- RCR also coordinates with Conversion R&D in support of BETO's goal to enable cost-effective and recyclable plastics by supporting research to separate plastics from MSW and to create plastics and plastic intermediates from renewable carbon resources like algae.

- RCR coordinates with DMA in support of all of BETO's performance goals by supplying data and, in turn, using DMA's modeling results and analyses to facilitate funding of the most environmentally sustainable practices.

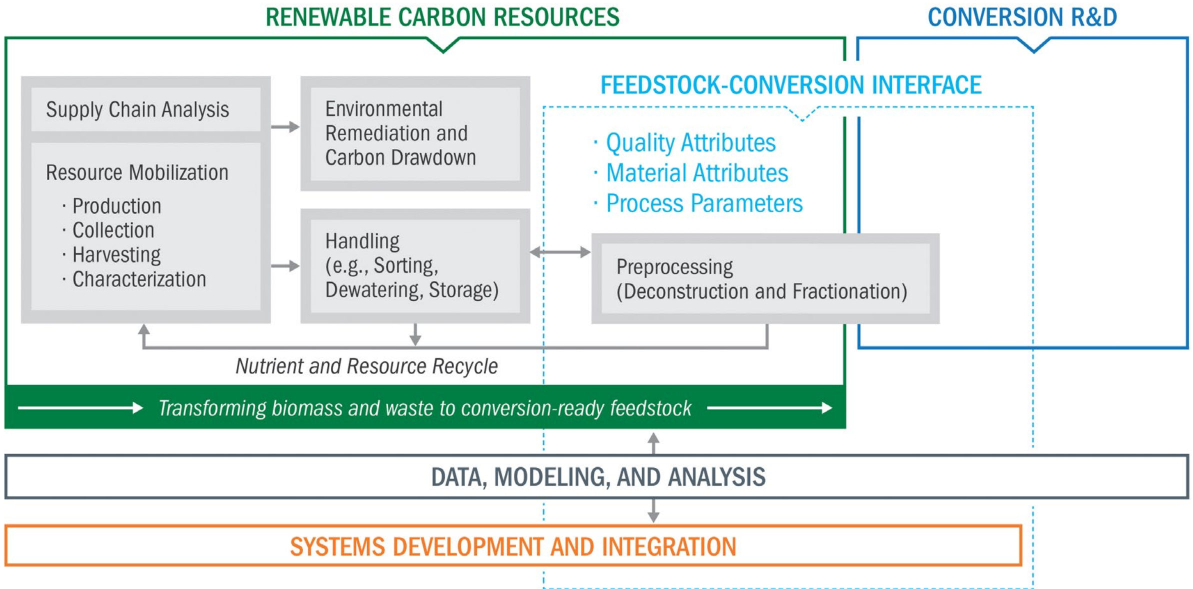

Figure 2-2. RCR RD&D scope and interface diagram

RCR RD&D Strategic Approach

RCR RD&D aims to unlock the domestic bioenergy resource potential to decarbonize the economy. The strategic approach of RCR RD&D to meet the BETO performance goals can be organized by activities focused on developing low-cost, reliable feedstock supply systems from the entire range of biomass and wastes; developing waste management and environmental remediation strategies; and developing carbon management strategies including soil carbon storage and carbon drawdown.

Strategy 1: Develop Low-Cost, Reliable Feedstock Supply Systems from the Entire Range of Biomass and Wastes

RD&D Challenges and Opportunities

The following are the research needs emphasized within the RCR subprogram grouped into three categories: Production and Sourcing, Logistics, and Feedstock-Conversion Interface.

RCR Challenge 1.1 Production and Sourcing

Prior to investing time and effort on developing any supply chain, it is critical to:

- Analyze potential quantities of renewable carbon resources and ensure sufficient supply of environmentally sustainable and economically available conversion-ready feedstocks. This includes developing and pursuing strategies to address gaps between what is in production today against future needs.
- Establish regional field trials to demonstrate yield improvements and environmental services with new varieties of industrially relevant purpose-grown energy crops.
- Identify and manage causes of crop losses such as pests and variable environmental conditions.
- Improve translatability between small-scale experimentation and modeling to large-scale outdoor demonstration.

RCR Challenge 1.2 Logistics

To encourage commercial mobilization of renewable carbon resources, it is critical to:

- Develop and optimize harvest, collection, storage, handling, and preprocessing technologies to reduce material losses and minimize logistics burden.
- Increase the value of biomass and waste by identifying, analyzing, and developing bioproduct supply chains.

RCR Challenge 1.3 Feedstock-Conversion Interface

RD&D is needed to develop fundamental understanding of:

- Feedstock quality impacts on preprocessing and conversion performance.
- Biomass flow behavior and robust particle mechanics computation models to improve feedstock flowability.
- Abrasion mechanisms for equipment design and wear resistance.
- Key feedstock and operation factors needed to establish feedstock quality specifications and to develop cost-effective mitigation strategies toward improving operational effectiveness for integrated supply-logistics-conversion systems.
- Intelligent control systems and performance criteria to actively manage feedstock quality and achieve high levels of continuous system reliability.

RD&D Activities

The RCR RD&D approach is organized around the following activities: Production and Sourcing RD&D, Logistics RD&D, and Feedstock-Conversion Interface RD&D.

RCR Activity 1.1 Production and Sourcing

Production and sourcing RD&D focuses on improving the economic production or supply of renewable carbon resources by developing novel sources or improving current systems. Ongoing resource production activities include supporting applied RD&D to:

- Perform resource supply chain and sustainability analysis to track RD&D performance against techno-economic and environmental sustainability goals and targets for specific feedstock-conversion pathways (e.g., analysis of forestry residues for use in high-temperature conversion to fuels and chemical, and of agricultural residues using low-temperature conversion to fuels and chemicals).

- Analyze potential biomass or waste supply availability under multiple resource mobilization scenarios.

- Collect and analyze data on energy crop production and traits (e.g., yields, composition, stress tolerance, pest and disease resistance, and water and nutrient use efficiency).

- Improve/evaluate new energy crop varieties through genetic engineering or traditional breeding.

- Develop best management and sustainability practices for energy crop systems.

- Investigate the production of energy crops on either unprofitable marginal lands, or as part of a landscape design where energy crops are grown in concert with commodity crops like corn and soybeans to increase profits and provide ecosystem services.

- Improve algae cultivation through strategies that include management of the microbial community, efficient delivery of resources, pest mitigation, mixotrophy, integration of co- or polycultures, water use management, temperature management, seasonal succession, and development of tools and sensors to optimize the biomass characteristics of the algal community.

RCR Activity 1.2 Logistics

Resource logistics encompasses the unit operations necessary to harvest or collect a renewable carbon resource and move it from its point of origin to the conversion reactor at the biorefinery, while ensuring the delivered feedstock meets the specifications of the biorefinery conversion process. These activities include supporting applied RD&D to:

- Identify factors affecting degradation of stored biomass and wastes, and procedures to reduce mass loss during storage while maintaining composition quality.
- Develop advanced preprocessing strategies and technologies, such as moisture reduction/dewatering and ash mitigation that can reduce the overall logistics cost, reduce the energy usage, and upgrade a wide variety of renewable carbon sources into on-specification, high-quality, conversion-ready feedstock.
- For algae, improve integration and reduce cost and energy intensity of on-farm cultivation, primary harvest, concentration, and preprocessing systems.
- For terrestrial energy crops and agricultural residues:
  - Utilize real-time sensors to enable immediate decisions toward optimizing biomass quality for efficient conversion.
  - Understand densification mechanisms from molecular scale to bulk scale to optimize the technology for improved material durability and bulk density.
- Increase system efficiency (including transportation of biomass to conversion facility) and capacities while minimizing risk of supply disruption and cost fluctuations.
- Optimize feedstock cost by identification and development of high-value renewable chemicals and materials or services (e.g., water treatment, remediation).
- Improve the harvest, collection, transportation, utilization, and storage of salvage treatments from forest stands impacted by fire, pests, severe weather, and other unpredictable events.

RCR Activity 1.3 Feedstock-Conversion Interface

Feedstock-conversion interface RD&D activities address challenges related to the behavior and performance of biomass in supply, preprocessing, and conversion process operations. These activities focus on identifying key feedstock qualities and operation factors, and developing technologies to:

- Quantify and better understand variability in the targeted feedstock materials, from field through preprocessing to conversion reactor, to manage how biomass composition, structure, and behavior impact system performance.
- Develop and implement mitigation strategies into the processes of resource supply, preprocessing, and conversion, and benchmark and verify feedstock performance in integrated operations.
- Analyze systemwide throughput to benchmark integrated system reliability, process economics, and environmental impacts, and estimate how system reliability changes with the implementation of mitigation strategies.
- Optimize feedstock cost by identification and development of high-value coproducts or services (e.g., water treatment, remediation) that could be upstream from conversion of the remaining off-specification or low-quality material to biofuels and renewable chemicals and materials.
- Control and optimize processes with in-line sensors and feedback control logic to monitor performance at critical points in the integrated systems and adjust throughput to achieve high levels of system reliability over time.
- Model the behavior and performance of selected feedstocks in gravity flow and conveyance operations, based on the understanding of the dynamics of preprocessing and their effects on critical characteristics for efficient conversion.

Strategy 2: Develop Waste Management and Environmental Remediation Strategies

RD&D Challenges and Opportunities

RCR Challenge 2.1 Waste Management

Waste resources present unique value propositions as they frequently represent a liability due to existing disposal costs. However, the following RD&D challenges need to be overcome:

- MSW, while found in population centers, has distributed availability and can be lower in volume relative to other bioenergy resources,[22] making it costly to transport for bioenergy use.
- Waste disposal sites are often disproportionately located in underserved communities, and substantial community partnerships will be needed to successfully implement new approaches and technologies.
- Waste resources are highly variable, geographically and seasonally. Their variable composition, high moisture, and contaminants can negatively affect the convertibility of these waste resources.

RCR Challenge 2.2 Environmental Remediation

RD&D is needed to develop algae-based low-energy, highly effective wastewater treatment technologies. Algae can utilize nutrients from municipal wastewater treatment plants, food processing effluent, industrial effluents, and polluted natural water bodies. Algal systems can be integrated into wastewater treatment operations and leverage photosynthetic growth to offer nutrient removal that enables operators to meet stringent new effluent discharge regulations. The water treatment service itself is highly valuable, resulting in a cost-advantaged algal biomass that is rich in nutrients and suitable for conversion to fuels, products, and fertilizers in a biorefinery.

Growing plants, including energy crops, on abandoned mine land and industrial brownfield sites has been demonstrated as a cost-effective approach to land remediation. The use of energy crops for remediation has the potential to both provide environmental benefits and increase the available land area where energy crops can be planted without land use change concerns, though much more research is needed to quantify and develop these benefits.

RD&D Activities

The RCR RD&D approach to developing waste management and environmental remediation strategies is focused on supporting applied RD&D in the following categories.

RCR Activity 1.1 Waste Management

- Develop technologies to characterize, separate, fractionate, and preprocess waste streams.

[22] U.S. Department of Energy, *2016 Billion-Ton Report*.

- Develop coproducts from the low-quality fraction of wastes.
- Create a public, nationwide database of waste characteristics focused on specific conversion pathways.

RCR Activity 1.2 Environmental Remediation

- Develop technologies that enable the utilization of algae in wastewater treatment to offer LCA-advantaged algae-based products or services while keeping systems cost on par with incumbent technology.
- Identify practical methods to maximize the ability of biomass to manage nutrients. This includes running field trials to optimize the use of energy crops in buffer zones to reduce runoff from adjacent fields, developing decision criteria for each management component, and examining multiple potential conservation practices together (e.g., saturated buffers and winter cover crops) to detect whether effects are additive. For algae including seaweeds (also known as macroalgae), this includes recovering nutrients from polluted waters and applying the algal biomass back to the land as soil amendments.
- Test available energy crop cultivars and clones on their ability to reclaim mine and brownfield sites while producing sufficient biomass for use in conversion to biofuel.
- Mitigate environmental problems caused by harmful algal blooms, invasive species, and natural disasters. The main priority with these efforts is to restore ecosystem health, and extreme caution is used to assess all health indicators including wildlife habitat, soil and water quality, seed banks, and biodiversity.

Strategy 3: Develop Carbon Management Strategies Including Soil Carbon Storage and Carbon Drawdown

RD&D Challenges and Opportunities

The following are the carbon management research needs emphasized within the RCR subprogram.

RCR Challenge 3.1 Carbon Management

- To offset GHG emissions from various sectors, sinks are needed for carbon capture, such as growth of deep-rooting perennial energy crops and cover crops, conservation or no-tillage land management practices, and applications of soil amendments, such as biochar (Figure 2-3).

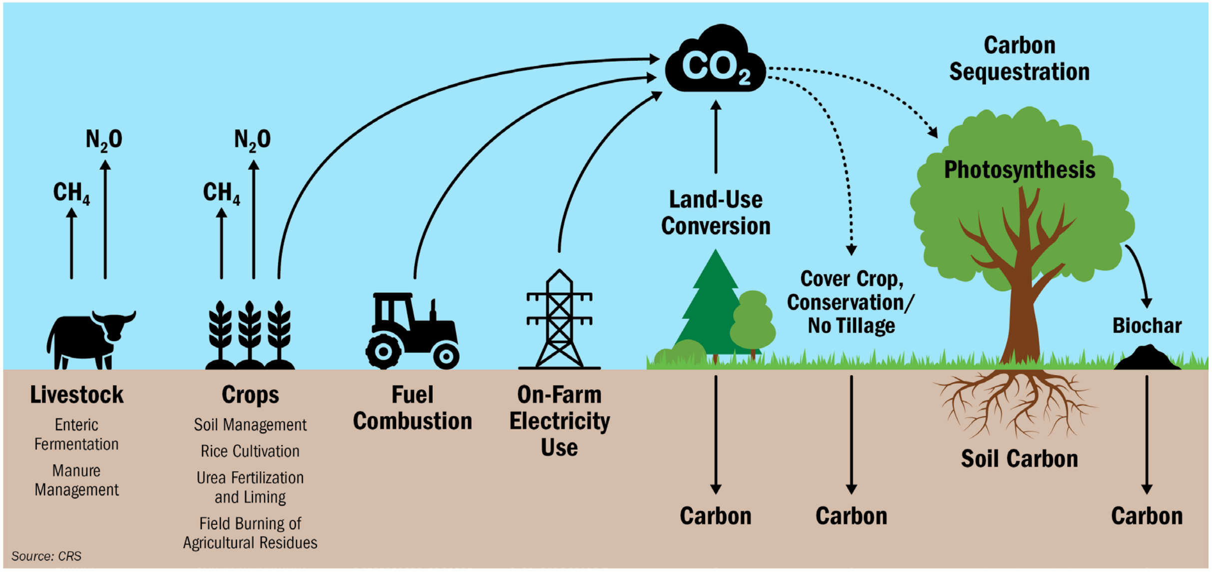

Figure 2-3. Examples of GHG sources and sinks from agricultural activities[23]

- Fertilizer production and feedstock production account for more than 40% of GHG emissions along the biofuel supply chain.[24] Reducing the CI associated with feedstock production, from site preparation through the harvesting of the biomass, is needed. By reducing the CI of feedstock production, fuels and coproducts derived from these feedstocks will also bear lower CI values, helping, in turn, to decarbonize the transportation and industrial sectors.

- The resources required for algal cultivation, including CO_2, nutrients, and water, comprise more than one-third of the overall cost of producing algal biofuels and renewable chemicals and materials. Algae grow much better when supplied with a concentrated CO_2 source such as CO_2 from emissions from industrial point-source emitters or from CO_2 generated through direct air capture (DAC) technologies. RD&D is needed to develop strategies to better integrate DAC units with algae cultivation systems. Alternatively, using CO_2 directly from the air in algal cultivation has the potential to provide significant cost savings and lead to algae farms that are decoupled from large-scale CO_2 sources, thereby increasing the number of sites for large algae farms and the overall resource potential of algae. RD&D is needed to better use CO_2 directly from the air and increase CO_2 utilization efficiency within algal cultivation systems.

- Forests and other ecosystems can be managed to maximize carbon storage and stability, and more RD&D is needed to assess geographic variability and vulnerability to loss from disturbance, and to account for associated economic and environmental impacts and

[23] Figure adapted from Congressional Research Service, "Greenhouse Gas Emissions and Sinks in U.S. Agriculture," Jan. 9, 2020, https://crsreports.congress.gov/product/pdf/IF/IF11404/2.
[24] Argonne National Laboratory, *Developing a Framework for Lifecycle Analysis of Biofuels on the Farm Level*, final report to ARPA-E (2019).

ecosystem service co-benefits, including land use change, water quality, wildlife habitat, and harvested products.

RD&D Activities

The RCR RD&D approach to developing carbon management strategies is focused on supporting applied RD&D in the activities described below.

RCR Activity 3.1 Carbon Management

The RCR supports applied RD&D to:

- Increase soil carbon in bioenergy applications with a focus on sustainability and ecosystem services, particularly enhancement in soil health.
- Reduce the CI of feedstock production. Several climate-smart agricultural practices, such as enhanced-efficiency fertilizers and nutrient management, will help to limit GHG emissions during feedstock production, particularly that of nitrous oxide (N_2O), a GHG that has 300 times the warming potential of CO_2.
- Investigate opportunities to improve biochar quality and economics, and assess the impact of biochar applications on land remediation and soil carbon sequestration.
- Increase CO_2 utilization efficiency within algal cultivation systems while optimizing CO_2 utilization from air. There are many strategies under development for cultivating algae using CO_2 directly from the air. These include but are not limited to improving the rate of carbon fixation, system delivery/dispersion mechanisms, and cultivation system improvements specifically related to CO_2 delivery and utilization.
- Develop and integrate DAC technology with algae systems to maximize algal productivity in outdoor algae farms.
- Develop feedstock supply systems for forest residues produced from forest restoration and fire mitigation efforts.
- Protect and restore habitats such as salt marshes, mangroves, seagrass beds, and kelp forests to increase CO_2 storage, protect coasts from flooding, and prevent erosion and habitat loss.

2.5 Conversion R&D

The Conversion R&D subprogram focuses on technologies and processes that break down feedstocks and reassemble them into useful products. Conversion R&D develops technologies that enable the cost-effective production of low-CI bioenergy and renewable chemicals and materials from renewable carbon resources.

The conceptual block flow diagram in Figure 2-4 depicts many of the possible pathways combining process steps or unit operations to create an end product. Since BETO cannot directly pursue all possible process configurations, the goal is instead to overcome the technical barriers in critical process steps to facilitate a diverse set of options from which industry will select the technology combinations that provide the strongest market advantage.

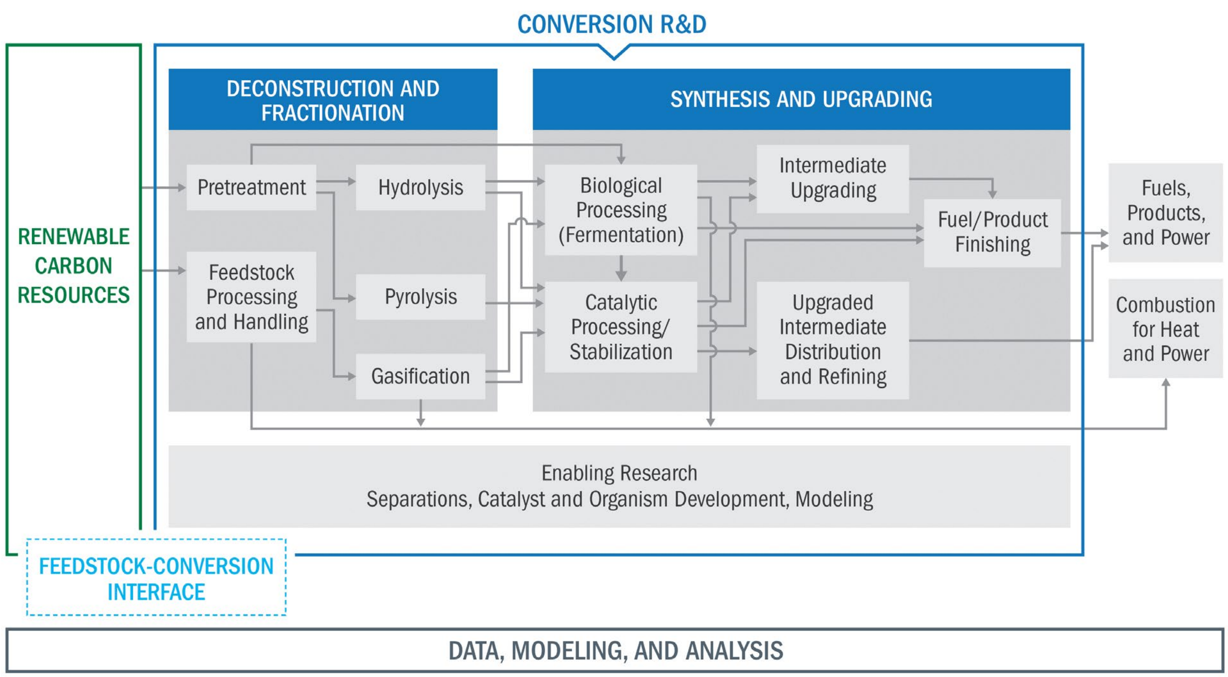

Figure 2-4. Conversion pathways from feedstock to products

As depicted in Figure 2-4, these process steps can be grouped into the broader categories of:

- **Deconstruction and Fractionation:** Breaking down feedstocks into upgradable intermediates. For example, gasification breaks down feedstock into a synthesis gas, pyrolysis breaks down feedstock into a bio-oil intermediate, and pretreatment and hydrolysis deconstruct biomass into simple sugars and other carbohydrate intermediates.

- **Synthesis and Upgrading:** Converting those intermediates into useful end products. These products can include finished fuels; fuel precursors; high-quality intermediates such as sugars, synthesis gas (syngas), or stabilized bio-oils; and bio-based chemicals or products.

To have the greatest impact on the largest number of alternatives, BETO analyzes various reference configurations for these technology and process combinations (i.e., technology pathways). Based on this analysis and external expert feedback, the Conversion R&D subprogram supports R&D on unit operations or key processing components that will contribute cost and sustainability improvements. The Conversion R&D subprogram assesses technologies for economic viability and sustainability metrics (e.g., GHG emissions, water use), and then adjusts R&D strategies accordingly.

In addition, the Conversion R&D subprogram supports enabling research, building on fundamental knowledge and research from the DOE Office of Science. Enabling research reduces the time and cost required to improve conversion efficiencies through targeted activities such as developing new and improved catalysts and organisms, as well as engineering more efficient and less expensive separations. In the same way that research on individual process steps can benefit a number of technology pathways, enabling research on methods, capabilities, and tools benefits a number of technologies in a process step and improves final production costs.

Conversion R&D Strategic Objective

The strategic objective of the Conversion R&D subprogram is to decarbonize the U.S. economy by developing efficient and economical biological and chemical technologies to convert renewable carbon resources into bioenergy and renewable chemicals and materials.

Conversion R&D Support of the BETO Performance Goals

Conversion R&D supports the BETO performance goal to enable delivery, preprocessing, and deconstruction of biomass and waste feedstocks to biofuel intermediates that can meet industry-relevant cost and performance requirements, with a focus on SAF capable of >70% reduction in GHG emissions relative to petroleum through investment in preprocessing and deconstruction technologies. This research focuses on improving process robustness, as well as ensuring that the resulting intermediates are amenable for subsequent upgrading to fuels and chemicals via biological and catalytic synthesis technologies that are also pursued by the Conversion R&D subprogram.

Conversion R&D supports the BETO performance goal to enable >10 commercial renewable chemicals and materials with >70% GHG reduction relative to relevant petroleum-derived counterparts, supporting >1 million metric tons/yr CO_2e emissions reductions through strategic investment in technologies that generate chemicals from renewable carbon and waste resources.

This includes direct chemical replacements, as well as bio-based chemicals and materials with performance advantages over fossil-derived incumbents.

Conversion R&D supports the BETO performance goal to enable at least one cost-effective and recyclable bio-based plastic that mitigates ≥50% GHG emissions relative to virgin resin or plastic intermediates through investment in R&D to produce polymers from biomass and other waste resources that reduce the need for virgin plastics, can be recycled or upcycled, and would support a circular economy.

Conversion R&D coordinates closely with other BETO subprograms in support of BETO's additional performance goals:

- Conversion R&D coordinates closely with RCR in support of BETO's goal to demonstrate over three place-based strategies for climate-smart agriculture, waste management, environmental remediation, or other beneficial uses of renewable carbon resources through support for sustainability indicator identification, quantification, and monitoring, and by developing technology solutions that can be tested and evaluated in tandem with community partners.

- Conversion R&D coordinates closely with SDI in support of BETO's goal to support scale-up of multiple biofuel production pathways with a focus on SAF capable of >70% GHG reduction by enabling the construction and operation of at least four demonstration-scale integrated biorefineries by investing in initial process engineering and unit optimization to provide confidence that further efforts can progress to the piloting stage.

Conversion R&D Strategic Approach

Conversion technologies can produce intermediates such as sugar and lignin from low-temperature deconstruction, and bio-oil and gaseous intermediates from high-temperature deconstruction. These intermediates can be recombined using a variety of biological and catalytic techniques to produce biofuels and renewable chemicals and materials. Additionally, the use of resources like CO_2 and plastics can provide sources of carbon that can be redirected from waste streams to valuable products. The diversity of feedstocks, intermediates, and end products reflects a need for a variety of conversion technologies. Therefore, the strategic approach of Conversion R&D to meet the BETO performance goals can be organized around the development of gaseous, sugar and lignin, oil, and direct chemical production platforms as outlined below.

Strategy 1: Develop Gaseous Platforms

R&D Challenges and Opportunities

Conversion R&D includes the development of gaseous platforms. This includes generating, cleaning, and upgrading syngas via the gasification of feedstocks, utilizing waste gas streams from industrial processes, cleanup of landfill gas and biogas, and the conversion of CO_2 to fuels and chemicals. Each of these research areas has unique challenges that must be overcome, and they are explored in coordination with the DOE Office of Fossil Energy and Carbon Management. The following are the research needs related to gaseous platforms emphasized within the Conversion R&D subprogram and addressed through applied R&D.

Conversion Challenge 1.1 Gasification Optimization

Successful commercial deployment of bioenergy gasification systems requires thermodynamic, kinetic, and practical reactor design and operation appropriate for the conversion of solid feedstocks to quality syngas. Feedstock variability and quality, reactor design, and overall system controls have a high impact on syngas quality. The main opportunities for syngas research include:

- Improving operational reliability, including the ability to reliably feed various renewable carbon resources at pressure and adequately clean syngas streams to allow post-gasification compression and upgrading.

- Improving processing efficiencies in converting syngas to intermediates and end products and improved process designs that can reduce costs and maximize carbon and energy efficiency.

- Finding solutions for inorganic contaminants that interfere with conversion and upgrading processes. These contaminants can result in issues such as catalyst poisoning and side reactions. Additionally, their presence in product streams can lead to off-specification intermediates that are unacceptable for biofuels or renewable chemicals and materials.

Conversion Challenge 1.2 Gaseous Fermentation Development

Gas fermentation is a technology that has been demonstrated at commercial scale and represents a promising avenue for the deployment of biofuels and renewable chemicals and materials. A prominent example is the generation of ethanol through the biological conversion of a mixture of carbon monoxide (CO), CO_2, and hydrogen (H_2) from an industrial waste gas stream. However, this feedstock can also be produced from the gasification of biomass, MSW, or the chemical reduction of CO_2. Enabling this technology to decarbonize a broader portion of the economy will require:

- Microbial development in a number of host organisms to provide routes to new products. This will necessitate the application of the requisite genetic tools to engineer relevant metabolic pathways.

- Innovative reactor designs and fermentation optimization to maximize mass transfer of gas into solution and increase efficiency.

Conversion Challenge 1.3 Catalyst Development

Catalytic processes offer many routes in the conversion of gaseous feedstocks to fuels and chemicals. R&D of these catalysts in the appropriate environment can overcome their challenges and hasten their implementation. Such opportunities include:

- Improving the selectivity to desired molecules, ideally in single-pass conversion to improve process carbon and energy efficiency.

- Assessing the impacts of impurities present in bio-derived streams on catalyst performance. This defines the requirement to mitigate such impacts through cleanup, separations, or by catalyst reformulation.

- Investigating catalyst deactivation mechanisms through joint computational and experimental approaches to improve catalyst formulation.

- Shortening the time frame of technology development through engineered catalyst forms early in the research process.

Conversion Challenge 1.4 Carbon Dioxide Utilization

While CO_2 as a feedstock can help a decarbonized economy meet its renewable carbon needs, it is fully oxidized and needs considerable energy input before it can be converted into biofuels and renewable chemicals and materials. The two main categories of challenges to this technology include:

- Electrochemical or biochemical reduction of CO_2 into intermediates. Leveraging renewable electricity to provide the energy for this step provides an opportunity to generate biofuels and renewable chemicals and materials of very low carbon intensity; however, doing so sustainably requires an amount of renewable electricity that does not yet exist nationally.

- Upgrading of CO_2-derived intermediates. Once reduced, carbon intermediates such as CO, formic acid, or methanol can be subsequently upgraded to a wide variety of products through various thermochemical and biochemical routes. Some of these upgrading options have already been established and scaled up, while others remain at much lower TRL.

R&D Activities

The Conversion R&D subprogram activities that address these challenges are listed in the following subsections.

Conversion Activity 1.1 Gasification Optimization

- Defining feedstock quality material attributes (e.g., moisture content, ash speciation/content, size reduction optimization for heating rate) to quantify trade-offs between cheaper, lower-quality feedstocks (including blends) and product yields, maintenance cycles, and costs, which will inform reliable and economic operations of gasification technologies.

- Identifying effective mitigation strategies, such as treatments or separations, that can deal with inorganic species found in feedstocks.

- Validating long-term integrated operations of feeding, gasification, and upgrading unit operations in partnership with BETO's SDI subprogram and the DOE Office of Fossil Energy and Carbon Management. Computational approaches can avoid costly physical plants and testing.

Conversion Activity 1.2 Microbial Engineering and Fermentation Development for Waste Gas Conversion

- Genetic engineering of microorganisms that can use $CO/CO_2/H_2$ streams to make biofuels and renewable chemicals and materials. This includes work on improving native pathways to products, constructing novel pathways, and engineering aerobic and anaerobic microbes for increased robustness during extended and variable fermentations.

- Investigating how reactor design and conditions affect fermentation efficiency and mass transfer of gaseous substrate.

Conversion Activity 1.3 Catalyst Development

- Advancing technology readiness of catalysts used in conversion processes such as syngas to fuel or ethanol to fuel.

- Continued research on the conversion of cellulosic ethanol to SAF via ketones to improve on the two-stage ethanol to ethylene to butene technology.
- Developing catalysts for the conversion of cellulosic ethanol to SAF via butenes in a single-stage process.
- Developing pathways that convert CO_2-rich syngas to SAF to improve upon capital-intensive processes that are currently used for syngas upgrading.
- Pursuing syngas-to-methanol synthesis and methanol-to-olefins technology to SAF, with a particular emphasis on improving the oligomerization of C2–C5 olefins to C8+ olefins.

Conversion Activity 1.4 CO_2 Reduction to Intermediates and Intermediate Upgrading

- Investing in strategies that rely on renewable electricity to provide the energy needed to reduce CO_2 to C1 or C2 intermediates, with a focus on electrolyzer design and improving electrocatalysis current density, overpotential, and carbon efficiency.
- Exploring strategies for upgrading intermediates from CO_2 reduction, including CO, methanol, and formate.
- Integrating CO_2 reduction and downstream upgrading strategies, such as ensuring that the output of electrocatalysis matches the needs for biological conversion.

Strategy 2: Develop Sugar and Lignin Platforms

R&D Challenges and Opportunities

Conversion R&D includes the development of sugar and lignin utilization strategies. This includes the fractionation of biomass into those constituent components and the subsequent upgrading of the resulting cellulose, hemicellulose, and lignin streams. The following are the research challenges and opportunities related to sugar and lignin platforms explored within the Conversion R&D subprogram.

Conversion Challenge 2.1 Deconstruction of Lignocellulosic Biomass into Sugars and Lignin

While significant progress has been made toward the production of clean sugars, notable challenges remain in biomass deconstruction, including:

- Lowering the cost of cellulosic sugar production, including improvements to pretreatment, sugar concentration, and separation from lignin.

- Dealing with the alterations to lignin chemistry that occur during high-temperature and acidic pretreatments, which make it difficult to convert.

Conversion Challenge 2.2 Conversion of Cellulosic Sugars

Carbon intensity and production cost remain the key barriers to the adoption of cellulosic sugar as a feedstock for producing biofuels and renewable chemicals and materials. Notable challenges include:

- Reducing or avoiding the use of carbon-intensive chemicals.
- Enabling the concurrent conversion of hexose (C6) and pentose (C5) sugars at the same rates.
- Improving biological and catalytic sugar upgrading strategies.

Conversion Challenge 2.3 Conversion of Lignin

Lignin is a class of complex organic polymers that form key structural materials in the support tissues of most plants. Although this complex structure presents significant challenges to its use, its unique architecture also provides opportunities. These challenges and opportunities include:

- Depolymerizing lignin into low-molecular-weight compounds that can be upgraded.
- Synthesizing high-performance products such as fibers, resins, and foams that leverage structural properties of native lignin.
- Leveraging the structure of lignin to meet the cycloalkane and aromatic needs of SAF blendstock.

R&D Activities

The Conversion R&D approach to developing sugar and lignin platforms is organized around the following activities: Lignocellulosic Biomass Deconstruction and Fractionation, Lignin Deconstruction and Valorization, and Biological/Low-Temperature Conversion Strategies.

Conversion Activity 2.1 Lignocellulosic Biomass Deconstruction and Fractionation

Efforts continue within Conversion R&D to convert lignocellulosic biomass into sugars that can achieve comparable performance to starch-derived sugars, as well as lignin that can be upgraded. Activities in this area include:

- Quantifying the impact of feedstock variability on biomass deconstruction and on downstream conversion performance, in coordination with RCR.
- Exploring the use of low-CI chemicals and processes (or avoidance altogether).
- Investigating pretreatment strategies that can preserve natural lignin chemistry.
- Enabling the fractionation of separate hexose and pentose sugar streams.

Conversion Activity 2.2 Lignin Conversion

Conversion R&D conducts research into a variety of strategies to deconstruct lignin and achieve high-yield conversion to products from lignin-derived intermediates, including:

- Approaches that remove lignin prior to other deconstruction processes.
- Solvent-based processes that can dissolve lignin monomers into liquid phase.
- Catalysts and biocatalysts that can selectively separate lignin into monomers and oligomers, as well as those that can upgrade such intermediates to biofuels and renewable chemicals and materials.
- Approaches to utilizing lignin in its raw polymeric form for a variety of applications.

Conversion Activity 2.3 Biological/Low-Temperature Sugar Conversion

In addition to deconstruction and pretreatment technologies, a key R&D need is the development of systems that can biologically convert sugars to biofuels and renewable chemicals and materials. BETO prioritizes several approaches to accomplishing this:

- Engineering microbial hosts to produce intermediates from sugar that can be converted to biofuels and renewable chemicals and materials.
- Solutions for co-utilizing hexose and pentose sugars at equal rates, including genetic engineering strategies for rapid pentose transport and uptake that are compatible with a wide variety of microbial hosts.

Conversion Activity 2.4 Upgrading of Biochemically Derived Intermediates

Pathways that feature the catalytic upgrading of biochemically derived intermediates that can then be upgraded into specific fuel molecules, blendstock components, and other products are of high interest. Conversion R&D in this area focuses on the catalytic upgrading of volatile fatty acids, 2,3-butanediol, and furanic intermediates. Specific activities include:

- Improving catalyst stability while keeping conversion higher than 90%.
- Determining the tolerance threshold of the catalysts to the impurities present in fermentation broths.
- Demonstrating the viability of new pathways that decrease reliance on upstream separation processes.

BETO Strategy 3: Develop Oil Platforms

R&D Challenges and Opportunities

Conversion R&D includes the development of oil platforms that can generate and upgrade liquid organic products from feedstocks. Typical liquefaction technologies include fast pyrolysis, catalytic fast pyrolysis, and hydrothermal liquefaction, and advantages to oil platforms include high carbon conversion to liquid organic products and the ability to leverage existing refinery infrastructure for upgrading to fuels and chemicals. Previous advances have overcome many of the technical barriers around the production of bio-oils and stand-alone upgrading, though operational reliability and high capital costs remain core challenges. Coprocessing within petroleum infrastructure represents a near-term opportunity to incorporate large volumes of bio-oils to partially decarbonize fuels and chemicals. Upgrading bio-oils to final products efficiently and economically while reducing impacts to existing refinery infrastructure remains a notable barrier to commercialization. The following are the research challenges associated with oil platforms.

Conversion Challenge 3.1 Generating and Stabilizing Bio-Oils

- Maintaining high overall conversion to liquid product yields while minimizing char and light gases and other “bad actors” in the bio-oil.
- Identifying critical material attributes of bio-oils as they relate to downstream upgrading equipment and processes.
- Identifying robust catalysts that can produce sufficiently stable bio-oils at high carbon yields.
- Energy-efficient separations of solids (char), light gases, and liquids for side-stream valorization.

Conversion Challenge 3.2 Hydroprocessing and Catalytic Upgrading of Bio-Oils

- Long-duration catalyst viability and catalyst regeneration.
- Technology improvements and upgrading catalysts capable of reducing the concentrations of oxygen and nitrogen to meet fuel specifications, especially for SAF.
- Cracking and isomerization.
- Improvements to jet-range yield and meeting cold flow properties and energy density for fuels derived from bio-oils.
- Compatibility with existing upgrading processes is not well understood and is highly feedstock-dependent.
- Investigating the compatibility of existing hydroprocessed esters and fatty acids (HEFA) catalysts with emerging oilseed crops (e.g., carinata, camelina, pennycress) and other waste oil sources (e.g., brown grease) and the degree to which removal of contaminants might be necessary.

Conversion Challenge 3.3 Compatibility for Coprocessing/Co-Hydrotreating

- Compatibility and miscibility with refinery insertion points at various blend volumes is needed to understand long-term impacts to catalysts, equipment, and overall yields to products.
- Producing representative quantities of bio-oil required for testing/evaluation in refinery processes.
- Developing near-real-time analytics that can track the fate of renewable bio-oil through refineries to quantify the renewable carbon content for Renewable Fuel Standard and Low Carbon Fuel Standard calculations, as well as operational optimization.

Conversion Challenge 3.4 Volatile, Aqueous, and Solid Stream Management

- Developing solutions for dealing with the aqueous streams from pyrolysis and hydrothermal liquefaction technologies; such high-strength wastewaters are not compatible with existing wastewater treatment facilities and require dedicated industrial wastewater solutions.
- Developing strategies to minimize, recycle, or further upgrade the volatile or light gases produced during liquefaction to increase carbon efficiency.

- Minimizing or valorizing solid streams (char) resulting from liquefaction, which can contain inorganics and other contaminants that may require costly disposal or removal.

R&D Activities

The Conversion R&D approach to developing oil platforms is organized around the following activities.

Conversion Activity 3.1 Generating and Stabilizing Bio-Oils

- Reducing coking and external hydrogen use.
- Exploring catalyst modification to improve selectivity, costs, and robustness.
- Optimizing reactor operation.
- Understanding feedstock parameters to connect critical material attributes to downstream upgrading performance.
- Investigating fundamental catalyst deactivation mechanisms through joint computational and experimental approaches that utilize advanced characterization approaches.
- Exploring downstream fractionation/separations approaches beyond the use of fluidized bed or circulating fluidized beds for pyrolysis of biomass and wastes to improve overall economics, particularly related to solids removal and light gases valorization.
- Researching other process intensification efforts to enable additional improvements to carbon and energy efficiency.

Conversion Activity 3.2 Hydroprocessing and Catalytic Upgrading of Bio-Oils

- Investing in long-duration catalyst studies, including regeneration, to understand deactivation mechanisms while generating sufficient yields to fuel products.
- Evaluating the effect of emerging sustainable oilseeds and waste oil sources on HEFA catalysts to establish catalyst durability.

Conversion Activity 3.3 Compatibility for Coprocessing/Co-Hydrotreating

- Researching miscibility and limits of blending of bio-oils with fossil streams and exploring impacts to product slate and refinery processes. Understanding bio-oil properties to connect critical material attributes to blending scenarios.
- Upgrading blends of bio-oils with varying oxygen content to optimize fuel properties and determine impacts to upgrading catalysts and equipment.
- Collaborating with expertise in refinery modeling (e.g., DMA subprogram) to quantify the air, water, emissions, quality of life, and other key impacts of refinery coprocessing.
- Developing alternative methods for biogenic carbon accounting in coprocessing/co-hydrotreating approaches that can provide near-real-time feedback. Adapting analysis equipment and procedures from other industries is an example of activities being explored to enable faster biogenic accounting.

Conversion Activity 3.4 Volatile, Aqueous, and Solid Stream Management

- Exploring long-duration aqueous treatment tests to ensure process robustness and potential for recycling to existing wastewater treatment infrastructure; investigating efficacy of treatments and overall energy to understand impacts to the overall process.

Strategy 4: Develop Targeted Chemical Production Platforms

R&D Challenges and Opportunities

Conversion R&D includes the development of chemical production strategies. The production of renewable chemicals contributes to BETO's goals for the decarbonization of the industrial sector. The current chemical manufacturing industry predominantly produces chemicals from fossil sources, and the majority of industrial decarbonization approaches are currently focused on making existing manufacturing processes more energy efficient. Generating chemicals from renewable carbon resources not only provides an opportunity for lowering the overall process energy, but also enables the replacement of fossil carbon with renewable carbon. It is also a near-term opportunity to commercialize bioenergy strategies that can pave the way for decarbonization in other sectors, such as transportation. The following are the research needs related to renewable chemical production emphasized within the Conversion R&D subprogram and addressed through applied R&D.

Conversion Challenge 4.1 Determining What Chemicals to Target for Decarbonization

Product selection impacts the decarbonization potential of a process, the ability to compete with and replace the incumbent chemical, and the potential for commercial deployment, and provides opportunities to create new markets. Research aimed at understanding the challenges and needs for pinpointing the right products that appropriately leverage the unique structure of biomass is essential. The production of novel products that confer a performance advantage over their fossil incumbent could provide market pull. Reduced GHGs and environmental impact similarly can contribute market pull, in addition to demand for renewable products. Enabling this opportunity requires:

- Targeting the largest impact from an LCA perspective.
- Identifying near-term deployment opportunities.
- Identifying products that have production process or performance advantages in comparison to their incumbent.
- Building an identification and prioritization framework for chemicals that are readily accessed from biochemical and catalytic conversion of renewable carbon resources in an atom-efficient manner.

Conversion Challenge 4.2 Producing Chemicals for Industrial Decarbonization

The decarbonization potential of renewable chemical production depends on several factors, such as feedstock selection, conversion route used, bioprocess design and efficiency, and the carbon intensity of the original chemical that is being displaced. Each of these considerations present a unique challenge to solve to facilitate decarbonization of industry.

R&D Activities

The production of renewable chemicals relies on much of the same feedstocks, infrastructure, and conversion technologies that are central to biofuel production. The difference between producing a biofuel or a bioproduct often lies in the upgrading strategy chosen for the deconstructed biomass intermediate. The Conversion R&D approach to developing renewable chemicals is focused on identifying the right chemicals to target and how to make them; this work is done in collaboration with partners in DOE’s AMMTO and includes the following activities.

Conversion Activity 4.1 Identifying Strategic Opportunities for Direct Renewable Chemical Replacement

- Analyses to identify products that have promise for near-term deployment and impact.
- Developing decision matrices regarding cost, performance, and life cycle impacts of the targeted renewable chemical.
- Understanding the process advantages, market size, and supply chain dynamics that would favor renewable chemicals to replace the incumbent.

Conversion Activity 4.2 Exploring Novel Compounds That Can Be Derived from Renewable Carbon

- Investigating the unique benefits that can be provided by the structure of biomass and conversion strategies that cannot be matched by fossil carbon.
- Determining the end product performance needs and standards of incumbent chemicals and identifying unique compounds that can be derived from biomass that offer improved performance.
- Developing unique biochemical and catalytic conversion strategies to such end products.

Strategy 5: Develop Bioplastic Design and Plastic Recycling Platforms

R&D Challenges and Opportunities

Conversion R&D includes the development of platforms for bioplastic design and plastic recycling. Recovery of waste carbon from plastics faces many of the same challenges and opportunities as biomass and can be accomplished via many of the same technologies or processes. Reducing the plastics industry's dependence on virgin petroleum sources through the promotion of recycling and redesign is critical to decarbonization. The following are the research challenges related to bioplastic design and plastic recycling emphasized within the Conversion R&D subprogram and addressed through applied R&D in collaboration with AMMTO.

Conversion Challenge 5.1 Deconstruction, Valorization, and Understanding the Fate of Plastics

The development of new chemical and biological methods for efficient plastic deconstruction into useful chemical intermediates is required to recycle polymers back into carbon-rich starting materials. The development of new technologies for generating high-value chemical intermediates and products from plastic waste requires the discovery of economically viable biological and chemical mechanisms that couple deconstruction with reconstruction and functionalization. Some broad challenges include:

- Leveraging the recalcitrant nature of current plastics waste as a feedstock for generating high-value products with a reduction in GHGs.
- Developing selective methods for specific plastics, as well as broad methods to process mixed, contaminated waste streams and plastics that are not currently recyclable.
- Developing deconstruction approaches for flexible plastic packaging, including multilayer materials, which are not currently recyclable.
- Integrating experimental, computational, and data science tools to elucidate the mechanisms and kinetics of deconstruction, reconstruction, and material performance.
- Understanding the end-of-life impacts of the material on the environment, human health, and future recycling.
- Analysis to support the selection of valorization pathways, products, and markets with specific focus on reducing GHGs.

Conversion Challenge 5.2 Designing Bioplastics for Recyclability

Enabling processes to develop new plastics out of renewable feedstocks with both deconstruction and reconstruction in mind will ultimately be required to enable a circular plastics economy. A key set of challenges facing the development of these materials includes:

- Understanding the relationship between polymer structure and desired functionality to optimize recyclable bio-based polymers with reduced GHG and environmental impacts.
- Developing approaches for the synthesis, breakdown, separation, and manufacturing of new plastics that can be integrated with existing infrastructure and facilitate industry adoption.
- Improving chemical and biological technologies to convert alternative carbon feedstocks into monomers and polymers to complete a carbon-reducing circular life cycle.

R&D Activities

The Conversion R&D approach to developing platforms for bioplastic design and plastic recycling includes reducing and removing plastic waste from the environment by developing improved recycling and "upcycling" technologies, reducing the GHG footprint of plastics production through development of bio-based plastics, and ensuring technologies are scalable and provide cost and environmental benefits sufficient to motivate their deployment. These activities are pursued in collaboration with DOE's AMMTO and are organized around the following processes.

Conversion Activity 5.1 Thermal Processes

- Investigating thermal depolymerization processes to understand and control reaction pathways for gasification and pyrolysis of plastics.
- Exploring the impact of impurities and additives on the deconstruction of mixed streams.
- Reducing the cost and improving efficiency of thermal processes to gas and liquid intermediates that can be sustainably recycled or valorized.

Conversion Activity 5.2 Catalytic Chemical Processes

- Designing new selective catalysts to enable precision cleavage of polymeric bonds.
- Exploring new circular chemistries that enable easy synthesis and depolymerization for recycling and recovery.
- Developing selective polymer functionalization for dynamic or reactive separation strategies to facilitate monomer recovery in complex streams.

Conversion Activity 5.3 Biological Processes

- Enabling novel biological mechanisms, enzymes, and pathways to deconstruct and convert plastic polymers into a diverse range of products.
- Identifying biological pathways to produce novel plastics from renewable resources.

Conversion Activity 5.4 Physical Processes

- Integrating chemical recycling within the existing chemical manufacturing industry to improve value propositions that will ultimately reduce plastic waste generation.

- Enabling existing recycling infrastructure to overcome challenges associated with mixed plastic waste including sorting, contamination, and mechanical processing, as well as collection and transport.

Strategy 6: Develop Waste Management and Environmental Remediation Strategies

R&D Challenges and Opportunities

Conversion R&D includes development of conversion approaches for waste management and environmental remediation. Organic waste streams represent economic, environmental, and social sustainability liabilities to the communities that manage them. These include high costs of management, fugitive methane emissions, air and water quality impairments, and decreased quality of life for those who live near waste management facilities. Conversion R&D focuses on development of processes and strategies that can improve resource and energy recovery from these wastes and avoid landfill disposal. The following are the research challenges related to waste management and environmental remediation emphasized within the Conversion R&D subprogram and addressed through applied R&D.

Conversion Challenge 6.1 Maximizing Resource/Energy Recovery from Waste Streams

Waste streams contain valuable nutrients such as nitrogen and phosphorus. Developing ways to ensure these side streams are valorized can further create value and local resilience to these communities. It also prevents the creation of further waste stream management challenges.

Conversion Challenge 6.2 Place-Based Challenges

Local and regional factors such as waste compositions, existing infrastructure, policies/statues, and others create the need for local analysis and scoping.

Conversion Challenge 6.3 Emerging Contaminants

Fluorinated species (e.g., per- and polyfluoroalkyl substances [PFAS], perfluorooctane sulfonic acid [PFOS]), pharmaceutical residues, and other emerging contaminants of concern are a burgeoning challenge for communities. Technologies are needed to address these emerging environmental challenges and to address rising costs of waste management.

Conversion Challenge 6.4 Community Capacity and Tolerance for Risk

Waste management infrastructure is disproportionately sited in disadvantaged and pollution-burdened communities. Capacity of local decision makers and staff to evaluate new technology solutions or approaches and their risk tolerance can vary widely and requires community input and partnership to determine.

A critical challenge of next-generation waste systems is to ensure that they are sufficiently robust to replace the incumbent practices (e.g., traditional anaerobic digestion, incineration). Process failure can result in accumulation of waste, which is an unacceptable outcome from an environmental, social, and economic perspective.

R&D Activities

The Conversion R&D approach to developing platforms for waste management and environmental remediation is ultimately prioritized at reducing volumes of organic waste that are landfilled and recovering resources and energy from these streams. Priorities in this area of the Conversion R&D subprogram are to develop solutions that are capital efficient compared to incumbent processes, are sufficiently robust and de-risked, and that support the multiple needs of communities that ultimately can implement them. These activities build on collaborations with offices within DOE (Weatherization and Intergovernmental Programs, AMMTO), USDA, and the Environmental Protection Agency.

Conversion Activity 6.1 Development of Next-Generation Resource and Energy Recovery Processes for Waste Feedstocks

- Developing systems with lower capital costs that can convert and recover additional value, with preference for processes that can produce readily transportable products or intermediates.
- Conducting long-duration (thousands of hours) experimental studies from real waste streams or blends and making those results publicly available.
- Developing methods for stable and continuous separations of products and intermediates from these new processes.

Conversion Activity 6.2 Support for Local Decision Making and Understanding of Risk

- Supporting local feasibility analysis and stakeholder engagement to enable place-based solution implementation.
- Creating partnerships between local decision makers and industrial entities and researchers to evaluate the technology readiness and risks of emerging technologies.

- Collaborating with expertise in other disciplines (e.g., DMA subprogram) to quantify the air, water, emissions, quality of life, and other key impacts of emerging technologies.
- Conducting and communicating risk analysis for novel approaches.

2.6 Systems Development and Integration

The SDI subprogram develops, tests, and verifies pre-pilot-, pilot-, and demonstration-scale biorefinery process performance to reduce technology uncertainty and enable subsequent industry-led scale-up activities leading to full commercialization. In addition, SDI develops novel methods to expand end-user acceptance of bioenergy and renewable chemicals and materials and identifies new, robust market opportunities. SDI conducts integrated systems research—combining technology components, unit operations, or subsystems; testing under integrated operations; downstream testing of fuel and product specifications; and verifying the integrated process at various scales. Furthermore, SDI invests in technologies aimed at decarbonizing energy-intensive industries.

SDI's integrated systems research at engineering scale provides a foundation for industry to advance these technologies through scale-up and deployment as measured by TRL. "Engineering scale" is the range of development steps beyond laboratory- or bench-scale activities that integrates the major components and subsystems, tests and demonstrates the operational performance, and facilitates the design and optimization of pre-pilot-, pilot-, and/or demonstration-scale systems in increasingly relevant and realistic environments. Engineering-scale work is supported by SDI in partnership with national laboratories, academia, and industry through competitive awards.

Verifying technologies at appropriate partially or fully integrated scales is important to reducing technology uncertainty and overcoming operational challenges. As illustrated in Figure 2-5, SDI works with the RCR, DMA, and Conversion R&D subprograms to investigate and develop a variety of industrially relevant biomass feedstocks and conversion pathways. The TRL 2–5 research done in these subprograms informs SDI's portfolio of technologies that show promise and warrant systems integration and development to advance these technologies beyond TRL 5 at more commercially relevant scales. Testing components or subsystems in an experimental prototype and in a relevant operating environment often identifies further R&D needs that are fed back to the other BETO subprograms. In addition, sufficient quantities of target products are needed for applicable quality control testing to verify existing infrastructure compatibility and potential end-user specifications. Engineering-scale verification data are also needed to evaluate R&D techno-economics and sustainability progress.

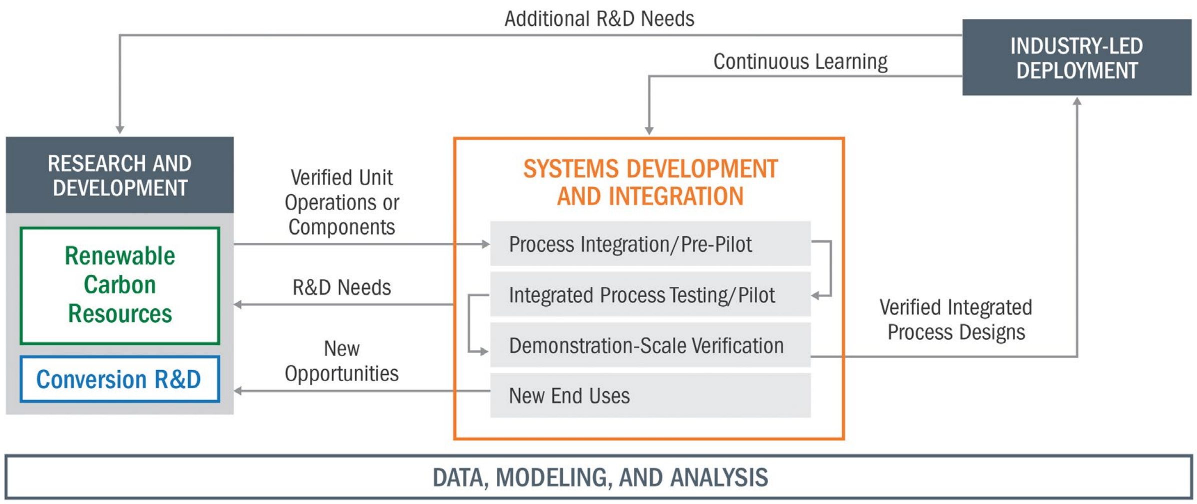

Figure 2-5. SDI scope and interfaces

Potential product slates include biofuels for the aviation, marine, rail, and heavy-duty long-haul trucking industries, as well as renewable home heating oil, renewable chemicals and materials, and biopower. Each alternative feedstock-conversion technology pathway must be tested and verified at different engineering scales to sufficiently reduce technology uncertainty, de-risk scale-up and commercialization, ensure target product specifications, verify techno-economics and life cycle emissions, and reach widespread acceptance, as illustrated in Figure 2-6.

Figure 2-6 illustrates how SDI supports scaling an IBR facility and the foundation for technology development at increasing scales. The concentric ovals indicate that each stage builds on the results of the prior. The figure also describes the unique objectives at each stage, including the eventual first-of-a-kind commercial-scale or pioneer plant, which represents the handoff to industry.

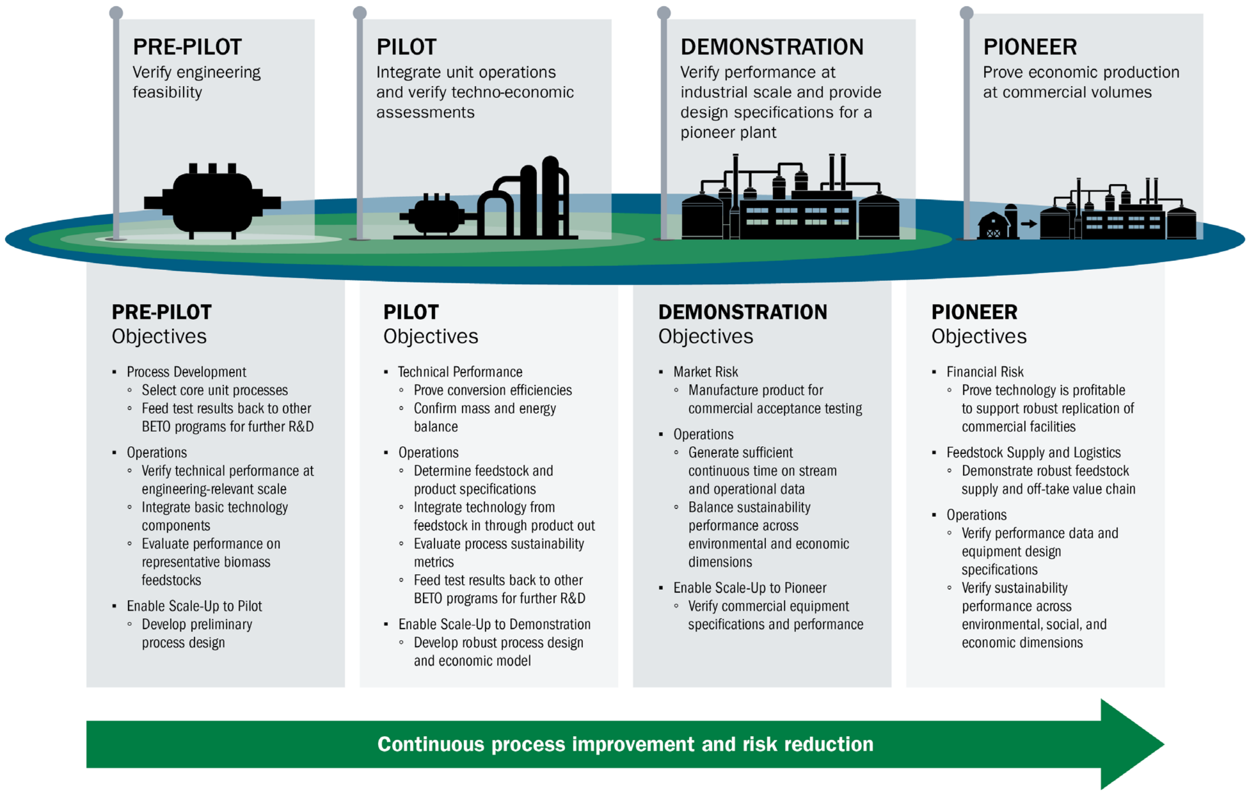

Figure 2-6. Description of key objectives and progression of scale-up of IBRs

SDI RD&D Strategic Objective

The strategic objectives of the SDI subprogram are to develop and test bioenergy production technologies through verified proof of performance at pre-pilot-, pilot-, and demonstration-scale systems in relevant environments; research methods and tools to enhance scaling and integration to de-risk bioenergy production processes; and accelerate the uptake and commercialization of these technologies by the private sector.

SDI Support of the BETO Performance Goals

SDI directly supports BETO's goal to scale up multiple biofuel production pathways, with a focus on SAF capable of >70% GHG reduction, by enabling the construction and operation of at least four demonstration-scale integrated biorefineries. The primary approach to meeting this performance goal is competitively awarded, cost-shared funding opportunities aimed at optimizing and de-risking technologies for SAF production and other hard-to-decarbonize transportation fuels at the pre-pilot, pilot, and demonstration scales. SDI also supports the qualification of new SAF pathways in accordance with applicable ASTM International standards to accelerate new biofuel safety testing, evaluation, and specification activity, which helps to reduce the cost and time for new approvals while expanding the range of qualified fuels to include new critical pathways that will enable expansion of SAF supply. The scale-up of these technologies is intended to facilitate BETO's strategic goals of decarbonizing the transportation sector through SAF and other biofuels production, decarbonizing the industrial sector, and supporting technologies that lower the CI of the agricultural sector.

SDI also supports BETO's performance goal to enable delivery, preprocessing, and deconstruction of biomass and waste feedstocks to biofuel intermediates that can meet industry-relevant cost and performance requirements, with a focus on SAF capable of >70% reduction in GHG emissions relative to petroleum, through the integration of individual unit operations developed by the RCR and Conversion R&D subprograms, while also enabling end use. Investing in SAF production infrastructure to support industry deployment will attract industry investment in SAF production capacity. In addition, SDI's focus on integration and scaling of sustainable feedstocks will enable innovations in technologies and strategies that increase the availability of renewable carbon resources at reduced CI and cost. This includes addressing the social, environmental, and economic sustainability aspects of feedstock supply chains.

SDI's portfolio aims to mature the pipeline of BETO-funded technologies through collaboration with BETO's subprograms. SDI conducts a rigorous, metrics-driven selection process, adding new projects to the portfolio to support de-risking and demonstration of production processes for fuels from a variety of domestic renewable carbon resources and downselecting the strongest projects to construction. To improve first-of-a-kind biorefinery success, SDI supports the establishment and utilization of a risk mitigation plan framework for bioenergy systems scale-up using data collected from competitively awarded projects. The successful scale-up and commercial deployment of these integrated biorefineries will enable volumes of SAF to enter the market and contribute to decreasing CO_2 emissions by 450 million metric tons per year by 2050.

SDI coordinates closely with each of the other subprograms in support of BETO's additional performance goals:

- SDI coordinates with RCR in support of BETO's goals to enable delivery, preprocessing, and deconstruction of biomass and waste feedstocks to biofuel intermediates that can meet industry-relevant cost and performance requirements through activities coordinating gap areas that focus efforts on providing conversion-ready feedstocks that can overcome barriers related to materials of construction, material handling, and feeding and flow issues at scale. RCR provides feedstock supply availability across the United States that informs the near-term commercialization of bioenergy production and supports planning for long-term opportunities.

- SDI coordinates with the Conversion R&D subprogram in support of BETO's performance goal to enable >10 commercial renewable chemicals and materials with >70% GHG reduction through support of process development units (PDUs) that enable testing at scales larger than bench scale and provide a feedback loop identifying risks that need further research before integration and scaling. These facilities are maintained in the national laboratories and are available to external stakeholders, reducing the investment in expensive capital for testing at early scale-up stages of development.

- SDI coordinates with DMA in support of BETO's performance goals by supplying data and, in turn, using DMA's analyses to facilitate the integration and scaling of the most environmentally sustainable and economically feasible practices.

SDI RD&D Strategic Approach

SDI RD&D aims to reduce the risk of scaling bioenergy technologies, preparing them for handoff to commercial industry and for market adoption. The strategic approach of SDI RD&D to meet the BETO performance goals can be organized by activities focused on the integration and scale-up of production platforms for SAF, other strategic transportation fuels, and renewable chemicals and materials, and developing market solutions for hard-to-decarbonize modes of transportation.

Strategy 1: Integration and Scale-Up of Production Platforms for SAF, Other Strategic Transportation Fuels, and Renewable Chemicals and Materials

RD&D Challenges and Opportunities

Integrating and scaling renewable carbon resources with conversion technologies faces several challenges hindering larger engineering scales and end product market penetration. Below are some examples of the challenges associated with scaling bioenergy technologies that must be met for successful commercialization.

SDI Challenge 1.1 Validating Performance of Critical Unit Operations

Based on lessons learned from previous integrated biorefineries, there are critical unit operations that should be tested and validated individually to allow for the better design implementation of an integrated system. These critical unit operations may include new technologies that are being incorporated into an existing process or existing technologies that are being used under new operating conditions, which may increase risk for overall system performance. Some of the challenges associated with these critical unit operations include:

- Mass and energy balances are unproven at smaller scales, even though assumptions can be tailored to ensure economic and life cycle attributes for the unit operation(s) meet business models.

- Economic drivers often dictate that a process be continuous to meet throughput requirements. When moving a process from batch to continuous operations there are always associated challenges including material handling, flowability, feed rates, separations, cleaning in place, and many others.

- Utilizing real vs. "ideal" feeds can introduce new variables. At smaller scales, feedstock quality can be easily controlled and manipulated. While conversion technologies should always utilize "real-world" feeds whenever possible, the amount of feedstock often required at larger scales tends to be provided through industrial suppliers. Switching feedstock suppliers presents a number of challenges including differing material properties, material specifications, and new or unknown contaminants.

- Feeding solid biomass into high-pressure systems remains one of the biggest challenges to bioenergy scale-up. Blowback at large scale creates a safety hazard as well as operational anomalies that can increase downtime and maintenance costs.

SDI Challenge 1.2 End-to-End Process Integration

Individual unit operations may operate sufficiently on their own, but do not always perform as designed when tied into a system. Demonstrating and validating total process integration, from feedstock in through product out, is crucial as it impacts performance, economic, and sustainability goals. Some challenges associated with end-to-end process integration include:

- Heat integration and the amount of energy required, based on various heat transfer rates, can affect all aspects of the material handling, conversion, and upgrading processes including retention time, yields, material flow, overall energy usage, and final product(s) specifications. Typically, a shared heating source is used to provide the energy input to the entire process.

- Feedstock variability has an impact on all downstream operations. Fully integrated processes experience the majority of these process upsets due to known or unknown impurities, out-of-spec sizing/content, handling difficulties, and possible plugging, which all impact the final fuel/product specifications.

- Operational reliability of subsystems, such as pumping, mixing, separations, solvent recovery, catalyst regeneration or poisoning, cleanup, and conditioning can decline as time on stream increases.

SDI Challenge 1.3 Capital and Operational Costs

As bioenergy technologies increase to the next scale, they may encounter new technology risks that can lead to unplanned increases in capital and operational costs that project developers often do not include in initial techno-economic estimates. Capital and operational cost challenges associated with scaling bioenergy technologies include:

- Materials of construction required for larger-scale operations differ from smaller-scale technologies, which benefit from more readily available options for piping, tubing, pumps, etc. At larger scales, the materials available can be more limited, which poses a challenge in itself to determine corrosion, erosion, and other forms of equipment damage prevention and appropriate preventative maintenance.
- Equipment costs can vary from assumptions made at smaller scales. Entities may struggle to identify technology suppliers at the scales needed. This can lead to additional cost and risk because the suppliers may have to custom fabricate the equipment and may not provide the performance guarantees due to the customization. Even “off-the-shelf” commercially available equipment that is operated in new or modified environments adds risks, which the supplier may not underwrite.
- Operating expenditures such as staffing, material costs, and possible equipment redesigns or charge orders associated with commissioning can often drain available funding before adequate data and product(s) are produced. Operational issues can require shutdowns, remediations, and debottlenecking for successful operations.

RD&D Activities

The SDI approach to overcoming the above challenges is organized around the following activities: Validating Performance of Critical Unit Operations, End-to-End Process Integration, and Capital and Operational Costs. SDI must demonstrate successful execution of these activities to advance the commercial scaling of bioenergy technologies.

SDI Activity 1.1 Validating Performance of Critical Unit Operations

SDI organizes its RD&D approach to meet critical unit operation challenges by:

- Selecting "pre-pilot-scale" projects (Figure 2-6) that focus on critical unit operation RD&D priorities brought forth by industry partners, national labs, or other BETO subprograms. These projects can address a wide variety of real-world issues regarding the scale-up of bioenergy technologies by validating performance of new technologies at relevant engineering scale before they are integrated into a full end-to-end system.
- Encouraging the use of modeling throughout the scale-up process, including modeling individual unit operations or key integrations, can identify and address design issues to improve overall performance before expensive equipment is purchased or fabricated.
- Providing feedback loops to BETO's other R&D subprograms through biennial peer reviews and other formal and informal exchanges. This allows BETO's other subprograms and industry to prioritize R&D for individual unit operation(s) that are not yet ready to scale up.

SDI Activity 1.2 End-to-End Process Integration

SDI organizes its RD&D approach to meet end-to-end process integration challenges in its fully integrated "pilot-" and "demonstration-scale" projects (Figure 2-6) by:

- Verifying performance at previous scales, utilizing third-party independent engineers, to determine readiness to scale up.
- Requiring throughput metrics such as 0.5 tons per day or a specific number of gallons of biofuel per year equivalent.
- Mandating the use of "real-world" feedstocks in funded projects.
- Requiring extended performance testing with time-on-stream goals such as 500 hours of continuous and 1,000 hours cumulative (for pilot scale) to shake down an integrated process, uncover operational issues, and provide sufficient data to inform future scale-up designs.
- Supporting the PDUs at DOE's national laboratories, which provide existing equipment, operational know-how, and experienced operators to integrate biorefinery unit operations without having to pay to build and operate a complete system.
- Implementing a two-phase project management approach to thoroughly vet and lock designs prior to capital investments:
    - Phase 1 awards provide awardees with funding to perform detailed design including finalization of process flow diagrams, mass and energy balances, procurement-ready

equipment specifications, mechanical layout drawings, piping and instrumentation drawings, ±15% budget estimates, and construction schedules. This allows awardees to complete designs without the capital associated with constructing and operating the integrated biorefinery.

- Phase 2 awards provide awardees with funding to finalize permitting, construct, and operate the fully integrated biorefinery. Awards are structured such that Phase 1 awardees can go through a downselect process to determine the readiness to proceed into Phase 2 without having to recompete for funding. While Phase 2 funds are not guaranteed to Phase 1 awardees, it allows those who have a final design package ready to proceed straight into construction and operation.

SDI Activity 1.3 Capital and Operational Costs

SDI organizes its RD&D approach to meet capital and operational cost challenges by:

- Leveraging commercial technology and existing capital equipment, such as utilizing petroleum refinery infrastructure through coprocessing of biointermediates.
- Verifying design packages and successful performance at previous scales, using third-party independent engineers prior to making capital investments at larger scales.
- Requiring a minimum of 25% of total project costs as contingency reserve for startup, shakedown, and operations to ensure sufficient funding to produce the required data and amounts of product needed for further testing.

Strategy 2: Develop Market Solutions for Hard-to-Decarbonize Modes of Transportation

RD&D Challenges and Opportunities

SDI Challenge 2.1 Solutions for Hard-to-decarbonize Modes of Transportation

To meet BETO's goals associated with decarbonizing the entire transportation sector, research is necessary to provide low-carbon fuel solutions for the range of hard-to-decarbonize modes of transportation.

- The aviation industry accounts for 11% of transportation-related GHG emissions within the United States. Air travel and transport is estimated to grow in the coming years, and aircraft are particularly reliant on liquid fuels. There are still many barriers that need to be overcome in order to create “drop-in” biofuels that are compatible with existing infrastructure and equipment from original equipment manufacturers such as materials compatibility (e.g., seal swelling), process flexibility to produce higher yields of jet fuel vs. diesel fuel based on market demand, feedstock availability, and time/cost to get ASTM approval on new SAF pathways, to name a few.

- The marine industry accounts for 3% of transportation-related GHG emissions within the United States. Due to the global nature of the maritime industry, solutions to decarbonize are very complex and difficult. As such, challenges include more than fuel types, their associated characteristics, and scaling up of processes. Additional challenges including global production limitations, port-to-port infrastructure, bunkering logistics, and working with other potential decarbonizing maritime fuels (e.g., ammonia, methanol, hydrogen) will be investigated to develop strategies that cover many vessel types and operations.
- The rail industry accounts for 1.9% of transportation-related GHG emissions within the United States. One of the main challenges facing decarbonization of the rail sector is the longevity of their capital investments. Many of the current locomotives in the United States have the ability to continue service for another 30–50 years. Decarbonization solutions for the rail industry must include near-term drop-in fuel options and retrofits along with R&D on long-term solutions such as electrification and hydrogen fuels.

RD&D Activities

SDI Activity 2.1 Solutions for Hard-to-Decarbonize Modes of Transportation

SDI works to investigate, demonstrate, and accelerate the industrial production of biofuels for the aviation, rail, and marine sectors that can achieve at least 70% lower carbon emissions as compared to petroleum. These strategies include:

- Conducting feasibility studies and demonstrating technologies and strategies to significantly reduce GHG emissions from first-generation ethanol facilities. If deployed widely, these strategies could yield significant GHG emissions in the near term and enable these existing supply chains to support production of drop-in biofuels for hard-to-decarbonize modes of transportation in the future.

- Prioritizing investments to demonstrate production using the seven ASTM-approved SAF pathways (Figure 2-7, left) and enabling ASTM approval of several new SAF routes that are currently in development (Figure 2-7, right).

- Supporting R&D into possible fuel improvements for SAF through the ability to fine-tune fuel characteristics such as improved molecules that can reduce the formation of contrails, reduce emissions, or deliver higher energy densities that would allow for additional payload weights and improved fuel economy.

- Collaborating with interagency and international partners to investigate a variety of fuel types for potential use in the maritime sector (e.g., renewable diesel, bio-oil, bio-crude, partially upgraded biointermediates, methanol, ammonia), transitional strategies, and usage cases such as pilot fuels and engine/vessel type with LCAs, TEAs, and scenario analyses.

- Conducting techno-economic feasibility studies on the potential for near-term adoption of liquid fuels for use by U.S. freight rail companies (e.g., biodiesel, renewable diesel, bio-oils, ethanol, methanol, dimethyl ether, green ammonia) and characterize major technical challenges and cost drivers to guide future R&D needs.

- Engaging with policymakers and industry stakeholders to catalyze actions and facilitate joint planning and investment in biofuel production and supporting infrastructure to support the deployment of drop-in biofuels, such as building coalitions among airports, airlines, fuel producers, and fueling infrastructure owner/operators.

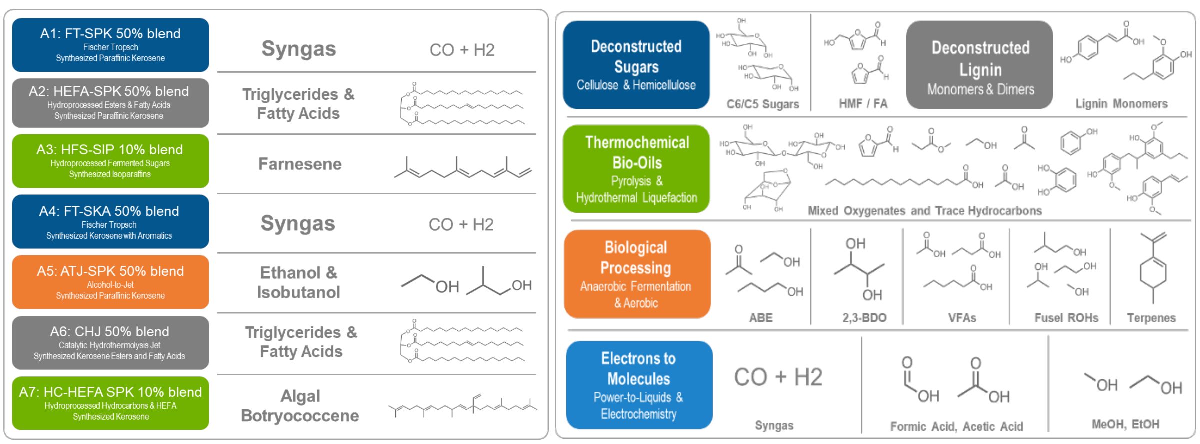

Figure 2-7. (Left) Current ASTM-approved SAF pathways[25] and (right) emerging SAF pathways that still need ASTM approval[26]

2.7 Data, Modeling, and Analysis

Delivering affordable, reliable, and environmentally sustainable energy requires consideration of technology and environmental factors, awareness of policy and market developments, and collaborative solutions with diverse stakeholders. BETO supports analysis, research, and

[25] ASTM International, *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*, West Conshohocken, PA: ASTM International, ASTM D7566-20 (2020); W.-C. Wang, L. Tao, J. Markham, Y. Zhang, E. Tan, L. Batan, E. Warner, and M. Biddy, *Review of Biojet Fuel Conversion Technologies*, Golden, CO: National Renewable Energy Laboratory, NREL/TP-5100-66291 (2016), https://www.nrel.gov/docs/fy16osti/66291.pdf; J. Holladay, Z. Abdullah, and J. Heyne, *Sustainable Aviation Fuel: Review of Technical Pathways*, Washington, D.C.: Office of Energy Efficiency and Renewable Energy, DOE/EE-2041 (2020), https://doi.org/10.2172/1660415.
[26] Wang et al., *Biojet Fuel Conversion Technologies* (2016); Holladay, Abdullah, and Heyne, *Sustainable Aviation Fuel* (2020); L. Zhang, T. L. Butler, and B. Yang, "Chapter 5: Recent Trends, Opportunities and Challenges of Sustainable Aviation Fuel," in *Green Energy to Sustainability: Strategies for Global Industries*, A. A. Vertès, N. Qureshi, H. P. Blaschek, and H. Yukawa (eds), New York, NY: John Wiley & Sons, https://doi.org/10.1002/9781119152057.ch5

development that enables bioenergy technologies that are cost-effective, protect natural resources, and enhance and equitably distribute economic, environmental, and social benefits.

DMA supports research, analysis, and tool development that helps experimentalists and decision makers across the bioenergy supply chain identify the highest-value fuels and products while also maximizing decarbonization potential. DMA activities are performed by national laboratories, academia, and industry.

A key portion of these analyses are TEAs and LCAs:

- TEAs assess the economic viability of example process configurations (i.e., technology pathways), identify potential cost reductions, inform R&D needs, assess progress, and provide input into portfolio development and technology verification.

- LCAs, also referred to as supply chain sustainability assessments, evaluate the environmental and energy effects of new bioenergy and bioproduct technologies holistically along their supply chain, identify the potential for improving the environmental and energy performance of new processes and technologies, and provide input into portfolio development and technology verification.

Life Cycle Assessment

For bioenergy pathways, the system boundary of a typical TEA and LCA runs from the farm gate through to the finished fuel and includes planting and harvesting costs and emissions, as well as the emissions associated with burning the fuel itself. BETO typically conducts LCAs in the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model, which is housed at Argonne National Laboratory and is a publicly available suite of tools for LCA that can be used to evaluate energy and emission impacts of advanced vehicle technologies and new transportation fuels. GREET computes a number of environmental metrics including fossil, petroleum, and total energy use; GHG emissions; water consumption; and emissions of six air pollutants. In addition to direct LCA effects, BETO also considers land use change impacts of bioenergy pathways. This assessment is done through a variety of different modeling frameworks.

Coordination

Internal: The subprogram works with RD&D subprograms to conduct integrative analyses that facilitate insights across the bioenergy supply chain. This includes analyses that integrate economic and environmental dimensions to understand trends, synergies, and trade-offs.

External: DMA also coordinates office collaboration with other federal, state, and local agencies to ensure that universal assumptions are being used in bioenergy modeling and tool development. DMA also helps to provide feedback on how technical progress on DOE-funded technologies may impact national and international policies and related decisions.

The DMA subprogram's crosscutting role is shown in Figure 2-8.

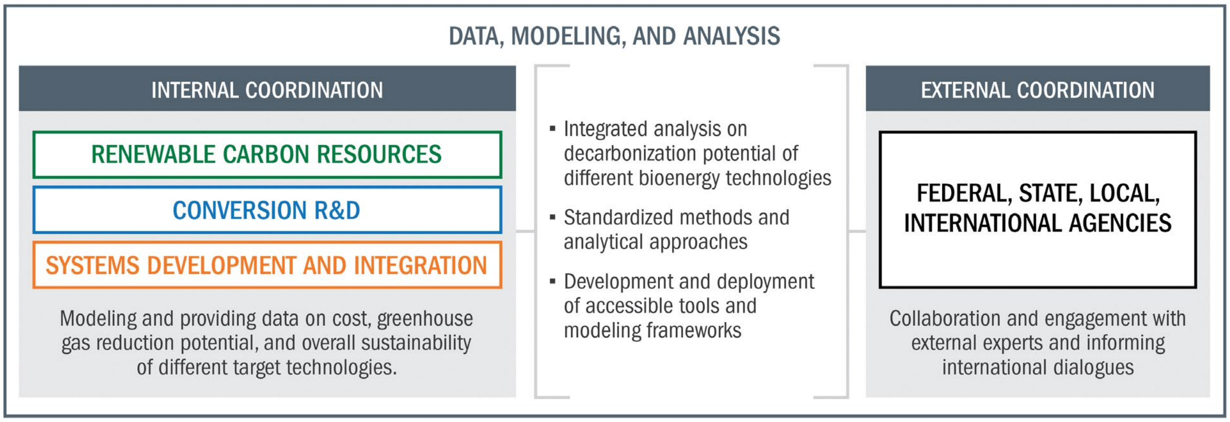

Figure 2-8. DMA scope and interface diagram

DMA Strategic Objective

The strategic objective of the DMA subprogram is to develop and deploy accessible modeling frameworks and tools to enable quantification of the environmental, social, and economic sustainability of renewable carbon resource utilization.

DMA Support of the BETO Performance Goals

Due to the subprogram's crosscutting nature, DMA supports all six of BETO's performance goals by developing modeling frameworks and tools across the bioenergy supply chain and ensuring access to high-quality data on performance and sustainability metrics of different technologies.

DMA also works closely with other BETO subprograms to address specific goals:

- DMA coordinates closely with the RCR subprogram on modeling and providing data on cost, GHG reduction potential, and overall sustainability of different target feedstocks. These data are used to help researchers target specific feedstock types and preprocessing techniques that are most likely to meet additional BETO performance goals.
- DMA coordinates closely with the Conversion R&D subprogram on modeling and providing data on cost, GHG reduction potential, and overall sustainability of different pathways to SAF

and other high-value end products. These data are used to help researchers target pathways and technologies most likely to meet additional BETO performance goals.

- DMA coordinates closely with the SDI subprogram on assessing the environmental impacts and overall sustainability of demonstration-scale facilities to ensure that they can hit the overall target of 50% reduction in GHG emissions relative to petroleum.

DMA R&D Strategic Approach

DMA provides quantitative analysis to inform BETO's decisions regarding the future direction and scope of its RD&D portfolio. DMA supports the RD&D strategies of the other subprograms, even if not specifically highlighted below, by developing models and tools that can assess the impact of developing all resources and end products under consideration by BETO. Most analyses and R&D in DMA focus on a subset of renewable carbon resources and upgrading pathways but can cross between different BETO strategies as needed depending on the inputs and variables considered.

Analysis Challenges and Opportunities

Because the strategic approach of DMA spans the entire bioenergy supply chain, it addresses a number of gaps and activities that apply to all BETO RD&D strategies:

- Improving data accessibility and streamlining assumptions across stakeholder groups to accelerate efforts to understand all relevant dimensions of bioenergy production and use and inform model development.

- Quantifying the economic, environmental, and social benefits of bioenergy and renewable chemicals and materials to better define their value proposition and to make comparisons among energy alternatives. Through a clear and quantitative examination of the benefits and shortcomings of different bioenergy technologies, the DMA subprogram will ensure that the most sustainable bioenergy technologies will be adopted by the private sector.

- Addressing the need for improved mechanisms to inform and involve stakeholders including landowners, technology developers, local communities, environmental organizations, regulatory bodies, and the broader public in developing context-specific energy and decarbonization goals that consider local opportunities and constraints.

- Closing data gaps that occur because bioenergy systems are highly localized and varied across the United States, meaning models may not cover all potentially relevant scenarios without continued data collection and updating. Additionally, models may require advanced computing resources to run, which may not always be available to all relevant stakeholders.

Activities and Approach

DMA works to address these challenges across the bioenergy supply chain by engaging in the following core activities:

- Researching, developing, and deploying science-based tools and standardized practices to accelerate learning and continuous improvement across the bioeconomy.
- Conducting integrative and spatial analyses at different geographic scales and across multiple supply chain components and sustainability categories.
- Developing, refining, and deploying high-quality publicly available analytical tools and models to better understand bioenergy supply chain systems, linkages, and dependencies.

Strategy 1: Develop Low-Cost, Reliable Feedstock Supply Systems from the Entire Range of Biomass and Wastes

DMA produces models and tools that support the development of cost-effective, reliable feedstock systems and assist other subprograms with addressing their RD&D challenges.

Analysis Challenges and Opportunities

DMA works closely with experimental teams to understand priority model and tool development and sustainable design challenges for feedstock producers and end users.

DMA Challenge 1.1 Model and Tool Development

- Limitations of existing data sources to capture the dynamic state of land use and management, as well as an incomplete understanding of the drivers of land use and land management changes.

DMA Challenge 1.2 Sustainable Landscape Design

- Need for science-based, multi-stakeholder strategies to integrate bioenergy with agricultural and forestry systems in a way that reduces wastes, maintains crop yields, enhances resiliency, and supports multiple ecosystem services without increasing pressure on native habitats and wildlife.

Activities and Approach

Activities in this area are organized around model and tool development and analysis to better understand land use change implications and landscape design benefits.

DMA Activity 1.1 Model and Tool Development

Specific DMA modeling and tool analysis activities include:

- Developing models that accurately assess the impact of land use change that occurs because of bioenergy development, and ensuring efforts to quantify land use change are standardized across work done by relevant stakeholders.

- Developing spatial planning models and tools that allow landowners to assess biomass production potential on specific land parcels and increase the value of land not suitable for traditional crop production.

DMA Activity 1.2 Sustainable Landscape Design

- Researching and developing sustainable landscape design approaches that increase bioenergy and bioproduct production while enhancing ecosystem services.

Strategy 2: Develop Gaseous, Sugar/Lignin, and Oil Platforms

DMA supports the development of multiple conversion platforms utilizing gaseous, sugar/lignin, and oil intermediates. Analysis focuses on designing models and tools to assess cost and technical feasibility of multiple conversion routes and allows for streamlined feedback between experimental teams and modelers.

Analysis Challenges and Opportunities

DMA Challenge 2.1 Conversion Pathway Analysis

- Developing methods to analyze the economic and environmental impacts of multiple candidate bioenergy and bioproduct pathways in the early stages of research to prioritize end products that are cost-effective and maximize potential GHG reductions and environmental benefits.

- Working with experimental teams to identify portions of conversion processes that have high economic and environmental impacts to help develop solutions that improve system performance and economic and environmental outcomes during the design process.

- Conversion platforms often have the same basic unit of operation structure, but vary depending on feedstock, organism host, or catalyst type. Providing data and tools on sample platforms useful to a broad group of stakeholders while still being customizable for individual processes is critical.

Activities and Approach

DMA Activity 2.1 Conversion Pathway Analysis

Ongoing research activities to support the development of these platforms aim to:

- Conduct full LCAs on each representative bioenergy and bioproduct technology pathway to enable a more comprehensive understanding of how process improvements and cost reductions made through BETO-supported RD&D affect the energy consumption, GHG emissions, criteria pollutant emissions, resource utilization, and water consumption associated with a particular pathway.
- Assist experimental teams with comparing the GHG impacts of different end products and unit operations to prioritize processes that maximize the GHG reduction potential of the bioenergy industry.
- Assess the near- and long-term potential supply chain impacts of different upgrading technologies and final fuel products on a regional and national scale. Supply chain impacts may include job creation, resource use, infrastructure needs, and production projections.

Strategy 3: Develop Waste Management and Environmental Remediation Strategies

DMA supports the development of environmental remediation strategies by modeling the potential of bioenergy systems to improve overall environmental health and quality across a variety of metrics and indicators.

Analysis Challenges and Opportunities

The following are the challenges associated with developing sustainability metrics and environmental quality indicators specific to waste management and environmental remediation strategies.

DMA Challenge 3.1 Metrics and Indicators Development

- Generating accurate models of localized environmental quality indicators for both bioenergy feedstock production and engineering-scale facilities is important for obtaining buy-in from local communities for the siting of these facilities.
- It can be difficult to assign monetary value to the ecosystem benefits that bioenergy systems may have on biodiversity and other environmental indicators. Gaining a better understanding of how these benefits and other relevant ecosystem services can be monetized will help

landowners make informed decisions on how to integrate bioenergy into existing cropping systems.

Activities and Approach

DMA undertakes the following activities to address challenges associated with developing sustainability metrics and environmental quality indicators.

DMA Activity 3.1 Metrics and Indicators Development

- Utilizing historic data from a variety of regions and potential bioenergy feedstock systems to model environmental benefits of bioenergy including water quality improvement and reduced soil erosion and degradation.
- Comparing potential impacts of multiple feedstock and conversion systems to better understand potential trade-offs between lower cost or better overall performance and increased environmental impacts.
- Ensuring models developed as a result of these efforts are accessible to relevant stakeholders and that stakeholders are able to provide feedback on model development and design.

Strategy 4: Develop Carbon Management Strategies Including Soil Carbon Storage and Carbon Drawdown

DMA supports the development of carbon management strategies including soil carbon storage and carbon drawdown by helping to develop models and tools to estimate the impact of renewable carbon resources in these areas and by assisting with broader impact analysis of different bioenergy and bioproduct production scenarios.

Analysis Challenges and Opportunities

The following are the challenges associated with developing models and tools to assess carbon management strategies.

DMA Challenge 4.1 Carbon Management Modeling and Tools

- The impact of many bioenergy feedstock systems and conversion technologies is highly local in nature, meaning it may be difficult to extrapolate potential impacts on global carbon management systems with limited data. The ability to extrapolate existing studies to new areas and technologies is important.

- Understanding and accurately modeling land use changes that result from producing biomass is a challenge, as is helping to synchronize related assumptions in this area across the national and international community of bioenergy stakeholders.

Activities and Approach

The following are the DMA activities associated with addressing challenges when developing models and tools to assess carbon management strategies.

DMA Activity 4.1 Carbon Management Modeling and Tools

Specific activities to address the challenges in this area span the entire DMA portfolio and aim to:

- Review the potential for biofuels in hard-to-decarbonize sectors including aviation, marine, and other non-road areas. Assess additional chemical and transportation markets to better target areas with a high potential for decarbonization.

- Inform policy development for deploying target fuels and products by assessing the impact of different policies on national carbon management strategies.

- Identify the best distribution of renewable carbon resources across different bioenergy and bioproduct pathways, as well as carbon capture and storage opportunities to maximize GHG reduction potential. This process includes TEA that helps determine which pathways and end uses can reduce emissions the most for the lowest cost.

- Quantify environmental performance and potential costs and benefits of bioenergy and renewable chemicals and materials relative to conventional systems, and track potential social impacts of proposed bioenergy solutions through appropriate indicators.

Appendix: Subprogram Strategies and Activities

Renewable Carbon Resources RD&D

	BETO Strategy		RCR Activity
1	Develop Low-Cost, Reliable Feedstock Supply Systems from the Entire Range of Biomass and Wastes	1.1	Production and Sourcing
		1.2	Logistics
		1.3	Feedstock-Conversion Interface
2	Develop Waste Management and Environmental Remediation Strategies	2.1	Waste Management
		2.2	Environmental Remediation
3	Develop Carbon Management Strategies Including Soil Carbon Storage and Carbon Drawdown	3.1	Carbon Management

Conversion R&D

	BETO Strategy		Conversion Activity
1	Develop Gaseous Platforms	1.1	Gasification Optimization
		1.2	Microbial Engineering and Fermentation Development for Waste Gas Conversion
		1.3	Catalyst Development
		1.4	CO_2 Reduction to Intermediates and Intermediate Upgrading
2	Develop Sugar and Lignin Platforms	2.1	Lignocellulosic Biomass Deconstruction and Fractionation
		2.2	Lignin Conversion
		2.3	Biological/Low-Temperature Sugar Conversion
		2.4	Upgrading of Biochemically Derived Intermediates

BETO Strategy		Conversion Activity	
3	Develop Oil Platforms	3.1	Generating and Stabilizing Bio-Oils
		3.2	Hydroprocessing and Catalytic Upgrading of Bio-Oils
		3.3	Compatibility for Coprocessing/Co-Hydrotreating
		3.4	Volatile, Aqueous, and Solid Stream Management
4	Develop Targeted Chemical Production Platforms	4.1	Identifying Strategic Opportunities for Direct Renewable Chemical Replacement
		4.2	Exploring Novel Compounds That Can Be Derived from Renewable Carbon
5	Develop Bioplastic Design and Plastic Recycling Platforms	5.1	Thermal Processes
		5.2	Catalytic Chemical Processes
		5.3	Biological Processes
		5.4	Physical Processes
6	Develop Waste Management and Environmental Remediation Strategies	6.1	Development of Next-Generation Resource and Energy Recovery Processes for Waste Feedstocks
		6.2	Support for Local Decision Making and Understanding of Risk

Systems Development and Integration

BETO Strategy		SDI Activity	
1	Integration and Scale-Up of Production Platforms for SAF, Other Strategic Transportation Fuels, and Renewable Chemicals and Materials	1.1	Validating Performance of Critical Unit Operations
		1.2	End-to-End Process Integration
		1.3	Capital and Operational Costs

2	Develop Market Solutions for Hard-to-Decarbonize Modes of Transportation	2.1	Solutions for Hard-to-decarbonize Modes of Transportation

Data, Modeling, and Analysis

BETO Strategy		RCR Activity	
1	Develop Low-Cost, Reliable Feedstock Supply Systems from the Entire Range of Biomass and Wastes	1.1	Model and Tool Development
		1.2	Sustainable Landscape Design
2	Develop Gaseous, Sugar/Lignin, and Oil Platforms	2.1	Conversion Pathway Analysis
3	Develop Waste Management and Environmental Remediation Strategies	3.1	Metrics and Indicators Development
4	Develop Carbon Management Strategies Including Soil Carbon Storage and Carbon Drawdown	4.1	Carbon Management Modeling and Tools

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