Sustainable Aviation Fuels Implementation Framework: Pathways to 2030 and 2050

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Executive Summary

The Sustainable Aviation Fuel (SAF) Grand Challenge was announced in September 2021 in a Memorandum of Understanding between the U.S. Department of Agriculture (USDA), U.S. Department of Energy (DOE), and U.S. Department of Transportation (DOT).[1] The SAF Grand Challenge set forth a governmentwide effort including the U.S. Department of Defense (DOD), National Aeronautics and Space Administration (NASA), and Environmental Protection Agency (EPA) to help drive innovation that reduces cost, enhances sustainability, and expands production and use of SAF. The SAF Grand Challenge set goals to produce 3 billion gallons of domestic SAF per year that achieves a minimum of a 50% reduction in life cycle greenhouse gas (GHG) emissions compared to conventional jet fuel by 2030, and 35 billion gallons of SAF per year to satisfy 100% of projected U.S. aviation fuel use by 2050.

The SAF Grand Challenge Roadmap,[2] published in September 2022, outlined a whole-of-government approach to work with and support industry to meet the goals of the SAF Grand Challenge. The roadmap outlines six action areas and specific activities that should be coordinated and undertaken by the Federal agencies within the limits of government policy to support achievement of both the 2030 and 2050 goals of the SAF Grand Challenge.

SAF Grand Challenge Roadmap Implementation Framework Overview

Following publication of the roadmap, the SAF Grand Challenge Interagency Working Group undertook an effort to inventory and map current Federal agency capabilities and programs to the actions called out in the roadmap. These maps were then used to identify gaps in current Federal agency efforts relative to the roadmap actions.

This roadmap implementation framework represents an overview of that mapping and gap analysis effort. It is intended to provide SAF stakeholders with an understanding of agency capabilities and information on current Federal programs addressing the workstreams and activities identified in the roadmap. Importantly, the framework highlights barriers and areas where Federal efforts are currently insufficient to meet the SAF Grand Challenge goals.

Although the roadmap and framework do not identify specific policy recommendations, the framework does identify where current policies may present a barrier to achieving the SAF Grand Challenge goals, and where additional data and analysis will be helpful to inform new policy direction and decisions.

[1] DOE. 2021. "Memorandum of Understanding: Sustainable Aviation Fuel Grand Challenge." Sept. 8, 2021. www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21_0.pdf.
[2] DOE, DOT, USDA, and EPA. 2022. *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel*. www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

Federal Agency Capabilities and Programs Summary

The Federal agencies behind the SAF Grand Challenge are committed to supporting achievement of the SAF Grand Challenge Goals as demonstrated through efforts such as:

- DOE's Bioenergy Technologies Office (BETO) is researching and developing sustainable feedstock and fuel production technologies, providing support for technology scale-up and advancing environmental analysis of SAF.
- USDA is supporting U.S. farmers with climate-smart agriculture practices and research, including biomass feedstock genetic development, sustainable crop and forest management at scale, and post-harvest supply chain logistics. USDA is also supporting fuel producers with carbon modeling components of aviation biofuel feedstocks.
- DOE's Loan Programs Office (LPO) and USDA loan programs such the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program (Section 9003) are offering loan guarantees to commercial-scale SAF projects that utilize innovative technology to convert feedstock to SAF and avoid, reduce, or sequester GHG emissions.
- DOT and the Federal Aviation Administration (FAA) provide capabilities and funding to support SAF qualification and certification, U.S. and international standard-setting, and development of infrastructure and transportation systems.
- FAA facilitates coordination of a broad range of SAF stakeholders through The Commercial Aviation Alternative Fuels Initiative (CAAFI) (caafi.org/about/caafi.html), a coalition of airlines, aircraft and engine manufacturers, energy producers, researchers, international participants, and U.S. Government agencies working together to build relationships, share and collect data, identify resources, and direct research, development, and deployment of SAF.
- EPA is working with the other agencies to identify data collection needs, assess technical information, and take other steps designed to expedite the regulatory approval process to support newly developed fuels and feedstocks that achieve significant lifecycle GHG reductions.
- NASA is collaborating with the FAA and industry to accelerate the maturation of aircraft and engine technologies that enable utilization of SAF and reduce GHG emissions.

SAF Grand Challenge Roadmap Gap Analysis Summary

The agencies currently have programs in place to address many—but not all—of the roadmap actions. A summary of barriers and areas where there are gaps in current U.S. Government programs is presented below. Many of these gaps need support from SAF stakeholders to meet the SAF Grand Challenge goals. Additional details on these "gaps" are found in the framework report.

Certainty in U.S. Government policy to support the build-out of SAF supply chains. Durable policies that clearly and rigorously demonstrate the near-, medium-, and long-term commitment of the U.S. Government to domestic production and use of SAF can play a key role in catalyzing effective private investment in SAF projects that will bring about the environmental, economic, and social benefits of the SAF Grand Challenge. Furthermore, U.S. and international policies must align to ensure that domestically produced SAF will be useful for airlines serving international markets.[3] This will require continuous commitment to improving data collection, model development, analyses, and verification and tracking programs to ensure that the availability and use of SAF continues to grow to help the aviation industry meet the goals that governments and industry have adopted.

Expanded data and analysis and improved models to perform transparent and credible SAF supply chain analysis to inform business models and policy development. Improved data and modeling are critical for evaluating cross-sectoral strategies for decarbonization; guiding Federal investments in research, development, demonstration, and deployment (RDD&D); and informing both private sector business models and policy development. Current programs do not adequately address many of the data, modeling, and analysis needs identified in the roadmap activities. Some key gaps include:

- Data and analyses to quantify, validate, and appropriately account for the environmental impacts and ecosystem co-benefits of SAF supply chains from feedstock production (e.g., soil health, soil organic carbon sequestration, water quality, nutrient management) to end use (e.g., effects on non-carbon dioxide [CO_2] impacts such as contrails).
- Induced land use change resulting from biomass utilization. Better data and analyses are needed to understand and account for the ecosystem impacts of induced land use change.
- An update to DOE BETO's Billion-Ton study was published on March 15, 2024 at www.energy.gov/sites/default/files/2024-03/beto-2023-billion-ton-report_2.pdf. Regularly updating renewable carbon resource assessments is necessary to underpin key techno-economic, life cycle, and SAF production potential analyses.
- Developing national-scale scenarios that capture all aspects of SAF supply chains from feedstock availability through SAF production potential is required. Further work is needed to tailor existing modeling platforms to provide outputs for SAF, to develop new modeling capabilities needed to identify SAF infrastructure requirements, and to provide a centralized, public location to download and access input datasets.

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[3] International drivers for SAF creation include commitments by the United States and U.S. air carriers to the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the long-term aspirational goal for international aviation to reach net-zero carbon emissions by 2050, and the near-term collective vision of achieving a 5% reduction in carbon emissions for international aviation through the use of high-integrity SAF and other cleaner aviation energies by 2030.

Expanding purpose-grown feedstocks and tapping the potential of waste and residual feedstocks.

- Aside from corn and soybeans, no purpose-grown biofuel feedstock crops are grown at scale today. The U.S. Government needs to support R&D to increase the production and collection of biomass resources. In addition to efforts aimed at improving conversion technologies, policies and programs are needed to improve aggregation and collection of wastes and residuals, expand woody biomass use and incentives, conduct long-term biomass crop production trials, and analyze the use of algae and gaseous carbon feedstocks at scale.
- Near-term production of hydroprocessed esters and fatty acids (HEFA)-based SAF depends largely on an adequate supply of affordable, sustainable lipids (fats, oils, and greases) at scale. Currently, lipid availability is subject to competition to produce renewable diesel and biodiesel, food, and other products. To address this gap there needs to be further coordination of U.S. Government support for near-term lipid crop and residual expansion.

Optimizing economically viable and sustainable feedstock supply chains.

- Economic, environmental, and social sustainability are key to building resilient SAF biomass feedstock supply chains. Developing and implementing climate-smart agriculture and forestry are critical to achieving sustainability goals. Important gaps in current programs and activities include further improvements in commodity crop sustainability (corn and soybeans), improvements in crop and agroforest system management and genetic development of sustainable crops and trees, clearly understanding forest-related environmental services, and giving value to ecosystem services, as well as research supporting sustainable emerging crops.
- Feedstock logistics and the reliability of feedstock handling systems make or break the potential for expanded feedstock production. While DOE and USDA are undertaking considerable R&D in these areas, much more work is needed. USDA is also contributing to the development of sustainable feedstock supply chains through its Partnerships for Climate-Smart Commodities program. It will be critical to work closely with industry on regional equipment and system development and evaluate expanded conventional and emerging feedstock supplies, including biomass supplies.

Using existing ethanol and petroleum industry infrastructure to rapidly scale-up and deploy.

- Reducing the carbon intensity of the existing ethanol industry is a key opportunity to expand SAF production. A combination of advancements will be required to achieve carbon intensity (CI) reductions necessary to meet SAF goals. In addition to applying climate-smart agriculture to reduce the CI of starch-based ethanol, renewed and expanded effort will be needed to develop low-CI sugar feedstocks from agricultural residues. Research is also needed to determine how much residue can be obtained from climate-smart systems without forgoing the climate and agronomic benefits of leaving some residues in the field.

- As demand for petroleum-derived fuels decreases, it will be critical and advantageous to leverage existing infrastructure and skilled labor resources. There is a need for expanded RDD&D on the compatibility of existing petroleum hydrotreaters and infrastructure assets with emerging biointermediates like bio-oils. In addition, large quantities of biointermediates will be needed for testing, blending studies, and development of analytical tracking methodologies.
- Pathways that have already been qualified by ASTM International will be critical for meeting the 2030 goal and early SAF build-out. Additional RDD&D is needed to adapt catalysts to new seed oils and expand detailed analysis to identify opportunities for process intensification and modular build-out.

Risk reduction and coalition-building. Critical gaps exist in scale-up and demonstration of SAF supply chains. These include a lack of sustainable feedstocks available at requisite quality, cost, and scale; risks in technology scale-up and demonstration; difficulties in securing project funding; a lack of SAF supply chain infrastructure; and policy uncertainty.

- History has shown time and again that skipping or limiting the duration of integrated piloting and/or demonstration in technology scale-up leads to failures in first-of-a-kind commercial-scale plants. Process development at these scales is costly but critical to reducing scale-up risk. Furthermore, the volumes of fuel produced in these stages are required for fuel testing and qualification. Expanded investment is required to share risk and accelerate the development of SAF production capability along the entire SAF supply chain. Continued and expanded access to risk capital (including both private sector risk capital and, as appropriate, Federal loan guarantee programs) will help enable build-out of supply chains and infrastructure necessary to the production and use of SAF.
- Regional coalitions of stakeholders across the supply chain are vital to developing regional solutions to build a SAF industry that improves environmental and economic performance while supporting job creation and social equity. Expanded efforts will be needed to identify high-impact regional SAF stakeholder coalition opportunities, accelerate outreach efforts with SAF supply chain stakeholders, and incentivize stakeholder coalitions to form, plan, and take action to stand up regional SAF supply chains.

Transparent and effective communication of progress and benefits of the SAF Grand Challenge. Although the agencies have made good progress in this area (e.g., the SAF Grand Challenge website and several workshops), there is much work to be done that is outside of currently scoped communication plans. A key gap exists in programs to monitor SAF Grand Challenge progress and impacts (e.g., fuel volumes produced, CO_2 reductions) necessary to build awareness and support.

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Introduction

The Sustainable Aviation Fuel (SAF) Grand Challenge was announced in September 2021 in a memorandum of understanding between the U.S. Department of Agriculture (USDA), U.S. Department of Energy (DOE), and U.S. Department of Transportation (DOT).[4] The SAF Grand Challenge set forth a governmentwide effort including the U.S. Department of Defense (DOD), National Aeronautics and Space Administration (NASA), and Environmental Protection Agency (EPA) to help drive innovation that reduces cost, enhances sustainability, and expands production and use of SAF. The SAF Grand Challenge set goals to achieve 3 billion gallons per year of domestic SAF production that achieves a minimum of a 50% reduction in life cycle greenhouse gas (GHG) emissions compared to conventional jet fuel by 2030, 35 billion gallons per year, by 2050.

In September 2022, an interagency team led by DOE, DOT, and USDA published the SAF Grand Challenge Roadmap.[5] The roadmap outlines a whole-of-government approach to work with and support industry to meet the goals of the SAF Grand Challenge. The roadmap covers the entire SAF supply chain including feedstock production, collection, and distribution to SAF production facilities; conversion of feedstock to fuel; transport of finished fuel to the infrastructure required to fuel aircraft; and final combustion in aircraft jet engines. The roadmap laid out six action areas, as well as the workstreams and activities within those areas needed to achieve the SAF Grand Challenge objectives of (1) expanding SAF supply and end use, (2) reducing the cost of SAF, and (3) enhancing the sustainability of SAF. The six action areas, depicted graphically in Figure 1, are:

1. Feedstock Innovation (FI);
2. Conversion Technology Innovation (CT);
3. Building Supply Chains (SC);
4. Policy and Valuation Analysis (PA);
5. Enabling End Use (EU); and
6. Communicating Progress and Building Support (CP).

[4] DOE. 2021. "Memorandum of Understanding: Sustainable Aviation Fuel Grand Challenge." September 8, 2021. www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21_0.pdf.
[5] DOE, DOT, USDA, and EPA. 2022. *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel*. www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

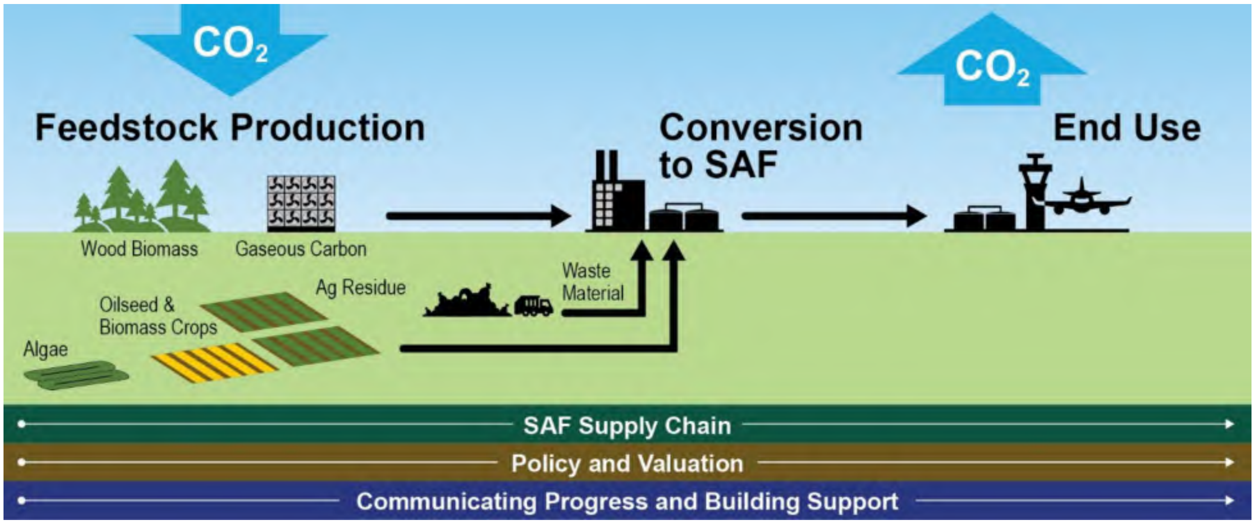

Figure 1. Graphic representation of the SAF Grand Challenge Roadmap

SAF Grand Challenge Roadmap Implementation Framework

The SAF Grand Challenge Roadmap Implementation Framework is a supplement to the SAF Grand Challenge Roadmap. Whereas the roadmap identified the actions needed to achieve the goals of the SAF Grand Challenge, this framework report provides SAF stakeholders with an understanding of what capabilities and programs Federal agencies currently have in place to implement the roadmap actions. Importantly, it also identifies known gaps in current programs and barriers to achieving the goals of the SAF Grand Challenge.

Following publication of the roadmap, the SAF Grand Challenge Interagency Working Group undertook an effort to inventory and map current Federal agency capabilities and programs to the actions, workstreams, and activities called out in the roadmap. This was then used to identify gaps in current Federal agency efforts relative to the roadmap. This implementation framework report summarizes the output of the SAF Grand Challenge Interagency Working Group mapping and gap analysis effort. It provides a guide for implementing the SAF roadmap at a relatively high level of coordination and planning due to the complexity of having multiple agencies involved with different missions and approaches.

The framework report is organized by roadmap action area. Within each action area, an overview of current agency capabilities and programs is organized by Federal agency. Following this, a breakdown of key gaps and barriers is organized by roadmap action area workstreams.

Feedstock Innovation

The Feedstock Innovation (FI) Action Area's objective is to promote sustainable feedstock supply system innovations across the range of SAF-relevant feedstocks, as well as to enable supply chain optimization to reduce cost and risk, and increase yield and sustainability (e.g., reducing corn carbon intensity [CI] to enable optimization of SAF precursors ethanol and isobutanol). While focus is often on the production and supporting policy for SAF, there needs to be a concomitant and commensurate investment in feedstock supply chains that includes research, development, demonstration, and consideration of policies to support feedstock availability and cost. Using an evolving multigenerational approach, feedstock supply systems will be developed to interface with existing or emerging conversion technologies to enable SAF production to meet near-term (2030) and longer-term (2050) U.S. SAF production targets.

The key actions supporting the FI Action Area are:

- **Ensuring a national lipid supply** that will allow production of SAF, renewable diesel, and other fuels and products without displacing other markets.
- **Growing the ability to use non-sawlog wood biomass** to produce cost-effective SAF precursors at scale.
- **Developing the potential for dedicated lignocellulosic biomass feedstocks at scale** to contribute to the 2050 goal of 35 billion gallons per year of SAF production in the United States.
- **Optimizing biomass feedstock supply chain logistics** for harvest and collection, transportation, storage, and preprocessing.
- **Enhancing biomass feedstock productivity** to ensure SAF demand can be met without expanding land use for feedstock production.
- **Continue to align biomass production with recognized climate-smart best practices**, work to ensure international acceptance of U.S. sustainably produced SAF and continue to work with international partners to refine valuation schemes.

Current Federal Agency Capabilities and Programs

USDA

USDA focuses on feedstock development, production, logistics, sustainability (i.e., economic, environmental, social), education, and extension and outreach. Agencies within USDA conduct and support research, development, and demonstration (RD&D) and support crop production and farmland and forest conservation.

USDA Agricultural Research Service (ARS)

ARS supports the FI Action Area primarily through the four regional Biomass Research Centers (ars.usda.gov/research/usda-regional-biomass-research-centers/). These virtual centers cover a wide range of biomass feedstock crops and include genetic development and evaluation, climate-smart production and management, and supply chain logistics linked to SAF production. The ARS Crop Production and Protection program oversees the regional Biomass Research Centers and recently released a 10-year strategic plan for the U.S. National Plant Germplasm System, including genetic resources used to improve many crops used as feedstocks for SAF (ars.usda.gov/crop-production-and-protection/plant-genetic-resources-genomics-and-genetic-improvement/docs/npgs-plan/).

USDA Forest Service

The Forest Service's Bioenergy and Biobased Products R&D program integrates all aspects of sustainable production and management, harvest and delivery, and conversion and utilization research, and spans the scale from molecular to global analysis. The agency's work considers the supply chain of forest bioenergy and bioproducts, with the goal of ensuring productive, sustainable, efficient, and affordable forest bioenergy systems and options. The R&D program is focused on delivering value in the following three areas:

- **Provide the nation with sustainable and economical forest biomass management and production systems.** Capturing the potential of forest biomass resources will not happen without addressing some major challenges, such as developing a reliable and sustainable feedstock supply, understanding and quantifying land use change and competition, and reducing costs for growing, recovering, and transporting feedstocks.
- **Provide the nation with competitive biofuels and biopower conversion technologies and bioproducts that reduce GHG emissions and fossil fuel use.** Challenges exist in developing competitive technologies and processes that can reduce the cost and increase the efficiency of producing biofuels, products, and power. Efficiencies can be achieved through methods for increasing the yields derived from biochemical and thermochemical conversion of forest feedstocks, as well as developing new products.
- **Provide the nation with information and tools for decision-making and policy analysis.** Working with partners, the Forest Service's R&D deputy chief area provides information to analyze and inform policy and develops a variety of tools useful for on-the-ground decision-making by landowners and land managers. These information sources and data include national and regional assessments—such as the Resources Planning Act assessments and Forest Inventory and Analysis data—that provide information on past and expected trends in markets, products, demand, supply, and forest productivity, harvest, conditions, and distribution. Examples of recent products contributing to this goal include work done to update and publish the DOE Bioenergy Technologies Office 2023 Billion-Ton Report.

The Forest Service's work will build on a long history of wood products research and partnerships with industry and academic institutions. It will include research in conversion processes, wood quality, advanced composites, advanced housing, wood chemistry and physics, microbiology, enzyme technology, chemical engineering, economics, and marketing.

In addition, the Forest Service's Forest Products Laboratory is advancing wood product innovations and wood product markets. This is a priority because a robust forest products industry is needed to help sustain the health, diversity, and productivity of forests across the county. The United States relies on the forest products industry to harvest and thin forests to keep them from becoming overstocked and to help pay for that management by selling the wood products. In addition, the industry makes sustainable products that our nation needs and provides jobs to support forest communities, which in turn support the forests. Forest Service R&D has 55 scientists dedicated to this priority, with 50 at the Forest Products Laboratory and another five distributed across other stations. Main contributions regarding SAF is the research line on biorefineries to convert wood into aviation fuel from old pulp mills (www.fs.usda.gov/research/treesearch/64846).

USDA National Institute of Food and Agriculture (NIFA)

Agriculture and Food Research Initiative

- The Agriculture and Food Research Initiative Sustainable Agricultural Systems program supports Coordinated Agricultural Projects that provide an excellent framework for regional stakeholder coalitions supporting emerging supply chains, including SAF. These projects integrate research, outreach, and education to support de-risking feedstock supply chains linked to emerging or existing conversion technologies. Additionally, USDA-NIFA is collaborating with DOE's Clean Fuels & Products Shot™ Regional Biomass Resource Hubs to advance development and commercialization of low-carbon bioenergy and bio-based products. Projects selected for funding under this focus area will gain access to regional and national models to further advance their individual goals and objectives and will contribute field trial results, including CI metrics, to the Regional Biomass Resource Hub network to serve as a reference for stakeholders across the bioeconomy. Participants in biomass supply chains can leverage these and other Federal grant opportunities to invest in process technologies to convert feedstock to fuel, reduce risk, and prove performance by maturing from the lab to pilot scale and on to demonstration scale.
- The Agriculture and Food Research Initiative Foundational and Applied Science Program allows smaller groups of researchers, developers, and outreach participants to conduct targeted activities supporting SAF outcomes through subprograms including agroecosystems, bio-based products and materials, genetic development, and management of emerging feedstock crops.
- The Small Business Innovation Research and Small Business Technology Transfer programs support pre-commercialization R&D and technology transfer with potential to impact SAF on crop genetic development, sustainable production and management, supply

chain logistics, and production of value-added coproducts. Small businesses can apply to a range of topic areas (8.1: Forests and Related Resources, 8.2: Plant Production and Protection – Biology, 8.7: Aquaculture [algae], 8.8: Biofuels and Biobased Products, and 8.13: Plant Production and Protection – Engineering).

- **NIFA capacity funding for state agricultural research and extension centers** supports critical research, development, and outreach at a range of state universities, minority-serving institutions, and forest resources institutions, allowing critical activities supporting SAF to move forward.

USDA Farm Production and Conservation Mission Area

Farm Production and Conservation agencies, including the Natural Resources Conservation Service, Farm Service Agency, and Risk Management Agency, manage critical support for U.S. agriculture through programs supporting biomass feedstock production and management, soil and water conservation, and crop insurance.

The Natural Resources Conservation Service runs the Partnerships for Climate-Smart Commodities grant program (usda.gov/climate-solutions/climate-smart-commodities),[6] which provides technical and financial assistance to farmers, ranchers, and forestland owners for implementing and evaluating climate-smart practices and for developing markets for climate-smart commodities. As part of these efforts, projects are developing systems to implement climate-smart agriculture and forestry practices and to track them through supply chains. Projects cover a wide range of activities relating to bioenergy, such as development of low-carbon biofuels and the large anaerobic digestion project pictured in Figure 2 that uses cover crops and perennial prairie grasses with manure to produce renewable energy.

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[6] USDA. 2022. "Partnerships for Climate-Smart Commodities." Factsheet. usda.gov/sites/default/files/documents/usda-partnerships-climate-smart-factsheet-22.pdf.

Figure 2. Large Midwest anaerobic digestion facility.

Photo courtesy of Roeslein Alternative Energy

DOE Bioenergy Technologies Office (BETO)[7]

BETO's Renewable Carbon Resources (RCR) subprogram (energy.gov/eere/bioenergy/renewable-carbon-resources) 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. The RCR subprogram supports both applied research projects and pilot-scale projects on the production, harvesting and collection, supply logistics, storage, and preprocessing of biomass and wastes to feedstock. Feedstocks are defined as renewable carbon resources that have undergone one or more preprocessing operations to meet the quality characteristics required for feeding into reactors and efficient conversion into bioenergy and bioproducts.[8] RCR coordinates closely with the Conversion Technologies program to ensure the qualities of the feedstock align with conversion pathways under development (energy.gov/eere/bioenergy/feedstock-conversion-interface).

[7] BETO. 2023. *Bioenergy Technologies Office Multi-Year Program Plan: 2023*. Washington, D.C.: BETO. DOE/EE-2698. energy.gov/sites/default/files/2023-03/beto-mypp-fy23.pdf.
[8] J. Richard Hess, Allison E. Ray, and Timothy G. Rials. 2019. "Editorial: Advancements in Biomass Feedstock Preprocessing: Conversion Ready Feedstocks." *Front. Energy Res.* 7. doi.org/10.3389/fenrg.2019.00140.

The RCR subprogram scope includes agricultural residues (e.g., corn stover—corn stalks, cobs, and leaves), forestry residues (e.g., logging residues, forest thinning), purpose-grown energy crops (e.g., algae, herbaceous and woody crops, secondary crops), waste streams (e.g., the nonrecycled organic portion of municipal solid waste, biosolids, sludges, plastics, carbon dioxide [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), and commodity crops (e.g., corn, grain sorghum, oilseed crops). The periodic Billion-Ton report updates are conducted within this program, coordinating with the USDA and EPA.[9]

BETO's Biomass Feedstock National User Facility (BFNUF) (inl.gov/bfnuf/) at Idaho National Laboratory (INL) offers technology and expertise to help the U.S. bioenergy industry overcome biomass challenges during scale-up and integration of biomass preprocessing facilities. The BFNUF provides a reconfigurable preprocessing test bed that is utilized by both public and private sectors to rapidly scale up new processes. BFNUF research at INL focuses on supply and logistics, analysis and sustainability, preprocessing, and characterization. BFNUF also includes the Biomass Feedstock Library—a physical repository for over 100,000 biomass samples, as well as a bioenergy characterization database for more than 50,000 samples.

[9] U.S. Department of Energy. 2024. *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources*. M. H. Langholtz (Lead). Oak Ridge, TN: Oak Ridge National Laboratory. ORNL/SPR-2024/3103. www.energy.gov/sites/default/files/2024-03/beto-2023-billion-ton-report_2.pdf.

Figure 3. Biomass Feedstock National User Facility.

Photo courtesy of Idaho National Laboratory

DOE Office of Science

DOE's Office of Science Biological and Environmental Research (BER) program supports basic plant biology research on potential biomass crops and enables development of feedstocks with improved traits for productivity and downstream conversion. BER science also examines the intersection between plants, their associated microbiomes, and their ecosystems to understand responses to changing environmental variables and identify factors critical to sustainable biomass production. BER also supports four Bioenergy Research Centers (genomicscience.energy.gov/bioenergy-research-centers/) that conduct fundamental research to support aspects of the full biofuels and bioproducts supply chain, including sustainability and feedstock production.

Within DOE's Office of Science Basic Energy Sciences (BES) program, the Photosynthetic Systems and Physical Biosciences programs support basic research to understand the fundamental mechanisms of energy capture, conversion, and storage in plants and microbes. Such insights could help enable new biochemical processes or components for sustainable biomass production and use.

DOT Federal Aviation Administration (FAA)

Center of Excellence for Alternative Jet Fuels and the Environment

The FAA, along with NASA, DOD, Transport Canada, and the EPA, funds the Aviation Sustainability Center (ASCENT) (ascent.aero/). ASCENT is a cooperative aviation research organization co-led by Washington State University and the Massachusetts Institute of Technology.

Under ASCENT Project 001, "Alternative Jet Fuel Supply Chain Analysis" (ascent.aero/project/alternative-jet-fuel-supply-chain-analysis/), FAA drives work related to the FI Action Area, including:

- **Existing feedstock market evaluation**. Assessment is underway to determine the volume of lipids available and the impact of Federal and state policy support on the price required to increase the production of second crop oilseeds. Soybean oil and starch-based ethanol production and multiple methods to reduce the CI of these SAF feedstocks is underway. Forest residual and forest product mill waste is documented on a national level using Land Use and Resource Allocation (LURA) modeling.
- **Soybean oil and market impact of SAF**. Cooperative work with the USDA Office of the Chief Economist assesses the impact of Federal and state policy support for SAF on the price that a hydroprocessed esters and fatty acids (HEFA) SAF producer could pay for soybean oil and what this might do to the soybean oil market.
- **Fire remediation**. A joint project with the U.S. Forest Service titled, "Advanced supply chain engineering to support fuel treatment and forest restoration," includes volume assessment of forest biomass that could be used as feedstock for SAF.

Commercial Aviation Alternative Fuels Initiative (CAAFI)

CAAFI (caafi.org/about/caafi.html) is a public-private partnership founded in 2006 by the FAA with industry to support development and deployment of SAF. CAAFI has also developed publicly available SAF readiness tools that will aid regional coalitions in assessing their stage of development, including the Feedstock Readiness Level Tool (caafi.org/tools/Feedstock_Readiness_Level.html) to gather data to assess the technology readiness level (TRL) of existing and emerging biomass feedstocks.

DOT Volpe Transportation Research Center

The Freight and Fuel Transportation Optimization Tool (volpe.dot.gov/our-work/policy-planning-and-environment/volpe-tool-evaluates-freight-and-fuel-transport-options) is designed to analyze the transportation needs and constraints associated with fuel and raw material (including biomass) collection, processing, and distribution in the continental United States.

EPA

EPA administers the Renewable Fuel Standard (RFS) program put in place by the Energy Independence and Security Act of 2007. The standards finalized for 2025 will require the use of 22.33 billion gallons of a wide range of renewable fuels from a wide range of feedstocks. In implementing the program, EPA evaluates and approves pathways (feedstock, conversion process, and fuel type) that allow the resulting renewable fuels to generate credits (renewable identification numbers [RINs]) that subsidize their production and use. There are currently several approved pathways for jet fuel to generate RINs in the RFS program, and others are under review. EPA works with USDA's Animal and Plant Health Inspection Service to determine if emerging feedstocks that have applied to be eligible for RINs are invasive species that could damage agronomic, forest, or range ecosystems.

Current Program Gaps and Barriers

FI.1: Understand Resource Markets and Availability

Farmers and forestland owners will not dedicate land to purpose-grown biomass without a viable market. Consequently, key sets of data acquisitions, analyses, and model development need to be undertaken:

- Updated data on current oilseed production and ability to expand oilseed crop production, including the consequences of increasing oilseed crop acreages.
- Update on corn-based ethanol market.
- Updated analysis of wood pellet supply and markets.
- Comprehensive national and regional woody biomass inventory and analysis (forests, plantation, urban waste, primary and secondary mill residuals, forest and fuels treatments, and nonmarketable waste).

FI.2: Maximize Sustainable Lipid Supply

Near-term production of SAF depends largely on an adequate supply of affordable lipids (fats, oils, and greases) available at scale. Currently, lipid availability is subject to competition to produce renewable diesel and biodiesel, food, and other products. Developing a lipid project plan and coordinating U.S. Government support for near-term lipid crop and residual expansion are necessary to address these needs. The plan should help understand:

- Sustainable waste lipid aggregation potential, including livestock and poultry slaughterhouse analysis, brown grease market analysis, and cleanup cost.
- Sustainable lipid potential from industrial effluents and byproducts.
- Current oilseed production and ability to expand oilseed crop production, including the consequences of increasing oilseed crop acreages.
- The potential and barriers for the cultivation of intermediate oilseed crops, including acreage and contribution to oil supply, agronomic impacts on crop portfolios, access to incentives and crop insurance, and new paradigms for incorporating intermediate oilseed crops into row crop portfolios that maintains the full risk reduction programs and policy impacts for the row crops.

FI.3: Increase Production of Purpose-Grown Biomass Resources and Collection of Wastes and Residues

Aside from corn and soybeans, no purpose-grown biofuel feedstock crops are grown at scale today. For example, there are hundreds of millions of acres of agricultural production lands that could host annual harvestable cover crops. However, current cover crop adoption remains below 10% nationally. There needs to be a set of regionally appropriate vetted business models underpinned by supportive policy to allow farmers and forestland owners to make economically and sustainability-driven decisions on how purpose-grown crops and/or cover crops may be incorporated into their production landscapes based upon climate-smart practices. Below are needs to enable these emerging crops and expand biomass availability for SAF production (there is a need to align industry and Federal activities):

- Policy analysis in support of dedicated (purpose-grown) biomass crops and harvestable cover crops, building frameworks that consider crop portfolio risk management (crop insurance, pesticide and herbicide labeling, planting incentives for both purpose-grown and cover crops, and carbon accounting and payment for carbon sequestration and reduced emissions).
- Understand social science factors that determine what farmers require financially to make long-term commitments and/or incentivize the adoption and use of purpose-grown biomass crops and harvestable cover crops.
- Expand regional understanding of collection, sorting, and decontaminations of municipal solid waste and expanded agricultural and forestry residuals collection, including competing markets and applications.
- Increase utilization of residual non-sawlog woody biomass from mills and forestry operations, particularly in connection with forest health treatments and hazardous fuels removals.
- Policy support for incentivizing use of non-sawlog wood biomass and allowing wood biomass from Federal lands to qualify for biofuel incentives (e.g., RINs).
- Continue and expand regional long-term trials in purpose-grown biomass crop production, including production and management on economically marginal lands, analysis of competing uses of marginal lands (e.g., solar energy), evaluating precision landscape design methodology and adoption potential, and identifying and expanding high-yielding genotypes on marginal lands.
- Similarly, there is need to evaluate the potential for microalgae and macroalgae production, along with evaluation of other biomass residuals including sludge, manure, and industrial and food waste streams, including the production of renewable natural gas that itself may be used as a SAF feedstock.
- Evaluation and analysis of gaseous carbon feedstocks (e.g., CO_2 from ethanol production).

Figure 4. Oilseed cover crop, *Brassica carinata*.

Photo courtesy of William Goldner, Ph.D., U.S. Department of Agriculture

FI.4 and FI.5: Improve Feedstock Supply Logistics and Resilience and Reliability of Feedstock Handling Systems

Feedstock logistics and the reliability of feedstock handling systems make or break the potential for expanded biomass feedstock production. While DOE and USDA are undertaking considerable R&D in these areas, much more work is needed. It will also be critical to work closely with industry on regional equipment and system development and evaluation. Overall needs include:

- Expanding modeling, design, and demonstration activities on conventional biomass supply chain systems including traditional row crops, the inclusion of cover crops, and the introduction, evaluation, and optimization of climate-smart agricultural production practices linked to harvest and subsequent logistics.
- Expanding modeling, design, and demonstration activities on emerging biomass supply chains, including purpose-grown biomass crops, residual non-sawlog woody biomass (including forestry and mill operations), and microalgae and macroalgae production, harvest, and dewatering (including seagrasses).
- Improving the understanding of the basic science behind the flowability and processing of solid biomass and waste materials.

FI.6: Improve Sustainability and Productivity of Biomass and Waste Feedstock Supply Systems

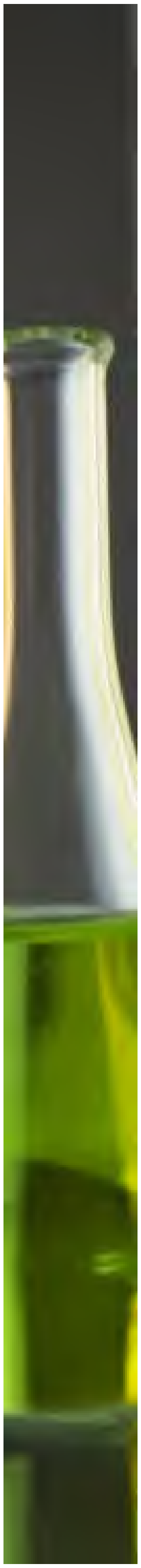
Economic, environmental, and social sustainability are key to building resilient SAF biomass feedstock supply chains. Below are gaps and activities that will support supply chain system sustainability. Some of these activities are underway but need additional breadth and depth to make a difference in SAF production from now to 2030 and well beyond:

- Improve corn and soybean sustainability, including calculation of CI scores, to meet thresholds for SAF production and market access.
- Expand research on the relationship between utilization of non-sawlog woody biomass and forest ecosystem services, in land and watershed management planning, including in wildland-urban interfaces.
- Expand sustainability research to cover emerging and dedicated energy and cover crops.
- Identify and fulfill needs for additional data collection to develop policy recommendations relating to valuation of ecosystem services such as carbon sequestration, water quality, biodiversity, reduction of invasive species, and pollinator and wildlife habitats.
- Identify and fulfill needs for additional data collection to develop policy recommendations for incentivizing the utilization of residual non-sawlog woody biomass from mills and forestry operations, including forest health treatments and hazardous fuels removals.
- Evaluate the social, economic, and environmental costs and benefits of using biomass and water resources to produce biofuels, particularly in underserved communities.
- Expand the assessment of the increase in carbon sequestration, GHG emissions reduction, and nutrient and pesticide/herbicide runoff in biomass production systems.
- Expand crop genetic development and improve climate-smart agronomic practices to continuously increase crop yields and sustainability.

Productivity increases in corn and soybean systems over the past two decades have allowed virtually all increases in demand for biofuels to be met from existing croplands without reductions in exports. Aggregate biofuel production in the United States has grown from less than 1 billion gallons per year in 1991 to more than 18 billion gallons per year in 2022. During this period, cropland in cultivation has declined and exports of corn and soybeans have remained stable. Dual-use crops, such as corn or soybeans, can support food, feed, or biomass feedstock markets. These crops have several advantages that make them promising feedstocks for supporting SAF markets. Multiple potential markets for the feedstocks lower risk, annual crops provide farmers greater flexibility to shift and adapt to market conditions, and infrastructure and processing of the feedstocks are not entirely dependent on a single use. Continued productivity gains in corn and soybean systems will be important to support an expansion of SAF production. Federal policies to date have had limited effect on the CI of conventional biofuels. Because of the focus on CI, state policies such as California's Low Carbon Fuel Standard have created strong incentives and have been a driver in improving GHG performance. Emerging technologies are offering pathways to further decarbonize conventional biofuel pathways and ensure dual-purpose feedstocks continue to play a major role in biofuel production in the future. Research and deployment challenges and gaps include:

- Continuing and accelerating productivity gains for dual-purpose feedstocks.
- Deploying climate-smart farming practices, such as no-till, cover crops, and improved fertilizer management, and establishing policies to account for these benefits in the CI scores of SAF.

Conversion Technology Innovation



The Conversion Technology Innovation (CT) Action Area's objective is to conduct R&D (through pilot scale) from the receipt of biomass through to finished fuels. The research focuses on technology improvements to improve yield, improve integration of process steps, reduce CI, and reduce scale-up risk. Efforts include processes that are already commercial, such as HEFA, or nearing commercialization (alcohol to jet), and consider processes that will be ready for commercialization beyond 2030 but require development now to contribute to 2050 production targets.

Conversion from biomass to finished fuels requires numerous processing steps that employ combinations of biological, chemical, and electrochemical upgrading steps; separations; and purifications, among others. Thus, there is a vast number of process configurations that can be used to convert biomass into finished fuels of various types. At a high level, these are categorized into the following three areas:

- **Biomass deconstruction**. Many sustainable biomass feedstocks (especially lignocellulosic feedstocks) are inherently recalcitrant and require deconstruction steps prior to upgrading to hydrocarbon fuels. A variety of biological, thermochemical, and hybrid processes are employed to deconstruct the macromolecules that make up biomass (cellulose, hemicellulose, lignin, proteins, and fats) into readily upgradable intermediates.
- **Biomass intermediates upgrading**. Once deconstructed, the intermediates derived from biomass require upgrading to finished fuels. There are many combinations of technologies that can convert these intermediates into finished fuels that employ a combination of biological, chemical, and electrochemical technologies.
- **Enabling conversion technologies**. Some process improvements affect multiple unit operations or benefit multiple processes. These include improved biological and chemical catalysts, intermediate separations or purification of molecules, computational modeling, and techno-economic analysis (TEA) and life cycle analysis (LCA).

The key actions supporting the CT Action Area are:

- **Improvements to the fermentation fuel industry** to reduce the CI of the existing starch ethanol industry and increase its production capacity without requiring the planting of additional corn.
- **Improvements to existing ASTM-qualified pathways** to accelerate deployment of pathways that have already been qualified.

- **Development of biointermediates and pathways for compatibility with existing capital assets** to accelerate production and reduce the cost of SAF.
- **Reductions in scale-up and operational risk** by proactively addressing resiliency in process and equipment design.
- **Development of innovative unit operations and pathways** to broaden the availability of SAF.

Current Federal Agency Capabilities and Programs

An overview of current Federal agency capabilities and programs addressing the roadmap CT Action Area is provided below.

DOE Office of Science

Within the Office of Science, both the BER and BES programs conduct foundational science and early-stage (technology readiness level [TRL] 1–2) research on activities covering biomass deconstruction, biomass intermediates upgrading, and enabling conversion technologies. These low-TRL activities are occurring in laboratory settings, with promising technologies maturing to other DOE programs such as BETO or the Advanced Research Projects Agency – Energy (ARPA-E).

Within BER, notable examples include work to develop novel biomass pretreatment technologies to improve lignin and sugar conversion, development of new microbial strains with improved conversion and fuels synthesis characteristics, and computational modeling of biomass from the atomic scale to particle scale.

BER funds four Bioenergy Research Centers (genomicscience.energy.gov/bioenergy-research-centers/) that focus on various elements relevant to the CT Action Area:

- **Great Lakes Bioenergy Research Center**. Research explores ways to improve conversion of plant feedstocks to fuels with new platform microbial strains and solvolysis methods. Researchers also investigate how to alter lignin to improve the efficiency of biomass deconstruction.
- **Joint BioEnergy Institute.** Focus areas include development of novel ionic liquid-based biomass deconstruction technologies as well as genetic engineering and synthetic biology approaches for microbial conversion of biomass-derived sugars into liquid transportation fuels.
- **Center for Bioenergy Innovation**. Researchers are studying the breakdown of cellulosic biomass into sugars, specifically the use of consolidated biomass processing approaches that can simultaneously deconstruct and convert biomass into intermediates and fuels using engineered microbes. The center also conducts sustainability and economic analysis of new approaches.

- **Center for Advanced Bioenergy and Bioproducts Innovation**. Research is focused on genetic engineering and bioprocess development, predominantly to produce chemical and product precursors suitable for conversion to transportation fuels and other bioproducts.

Within BES, the Chemical Sciences, Geosciences, and Biosciences division supports fundamental research that may benefit processes and components for biomass conversion. For example, the Catalysis Science program supports fundamental chemical catalysis research that can enable more efficient biomass feedstock conversion. This includes atomic simulations, synthesis and testing of new catalysts at small scale, and other research that supports discovery and/or design of novel catalysts. The BES Separation Science program supports fundamental research that could advance design of separation systems with high selectivity, capacity, and throughput. Finally, BES stewards a suite of scientific user facilities—X-ray light and neutron sources, and multi-disciplinary research centers for nanoscale science—that provide leading-edge tools to enable the study of complex chemical, biological, and materials systems, including in situ and in operando.

DOE BETO

BETO's Conversion Technologies program (energy.gov/eere/bioenergy/conversion-technologies) supports applied research (TRLs 2–6 to deconstruct, upgrade, and enable technologies to convert biomass) in both the national laboratories and competitive awards with academia and industry. Many of the technologies that are optimized and further developed in BETO achieved proof of principle in the Office of Science. However, significant process development, reactor design, integration, and other system readiness improvements are required before scale-up is appropriate. The subprogram has worked in biological and thermochemical conversion processes to ensure efficiency in conversion-feedstock pathways that can then go on to scale-up by industry or through public/private partnerships.

Notable activities in BETO's Conversion Technologies R&D program National Laboratory portfolio include:

- Agile BioFoundry (agilebiofoundry.org/). A consortium of national laboratories that seeks to accelerate the development and deployment of biocatalysts by achieving commercial product yields, production rates, and product concentrations. The Agile BioFoundry also partners with industrial entities to support their commercialization efforts by providing them with genetic improvements.
- Chemical Catalysis for Bioenergy Consortium (chemcatbio.org/). This consortium seeks to accelerate the deployment of catalysts for bioenergy applications, with a particular focus on engineered or industrially manufactured catalysts. The work includes understanding of impurity tolerance and deactivation mechanisms to develop more robust catalysts. The consortium also develops processes that can upgrade intermediates into finished fuels through chemical catalysis and pyrolysis methods.

- Consortium for Computational Physics and Chemistry (energy.gov/eere/bioenergy/consortium-computational-physics-and-chemistry). This consortium develops reactor-scale models to enable process and reactor design and validates system performance with associated experimental research. The consortium also performs work for industrial partners that may not possess modeling or high-performance computing capabilities.
- Bioprocessing Separations Consortium (bioesep.org/). This research supports product purification and separations to ensure that next-generation bioprocesses meet specifications of downstream processes. The consortium partners with other high-TRL research groups and industrial partners to develop alternatives to thermal separation methods (evaporation or distillation) that can improve overall process efficiency.
- CO_2 Reduction and Upgrading for e-Fuels Consortium (energy.gov/eere/co2rue). This research group focuses on technologies that can efficiently recapture and upgrade CO_2 (especially derived from fermentation processes) into additional fuels and products. This includes work on electrochemical systems and the upgrading of these electrochemically derived intermediates.
- Feedstock-Conversion Interface Consortium (energy.gov/eere/bioenergy/feedstock-conversion-interface-consortium). This research group develops knowledge and tools for industry to address biomass handling and impurity challenges. The consortium employs a quality-by-design framework developed by the automotive and pharma industries to ensure material and quality attributes are met at each step of the process. The consortium focuses on pyrolysis, gasification, and fermentation from several sustainable feedstocks (corn stover, wood residues, and landfill-bound municipal solid waste).

DOE Office of Fossil Energy and Carbon Management (FECM)

FECM's Carbon Conversion Program invests in RD&D of technologies that convert captured carbon oxides, primarily CO_2, into economically valuable products such as chemicals, fuels, building materials, plastics, and bioproducts. These conversion technologies are among a portfolio of approaches required to mitigate the gigaton scale of CO_2 emissions to be removed from the atmosphere annually. The technical strategy of the Carbon Conversion Program focuses primarily on the development of CO_2 conversion technologies along three pathways: biological uptake, carbon conversion, and mineralization, including reactive capture. Catalytic conversion pathways include thermochemical, electrochemical, plasma, and microbially mediated approaches. Through these methods, waste carbon can be transformed into numerous products, including synthetic fuels and chemical intermediaries. This provides critical net-zero and low-carbon pathways for hard-to-decarbonize sectors including aviation.

Relevant activities and resources in the FECM's portfolio include the LCA Guidance Toolkit (netl.doe.gov/LCA/UPgrants), prepared in partnership with the National Energy Technology Laboratory. The toolkit provides resources for carbon utilization LCAs, including comparison product baselines. Robust LCA is critical for evaluating conversion technologies across various pathways to validate and quantify emissions reductions.

DOE ARPA-E

ARPA-E funds high-risk, high-reward research on a variety of energy technologies. Some have been relevant to potential SAF conversion pathways, such as Energy and Carbon Optimized Synthesis for the Bioeconomy (arpa-e.energy.gov/technologies/programs/ecosynbio), which funds biocatalyst development that can avoid CO_2 emissions.

USDA ARS

ARS funds a limited amount of conversion research at its research centers, located in numerous locations across the United States. The research taking place is at TRL 1–6, with work taking place predominantly at the interface of the feedstocks and biomass deconstruction. This includes work on pyrolysis of woody residues, fermentation of sugars to alcohols, and conversion of lignin. ARS houses the world's largest collection of microbial species (110,000 strains) critical to and utilized in biorefining, along with the ability to genetically modify microbial species to specifically create new/robust microbial species to address unique and difficult feedstock conversion problems. The ARS facilities have had numerous collaborations as subrecipients on work funded by BETO and the Office of Science.

Most of the ARS Biomass Research Centers are focused on upstream feedstock conversion issues, but there are several activities relevant to the CT Action Area. At the Northwestern Regional Biomass Research Center, researchers evaluate the breakdown and conversion of various biological feedstocks (crop residues, woody material, and municipal waste). They also focus on oilseed crops that could be used for SAF.

ARS is working on feedstock conversion improvements, biofuels, and value-added bioproducts and subsequent coproducts via collaborations with four ARS utilization centers. The Eastern Regional Research Center (ars.usda.gov/northeast-area/wyndmoor-pa/eastern-regional-research-center/), National Center for Agricultural Utilization Research (ars.usda.gov/midwest-area/peoria-il/national-center-for-agricultural-utilization-research/), Southern Regional Research Center (ars.usda.gov/southeast-area/new-orleans-la/southern-regional-research-center/), and Western Regional Research Center (ars.usda.gov/pacific-west-area/albany-ca/wrrc/) develop conversion technologies that enable growth and profitability in biofuels by increasing the processing technology efficiencies and value of existing products from feedstocks and coproducts to increase long-term profitability of biorefineries with parallel development of markets for biofuels, bioproducts, food, and feeds. Bioproducts (often sold at higher margins) and food products can support the overall economics of biorefineries and help reduce costs for biofuel products. Several conversion process steps that enable bioproducts are the same for biofuels.

ARS researchers utilize a number of feedstocks (rice, wheat, barley, corn, and soy waste streams; sorghum; switchgrass; algae; sugarcane; forest trimmings; potato peelings; dried distiller grains; food waste; and comingled urban waste) through various conversion technologies (catalytic and non-catalytic pyrolysis, torrefaction, esterification and transesterification, anaerobic digestion, enzymatic hydrolysis, enzyme-protein pectin-degrading enzymes, simultaneous scarification and fermentation, and microbial, fungal, bacterial, and yeast enzymes) to produce various biofuels (ethanol, SAF, butanol, liquefied natural biogas, biodiesel, and pyrolysis oils).

DOT FAA

FAA collaborates with a variety of research laboratories under the ASCENT program to support early-stage fuel property testing for emerging SAF molecules or blends. This work informs small-scale test systems that can be used to perform initial screening of pathways without the need for thousands of gallons. Under ASCENT Project 001, FAA facilitates research of alternative fermentation products, explores diverse applications for residual lignin, and assesses and validates next-generation carbon capture and utilization technologies. Under ASCENT Project 065, universities are advancing pre-screening techniques to model fuel properties using small fuel volumes. This work enables more efficient process optimization and scale-up to support fuel qualification.

Current Program Gaps and Barriers

Challenges and gaps to be considered in working to develop processes for converting existing and emerging feedstocks to SAF are considered below. Given the interdisciplinary nature of these processes, readers should refer to the other action areas for descriptions of current activities and future developmental needs to address the short- and long-term goals articulated in the SAF Grand Challenge.

CT.1: Decarbonize, Diversify, and Scale Current Fermentation-Based Fuel Industry

One of the largest remaining challenges toward reducing the CI of ethanol is the CI of the sugar feedstock for fermentation. Feedstock innovations, including carbon-smart agricultural practices, are focused on reducing the CI of the first-generation biofuel feedstocks (see FI.6: Improve Sustainability and Productivity of Biomass and Waste Feedstock Supply Systems). While considerable investment has been made into utilizing low-CI second-generation or cellulosic sugars, cellulosic sugar quality specifications and acceptability by existing fermentation facilities will be lacking until cellulosic sugar processes and providers are operational. There are a variety of scale-up challenges and gaps in research associated with using cellulosic feedstocks to produce additional sugar for fermentation, including:

- Separations and purifications, especially evaluation of contaminant buildup and downstream compatibility.
- Further refinement of upgrading catalysts in engineered forms and reactor engineering for these unit operations.
- Long-duration tests (thousands of hours) to generate performance guarantees for these unit operations.
- Long-duration tests to generate fuel quantities for certification testing.

Additionally, CO_2 emitted from first-generation ethanol facilities can be captured and sequestered or utilized, further reducing the CI. Needs in this area include:

- Expanding the use of CO_2 capture and storage from ethanol facilities. Invest in the infrastructure, including CO_2 pipelines and geologic storage to support this expansion.
- Research on integrating novel decarbonization approaches such as electrochemical, biochemical, and other CO_2-to-fuels pathways or technologies to store CO_2 in the form of a product.
- Updating and strengthening safety standards for CO_2 pipelines and related infrastructure.

CT.2: Develop Options to Increase Production and Reduce CI of Existing ASTM-Qualified Pathways

To meet the goal of 35 billion gallons needed for the U.S. aviation sector in 2050, in addition to existing feedstocks, new feedstocks including secondary crops, purpose-grown energy crops, and solid, wet, and gaseous waste streams will be needed. While ASTM-qualified pathways exist, some technology adaptation on preprocessing, pretreatment, and initial conversion steps is expected to be necessary for these feedstocks, including:

- Catalyst testing on emerging oilseeds and secondary crops (pennycress, camelina, and carinata) has not occurred at scales or durations required to pursue coprocessing or co-hydrotreating.
- Completion of state-of-industry analysis and detailed TEA and LCA of existing pathways that will lead to the identification of priority focus areas and identification of additional process intensification or biomass-specific research needs and/or scale-up priorities.
- Dedicated modular R&D for certain feedstock/conversion processes to accommodate the need for systems with lower capital expenses to make them amenable to distributed deployment scenarios.

CT.3: Develop Biointermediates and Pathways for Compatibility with Existing Capital Assets

Compelling business models are necessary to encourage industry investment, and this requires understanding of priority intermediates and the critical material attributes of these intermediates. Needs here include conducting analysis with a variety of stakeholders to identify priority intermediates for coprocessing and co-hydrotreating, especially to inform business models, modular system design, and research needs.

The major guiding premise of biointermediates is that they provide an opportunity to leverage existing hydrotreating infrastructure. However, there is a comparatively small amount of R&D being performed on the compatibility of these hydrotreaters with emerging biointermediates (e.g., pyrolysis oil, hydrothermal liquefaction oil, emerging oilseeds). Pilot runs to assess compatibility require hundreds to thousands of gallons. Thus, there are gaps in:

- Producing the hundreds to thousands of gallons of these biointermediates necessary to generate reliable data in the coprocessing or co-hydrotreating system.
- Blending and miscibility studies to identify optimal refinery insertion points.
- Developing analytical tracking methodologies that are accepted by regulatory agencies for biointermediates, especially those with lower analytical burdens.

CT.4: Reduce Risk During Scale-Up and Operations

There is a significant amount of effort in project scale-up through integrated pilot and demonstration of promising technologies. However, where possible, process performance and intermediate quality guarantees are needed to limit risk. Notable gaps include:

- Work in existing pilot- and demonstration-scale projects to explore operational failures, durability, and long-run (8,000-hour) information to develop risk assessments supporting future work.
- Lack of ad hoc technical assistance for these first-of-a-kind demonstration facilities to enable fast resolution to problems encountered.
- To date, funding for operations of pilot-scale systems has not been provided by government agencies. Operational run times of less than 2,000 hours are insufficient for further financing.
- Formal risk analysis of these processes has not been conducted at the portfolio level. Most risk analysis, if conducted, occurs on a project-by-project basis.
- Process stability data do not exist for many emerging technologies due to a lack of operational engineering- and pilot-scale systems.

Figure 5. Researchers at the National Renewable Energy Laboratory (NREL) explore why promising fermentation processes that excel in small-scale bioreactors fail in large-scale bioreactors.

Photo courtesy of NREL

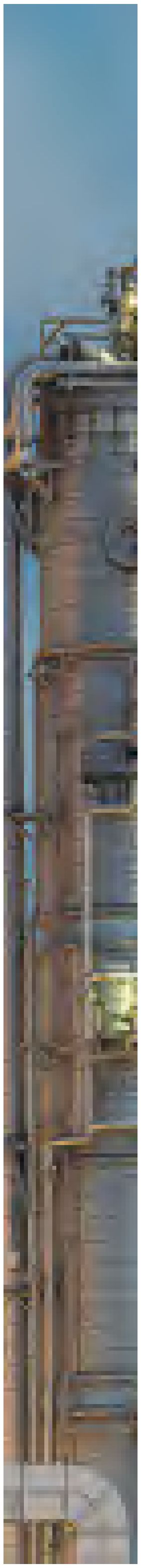
CT.5: Develop Innovative Unit Operations and Pathways

Additional R&D is needed before optimization and engineering can occur to access all potentially available feedstocks. Specific examples include:

- Electrocatalysis is an emerging technology with only limited testing beyond bench scale to produce fuels. Long-duration testing has occurred only in limited settings, and fouling management approaches are needed along with research into standardization and challenges encountered as electrocatalytic reactors scale.
- Pathways to produce aromatic- or cycloparaffin-rich fuel streams are limited, and additional testing is necessary to evaluate seal-swell requirements, gather emissions data, and establish blend levels. These pathways may enable additional local air quality benefits compared to conventional, petroleum-derived fuels, while providing a route for 100% unblended drop-in SAF. Preliminary studies have shown reduced particulate matter emissions from SAF with synthetic aromatics versus conventional jet fuel.
- Deep hydrodenitrification and hydrodeoxygenation catalysts require dedicated long-duration tests. These catalytic processes are needed for utilization of multiple biointermediate streams including pyrolysis biocrude, hydrothermal liquefaction biocrude, and other sustainable oils and greases.

- Multi-feedstock conversion technologies largely do not exist, as they dramatically increase process risk and complexity. Corresponding feedstock aggregation and blending analysis is necessary to justify business plans and infrastructure investments.

Building Supply Chains



The objective of the Building Supply Chains (SC) Action Area is to support SAF production expansion through the integration of R&D transitions from pilot- to large-scale demonstration projects, validate supply chain logistics and business models, and enable and leverage public-private partnerships and collaboration with regional, state, and local stakeholders. The SC Action Area encompasses feedstock production, collection, and distribution to SAF production facilities; conversion of feedstock to fuel; and transport of finished fuel to the infrastructure required to fuel aircraft.

Within the action area are four workstreams, each defining a critical topic to be addressed in the pursuit of the SAF Grand Challenge objectives:

- **Convene regional stakeholder coalitions** to lead the exploration and development of SAF supply chains and provide outreach, extension, and education supporting SAF supply chain growth.
- **Develop and disseminate comprehensive data, analysis, and modeling tools** as a foundation for the development of low-GHG, cost-effective deployment of feedstock-to-fueling supply chains, SAF manufacturing, and logistics solutions.
- **Support feedstock-to-fueling demonstration projects** to de-risk and mature key elements in the supply chain from feedstock through airport fueling infrastructure.
- **Invest in commercial-scale SAF production infrastructure and facility development** with existing and new public-private partnerships to expand domestic SAF supply.

Current Federal Agency Capabilities and Programs

U.S. Government-led research, development, demonstration, and commercial deployment support is playing a critical role in reducing production costs, maximizing sustainability benefits, developing supply chains, and expanding commercial production infrastructure. Ongoing R&D efforts by various government organizations are focused on work across the entire SAF supply chain and development space. These coordinated R&D strategies aim to achieve rapid development and deployment of SAF and identify how each agency is addressing specific SAF challenges, from feedstocks to conversion and fuel testing, including testing military-grade fuels. Continued coordination between Federal offices, agencies, and departments can enable the sustainable growth and expansion of a successful bioeconomy.

DOE BETO

BETO's Systems Development and Integration (SDI) subprogram (energy.gov/eere/bioenergy/systems-development-and-integration) 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. Engineering-scale verification data from SDI-funded projects are used to evaluate R&D techno-economics and sustainability progress. Through 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 is working to enable the construction and operation of at least four demonstration-scale integrated biorefineries. 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 reduce the cost and time for new approvals while expanding the range of qualified fuels to include new critical pathways that will enable the expansion of SAF supply.[10]

DOE ARPA-E

ARPA-E supports six projects as part of the Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management (SMARTFARM) program (arpa-e.energy.gov/technologies/programs/smartfarm). These projects will develop technologies that bridge the data gap in the biofuel supply chain by quantifying feedstock-related GHG emissions and soil carbon dynamics at the field level.

DOE Office of Manufacturing and Energy Supply Chains

The DOE Office of Manufacturing and Energy Supply Chains (MESC) is dedicated to enhancing U.S. manufacturing capabilities and securing resilient supply chains for energy technologies. MESC serves as the frontline of clean energy capital deployment to accelerate America's transition to a resilient, equitable energy future via direct investment in manufacturing capacity and workforce development. MESC focuses on strengthening and securing supply chains needed to modernize the nation's energy infrastructure, supporting workforce education and training and providing robust manufacturing modeling to guide and support investments and policy recommendations. MESC operates in late-stage technology development, driving large-scale deployment of new technologies.

The Qualifying Advanced Energy Project Credit (48C) is a tax incentive program designed to support and accelerate investments in advanced energy projects in the United States. Administered by DOE, this credit targets projects that promote energy efficiency, reduce

[10] BETO. 2023. *Bioenergy Technologies Office Multi-Year Program Plan: 2023.*

greenhouse gas emissions, and contribute to the transition to a cleaner energy economy. The program provides financial incentives in the form of tax credits, which can be used to offset a portion of the capital costs associated with these projects. This initiative aims to stimulate innovation in the energy sector while aligning with broader national goals of sustainability and energy security. The Qualifying Advanced Energy Project Credit (48C) program supply chain support for SAF production includes feedstock, pre-treatment equipment, biofuel reactors, chemical conversion catalysts, and storage and delivery infrastructure.

DOE Office of Clean Energy Demonstrations

The Office of Clean Energy Demonstrations (OCED) (https://www.energy.gov/oced/office-clean-energy-demonstrations) is managing more than $25 billion in funding to deliver clean energy demonstration projects at scale in partnership with the private sector to accelerate deployment, market adoption, and the equitable transition to a decarbonized energy system. OCED can assist clean energy projects by providing cost-share grants to demonstration projects for emerging clean-energy technologies. Current demonstrations in OCED's portfolio include clean hydrogen, carbon management, industrial decarbonization, advanced nuclear reactors, long-duration energy storage, demonstration projects in rural or remote areas and on current and former mine land. Clean hydrogen is a necessary input for all low CI SAF pathways. OCED is providing $7 billion in funding through the Bipartisan Infrastructure Law (https://www.whitehouse.gov/build/guidebook/) for seven Regional Clean Hydrogen Hubs (https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0).

DOE Loan Programs Office

The Loan Programs Office (energy.gov/lpo/overview) serves to fill the gap in commercial deployment of decarbonization technologies by serving as a bridge to bankability for innovative and high-impact energy technologies. The office helps technology developers by providing them with access to much-needed loans and loan guarantees when project and market risks may still be too great for private lenders to provide financing. The Loan Programs Office can assist with first commercial-scale deployments of new technologies to address the engineering scale-up challenges and demonstrate technology effectiveness at scale. Under Title 17 Clean Energy Financing Program (https://www.energy.gov/lpo/title-17-clean-energy-financing), the Loan Programs Office can lend to innovative projects under T1703 and non-innovative retrofits of existing petroleum assets under the T1706 program. These programs can help bridge the funding gap.

USDA

USDA focuses on feedstock development, production, logistics, sustainability (i.e., economic, environmental, social), education, and outreach. Agencies within USDA provide grants for expanding the nationwide availability of renewable-fuel-compatible equipment at stations. USDA also provides financial assistance to owners and operators of agricultural and nonindustrial private forestland who wish to establish, produce, and deliver biomass feedstocks.

Through NIFA's Agriculture and Food Research Initiative's Sustainable Agricultural Systems program, the USDA funds SAF supply chain Coordinated Agricultural Projects. A Coordinated Agricultural Project can provide an excellent framework for regional stakeholder coalitions to coalesce around emerging supply chains. These projects integrate research, outreach, and education to support de-risking feedstock supply chains linked to emerging or existing conversion technologies. Participants in SAF supply chains can leverage these and other Federal grant opportunities to invest in process technologies to convert feedstock to fuel, reduce risk, and prove performance by maturing from the lab to pilot scale and on to demonstration scale.

USDA loan guarantee programs such the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program (Section 9003) (rd.usda.gov/programs-services/energy-programs/biorefinery-renewable-chemical-and-biobased-product-manufacturing-assistance-program) provides loan guarantees up to $250 million to assist in the development, construction, and retrofitting of new and emerging technologies for advanced biofuels, renewable chemicals, and bio-based products.

EPA

EPA administers the RFS program put in place by the Energy Independence and Security Act of 2007. The standards finalized for 2025 will require the use of 22.33 billion gallons of a wide range of renewable fuels from a wide range of feedstocks. In setting these standards, EPA evaluates the potential supply and use of all forms of qualifying renewable fuels. This includes all things that impact supply of renewable fuels, including the supply, distribution, and blending of renewable fuels, as well as the issues and constraints associated with their use. As part of this, EPA also addresses the environmental impacts of biofuels and bioproducts. This includes assessing materials compatibility issues and testing underground storage tank systems and other equipment in which SAF will be stored and used, as well as understanding the potential air quality impacts of biofuels and bioproducts at the points of end use and along the supply chain. EPA also qualifies new biofuels for inclusion under the RFS program based on their life cycle GHG emissions and other requirements. These Federal activities are helping to identify the challenges and impacts associated with increased roadway, rail, marine, and pipeline transport of feedstock and bioproducts across the supply chain. They are also addressing issues inhibiting biofuel end use distribution infrastructure and supporting biofuels adoption among all modes of transportation.

DOT

Multiple modal administrations within DOT are engaged in activities related to transporting and distributing biofuels and bioproducts, as part of the agency's critical mission. DOT is responsible for critical aspects of alternative fuel transport, distribution, and end use, including safety, infrastructural adequacy, potential materials compatibility issues, emergency responder education, and training on optimal emergency response to renewable fuels spill incidents.

DOT's Volpe Center (volpe.dot.gov/) developed the Freight and Fuel Transportation Optimization Tool (FTOT) as a flexible scenario-testing tool that optimizes the transportation of materials for energy and freight scenarios. The tool is designed to analyze the transportation needs and constraints associated with material collection, processing, and distribution to provide an optimal solution to supply chain routing and flows.

DOT works with DOE and USDA to provide supporting science for fuel and lubricant specifications, with standard-setting organizations such as ASTM International, with EPA to meet requirements of the RFS, and with the Food and Drug Administration to determine acceptable human exposure and/or consumption specifications.

DOT FAA

The FAA supports testing to ensure fuels are safe for use; supports analysis to understand their economics, environmental impacts, and potential production; and plays a significant role in coordination among industry, Federal agencies, and the international community.

Under ASCENT Project 001, "Alternative Jet Fuel Supply Chain Analysis," FAA is approaching sustainable jet fuel production holistically, considering technological, environmental, economic, and social elements. Researchers are evaluating fuel production pathways, feedstock and infrastructure requirements, and commercial fuel demand to create scenarios for future production. This project quantifies SAF economic and environmental benefits and cost as its main goal.

The FAA also facilitates coordination of a broad range of SAF stakeholders through CAAFI, a coalition of airlines, aircraft and engine manufacturers, energy producers, researchers, international participants, and U.S. Government agencies working together to build relationships, share and collect data, identify resources, and direct research, development, and deployment of SAF.

FAA's Community Assets and Attributes Model (dgss.wsu.edu/services/caam/) helps aviation biofuel researchers and practitioners better consider and include social assets of communities in their biofuel facility site selection models. The model helps identify potential social barriers or aptitude for developing a regional supply.

Fueling Aviation's Sustainable Transition (FAST) (faa.gov/general/fueling-aviations-sustainable-transition-fast-grants) is a new discretionary grant program administered by the FAA and authorized under Section 40007 of the Inflation Reduction Act of 2022. The grant program makes investments to accelerate the production and use of SAF and the development of low-emission aviation technologies to support the U.S. aviation climate goal to achieve net-zero GHG emissions by 2050. Under the SAF portion of the program, there are seven scoping studies related to infrastructure needs for SAF being funded at a total of $1.7 million.

Under ASCENT Project 093, Collaborative Research Network for Global SAF Supply Chain Development (ascent.aero/project/collaborative-research-network-for-global-saf-supply-chain-development/), FAA uses the experience gained from developing domestic supply chains to enable SAF production and associated analytical tools that will be leveraged and adapted to understand the potential environmental and economic benefits that could result from the development of global supply chains while also working to understand the barriers to their development. The overall effort focuses on three distinct geographical areas with different characteristics: sub-Saharan Africa, Latin America and the Caribbean, and Southeast Asia.

Figure 6. Aerial view of ethanol biorefinery with railcar receiving and distribution.

Photo from iStock

Current Program Gaps and Barriers

The development of a successful SAF supply chain requires maturation and integration of technology pathways and carrying out large-scale coordination efforts along each stage of SAF production and distribution. With the crosscutting nature of this work, the knowledge and technology gaps facing the SC Action Area are generally inclusive of the major gaps facing the other five action areas of the SAF Grand Challenge Roadmap. Readers are referred to the other action areas for descriptions of current activities and future developmental needs to address the short- and long-term goals articulated in the SAF Grand Challenge.

Gaps and barriers to be considered in working to build out a mature SAF supply chain are considered below.

SC.1: Build and Support Regional Stakeholder Coalitions through Outreach, Extension, and Education

An effective approach to standing up new SAF supply chains is to assemble diverse groups of stakeholders with a mission to evaluate all elements of the supply chain and provide recommendations to advance deployment, attract investment, advocate for policy change, and identify solutions to deployment barriers and risks. Coalitions should determine how state clean energy policies, feedstock availability, and planned production facilities will shape the regional deployment of SAF to supply medium and large airport hubs.

Prior efforts to establish coalitions representing the SAF supply chain elements from feedstock production through fueling infrastructure have not taken a systems-level approach that integrates participants and assets (e.g., modeling tools) along the supply chain and the representative workstreams in this action area. Additional stakeholder coalition development needs are identified below:

- Review prior efforts to establish coalitions and establish a reproducible methodology to jump-start coalitions that integrate stakeholders across the SAF supply chain.
- Accelerate outreach efforts with SAF supply chain stakeholders to catalyze and coordinate regional stakeholder coalitions. Frequently, this requires identification of an anchor participant (e.g., a conversion technology company with an interest in SAF plant construction development).
- Incentivize stakeholder coalitions to form, meet, plan, and execute.
- Conduct analysis to identify high-impact regional stakeholder coalition opportunities.
- Expand support of regional workforce development and educational programs that lead to skilled resources across the SAF supply chain.
- Increase international engagement through initiatives such as the International Aviation Climate Ambition Coalition, the International Civil Aviation Organization, the Clean Energy Ministerial, IEA Bioenergy Technology Collaboration Programme, Global Biofuels Alliance, Canadian Council for Sustainable Aviation Fuels, and other international efforts to ensure a global focus.

SC.2: Model SAF Supply Chains

The development of national-scale scenarios that capture feedstock availability and SAF production potential are critical for supporting cross-sectoral strategies for decarbonization; guiding Federal investments in research, development, and deployment; and informing policy development. Refer to the Feedstock Innovation Action Area section for ongoing work and gaps in modeling feedstock supply chains. Refer to the Policy and Valuation Analysis Action Area section for ongoing work and gaps in developing models to inform policy.

U.S. Government agencies have supported development and use of models relevant to the SAF supply chain landscape. These models vary in structure, level of detail, intended audience, and their availability. A map of these is shown in Figure 7.

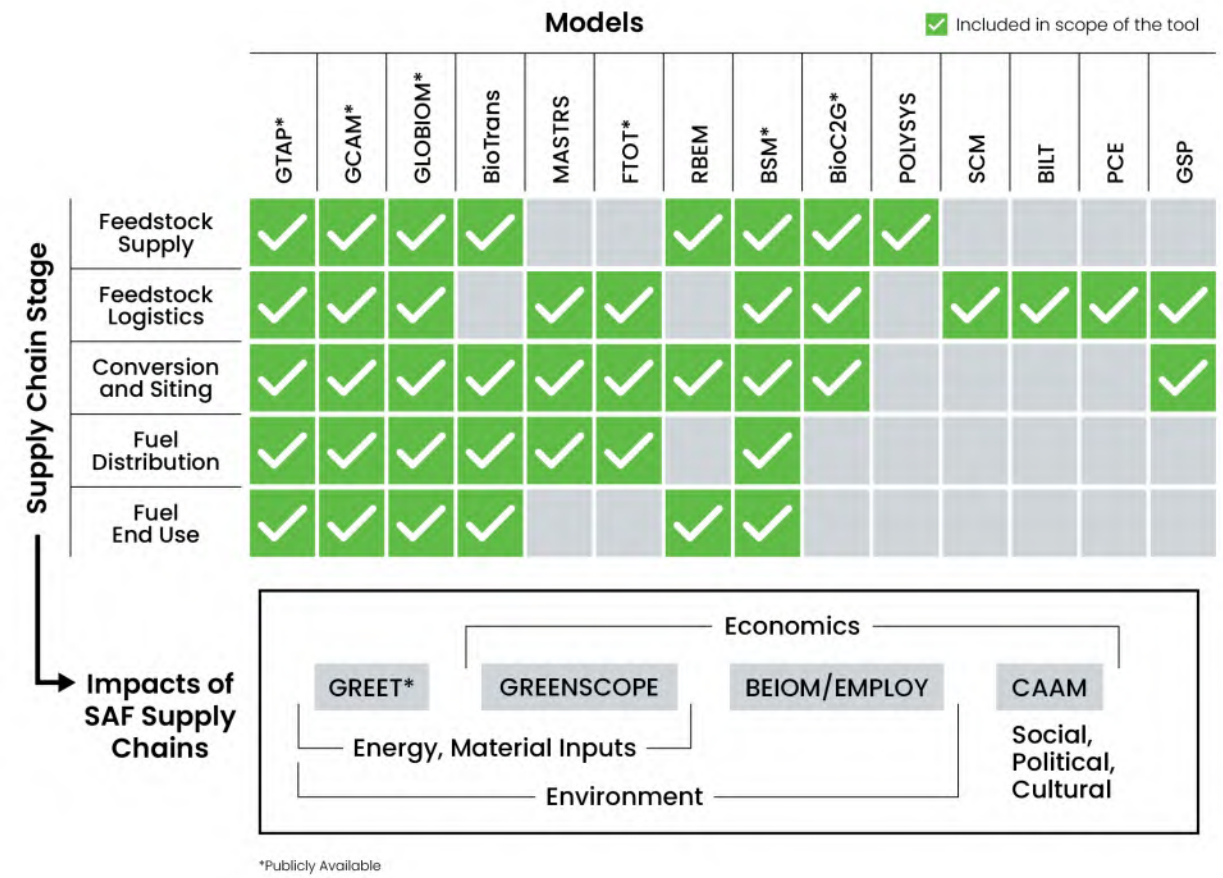


Figure 7. Available models relevant to the SAF supply chain landscape.[11]

GTAP: *Global Trade Analysis Project;* ***GCAM:*** *Global Change Analysis Model;* ***GLOBIOM:*** *Global Biosphere Management Model;* ***MASTRS:*** *Multi-Objective Analysis of Supply Chain Transformations for Sustainable Regional Systems;* ***FTOT:*** *Freight and Fuel Transportation Optimization Tool;* ***RBEM****: Regional Bio-Economy Model;* ***BSM:*** *Bioenergy Scenario Model;* ***BioC2G:*** *Bio-Cradle-to-Grave;* ***POLYSYS:*** *Policy Analysis System Model;* ***SCM:*** *Supply Characterization Model;* ***BILT:*** *Biofuel Infrastructure, Logistics and Transportation;* ***PCE:*** *Pre-Commercial Evaluation;* ***GSP:*** *Geospatial Supply Chain Planning;* ***GREET:*** *Greenhouse gases, Regulated Emissions, and Energy use in Technologies;* ***GREENSCOPE:*** *Gauging Reaction Effectiveness for the ENvironmental Sustainability of Chemistries with a Multi-Objective Process Evaluator;* ***BEIOM/EMPLOY:*** *Biomass Emissions and Impacts Occupational Model/ Environmentally-extended Multi-regional Projection of Lifecycle and Occupational Energy Futures;* ***CAAM:*** *Community Assets and Attributes Model*

Needs in this area include:

- Identifying the target audiences for the existing suite of models to ensure they are designed to meet the needs of the audience.
- Providing a centralized location for links to download relevant input datasets or direct downloads of input data, where possible, to expand the impact of Federal investments in supply chain models and reduce duplicative efforts funded across agencies.

[11] The U.S. Government has not funded development of GLOBIOM. It is included here because of its use in CORSIA. Details on the use cases and methodological differences between the three economic models (GLOBIOM, GTAP, and GCAM) are provided in EPA's *Model Comparison Exercise* (nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1017P9B.pdf).

- Tailoring optimization-based tools, such as DOT Volpe Center's FTOT, and the Biofuel Infrastructure, Logistics and Transportation Model, to provide outputs for SAF.
- Designing a model to identify infrastructure needs, such as blending terminals, multimodal terminals, or new pipelines. New modeling capabilities in this area would ideally be designed based on feedback from potential users to maximize usefulness for decision support.
- Developing models that will indicate how the utilization of book and claim may alter costs and emissions for SAF supply chains.
- Developing a SAF supply chain model that incorporates the need to generate zero-carbon hydrogen on-site or import hydrogen from off-site sources.
- Incorporating into SAF models the Roads to Removal project's updated data on geologic storage resources across the United States and the expected costs per ton of CO_2 injected.[12]

SC.3: Demonstration of SAF Supply Chains

Identifying and overcoming the critical gaps associated with the demonstration of supply chain elements will help avoid costly changes as SAF production volumes increase and reduce risks at the biorefinery and throughout the entire supply chain. DOE, USDA, and other Federal agencies are investing in partnered efforts to fund energy innovations from R&D up through technology scale-up and demonstration and build investor confidence in these technologies. The "Sustainable Aviation Fuel (SAF) Grand Challenge: Building Supply Chains Request for Information" closed in November 2023 and sought stakeholder feedback on the most critical gaps facing the demonstration of SAF supply chain elements. Among others, these gaps included a lack of sustainable feedstock, risks due to technology readiness, difficulties in securing funding, a lack of SAF infrastructure, and policy uncertainty. A report summarizing stakeholder responses is under development.

The costs of supplying biomass using current practices and technologies are too high for market acceptance of biofuels. Without further development of biomass production technologies, the challenges associated with the inherent heterogeneity of biomass and inconsistent and low-quality feedstocks remain. See the Feedstock Innovation Action Area section for further discussion and gaps in this area.

The pilot and demonstration of first-of-a-kind technologies will inevitably result in the need to conduct additional research to overcome unforeseen barriers or failures as scaling occurs. See the Conversion Technology Innovation Action Area section for gaps in this area, including the need for operational data from existing scale-up activities to identify the needed areas for R&D and ad hoc support for active projects that are scaling.

[12] Roger Aines. 2023. "Roads to Removal." Presented at the BETO 2023 Project Peer Review, April 4, 2023. energy.gov/sites/default/files/2023-05/beto-09-project-peer-review-feed-apr-2023-aines.pdf.

As this is an emerging industry, the demonstration of supply chain elements at intermediate or pre-commercial scale is difficult for producers of feedstocks and fuels due to the relatively low volumes of product being handled. These barriers ultimately hurt the overall process economics for producers. Tapping into existing industry could offer support for early demonstrations, such as leveraging existing refining capacity to inexpensively upgrade bio-derived intermediates and oils. Needs in this area include:

- Developing strategies to normalize and control consistent intermediate production from biomass.
- Demonstrating the use of pipelines to transport advanced hydrocarbon fuels that alleviate the concerns of cross-contamination, blending tracking, and economic viability, as well as the potential for sufficient volumes to build comfort in the industry.
- Developing guidelines and increasing pipeline operators' comfort levels to transport these fuels efficiently.

Biomass from agricultural and forest resources have various bulk loads and energy densities, requiring high transport volumes, which means that feedstock movements pose a significant transportation challenge. Biomass transportation by truck is costly over long distances and, at high volumes, can damage roadways and lead to increased congestion. The emerging industry will also need distribution of product infrastructure investments. Needs in this area include:

- Research to improve understanding of the implications of trucking regulations on payload limits, costs, and roadway maintenance needs, as well as to explore opportunities to use other transport modes, such as rail and barge, for biomass transport or to adopt a more efficient conversion system to minimize these issues.
- Coordinating Federal programs that support underlying research with existing pilot and demonstration projects to ensure partners have access to all available resources to support successful demonstration. For example, enable biorefinery demonstration projects to get support by leveraging Bipartisan Infrastructure Law feedstock subsidies to reduce risk.
- Supporting water and soil remediation demonstration projects with biochar. R&D projects are needed to optimize biochar to remove heavy metals (e.g., mercury) and organic contaminants (e.g., per- and polyfluoroalkyl substances [PFAS]) and develop processes for applying and removing the biochar after cleanup.[13,14]
- Engaging relevant agencies (EPA, U.S. Geological Survey, and USDA) to work together to develop lower-cost, sustainable solutions with biochar from Federal lands.

[13] Carlos Rodriguez-Franco and Deborah S. Page-Dumroese. 2021. "Woody biochar potential for abandoned mine land restoration in the U.S.: a review." *Biochar* 3: 7–22. doi.org/10.1007/s42773-020-00074-y.
[14] Carlos Rodriguez-Franco. 2020. "U.S. Forest Service National Biochar Initiative: Developing At-Scale Biochar Markets and Industry." Presented at National Biochar Week, 7–11 December 2020. biochar-us.org/presentation/developing-scale-biochar-markets-and-industry.

- Provide support for integrated demonstration units to test production at commercial scale.
- Supporting integrated demonstration unit projects for use of multiple types of feedstocks, such as agriculture and forest residues together in a common supply chain.
- Developing scenarios for distribution pathways, transport, and infrastructure needs that are consistent with the emerging bioeconomy and the biofuel and bioproduct industries.
- Accelerating fit-for-purpose, compatibility, and performance testing to qualify new products under existing bodies such as ASTM to support end use investments.

SC.4: Invest in SAF Production Infrastructure to Support Industry Deployment

Federal loan guarantee programs, such as USDA's Section 9003 loan guarantee program and the DOE Loan Programs Office, can provide forms of debt financing for SAF projects. Programs like these can be more receptive to financing first-of-a-kind commercial deployments of new technologies given USDA and DOE's familiarity with many of these new technologies. In addition to Federal loan assistance, these first-of-a-kind commercial projects will require a significant investment of private capital, which can come from various sources, including owner equity, venture capital, corporate investors, green funds, institutional investors, and various philanthropic investments. The risk associated with this investment of private capital is elevated significantly due to the following barriers and gaps:

- Developing more reliable, long-term, SAF-related policies and incentives to reduce risk for technology developers and potential financing partners and increase the likelihood of long-term binding offtake contracts that can enhance market demand certainty.
- Engaging stakeholders earlier in the research, development, and implementation cycle to better align goals and priorities at the local, regional, and national levels.
- Proactively engaging communities to understand the public health, economic, environmental, and social benefits of SAF compared to conventional fuels, and working toward acceptance of new facilities and scale-up activities to avoid project risks from public opposition down the line, which delays projects, holds up the entire supply chain, and decreases investor confidence.
- Designing feedstock insurance programs that can build confidence for feedstock producers who operate on tight margins and will need to take on risk with the adoption of new practice.
- Building out infrastructure projects that will facilitate the production and use of SAF.

Policy and Valuation Analysis

The objective of the Policy and Valuation Analysis (PA) Action Area is to develop the data, tools, and analyses that could be used by decision makers to develop SAF policies. Although existing policies, including those introduced under the Inflation Reduction Act of 2022, support SAF development, modified or new policies will be needed to achieve the goals of the SAF Grand Challenge. This implementation report does not advocate for any policy position but instead focuses on ensuring that data, tools, and analysis are available to inform the decision-making process. This action area will focus on developing and improving modeling tools, data, and expertise within Federal Government agencies, national laboratories, academic institutions, and industry. The focus will be on analysis of U.S. domestic Federal and state policies as described below, although the data and tools will be available for international decision makers in their SAF development activities. Within the PA Action Area, three workstreams are directed toward achieving SAF Grand Challenge goals:

- **Develop improved environmental and socioeconomic data and analytical tools for SAF** to ensure their environmental integrity; align with international standards and commitments; and appropriately account for their environmental and socioeconomic impacts, including air quality effects and life cycle GHG emissions, using interagency-agreed-upon LCA methodologies.
- **Conduct techno-economic and production potential analysis** to guide decision makers on expanding SAF production in a manner that carefully considers GHG reductions, cost of production, and policy needs.
- **Inform SAF policy development** by conducting analyses that define conditions needed for successful development and deployment of SAF.

Current Federal Agency Capabilities and Programs

DOE BETO

BETO collaborates with National Laboratories, universities, other Federal agencies, and private industry to conduct analysis and R&D to improve the benefits of advanced bioenergy relative to conventional energy systems (energy.gov/eere/bioenergy/data-modeling-and-analysis). BETO's Data, Modeling, and Analysis program (energy.gov/eere/bioenergy/data-modeling-and-analysis) supports research, analysis, and tool development to address the economic and environmental dimensions of bioenergy and bioproducts. BETO's Sustainability subprogram (energy.gov/eere/bioenergy/sustainability) generates scientific knowledge that proactively addresses issues affecting the scale-up potential, public acceptance, and long-term viability of advanced bioenergy systems.

Notable BETO program activities in support of this action area include:

- **Policy analysis modeling**. BETO works with national laboratories, academia, and industry to develop policy analysis tools. These tools generate scenarios of possible outcomes given certain assumptions about policy incentives, state of the market (oil prices), and technological readiness of SAF conversion processes. New data and updates are regularly added to these models to provide the latest perspective on potential outcomes. For example, the Biomass Scenario Model (nrel.gov/analysis/bsm/) is publicly available to provide decision makers a range of possible scenarios that might develop under specific assumptions.
- **TEA**. BETO supports rigorous TEA at several National Laboratories (National Renewable Energy Laboratory [NREL], Pacific Northwest National Laboratory, Oak Ridge National Laboratory, and Idaho National Laboratory).[15,16,17,18] BETO TEAs consider technology maturity (e.g., scale at which it has been demonstrated), potential for future cost reductions through scale-up or replication, pioneer plant cost and its correlation with future mature plant costs, valuation of coproducts and how they may impact cost of fuel production, financial assumptions, policy incentives, and other factors. BETO TEAs are subject to a rigorous independent review process involving leading experts in the field. After review, TEAs are published as laboratory technical reports (energy.gov/eere/bioenergy/data-modeling-and-analysis-related-links) and may be subsequently revised and edited for publication in scientific journals.
- **LCA**. Under BETO sponsorship, Argonne National Laboratory (ANL) has been developing the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) suite of LCA. GREET is a tool that assesses environmental impacts associated with all stages of the supply chain of a technology or product. It is used to guide decision-making and R&D and inform policy and regulations related to the transportation and energy sectors. DOE and USDA are collaborating with other Federal agencies to develop the model to calculate the emissions reduction percentages under the Sustainable Aviation Fuel Tax Credit per Section 40B(e)(2) of the Inflation Reduction Act. DOE released the 40BSAF-

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[15] A.H. Bhatt et al. 2023. "Evaluation of Performance Variables to Accelerate the Deployment of Sustainable Aviation Fuels at a Regional Scale." *Energy Conversion and Management* 275: 116441. doi.org/10.1016/j.enconman.2022.116441.

[16] K. Moriarty et al. 2021. *Port Authority of New York and New Jersey Sustainable Aviation Fuel Logistics and Production Study*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-80716. www.nrel.gov/docs/fy22osti/80716.pdf.

[17] K. Harris et al. 2021. "A Comparative Techno-Economic Analysis of Renewable Methanol Synthesis from Biomass and CO_2." *Applied Energy* 303. doi.org/10.1016/j.apenergy.2021.117637.

[18] N.A. Huq et al. 2021. "Toward Net-Zero Sustainable Aviation Fuel with Wet Waste-derived Volatile Fatty Acids." *Proceedings of the National Academy of Sciences* 118 (13): doi.org/10.1073/pnas.2023008118.

GREET 2024 model on April 30, 2024 (www.energy.gov/media/322677). In 2023, USDA supported ANL with adding oilseed cover crops into GREET.

- **Bioenergy modeling**. DOE and BETO support development and application of a wide variety of models across all elements of the SAF supply chain. A list and interactive map of national laboratory-developed bioenergy models based on their analytical purpose and the supply chain stages they incorporate are available through NREL. (bioenergymodels.nrel.gov/models/).
- **Resource assessments**. BETO collaborates with USDA and EPA on comprehensive renewable carbon resources assessments (energy.gov/eere/bioenergy/renewable-carbon-resources). The 2016 Billion-Ton Report[19] has been updated with new data, additional categories of domestic waste feedstocks, and comprehensive treatment of sustainability practices. An updated version of the resource assessment was published in March 2024.[20]

DOE Vehicle Technologies Office (VTO)

DOE is coordinating with FAA and NASA to better understand, quantify, and mitigate the non-CO_2 emissions of SAF combustion. DOE is leveraging the unique capabilities at DOE labs to deliver fundamental science, computational tools, and new data for industry to design the next generation of jet propulsion and fuels to reduce aviation emissions. Notable sponsored work related to reducing aviation emissions include:

- Quantifying the role of soot surface properties on water droplet nucleation (related to contrail formation and persistence).[21]
- Comparing sooting propensity and ice nucleation propensity of various candidate blends of cycloalkanes and cycloalkenes suitable for use in SAF as potential partial replacements for aromatic compounds.
- Fundamental modeling of ice nucleation processes and their dependence on soot characteristics, including surface morphology and chemical composition.[22]

[19] M. H. Langholtz, B. J. Stokes, and L. M. Eaton. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy*. Washington, D.C.: BETO. DOE/EE-1440. doi.org/10.2172/1271651.
[20] U.S. Department of Energy. 2024. *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources.* M. H. Langholtz (Lead). Oak Ridge, TN: Oak Ridge National Laboratory. ORNL/SPR-2024/3103. www.energy.gov/sites/default/files/2024-03/beto-2023-billion-ton-report_2.pdf.
[21] J. Manin. 2023. "SAF Combustion & Soot Processes." Presented at the 2023 VTO Annual Merit Review. www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/DORMA018_Manin_2023_o%20-%20Isaac%20Ekoto.pdf.
[22] S. W. Wagnon and M. J. McNenly. 2023. "SAF Contrail Modeling." Presented at the 2023 VTO Annual Merit Review. www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/DORMA020_mcnenly_2023_o%20v2%20-%20Matt%20McNenly.pdf.

- Performing numerical simulations to assess the effect of fuel component molecular structure on sooting and other aspects of combustion.[23]
- Experiments and computational fluid dynamics modeling of post-combustor soot evolution and near-field plume dynamics and mixing modeling of gas turbine exhaust.[24,25]
- Kinetics modeling of soot and soot precursors in real and simplified surrogate SAF.[26]

DOT FAA

Under ASCENT Project 001, Alternative Jet Fuel Supply Chain Analysis, FAA is approaching SAF production holistically, considering technological, environmental, economic, and social elements. FAA spearheads the development of robust data, analyses, and methodologies supporting the integration of SAF pathways into state, national, and international policies. Efforts involve community engagement to examine the potential of, and challenges with, book-and-claim mechanisms, as well as coordinated research clarifying the environmental advantages of SAF over conventional jet fuel. These efforts have facilitated the establishment of techno-economic modeling groups to streamline approaches, aid in policy evaluations, and guide R&D decisions.

Several ASCENT projects are examining the impact of the use of SAF on air quality and climate change. Recent efforts have also focused on measurements and modeling related to aviation-induced cloudiness, as well as the role that SAF can play in mitigating associated climate impacts. ASCENT Project 02, Understanding Changes in Aviation Emissions due to SAF with new Combustor Engine Technology, investigates the effects of engine technology and fuel composition on combustion and subsequent impacts on climate and air quality (ascent.aero/project/understanding-changes-in-aviation-emissions/). ASCENT Project 102, Assessment of Contrail Formation via Combustion of Sustainable Aviation Fuel, is working to understand the physics of contrail formation and investigating contrail formation for fuels with varying composition, including SAF (ascent.aero/project/assessment-of-contrail-formation-via-combustion-of-sustainable-aviation-fuel/).

The FAA is also coordinating with DOE and NASA on efforts to better understand, quantify, and mitigate the environmental impacts of non-CO_2 emissions.

[23] B. S. Soriano and J. Chen. 2023. “DORMA003: DNS/LES and Modeling of SAF Flame Stabilization.” Presented at the 2023 VTO Annual Merit Review. www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/DORMA003_Soriano_2023_o%20-%20Bruno%20Soriano.pdf.

[24] B. Sforzo. 2023. “Multi-Phase Flow Studies of SAFs for Industry-Relevant Conditions and Geometries.” Presented at the 2023 VTO Annual Merit Review. www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/DORMA019_Sforzo_2023_o%20-%20Brandon%20Sforzo.pdf.

[25] D. Dasgupta. 2023. “Towards Accurate Reacting Flow Simulations of SAF.” Presented at the 2023 VTO Annual Merit Review. www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/DORMA038_Dasgupta_2023_o%20-%20Debolina%20Dasgupta.pdf.

[26] S. W. Wagnon and M. J. McNenly. 2023. “SAF Contrail Modeling.”

USDA

The Office of the Chief Economist provides analysis on biofuel production, participates on the SAF Grand Challenge LCA team, and evaluates policy impacts on markets.

The Economic Research Service and National Agricultural Statistics Service provide data and analysis on feedstock production.

EPA

EPA administers the RFS program put in place by the Energy Independence and Security Act of 2007. The standards finalized for 2025 will require the use of 22.33 billion gallons of a wide range of renewable fuels from a wide range of feedstocks. In setting these standards, EPA evaluates and balances a broad range of environmental, economic, and other impacts associated with the growth in the use of renewable fuels and their feedstocks. To support this rulemaking effort, EPA also evaluates renewable fuel impacts on endangered species and critical habitat to ensure compliance with the Endangered Species Act.

As part of its administration of the RFS program, EPA conducts LCA modeling of renewable fuel pathways consistent with Section 211(o) of the Clean Air Act to evaluate these pathways for potential inclusion within the RFS program. Most recently, EPA published a *Model Comparison Exercise Technical Document*, which accompanied the standards finalized for 2023 through 2025.[27] This document describes the current state of science in this area and presents illustrative results and analysis from an array of biofuel LCA models and analytical frameworks. For this rulemaking, EPA also conducted an extensive literature review of LCA estimates for renewable fuels and summarized the results in the regulatory impact analysis.

Current Program Gaps and Barriers

PA.1: Develop Improved Environmental Models and Data for SAF

Induced land use change resulting from biomass utilization is a controversial topic that is currently modeled using agricultural or climate models. Existing models have large variability in results and are based on numerous assumptions. Small changes in assumptions can drastically change results. Better data are needed to understand the drivers of land use change globally, including:

- A new generation of models that can provide more accurate predictions of outcomes that will help to avoid use of non-sustainable biomass feedstocks.
- Models to account for all driving factors of global land use change including urbanization, mining, agriculture, biofuels, and other motivations.

[27] EPA. 2023. *Model Comparison Exercise Technical Document*. EPA-420-R-23-017. www.epa.gov/renewable-fuel-standard-program/final-renewable-fuels-standards-rule-2023-2024-and-2025.

- Models to accurately establish cause-and-effect relationships of land use change. Replication of historical trends in land use change would increase confidence that the models reliably evaluate potential SAF land use change impacts.
- Models using the latest platforms such as satellite imagery data from relevant sources. Satellite-derived data can provide historical perspectives and could be correlated with ground observations. Data analysis tools can be used to develop empirical equations that forecast scenarios of future land use change.

The non-CO_2 environmental benefits of SAF use on air quality and climate change are just starting to be understood. The chemical and physical conditions that lead to reduced emissions and contrails need to be better understood to design improved SAF, including:

- Laboratory-scale experiments and measurements to better understand soot chemistry, morphology, and conditions that lead to soot formation.
- Testing and data collection at appropriate atmospheric conditions to determine impact of nozzle geometries, combustion characteristics, temperature, and pressures on rate of soot formation and emissions of soot particles.
- A roadmap of the Federal Government activities developed to coordinate Federal activities (involving NASA, FAA, and DOE) with engine manufacturers, academia, National Laboratories, and international organizations.

Climate-smart agricultural and forestry practices[28] applied to SAF feedstock production promise improved crop resiliency and ecosystem health. Improved data and expanded analysis are needed to quantify the co-benefits of SAF feedstock production (e.g., soil health, water quality, nutrient management), including to:

- Expand data collection and analysis of the crop diversity benefits of feedstocks grown on marginal lands (e.g., soil organic carbon, nutrient management, reduced erosion impacts).
- Develop technologies for production of lower-carbon-emitting fertilizer.
- Invest in SAF feedstock crops that can fix nitrogen to reduce nitrogen runoff from farms. Other areas of potential investment in improving SAF feedstock crops are higher yields and shorter growth cycles to enable double cropping.
- Develop livestock grazing practices that allow for regeneration of grassland and result in reduced fertilizer use.
- Develop new feed compositions that reduce methane emissions from livestock.
- Enhance water quality by planting riparian barriers along streams that can eventually be harvested as biomass feedstock.

[28] USDA. 2023. "Climate-Smart Agriculture and Forestry." Factsheet. www.nrcs.usda.gov/sites/default/files/2023-04/Climate-Smart%20Agriculture%20and%20Forestry%20factsheet.pdf.

- Where applicable, encourage and incentivize the use of harvestable cover crops (e.g., camelina, pennycress, carinata) and prairie strips that reduce fertilizer runoff, reduce erosion, support biodiversity, and help pollinators. These winter crops can be harvested to provide additional biomass for SAF.

PA.2: Conduct Techno-Economic and Production Potential Analysis

Updated biomass resource assessments are critical to underpin TEA and production potential analyses. Significant farm-level data and understanding of land use patterns are needed to generate results using models such as the Policy Analysis System Model (POLYSYS), Global Trade Analysis Project (GTAP), and Global Change Analysis Model (GCAM). The focus of this effort will be on U.S. domestic resources, with the acknowledgment that imports of feedstocks could occur depending on economic and policy environment in the United States and surrounding countries. These include efforts to:

- Update resource assessments on an ongoing basis as new crops and harvesting technologies are developed.
- Begin data collection and inclusion of regions outside the United States within existing modeling frameworks (e.g., POLYSYS) so that the potential for trade in biomass and biofuels is better understood.
- Develop a globally expanded version of modeling frameworks such as POLYSYS to construct supply curves for various feedstocks.
- Use new and updated biomass resource assessments to analyze SAF volumes that could be produced under specific economic and policy assumptions, both in the United States and globally.

New oilseed crops (e.g., carinata, camelina, and pennycress) are expected to play a crucial role in meeting the goals set forth in the SAF Grand Challenge. In addition to expanding SAF supplies, these crops may provide environmental benefits (e.g., increased soil organic carbon sequestration and soil protection) while providing substantial economic benefits to farmers. Data, analysis, and tools are needed to determine the impact of new oilseed crops as secondary cover crops in the U.S. agricultural system.

PA.3: Inform SAF Policy Development

- The existing market for cleaner fuels, including biofuels, is growing due to Federal policies such as the RFS and Inflation Reduction Act of 2022 (Section 40B, Sustainable Aviation Fuel Credit, and Section 45Z, Clean Fuels Production Credit). Continuing existing policies and developing new policies will facilitate the scale-up and deployment of these fuels in the United States. Section 45Q of the Inflation Reduction Act provides incentives for carbon capture and sequestration, which can be helpful in reducing the CI of SAF pathways. Needs include:

- Analysis of policies to quantify the impact of incentives for the production and processing of new and underutilized biomass sources (pennycress, camelina, carinata, switchgrass, algae, purpose-grown crops, and crop residues).
- Analysis of multiple Inflation Reduction Act credits to determine how these could be used on a consistent basis to reduce the cost of SAF production.
- Analysis of the potential to combine the tax credits under the Inflation Reduction Act with other state and Federal credits to reduce the cost of SAF production.
- Determining the impact of sensitivities such as longer eligibility periods and different tax credit amounts on the potential for SAF production.
- Research and analysis of SAF production pathways to ensure that domestic feedstocks have the most accurate CI estimates. Accurate data can provide the foundation for domestic refiners to have a comprehensive suite of options (e.g., climate-smart farming practices, sourcing renewable natural gas, sourcing renewable electricity, and carbon capture and storage) to reduce their CI.
- Analysis and structuring policy to incentivize the production of SAF feedstocks with climate-smart farming practices.
- Analysis of gaps in policy needed to support durable investment in SAF.

Multiple states have adopted low-carbon fuel standards, and more states are considering legislative action using similar approaches. State policies in combination with Federal policies provide a supportive environment for SAF development and enable the scale-up and deployment of commercial-scale production facilities in the United States. However, additional analysis is needed to:

- Understand the implications of the potential to stack state policies with Federal incentives and to quantify their impact on TEAs.
- Identify key elements needed for the integrity of book-and-claim systems in the context of existing and potential state and Federal policies and international frameworks.
- Conduct sensitivity analysis to quantify the SAF volumetric impacts of, and integrity mechanisms needed for, potential book-and-claim arrangements.

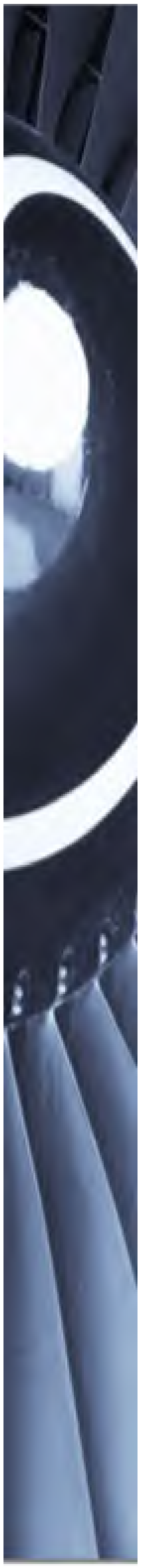
Climate-smart agriculture and forestry practices need to be appropriately credited in regulations, offset markets, tax credits, and other relevant programs. Revenue generation from climate-smart agricultural practices can alter land management practices toward a more sustainable direction and be an engine for economic growth in rural communities. Additional needs are:

- Analysis to quantify the impact of climate-smart agricultural practices under different conditions.
- Analysis to quantify the use of potential credits from climate-smart agricultural practices and their impact on TEA.

- Analysis in support of dedicated (purpose-grown) biomass crops and harvestable cover crops and building frameworks that consider risk crop portfolio risk management (pesticide/herbicide labeling, planting incentives for both purpose-grown and cover crops, and carbon accounting and payment for carbon sequestration and reduced emissions).
- Analysis to inform policy recommendations for giving value to ecosystem services including carbon sequestration, water quality enhancement, biodiversity, reduction of invasive species, and creation of pollinator or wildlife habits.
- Analysis to inform policy recommendations for incentivizing the utilization of small-diameter timber, biochar, and forest health and wildfire mitigation materials.

The International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) also has relevant policies that affect domestic SAF production. The U.S. Government can continue to work within the International Civil Aviation Organization's Committee on Aviation Environmental Protection's Fuel Task Group to ensure that CI estimates for domestic feedstocks are based on the most accurate data available and that domestic producers are treated equitably as international producers.

Enabling End Use



The Enabling End Use (EU) Action Area focuses on addressing critical barriers and requirements for safe and cost-effective use of SAF via standards development and critical R&D and analysis. It facilitates the end use of SAF by civilians and the military through efficient evaluation of fuel engine and aircraft performance and safety, advancement of qualification processes, expansion of existing blend limits, and integration of SAF into fuel distribution infrastructure. Within the EU Action Area are four workstreams, each defining a critical element to be addressed in the pursuit of the SAF Grand Challenge objectives:

- **SAF evaluation, testing, qualification, and specification**. Supporting fuel qualification via the ASTM D4054 standard (Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives) Clearinghouse can alleviate the testing burden on fuel producers.
- **Enable use of drop-in unblended SAF and SAF blends up to 100%**. Work to develop specifications for 100% SAF, both in neat form and blended with other SAF, enables additional opportunities for fuel producers and suppliers to simplify distribution logistics and reduce risk along the supply chain.
- **Investigate Jet A fuel derivatives offering performance or producibility advantages**. Understanding the advantages and challenges of novel jet fuels with unique performance differences, such as greater energy density, will help identify reasonable opportunities that may exist for such fuels.
- **Integrate SAF into fuel distribution infrastructure**. Although the focus of the SAF Grand Challenge is on drop-in SAF, fully fungible with existing supply and distribution infrastructure and aircraft, there are logistical questions related to fuel blending and efficient integration into existing fuel supply infrastructure that must be addressed for scaling up SAF delivery to airports.

Current Federal Agency Capabilities and Programs

DOT FAA

ASCENT

FAA leads the evaluation, testing, qualification, and specification of SAF through the ASCENT program. ASCENT projects in the Alternative Fuels topic area (ascent.aero/topic/alternative-fuels/) enable fuel qualification via support for the ASTM D4054 standard (Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives) Clearinghouse at the University of Dayton Research Institute, research to investigate fuel compatibility with nonmetallic materials and fuel tank gauging, evaluations of high-performance novel fuels, and surveys of fuel physical properties and chemical compositions to inform further research and standards development. Through ASCENT, FAA is leading technical work to set international standards to account for life cycle GHG emission reductions within CORSIA, as well as doing the testing that is required within the ASTM fuel qualification process.

A major area of work for the FAA going forward will be working with industry to gain approval for the use of 100% SAF in today's fleet of aircraft. Under ASCENT Project 088, A Method for Rapidly Assessing Jet Fuel Compatibility with Non-Metallic Materials, FAA targets research to address some of the research questions around the use of 100% SAF in existing engines and aircraft (ascent.aero/project/a-method-for-rapidly-assessing-jet-fuel-compatibility-with-non-metallic-materials-2/). Under ASCENT Project 089, Characterization of Compositional Effects on Dielectric Constant, novel dielectric testing methods are being developed to advance the current understanding of dielectric constant and fuel composition relations (ascent.aero/project/characterization-of-compositional-effects-on-dielectric-constant/). Dielectric constant is a key fuel property, critical for fuel gauging systems. This is a critical need identified by both the aviation original equipment manufacturer community and ASTM International stakeholders involved in the jet fuel qualification process.

The FAA is also supporting a jet fuel sampling and testing program through ASCENT Project 090, World Fuel Survey (ascent.aero/project/world-fuel-survey/). The work is focused on gathering a diverse set of jet fuel samples, from both the point of manufacture (i.e., fuel refineries) and the point of use (i.e., airports) to monitor the integration of SAF into fuel supply infrastructure. The initial focus is on domestic jet fuels currently in use and will expand to global sampling.

Continuous Lower Energy, Emissions and Noise (CLEEN)

The CLEEN Program (faa.gov/about/office_org/headquarters_offices/apl/eee/technology_saf_operations/cleen) is the FAA's principal environmental effort to accelerate the development of new aircraft and engine technologies that will reduce noise, emissions, and fuel burn. The program supports and facilitates work on SAF properties and performance testing and demonstrations, enabling SAF pathway qualification via ASTM International.

CAAFI

FAA facilitates coordination of a broad range of SAF stakeholders through CAAFI, a public-private partnership founded in 2006 by the FAA with industry to support development and deployment of SAF. CAAFI has also developed publicly available SAF readiness tools along the fuel pathway that will aid regional coalitions in assessing their stage of development.

FAST

The FAA announced award recipients for a new competitive grant program, FAST, made possible by the Inflation Reduction Act of 2022. The FAST grant program makes investments to accelerate the production and use of SAF and the development of low-emission aviation technologies to support the U.S. aviation climate goal to achieve net-zero GHG emissions by 2050. The SAF elements of the program will provide $245 million to advance the deployment of jet fuels made from renewable sources that provide a greater than 50% reduction in life cycle CO_2 emissions compared to conventional jet fuel, and which can be used safely in today's aircraft and engines. FAST supports the build-out of infrastructure projects related to SAF production, transportation, blending, and storage. A total of $242.8M has been allocated among 15 projects that are related to SAF infrastructure development. Two SAF related projects were also funded under the Tech category at a total of $4.5M.

DOE VTO

VTO is coordinating with FAA and NASA to accelerate SAF adoption to decarbonize aviation. DOE is leveraging the unique capabilities at DOE labs to deliver fundamental science, computational tools, and new data for industry to design the next generation of jet propulsion and fuels. Notable sponsored work aligned with the EU Action Area includes:

- A series of workshops and meetings that brought together experts from national laboratories, industry, government, and academia to discuss and assess the challenges and prospects of SAF adoption in end use applications.[29]
- Experimental and modeling work on spray and combustion in turbine geometries of interest to industry (via cooperative research and development agreements).[30]
- Improvements to reacting flow simulations in aircraft engines operating on more than 50% SAF blends.[31]
- Gas phase combustion properties of SAF measured and used to calibrate kinetic models and develop new kinetic mechanisms.[32,33]
- Fuel property measurements and characterization of different SAF to expand the potential supply of SAF qualified through ASTM International.[34]
- Development of a platform for complete virtual jet engine simulation.[35]

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[29] D. Dasgupta et al. 2023. *Workshop on Sustainable Aviation Fuel-Use Research Opportunities*. Lemont, IL: Argonne National Laboratory. ANL-23/13. publications.anl.gov/anlpubs/2023/04/181153.pdf.
[30] I. Ekoto et al. 2023. "Sustainable Aviation Fuel (SAF) End-Use Research Opportunities." Presented at the 2023 VTO Annual Merit Review. www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/Updated_DORMA017_Som_2023_o_final%20-%20Copy.pdf.
[31] D. Dasgupta. 2023. "Towards Accurate Reacting Flow Simulations of SAF."
[32] J. Manin. 2023. "SAF Combustion & Soot Processes."
[33] B. Sforzo. 2023. "Multi-Phase Flow Studies of SAFs for Industry-Relevant Conditions and Geometries."
[34] G. M. Fioroni et al. 2023. "Sustainable Aviation Fuel (SAF) Specifications and Testing Protocols." Presented at the 2023 VTO Annual Merit Review. www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/DORMA037_Fioroni_2023_o%20%20-%20Gina%20Fioroni.pdf.
[35] E. Ringle. 2024. "On the Ground in Colorado, NREL Is Simulating Sustainable Aviation Fiel Combustion During Flight." NREL News, Jan. 29, 2024. www.nrel.gov/news/features/2024/on-the-ground-in-colorado-nrel-is-simulating-sustainable-aviation-fuel-combustion-during-flight.html.

NASA

Sustainable Flight National Partnership

The Sustainable Flight National Partnership (www.nasa.gov/directorates/armd/sfnp/) focuses on ultra-efficient airliner technologies such as airframe, manufacturing, and propulsion, including electrification, more efficient airspace operations, and adoption of SAF. NASA projects enter cost-sharing partnerships with U.S. industry, airlines, and other government agencies to demonstrate and transfer the most promising technologies to enable up to a 30% reduction in fuel use for new aircraft that may enter service in the 2030s using SAF and flying optimal trajectories. NASA research includes sampling and characterizing SAF emissions to verify performance and ensure compatibility with existing and future aircraft and advances the understanding of non-CO_2 impacts including persistent contrails and aviation-induced cloudiness. The following NASA projects include research toward advancement of SAF:

Transformational Tools and Technology Project

The Transformational Tools and Technologies project (nasa.gov/directorates/armd/tacp/ttt/) develops state-of-the-art computational and experimental tools and technologies to advance prediction of future aircraft performance in flight. This project includes combustor modeling and measurements and the impact of SAF on fuel sprays and emissions.

Advanced Air Transport Technology Project

The Advanced Air Transport Technology project (nasa.gov/directorates/armd/aavp/aatt-project/) focuses on advanced fixed-wing transport aircraft and develops technologies and concepts for energy efficiency and environmental compatibility. This project has objectives to advance combustor technologies for SAF and increase the understanding of their overall impact. The work includes partnership with industry and other government agencies with combustor, engine, and aircraft ground and flight tests, including on-wing emissions research to advance the scientific understanding of contrails, their persistence, and their sensitivity to combustor technology and various SAF.

Hybrid Thermally Efficient Core Project

The Hybrid Thermally Efficient Core project (nasa.gov/directorates/armd/aavp/hytec/) partners with industry to develop small-core engine technologies to reduce fuel burn, develop hybrid electric technology, and advance engine operability and compatibility with SAF. This project currently supports combustor operability testing of new small-core combustor designs with 80%–100% SAF.

Figure 8. Graphic representation of small-core combustor design.

Graphic courtesy of NASA

Commercial Supersonic Technology Project

The Commercial Supersonic Technology Project (nasa.gov/directorates/armd/aavp/cst/) conducts supersonic vehicle research through the development of tools and technologies that will eliminate the technical barriers to quiet and sustainable commercial supersonic flight. This project supports the development of combustion technology and assesses the impact of burning SAF on emissions.

DOD

DOD (Army, Navy, and Air Force) is engaged in efforts to align military SAF approvals with those in the commercial sector. Currently, Fischer-Tropsch and HEFA are the only conversion pathways approved across all three services. It is anticipated that several other pathways in ASTM D7566, as well as coprocessing pathways in ASTM D1655, will be approved in 2024 or 2025. Plans and protocols are in place to evaluate and potentially approve additional new SAF conversion pathways that show promise toward commercialization.

USDA Rural Development Programs

USDA loan guarantee programs such the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program (Section 9003) provide loan guarantees up to $250 million to assist in the development, construction, and retrofitting of new and emerging technologies for advanced biofuels, renewable chemicals, and bio-based products.

Current Program Gaps and Barriers

Facilitating the end use of SAF by civil and military users is critical to fulfilling the goals of the SAF Grand Challenge. This includes testing various SAF pathways and enabling their qualification under ASTM International, developing the technology for neat or 100% drop-in SAF to be safe for use in aircraft and fueling infrastructure, and investigating fuels with different compositions that may increase performance and reduce emissions.

There are several gaps that need to be addressed to enable the safe and cost-effective use of SAF. Addressing these gaps will help overcome critical barriers to SAF end use. The specific activities within the workstreams that require further action are discussed below.

EU.1: Support SAF Evaluation, Testing, Qualification, and Specification

- Develop new standardized test methods to increase the resolution of measurements and increase the confidence in fuel compositions that have been identified through interlaboratory studies. Examples include two-dimensional gas chromatography vacuum ultraviolet measurements and inductively coupled plasma triple quadrupole measurements for olefin and trace metal quantification, respectively. A specified test method for both techniques will enable improved production compositional control in a format that can be integrated into the ASTM D4054 process.
- Develop an expedited route toward qualification of similar fuels through ASTM D4054 to enable a diversity of SAF pathways. For example, defining a D7566 specification that simplifies the need for the definition of a feedstock or conversion process will lead to increased SAF production.

EU.2: Enable Use of Drop-In Unblended SAF and SAF Blends up to 100%

- Conduct additional research on adequate lubricity of fuels needed to ensure that fuel handling and transport infrastructure is compatible with drop-in SAF to enable cost-effective transport of fuels through pipelines.
- Develop 100% SAF that is drop-in compatible with today's fleet of aircraft and engines to improve local air quality in communities near airports and reduce emissions of other harmful materials into the atmosphere.

EU.3: Investigate Jet A Fuel Derivatives Offering Performance or Producibility Advantages

- Conduct additional research into the performance of novel fuels being developed that have chemical compositions that are substantially different from those currently qualified through ASTM.

EU.4: Integrate SAF into Fuel Distribution Infrastructure

- Develop a better understanding of current fuel distribution infrastructure standards to properly address concerns related to the transportation of 100% drop-in SAF. This includes developing new standards and/or provisions for transporting SAF blend components through pipelines.

Figure 9. World's first commercial flight using cellulosic-based SAF, produced by a Northwest Advanced Renewables Alliance project funded by USDA.

Photo courtesy of Washington State University and Alaska Airlines

Communicating Progress and Building Support

The Communicating Progress and Building Support (CP) Action Area objectives are to engage stakeholder organizations, monitor and measure progress against SAF Grand Challenge goals, provide public information resources, and communicate benefits of the SAF Grand Challenge. Success of the SAF Grand Challenge is dependent on maintaining and increasing public support. Communication products put SAF costs, benefits, and impacts in the right context for policymakers, stakeholders, and the public. Public engagement by SAF stakeholders has increased substantially since the announcement of the SAF Grand Challenge and subsequent release of the roadmap. Government activities are intended to supplement those efforts by providing trusted, science-based data and information, including benefit and impact assessments made publicly available. Agencies will continue to engage industry, agricultural, and environmental stakeholders. SAF activities will continue to be emphasized across department strategic plans.

The key actions supporting the CP Action Area are:

- **Stakeholder outreach and engagement on sustainability** to exchange information about best practices to reduce life cycle GHG emissions from agricultural- and forest-derived feedstocks.
- **Conducting benefits assessment/impact analysis of the SAF Grand Challenge** to inform decisions, demonstrate benefits, and mitigate negative impacts.
- **Measuring progress of the SAF Grand Challenge** to provide updates, measure success, and show where progress needs to be made.
- **Communicating public benefits of the SAF Grand Challenge** to address common concerns and misconceptions and further build public support.

Current Federal Agency Capabilities and Programs

SAF communications efforts have been conducted by all three agencies, including press releases, blogs, papers, conferences, and stakeholder engagement. All agencies involved with the SAF Grand Challenge continue to coordinate on communication efforts, build out new communication efforts, and incorporate consistent messaging into leadership talking points. All three agencies provide updates via CAAFI webinars and conferences (e.g., Advanced Bioeconomy Leadership Conferences). An interagency SAF Grand Challenge website (biomassboard.gov/sustainable-aviation-fuel-grand-challenge) has been created to share consolidated information, a roadmap overview, recent news, and related resources. The site links to individual agency sites and resources at DOE, DOT, and USDA.

DOE

Communication and stakeholder engagement on SAF has been led by BETO, particularly on bioenergy crop sustainability. For example, DOE conducted a workshop in June 2023 on SAF and bioenergy feedstocks with the research community to guide an upcoming funding opportunity, with USDA participation. BETO leadership regularly discusses SAF priorities and actions via panels, media engagement, and conference presentations. BETO shares additional information and activities through a DOE SAF website (www.energy.gov/eere/bioenergy/sustainable-aviation-fuels).

DOE provides additional public information on SAF through the Alternative Fuels Data Center (afdc.energy.gov/fuels/sustainable_aviation_fuel.html). This resource provides information, data, and tools to help fleets and other transportation decision makers find ways to reach their energy and economic goals using alternative and renewable fuels, advanced vehicles, and other fuel-saving measures. The Alternative Fuels Data Center provides an overview of SAF benefits, production pathways, distribution, and R&D links.

To enhance awareness of the SAF Grand Challenge, SAF has been incorporated into forward-looking DOE strategy documents such as the DOE section of the Bold Goals for U.S. Biotechnology and Biomanufacturing,[36] The U.S. National Blueprint for Transportation Decarbonization (with DOT),[37] and BETO's 2023 Multi-Year Project Plan.[38]

DOT FAA

The Office of the Secretary of Transportation conducts a range of activities on stakeholder engagement on SAF, including convenings and roundtables, representation in domestic and international forums, and meetings with large and small airports.

CAAFI, funded in part by FAA, is one of the primary organizations for stakeholder engagement on SAF. The CAAFI coalition focuses the efforts of the commercial aviation sector to engage the emerging alternative fuels industry. CAAFI enables its diverse participants—representing all the leading stakeholders in the field of aviation—to build relationships, share and collect data, identify resources, and direct research, development, and deployment of SAF. CAAFI hosts technical workshops, coordinates with domestic and international aviation interests, participates

[36] The White House. 2023. *Bold Goals for U.S. Biotechnology and Biomanufacturing: Harnessing Research and Development to Further Societal Goals*. www.whitehouse.gov/wp-content/uploads/2023/03/Bold-Goals-for-U.S.-Biotechnology-and-Biomanufacturing-Harnessing-Research-and-Development-To-Further-Societal-Goals-FINAL.pdf.

[37] DOE, DOT, EPA, 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. www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf.

[38] BETO. 2023. *Bioenergy Technologies Office 2023 Multi-Year Program Plan*. www.energy.gov/eere/bioenergy/articles/2023-multi-year-program-plan.

in energy and financial industry forums, and communicates with stakeholders via webinars, presentations, and print media.

Under ASCENT Project 001, FAA conducts stakeholder outreach activities including:

- Holding consultations and listening sessions with the nongovernmental organization community about best practices to reduce life cycle GHG emissions from agriculture- and forest-derived feedstocks.
- Holding consultations and listening sessions with agricultural and forestry communities to understand needs to improve sustainability.

Additionally, FAA contributes to:

- Creating a coordinated interagency approach to tracking SAF production and use data and making this publicly available (common database on biorefineries, production, and end use).
- Developing a coordinated communications strategy.
- Developing communications products and engaging stakeholders to improve awareness of SAF benefits, alongside CAAFI.

USDA

Communication efforts on USDA R&D have been led by NIFA and the Office of the Chief Scientist. Communication on SAF is being conducted by office directors, national program leaders, and subject matter experts across USDA agencies. USDA staff have participated in sessions with agricultural groups, forestry, and processors on the status of the SAF Grand Challenge, including a feedstock innovation and supply chain webinar (March 28, 2023) and Penn State's Center for Biorenewables Symposium (April 21, 2023). To further engage the agricultural community, USDA participated in the Ag-SAF Summit with DOE (September 7, 2023) and met with large Midwest agricultural producers, trade associations, and state departments of agriculture. The SAF Grand Challenge is regularly incorporated into USDA leadership talking points at major events such as the annual Agricultural Outlook Forum (usda.gov/oce/ag-outlook-forum), USDA's oldest and largest annual gathering of key stakeholders from the agricultural sector. SAF was also featured in the 2022 Agricultural Outlook Forum session, "Opportunities in the Biobased Economy."

Outreach, education, and engagement are required components of USDA NIFA Coordinated Agricultural Projects. These $10 million projects develop feedstocks for advanced biofuels and include public-private partnerships (see the Feedstock Innovation section for more detail). NIFA Coordinated Agricultural Projects include the analysis of impacts on agricultural and forestry markets, rural communities, and ecosystems. (Note that the projects have developed feedstocks that could be used for SAF but are not solely focused on SAF.)

For feedstock production tracking, the USDA Economic Research Service combines data from DOE's Energy Information Administration and agricultural data sources, including the National Agricultural Statistics Service and Economic Research Service, to create statistics on biofuel-based demand for agricultural feedstocks—primarily for corn ethanol, biodiesel, and renewable diesel (ers.usda.gov/data-products/u-s-bioenergy-statistics/). To enhance awareness of the SAF Grand Challenge, SAF has been incorporated into USDA priority and strategy documents, including the Strategic Plan: Fiscal Years 2022–2026 under Objective 3.2: Expand Markets for Emerging Technologies, Sustainable Products, and Novel Products[39] and the USDA Science and Research Strategy, 2023–2026.[40]

Figure 10. Staff lead tours of NREL's Integrated Biorefinery Research Facility.

Photo courtesy of NREL

Current Program Gaps and Barriers

CP.1: Stakeholder Outreach and Engagement on Feedstock Sustainability

Outreach and engagement with stakeholder groups will continue to be critical for building support and exchanging knowledge to achieve the 2030 and 2050 goals. Continuous discussions with stakeholders are needed to explore the environmental and social impacts of a SAF build-out.

- Increase public engagement with the environmental nongovernmental organization community to build and maintain support, while also meeting community needs.

[39] USDA. 2022. *Strategic Plan: Fiscal Years 2022–2026*. www.usda.gov/sites/default/files/documents/usda-fy-2022-2026-strategic-plan.pdf.
[40] USDA. 2023. *USDA Science and Research Strategy, 2023–2026*. www.usda.gov/sites/default/files/documents/usda-science-research-strategy.pdf.

- Develop best practices and identify key pollutants and other sustainability indicators of concern.

CP.2: Conduct Benefits Assessment/Impact Analysis of SAF Grand Challenge

Analysis of environmental and socioeconomic impacts must have the information needed to limit negative effects on communities and ensure equitable distribution of resources. Accurate, objective, and accessible information and analysis will aid in decisions on feedstock production, biorefinery siting and permitting, and supply chain networks, as well as state and local policies that facilitate SAF production.

- Create public tools that evaluate regional economic and environmental impacts of SAF production.
- Coordinate agency efforts to conduct socioeconomic analysis of impacts of SAF production to identify where additional efforts are required to limit negative effects and promote equitable distribution of resources across communities.
- Create a publicly available central repository for data.

CP.3: Measure Progress of the SAF Grand Challenge

A coordinated system to monitor progress toward the SAF Grand Challenge goals is needed to demonstrate success and indicate where progress needs to be made. Continuous cooperation with industry is needed for tracking and sharing metrics on feedstock-to-SAF production and use.

- Develop a sustainable information-sharing system and tracker through a common database on SAF biorefineries, production, and end use (with the ability to cross-check end use with the CORSIA Central Registry) that includes information on pilot through commercial facilities, feedstock availability, production volumes, and life cycle CO_2 emission reductions to track and demonstrate progress.
- Develop systems to protect the confidentiality of producers, distributors, and end users to promote information sharing.

CP.4: Communicate Public Benefits of the SAF Grand Challenge

Effective communication that transparently demonstrates the environmental, climate, and economic benefits of SAF is vital to building public trust and increasing support. As more information is accumulated, an expanded strategy and repository is needed to ensure data and reports are readily accessible to increase public awareness and support.

- Develop a strategy to ensure data, reports, and other information from the relevant SAF Grand Challenge action areas are captured on the SAF Grand Challenge website.
- Create easy-to-understand metrics for the public (e.g., health measures, jobs created, environmental benefits) and outreach to the public at county fairs, public schools, or paid commercials.