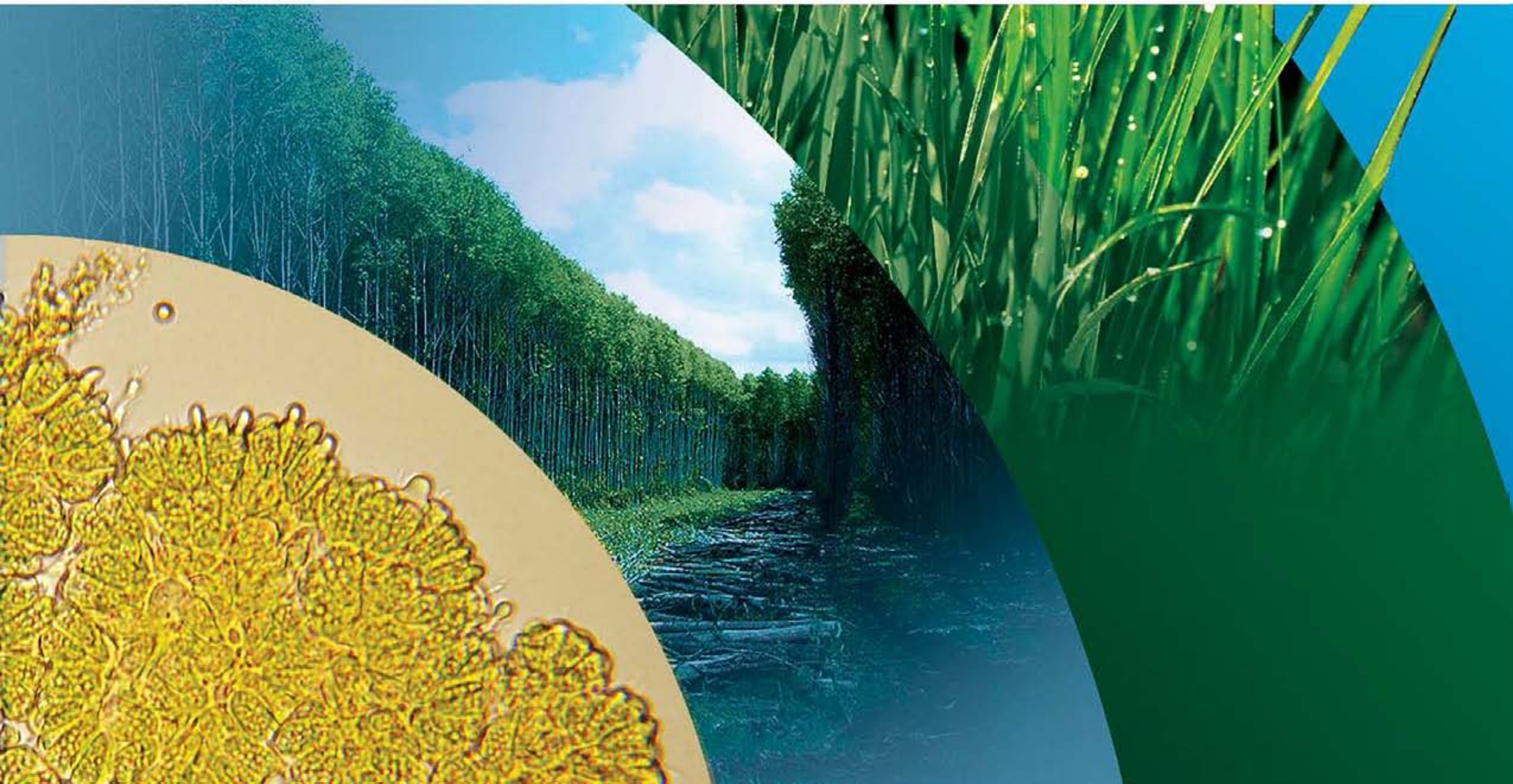
U.S. DEPARTMENT OF
ENERGY
Energy Efficiency &
Renewable Energy

BIOENERGY TECHNOLOGIES OFFICE

Multi-Year Program Plan

March 2016



EXECUTIVE SUMMARY

The Bioenergy Technologies Office is one of the 10 technology development offices within the Office of Energy Efficiency and Renewable Energy at the U.S. Department of Energy. This Multi-Year Program Plan (MYPP) sets forth the goals and structure of the Bioenergy Technologies Office (the Office). It identifies the research, development, and demonstration (RD&D), and market transformation and crosscutting activities the Office will focus on over the next five years and outlines why these activities are important to meeting the energy and sustainability challenges facing the nation.

This MYPP is intended for use as an operational guide to help the Office manage and coordinate its activities, as well as a resource to help communicate its mission and goals to stakeholders and the public.

Bioenergy Technologies Office Mission and Goals

The mission of the Office is to

> *Develop and demonstrate transformative and revolutionary bioenergy technologies for a sustainable nation.*

The goal of the Office is to develop commercially viable bioenergy and bioproduct technologies to

- *Enable sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure, can reduce greenhouse gas emissions relative to petroleum-derived fuels, and can displace a share of petroleum-derived fuels to reduce U.S. dependence on foreign oil*
- *Encourage the creation of a new domestic bioenergy and bioproduct industry.*

Technology Portfolio

The Office manages a diverse portfolio of technologies across the spectrum of applied research, development, and demonstration (RD&D) within the dynamic context of changing budgets and Administration priorities. The Office portfolio is organized according to the biomass-to-bioenergy supply chain—from the feedstock source to the end user (see Figure A)—with major focus on feedstock supply and biomass conversion.

Figure A: Biomass-to-bioenergy supply chain

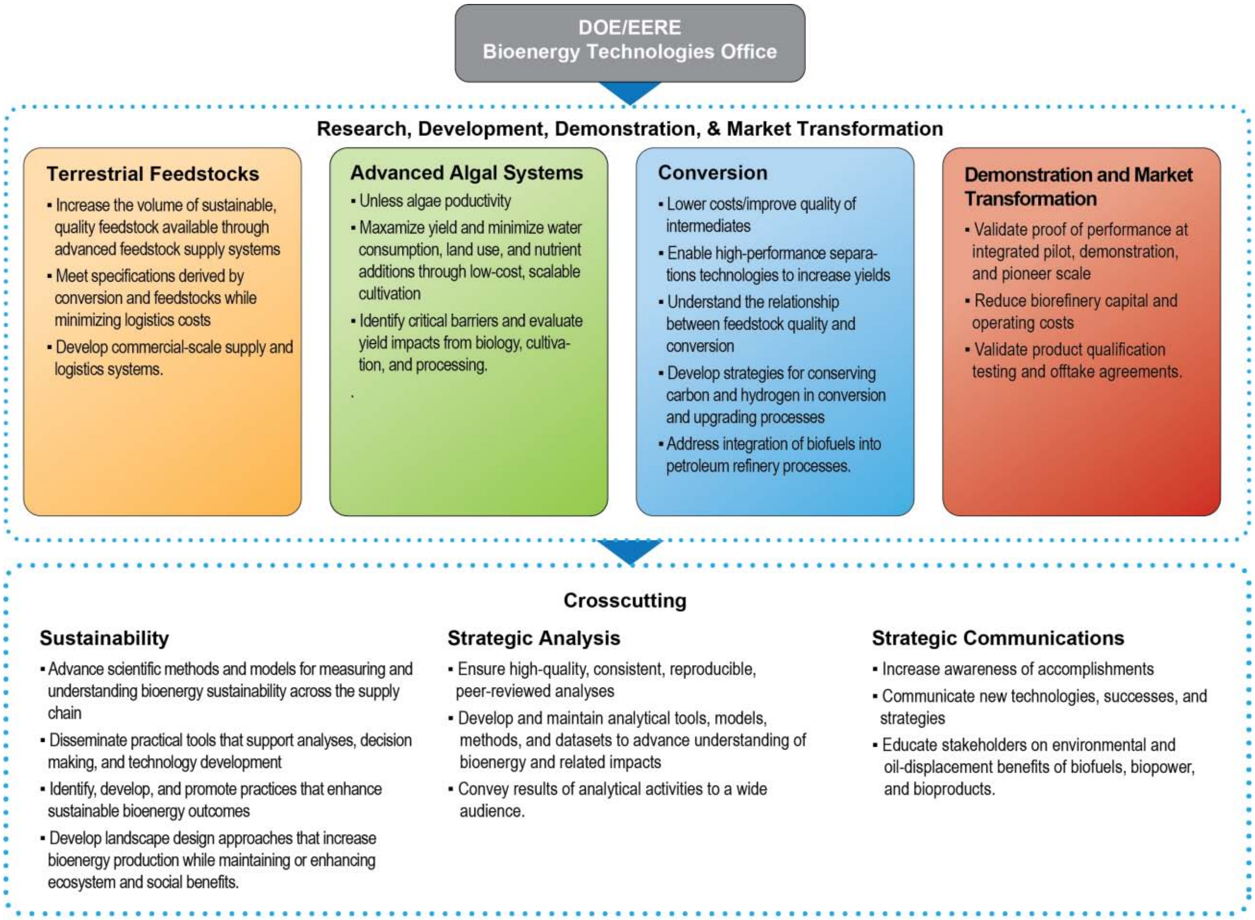
The Office has developed a coordinated framework for managing its portfolio based on systematically investigating, evaluating, and selecting the most promising opportunities across a wide range of emerging technologies and technology-readiness levels. This approach is intended to support a diverse technology portfolio in applied research and development (R&D), while identifying the most promising targets for follow-on industrial-scale demonstration with increasing integration and complexity.

Key components of the portfolio include the following:

- R&D on productive and competitive advanced algal systems
- R&D on sustainable, high-quality feedstock supply systems
- R&D on biomass conversion technologies
- Demonstration and validation of integrated biorefinery technologies up to industrial scale
- Crosscutting sustainability, analysis, and strategic communications activities.

Technology Development Timeline and Key Activities

In order to achieve the Office's goals, all of the challenges and barriers identified within this MYPP need to be addressed. However, the issues identified in Figure B are critical to reaching five-year goals and will be emphasized within the Office's efforts over the next five years.



DOE/EERE
Bioenergy Technologies Office

Research, Development, Demonstration, & Market Transformation

Terrestrial Feedstocks

- Increase the volume of sustainable, quality feedstock available through advanced feedstock supply systems
- Meet specifications derived by conversion and feedstocks while minimizing logistics costs
- Develop commercial-scale supply and logistics systems.

Advanced Algal Systems

- Unless algae poductivity
- Maxamize yield and minimize water consumption, land use, and nutrient additions through low-cost, scalable cultivation
- Identify critical barriers and evaluate yield impacts from biology, cultivation, and processing.

Conversion

- Lower costs/improve quality of intermediates
- Enable high-performance separations technologies to increase yields
- Understand the relationship between feedstock quality and conversion
- Develop strategies for conserving carbon and hydrogen in conversion and upgrading processes
- Address integration of biofuels into petroleum refinery processes.

Demonstration and Market Transformation

- Validate proof of performance at integrated pilot, demonstration, and pioneer scale
- Reduce biorefinery capital and operating costs
- Validate product qualification testing and offtake agreements.

Crosscutting

Sustainability

- Advance scientific methods and models for measuring and understanding bioenergy sustainability across the supply chain
- Disseminate practical tools that support analyses, decision making, and technology development
- Identify, develop, and promote practices that enhance sustainable bioenergy outcomes
- Develop landscape design approaches that increase bioenergy production while maintaining or enhancing ecosystem and social benefits.

Strategic Analysis

- Ensure high-quality, consistent, reproducible, peer-reviewed analyses
- Develop and maintain analytical tools, models, methods, and datasets to advance understanding of bioenergy and related impacts
- Convey results of analytical activities to a wide audience.

Strategic Communications

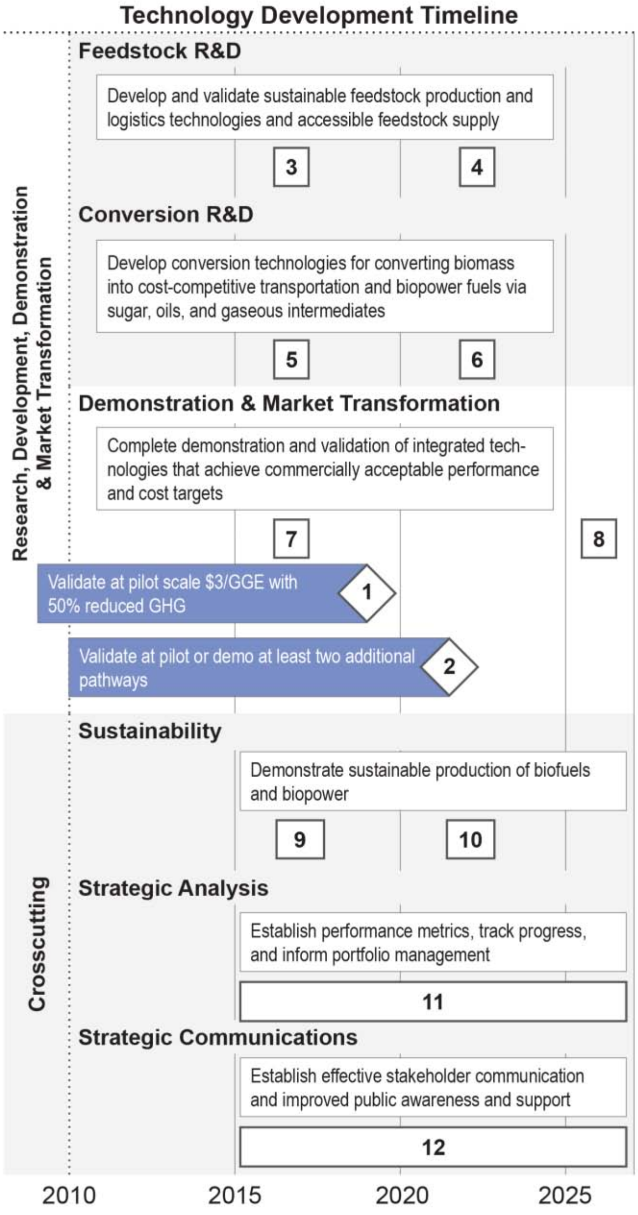
- Increase awareness of accomplishments
- Communicate new technologies, successes, and strategies
- Educate stakeholders on environmental and oil-displacement benefits of biofuels, biopower, and bioproducts.

Figure B: High-impact research areas

Figure C illustrates the near-term technology development timeline and key activities of the Office. In the longer term, the Office will continue to support focused science and RD&D of advanced biomass utilization technologies. Detailed life-cycle analysis of environmental, economic, and social impacts will continue to inform decisions regarding Office activities.

This approach ensures the development of the required technological foundation, leaves room for pursuing solutions to technical barriers as they emerge, and enables demonstration activities that are critical to reduce risks and validate a robust process. This approach lays the groundwork for future commercial deployment as it reduces technical risks, which enables the emerging industries to grow and attract private investment. The plan addresses important technological advances in producing biofuels, as well as in the underlying infrastructure needed to ensure that feedstocks are available and products can be distributed safely with the quality and performance demanded by end consumers.

This MYPP is designed to allow the Office to progressively enable deployment of increasing amounts of biofuels, bioproducts, and biopower across the nation from a widening array of feedstocks. This approach will have a significant near-term impact on offsetting petroleum consumption and facilitate the shift to renewable, sustainable bioenergy technologies in the long term, while allowing the market to determine the ultimate implementation across diverse U.S. resources.



Legend for Technology Development Timeline

Overall

◇1 By 2017, validate at pilot scale at least one technology pathway for hydrocarbon biofuel production at a mature modeled price of $3/GGE (2014$) with GHG emissions reduction of 50% or more compared with petroleum-derived fuel.

◇2 By 2022, validate hydrocarbon biofuel production from at least two additional pathways at pilot or demonstration scale (<1 ton/day).

Feedstock R&D

3. By 2017, establish criteria under which the industry could operate at 245 MDT/year of biomass; validate feedstock supply and logistics systems that can deliver feedstock at or below $84/dry ton (2014$).
4. By 2022, demonstrate technologies to produce sustainable algal biofuel intermediate feedstocks in support of $3/GGE goals, and validate feedstock supply and logistics systems that can supply 285 MDT/year utilizing a diversity of biomass resources at a cost of $84/dry ton.

Conversion R&D

5. By 2017, validate an nth plant modeled MFSP of $3/GGE (2014$) via a conversion pathway to hydrocarbon biofuel with GHG emissions reduction of 50% or more compared to petroleum-derived fuel.
6. By 2022, validate an nth plant modeled MFSP of $3/GGE (2014$) for two additional conversion pathways to hydrocarbon biofuel with GHG emissions reduction of 50% or more compared to petroleum-derived fuel.

Demonstration & Market Transformation

7. By 2017, validate mature technology modeled cost of cellulosic ethanol production, based on actual IBR performance data, and compare to the target of $2.65/gallon ethanol (2014$).
8. By 2027, validate mature technology modeled cost of infrastructure compatible hydrocarbon biofuel production, based on actual IBR performance data, and compare to the target of $3/GGE (2014$).

Sustainability

9. By 2017, identify conditions under which at least one hydrocarbon biofuels pathway, validated above R&D scale at a mature modeled price of $3/GGE, reduces GHG emissions by 50% or more compared to petroleum fuel, and meets targets for water use, wastewater, and air emissions.
10. By 2022, validate landscape design approaches for two bioenergy systems that increase land-use efficiency and maintain ecosystem and social benefits; and evaluate environmental and socioeconomic indicators across the supply chain for three cellulosic and algal bioenergy production systems to validate GHG reduction of at least 50% compared to petroleum, water consumption and air emissions targets, and socioeconomic benefits.

Strategic Analysis

11. Provide context and justification for decisions at all levels by establishing the basis for quantitative metrics, tracking progress, and informing portfolio managment.

Stategic Communications

12. Promote the economic and job creation, environmental, and energy security benefits of sustainable biofuels production. Increase awareness of and support for the Office's accomplishments and educate audiences about the environmental and economic opportunities and social benefits.

GGE = gallon gasoline equivalent, GHG = greenhouse gas, MDT = million dry tons

Figure C: Bioenergy Technologies Office strategy and timeline for technology development

Contents

List of Abbreviations

AHTL – Algal Hydrothermal Liquefaction
AMO – Advanced Manufacturing Office
ANL – Argonne National Laboratory
ANSI – American National Standards Institute
API – American Petroleum Institute
ARPA-E – Advanced Research Projects Agency-Energy
ARRA – American Recovery and Reinvestment Act
ASTM – American Society for Testing and Materials
BCAP – Biomass Crop Assistance Program
BIWG – Biofuels Interagency Working Group
BRDi – Biomass Research and Development Initiative
BSM – Biomass Scenario Model
CO_2 – carbon dioxide
CPS – Corporate Planning System
DME – dimethyl ether
DMT – Demonstration and Market Transformation
DOE – U.S. Department of Energy
DOD – U.S. Department of Defense
DOI – U.S. Department of the Interior
DOT – U.S. Department of Transportation
DT – dry tons
EERE – Office of Energy Efficiency and Renewable Energy
EIA – Energy Information Administration
EISA – Energy Independence and Security Act of 2007
EPA – U.S. Environmental Protection Agency
EPAct – Energy Policy Act of 2005
EU – European Union
EV – electric vehicle
FAA – Federal Aviation Administration
FAME – fatty acid methyl ester
Farm Bill – The Agricultural Act of 2014
FCT – Fuel Cell Technologies Office
FE – Office of Fossil Energy
FEMP – Federal Energy Management Program Office
FFVs – flexible-fuel vehicles
GBEP – Global Bioenergy Partnership
GGE – gallon gasoline equivalent
GHG – greenhouse gas
GIS – Geographical Information Systems
GPRA – Government Performance and Results Act
GREET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HTL – Hydrothermal Liquefaction
IBR – integrated biorefinery
IBSAL – Integrated Biomass Supply Analysis and Logistics

Infrastructure – Biofuels Distribution Infrastructure and End Use
ILUC – indirect land use change
INL – Idaho National Laboratory
ISO – International Organization for Standardization
KDF – Knowledge Discovery Framework
LHV – lower heating value
LPO – DOE Loan Programs Office
LUC – land-use change
MARKAL – market allocation
MESP – minimum ethanol selling price
MFSP – minimum fuel selling price
MSW – municipal solid waste
MTBE – methyl tertiary butyl ether
MYPP – Multi-Year Program Plan
NAABB – National Alliance for Advanced Biofuels and Bioproducts
NABC – National Advanced Biofuels Consortium
NASA – National Aeronautics and Space Administration
NEMS – National Energy Modeling System
NG – natural gas
NIFA – The U.S. Department of Agriculture's National Institute on Food and Agriculture
NIST – National Institute of Standards and Technology
NREL – National Renewable Energy Laboratory
NSF – National Science Foundation
the Office – The Bioenergy Technologies Office
OSBL – outside battery limits
OPEX – operating expense
ORNL – Oak Ridge National Laboratory
PBA – EERE Office of Planning, Budget, and Analysis
PMC – Project Management Center
PMP – project management plan
PNNL – Pacific Northwest National Laboratory
Psia – pounds per square inch absolute
R&D – research and development
RD&D – research, development, and demonstration
RFS – Renewable Fuel Standard
RLP – Resource Loaded Plan
RPS – Renewable Portfolio Standard
RSB – Roundtable on Sustainable Biomaterials
SC – Office of Science
scf – standard cubic feet
SMR – steam methane reformer
SOT – State of Technology
SUV – sport utility vehicle
SWAT – Soil and Water Analysis Tool
TRL – technology readiness level
UL – Underwriters Laboratory

UN FAO – Food and Agriculture Organization of the United Nations
USDA – United States Department of Agriculture
VTO – Vehicle Technologies Office
WBS – work breakdown structure
wt% – percentage by weight

Section 1: Office Overview

Growing concerns over climate change, as well as the desire to stimulate a new bioenergy economy, the need to maintain a competitive advantage for the United States in renewable technologies, and the development of future generations of green jobs, have renewed the urgency for developing sustainable bioenergy and bioproducts. Biomass utilization for fuels, products, and power is recognized as a critical component in the nation's strategic plan to address our continued dependence on volatile supplies and prices of imported oil. U.S. dependence on imported oil exposes the country to critical disruptions in fuel supply, creates economic and social uncertainties for businesses and individuals, and exports revenues that could be invested in the U.S. economy.

Biomass utilization plays an important role in implementing the President's Climate Action Plan to reduce carbon pollution in United States within the transportation sector. This plan calls for accelerated development of cost-competitive advanced biofuels that will reduce the carbon footprint of our national transportation sector as well as new fuel economy standards to reduce emissions and improve vehicle efficiency.[1]

Biomass

Biomass is an energy resource derived from plant- and algae-based material that includes agricultural residues, forest resources, perennial grasses, woody energy crops, algae, wet waste (e.g., biosolids), municipal solid waste, urban wood waste, and food waste. It is unique among renewable energy resources in that it can be converted to carbon-based fuels, chemicals, or power.

Biomass is the only renewable energy source that can offer a substitute for fossil-based, liquid transportation fuels in the near- to mid-term. The United States has the capacity to produce more than one billion tons[2] of sustainable biomass, which can be used to produce reduced-carbon-emission fuel for cars, trucks, and jets; chemicals; and renewable power to supply the grid. Biofuel, bioproduct, and biopower production can create new domestic economic opportunities and jobs in agriculture, manufacturing, and service sectors, while reducing future climate impacts.

The Energy Independence and Security Act of 2007 (EISA) sets aggressive goals to reduce the nation's dependence on fossil fuels and reduce greenhouse gas (GHG) emissions from the transportation sector by increasing the supply of renewable transportation fuels to 36 billion gallons by 2022.[3]

To support pursuit of these goals, the Bioenergy Technologies Office (the Office), within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE), is focused on forming public-private partnerships with key stakeholders to research,

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[1] Executive Office of the President (June 2013), *The President's Climate Action Plan*, http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf.

[2] U.S. Department of Energy (2011), *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224, Oak Ridge National Laboratory, Oak Ridge, TN, 227p., http://www.energy.gov/sites/prod/files/2015/01/f19/billion_ton_update_0.pdf.

[3] United States Congress (2007), *Energy Independence and Security Act of 2007*, Washington: Government Printing Office, http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf.

develop, and demonstrate technologies to produce advanced bioenergy and bioproducts from lignocellulosic and algal biomass. The Office focuses on reducing technology risks, from feedstock supply and logistics through development of biorefinery technologies, to enable industry investment in technology deployment at scale.

Scope of Effort/Framework for Success

Meeting these goals requires significant and rapid advances in the entire biomass-to-bioenergy supply chain—from the biomass source to the consumer (see Figure 1-1).

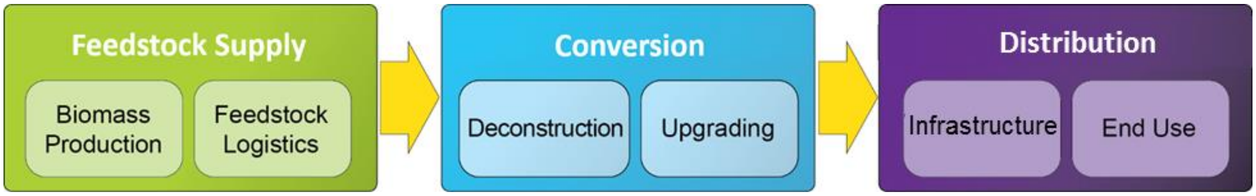

Figure 1-1: Biomass-to-bioenergy supply chain

Each element of the supply chain must be addressed to enable bioenergy and bioproducts to reach the market and ensure market acceptance. The biomass-to-bioenergy supply chain elements are as follows:

- **Feedstock Supply:** Produce large, sustainable supplies of regionally available biomass and implement cost-effective feedstock infrastructure, equipment, and systems for harvesting, collection, storage, preprocessing, and transportation
- **Conversion:** Develop and deploy cost-effective, integrated conversion technologies for the production of bioenergy and bioproducts
- **Distribution:** Implement biofuels distribution infrastructure (storage, blending, and transportation—both before and after blending and dispensing), assess impact of renewable fuel blends and bioproducts on end-user applications, and educate users.

This breadth of scope requires the participation of a broad range of public and private stakeholders of the evolving bioenergy sector, including the general public, the scientific/research community, trade and professional associations, environmental organizations, the investment and financial community, existing industries, and government policy and regulating organizations. These stakeholders possess valuable perspectives that can help identify the most critical challenges and better define strategies for effectively deploying bioenergy and bioproducts. The framework for success also requires extensive coordination and collaboration across multiple federal stakeholder agencies.

Bioenergy Technologies Office's Framework for Research, Development, and Demonstration

A critical measure of the Office's success is the development and demonstration of technologies within integrated biorefineries that can be subsequently commercially deployed and replicated. Similar to biorefineries that produce ethanol from starch and biodiesel from oil seeds and waste oils, integrated biorefineries are expected to produce multiple products to take advantage of the diverse biomass components and processing intermediates. This approach maximizes the value and decreases the waste derived from the biomass feedstock.[4]

Biorefinery

A biorefinery is a facility that converts biomass into fuels, power, and chemical products. The biorefinery concept is analogous to a petroleum refinery, which produces a slate of multiple fuels and products from a petroleum feedstock.

The wide diversity of potential biomass feedstocks, conversion technologies, and product suites allows for a multitude of biorefinery integration options. Determining which technology options are closest to commercialization is based on a number of factors, including feedstock risk, technology risk, and market size. The Office actively identifies and evaluates feedstock and technology risks through analyses of data from research, development, and demonstration (RD&D) into a broad-based set of feedstocks and conversion technologies. By applying a methodical approach to evaluating opportunities within the available feedstocks and technology options, the Office is able to prioritize RD&D at increasing scale on high-impact technologies that were assessed to have significant impacts on nearer-term bioenergy production and will most benefit from government investment.

Specific, focused technology pathways are prioritized for development to pilot-scale validation based on techno-economic analyses, feedstock impact, and market potential. Pilot-scale validation of selected technologies provides a transparent, accessible example against which private partners can assess their own technological progress while maintaining the scientific and engineering expertise to support and validate development of emerging technologies.

This approach has several distinct advantages:

- It maintains a balanced portfolio of RD&D to maintain earlier-stage, promising technologies for which specific pathways may not yet be adequately developed, while building a knowledge base of that technology relative to feedstock characteristics and potential.
- It ensures the Office will examine diverse feedstocks and conversion technologies for producing biofuels, bioproducts, and biopower.
- It effectively links resources with the stages of technology readiness, from applied research through commercial demonstration.
- It leverages breakthroughs from the Office of Science (SC) and the Advanced Research Projects Agency–Energy (ARPA-E) as a means to continually repopulate the EERE RD&D pipeline.

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[4] National Renewable Energy Laboratory (2009), "What Is a Biorefinery?" http://www.nrel.gov/biomass/biorefinery.html.

- It helps identify gaps within the portfolio, as well as crucial linkages across RD&D stages.
- It is adequately flexible to accommodate new ideas and approaches, as well as various combinations of feedstocks and processes in real biorefineries.

Expanded Office Focus on Advanced Biofuels

Historically, the Office's focus was on RD&D for ethanol production from lignocellulosic biomass. Since 2012, the Office has demonstrated technologies that can be scaled up to produce modeled price-competitive cellulosic ethanol. This achievement is the culmination of two decades of conversion technology research and development (R&D). DOE-funded R&D in this area has led to a well-developed body of work regarding the performance of ethanol as both a low-volume percentage (E10) gasoline blend in conventional vehicles and at higher blends (E85) in flexible-fuel vehicles.[5] (See Appendix C for more information about accomplishments in cellulosic ethanol.) Since the achievement of the cellulosic ethanol cost targets, the Office has shifted its focus toward developing other advanced biofuels that will contribute to the Renewable Fuel Standard (RFS) volumetric requirements. By focusing on these biomass- and algae-based hydrocarbon fuels (renewable gasoline, diesel, and jet fuel), the Office seeks to engage the refinery industry in developing solutions utilizing existing infrastructure as much as possible. The Office's investments in technologies that can reduce the recalcitrance of lignocellulosic biomass are being leveraged toward developing new hydrocarbon biofuels that can directly replace products created from the whole barrel of oil.

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[5] U.S. Department of Energy (2013), *Intermediate Ethanol Blends*, http://energy.gov/eere/vehicles/vehicle-technologies-office-intermediate-ethanol-blends.

1.1 Market Overview and Federal Role of the Office

Markets for biofuels, bioproducts, and biopower exist today both in the United States and around the world, yet the untapped potential is enormous. Industry growth is currently constrained by high production costs, competing energy technologies, limited infrastructure, and other market barriers. Market incentives and legislative mandates focused at helping overcome some of these barriers, if maintained, can reduce uncertainty for investors.

1.1.1 Current and Potential Markets

Major end-use markets for biomass-derived products include transportation fuels, products, and power. Today, biomass is used as a feedstock in all three categories, but the contribution is small compared to oil and other fossil-based products. Most biomass-derived products are now produced in facilities dedicated to a single primary product, such as ethanol, biodiesel, plastics, paper, or power (corn wet mills are an exception). The primary feedstock sources for these facilities are conventional grains, plant oils, and wood.

To meet national goals for increased production of renewable fuels, products, and power from biomass, a more diverse feedstock resource base is required—one that includes biomass from agricultural and forest residues, as well as dedicated energy crops and other waste streams. Ultimately, the industry is expected to move toward large biorefineries that produce a mix of biofuels and bioproducts, with integrated, onsite cogeneration of heat and power, as well as towards scenarios in which the production of renewable fuels and products are integrated with existing petroleum refineries or corn ethanol plants.

Transportation Fuels: America’s transportation sector relies almost exclusively on refined petroleum products, which account for more than 71% of the oil used. Oil accounts for 90% of transportation fuel use, with biofuels, natural gas, and electricity accounting for the balance.[6] Nearly 8.1 million barrels of oil are required every day to fuel the 232 million vehicles that constitute the U.S. light-duty transportation fleet.[7]

Biomass is a direct, near-to-mid-term alternative to oil for supplying liquid transportation fuels to the nation. In the United States, nearly all gasoline is now blended with ethanol up to 10% by volume (E10), and cars produced since the late 1970s can run on this fuel. In January 2011, the U.S. Environmental Protection Agency (EPA) issued partial waivers that permit the use of E15 (up to 15% ethanol) in model-year 2001 vehicles and newer. While E15 has not yet entered the market at significant volumes, most of the remaining hurdles are at the state level. While there are alternatives to fossil-derived fuels for light-duty vehicles, diesel and jet fuel markets have few alternatives. Diesel consumption in the United States is 54 billion gallons per year,[8] and jet

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[6] U.S. Energy Information Administration (September 2015), *Monthly Energy Review*, Washington: Government Printing Office, DOE/EIA-0035, https://www.eia.gov/totalenergy/data/monthly/previous.cfm.

[7] U.S. Energy Information Administration (2015), “Transportation Sector Key Indicators and Delivered Energy Consumption,” *Annual Energy Outlook 2015*, http://www.eia.gov/forecasts/aeo/data/browser/.

[8] U.S. Energy Information Administration (2015), “Transportation Sector Key Indicators and Delivered Energy Consumption.”

fuel consumption is 23 billion gallons per year.[9] Conversion technologies that produce renewable diesel and renewable jet fuel can fill the need for biomass-based alternatives for these diesel and jet markets.

Historically, volatile oil prices, supportive government policies, growing environmental and energy security concerns, and the availability of low-cost corn and plant oil feedstocks have provided favorable market conditions for biofuels. Ethanol, in particular, has been buoyed by the need to replace the octane and clean-burning properties of MTBE (methyl tertiary butyl ether), which has been removed from gasoline because of groundwater contamination concerns. As shown in Figure 1-2, in recent years, domestic production capacity of ethanol has increased rapidly—from under 7 billion gallons per year in 2007 to nearly 15 billion gallons in 2014.

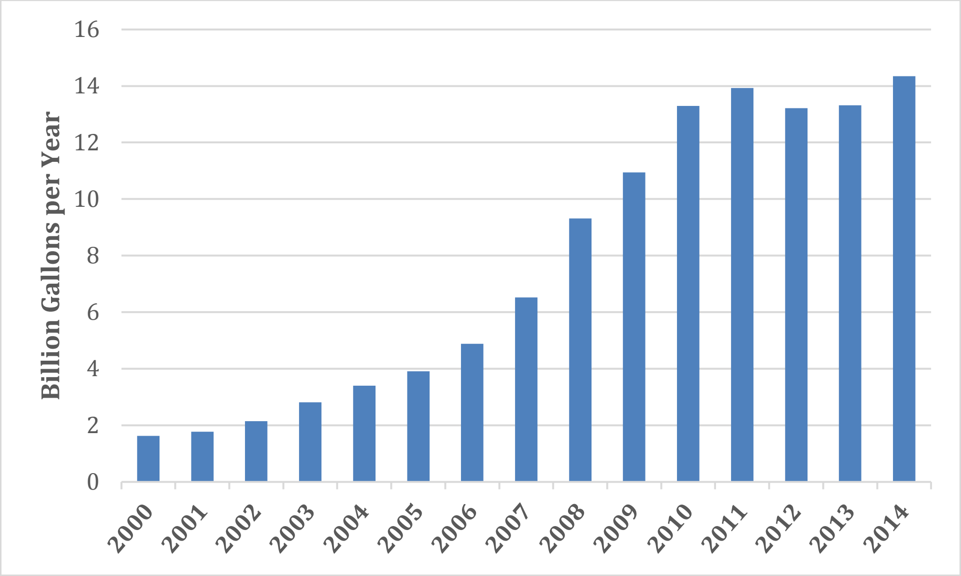

Figure 1-2: U.S. ethanol production capacity[10]

Over the last few years, commodity prices have fluctuated dramatically, creating market risks for biofuel producers and the supply chain. The national RFS legislated by EISA was designed to provide a reliable market for biofuels of 21 billion gallons of advanced biofuels by 2022. Blender tax credits for ethanol and biodiesel have historically helped to ensure that biofuels can compete with gasoline. Tax credits for conventional ethanol and biodiesel expired in January 2011, while cellulosic biofuel production credits were recently extended through January 1, 2017.

To successfully penetrate the target market, however, the minimum profitable biofuel price must be low enough to compete with gasoline. A minimum profitable fuel selling price of $3 per gallon gasoline equivalent (GGE) can compete on an energy-adjusted basis with gasoline derived from oil costing $75–$90 per barrel. Given recent declines in oil prices and historical volatility as

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[9] U.S. Energy Information Administration (2013), "Jet Fuel Consumption, Price, and Expenditure Estimates 2014," http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_fuel/html/fuel_jf.htm.

[10] Renewable Fuels Association (2015), "Industry Statistics," http://www.ethanolrfa.org/pages/statistics.

illustrated by the broad range of oil prices projected by the Energy Information Administration (EIA) for 2022 ($61–$156 per barrel),[11] bioenergy technology may continue to require policy support and regulatory mandates in order to enable the new bioenergy sector while it is being established.

Consumer attitudes about fuel prices and performance, biofuel-capable vehicles, and the environment also affect demand for biofuels and renewable products. Consumers who are generally unfamiliar with biofuels and have been hesitant to use them, even where they are available, may shift preferences as consumer confidence in biofuel use increases and as public awareness of the positive effect of biofuels on climate change grows.[12]

Products: Up to 16% of U.S. crude oil consumption is used to make chemicals and products, such as plastics for industrial and consumer goods,[13] contributing a value added to the U.S. economy of $812 billion. Many products derived from petrochemicals could be replaced with biomass-derived materials. Less than 4% of U.S. chemical sales are biobased.[14] Organic chemicals such as plastics, solvents, and alcohols represent the largest and most direct market for bioproducts.[15] The market for specialty chemicals is much smaller but is projected to double in 15 years[16] and offers opportunities for high-value bioproducts that have higher profitability potential than the commodity fuels market. Due to this potential, bioproduct manufacturing represents a near-term market opportunity to support the development of the biorefining industry.

Some traditional fossil-based chemical companies are forming alliances with food processors and other firms to develop new chemical products that are derived from biomass, such as natural plastics used in PET Bottling, fibers, cosmetics, paints, industrial adhesives, composite materials, liquid detergents, and a natural replacement for petroleum-based antifreeze.[17] These manufacturing alliances will need to demonstrate integrated production, including feedstock production and logistics through conversion, separation, purification, and market acceptance testing.

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[11] U.S. Energy Information Administration (2015), "Energy Prices," *Annual Energy Outlook 2015*, http://www.eia.gov/forecasts/aeo/section_prices.cfm.

[12] National Science Foundation (2010), *The Roadway to Partial Petroleum Replacement with Biomass-Derived Fuels—A Report Along the Way*, available from Northeast States for Coordinated Air Use Management: http://www.nescaum.org/activities/meetings-and-workshops/endicott-house-symposia/policy-instruments-for-a-new-economic-era/antos.pdf/view.

[13] American Chemical Council (2014), *Guide to the Business of Chemistry—2014*, http://store.americanchemistry.com/Guide-to-the-Business-of-Chemistry-2014-(electronic-version).

[14] J.S. Golden et al. (2015), "A Report to the Congress of the United States of America," *An Economic Impact Analysis of the U.S. Biobased Products Industry*, U.S. Department of Agriculture, http://www.biopreferred.gov/BPResources/files/EconomicReport_6_12_2015.pdf.

[15] A. Lovins, et al. (2004), *Winning the Oil Endgame: Innovation for Profits, Jobs, and Security*, Rocky Mountain Institute, http://www.rmi.org/Knowledge-Center/Library/E04-07_WinningTheOilEndgame.

[16] Biotechnology Industry Organization (March 2010), *Biobased Chemicals and Products: A New Driver for Green Jobs*, http://www.bio.org/articles/biobased-chemicals-and-products-new-driver-green-jobs.

[17] U.S. Department of Energy (2004), *Top Value Added Chemicals from Biomass: Volume I—Results of Screening for Potential Candidates from Sugars and Synthesis Gas,* http://www.nrel.gov/docs/fy04osti/35523.pdf and University of Florida IFAS Extension, *Bio-based Products from Biomass*, http://edis.ifas.ufl.edu/ae483.

Biomass-derived products will also compete with existing starch-based bioproducts, such as poly lactic acid. For biomass-derived products to compete, they must be price competitive with these existing products and address commodity markets. New biomass-derived products will also have to compete globally and will, therefore, require efficient production processes and low production costs.

Power: Less than 1% of the oil consumed in the United States is used for electric power generation. Fossil fuels dominate U.S. power production and account for more than 63% of generation, with coal comprising 42%, natural gas 21%, and oil less than 1%. The balance is provided by nuclear (21%) and renewable sources (13%), including 1% [18] provided by biopower. New natural-gas-fired, combined-cycle plants are expected to increase the natural gas contribution, with coal-fired power maintaining a dominant role. Renewable energy, which includes biopower, is projected to have the largest increase in production capacity between 2012 and 2040.[19]

Dedicated utility-scale biopower applications are a potential route to further reduce U.S. reliance on fossil fuels and improve the sustainability associated with power generation. Limits to the availability of a reliable, sustainable feedstock supply, as well as competing demands for biofuels to meet EISA goals, may constrain the feedstock volumes available for utilization in biopower applications and may also increase feedstock costs for both applications. A near-term opportunity to increase the use of biomass for power generation, thereby reducing GHG emissions, is to increase the deployment of co-firing applications for biomass and biomass-derived intermediates in existing power-generating facilities. However, as there are currently 2,219 registered biomass-to-power generation facilities in the U.S., BETO considers this technology to be commercially mature, and not in need of additional R&D support.[20]

1.1.2 State, Local, and International Political Climate

State and Local Political Climate

States play a critical role in developing energy policies by regulating utility rates and the permitting of energy facilities. Over the last two decades, states have collectively implemented hundreds of policies promoting the adoption of renewable energy. To encourage alternatives to petroleum in the transportation sector, states offer financial incentives for producing alternative fuels, purchasing flexible-fuel vehicles, and developing alternative fuels infrastructure. In some cases, states mandate the use of ethanol and/or biodiesel. Several states have also established renewable portfolio standards to promote the use of biomass in power generation.[21]

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[18] U.S. Energy Information Administration (2015), "Energy Consumption by Sector and Source," *Annual Energy Outlook 2015*, http://www.eia.gov/forecasts/aeo/data/browser/#/?id=2-AEO2015.

[19] U.S. Energy Information Administration (2015), "Total Energy Supply, Disposition, and Price Summary," *Annual Energy Outlook 2015,* http://www.eia.gov/forecasts/aeo/data/browser/#/?id=1-AEO2015&region=0-0&cases=ref2015&start=2012&end=2040&f=Q&linechart=ref2015-d021915a.3-1-AEO2015&sourcekey=0.

[20] U.S. Energy Information Administration (2013), "Existing Capacity by Energy Source," http://www.eia.gov/electricity/annual/html/epa_04_03.html.

[21] U.S. Department of Energy, Energy Efficiency & Renewable Energy Office (2014), "State Laws and Incentives," Alternative Fuels Data Center, http://www.afdc.energy.gov/laws/state.

Many states encourage biomass-based industries to stimulate local economic growth—particularly in rural communities that are facing challenges related to demographic changes, job creation, capital access, infrastructure, land use, and environment. Growth in the biofuels industry creates jobs through plant construction, operation, maintenance, and support, while providing risk reduction to farmers through inter-cropping and market expansion. Several states have also recently begun to develop policies to reduce GHG emissions and are looking to biopower and biofuel applications as a means to achieve targeted reductions. California has recently implemented aggressive emissions reductions targets, which call for a 10% reduction in the state's transportation sector's carbon footprint by 2020[22] and a 50% decrease in petroleum use by 2030.[23]

International Political Climate

Oil is expected to remain the dominant energy source for transportation worldwide through 2035, with overall oil consumption expected to increase from 98 million barrels per day in 2015 to about 121 million barrels per day in 2040.[24] However, the international use of renewable fuels is rising. Many nations are seeking to reduce petroleum imports, boost rural economies, and improve air quality through increased use of biomass. Some countries are pursuing biofuels as a means to reduce GHG emissions. Brazil and the United States lead the world in production of biofuels for transportation, primarily ethanol (see Figure 1-3), and several other countries have developed ethanol programs, including China, India, Canada, Thailand, Argentina, Australia, and Colombia.[25]

As countries are developing policies to encourage bioenergy, many are also developing sustainability criteria for the bioenergy they produce and use within their countries. Both the United States and the European Union (EU) specify certain land-use restrictions and GHG reduction requirements for renewable fuels.[26] The EU is also implementing additional biofuel sustainability criteria and reporting requirements.

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[22] California Air Resources Board (2015), "California Climate Plan," http://www.arb.ca.gov/cc/cleanenergy/clean_fs2.htm.

[23] California Air Resources Board (2015), "California's 2030 Climate Commitments: Cutting Petroleum Use in Half by 2030," http://www.arb.ca.gov/newsrel/petroleum_reductions.pdf.

[24] U.S. Energy Information Administration (2015), "Comparison of AEO2015 and AEO2014 Reference cases and key updates to models and data," *Annual Energy Outlook 2015*, p. E-2, http://www.eia.gov/forecasts/aeo/.

[25] U.S. Department of Energy Alternative Fuels Data Center (2013), "Global Ethanol Production," http://www.afdc.energy.gov/data/10331.

[26] European Biofuels Technology Platform (2015), "Biofuels Policy and Legislation," European Biofuels Technology Platform, http://www.biofuelstp.eu/biofuels-legislation.html.

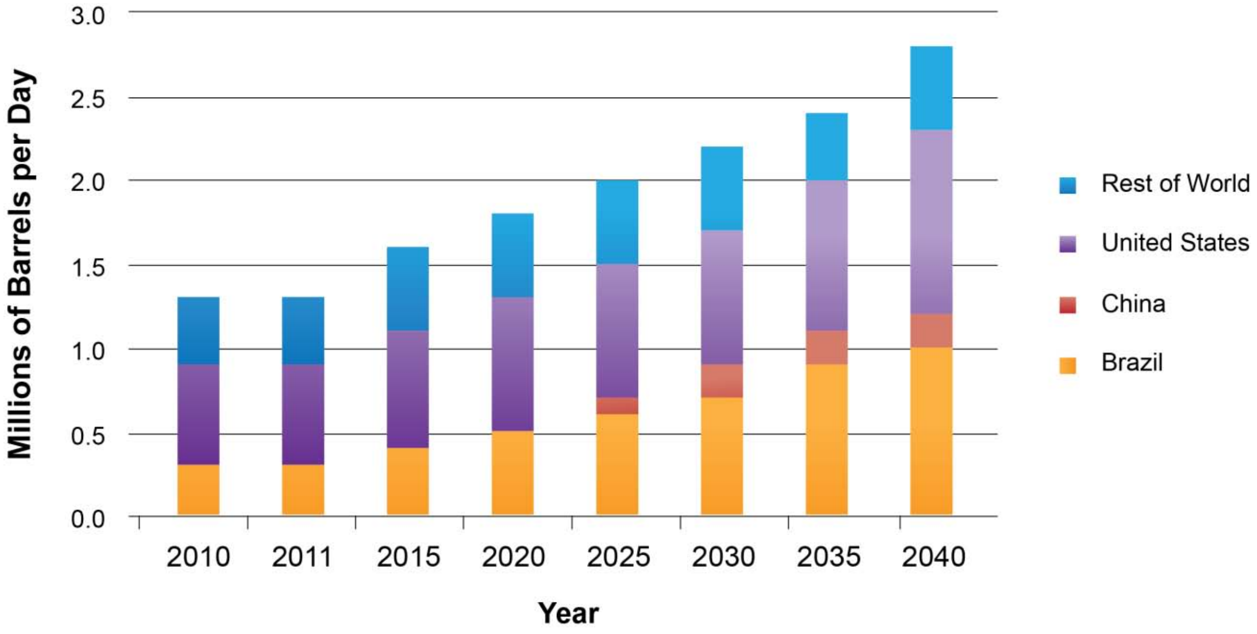

Figure 1-3: Global production of biofuels[27]

Several international groups are developing or implementing sustainability criteria and standards to promote responsible practices across the bioenergy supply chain, from biomass production to end use. For example, the Roundtable on Sustainable Biomaterials develops and maintains a global standard and certification system for organizations demonstrating compliance and commitment to sustainable and responsible practices. The International Organization for Standardization is developing criteria to advance international trade and the use of sustainable bioenergy. The Global Bioenergy Partnership facilitates information exchange, capacity building, and the adoption of voluntary sustainability criteria and indicators. These efforts, which address environmental, social, and economic aspects of bioenergy production, are building consensus among key partners on acceptable metrics and criteria to enable deployment of responsible industry practices worldwide.

The relationship among bioenergy, agriculture, and land-use change has been the subject of increasing attention, particularly with regard to the conversion of old growth forests and native prairies into agriculture production. Policymakers, eager to address this issue, have encouraged scientists in the bioenergy field to focus on researching the indirect impacts of bioenergy production in order to understand the magnitude of the linkage, as well as to identify and protect any vulnerable areas valued for their role in preserving biodiversity and sequestering carbon. Historical studies and reports, such as the UN's Sustainable Bioenergy Framework for Decision Makers complement current efforts within the Bioenergy Technologies Office.[28]

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[27] U.S. Energy Information Administration (2013), *International Energy Outlook 2013*, Washington: Government Printing Office, DOE/EIA-0484. http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf.

[28] United Nations Environment Programme (2007), *Sustainable Bioenergy: A Framework for Decision Makers*, http://www.fao.org/docrep/010/a1094e/a1094e00.htm.

In recent years, attention has focused on how the expanding production of bioenergy crops can influence international markets, potentially triggering price surges and price volatility for staple foods. Some governments have addressed this issue by discouraging the use of food-based feedstocks for bioenergy production. Over the past several years, China halted construction of new food-grain-based ethanol plants and has worked to promote policies that encourage the production of biofuels from non-food feedstocks grown on marginal land. Many countries—particularly in the developing world—have identified ways to minimize competition. Others have identified strategies for producing bioenergy from residues in conjunction with food, feed, and other products that can increase food security by generating employment, raising income in farming communities, and promoting rural development (Food and Agriculture Organization of the United Nations, i.e., UN FAO).[29]

DOE develops technologies that produce biofuels from feedstocks that have no or minimal impacts on food crops. As such, DOE R&D activities focus on developing feedstocks such as agricultural residues, forestry residues, urban wood waste/mill residues, energy crops, and wet wastes (e.g., biosolids).

The EU has enacted a variety of environmental policies that have impacted bioenergy markets in the United States. European targets for the production of 20% renewable power by 2020[30] have led to an expanding market for American and Canadian wood pellets and raw biomass feedstock. The EU Emissions Trading System has expanded interest in biobased aviation fuels. It caps the total amount of allowable carbon emissions across industrial sectors, including emissions from aircraft operators performing aviation activities in the EU and European Free Trade Association states.[31] Most recently, the European Parliament has moved to impose limits on the volume of conventional biofuels in the EU market, while potentially increasing incentives for the production of cellulosic and other advanced biofuels.

1.1.3 Other Fuel Alternatives

The principal technologies that compete with biomass today rely on continued use of fossil energy sources to produce transportation fuels, products, and power in conventional petroleum refineries, petrochemical plants, and power plants. Today, there are several readily available fuel alternatives to petroleum-based liquids, such as fully electric vehicles, hybrid vehicles, and fuel cell vehicles, which store energy in the form of hydrogen.

- **Electricity:** Electricity can be used to power electric vehicles, which either store potential energy in a battery or produce power from a fuel cell as the vehicle is operating.

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[29] Food and Agriculture Organization of the United Nations (2015), “Bioenergy and Food Security,” http://www.fao.org/bioenergy/foodsecurity/befs/en/.

[30] European Commission: Energy (2015), “Renewable Energy,” https://ec.europa.eu/energy/en/topics/renewable-energy.

[31] European Commission (2015), “The EU Emissions Trading System (EU ETS),” http://ec.europa.eu/clima/policies/ets/index_en.htm.

Sales of electric vehicles are accelerating quickly, with global sales growing by 53% from 2013 to 2014.[32]

- **Hydrogen:** Hydrogen can be produced via multiple routes, including water electrolysis, algae, reforming renewable liquids or natural gas, coal gasification, or nuclear synthesis.
- **Gas-to-Liquids**: Hydraulic fracturing and horizontal drilling technologies have enabled increased production of natural gas in the United States. Natural gas can be converted to liquid transportation fuels (diesel, jet, and gasoline) and chemicals by steam-methane reforming reactions and Fischer-Tropsch conversion processes; these are technologies that are different from those used with crude oil.
- **Coal-to-Liquids:** In terms of cost, coal-derived liquid fuels have traditionally been non-competitive with fuels derived from crude oil. While conventional coal-to-liquid technologies can be adapted to use biomass as a feedstock, both in standalone applications or blended with coal, the biomass resource does not scale as well as coal.

1.1.4 Market Barriers

Biorefineries that use cellulosic and algal biomass as feedstocks face market barriers at the federal, state, and local levels. Feedstock availability, production costs, investment risks, consumer awareness and acceptance, and infrastructure limitations pose significant challenges for the emerging bioenergy industry. Widespread deployment of integrated biorefineries will require demonstration of cost-effective biorefinery systems and sustainable, cost-effective feedstock supply infrastructure. The following market barriers are also discussed in Section 2:

Ft-A Terrestrial Feedstock Availability and Cost
Im-A Inadequate Supply Chain Infrastructure
Im-B High Risk of Large Capital Investments
Im-C Codes, Standards, and Approvals for Use
Im-D Cost of Production
Im-E Offtake Agreements
Im-F Uncertain Pace of Biofuel Availability
Im-G Biofuels Distribution Infrastructure
Im-H Lack of Acceptance and Awareness of Biofuels as a Viable Alternative
It-A End-to-End Process Integration
It-B Risk of First-of-a-Kind Technology
It-C Technical Risk of Scaling

The following additional barriers cross the entire supply chain and so are not specific to any particular technology area.

- **Mm-A: Lack of Understanding of Environmental/Energy Tradeoffs.** There is a need for a more thorough, systematic evaluation of the impact of expanded biofuels production on the environment and food supply for humans and animals. Sufficient data needs to be generated from various operational facilities' designs to provide

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[32] International Energy Agency (2015), "Global EV Outlook 2015," http://www.iea.org/evi/Global-EV-Outlook-2015-Update_1page.pdf.

valid sustainability benchmarks for the nascent industry. Analytical tools are needed to facilitate consistent evaluation of energy benefits and GHG emissions impacts of all potential advanced biofuel feedstock and conversion processes. EISA requires that all biofuels be evaluated for their reduction in GHG emissions in order to qualify under the RFS. Cellulosic biofuels, a subset of "advanced biofuels," must achieve at least a 60% reduction in GHG emissions, relative to a 2005 baseline of the petroleum displaced, including indirect land-use change. Advanced biofuels must achieve at least a 50% reduction in GHG emissions. EPA has established the methodology for evaluating these impacts for some pathways.

- **Mm-B: Inconsistent or Competing Policies and Drivers to Facilitate Multi-Sector Shifts.** Expanding biofuels production to meet federal goals will require managing and responding to different markets and policy drivers and considerable federal, state, and local investments. Proper alignment and careful choice of policy tools across several different sectors is crucial. Legislation may ultimately determine the future portfolio mix for bioenergy production and use.
- **Mt-A: Optimization of Supply Chain Interfaces and Cross-System Integration.** The commercialization of biofuels technology will involve industrial-scale technology deployment across a dispersed supply chain. This will require integration and optimization of technologies within and across agricultural, forestry, equipment manufacturing, and biorefinery sectors to address cross-system risks and leverage cross-system positive synergies. Integrating information across sector interfaces will be critical to harnessing efficiencies and driving down costs.

1.1.5 History of Public Efforts in Biomass RD&D

Federal efforts in bioenergy were initiated by the National Science Foundation and subsequently transferred to DOE in the late 1970s. Early projects focused on biofuels and biomass energy systems. In 2002, the Bioenergy Technologies Office (formerly the Office of the Biomass Program) was formed to consolidate the biofuels, bioproducts, and biopower research efforts across EERE into one comprehensive office. From the 2002 to the present, DOE has invested more than $3 billion [including more than $900 million in American Recovery and Reinvestment Act of 2009 (i.e., ARRA) funds] in a variety of RD&D programs covering biofuels, biopower, feedstocks, municipal wastes, and a variety of biobased products. Considerable progress has been made in many areas, including the Office's R&D-scale validation of technologies capable of producing modeled price-competitive cellulosic ethanol. However, continued federal support is needed to fully commercialize ethanol, other hydrocarbon fuels, and other advanced biomass technologies. Key policy shifts, major new legislation, and EERE funding levels are shown in Figure 1-4. This figure does not include bioenergy-related funding for other DOE or EERE offices.

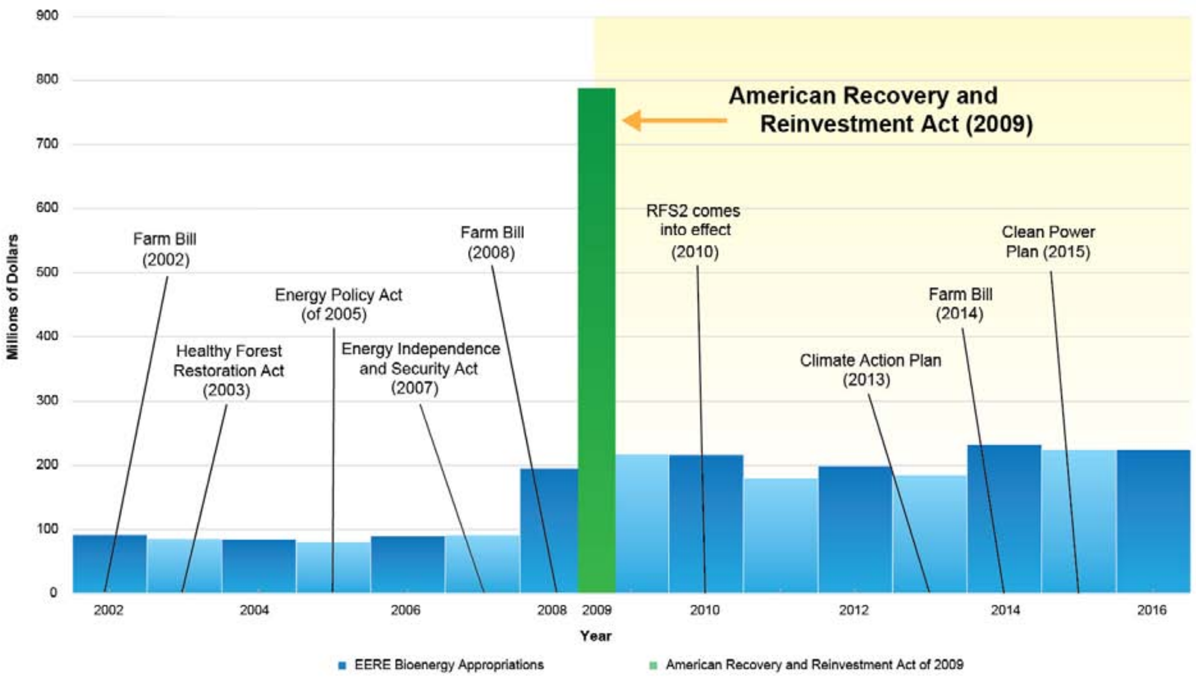

Figure 1-4: DOE EERE funding for biomass RD&D

Especially in recent years, several legislative, regulatory, and policy efforts have increased and accelerated biomass-related RD&D. These efforts are summarized in Table 1-1.

1.1.6 Bioenergy Technologies Office Justification

The Bioenergy Technologies Office is accelerating the commercialization of first-of-a-kind technologies designed to use the nation’s abundant renewable biomass resources for the production of advanced biofuels and biobased products. The Office is also investigating how to improve the economics of biofuel production by converting biomass into high-value chemicals and products that are historically derived from petroleum. As the United States continues to experience the highs and lows of a volatile transportation energy market driven by fossil fuels, the need to find stabilizing solutions becomes increasingly important.

The benefits of biofuels, bioproducts, and biopower include greater economic security, as significant amounts of sustainable, domestically produced feedstocks are directed to the production of renewable energy. The environmental and social benefits of biofuels, bioproducts, and biopower include both a reduction in the GHG emissions that lead to climate change and an increase in economic activity across the entire supply chain. From new jobs in the farms and forests of rural America to growing the U.S. construction and manufacturing industries with the production of bioenergy, biochemical, and vehicles, reinvesting in new U.S. technologies helps secure our national competitive advantage and enables opportunities in the renewable energy sector for future generations.

Table 1-1: Legislative, Regulatory, and Policy Efforts

August 2015	Clean Power Plan	• Established national standards that reduce carbon pollution from power plants and set goals to reduce carbon pollution from the U.S. power sector 32% lower than 2005 levels by 2030. • Targeted reductions of sulfur and nitrogen oxides 90% and 72% below 2005 levels by 2030, respectively.
Feb 2014	Agricultural Act of 2014 (Farm Bill)	• Continued several bioenergy-related programs, including Repowering Assistance Program, Bioenergy Program for Advanced Biofuels, and the Biomass Research and Development Initiative. • Modified the Biomass Crop Assistance Program to extend crop exclusions (whole grain, algae, and bagasse) and limit one-time establishment payments to no more than 50% of the cost of establishment. • Expanded the "Biorefinery, Renewable Chemical and Biobased Product Manufacturing Assistance Program (Section 9003)" (formerly the Biorefinery Assistance Program) to include renewable chemicals and biobased product manufacturing.
June 2013	President's Climate Action Plan	• Set goals to reduce carbon pollution in America by 17% by 2020 from 2005 levels. • Outlined a strategy that focuses in part on Building a 21st Century Transportation Sector and Developing and Deploying Advanced Transportation Technologies. • Promoted partnerships between the private and public sectors to deploy cleaner fuels.
March 2011	Blueprint for a Secure Energy Future	• Outlined a comprehensive energy policy to cut U.S. oil imports by one-third by 2025 by reducing the nation's dependence on oil with cleaner alternative fuels and greater efficiency. • Promoted collaboration with international partners to increase bioenergy production. • Included research and incentives to reduce barriers to increased biofuels use and the commercialization of new technologies.
June 2011	A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022	• Developed a comprehensive regional strategy targeting barriers to the development of a successful biofuels market that will achieve, or surpass, the current U.S. Renewable Fuel Standard.
May 2009	Presidential Memorandum on Biofuels	• Established a Biofuels Interagency Working Group to consider policy actions to accelerate and increase biofuels production, deployment, and use. The group is co-chaired by the Secretaries of the U.S. Departments of Energy and Agriculture and the Administrator of the Environmental Protection Agency.
Feb 2009	American Recovery and Reinvestment Act of 2009	• Provided funds for grants to accelerate the commercialization of advanced biofuels R&D and pilot-, demonstration-, and commercial-scale integrated biorefinery projects. • Provided funds to other DOE programs for applied R&D, innovative research, tax credits, and other projects.
May 2008	The Food, Conservation, and Energy Act of 2008 (Farm Bill)	• Provided grants, loans, and loan guarantees for developing and building demonstration- and commercial-scale biorefineries. • Established a $1.01 per gallon producer tax credit for cellulosic biofuels. • Established the Biomass Crop Assistance Program to support the production of biomass crops. • Provided support for continuation of the Biomass R&D Initiative, the Biomass R&D Board, and the Biomass R&D Technical Advisory Committee.
Dec 2007	Energy Independence and Security Act of 2007	• Supported the continued development and use of biofuels, including a significantly expanded Renewable Fuels Standard, requiring 36 billion gallons per year of renewable fuels by 2022, with annual requirements for advanced biofuels, cellulosic biofuels, and biobased diesel. • The full RFS2 regulatory program went into effect July 2010, with EPA determining required cellulosic biofuel volumes annually.
Aug 2005	Energy Policy Act of 2005	• Renewed and strengthened federal policies fostering ethanol production, including incentives for the production and purchase of biobased products; these diverse incentives range from authorization for demonstrations to tax credits and loan guarantees.

From 2015 to 2040, U.S. energy consumption is projected to rise by 8%, while domestic energy production is expected to rise by nearly 19%.[33] Renewable liquid fuels, including biofuels, are projected to have the largest increase in meeting domestic transportation consumption—growing from 5% in 2011 to 15% of liquid fuels in 2035.[34] This decreased reliance on imported energy improves our national security, economic health, and future global competitiveness and revitalizes investment and cash flows in the United States, which are vital for a growing economy.

The U.S. transportation sector is responsible for 26% of U.S. carbon dioxide (CO_2) emissions, the principal GHG contributing to climate change.[35] Increased use of biofuels, bioproducts, and biopower can decrease life-cycle emissions of GHG and other pollutants substantially, depending on feedstock type, crop management practices, and processing. For liquid transportation fuels, biofuels are one important option for achieving such reductions, especially for diesel trucks, jet aircraft, and marine vessels. Liquid hydrocarbon transportation fuels made from biomass are advantageous because they are largely compatible with existing infrastructure to deliver, blend, and dispense fuels.

The resulting supply of domestically produced biofuels—intended to replace petroleum imported for the chemical and fuels industry—will also retain the full U.S. investment and help reduce price volatility. This point is underscored by the Defense Department's effort to increase national energy security through energy independence, beginning with reducing U.S. exposure to volatile global oil markets. Price spikes in these markets can have profound effects on total fuel costs for the U.S. armed services.

Despite the economic, environmental, and social benefits of bioenergy production, there are significant challenges keeping the industry from its full potential. Similar to other process industries, the advanced bioenergy industry faces significant challenges and risks in the scale-up to pilot, demonstration, and pioneer scales. These risks are related to technology, construction, environmental impact, feedstock supply, operations, market offtake, and financing.[36] The specific risks of feedstock supply and market offtake are more pronounced for advanced biofuels than for other renewable sources of energy because of the variability inherent in biomass and the lack of long-term offtake agreements in the fuel and chemicals markets.

The primary challenges of sustainable feedstock supply and logistics, cost and technical risk reduction in conversion processes, and integrated performance validation at large-scale operation

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[33] U.S. Energy Information Administration (2015), "Total Energy Supply, Disposition, and Price Summary," *Annual Energy Outlook 2015,* http://www.eia.gov/forecasts/aeo/data/browser/#/?id=1-AEO2015&region=0-0&cases=ref2015&start=2015&end=2040&f=Q&linechart=ref2015-d021915a.3-1-AEO2015&sourcekey=0.

[34] International Energy Agency (2013), "Ethanol and biodiesel consumption in road transport by region in the New Policies Scenario," *World Energy Outlook 2013*, p. 205, http://www.worldenergyoutlook.org/media/weowebsite/2013/weo2013_ch06_renewables.pdf.

[35] Environmental Protection Agency (2015), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013*, http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf.

[36] S.E. Koonin and Gopstein, A.M. (2011), "Accelerating the Pace of Energy Change," *Issues in Science and Technology* 27(2), http://issues.org/27-2/koonin/.

need to be addressed to demonstrate robust processes that are ready for commercialization and replication by industry.

There is a unique federal role in partnering with leading R&D entities and industrial technologists across the entire bioenergy supply chain. From the development of sustainability standards and the logistics to reliably produce and deliver up to one billion tons of biomass to biorefineries, the federal government enables the teaming of experts to develop robust and selective conversion technologies and demonstrate the reduction of technical risk.

The Office is uniquely positioned to leverage its legislative authority for financial assistance and leverage DOE's successful track record in commercialization to assist developers in de-risking technologies through validated proof of performance at the pilot, demonstration, and pioneer scales. Obtaining traditional financing is a challenge for new innovative bioenergy technologies, and most pioneer facilities require equity financing of $200 million or more. Two recent industry studies have highlighted the necessary government role in supporting this industry, showing that 86% of the large-scale biorefinery projects in the United States have been at least partially funded by DOE.[37] The Office's support for validation of these new technologies at large scale helps to overcome financing barriers both through direct financial assistance and de-risking the technology through proof-of-performance testing.

The overarching federal role is to ensure the availability of a reliable, affordable, and environmentally sound domestic energy supply. Billions of dollars have been spent over the last century to construct the nation's energy infrastructure for fossil fuels.[38] The production of alternative transportation fuels from new primary energy supplies, like biomass, is no small undertaking. The role of federal programs is to invest in the high-impact, high-value bioenergy technology RD&D that is critical to the nation's future and that industry would be unable to pursue independently. States, associations, and industry will be key participants in deploying biomass technologies once risk reductions have been sufficiently demonstrated by federal programs.

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[37] Bacovsky, Ludwiczek, Ognissanto, Wörgetter (March 2013), Status of Advanced Biofuels Demonstration Facilities, IEA Task 39-P1b, http://task39.sites.olt.ubc.ca/files/2013/12/2013_Bacovsky_Status-of-Advanced-Biofuels-Demonstration-Facilities-in-2012.pdf.

[38] U.S. Energy Information Agency (July 2011), *Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2010*, http://www.eia.gov/analysis/requests/subsidy/pdf/subsidy.pdf.

1.2 Office Vision and Mission

EISA aimed to increase the supply of alternative fuels and set a target for the use of 36 billion gallons of renewable fuels, including advanced and cellulosic biofuels and biomass-based diesel, by 2022. DOE has set a goal in its strategic plan to support a more economically competitive, environmentally responsible, secure and resilient U.S. energy infrastructure.[39]

To meet both EISA and DOE goals, the Office is focused on developing and demonstrating bioenergy and bioproducts technologies in partnership with other government agencies, industry, and academia. The Office supports four key goals of the recently updated EERE Strategic Plan:[40]

- Accelerate the development and adoption of sustainable transportation technologies
- Stimulate the growth of a thriving domestic clean energy manufacturing industry
- Lead efforts to improve federal sustainability and implementation of clean energy solutions
- Enable a high-performing, results-driven culture through effective management approaches and processes.

The Office's vision, mission, and goals are shown in Figure 1-5.

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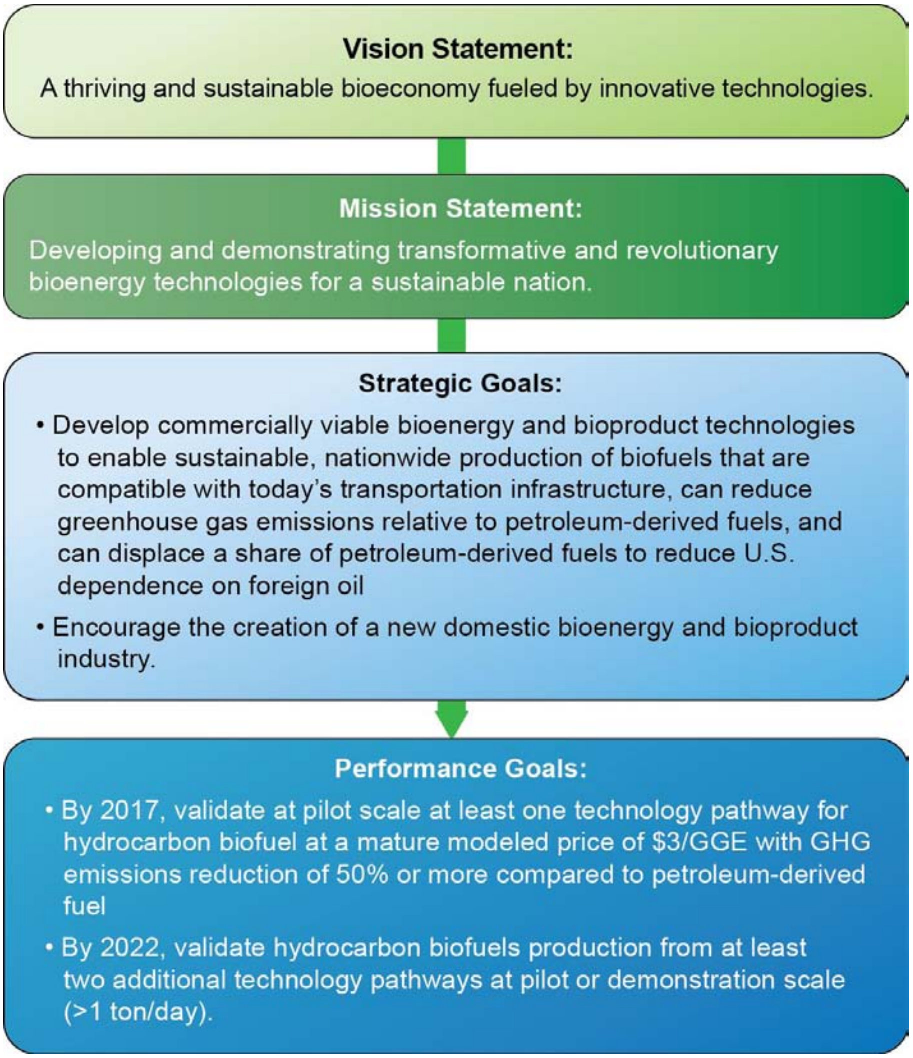
[39] U.S. Department of Energy (2014), *U.S. Department of Energy Strategic Plan 2014-2018*, DOE/CF-0067, http://energy.gov/downloads/2014-2018-strategic-plan.

[40] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2016), *2016–2020 Strategic Plan and Implementing Framework*, http://www.energy.gov/eere/downloads/eere-strategic-plan.



Vision Statement:

A thriving and sustainable bioeconomy fueled by innovative technologies.

Mission Statement:

Developing and demonstrating transformative and revolutionary bioenergy technologies for a sustainable nation.

Strategic Goals:

- Develop commercially viable bioenergy and bioproduct technologies to enable sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure, can reduce greenhouse gas emissions relative to petroleum-derived fuels, and can displace a share of petroleum-derived fuels to reduce U.S. dependence on foreign oil
- Encourage the creation of a new domestic bioenergy and bioproduct industry.

Performance Goals:

- By 2017, validate at pilot scale at least one technology pathway for hydrocarbon biofuel at a mature modeled price of $3/GGE with GHG emissions reduction of 50% or more compared to petroleum-derived fuel
- By 2022, validate hydrocarbon biofuels production from at least two additional technology pathways at pilot or demonstration scale (>1 ton/day).

Figure 1-5: Strategic framework for the Bioenergy Technologies Office[41]

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[41] Methodology for developing performance goals is detailed in Appendix B.

1.3 Office Design

1.3.1 Office Structure

As shown in Figure 1-6, the Bioenergy Technologies Office administration and work breakdown structure is organized around two broad categories of effort: RD&D and Crosscutting Activities. The first category is comprised of three technical program areas: Feedstock R&D, Conversion R&D, and Demonstration and Market Transformation. The Office's crosscutting program areas are Sustainability, Strategic Analysis, and Strategic Communications. A fourth crosscutting area is Office Portfolio Management.

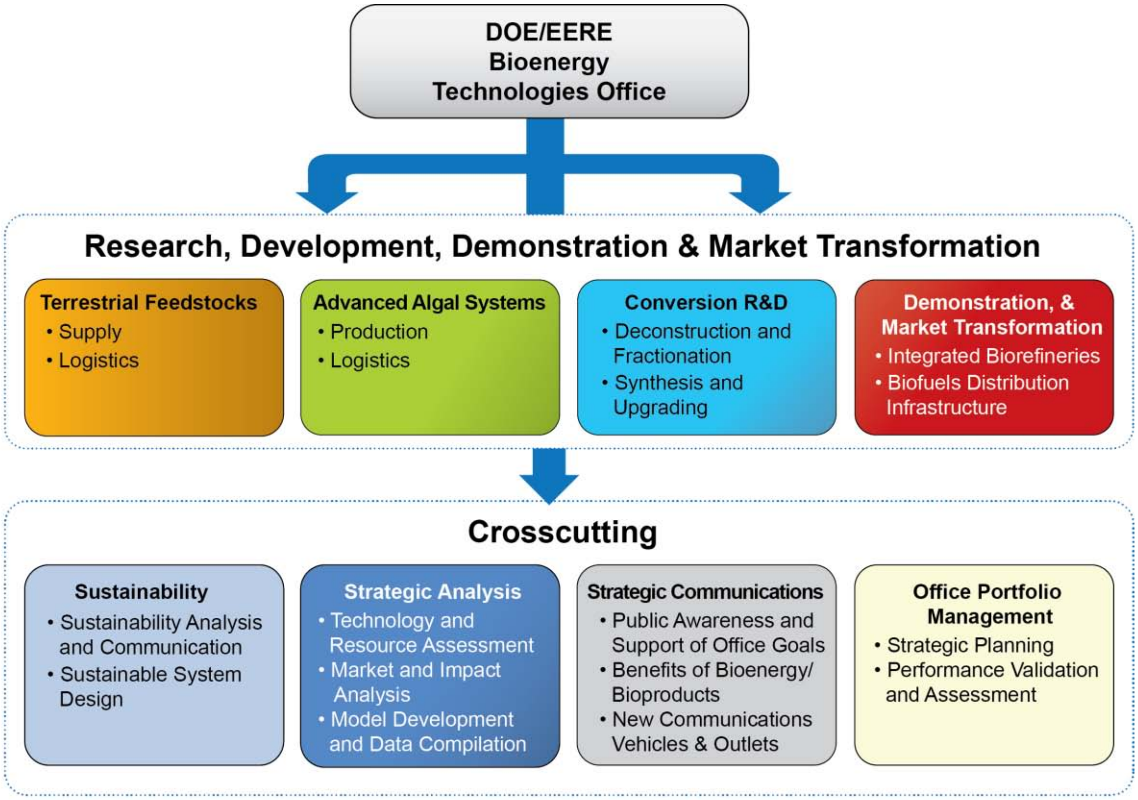

Figure 1-6: Structure of the Bioenergy Technologies Office

This approach provides for the development of pre-commercial, enabling technologies, as well as the integration and demonstration activities critical to proof of performance at increased scale and integration. It also accommodates the Sustainability, Analytical, and Strategic Communications activities needed to help the nation overcome market barriers and accelerate technology deployment.

The organization, activities, targets, and challenges of each of the Office's three technical program areas and three crosscutting program areas are described in detail in Section 2. The fourth crosscutting area, Office Portfolio Management, is described in Section 3.

1.3.2 Portfolio Logic

The portfolio logic diagram shown in Figure 1-7 identifies inputs that guide the Office strategy and external factors that require continuous monitoring to determine the need for any programmatic adjustments. The diagram shows portfolio activities and their outputs, leading to outcomes that support the Office mission and vision. This progression of linkages supports the framework for the Office strategy and this Multi-Year Program Plan.

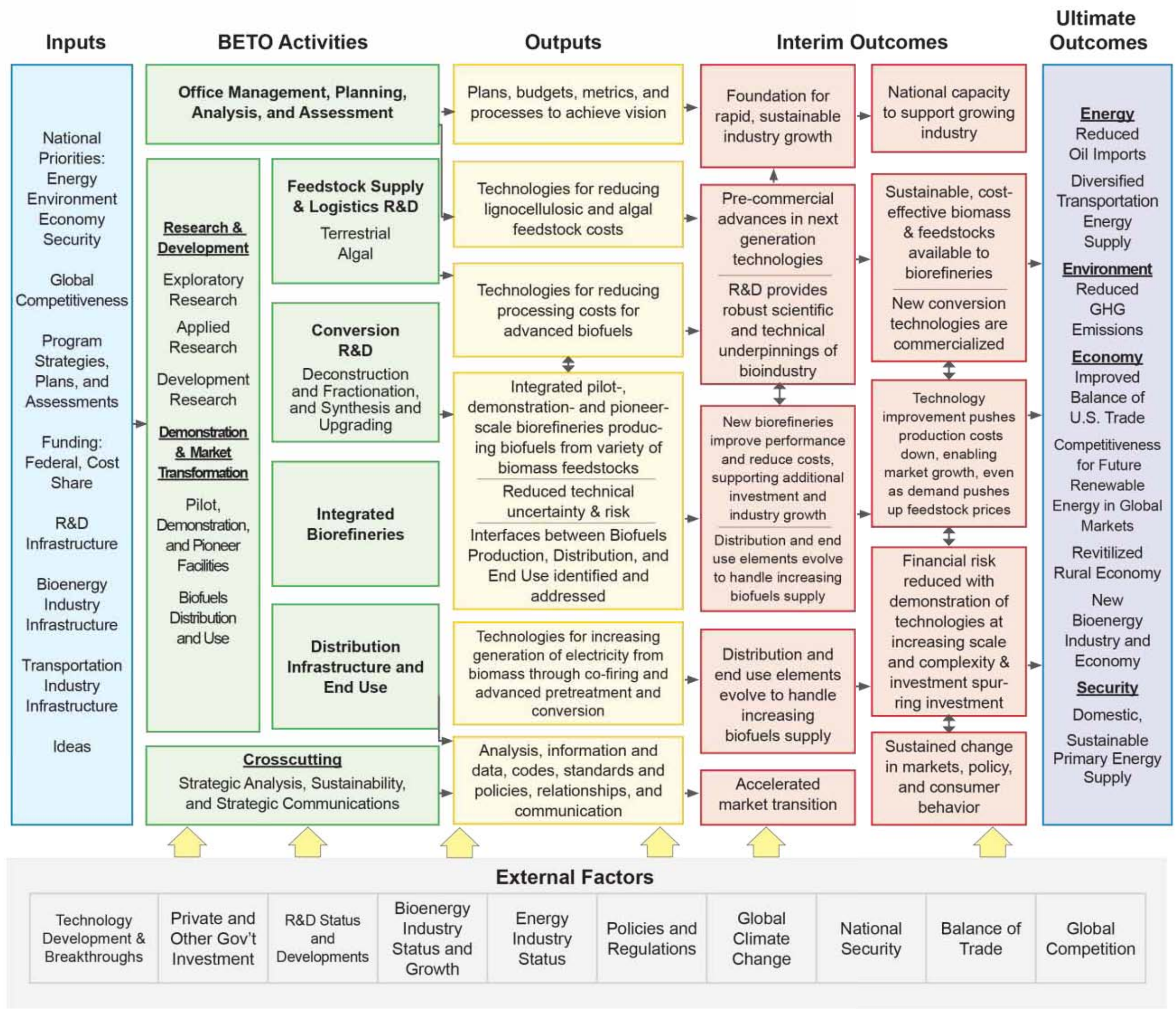

Figure 1-7: Bioenergy Technologies Office portfolio logic diagram

1.3.3 Relationship to Other Offices within DOE and Other Federal Agencies

Coordination with other DOE offices and government agencies involved in bioenergy development is essential to avoid duplication, leverage limited resources, optimize the federal investment, ensure a consistent message to stakeholders, and meet national energy goals. Collaboration is also essential for the realization of a sustainable bioeconomy, defined as "the global industrial transition of sustainably utilizing renewable aquatic and terrestrial biomass resources in energy, intermediate, and final products for economic, environmental, social, and national security benefits."[42] The Office maintains key partnerships with other DOE offices as shown in Table 1-2 and Figure 1-8.

Table 1-2: Summary of Partnerships with Other DOE Offices

DOE Office	Partnership Description
Office of Science	• The Office regularly coordinates with the Office of Science by focusing on fundamental and applied research activities regarding biomass and biofuels with eventual commercial applications for bioenergy.
Loan Programs Office	• The Loan Programs Office provides finance guarantees to BETO for commercial biorefinery projects to spur further investments in the bioenergy sector.
Office of Fossil Energy	• The Office collaborates with the Office of Fossil Energy to examine technology development improvements to increase the efficiency, environmental performance, and economic viability of utility-scale biopower and carbon reuse applications.
Energy Information Agency	• The Office contributes data to the Energy Information Agency to support accurate forecasting of production and consumption.
EERE Office	**Partnership Description**
Advanced Manufacturing Office	• AMO works with the Office to research and develop biomass-based technologies such as renewable, low-cost carbon fiber for lightweight vehicles, in addition to the production of biomass fuels, chemicals, materials, heat, and electricity. AMO invests in emerging technologies that include the use of biomass for fuels, chemicals, materials, heat, and electricity.
Advanced Research Projects-Energy	• ARPA-E invests in innovative technologies that include electro-fuels and the Plants Engineered to Replace Oil (PETRO) program for direct biofuel production. The Office greatly benefits from information sharing with ARPA-E.
Federal Energy Management Program Office	• FEMP works with the federal fleet to increase the use of biopower, renewable and alternative fuels, and flexible-fuel vehicles.
Fuel Cell Technologies Office	• FCTO and the Office coordinate research efforts on reformation and gasification, the availability of biomass, and renewable hydrogen for biofuel production. In addition, the offices collaborate on using algae to produce biofuels and hydrogen.
Vehicle Technologies Office	• VTO partners with the Office on fuel and infrastructure characterization, as well as the co-optimization of fuels and engines. The Office also interfaces with VTO's Clean Cities Program, developing partnerships to promote alternative fuels, vehicles, and infrastructure.
Office of Strategic Programs	• The Office efforts are supportive of, and coordinate with, broader corporate efforts, such as communications outreach, strategic analysis, international partnerships, and legislative affairs.

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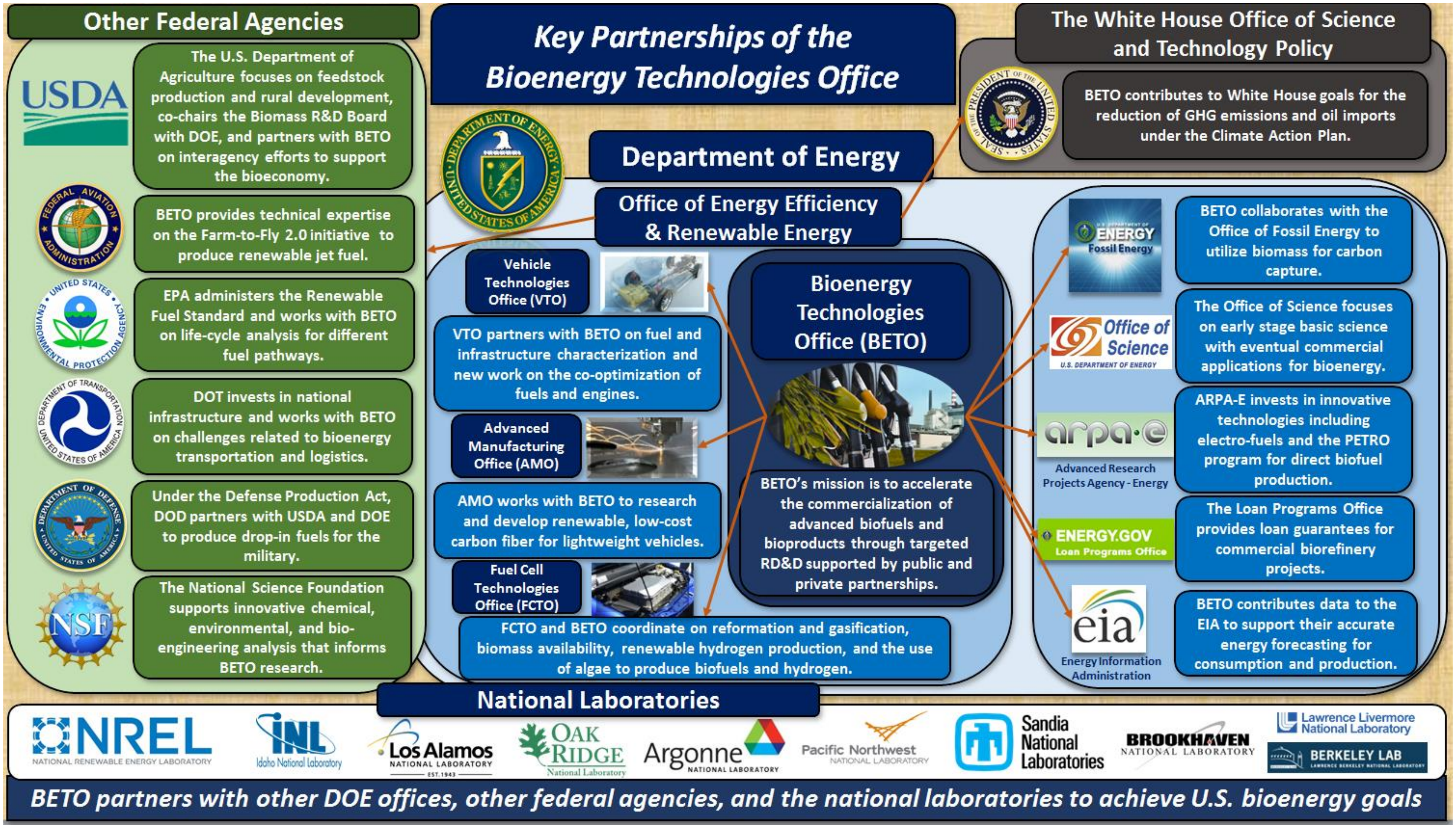
[42] Duke University Center for Sustainability & Commerce (2014), *Why Biobased? Opportunities in the Emerging Bioeconomy: Why BioPreferred*, http://www.biopreferred.gov/files/WhyBiobased.pdf.



Key Partnerships of the Bioenergy Technologies Office

Other Federal Agencies

USDA: The U.S. Department of Agriculture focuses on feedstock production and rural development, co-chairs the Biomass R&D Board with DOE, and partners with BETO on interagency efforts to support the bioeconomy.

BETO provides technical expertise on the Farm-to-Fly 2.0 initiative to produce renewable jet fuel.

EPA administers the Renewable Fuel Standard and works with BETO on life-cycle analysis for different fuel pathways.

DOT invests in national infrastructure and works with BETO on challenges related to bioenergy transportation and logistics.

Under the Defense Production Act, DOD partners with USDA and DOE to produce drop-in fuels for the military.

The National Science Foundation supports innovative chemical, environmental, and bio-engineering analysis that informs BETO research.

The White House Office of Science and Technology Policy

BETO contributes to White House goals for the reduction of GHG emissions and oil imports under the Climate Action Plan.

Department of Energy

Office of Energy Efficiency & Renewable Energy

Vehicle Technologies Office (VTO)

VTO partners with BETO on fuel and infrastructure characterization and new work on the co-optimization of fuels and engines.

Advanced Manufacturing Office (AMO)

AMO works with BETO to research and develop renewable, low-cost carbon fiber for lightweight vehicles.

Fuel Cell Technologies Office (FCTO)

FCTO and BETO coordinate on reformation and gasification, biomass availability, renewable hydrogen production, and the use of algae to produce biofuels and hydrogen.

Bioenergy Technologies Office (BETO)

BETO's mission is to accelerate the commercialization of advanced biofuels and bioproducts through targeted RD&D supported by public and private partnerships.

U.S. Department of Energy Fossil Energy: BETO collaborates with the Office of Fossil Energy to utilize biomass for carbon capture.

Office of Science, U.S. Department of Energy: The Office of Science focuses on early stage basic science with eventual commercial applications for bioenergy.

arpa-e, Advanced Research Projects Agency - Energy: ARPA-E invests in innovative technologies including electro-fuels and the PETRO program for direct biofuel production.

ENERGY.GOV Loan Programs Office: The Loan Programs Office provides loan guarantees for commercial biorefinery projects.

eia, Energy Information Administration: BETO contributes data to the EIA to support their accurate energy forecasting for consumption and production.

National Laboratories

NREL National Renewable Energy Laboratory
INL Idaho National Laboratory
Los Alamos National Laboratory
Oak Ridge National Laboratory
Argonne National Laboratory
Pacific Northwest National Laboratory
Sandia National Laboratories
Brookhaven National Laboratory
Lawrence Livermore National Laboratory
Berkeley Lab

BETO partners with other DOE offices, other federal agencies, and the national laboratories to achieve U.S. bioenergy goals

Figure 1-8: Key partnerships with other DOE offices and federal agencies

As shown in Table 1-2, the Office coordinates with several federal agencies through a range of informal and formal mechanisms. The Biomass R&D Board (the Board) is a particularly important coordination mechanism that was created by the Biomass Research and Development Act of 2000. Formed to maximize federal efforts to enhance the emerging biomass industry, the Board is an interagency collaboration co-chaired by the U.S. Department of Agriculture and DOE. Other Board partners include the Departments of Interior, Transportation, and Defense; EPA; the National Science Foundation; and the Office of Science and Technology Policy. Its members meet quarterly to discuss updates and implementation strategies across federal agencies in biofuels, biopower, and bioproducts R&D.

Table 1-2: Summary of Federal Agency Responsibilities in Supporting the Bioeconomy

Federal Agency or Partner	Feedstock Production	Feedstock Logistics	Conversion	Demonstration	Biofuels Distribution	Biofuels End Use
U.S. Department of Energy	• Plant and algal science • Genetics and breeding • Feedstock resource assessment • Sustainable land, crop, and forestry management • Algal feedstock cultivation and production systems.	• Sustainable logistics systems, including harvesting, handling, storage, & preprocessing systems • Testing logistics systems at demonstration scale.	• Biochemical conversion (pretreatment/enzyme cost reductions) • Recalcitrance of all biomass resources • Thermochemical conversion to increase yield of hydrocarbons to fuel blendstocks and energy (gasification and pyrolysis).	• Cost-shared projects and/or loan guarantees to biorefineries to demonstrate and deploy integrated conversion processes at pilot, demonstration, and pioneer scale.	• Transportation/distribution systems development • Material compatibility.	• Engine compatibility and optimization • Vehicle emissions testing • Bioproduct testing for market acceptance • Education regarding positive impacts of biofuels.
U.S. Department of Agriculture	• Sustainable land, crop, and forestry management • Payments to biomass crop producers • Plant science, genetics and breeding • Genetic improvement work directed at perennial grasses.	• Sustainable harvesting of biomass crop and forest residue removal • Equipment systems related to planting.	• Biochemical conversion (pretreatment/enzyme cost reductions) • Recalcitrance of forest resources • Thermochemical conversion to fuels and power • On-farm biofuels systems.	• Loan guarantees to viable pioneer-scale facilities and grants to demonstration-scale facilities • Payments to existing biorefineries to retrofit power sources to be renewable.	• Loan guarantees and grants to support (1) safe and sustainable biofuel transportation/ distribution (2) Refineries & blending facilities development (3) Flex-fuel pumps installation (4) Financing of transportation/ distribution industry/businesses.	• Market awareness and education for end users on advantages of increased biofuels use.
U.S. Environmental Protection Agency	• Effects of feedstock production systems, including effects on ecosystem services (water quality, quantity, biodiversity, etc.). • Assessment of bioenergy crop impacts.	• Mitigate negative impacts of feedstock production and logistics.	• Biowaste-to-energy • Characterization of air, water, and waste emissions • Regulations/permitting • TSCA (Toxic Substances Control Act) review of inter-generic genetically engineered microbes used for biomass conversion • Testing protocols and performance verification.	• Health/environmental impacts of biofuels supply chain life cycle • Characterization of air, water, and waste emissions; regulations/permitting • Policy and research on waste to energy • Testing protocols and performance verification • Market impact of biofuels production.	• Permitting, air emission characterization • Regulation of underground storage tanks • Emergency management and remediation of biofuel spills.	• Engine optimization/certification • Characterization of vehicle emissions and air quality, and environmental, and public health impacts • Regulation of air emissions • Market awareness/ impact of biofuels on public health, ambient air, and vehicles.
U.S. Department of Commerce/ National Institute for Standards and Technology			• Catalyst design, biocatalytic processing, biomass characterization, and standardization • Standards development, measurement, and modeling.		• Materials reliability for storage containers, pipelines, and fuel delivery systems.	• Standard reference materials, data, and specifications for biofuels.

Federal Agency or Partner	Feedstock Production	Feedstock Logistics	Conversion	Demonstration	Biofuels Distribution	Biofuels End Use
U.S. Department of Transportation		• Feedstock transport infrastructure development.			• Safe, adequate, cost-effective biofuels transportation/ distribution systems development.	• Promotion of safe and efficient transportation while improving safety, economic competitiveness, and environmental sustainability.
Federal Aviation Administration	• Rigorous research in advanced feedstock and renewable aviation fuel pathway development.		• Techno-economic analysis of processes that convert biomass to jet fuel.	• Builds relationships, share and collect data, identify resources, and direct research, development and deployment of alternative jet fuels by supporting Commercial Aviation Alternative Fuels Initiative.	• Safe, adequate, compatible, cost-effective biofuels transportation/ distribution system.	• Working toward certification of bio-derived jet fuels in coordination with the American Society for Testing and Materials with the entire aviation supply chain.
National Science Foundation	• Plant genetics, algal science, and other paths to improve biofuels feedstocks and wastes as energy sources.	• Basic research on modifications or processes to improve feedstock preprocessing.	• Basic and applied research on catalysts, processes, characterization for biochemical and thermochemical conversion technologies • Life-cycle analysis • Environmental impact amelioration.	• Supportive R&D on health/environmental impacts of biofuels and bioproducts		• Supportive R&D on health/ environmental/ safety/social issues of biofuels use.
Department of the Interior	• Forest management.	• Forest management/ fire prevention (recovery of forest thinnings).	• Biorefinery permitting on Department of Interior-managed lands.			
Department of Defense	• Basic R&D on feedstock processing (municipal solid waste/waste biomass).		• Solid waste gasification • Applied algal and cellulosic feedstock conversion R&D • Partner in Defense Production Act.	• Through Defense Production Act, support biorefineries to demonstrate and deploy integrated conversion at commercial scale.	• Safe, compatible, cost-effective biofuels transportation/ distribution systems developed for military use.	• Biofuels testing • Standard reference materials, data, and specifications for biofuels • Biofuel use in military vehicles/crafts.

1.4 Office Goals and Multi-Year Targets

This subsection describes the Office's goals and targets.

1.4.1 Office Strategic Goals

As stated in Section 1.2, the Office's overarching strategic goal is to *develop commercially viable bioenergy and bioproduct technologies to enable sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure, can reduce greenhouse gas emissions relative to petroleum-derived fuels, and can displace a share of petroleum-derived fuels to reduce U.S. dependence on foreign oil and encourage the creation of a new domestic bioenergy and bioproduct industry.*

The Office's high-level schedule, illustrated in Figure 1-9, aims for development of commercially viable renewable gasoline, diesel, and jet technologies by 2017 through R&D and enables a trajectory toward long-term renewable fuels goals.

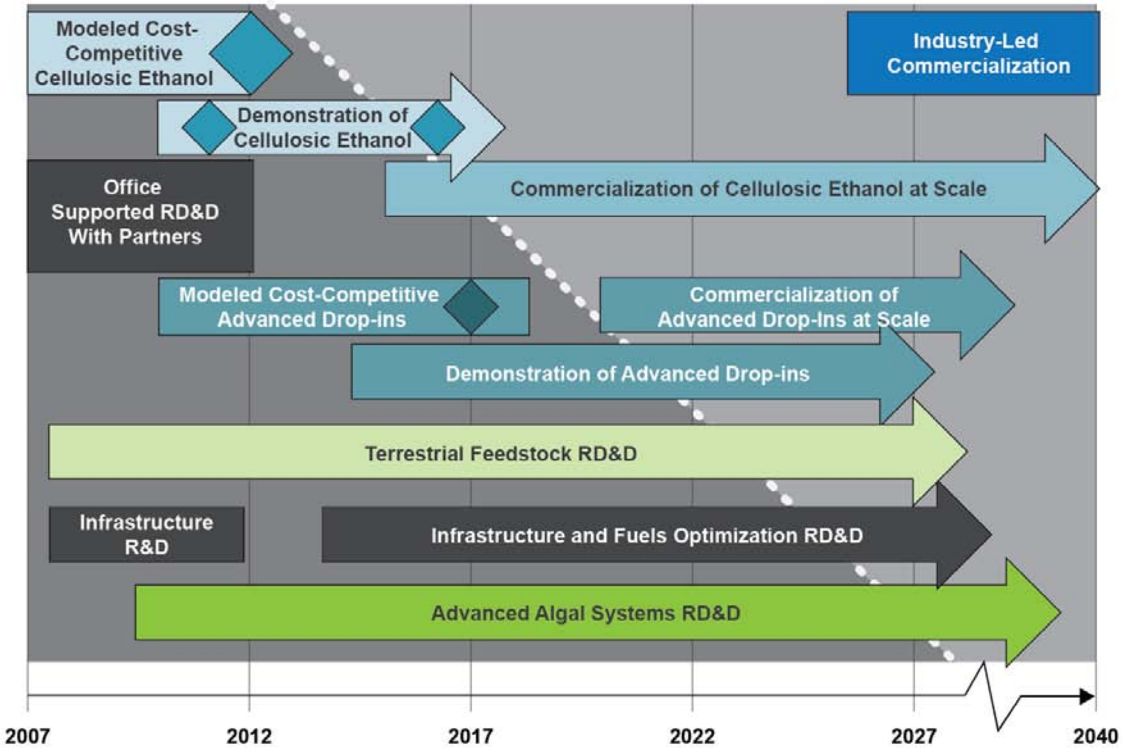
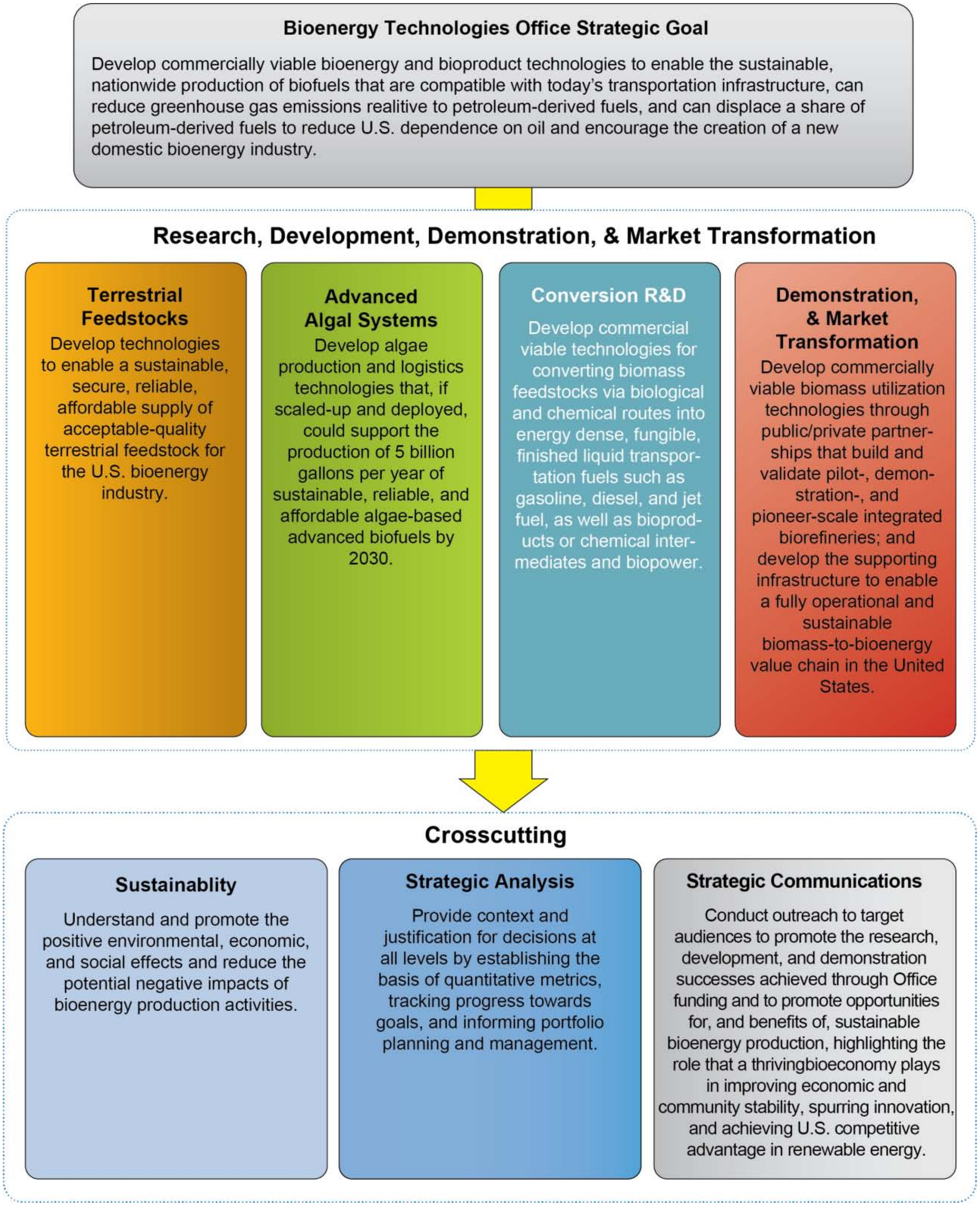


Figure 1-9: Technology Development Timeline

The strategic goals for each program area support the Office's overarching strategic goal, as shown in Figure 1-10. These goals are integrally linked: demonstration and validation activities, for example, will depend on an available, sustainable feedstock supply, commercially viable conversion technologies, adequate distribution infrastructure, and strategic alliances and outreach to catalyze market expansion.



Bioenergy Technologies Office Strategic Goal

Develop commercially viable bioenergy and bioproduct technologies to enable the sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure, can reduce greenhouse gas emissions realitive to petroleum-derived fuels, and can displace a share of petroleum-derived fuels to reduce U.S. dependence on oil and encourage the creation of a new domestic bioenergy industry.

Research, Development, Demonstration, & Market Transformation

Terrestrial Feedstocks

Develop technologies to enable a sustainable, secure, reliable, affordable supply of acceptable-quality terrestrial feedstock for the U.S. bioenergy industry.

Advanced Algal Systems

Develop algae production and logistics technologies that, if scaled-up and deployed, could support the production of 5 billion gallons per year of sustainable, reliable, and affordable algae-based advanced biofuels by 2030.

Conversion R&D

Develop commercial viable technologies for converting biomass feedstocks via biological and chemical routes into energy dense, fungible, finished liquid transportation fuels such as gasoline, diesel, and jet fuel, as well as bioproducts or chemical intermediates and biopower.

Demonstration, & Market Transformation

Develop commercially viable biomass utilization technologies through public/private partnerships that build and validate pilot-, demonstration-, and pioneer-scale integrated biorefineries; and develop the supporting infrastructure to enable a fully operational and sustainable biomass-to-bioenergy value chain in the United States.

Crosscutting

Sustainablity

Understand and promote the positive environmental, economic, and social effects and reduce the potential negative impacts of bioenergy production activities.

Strategic Analysis

Provide context and justification for decisions at all levels by establishing the basis of quantitative metrics, tracking progress towards goals, and informing portfolio planning and management.

Strategic Communications

Conduct outreach to target audiences to promote the research, development, and demonstration successes achieved through Office funding and to promote opportunities for, and benefits of, sustainable bioenergy production, highlighting the role that a thrivingbioeconomy plays in improving economic and community stability, spurring innovation, and achieving U.S. competitive advantage in renewable energy.

Figure 1-10: Strategic goals for the Bioenergy Technologies Office

1.4.2 Office Performance Goals

The overall performance goals set for the Office are shown below. These goals reflect the strategy of making advanced biofuels—renewable gasoline, diesel, and jet fuel—commercially viable, as the most effective path for stimulating an emerging bioenergy economy.

- By 2017, validate at a pilot scale at least one technology pathway for hydrocarbon biofuel production at a mature modeled price of $3/GGE with GHG emissions reduction of 50% or more compared to petroleum fuel.
- By 2022, validate hydrocarbon biofuels production from at least two additional technology pathways at pilot or demonstration scale (>1 ton/day).

1.4.3 Office Multi-Year Targets

The Office's multi-year targets for 2016–2027 are listed in Table 1-4, while the high-level milestones leading to these targets are listed in Table 1-5. Section 2 provides more detail on program area performance goals and high-level milestones for all Office programs.

Table 1-4: Office Multi-Year Performance Goals

Feedstock Supply and Logistics R&D
Terrestrial Feedstocks Supply and Logistics R&D
▪ By 2017, validate efficient, low-cost, and sustainable feedstock supply and logistics systems that can deliver feedstock to the conversion reactor throat at required conversion process in-feed specifications, at or below $84/dry ton (2014$) (including grower payment/stumpage fee and logistics cost). ▪ By 2017, establish geographic, economic, quality, and environmental criteria under which the industry could operate at 245 million dry ton per year scale (excluding biopower). ▪ By 2022, develop and validate feedstock supply and logistics systems that can economically and sustainably supply 285 million dry tons per year at a delivered cost of $84/dry ton (2014$) to support a biorefining industry (i.e., multiple biorefineries) utilizing a diversity of biomass resources.
Advanced Algal Systems R&D
▪ By 2022, demonstrate technologies to produce sustainable algal biofuel intermediate feedstocks that perform reliably in conversion processes to yield renewable diesel, jet, and gasoline fuels in support of the Office's $3/GGE advanced biofuels goal.
Conversion R&D
▪ By 2017, validate an nth plant modeled minimum fuel selling price (MFSP) of $3/GGE (2014$) via a conversion pathway to hydrocarbon biofuel with GHG emissions reduction of 50% or more compared to petroleum-derived fuel. ▪ By 2022, validate an nth plant modeled MFSP of $3/GGE (2014$) for two additional conversion pathways to hydrocarbon biofuel with GHG emissions reduction of 50% or more compared to petroleum-derived fuel.
Demonstration and Market Transformation
▪ By 2017, validate a mature technology modeled cost of cellulosic ethanol production, based on actual integrated biorefinery performance data, and compare to the target of $2.65/gallon ethanol (2014$). ▪ By 2027, validate a mature technology modeled cost of infrastructure-compatible hydrocarbon biofuel production, based on actual integrated biorefinery performance data, and compare to the target of $3/GGE (2014$).
Sustainability
▪ By 2017, identify conditions under which at least one technology pathway for hydrocarbon biofuel production, validated above R&D scale at a mature modeled price of $3/GGE, reduces GHG emissions by 50% or more compared to petroleum fuel, and meets targets for consumptive water use, wastewater, and air emissions. ▪ By 2022, validate landscape design approaches for two bioenergy systems that, when compared to conventional agricultural and forestry production and logistics systems, increase land-use efficiency and maintain ecosystem and social benefits, including biodiversity and food, feed, and fiber production ▪ By 2022, evaluate environmental and socioeconomic indicators across the supply chain for three cellulosic and algal bioenergy production systems. Environmental indicators will validate GHG reduction of at least 50% compared to petroleum, water consumption equal to or less than petroleum per unit of fuel produced, and that air emissions meet federal regulations. Socioeconomic indicators will validate socioeconomic benefits including job creation.
Strategic Analysis
▪ Ensure high-quality, consistent, reproducible, peer-reviewed analyses. ▪ Develop and maintain analytical tools, models, methods, and datasets to advance the understanding of bioenergy and its related impacts. ▪ Convey the results of analytical activities to a wide audience, including DOE management, Congress, the White House, industry, other researchers, other agencies, and the general public.
Strategic Communications
▪ Increase awareness of and support for the Office's advanced biomass RD&D and technical accomplishments, highlighting their role in achieving national renewable energy goals. ▪ Educate audiences about the environmental, economic opportunities and social benefits of biofuels, bioproducts, and a growing bioenergy industry.

Table 1-5: Office Multi-Year Milestones for 2013–2022

Feedstocks Supply and Logistics R&D
Terrestrial Feedstocks Supply and Logistics R&D
Supply
▪ By 2016, produce an updated, fully integrated assessment of potentially available feedstock supplies under previously established environmental and quality criteria.
▪ By 2017, establish available resource volumes for non-woody municipal solid waste and algal feedstocks at $84/dry ton delivered cost (including grower payment/stumpage fee and logistics costs).
▪ By 2017, determine the impact of competing uses, policy and market demands (e.g., biopower, pellet exports) on feedstock supply and price projections.
▪ By 2018, establish nationwide sub-county-level environmental impact criteria and logistics strategies for all potential energy crops, including agricultural and forestry residues, annual and perennial herbaceous energy crops, and short rotation woody energy crops.
▪ By 2019, validate a framework for biomass quality grading systems for at least one woody and one herbaceous biomass supply-shed associated with an existing or planned demonstration-scale (or larger) biorefinery.
▪ By 2020, determine the impact of advanced blending and formulation concepts on available volumes that meet quality and environmental criteria, while also meeting the $84/dry ton cost target (2014$) (including grower payment/stumpage fee and logistics costs).
Logistics
▪ By 2017, validate sustainable feedstock supply and logistics cost of $84/dry ton at conversion reactor throat (including grower payment and logistics cost) for at least one biochemical and one thermochemical conversion process.
▪ By 2022, validate one blendstock for thermochemical conversion and one blendstock for biochemical conversion at a scale of 1 ton per day while also meeting the $84/dry ton cost target (including grower payment/stumpage fee and logistics costs).
Advanced Algal Systems R&D
▪ By 2017, model the sustainable supply of 1 million metric ton ash free dry weight (AFDW) cultivated algal biomass.
▪ By 2018, demonstrate at non-integrated process development unit-scale algae yield of 2,500 gallons or equivalent of biofuel intermediate per acre per year.
▪ By 2019, demonstrate at non-integrated process development unit-scale production and recovery of valuable co-products that can be produced along with biofuel intermediates to increase the value of cultivated algal biomass by 30%.
▪ By 2020, demonstrate at non-integrated process development unit-scale algae yield of 3,700 gallons or equivalent biofuel intermediate per acre per year.
▪ By 2022, model the sustainable supply of 20 million metric ton AFDW cultivated algal biomass.
▪ By 2022, demonstrate at non-integrated process development unit-scale algae yield of 5,000 gallons biofuel intermediate per acre per year in support of nth plant model $3/GGE algal biofuels.
▪ By 2025, demonstrate at integrated process development unit-scale algal productivity of greater than 5,000 gallons biofuel intermediate per acre per year.
▪ By 2030, validate production of algae-based biofuels at total production cost of $3/GGE with or without co-products.
Conversion R&D
▪ By 2016, based on techno-economic analysis and available data, select vapor phase upgrading catalyst and process that can cost-effectively generate refinery-ready intermediates for the 2017 pyrolysis verification.
▪ By 2017, deliver feedstocks and complete verification operations at pilot scale with fuel production cost modeled at $3/GGE for 2,000 tonnes of feedstock/day.

▪ By 2018, select an integrated bench-scale lignin deconstruction and upgrading strategy for valorization of lignin in a hydrocarbon fuel production process.
▪ By 2020, provide enabling capabilities in synthetic biology for industrially relevant, optimized chassis microorganisms and Design-Built-Test-Learn cycles for fuel and chemical production that reduces time-to-scale-up by at least 50% compared to the current average of ~10 years.
▪ By 2021, complete R&D necessary to set the stage for a 2022 verification that produces both fuels and high-value chemical to enable a biorefinery to achieve a positive return on investment.
▪ By 2022, deliver feedstocks and complete verification operations at pilot scale for an alternate conversion pathway with fuel production cost modeled at $3/GGE for 2,000 tonnes of feedstock/day.
Demonstration and Market Transformation
▪ By 2022, validate successful runs of two biofuels and/or bioproducts manufacturing processes at pilot scale.
▪ By 2022, validate successful runs of one biofuels manufacturing process using a hydrocarbon fuels pathway at demonstration scale. By 2023, this successful demonstration of the technology enables the submission of a package for external funding sources (for example, loan guarantee) for the design and construction of a pioneer-scale facility on trajectory to market.
▪ By 2025, validate successful runs of one biofuels manufacturing process utilizing an additional pathway to fuels at pilot scale.
▪ By 2025, validate successful runs of one biofuels and/or bioproducts manufacturing process incorporating another compatible hydrocarbon biofuels/bioproducts pathway at demonstration scale. By 2026, this successful demonstration of the technology facilitates the submission of a package for external funding (for example, loan guarantee) for the design and construction of a pioneer-scale facility on trajectory to commercialization.
▪ By 2030, validate successful runs of one biofuels and/or bioproducts manufacturing process based on a different conversion pathway at demonstration scale. By 2031, this successful demonstration of the technology enables the submission of a package for external funding (for example, loan guarantee) for the design and construction of a pioneer commercial-scale facility on trajectory to market.
Sustainability
Analysis and Communication
▪ By 2016, evaluate environmental sustainability indicators for updated assessment of potentially available feedstock supplies and identify conditions or conservation practices under which feedstock production scenarios are likely to maintain or improve soil quality, biodiversity, and water quality in major feedstock production regions while meeting projected demands for food, feed, and fiber production.
▪ By 2016, coordinate with feedstock logistics and conversion R&D areas to set targets for GHG emissions, consumptive water use, wastewater, and air emissions for at least three renewable hydrocarbon pathways to be validated in 2017 and 2022.
▪ By 2019, quantify and clearly communicate the environmental and socio-economic benefits of emerging advanced bioenergy pathways through at least three case studies that apply BETO-supported analysis tools including but not limited to GREET, WATER, and LEAF. Disseminate findings through technical publications and public outreach.
Sustainable System Design
▪ By 2016, apply the Landscape Environmental Assessment Framework (LEAF) to model three distinct cropping systems to analytically demonstrate the potential for integrated landscape management to increase biomass availability (energy crop production and agricultural residue removal) by 50%, increase soil quality by at least 25%, reduce nutrient loss by 10%, and reduce the risk to surface water quality by 10% as measured by the Water Quality Index, as compared to current agricultural management (conventional row crop practices).
▪ By 2018, using available field data, validate case studies of feedstock production systems that reduce GHG emissions and maintain or improve water quality and soil quality compared to conventional agriculture and forestry systems; identify strategies to translate beneficial practices into broader application.

Strategic Analysis

- By 2016, develop and deploy a consistent methodology for including co-products in techno-economic analyses and design cases.
- By 2016, hold a workshop and publish a whitepaper on the techno-economic analysis of aviation biofuels pathways.
- By 2017, complete supply chain sustainability analyses for at least four technology GHG emissions across biofuel pathways.
- By 2018, complete analysis on impact of advanced biofuels use on gasoline and diesel prices.
- By 2022, identify near-term technology pathways for the Office based on reassessment of current state of technology development.

Strategic Communications

From 2016 through 2022:

- Develop infographics to demonstrate the economic and environmental impacts of biofuel technologies in development.
- Identify and set goals for outreach strategies to address stakeholder concerns and recommendations on technological advancements and how the Office is meeting national energy goals. Keep metrics to track progress toward these efforts.
- Continually update existing outreach to consumers on the benefits of biofuels and bioproducts.
- Develop or update education and communications products to address inaccurate information about bioenergy using science-based data.
- Develop and implement a comprehensive education and workforce development program for K-Grey (elementary, middle, high school, college; grey represents non-traditional education, informal education; and veterans).

- From 2017 through 2022, support information sessions for agriculture, algae, and forestry communities regarding the economic, environmental, and social benefits of participating in the bioeconomy.
- By 2016, begin to implement the Office’s new strategic plan communication and outreach activities to increase awareness of bioenergy to the general public as well as to educate decision makers on the benefits of a bioeconomy.
- By 2016, expand outreach efforts focused on the benefits of greenhouse gas emission reductions resulting from biomass-derived alternative fuels.
- By 2016, begin to develop and implement a robust communications and stakeholder engagement strategy around efforts to co-optimize the development of fuels and engines.

- By 2016, begin to implement the Office’s new strategic plan communication and outreach activities to increase awareness of bioenergy to the general public as well as to educate decision makers on the benefits of a bioeconomy.
- By 2016, expand outreach efforts focused on the benefits of greenhouse gas emission reductions resulting from biomass-derived alternative fuels.

- By 2018, produce communication products to support conversion RD&D pathway validation of modeled nth plant and minimum fuel selling price.
- By 2018, notify and educate BETO stakeholders about validation of efficient, low-cost, and sustainable terrestrial feedstock supply and logistics systems.
- By 2019, develop a multi-agency strategy to convey the results of analytical activities to a wide audience, including DOE senior management, Congress, the White House, industry, RD&D stakeholders, and the public.
- By 2022, amplify technologies that produce sustainable algal biofuel intermediate feedstocks that perform reliably in conversion processes to yield renewable diesel, jet, and gasoline fuels in support of the Office's advanced biofuels goal.

Section 2: Office Technology Research, Development, and Demonstration Plan

The Bioenergy Technologies Office's research, development, and demonstration efforts are organized around four key technical and three key crosscutting program areas (see Figure 2-1). The first three technical program areas—Terrestrial Feedstock Supply and Logistics R&D, Advanced Algal Systems R&D, and Conversion R&D—focus on research and development (R&D). The fourth technical program area—Demonstration and Market Transformation—focuses on integrated biorefineries and distribution infrastructure and end use. The crosscutting program areas—Sustainability, Strategic Analysis, and Strategic Communications—focus on addressing barriers that could impede adoption of bioenergy technologies. Organizing in this way allows the Office to allocate resources for technology development and pre-commercial demonstration of technologies across the biomass-to-bioenergy and bioproducts supply chain as well as addressing crosscutting efforts.

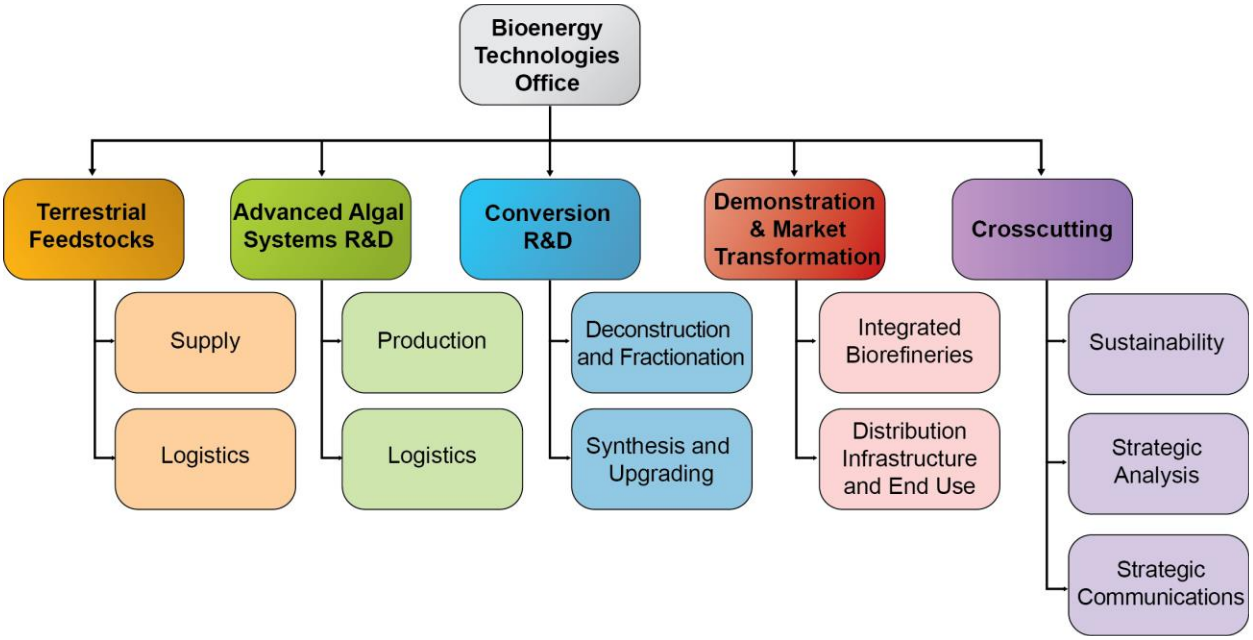


Figure 2-1: Bioenergy Technologies Office work breakdown structure

Bioenergy Technologies Office Organization

Research and Development

The R&D activities sponsored by the Office are focused on addressing technical challenges and opportunities, providing engineering solutions, and developing the scientific and engineering underpinnings of emerging bioenergy and bioproducts industries. Near- to mid-term R&D is focused on developing terrestrial feedstocks supply and logistics technologies from field to landscape to commodity scales, and moving algal feedstock and conversion technology development from concept to pre-commercial pilot-scale.

The goal of RD&D focused on the longer term is to accelerate technology implementation and develop new or improved technologies by developing deeper knowledge of terrestrial and algal biomass, feedstock supply systems, biological systems, and conversion processes. This knowledge can ultimately be used to increase the availability of biomass supplies at lower cost and higher quality, improve conversion efficiency, and reduce conversion cost while reducing carbon dioxide equivalent emissions and water use. Office-funded R&D is performed by national laboratories, industry, and universities.

The Office's R&D includes three technical program areas:

- **Terrestrial Feedstock Supply and Logistics R&D** is focused on developing technologies to provide a reliable, affordable, sustainable[1] supply of terrestrial biomass to enable a nascent and growing bioenergy industry. This R&D is focused on two areas—resource assessment of present and future sustainable terrestrial feedstock supplies, and feedstock logistics R&D focusing on lowering the cost and improving the efficiency of supply chain logistics operations (i.e., harvesting, storage, preprocessing, and transportation) in order to reduce the cost, improve the quality, and increase the volume of feedstock available for delivery to biorefinery conversion reactor inlets (for details, see Section 2.1.1).

- **Advanced Algal Systems R&D** is focused on two areas—algal biomass supply and logistics. Algal biomass supply includes resource assessment, algal strain improvement, and development of efficient cultivation systems to increase productivity. Algal logistics includes reducing costs and improving efficiencies of harvest/dewatering and sustainable intermediate production and stabilization (for details, see Section 2.1.2).

- **Conversion R&D** is focused on developing commercially viable technologies to convert terrestrial and algal feedstocks into liquid fuels, as well as bioproducts and biopower. The Office's Conversion R&D program area focuses on the deconstruction of feedstock into intermediate streams (sugars, intermediate chemical building blocks, bio-oils, and gaseous mixtures) followed by upgrading of these intermediates into fuels and chemicals (for details, see Section 2.2).

Demonstration and Market Transformation

The Office's Demonstration and Market Transformation program area focuses on validating integrated biorefinery (IBR) applications at increasing engineering scale and on biofuel distribution infrastructure and end use. The first goal is to develop emerging conversion technologies beyond bench scale to pre-commercial demonstration scale and reduce the technical risk at increasing complexities and increasing scales to enable the construction of pioneer biofuel production plants by industry. The second goal of Demonstration and Market Transformation is to develop the supporting infrastructure needed to enable a fully developed, operational, and sustainable biomass-to-bioenergy value chain in the United States.

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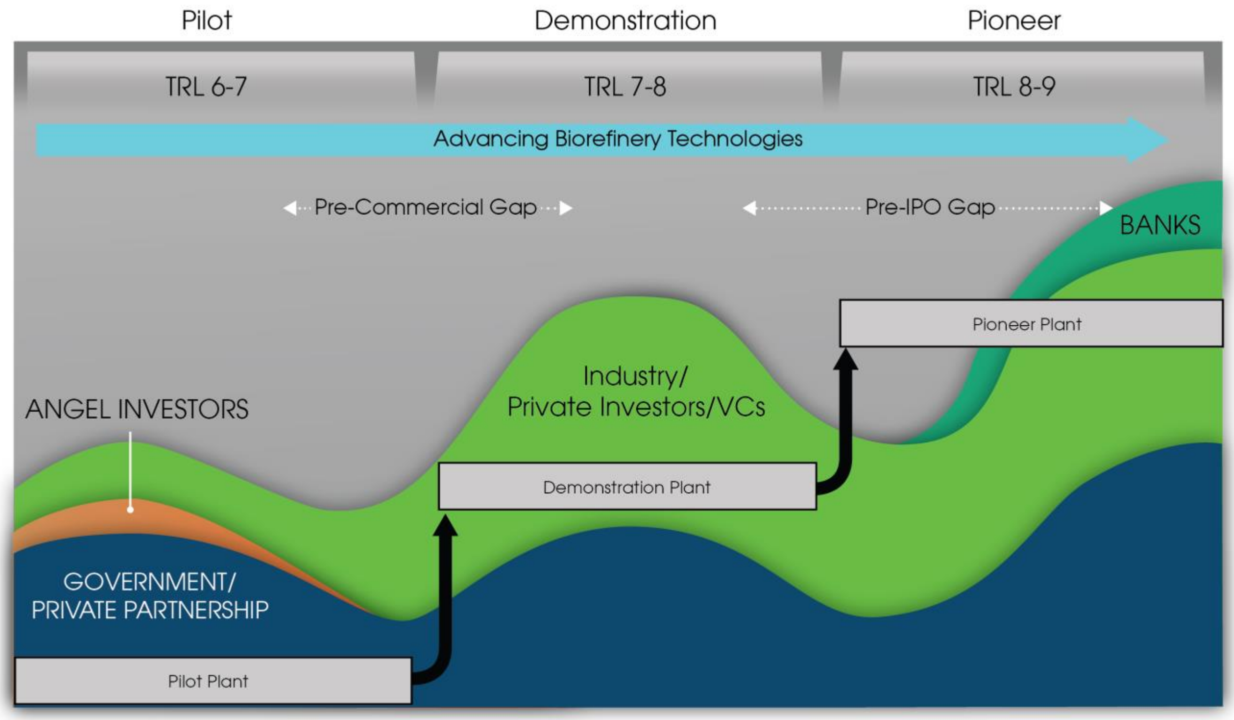
[1] The Bioenergy Technologies Office's approach to sustainability is consistent with Executive Order 13514, which provides the following definition: To create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations. For more on sustainability, see Section 2.4.

Demonstration and Market Transformation includes two areas:

- **IBR** activities focus on demonstration of integrated conversion processes at an engineering scale sufficient to demonstrate and validate commercially acceptable cost, performance, and environmental targets. IBR activities address problems encountered in the so-called "Valley of Death" between pilot-scale and pioneer-scale first-of-a-kind demonstration, as illustrated in Figure 2-2. These efforts are industry-led, cost-shared, and competitively awarded projects. Intellectual property and geographic and market factors will determine the feedstock and conversion technology options that industry will choose to demonstrate and commercialize. Government cost share of biorefinery development is essential due to the high technical and financial risk of first-of-a-kind biofuels production at increasing scale. The Office will continue to fund a number of pilot- and demonstration-scale biofuel production facilities over the next 10 years.

- **Biofuels Distribution Infrastructure and End Use** activities focus on coordinating with other federal agencies and DOE offices to develop the required biofuels distribution and end-use infrastructure. These activities include evaluating the performance and material compatibility, as well as the environmental, health, and safety impacts of advanced biofuels and biofuel blends. These efforts also include co-development of engines and fuels to optimize vehicle performance.

Demonstration and Market Transformation is conducted via Office partnerships with industry and other key stakeholders (for details, see Section 2.3).



TRL = technology readiness level, IPO = initial public offering, VC = venture capital

Figure 2-2: Technology development and scale-up to first-of-a-kind pioneer facility

Crosscutting Activities

The Office's crosscutting program areas include Sustainability, Strategic Analysis, and Strategic Communications. These three program areas work together to support a holistic body of knowledge and tools related to the economic, environmental, and social dimensions of advanced bioenergy. These areas also work together to engage with diverse stakeholders and decision-makers to ensure that these tools and information are accessible and effectively communicated.

- **Sustainability** activities focus on developing the resources, technologies, and systems needed to support a thriving bioenergy industry that protects natural resources and advances environmental, economic, and social benefits. The existing and emerging bioenergy industry—which includes such diverse sectors as agriculture, waste management, and fuel distribution—will need to invest in systems based on economic viability and market needs, as well as environmental and social aspects such as resource availability and public acceptance. To that end, the Office supports analysis, research, and collaborative partnerships to proactively identify and address issues that affect the scale-up potential, public acceptance, and long-term viability of advanced bioenergy systems (see Section 2.4.1).

- **Strategic Analysis** includes a broad spectrum of crosscutting analyses to support programmatic decision making, demonstrate progress toward goals, improve understanding of system behaviors, and direct research activities. Programmatic analysis helps frame the overall Office goals and priorities and covers issues that impact all program areas, such as life-cycle assessment (LCA) of carbon dioxide equivalent emissions from bioenergy and bioproducts. These analyses provide inputs into DOE and Office of Energy Efficiency and Renewable Energy (EERE) strategic plans—as well as the President's Climate Action Plan—and help define the impact of bioenergy on petroleum utilization in the transportation sector. Systems-level and technology specific analyses facilitate quantification, explore sensitivities, identify areas where investment may lead to the greatest impacts, and help to monitor Office accomplishments in each program area. Continued public-private partnerships with the bioenergy scientific community and multi-laboratory coordination efforts help ensure that model assumptions and analysis results from the Office are transparent, transferable, and comparable (see Section 2.4.2).

- **Strategic Communications** focuses on identifying and addressing non-technical and market barriers to bioenergy adoption and utilization in an effort to promote full-scale market penetration. It fosters awareness and acceptance by engaging a range of stakeholders in meaningful collaborations, promoting Office strategies, and increasing consumer acceptance. Strategic communications activities include distributing information to stakeholders and conveying key Office goals, priorities, activities, and accomplishments (see Section 2.4.3).

The Office's Technology Pathways Framework

The technology pathways framework integrates efforts among the technical program areas and aligns with major bioenergy industry market segments. Figure 2-3 illustrates how the Office program areas seek to leverage the broad diversity of potential bioenergy feedstocks while reducing supply risks through developing a wide range of conversion technologies to produce and distribute bioenergy and bioproducts.

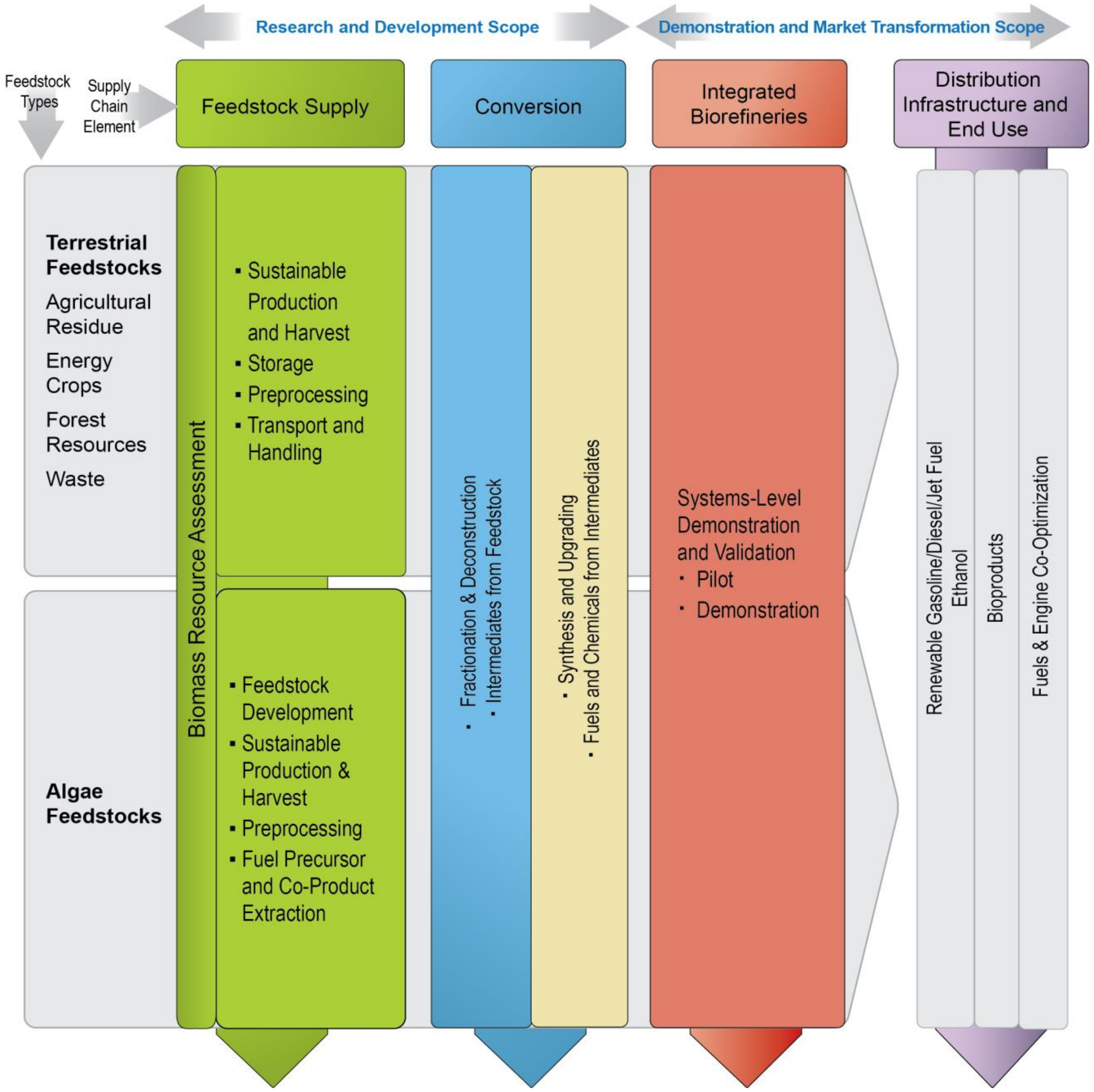


Figure 2-3: Office technical program area links to technology pathway framework

The Office uses this technology pathway framework to identify research, development, and demonstration (RD&D) priorities and balance the activities that are expected to have the greatest impact on achieving Office goals.

Emerging Areas

The Office continually evaluates emerging feedstock, conversion, and market transformation developments to incorporate emerging areas that may contribute to Office goals. For more details on this approach to evaluating emerging pathways, see Section 2.4.2—Strategic Analysis. The Office is currently evaluating the potential for using wet waste feedstocks as another way to meet Office goals.

Wet Waste to Energy:
Wet municipal, industrial, and agricultural wastes are a potential high-impact resource for the domestic production of biogas, biofuels, bio-product precursors, heat, and electricity. The *Biogas Opportunities Roadmap*[2] issued jointly by the USDA, EPA, and DOE estimates that the combination of biogas production from agricultural manure operations, landfills, and waste water treatment could yield 654 billion cubic feet of biogas per year—equivalent to 2.5 billion GGE on an energy basis.[3] While mature technologies exist for biogas production and its clean up and subsequent use, significant opportunities remain to produce heat for on-site use, hydrogen for transportation fuels, and higher hydrocarbons for use in biofuels and bioproducts. These opportunities could unlock greater value for wet wastes, grow the advanced bioeconomy, and displace greenhouse gas emissions from the use of fossil fuel feedstocks. See Section 2.1 for specific definitions of wet-waste-to-energy feedstocks.

Wet wastes are underutilized feedstocks that could feed an emerging pathway to advanced biofuels. They have the potential to make a significant contribution toward achieving the Office’s near-term and long-term advanced biofuel and bioproduct goals. Understanding the resource potential and the challenges to development and utilization of wet waste feedstocks is critical to their incorporation into the Office’s portfolio of advanced biofuel pathways. Recent workshops have focused on identifying potential entry points for research and development funding to accelerate the commercialization of wet waste technologies. These workshops, along with a systematic resource assessment currently being conducted, will inform the development of a wet waste-to-energy roadmap. Development of this roadmap will include engagement with industry, NGOs, other federal agencies, and DOE national laboratories.

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[2] U.S. Department of Agriculture, U.S. Environmental Protection Agency, U.S. Department of Energy (2014), *Biogas Opportunities Roadmap: Voluntary Actions to Reduce Methane Emissions and Increase Energy Independence*, http://www.usda.gov/oce/reports/energy/Biogas_Opportunities_Roadmap_8-1-14.pdf.

[3] U.S. Department of Agriculture, et al. (2014), *Biogas Opportunities Roadmap*.

Office Program Area Discussion

The remainder of Section 2 details plans for each Office program area:

Each program area discussion is organized as follows:

- Brief overview of the program area process concept and how it interfaces with other program areas of the Office (in the context of the biomass-to-bioenergy supply chain)
- Program area strategic goal, as derived from the Office strategic goals
- Program area performance goals, as derived from the Office performance goals
- Technical and market challenges and barriers
- Strategies for overcoming barriers, the basis for program area work breakdown structures (WBS; tasks and activities with links to barriers)
- Prioritization, milestones, and timelines.

2.1 Feedstock Supply and Logistics Research and Development

The strategic goal of Feedstock Supply and Logistics R&D is to *develop technologies to provide a sustainable, secure, reliable, and affordable biomass feedstock supply for the U.S. bioenergy industry,* in partnership with USDA and other key stakeholders.

Terrestrial plant and aquatic algal biomass is essentially solar energy stored as chemical energy via the biological process of photosynthesis. Biomass is the resource material for producing biofuels, bioproducts, and biopower, and no biomass conversion process can operate without it. Scaling up biomass conversion technologies and successfully maintaining them at industrial scale requires the availability of and access to a reliable supply of affordable, high-quality feedstock(s). Terrestrial feedstock supply and logistics and algae research and development (R&D) relate directly to, and strongly influence, all downstream elements of the biomass-to-bioenergy supply chain, as well as the achievement of overall Office goals and objectives (see Figure 2-4).

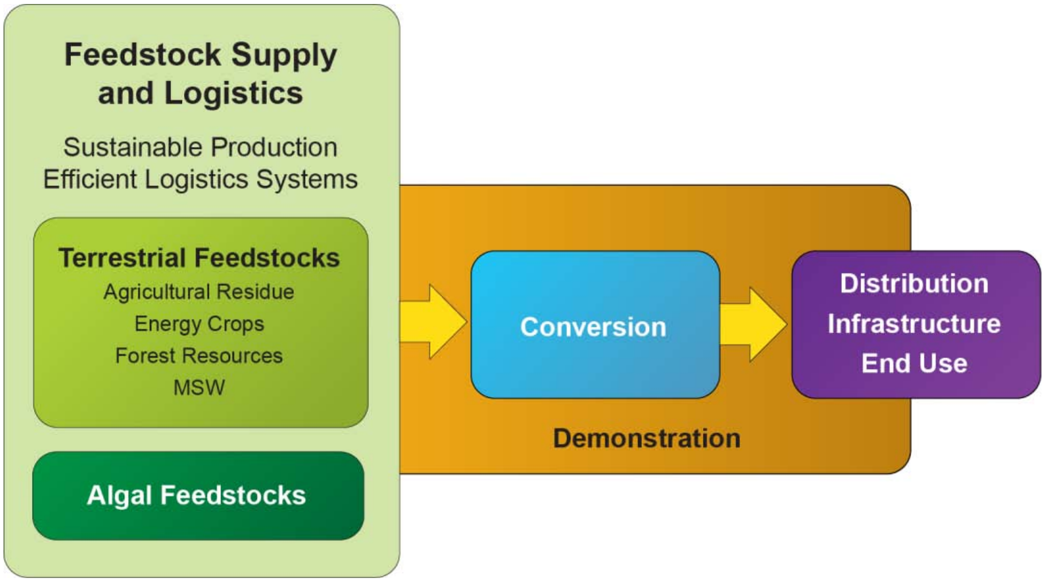

Figure 2-4: Feedstock supply and logistics as the starting point for the bioenergy supply chain

The Office distinguishes “biomass” from “feedstock.” For purposes of this document, “biomass” is defined as the raw, field-run material obtained at the site of production (e.g., field, forest, pond, or landfill). Examples of biomass include corn stover, forest residues, switchgrass, miscanthus, energy cane, sweet sorghum, high biomass sorghum, hybrid poplars, shrub willows, the non-recyclable organic portion of sorted municipal solid waste (MSW), biosolids and sludges, manure slurries, and whole algae. The term “feedstock” is used to denote biomass materials that have undergone one or more preprocessing operations (e.g., drying, grinding, milling or chopping, size fractionation, de-ashing, blending and formulation, densification, and/or extraction) to ensure that the physical and chemical quality characteristics are acceptable for feeding into a biorefinery process that can efficiently convert the feedstock at high yield into biofuels, biopower, and/or bioproducts.

Because of the distinct differences between technologies for agricultural cropping systems and algal production and harvesting and different objectives and challenges, these two areas are organized separately as shown in Fig. 2-4. Terrestrial Feedstock Supply and Logistics R&D—which includes lignocellulosic materials, such as agricultural residues, forest resources, dedicated energy crops[1], and select MSW resources—is detailed in Section 2.1.1. Advanced Algal Systems R&D is described in Section 2.1.2. Wet wastes may emerge as a third feedstock category.

The Office anticipates that USDA will lead the federal government's terrestrial feedstock production R&D, in accordance with the February 3, 2010, White House release of "Growing America's Fuel."[2] However, the Bioenergy Technologies Office continues to lead the federal government's terrestrial feedstock logistics R&D. The Office will coordinate efforts with USDA and other federal offices, to support development of a robust and sustainable domestic bioenergy industry.

The Office plays a leading role in the federal government's algae strain development, as well as algae feedstock production and logistics systems R&D. Algae production systems include open ponds, closed photobioreactors, mixotrophic growth, attached growth, and on- and off-shore macroalgae cultivation.

To stimulate the development and growth of the U.S. bioenergy industry, the Office coordinates feedstock efforts with other DOE offices and federal agencies, including the following:

- DOE—Advanced Research Projects Agency for Energy (ARPA-E); Office of Science via the Joint Genome Institute, as well as its three Bioenergy Science Centers and selected Energy Frontier Science Centers
- USDA—Agricultural and Food Research Institute's Regional Bioenergy Coordinated Agricultural Projects; Agricultural Research Service (ARS) and U.S. Forest Service (USFS) Regional Biomass Research Centers; ARS National Programs #213 ("Biorefining") and #301 ("Plant Genetic Resources, Genomics and Genetic Improvement"), and others
- DOE-USDA—Office of Science and National Institute of Food and Agriculture's joint annual solicitation on feedstock genomics
- Interagency—Biomass Research and Development Board; Biomass Research and Development Initiative (both terrestrial and algal)
- National Science Foundation—Directorate for Engineering, partnership on Interagency Opportunities in Metabolic Engineering
- EPA—Office of Research and Development algae program; Office of Pollution Prevention and Toxics Biotechnology Program (genetically modified organisms)
- U.S. Department of Defense—Defense Production Act.

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[1] Energy crops are produced primarily to be used as feedstocks for biofuel, biopower and/or bioproducts production—as opposed to an agricultural or forest residue, which is produced as a byproduct of another valuable commodity, such as grain or lumber.

[2] White House, *Growing America's Fuel: An Innovation Approach to Achieving the President's Biofuels Target*, http://www.whitehouse.gov/sites/default/files/rss_viewer/growing_americas_fuels.PDF.

Wet Waste-to-Energy Feedstocks

The Office is interested in the emerging area of waste to energy and in the potential of five kinds of wet waste feed streams:

- Commercial, institutional, and residential food wastes, particularly those currently disposed of in landfills
- Biosolids, organic-rich aqueous streams, and sludges from municipal wastewater treatment processes
- Manure slurries from concentrated livestock operations
- Organic wastes from industrial operations, including but not limited to food and beverage manufacturing, biodiesel production and integrated biorefineries as well as potentially other industries such as pulp and paper, forest products, and pharmaceuticals
- Biogas derived from any of the above feedstock streams, including but not limited to landfill gas.

Based on preliminary assessments of resource potential these materials may contribute significantly to bioenergy goals. These potential feedstocks may also prove to be more amenable to conversion processes than raw lignocellulosic materials.

2.1.1 Terrestrial Feedstock Supply and Logistics Research and Development

Feedstocks are essential to achieving Office goals. The volume of acceptable quality feedstocks available and accessible at an affordable price will determine the maximum amount of biofuels that can be produced. The 2011 *U.S. Billion-Ton Update*[3] evaluated a range of biomass supply scenarios at several price points showing the potential biomass resources that could be developed by 2030, leading to a sustainable national supply of more than 1 billion tons of biomass per year.

Terrestrial feedstock supply and logistics (FSL) R&D targets three key elements: (1) reducing the delivered cost of sustainably produced biomass, (2) preserving and improving the quality of harvested biomass to meet the needs of biorefineries and other biomass users, and (3) expanding the volume of feedstock materials accessible to the bioenergy industry. FSL R&D focuses on identifying, developing, demonstrating, and validating efficient and economical systems for harvest and collection, storage, handling, transportation, and preprocessing[4] raw biomass from a variety of herbaceous and woody crops and waste materials. This will enable the reliable delivery of high-quality, affordable feedstocks to an expanding biorefinery industry.

Terrestrial FSL R&D includes two main areas: (1) resource assessment—identifying and quantifying current and future land-based biomass resources and costs associated with their production and harvest, and (2) feedstock logistics—developing and demonstrating integrated and efficient purpose-designed supply systems capable of reliably delivering large volumes of feedstock that meet or exceed the quality specifications required by conversion processes (see Figure 2-5).

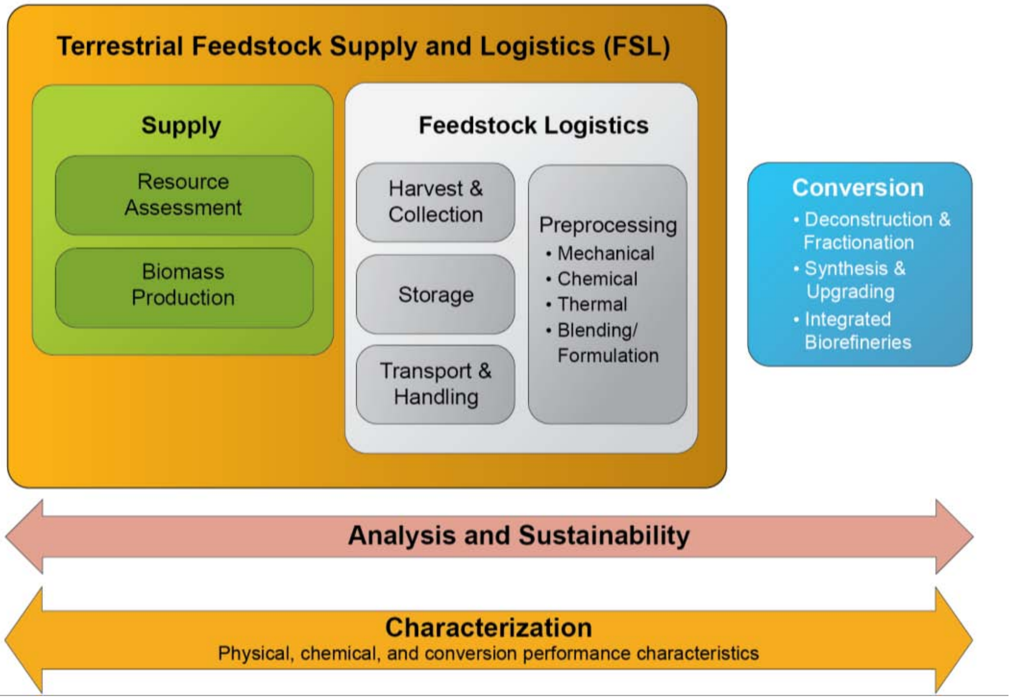

Figure 2-5: Terrestrial feedstock supply and logistics systems diagram

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[3] U.S. Department of Energy (2011), *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*.

[4] Note that some preprocessing research is detailed in the sections describing conversion programs, while other research is detailed under the feedstock logistics portfolio.

Sustainability and Strategic Analysis span both resource assessment and logistics activities. Sustainability activities and principles, including continuous improvement and minimization of inputs such as water and soil conservation, as well as Strategic Analysis activities, incorporate both production and logistics data (see Section 2.4).

Supply: Supply includes assessing the potential availability and quality characteristics of a variety of biomass resources, as well as assessing the production of biomass to demonstrate crop performance and estimate production costs under a variety of real-world conditions.

> **Resource Assessment** involves estimating current and future domestic biomass resources by type and their county level geographic distribution at different price points. It also includes understanding quality attributes (e.g., moisture, ash, and carbon content) associated with those resources as a function of geography and price, and understanding the environmental sustainability constraints associated with accessing those biomass resources over time.
>
> **Biomass Production** involves all of the operations, associated costs, and sustainability issues related to site preparation, crop establishment, growth, and maintenance of terrestrial biomass crops. The Office partners with USDA in these efforts.
>
> **Biomass Characterization** focuses on understanding the extent and causes of diversity in biomass and feedstock quality characteristics, and on identifying those characteristics that can significantly impact conversion process yield, kinetics, and profitability, as well as logistics operations. Characterization involves analysis of samples of raw biomass, preprocessed feedstock materials, and conversion process intermediates to measure a wide range of physical and chemical parameters, and the relationships of those parameters to conversion process performance. Such characterization helps identify key feedstock quality variables and quantify their impact on overall biofuel product yield and cost. This also includes the development and implementation of efficient, reliable, and affordable wet chemical and calibrated rapid analytical methods to measure biomass quality characteristics for woody and herbaceous biomass, relevant MSW fractions and process intermediates. Characterization research includes collaboration with the Conversion R&D (see Section 2.2) program area.

Feedstock Logistics: Feedstock logistics refers to all of the operations that occur after the biomass is produced and is standing in a field or forest ready for harvest and before it is introduced into the conversion process in-feed system (also referred to as the "reactor throat").

> **Harvest and Collection** involves the cost-effective and sustainable removal of raw biomass from the field or forest. These operations play a critical role in expanding the amount of biomass resources accessible to the bioenergy feedstock supply system. The harvest window for different crops varies with the growth cycle of the crop, and harvest timing may be constrained by the growing season of a primary crop (e.g., grain), as well as by weather conditions during the harvest window. Harvest timing and strategy may affect the resulting herbaceous and woody biomass quality parameters, such as chemical composition and structural features. Collection format (e.g., bales, loose chop, round wood, chips, etc.) can impact the efficiency and cost associated with downstream handling, storage, and transportation.

Storage includes methods and practices to cost-effectively store and preserve the quantity and quality of seasonally available herbaceous and woody biomass until required for processing. Preserving feedstock quality requires managing moisture content, minimizing degradation and material loss, and preventing undesirable changes in quality characteristics. This includes inventory management to monitor and maintain biomass and feedstock quality over longer storage times, while minimizing losses from handling and microbial degradation; and developing strategies to minimize fire risk from spontaneous combustion, lightning strikes, and human causes.

Preprocessing operations transform raw, field-run biomass into stable, standardized format feedstocks with physical and chemical characteristics that meet the required quality specifications of conversion facilities and that can be moved with existing, high-volume transportation and handling systems. Preprocessing operations such as drying and densification, stabilize biomass for longer-term storage and improve durability and performance in handling, transport, and conversion. Preprocessing operations, such as blending and formulation, can reduce the physical and chemical variability of raw biomass for more reliable, predictable, and efficient performance in downstream conversion.

Preprocessing includes mechanical, thermal, and chemical treatments, any or all of which could be applied at various points in the logistics chain. The most efficient and cost effective set of feedstock supply chain operations may vary with circumstances.

Mechanical preprocessing includes the following:

- Size reduction and separation based on particle size or density, and fractional deconstruction to reduce particle size of the raw biomass to achieve desired physical and/or chemical characteristics.
- Densification processes, such as pelletization, increase the bulk and energy density of raw biomass, improve stability during storage and handling, create flowable feedstocks that are compatible with existing handling systems, and improve transport efficiency and cost. Although baling is a densification process, it is considered part of harvest and collection.
- Formulation and blending involves mixing two or more biomass materials to produce a feedstock with preferred qualities and cost. It can mitigate the inherent variability of raw biomass to produce feedstocks with more consistent physical and chemical characteristics, reduce conversion performance variability, and/or reduce operating costs associated with feedstocks. By combining various biomass resources with different chemical, physical, and cost characteristics, feedstock quality and performance can be adjusted to required conversion process specifications and improve overall process economics. Blending and aggregating are examples of formulation processes. Including lower-quality or small-volume biomass materials as components of a blend or formulation can reduce the overall cost or adjust the physical or chemical characteristics of the blend. This strategy can also expand the volume of biomass available

to biorefineries to mitigate feedstock supply risk and improve overall process economics.

Thermal preprocessing, such as drying and torrefaction, reduces moisture content and increases the energy density of the material to improve stability during storage, transport efficiency and cost, and may improve conversion performance.

Chemical preprocessing upgrades biomass quality by reducing ash content, which can improve conversion process performance. Examples of chemical preprocessing include leaching or washing, treatment at basic pH, and dilute-acid treatment. Additional information on chemical preprocessing technologies can be found in the Conversion R&D section (Section 2.2).

Handling low-density, non-uniform raw biomass in existing high-volume, high-throughput materials handling systems presents many challenges. Improving handling characteristics early in the supply chain by processing raw biomass into formats compatible with existing high-capacity bulk handling and transportation infrastructures, such as those designed for the grain industry, may reduce delivered feedstock cost. Feedstock handling also involves minimizing fire risk during conveyance operations, where friction from the many moving parts can cause sufficient heating to ignite the flammable biomass.

Transport involves moving raw biomass from the field or forest to the preprocessing site *and* delivering preprocessed feedstocks to the throat of the conversion reactor. Biomass and feedstocks may be transported by truck, train, or barge using existing transportation infrastructure.

Connecting the Nation's Diverse Biomass Resource to the Bioenergy Industry

Sustainably supplying the required volumes of quality, affordable feedstock to the emerging biorefining industry as it grows and matures will be achieved through a transition from logistics systems that have been designed to meet the needs of conventional agriculture and forestry systems (conventional logistics systems) to more advanced, purpose-designed, economically advantaged systems (advanced logistics systems).

Conventional Logistics Systems have been developed for traditional agriculture and forestry systems and are designed to move biomass short distances for limited-time storage (i.e., less than one year). Conventional systems do not address the physical and chemical variability of biomass and are not designed to capture the full volume of diverse, nationally distributed U.S. biomass resource potential. Conventional systems tend to constrain biorefinery locations to areas where sufficient supplies of biomass exist within a relatively short distance, which limits the scale-up potential of a biorefinery and exposes the biorefinery and its investors to risk from potential local feedstock supply disruptions.

Advanced Logistics Systems are specifically designed to (1) sustainably harvest and collect the highest possible quality biomass from the field or forest, and (2) deliver infrastructure-compatible feedstocks that have predictable physical and chemical characteristics, stability during storage, and high-capacity bulk material handling characteristics. These infrastructure-compatible feedstocks can be economically transported over longer distances and can also be introduced directly into the conversion process with minimal additional processing. Advanced logistics systems deliver feedstocks with the properties needed for the development of a commodity-based, specification-driven supply system analogous to U.S. grain and coal commodity systems. Logistics systems designed for the purpose of bioenergy production will eliminate inefficiencies and reduce costs relative to conventional harvest and delivery systems. Affordable, reliable rapid analytical methods will also be developed to measure important feedstock quality characteristics at appropriate points in the supply chain.

Figure 2-6 shows a high-level depiction of how an advanced logistics system could draw in presently inaccessible resources via local preprocessing depots that transform biomass into a stable, bulk, densified, and flowable feedstock. The formatted feedstock is transported into a network of supply terminals, where material aggregated from a number of depots can be blended or further preprocessed to meet biorefinery specifications. A variety of feedstock preprocessing activities can be conducted at the depots for a particular market, thereby allowing multiple products to be created at the depot for multiple markets other than just biofuel (e.g., animal feed, biopower). This multiple market capability will help to minimize the financial risk to the depot operator.

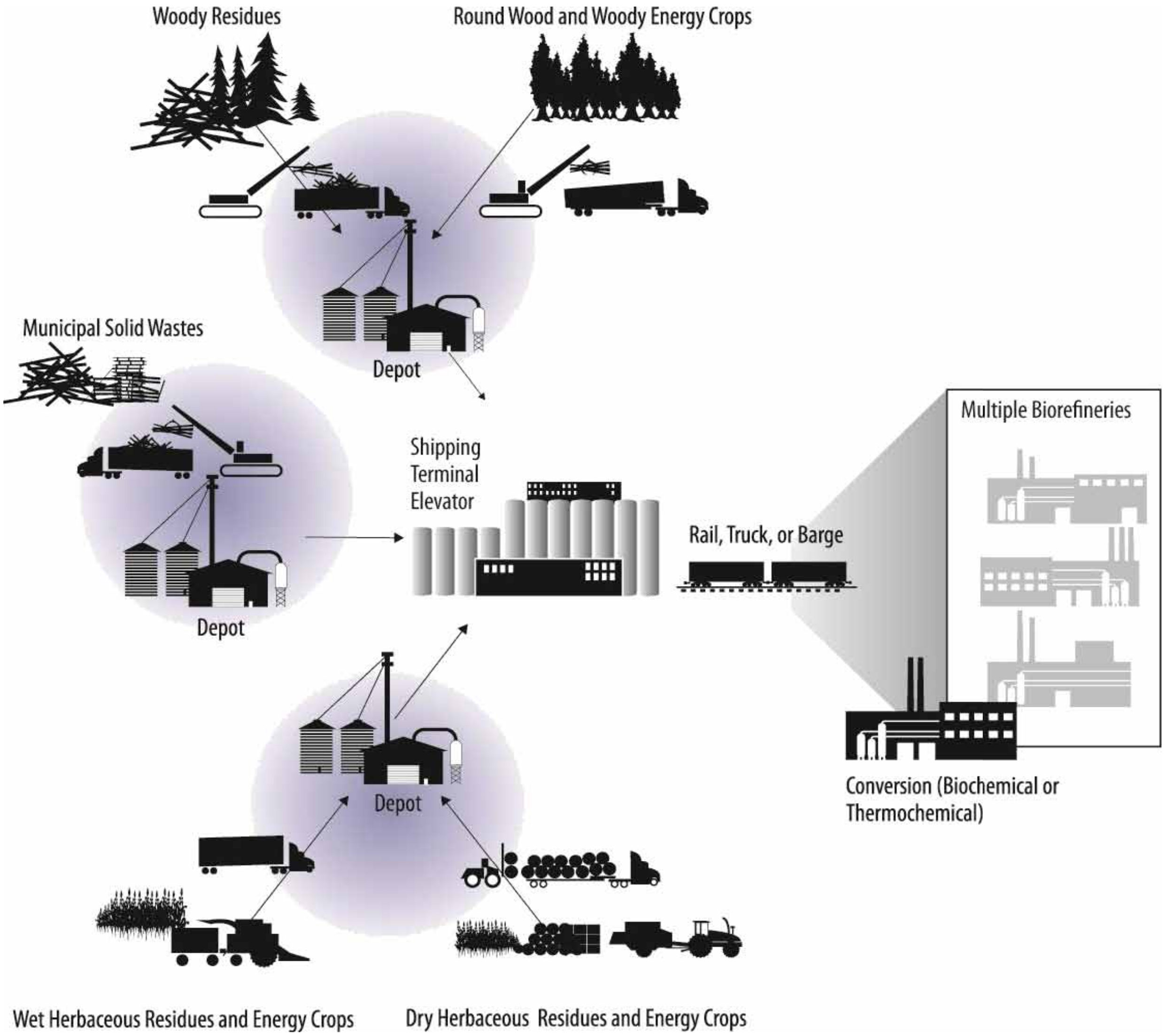

Figure 2-6: The Advanced Feedstock Supply System (“Depot”) Concept

2.1.1.1 Terrestrial Feedstock Supply and Logistics Research and Development Support of Office Strategic Goals

The strategic goal of Terrestrial FSL R&D is to *develop technologies to enable a sustainable, secure, reliable, affordable supply of acceptable-quality terrestrial feedstock for the U.S. bioenergy industry,* in partnership with USDA and other key stakeholders. This goal supports the long-term (beyond 2040) goal to develop technologies and methods that could sustainably supply more than 1 billion dry tons of biomass per year.

The Terrestrial FSL R&D program area directly addresses and supports resource assessment, sustainable crop production, biomass characterization, harvest, collection, storage, preprocessing, and delivery of feedstock for all potential biomass conversion pathways.

2.1.1.2 Terrestrial Feedstock Supply and Logistics Research and Development Support of Office Performance Goals

The performance goals for Terrestrial FSL R&D are as follows:

- By 2017, validate efficient, low-cost, and sustainable feedstock supply and logistics systems that can deliver feedstock to the conversion reactor throat at required conversion process in-feed specifications, at or below $84 dry ton (2014$) (including grower payment/stumpage fee[5] and all logistics costs).
- By 2017, establish geographic, economic, quality, and environmental criteria under which the biorefining industry could operate at 245 million dry tons per year scale (excluding biopower).[6]
- By 2022, develop and validate feedstock supply and logistics systems that can economically and sustainably supply 285 million dry tons per year (excluding biopower) at a delivered cost of $84 dry ton (2014$) to support a biorefining industry utilizing a diversity of biomass resources.

Terrestrial FSL R&D has several milestones charting the path to 2017 and 2022. These milestones are grouped into two categories: (1) supply and (2) logistics.

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[5] Grower payments are those made to feedstock producers over and above the costs incurred for harvest, collection, storage, preprocessing, and transport. For crop residues, the grower payment covers the environmental value of the residue removed (e.g., nutrients and organic matter), as well as profit. For woody residues, these payments cover the value of the residue. For dedicated energy crops, grower payments cover pre-harvest machine costs, variable inputs such as fertilizers and seed, and amortized establishment costs for perennial crops, which do not typically reach mature yields until the third growing season. The payments must also reflect what profit the land could produce if planted with other crops. Other factors also affecting grower payments include profits to growers for investment returns and risk taking, alternative financial arrangements (e.g., cooperatives), fixed pricing mechanisms, shared-equity arrangements between growers and processors, and other competitive uses. Note that the grower payment listed is the maximum amount required to acquire the specified volume of biomass (i.e., there are biomass resources available for a lower cost; however, none of the resources required would cost more). For a more extensive list of feedstocks and their associated grower payment, see the Bioenergy Knowledge Discovery Framework at www.bioenergykdf.net.

[6] Table A-1 in Appendix A.

Supply

- By 2016, produce an updated, fully integrated assessment of potentially available feedstock supplies under previously established environmental and quality criteria.
- By 2017, establish available resource volumes for non-woody MSW and algal feedstocks at $84/dry ton delivered cost (2014$; including grower payment/stumpage fee and logistics cost). (Note that woody MSW is currently incorporated into resource assessments.)
- By 2017, determine the impact of competing uses, policy and market demands (e.g., biopower, pellet exports) on feedstock supply and price projections.
- By 2018, establish nationwide sub-county-level environmental impact criteria and logistics strategies for all potential energy crops, including agricultural and forestry residues, annual and perennial herbaceous energy crops, and short rotation woody energy crops.
- By 2019, validate a framework for biomass quality grading systems for at least one woody and one herbaceous biomass supply-shed associated with an existing or planned demonstration-scale (or larger) biorefinery.
- By 2020, determine the impact of advanced blending and formulation concepts on available volumes that meet quality and environmental criteria, while also meeting the $84/dry ton delivered cost target (2014$; including grower payment/stumpage fee and logistics cost).

Logistics

- By 2017, validate an average annual sustainable delivered feedstock cost of $84/dry ton at conversion reactor throat (including grower payment and logistics cost) at a scale of 1 ton per day for at least one biochemical conversion process and one thermochemical conversion process.
- By 2022, validate one blendstock for thermochemical conversion and one blendstock for biochemical conversion at a scale of 1 ton per day, while also meeting the $84/dry ton delivered cost target (2014$; including grower payment/stumpage fee and logistics cost).

2.1.1.3 Terrestrial Feedstock Supply and Logistics Research and Development Technical Challenges and Barriers

Supply

Ft-A. Terrestrial Feedstock Availability and Cost: Reliable, consistent, and affordable feedstock supply is needed to reduce financial, technical, and operational risk to biorefineries and their financial partners. Reaching federally mandated national volumes of biofuels will require large amounts of sustainably available, quality-controlled biomass to enter the market at affordable prices. Purpose-designed, advanced logistics systems are required to expand the amount of biomass that can be cost-effectively delivered to biorefineries, and maximize the amount of biomass that can cost-effectively enter the system. Also, advanced feedstock supply systems are needed to address feedstock quality by actively minimizing the amount of soil contamination (i.e., extrinsic ash content) collected with the biomass.

Credible data and projections on current and future cost, location, environmental sustainability, quality, and quantity of available biomass are needed to reduce uncertainty for investors and developers of emerging biorefinery technologies. A better understanding of advances in genetics, production technologies, and supply chain strategies are needed to develop more accurate estimates of future biomass availability, cost, and quality.

Ft-B. Production: While the production systems and performance of traditional row crop species over multiple decades are well documented, and historical trends for yield increases permit a well-founded justification for extrapolating future yield increases, this is not true for less well characterized energy crop species. The range of real world, production-scale yields across genetics, environments, and agronomic practices and the magnitude of recent improvements in energy crop yields (e.g., switchgrass, energy cane, sorghum, poplar, willow) require validation to inform ongoing resource assessment efforts. Reliable production data, especially for energy crop species, are needed over several growing seasons and across many environments to make well-substantiated resource projections. The rate of change of yield increases in these species is also not yet well understood, which further compromises the reliability of resource projections. Comprehensive data from real world production operations are also needed not only to measure the environmental effects of energy crop production and biomass collection systems but also for complete life-cycle analysis of biorefinery systems and to address sustainability questions such as water and fertilizer inputs, soil carbon sequestration, greenhouse gas emission reductions, and establishment and harvesting impacts on soil quality and conservation. Gaps in production and sustainability data for conventional crop residues also still exist. BETO will leverage its relationships with USDA and USFS and mine the scientific literature to access the required data.

Ft-C. Terrestrial Feedstock Genetics and Variety Improvement: The productivity and robustness of terrestrial feedstock crops used for biofuel production could be significantly increased by developing improved energy crop varieties using traditional breeding and selection, and modern genetic technologies, such as marker-assisted breeding and transgenics. The importance of new energy crop varieties with increased yield and higher tolerance to a variety of biotic and abiotic stresses is critical to realizing mandated biofuel goals. Increased biomass yield per acre is needed to reduce the footprint of energy crops on the landscape to produce a given amount of biofuel and also reduce the average delivered cost per ton of feedstock from increased logistics operations efficiencies. Decreased production risk associated with more stress tolerant varieties is needed to encourage farmers, biorefineries, and financial institutions to seriously consider energy crops in the mix of crops they produce.

Feedstock Logistics

Ft-D. Sustainable Harvesting: Current crop harvesting machinery is unable to selectively harvest preferred components of cellulosic biomass (e.g., stems vs. leaves) while maintaining acceptable levels of soil carbon and minimizing soil compaction and erosion. Actively managing biomass variability and contamination of harvested biomass by soil in the field imposes additional functional requirements on biomass harvesting equipment that typically do not exist in conventional systems. With few exceptions, current systems cannot routinely meet the capacity, efficiency, quality or delivered price requirements of large cellulosic biorefineries. The availability of purpose-designed harvest, collection and transport systems is critical to reducing logistics costs to a minimum.

Ft-E. Terrestrial Feedstock Quality, Monitoring and Impact on Conversion Performance: A better understanding is needed of the physical, chemical, microbiological, and post-harvest physiological variations in biomass that arise from differences in genetics, relative crop maturity, agronomic practices and harvest methods employed, soil type, geographical location, and climatic patterns and events. This variability—some of which is avoidable and some of which is not—presents significant cost and performance risks for bioenergy systems. Currently, processing standards and specifications for cellulosic feedstocks are not as well developed as for mature commodities, and may vary from one conversion process to another. Available data and information are extremely limited on the physical and chemical quality characteristics of biomass, particularly in relation to their effect on conversion performance. Methods and instrumentation also are lacking for quickly, accurately, and economically measuring chemical, physical, and mechanical properties of biomass.

A better understanding is needed regarding the inherent variability in biomass physical and chemical quality parameters and cost between different species, within a species, and even between tissues of the same individual plant. Acceptable ranges of quality parameters for different conversion processes are poorly understood, and few genetic or preprocessing strategies have been developed to limit or control variability in biomass quality. Because many quality factors vary independently, it is not clear what fraction of available biomass materials will actually be able to meet in-feed specifications for the various conversion processes being developed and commercialized.

Knowledge about important feedstock quality characteristics and their effect on conversion process performance could provide the basis for establishing different quality grades of feedstock materials for the industry.

Ft-F. Biomass Storage Systems: Biomass that is stored with high moisture content or exposed to moisture during storage is susceptible to spoilage, rotting, spontaneous combustion, and odor problems under aerobic conditions. The impacts of these post-harvest biological processes must be controlled to ensure a consistent, high-quality feedstock supply, and managing moisture is key. Characterization and analysis of different storage methods and strategies are needed to better define preferred, affordable storage methodologies to preserve the volume and quality of harvested biomass over time and maintain or enhance its conversion performance.

Ft-G. Biomass Physical State Alteration: The initial sizing and grinding of cellulosic biomass affects conversion efficiencies and yields of all downstream operations, yet little information exists on how specific differences in these operations on each type of cellulosic biomass impact conversion cost and yields. New technologies and equipment are required to economically process biomass to meet biorefinery specifications, such as particle-size range and distribution.

Ft-H. Biomass Material Handling and Transportation: Raw herbaceous biomass is especially costly to handle, transport and convey because of its very low bulk density and fibrous nature. Conventional bale-based handling equipment and facilities cannot cost-effectively deliver and store high volumes of biomass, even with improved handling techniques. Current handling and transportation systems designed for moving woodchips (typically around 50% moisture content) can be inefficient for bioenergy processes due to the costs and challenges of transporting, storing, and drying high-moisture biomass.

Ft-I. Overall Integration and Scale-Up: Conventional supply systems used to harvest, collect, store, preprocess, handle, and transport biomass are not designed for the large-scale needs of a nationwide system of integrated biorefineries. The system needs to be dynamic and responsive to shortages and surpluses throughout the system in order to stay in balance and keep biofuel productivity at expected levels. The infrastructure for feedstock logistics has not been defined for the potential variety of locations, climates, feedstocks, storage methods, processing alternatives, etc., that will need to be implemented at a national scale. Integration of one or more aspects of the feedstock supply system—either alone or in combination with biorefinery operations—should lead to net gains in efficiency; however, the lack of analysis quantifying the relative benefits and drawbacks of potential integration options is a barrier to realization of cost savings, biorefinery efficiency improvement, and reduction of technical and financial risk.

2.1.1.4 Terrestrial Feedstock Supply and Logistics Research and Development Approach for Overcoming Challenges and Barriers

The Terrestrial FSL R&D approach for overcoming feedstock supply and logistics challenges and barriers is outlined in the work breakdown structure (WBS) as shown in Figure 2-7 and summarized in Table 2-1. It is organized around the following key activities: Analysis and Sustainability, Terrestrial Biomass Production and Characterization, Terrestrial Feedstock Logistics, Feedstock-Conversion Interface, and Feedstock-Demonstration Interface. Office-funded terrestrial FSL R&D activities are performed by national laboratories, universities, industry, consortia, and a variety of state and regional partners.

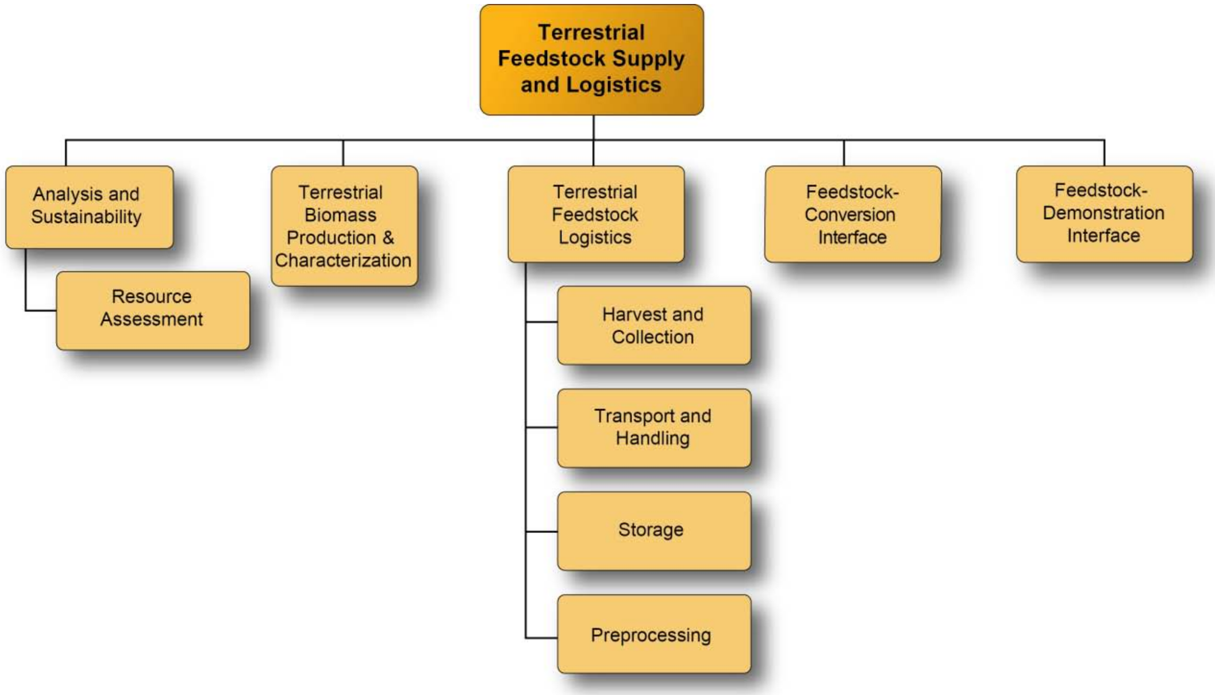

Figure 2-7: Terrestrial feedstock R&D work breakdown structure

The R&D approach of each WBS activity is described below:

Analysis and Sustainability

Primary areas of work within Analysis and Sustainability include resource assessment, system cost analyses, and risk assessment. Resource assessment provides critical data for establishing and measuring progress toward Office goals by forecasting the type and volume of biomass available over time in each county in the United States, and at what price. Location and yield of biomass, as well as price, are necessary for estimating total delivered feedstock cost. Resource assessment includes establishing a national inventory of biomass resource potential and assessing current and future environmentally sustainable biomass availability under conservative and optimistic crop yield improvement scenarios over time. County-level terrestrial biomass supply curves[7] were first published in a 2011 resource assessment study.[8] These supply curves are updated on an annual basis to reflect current supply demands, technology improvements, and evolving market conditions that underlie each reported feedstock. A completely revised and updated resource assessment study is planned for release in 2016. This information will be accessible to the public and maintained in the Bioenergy KDF, as discussed in Section 2.4.2.4.[9]

Analysis also includes developing and refining techno-economic assessments (TEAs) of feedstock supply systems to help set goals and targets, as well as tracking R&D progress through annual state-of-technology (SOT) assessments of feedstock supply systems across specific feedstock/conversion technology pathway combinations. Setting TEA targets requires working closely with researchers who are developing thermochemical and biochemical conversion processes to ensure that the delivered feedstock meets the conversion process material in-feed requirements, as well as tracking conversion and environmental performance. These activities also include risk assessments (strategic, economic, and operational risk) and incorporating those assessments into TEAs/LCA.

Terrestrial Biomass Production and Characterization

An important focus of feedstock production going forward is to understand the extent and causes of variability in the quality characteristics of the full range of energy crop species. Based on an understanding of the causes of variability, approaches can be developed to cost-effectively manage those characteristics in the field or during preprocessing operations. Sampling and characterizing a large feedstock supply-shed in a specific geographic area should generate a representative dataset that includes a cross-section of the crop genetics, current agronomic practices, soil types, weather patterns, etc. Based on this data, feedstock quality variation can be correlated with potential causes. This sampling and characterization work will focus first on a few biorefineries that are actively aggregating corn stover for use in their conversion processes.

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[7] Modeling is based on county-level data provided by the USDA National Agricultural Statistics Service among other sources, hence outputs are provided at the county level. See De la Torre Ugarte and Ray (2000) for application of POLYSYS to biomass feedstocks.

[8] U.S. Department of Energy (2011), *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*.

[9] Bioenergy Knowledge Discovery Framework, U.S. Department of Energy and Oak Ridge National Laboratory, http://www.bioenergykdf.net.

If these initial data collection efforts bring value to the biorefinery and yield useful information, the approach will be extended to other types of biomass.

Specific ongoing activities include collecting, organizing, and archiving raw biomass samples; assessing chemical and physical properties (including after preprocessing operations); preparing feedstock materials for testing of conversion processes; compiling the resulting data into the Biomass R&D Library; and correlating those data sets to understand causal relationships among quality characteristics and conversion performance parameters. The Biomass R&D Library, which is an element of the Biomass Feedstock National User Facility (BFNUF), includes three elements: (1) physical sample cataloguing and archiving, (2) characterization of physical and chemical attributes of collected biomass samples, and (3) a database in which all the characteristics of these samples are stored and made available to the research community and public. The Biomass R&D Library database includes information on sample origin and treatments, related publications, and all data related to each raw or preprocessed biomass sample, enabling all subsequent analyses conducted on that sample to be linked to its source. Library data enables improved understanding of the impact of feedstock variability on conversion process performance characteristics and biofuels production cost.

The Office continues to actively engage with USDA, DOE's Office of Science, and ARPA-E sponsored terrestrial crop variety improvement, crop genetics, genomics, and genetic engineering efforts. The Office also monitors the development of best management practices for energy cropping systems with USDA and with DOE's Office of Science and ARPA-E to ensure their production efforts support the attainment of Office and national goals.

Terrestrial Feedstock Logistics

Near-term Feedstock Logistics R&D continues to focus on reducing conventional system costs, while developing and demonstrating strategies for increasing the volumes of feedstock that can meet quality and affordability criteria for a variety of biomass conversion processes.

Mid-term R&D work focuses on meeting the cost, quality, and volume requirements associated with a growing biorefinery industry by developing and demonstrating strategies, technologies and machinery that address the limitations of conventional feedstock logistics technologies. This work will involve designing, constructing, demonstrating, and validating purpose-designed, field-scale equipment that (1) eliminates steps in the conventional process (e.g., single-pass harvesting eliminates a separate windrowing operation), (2) increases operational efficiencies and capacity, (3) implements in-field strategies to minimize contamination of harvested biomass by soil, (4) employs preprocessing strategies capable of upgrading the quality and reducing the variability of harvested biomass, (5) increases the amount of resources available for bioenergy production, and ultimately, (6) reduces overall logistics costs. In addition, rapid analytical methods capable of accurately assessing important quality parameters of biomass at critical points in the feedstock supply chain will be developed and validated. The need for purpose-designed equipment to supply the bioenergy industry will stimulate the U.S. farm and forestry manufacturing sector and create jobs in urban and rural communities across the country.

Longer-term R&D efforts focus on developing advanced preprocessing strategies and technologies that upgrade raw biomass into high-quality, infrastructure-compatible commodity feedstocks, while meeting conversion process in-feed specifications and balancing delivered feedstock costs against conversion performance characteristics to optimize overall process economics.

Feedstock-Conversion Interface

Effective communication between terrestrial FSL and conversion process researchers regarding conversion performance as a function of feedstock quality parameters and preprocessing operations is critical to developing an economically viable value chain. Feedstock-conversion interface efforts focus on correlating conversion performance characteristics (e.g., product yield, process kinetic parameters) with the physical and chemical characteristics of the feedstock and the preprocessing operating conditions to define ranges of acceptable/desirable conversion process input specifications to achieve techno-economic targets. This effort, therefore, develops and produces a variety of preprocessed feedstocks for testing in bench-scale reactors for different conversion pathways. As required, larger quantities of a specific feedstock that meets conversion performance specifications can be prepared for scaled-up testing of conversion process performance.

Feedstock-Demonstration Interface

Feedstock-Demonstration Interface activities extend development of the advanced preprocessing strategy system outlined above to address feedstock supply and logistics systems at scales to meet the needs of integrated biorefinery operations. These efforts include the design, operation, and validation of advanced preprocessing technologies and integrated supply chain components at pilot and demonstration scale.

Table 2-1: Terrestrial Feedstock R&D Activity Summary

WBS Element	Description	Barrier(s) Addressed
Analysis and Sustainability	- Resource assessment with projections of current and future potential domestic biomass resources by type and their geographic distribution at different price points; the quality attributes (e.g., moisture, ash, and carbon content) associated with those resources as a function of geography and price; and the environmental sustainability constraints associated with accessing those biomass resources over time.	Ft-A: Terrestrial Feedstock Availability and Cost Ft-B: Production Ft-C: Terrestrial Feedstock Genetics and Variety Improvement Ft-D: Sustainable Harvesting Ft-E: Terrestrial Feedstock Quality, Monitoring and Impact on Conversion Performance Ft-F: Biomass Storage Systems Ft-G: Biomass Physical State Alteration; Ft-H: Biomass Material Handling and Transportation Ft-I: Overall Integration and Scale-Up Ct-A: Feedstock Variability Ct-J: Process Integration Mm-A: Lack of Understanding of Environmental/Energy Tradeoffs Im-A: Inadequate Supply Chain Infrastructure Im-B: High Risk of Large Capital Investments Im-D: Cost of Production St-C: Sustainability Data across the Supply Chain St-E: Best Practices and Systems for Sustainable Bioenergy Production St-F: Systems Approach to Bioenergy Sustainability At-A: Transparent, and Reproducible Analyses At-B: Analytical Tools and Capabilities for System-Level Analysis At-C : Data Availability across the Supply Chain.
Production and Characterization	- Identify critical aspects of biomass and feedstock quality (feedstock characterization), including physical and chemical, characteristics, which can significantly impact downstream operations, including conversion process product yield and kinetics and process economics.	Ft-E: Terrestrial Feedstock Quality, Monitoring and Impact on Conversion Performance Ct-A: Feedstock Variability.
Logistics	- Identify the factors and their costs within each unit operation following harvest (drying, milling, densification, blending, etc.) that transforms the collected biomass into an acceptable feedstock for conversion. - Develop, test, and demonstrate sustainable cellulosic feedstock logistics systems. Physiochemical characterization of the biomass before and after preprocessing used to assess the magnitude of the preprocessing benefit.	Ft-A: Terrestrial Feedstock Availability and Cost Ft-B: Production Ft-E: Terrestrial Feedstock Quality, Monitoring and Impact on Conversion Performance Ft-F: Biomass Storage Systems Ft-G: Biomass Physical State Alteration Ft-H: Biomass Material Handling and Transportation Ft-I: Overall Integration and Scale-Up Ct-A: Feedstock Variability.
Feedstock-Conversion Interface	- Identify key feedstock-based characteristics that affect conversion process yields and economics in collaboration with conversion research efforts.	Ft-A: Terrestrial Feedstock Availability and Cost Ft-C: Terrestrial Feedstock Genetics and Variety Improvement Ft-G: Biomass Physical State Alteration Ft-I: Overall Integration and Scale-Up Ct-A: Feedstock Variability Ct-J: Process Integration.
Feedstock-Demonstration Interface	- Systems-level validation of all key technologies to utilize biomass feedstocks in biorefineries.	Ft-A: Terrestrial Feedstock Availability and Cost Ft-I: Overall Integration and Scale-Up Ct-A: Feedstock Variability Ct-J: Process Integration Im-A: Inadequate Supply Chain Infrastructure.

2.1.1.5 Prioritizing Terrestrial Feedstock Supply and Logistics Research and Development Barriers

To achieve the Terrestrial FSL R&D goal of developing sustainable technologies that provide a secure, reliable, and affordable feedstock supply for the U.S. bioenergy industry, the challenges and barriers identified need to be prioritized and addressed as funding permits. However, the following issues are considered most critical and will be emphasized within the program area's efforts:

- Increase the volume of sustainable, acceptable-quality, cost-effective feedstock available to biorefineries by developing advanced feedstock supply systems and strategies.
- Incorporate sustainability and feedstock supply risk into the resource assessments.
- Work with the Conversion program area to understand the range of acceptable physical and chemical in-feed specifications for the various conversion technologies. This information will help to refine the quality specifications Terrestrial FSL needs to better focus its R&D goals and objectives.
- Develop high-capacity, high-efficiency, low-cost, pilot- or demonstration-scale feedstock supply and logistics systems that deliver stable, dense, flowable, consistent-quality, infrastructure-compatible feedstock.

In the past, Office-funded Terrestrial FSL research focused on modifying conventional terrestrial feedstock logistics systems that were designed and manufactured for traditional agricultural and forestry industries. Conventional systems are suitable for high biomass-yielding regions, but not for medium-to-low-yield areas, or for most dedicated energy crops. More recent efforts have focused on the development and demonstration of purpose-designed harvest, collection, and delivery systems. Purpose-designed systems are more efficient because they reduce the number of machine operations and labor required to accomplish the job, which serves to lower the cost of logistics operations and expand the economically viable harvest area. Supplying feedstock to a growing bioenergy industry requires increasing the accessible volumes of affordable lignocellulosic feedstock, while increasing the emphasis on quality, as well as reducing variability and risk. One approach to achieving this is to apply preprocessing techniques, such as blending.[10]

Quality targets have large impacts on whether or not a particular feedstock is cost effective in the context of a particular conversion process, as well as how much material is available for conversion. As an example, the observed variability of one aspect of biomass quality, namely ash, for Midwestern corn stover is illustrated in Figure 2-8.[11]

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[10] Kenney et al. (2013), *Feedstock Supply System Design and Economics for Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Conversion Pathway: Biological Conversion of Sugars to Hydrocarbons The 2017 Design Case*, INL/EXT-13-30342, http://www.osti.gov/scitech/biblio/1130548.

[11] For a more in-depth discussion of biomass variability, see K. Kenney, W. Smith, G. Gresham, T. Westover (2013), "Understanding Biomass Feedstock Variability," *Biofuels* 4(1), http://www.tandfonline.com/doi/abs/10.4155/bfs.12.83#.VQiJzo7F--1.

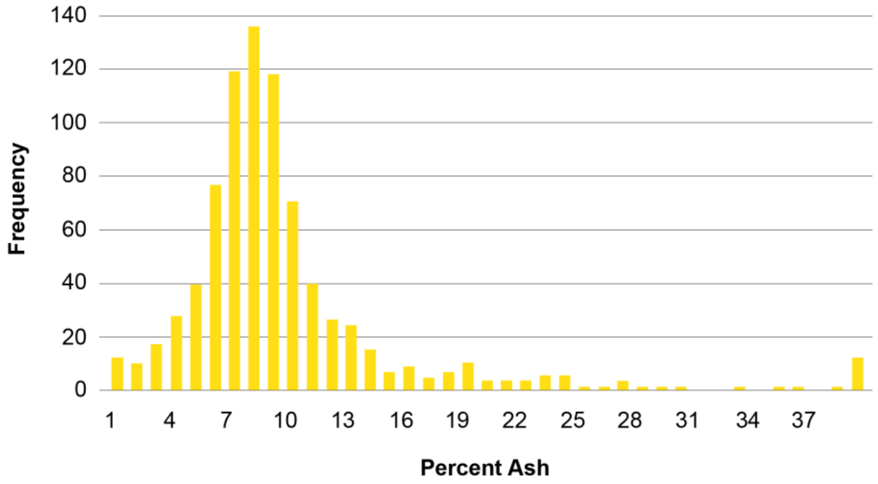

Figure 2-8: The variability of percent total ash content in corn stover, wheat straw, and miscanthus[12]

Ash is the inorganic or mineral content of biomass, and it varies considerably among and within biomass materials. Understanding biomass ash content, variability, and where it originates requires differentiation of the sources of ash, which include structural ash associated with the plant cell walls, vascular ash in the plant, and introduced ash resulting from soil contamination. Ash cannot be converted to a biofuel product and causes operational problems in downstream conversion processes, including increased equipment wear, quenching of catalysts, increased corrosivity and instability of pyrolysis oils, slagging and fouling in thermochemical equipment, and costs associated with ash disposal. Also, the proportion of convertible biomass content decreases with increasing ash content, effectively increasing the cost per dry ton of feedstocks. Even though it seems unlikely that any single conversion technology will be truly "feedstock agnostic," the known variability of biomass quality suggests a need to emphasize development of more robust biomass conversion technologies.

By combining analyses using biomass price projections with quality information obtained from the Biomass R&D Library, gains in the projected volumes available at cost and biorefinery specifications can be realized by transitioning to a blended feedstock approach. Figure 2-9—projected supply curves for terrestrial biomass in 2022—shows a step-wise supply curve that indicates increased cellulosic feedstock supplies in the market with increasing farm gate prices between $20 and $200 per dry ton, marginal price, and average price[13] (white line).

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[12] Data were extracted from the Biomass R&D Library. The data set includes 840 samples, including corn stover, miscanthus, and wheat straw.

[13] For the purpose of this figure, farmgate price is defined as the price needed for biomass producers to supply biomass to the roadside. It includes, when appropriate, the planting, maintenance (e.g., fertilization, weed control, pest management), harvest, and transport of biomass in the form of bales or chips (or other appropriate forms—e.g., billets, bundles) to the farmgate or forest landing. The term "marginal price" is used in biomass supply analysis to convey the price needed to supply an additional ton of biomass to either the farmgate, forest landing, biomass depot, or conversion facility. "Average price" is used in biomass supply analysis to convey the average price to acquire a stream of biomass, from the first to the last ton, over a specific period of time.

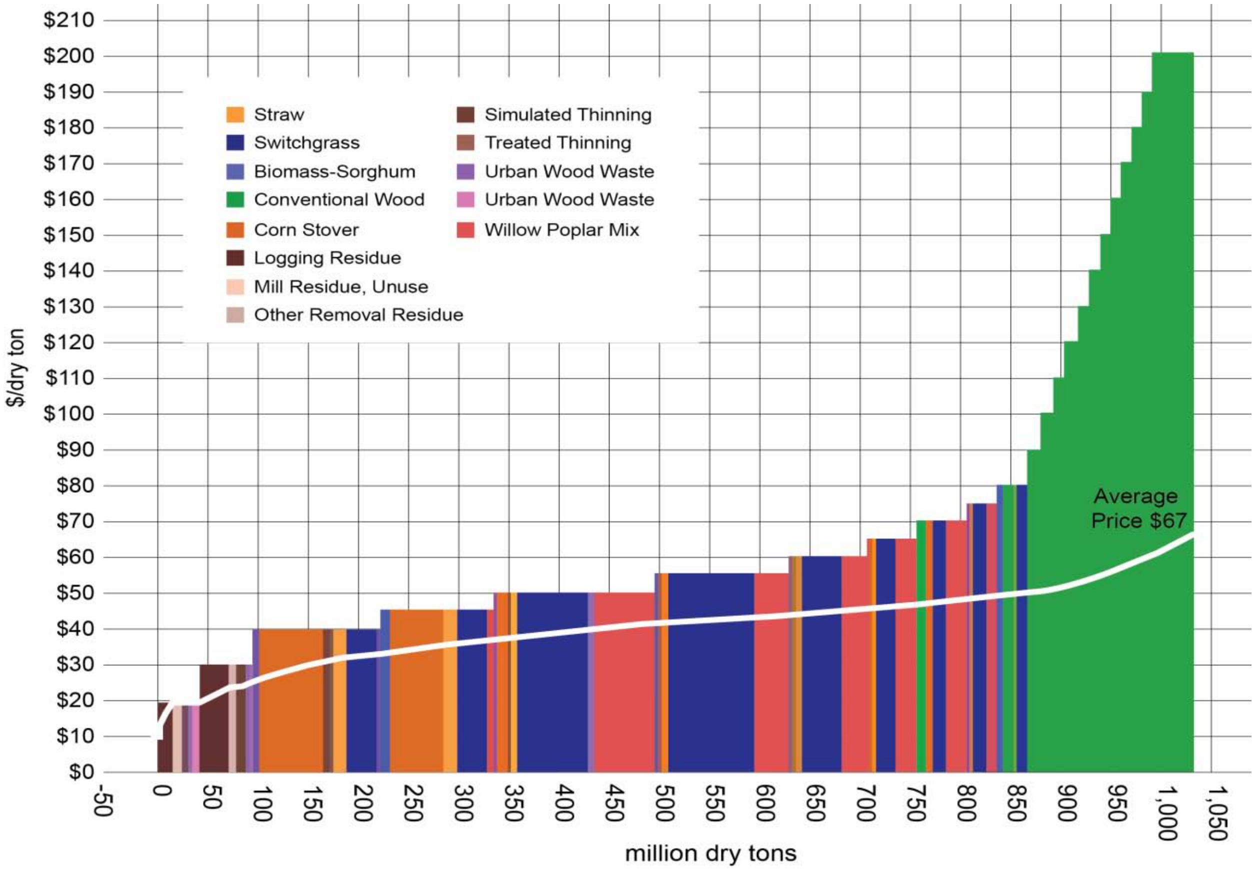

Figure 2-9: Biomass supply projections at marginal farm gate prices between $20 and $200/dry ton in 2022

Feedstock blending allows a biorefinery to collect less of any one feedstock and thus move down the cost versus supply curve, enabling biorefineries to pay a lower average price. Note that this does not change the supply versus cost curves for each resource, but it instead describes a system where purchasers are using a combination of least-cost resources and blending them to reach the biorefinery's desired cost and quality specifications.[14]

Formulating a designed feedstock through blending and other preprocessing methods allows low-cost and typically low-quality biomass to be blended with biomass of higher cost and typically higher quality to achieve the specifications required at the in-feed of a conversion facility (note that different conversion processes may require different specifications, and the cost required to meet those specifications will vary). The use of low-cost biomass allows the supply chain to implement additional preprocessing technologies that actively control feedstock quality, while also bringing more biomass into the system. This analysis and design approach is referred to as the "least-cost formulation" strategy.

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[14] D. Muth, J.J. Jacobson, K. Cafferty, and R. Jeffers (2013), *Define feedstock baseline scenario and assumptions for the $80/DT target based on INL design report and feedstock logistics projects*, ID#: 1.6.1.2.DL.4, 11.2.4.2.A.DL.2, Joule, WBS #: 1.6.1.2/11.2.4.2, Completion Date: 3/31/13, INL/EXT-14-31569.

Using a least-cost formulation analysis, Tables 2-2 and 2-3 illustrate that modeled feedstock cost and quality targets can be met for the bio-oil conversion pathway (fast pyrolysis) and biochemical conversion pathways, respectively.

The fast pyrolysis conversion pathway is currently designed for an ash content of less than 1% on a dry weight basis.[15] In the blending example illustrated in Table 2-2, low-cost, low-quality logging residues; switchgrass; and wood-based fractions of construction and demolition (C&D) waste are processed and blended with higher-cost, higher-quality debarked southern pine (i.e., loblolly pine) chips to meet conversion specifications. The exact quantity of each feedstock depends on the cost and characteristics of the individual feedstocks, as well as the target in-feed requirements. The modeled formulation uses 45% purpose-grown southern pine, 32% logging residues, 3% switchgrass, and 20% C&D waste as an example of this least-cost formulation strategy to obtain a blended feedstock that has an average delivered cost of $84/dry ton and cumulative ash content below 1% on a dry weight basis.

Table 2-2: Example of Modeled Costs and Specifications for Processed Woody Feedstocks and Blends for Fast Pyrolysis and Subsequent Upgrading to a Hydrocarbon Fuel[16]

Feedstock Component	Modeled Total Feedstock Cost* to Reactor Throat ($/dry ton) (2014$)	Formulation Fraction (% dry weight)	Ash Content at Reactor Throat[17] (% dry weight)
Purpose-Grown Pine (Wood)	105.02	45	0.5
Logging Residues[18]	71.26	32	1.0
Switchgrass	70.39	3	4.0
Wood Fraction of C&D Waste	61.35	20	1.0
Delivered Formulation Totals	**84.44**	**100**	**<1.0**

*Includes grower payment and all logistics costs up to the conversion reactor throat.
This example is for illustrative purposes only and is not intended to correspond to the case described in Table 2-4 and Figure 2-10.

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[15] Jones et al. (2013), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway*, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, PNNL-23053, NREL/TP-5100-61178, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf.

[16] Information extracted from Idaho National Laboratory (2014), *Feedstock Supply System Design and Analysis*, INL/EXT-14-33227.

[17] Note that Tables 2-2 and 2-3 are intended as a demonstration of the blending concept and are not intended to represent future quality targets. Values for pulpwood, residues, and C&D are from E. Lindstr. m, S. Larsson, D. Bostr. m, and M. Ohman (2010), "Slagging Characteristics During Combustion of Woody Biomass Pellets Made from a Range of Different Forestry Assortments," *Energy & Fuels* 24(6). Switchgrass values are extracted from S.Q. Turn, C.M. Kinoshita, and D.M. Ishimura (1997), "Removal of inorganic constituents of biomass feedstocks by mechanical dewatering and leaching," *Biomass and Bioenergy* 12(4).

[18] For the purposes of this analysis, residue costs do not include harvest and collection, as they are moved to the landing while attached to the merchantable portion of the tree.

Modeled costs for forest thinnings and logging residues are estimated using supply chains that incorporate technologies and strategies that are currently under development, such as an innovative ash-reduction unit operation, at costs below the $84/dry ton target. While the 45% fraction of debarked purpose-grown pine in Table 2-2 exceeds the $84/dry ton cost target (at a modeled cost of nearly $105/dry ton), it provides very low-ash material that helps the feedstock meet the thermochemical conversion quality specifications. When blended, the formulation meets both the cost and feedstock quality targets.

An analogous example for herbaceous biomass blending is presented in Table 2-3. Modeled costs are estimated using supply chains that incorporate technologies and strategies currently under development (such as advanced preprocessing) at costs below the $84/dry ton target. When blended, the formulation meets both the cost and current feedstock quality targets for biochemical conversion. Moving beyond 2017, the blending strategy will allow even more resources to be made economical and of appropriate quality for bioenergy production, while still hitting the $84/dry ton cost target.

Table 2-3: Example of Modeled Costs and Specifications for Processed Herbaceous Feedstocks and Blends for Biochemical Conversion to a Hydrocarbon Fuel[19]

Feedstock Component	Modeled Total Feedstock Cost* to Reactor Throat ($/dry ton) (2014$)	Formulation Fraction (%)	Ash Content at Reactor Throat[20] (% dry weight)	Carbohydrate Content (% dry weight)
Single-Pass Corn Stover	82.65	35	3.5	64
Multi-Pass Corn Stover	91.41	25	7	57
Switchgrass	84.02	35	4	57
Municipal Solid Waste	65.55	5	10	57
Delivered Formulation Totals	**84.47**	**100**	**4.9**	**59**

*Includes grower payment and all logistics costs up to the conversion reactor throat.
Note: This example is for illustrative purposes only and is not intended to correspond to the case described in Table 2-5 and Figure 2-12.

Prior to the transition to advanced systems that incorporate concepts such as blending, terrestrial FSL research was focused on improving conventional logistics systems. Through 2012, conventional woody supply system costs were reduced for niche opportunities by improving existing equipment efficiencies, adopting innovative ways of mitigating moisture content, and increasing grinder performance. The cost target of $46.37/dry ton (2007$, excluding grower payment) was achieved in 2012,[21] supporting Office goals at the time. Similarly, improvements to conventional herbaceous supply systems for high-yield situations focused on reducing field losses, improving other existing equipment efficiencies, and increasing grinder performance.

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[19] Information extracted from Idaho National Laboratory (2014), *Feedstock Supply System Design and Analysis*, Idaho National Laboratory, INL/EXT-14-33227.

[20] Note that Tables 2-2 and 2-3 are intended as a demonstration of the blending concept and are not intended to represent future quality targets.

[21] E. Searcy, J. Hess, C. Wright, K. Kenney, J. Jacobson (2010), *State of Technology Assessment of Costs of Southern Pine for FY10 Gasification*, Idaho National Laboratory, INL/LTD-10-20306.

Using these and other improvements, the 2012 herbaceous logistics cost target of $35.00/dry ton was achieved ($2007, excluding grower payment). The year 2013 marked the transition from a focus on conventional feedstock supply systems to advanced systems and non-ideal feedstock supply areas. This transition was based on the desire to increase the total volume of material that can be processed and enable more biorefinery options, to address quality, and to meet the 2017 cost target of $84/dry ton delivered to the throat of the biorefinery, including both grower payment and logistics cost. Moving beyond 2017, advanced systems will gradually bring in larger quantities of feedstock from an even broader resource base, as well as incorporate environmental impact criteria into availability determinations. Feedstock supplied after 2017 will continue to meet the $84/dry ton cost target and quality requirements of various conversion processes.

Through 2017, terrestrial FSL supports two separate feedstock designs: an herbaceous feedstock supply system design that supplies on-spec feedstock to a biochemical conversion process, and a woody feedstock supply system design that supplies on-spec feedstock to a thermochemical conversion process (conversion processes are described in Section 2.2). These feedstock designs converge in 2017 to the same cost target, $84/dry ton, when the blending concept is implemented.

Figures 2-10 and 2-12, and Tables 2-4 and 2-5 summarize historical and projected woody and herbaceous logistics costs. Figure 2-10 and Table 2-4 show potential reductions in the delivered feedstock costs from 2013 through 2019 for woody biomass undergoing conversion via a fast pyrolysis conversion process.[22]

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[22] In-feed specifications extracted from S. Jones, E. Tan, J. Jacobson, et.al. (2013), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Fast Pyrolysis and Hydrotreating Bio-oil Pathway*, Pacific Norwest National Laboratory, National Renewable Energy Laboratory, and Idaho National Laboratory, PNNL-23053, NREL/TP-5100-61178, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf.

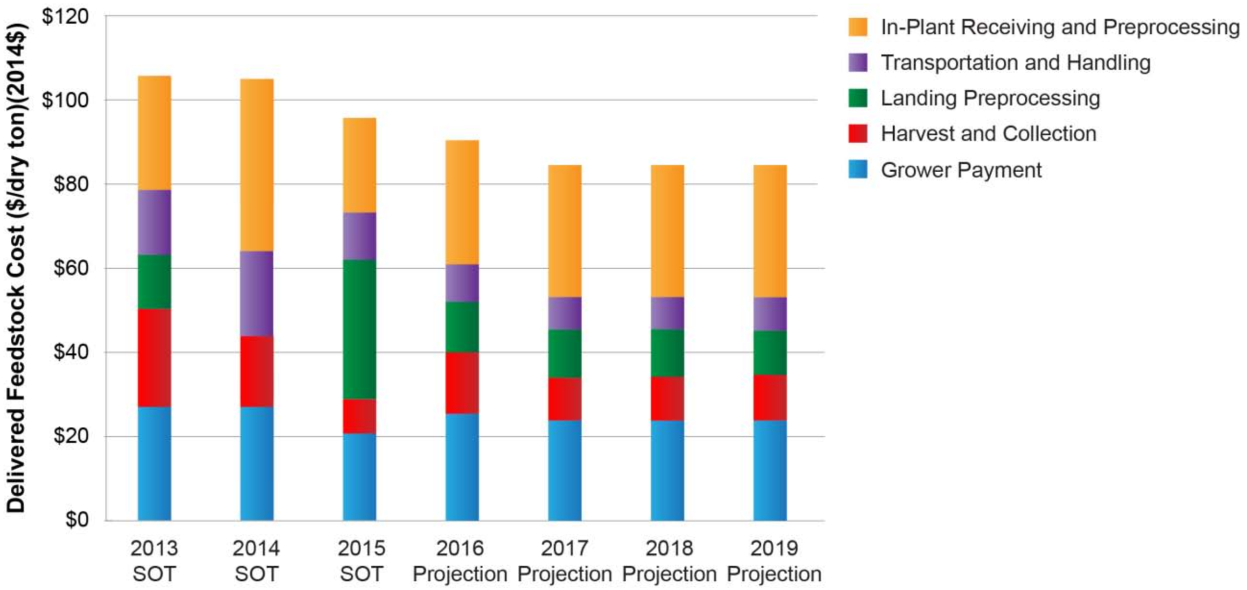

Figure 2-10: Historical and projected feedstock costs delivered to the reactor throat, modeled for pyrolysis conversion

Table 2-4: Feedstock Logistics Costs for a Woody Feedstock Delivered to the Reactor Throat for a Pyrolysis Conversion Process[23]

2014$	2013 SOT	2014 SOT	2015 SOT	2016 Projection	2017 Projection	2018 Projection	2019 Projection
Feedstock Type	Pine [1]	Pine [1]	Blend [2]	Blend [2]	Blend [2]	Blend [2]	Blend [2]
Total Delivered Cost $/dry ton	$107.80	$107.09	$97.34	$91.54	$84.45	$84.45	$84.45
Grower Payment $/dry ton	$26.39	$26.39	$20.49	$24.75	$23.12	$23.12	$23.12
Total Feedstock Logistics $/dry ton	$81.41	$80.70	$76.86	$66.79	$61.33	$61.33	$61.33
Harvest and Collection	$23.48	$16.90	$7.58	$15.26	$11.05	$11.05	$11.05
Landing Preprocessing	$12.85	N/A	$33.42	$11.63	$10.81	$10.81	$10.81
Transportation and Handling	$15.66	$20.45	$11.05	$8.95	$7.94	$7.94	$7.94
In-Plant Receiving and Processing	$29.42	$43.35	$24.80	$30.94	$31.53	$31.53	$31.53
Total Feedstock Logistics $/GGE *	$0.93	$0.92	$0.87	$0.76	$0.70	$0.70	$0.70
Harvest and Collection	$0.26	$0.19	$0.09	$0.17	$0.13	$0.13	$0.13
Landing Preprocessing	$0.15	$0.00	$0.38	$0.14	$0.13	$0.13	$0.13
Transportation and Handling	$0.18	$0.23	$0.13	$0.11	$0.10	$0.10	$0.10
In-Plant Receiving and Processing	$0.34	$0.50	$0.28	$0.35	$0.36	$0.36	$0.36

[1] Clean, debarked loblolly pine chips
[2] 45% clean loblolly pine chips (pulp wood), 35% loblolly pine logging residues, 20% C&D waste
* Feedstock logistics costs expressed on a per gallon of gasoline equivalent (GGE) are calculated assuming 87 GGE/dry ton of feedstock.

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[23] Note that the grower payment for 2017 projection is the weighted average associated with a blend scenario. Growers payment includes harvest, collection, and landing preprocessing costs, but these costs are also reflected in the feedstock logistics cost to demonstrate all logistics components.

Total modeled feedstock cost decreases through 2017 as the result of capacity and efficiency improvements, innovative design strategies (such as blending), novel preprocessing approaches, and integrated landscape management strategies. For example, blending reduces the harvest and collection cost. The 2013 SOT is based on purpose-grown trees, which incur a harvest and collection cost. Harvest and collection costs associated with residues, however, are allocated to the cash crop, such as timber or pulpwood. Switchgrass has a lower harvest and collection cost than purpose-grown wood, and C&D waste does not have a harvest cost. Therefore, blending these materials will result in a decreased harvest and collection cost. Note that the modeled costs do not decrease between the years 2017 and 2019; however, as shown in Figure 2-11, the volume of biomass available at the $84/dry ton target increases.[24]

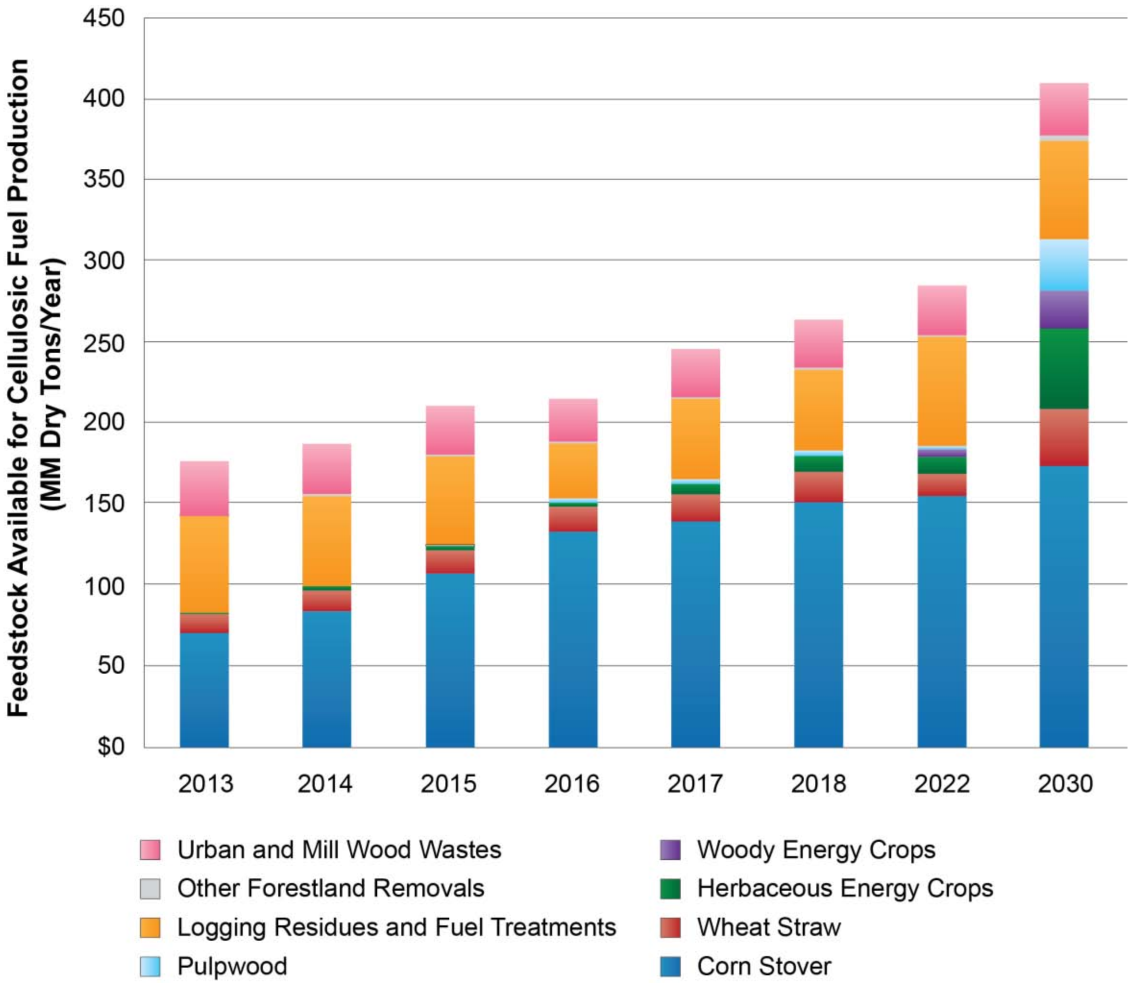

Figure 2-11: Historical and projected volumes of biomass available at a delivered cost of $84/dry ton (2014$) for various biomass types, accommodating multiple conversion processes[25]

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[24] See Appendix A Table A-1.

[25] These projected feedstock volumes will be revised after publication of updated data in the *2016 Billion-Ton Report*.

Note that the higher volumes in Figure 2-11 are due to a variety of factors, including increased biomass yields, capacity and efficiency improvements in logistics systems, and innovative logistics strategies, such as blending. Table 2-4 shows a reduction in grower payment of just more than $3/dry ton from 2013 to 2019, while concurrently increasing biomass resources available.

Preliminary results suggest that blending multiple preprocessed feedstocks enables the acquisition of higher biomass volumes and reduces feedstock variability to meet biorefinery in-feed specifications, while delivering feedstock to the biorefinery at $84/dry ton.[26] Research is needed on blending strategies; on the conversion performance of blended materials; and on other advanced design technologies to meet cost, quality, and volume targets.

One metric that is used to assess sustainability of logistics systems is GHG emissions. A GHG emissions assessment was conducted on the 2015 woody feedstock SOT shown in Table 2-4. The assessment included process inputs, fuels (diesel, natural gas), and electricity for all operations from harvest through reactor in-feed.[27] The total GHG emissions from logistics was found to be 223.3 kg CO_2e/dry ton, which is slight a reduction from the 230 kg CO_2e/dry ton reported in the 2013 SOT.

Figure 2-12 and Table 2-5 show potential reductions in herbaceous feedstock costs from 2013 through 2019, delivered for biological conversion of sugars to hydrocarbons, or catalytic conversion of sugars to hydrocarbons. Both of these pathways have an assumed feedstock in-feed specification of 20% moisture, 59% total carbohydrate, less than 5% ash, and ¼ inch particle size at conversion in-feed.[28]

Total modeled feedstock cost decreases through 2017 as a result of capacity and efficiency improvements, and improved system design. Specific examples include high-moisture densification, fractional milling, innovative design strategies (such as blending), and innovative cropping strategies to improve feedstock quality. As for woody feedstocks, blending reduces cost by combining lower cost feedstocks with higher cost feedstocks (Table 2-3). Note that the modeled costs do not decrease between the years 2017 and 2019; however, as shown in Figure 2-11, the volume of biomass available at the $84/dry ton target increases.[29]

Table 2-5 shows a reduction in grower payment of over $10/dry ton from 2013 to 2019 while concurrently increasing biomass resources available.

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[26] Idaho National Laboratory (2014), *Feedstock Supply System Design and Analysis*, INL/EXT-14-33227.

[27] Biomass production inputs, such as fertilizer, and greenhouse gases associated with feedstock conversion were not included.

[28] Davis et al. (2013), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons*, National Renewable Energy Laboratory, NREL/TP-510060223, http://www.nrel.gov/docs/fy14osti/60223.pdf.

[29] See Table A-1 in Appendix A.

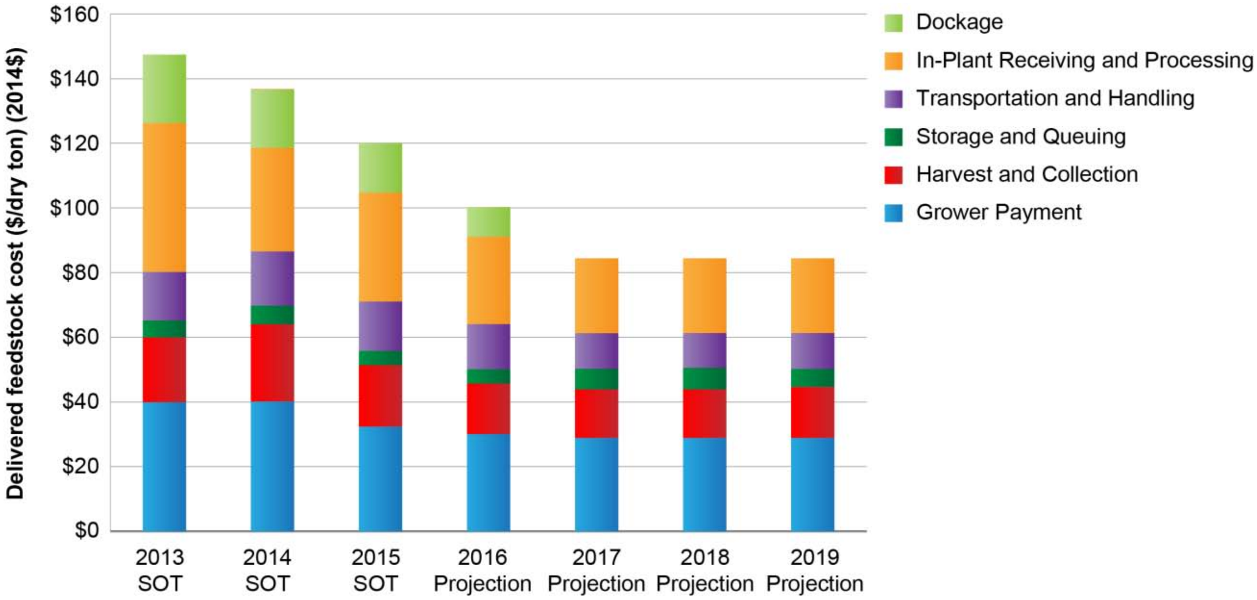

Figure 2-12: Historical and projected feedstock costs, modeled for herbaceous feedstock delivered to the reactor throat to meet biochemical conversion in-feed specifications

Table 2-5: Feedstock Logistics Costs for Herbaceous Feedstock Delivered to the Reactor Throat for a Biochemical Conversion Process[30]

2014$	**2013 SOT**	**2014 SOT**	**2015 SOT**	**2016 Projection**	**2017 Projection**	**2018 Projection**	**2019 Projection**
Feedstock Type	Corn Stover	Corn Stover	Blend	Blend	Blend	Blend	Blend
Total Delivered Cost $/dry ton	$147.46	$136.96	$119.94	$100.28	$84.45	$84.45	$84.45
Grower Payment $/dry ton	$40.11	$40.11	$32.32	$30.08	$29.24	$29.24	$29.24
Total Feedstock Logistics $/dry ton	$107.35	$96.85	$87.62	$70.20	$55.21	$55.21	$55.21
Harvest and Collection	$20.27	$24.48	$18.65	$15.65	$14.67	$14.67	$14.67
Storage and Queuing	$4.54	$5.23	$4.34	$3.69	$6.33	$6.33	$6.33
Transportation and Handling	$15.31	$16.72	$15.05	$14.67	$11.08	$11.08	$11.08
In-Plant Receiving and Processing	$46.02	$32.08	$34.43	$27.10	$23.12	$23.12	$23.12
Dockage	$21.21	$18.34	$15.15	$9.08	-	-	-

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[30] Note that the grower payment for 2017 projection is the weighted average associated with a blend scenario. Growers payment includes harvest, collection, and landing preprocessing costs, but these costs are also reflected in the feedstock logistics cost to demonstrate all logistics components.

Analysis suggests that blending multiple feedstocks enables the acquisition of higher biomass volumes and reduces feedstock variability to meet biorefinery in-feed specifications, while delivering feedstock to the biorefinery at $84/dry ton.[31] A dockage charge is applied to materials that do not meet biorefinery in-feed specifications, which blending helps to alleviate. Preliminary research suggests that blended feedstocks behave linearly in biochemical conversion processes. In other words, the conversion performance of the blended feedstock behaves essentially as the weighted average of its individual constituent feedstocks in terms of both initial composition and glucose yield from combined pretreatment and enzymatic saccharification reactions.

A GHG emissions assessment was conducted on the 2015 SOT shown in Table 2-5. The assessment included process inputs, fuels (diesel, natural gas), and electricity for all operations from harvest through reactor in-feed.[32] The total GHG emissions from logistics was found to be 169.5 kg CO_2e/dry ton, which is a significant decrease from the 2014 SOT (237.8 kg CO_2e/dry ton).

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[31] Idaho National Laboratory (2014), *Feedstock Supply System Design and Analysis*.

[32] Biomass production inputs, such as fertilizer, and greenhouse gases associated with feedstock conversion were not included.

2.1.1.6 Terrestrial Feedstock Supply and Logistics Research and Development Milestones and Decision Points

The key Terrestrial FSL program area milestones, inputs/outputs, and decision points to complete the tasks described in Section 2.1.4 are summarized in Figure 2-13.

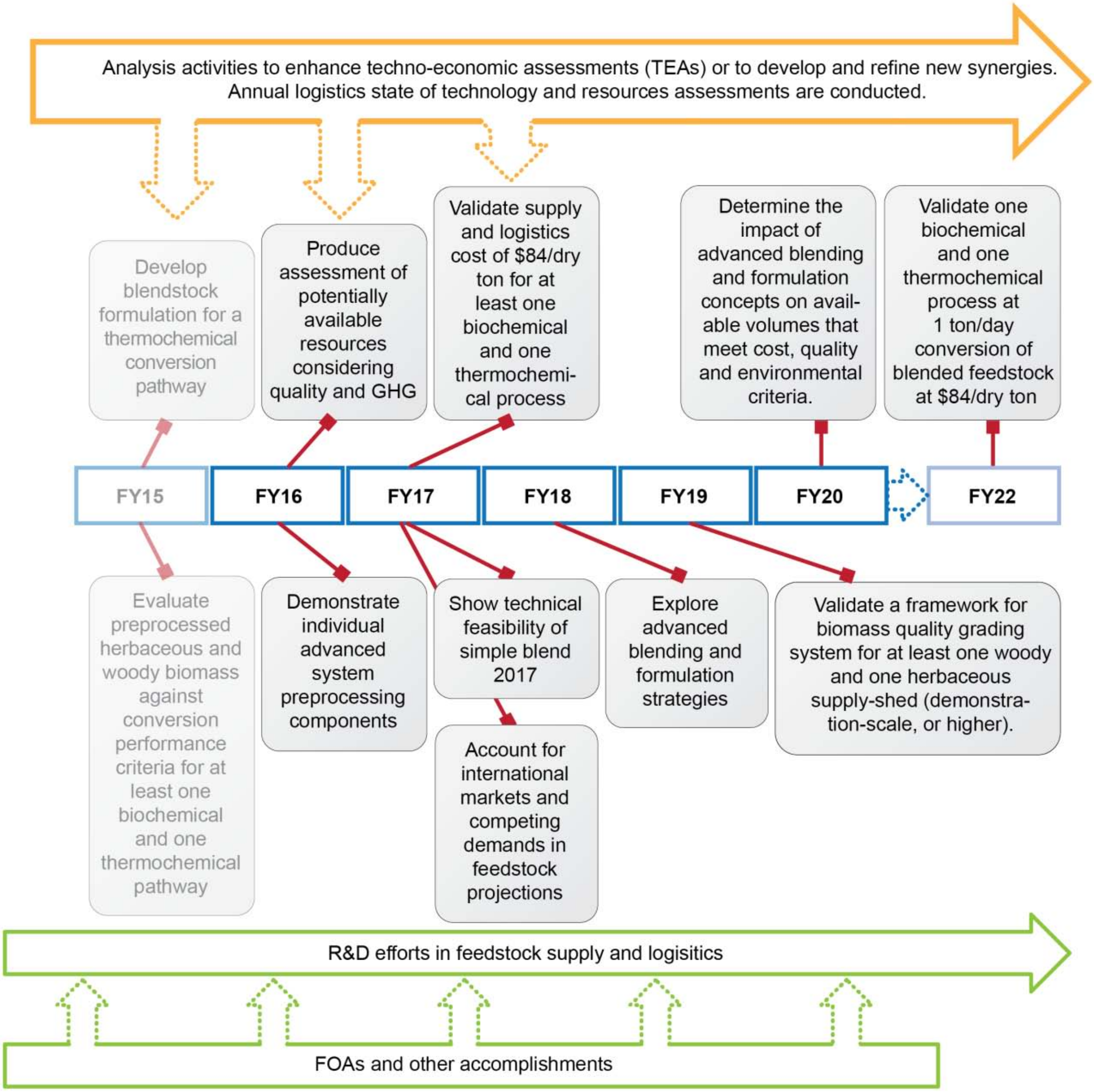

Figure 2-13: Terrestrial feedstock supply and logistics R&D key milestones and activities

2.1.2 Advanced Algal Systems Research and Development

Algal feedstocks can contribute significantly to expanding the domestic, advanced biofuel resource potential. This is based on the potential for harnessing photosynthesis[1] through highly productive algae while using non-arable land, brackish or salt water, and on the possibility of using waste nutrients and effluents. Also, due to the ability of photosynthetic algae to accumulate significant amounts of lipids, algae can be particularly well suited for conversion to hydrocarbon-based fuels, such as renewable diesel and jet.

Advanced Algal Systems R&D focuses on demonstrating progress toward achieving high-yield, low-cost, environmentally sustainable algal biomass production and logistics systems that produce biofuel intermediate feedstocks that are well suited for conversion to fuels and other valuable products. Algal biomass includes micro- and macro-algae, as well as cyanobacteria. Algal biofuel and bioproduct intermediates include extracted lipids, products derived from sugars or proteins (alcohol or hydrocarbon fuels), secreted metabolites (alcohols or others), or bio-crude resulting from hydrothermal liquefaction. These intermediate products must be upgraded and or blended and or purified to produce a finished fuel or bioproduct. Developing algal feedstocks to achieve the Office's advanced biofuel price goals requires breakthroughs along the entire algal biomass supply chain.

Algal Biofuel Intermediate Supply System

The conceptual flow diagram in Figure 2-14 outlines the main elements of a generic photosynthesis-based algae supply and logistics system to provide biofuel intermediates suitable for conversion to advanced biofuels. This diagram represents many—but not all—possible algae systems and describes the design basis used to establish cost projections. A range of alternative systems are discussed in the *National Algal Biofuels Technology Roadmap.*[2] The conceptual diagram in Figure 2-14 establishes a common baseline to communicate the relationship of system components and provides a basis for consideration of alternative and innovative processes and methods to achieve the cost goals needed for commercial applications.

This generic model of the algal biofuel intermediate supply system is based on literature and bench-scale and field-scale R&D efforts undertaken since 2009. Uniform biomass and intermediate specifications have not been established, though progress is being made.[3,4] Further, a harmonized approach to integrating resource assessment, life-cycle analysis (LCA) of energy use and GHG emissions, technoeconomics, and close coordination with conversion areas, is required to understand the potential of, and barriers to, national-scale algal biofuels. Much of the

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[1] Non-photosynthetic algae (heterotrophs) are considered, along with other microorganisms, in the Conversion R&D Program Area (Section 2.2).

[2] U.S. Department of Energy (2010), *National Algal Biofuels Technology Roadmap*, Washington, D.C.: Government Printing Office, http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf.

[3] NREL (2015), "Standard Procedures for Biomass Compositional Analysis," http://www.nrel.gov/biomass/analytical_procedures.html.

[4] Algae Biomass Organization (2015), *Industrial Algae Measurements, Version 7.0.*, http://www.algaebiomass.org/wp-content/gallery/2012-algae-biomass-summit/2015/09/2015_ABO_IAM_Web_HiRes_r4.pdf.

analysis around algal biomass is in the early stages of development, and significant refinements are expected as R&D investments mature.

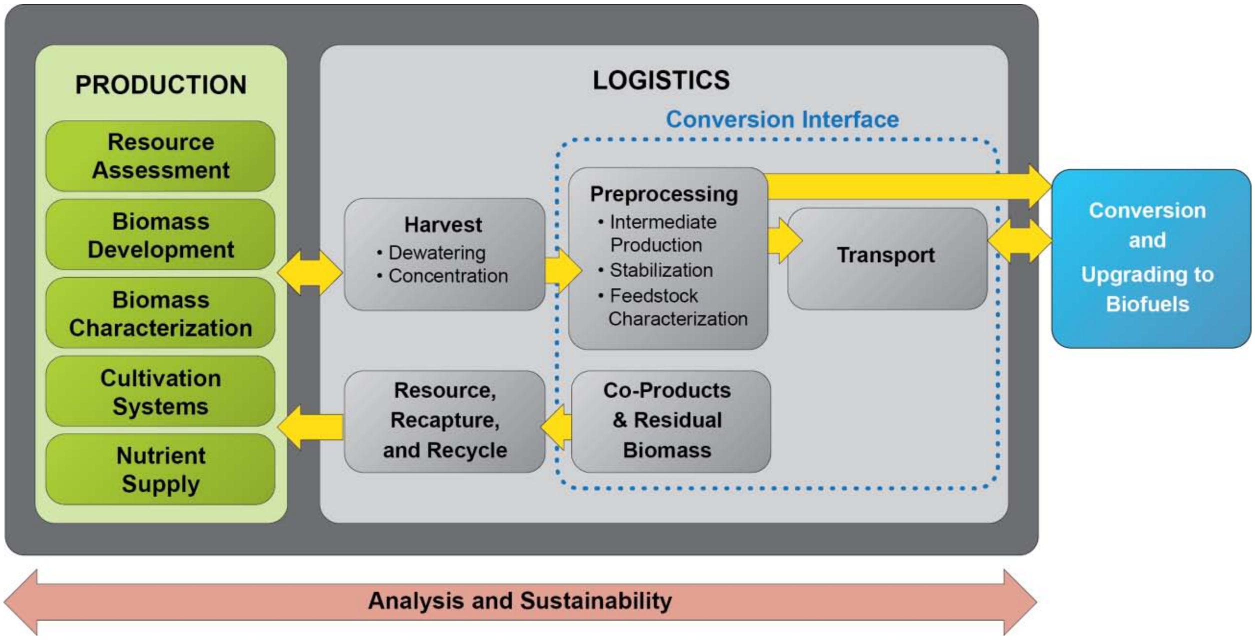

Figure 2-14: Generic algal biofuel intermediate feedstock supply and logistics flow diagram

Production: The production component of the supply system includes both resource assessment and technology development. Production technology development focuses on algal biomass development and characterization, cultivation system technologies, and nutrient supply systems.

Resource Assessment: Resources necessary to operate sustainable algal systems include sufficient solar insolation, non-arable land, non-potable water, waste-nutrient streams, waste CO_2, and supporting transport infrastructure to access downstream conversion processing. Development of an algal biofuel industry requires scaling-up from hundreds of acres currently in domestic algae cultivation to millions of acres of land resources. Algae resource assessment includes identifying potential geographic locations for algae farms based on resource access and availability, estimating costs for current and future resources, and assessing the environmental sustainability of the use of these resources.

Biomass Development: Algal biomass includes micro- and macro-algae, as well as cyanobacteria. Biomass development include prospecting and isolating algae strains to identify algae with desirable properties, and investigating potential biological improvements from breeding, modification, and genetic engineering to improve photosynthetic efficiency, growth rates, lipid productivity, biomass yield, or other desirable traits. Systems biology approaches to improve advantageous traits for production are also part of biomass development.

While heterotrophic algae is a not focus of the Advanced Algal Systems program area, heterotrophic microorganism development, including heterotrophic microalgae, is a focus area of the Conversion R&D program area (Section 2.2).

Biomass Characterization: Biomass characterization includes understanding the fundamental components (lipids, carbohydrates, and proteins) of algal biomass and correlating those characteristics to favorable production of biofuels and bioproducts. Understanding the biomass characteristics of algae with confidence at different time points in the growth cycle is critical in developing cultivation management strategies, downstream processes, and ultimate product valuations.

Cultivation Systems: Algae cultivation systems include—but are not limited to—open mixed ponds, attached growth systems, closed photobioreactors, or a combination of these. Cultivation systems must optimize transmission of sunlight, resource supply, materials and operating costs, and operability while maximizing productivity. Cultivation strategies include crop protection, mixotrophy, integration of co- or poly-cultures, water and nutrient management, light optimization, temperature management, and seasonal succession. Power consumption for culture mixing strongly influences life-cycle GHG emissions associated with algal fuels and must be constrained, especially during periods with lower productivity.

Nutrient Supply: Nutrient supply encompasses feeding algae both micro and macro nutrients, as well as CO_2 and recycled water necessary for their growth.

Logistics: Logistics includes downstream processing of cultivated algal biomass and includes harvest, preprocessing, and transport of processed biofuel intermediates to a conversion facility. Logistics also encompasses co-products and residual processing as well as resource recapture and recycle.

Harvest: Optimizing harvesting operations is critical to maximizing algal biomass yields while ensuring sustainability of the production system. Algal biomass can be harvested continuously or in daily or weekly batches. Harvest timing throughout the growth cycle may affect composition and structural features of the harvested algae. In fresh water, planktonic systems, water remaining after the algae are harvested must be recycled back into the cultivation system to minimize resource use. Water recycle may be important in saline systems as well depending on water source and facility siting. Macroalgae and attached growth systems that cultivate multi-cellular algae require a lower dewatering intensity. If the algae concentration at harvest is too low, excessive water movement will occur and this jeopardizes the life-cycle GHG emissions associated with the products.

Dewatering: Microalgae and cyanobacteria cultivated in water grow at dilute concentrations, with assumed solids at harvest typically ranging from 0.1 grams/liter to 4.0 grams/liter. Dewatering technologies—such as those used in wastewater treatment processes and the mining industry—isolate solids from high-volume, low-concentration effluents.

Concentration: Dewatered algal biomass may still be too dilute for effective preprocessing; it will require further concentration to boost algal biomass slurry concentrations to at least 15%–20% solids to be efficiently preprocessed, with the final target to be dictated by the preprocessing interface. Centrifugation or membranes are typically used for concentrating the solids.

Preprocessing: Algae preprocessing refers to the on-farm production of transportable intermediate products from harvested algal biomass. Algal biofuel intermediates should be energy-dense and compatible with existing handling, transport, and storage infrastructure. Preprocessing may improve algal biomass for long-term storage, handling, and transport, as well as prepare the raw material for efficient conversion to end-use products. Algal feedstock preprocessing steps may include the following:

> *Feedstock Characterization*: The impact of preprocessing operations and reaction conditions on the resulting product streams has important implications for conversion and upgrading, as well as co-products. Methods to characterize these streams and develop predictive models of reaction kinetics will enable robust integrated process development.
>
> *Intermediate Production*: Intermediate production includes the deconstruction of algal biomass into products such as extracted lipids, fuel/product derivatives from carbohydrates or protein, secreted metabolites (alcohols or others), or biocrude resulting from hydrothermal liquefaction. Maximizing throughput and efficiency while producing both energy-dense biofuel intermediates and useful remaining biomass or other co-products are key objectives for intermediate production. Regardless of which technology is used, the interface between feedstock characterization and downstream product requirements will play a role in determining appropriate intermediate production technology.
>
> *Stabilization*: The stability of intermediate products is important, particularly when the biofuel intermediate is transported offsite to a refinery for further upgrading. Methods of stabilization and storage may also have significant impacts on co-product generation.

Transport: Algal biofuel intermediate products may be transported using existing transportation infrastructure. This provides some advantages to using lower-cost methods, such as rail, but it also provides a number of challenges that still need to be addressed, such as local codes, standards, and U.S. Department of Transportation regulations. In addition, longer-term implementation may require specific handling or materials of construction to avoid contamination or fermentation. As with the transportation of other biomass and feedstocks, these transportation details must be further investigated as more processes and intermediates are developed.

Co-Products and Residual Carbon Processing: The algae components that will not be directly converted to biofuels can comprise 40%–75% wt% of the biomass depending upon the extraction or conversion method. Processing this residual organic matter can provide nutrients and power back to the production and logistics systems. Components of algal biomass not converted to biofuel or not recaptured for reuse in cultivation may be converted to valuable co-products, such as animal feeds, commodity chemicals, or other products.

Resource Recapture and Recycle: Recycling residual salts and organic material remaining after preprocessing and/or residual processing enables the recapture of valuable nitrogen, phosphorus, other minor nutrients, and carbon. Recycling can displace a portion of fresh fertilizer inputs in upstream cultivation. Life-cycle analyses of GHG emissions and energy use must account for residual streams because these streams can carry organic carbon and nitrogen that ultimately lead to GHG emissions. Life-cycle analyses results suggest that the recapture of nitrogen in particular is a critical component of a favorable GHG emissions profile for algal biofuels. Since nitrogen loss into the products must be accounted for in the economics of the value chain, innovative approaches must be developed to provide an addition that does not involve fresh fertilizer.

Conversion Interface: The production of clean, energy-dense, stable, and transportable intermediates suitable for refining to biofuels requires integration with R&D efforts in Conversion (see Section 2.2) and with Demonstration and Market Transformation (DMT) (see Section 2.3). Coordination on RD&D of preprocessing, transportation, co-products, and direct conversion of algal feedstocks to finished fuels occurs through this interface.

Analysis and Sustainability: Techno-economic analyses, resource assessments, and life-cycle assessments are used to identify key parameters with the greatest impact on the cost and sustainability of a fully integrated algae system. These analyses guide the management of RD&D projects and provide the rationale to down-select technologies that cannot achieve Office goals. These analyses are continuously refined with data from the RD&D projects.

2.1.2.1 Advanced Algal Systems Research and Development Support of Office Strategic Goals

The strategic goal of Advanced Algal Systems R&D is *to develop algae production and logistics technologies that, if scaled-up and deployed, could support the production of 5 billion gallons per year of sustainable, reliable, and affordable algae-based advanced biofuels by 2030*.

The strategic goal directly addresses and supports production of algal feedstocks for use by all potential conversion pathways to both biofuels and bioproducts.

2.1.2.2 Advanced Algal Systems Research and Development Support of Office Performance Goals

The performance goal is as follows:

- By 2022, demonstrate technologies to produce sustainable algal biofuel intermediate feedstocks that perform reliably in conversion processes to yield renewable diesel, jet, and gasoline fuels in support of the Office’s $3/gasoline gallon equivalent (GGE) advanced biofuels goal.

To track progress towards the performance goal, the Office has established one design for photoautotrophic cultivation of algal biomass in open raceway ponds[5] and two designs for

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[5] Davis, R. et al. (2015), *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, National Renewable Energy Laboratory, NREL/TP-5100-64772, http://www.nrel.gov/docs/fy16osti/64772.pdf.

conversion of algal biomass into advanced biofuels: (1) combined algal processing[6] (treatment of algal biomass with dilute acid under low pressure to release fermentable sugars followed by fermentation of the solubilized sugars and then wet extraction and upgrading of lipids) and (2) whole algae hydrothermal liquefaction[7] (treatment of algal biomass in hot, pressurized water followed by separation of bio-crude from water). The cultivation design TEA and the design cases and accompanying State of Technology for two advanced biofuel pathways are described in Section 2.1.2.5.

Alternative designs for innovative operations and additional products continue to be developed and evaluated, and they will be incorporated into the Office's strategic plans as they show promise.

Milestones in support of the Advanced Algal Systems R&D performance goal are to evaluate the potential domestic supply of algal biomass through the following steps:

- By 2017, model the sustainable supply of 1 million metric tonnes ash free dry weight (AFDW) cultivated algal biomass.
- By 2018, demonstrate at non-integrated process development unit-scale algae yield of 2,500 gallons or equivalent of biofuel intermediate per acre per year.
- By 2019, demonstrate at non-integrated process development unit-scale production and recovery of valuable co-products that can be produced along with biofuel intermediates to increase the value of cultivated algal biomass by 30%.
- By 2020, demonstrate at non-integrated process development unit-scale algae yield of 3,700 gallons or equivalent biofuel intermediate per acre per year.
- By 2022, model the sustainable supply of 20 million metric tonnes AFDW cultivated algal biomass.
- By 2022, demonstrate at non-integrated process development unit-scale algae yield of 5,000 gallons biofuel intermediate per acre per year in support of nth plant model $3/GGE algal biofuels.
- By 2025, demonstrate at integrated process development unit-scale algal productivity of greater than 5,000 gallons biofuel intermediate per acre per year.
- By 2030, validate demonstration-scale production of algae-based biofuels at total production cost of $3/GGE ($2011), with or without co-products.

2.1.2.3 Advanced Algal Systems Research and Development Technical Challenges and Barriers

Algae Production

Aft-A. Biomass Availability and Cost: The lack of credible data on potential price, location, seasonality, environmental sustainability, quality, and quantity of available algal biomass

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[6] Davis, R. et al.(2014), *Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products*, National Renewable Energy Laboratory, NREL/TP-5100-62498, http://www.nrel.gov/docs/fy15osti/62498.pdf.

[7] Jones et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading*, Pacific Northwest National Laboratory, PNNL- 23227, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf.

feedstock creates uncertainty for investors and developers of emerging biorefinery technologies. Established biomass production history is required to assure investors and other funding sources that the feedstock supply risk is sufficiently low. Reliable, consistent, and sustainable biomass supply is needed to reduce financial, technical, and operational risk to a biorefinery and its financial partners.

Aft-B. Sustainable Algae Production: Existing data on the productivity, energy use, and environmental effects of algae production and biomass collection systems are not adequate to support life-cycle analysis of biorefinery systems. A number of sustainability questions (e.g., water and fertilizer inputs, land conversion, and liner use) have not been comprehensively addressed. New production technologies for algae are also required to address cost, productivity, and sustainability issues.

Aft-C. Biomass Genetics and Development: The productivity and robustness of algae strains against perturbations such as temperature, seasonality, predation, and competition, could be improved by selection, screening, breeding, biologically mixed cultures, and/or genetic engineering. This will require extensive ecological, genetic, and biochemical information, which is currently lacking for most algal species. Any genetically modified organisms deployed commercially will also require regulatory approval by the appropriate federal, state, and local government agencies.

Algal Feedstocks Logistics

Aft-D. Sustainable Harvesting: Current algal biomass harvesting and dewatering technologies are costly and energy- and resource- intensive. Microalgae grown in liquid suspension are dilute (0.1–0.5 grams per liter in open ponds) and require multiple concentration steps to yield a harvested biomass that can be processed. While dewatering technology exists in wastewater treatment processes and the mining industry to isolate solids from high-volume, low-concentration effluents, these existing technologies may be too energy-, capital-, and reagent-intensive for the development of algal biofuels.

Aft-E. Algal Biomass Characterization, Quality, and Monitoring: Physical, chemical, biological, and post-harvest physiological variations in harvested algae are not well researched or understood. The fundamental components (lipids, carbohydrates, and proteins) of algal biomass vary greatly, within strains, among strains, and in comparison to plants. A better understanding of the effects of wide variability in feedstock characteristics on biorefinery operations and performance is needed. Standard procedures to reliably and reproducibly quantify biomass components from algae and close-mass balances are not readily available—a significant challenge as compared to traditional plant-based biomass.

Aft-F. Algae Storage Systems: Characterization and analysis of different algae storage methods and strategies are needed to better define storage requirements for seasonal variances or design flexibility; if needed, these storage methods should preserve harvested algal biomass or biofuel intermediates to maintain product yield over time. Energy use and sustainability implications must be understood.

Aft-G Algal Feedstock Material Properties: Data on algal feedstock quality and physical property characteristics in relation to conversion process performance characteristics are extremely limited. Methods and instruments for measuring physical, chemical, and biomechanical properties of biomass are lacking.

Aft-H. Overall Integration and Scale-Up: Integration of co-located inoculation, cultivation, primary harvest, concentration, and preprocessing systems is an expensive and challenging endeavor requiring interdisciplinary expertise. In addition, the potential for co-location with other related bioenergy technologies to improve balance of plant costs and logistics has not been evaluated to determine what cost savings could be achieved.

Aft-I. Algal Feedstock On-Farm Preprocessing: After cultivation and harvesting, algal biomass may require processing or fractionation into lipids, bio-oils, carbohydrates, and/or proteins before these individual components can be converted into the desired fuel and/or products. Current technologies for algal fractionation and product extraction are not commercial. Process options for commercial scale-up have been identified and are being researched (e.g., conversion of whole algal biomass via thermal liquefaction), but few data exist on the cost, sustainability, and efficiency of these processes.

Aft-J. Resource Recapture and Recycle: Residual materials remaining after preprocessing and/or residual processing may contain valuable nitrogen, phosphorus, other minor nutrients, and carbon that can displace a portion of fresh fertilizer inputs in upstream cultivation. The recapture of these resources from harvest and logistics process waste streams may pose separation challenges, and the recovered materials may not be in biologically available chemical forms. In closed-loop systems, the potential for buildup of inhibitory compounds also exists. In addition, new processes need to be evaluated that minimize the cost of nitrogen losses, such as the cultivation of feedstocks that produce nutrients for use in the cultivation system.

2.1.2.4 Advanced Algal Systems Research and Development Approach for Overcoming Challenges and Barriers

The Advanced Algal Systems R&D approach for overcoming the key challenges and barriers described above is outlined in its work breakdown structure (WBS), organized around five elements, as shown in Figure 2-15 and further summarized in Table 2-6. R&D activities are performed by national laboratories, universities, industry, consortia, and a variety of state and regional partners.

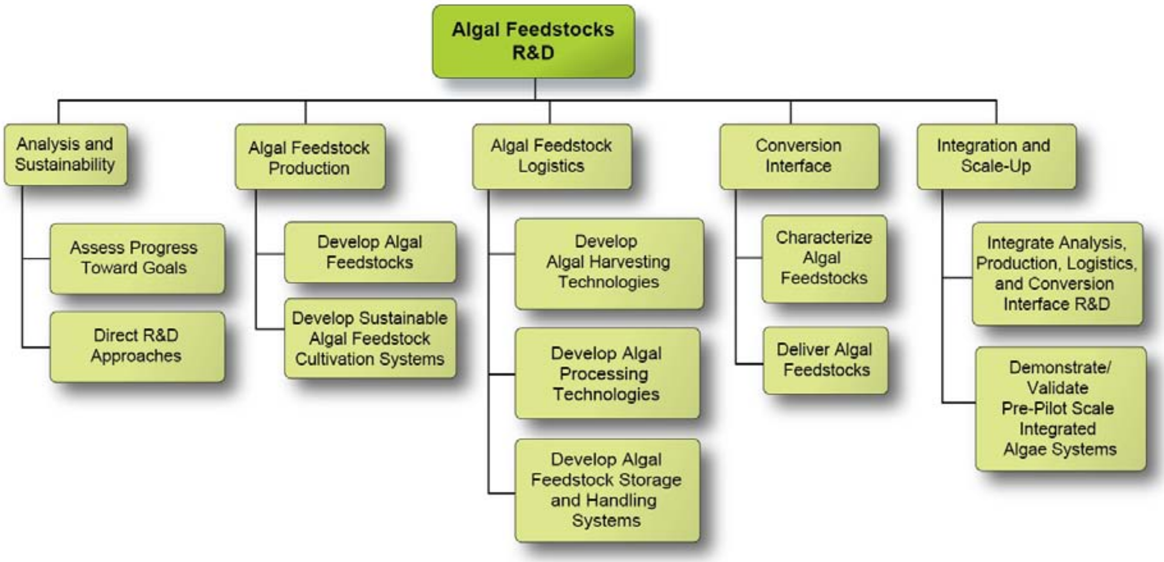

Figure 2-15: Advanced Algal Systems R&D work breakdown structure

Analysis and Sustainability

The primary work within the analysis and sustainability element focuses on assessing progress toward technical targets and cost goals and guiding the direction and priority of R&D. These analyses are continuously refined with technical and economic data from existing projects. Resource assessment is a second key area that includes establishing an inventory of national feedstock resource potential and assessing environmentally sustainable feedstock availability now and in the future. Planned R&D analysis activities for algal feedstock and processing systems include techno-economic and life-cycle analyses for multiple algal biomass production and processing scenarios.

Algal Biomass Production Research and Development

The focus of algal biomass production R&D is enabling the sustainable production of algae-derived products, including biofuels and high-value co-products by developing abundant, cost-effective, and sustainable algal biomass supplies in the United States. There are two main focus areas: (1) algal feedstock development and (2) cultivation systems development. Algal feedstock development focuses on developing stable algal strains that produce high yields and resist predators and that are suitable for cultivation in large-scale algal biofuel feedstock farming operations. Cultivation systems development focuses on developing materials, systems, and strategies to sustainably grow algal biomass suitable for downstream conversion.

Algal Feedstock Logistics Research and Development

The primary algal feedstock logistics R&D focus is to develop, test, and demonstrate technologies for the harvesting and processing of cultivated algae to create biomass feedstocks suitable for conversion to biofuels. Algal feedstock logistics focuses on three main areas: (1) algae harvesting, (2) harvested algae processing, and (3) processed algae stabilization and transport.

Conversion Interface R&D

The conversion interface element aims to identify key algal feedstock characteristics and standards for downstream conversion processes. A unique aspect of the conversion interface is the extent to which feedstock preprocessing and biofuel conversion technologies, such as lipid extraction or hydrothermal liquefaction, are physically integrated with algae production. Efficient and effective linkage between algal feedstock and conversion processes is critical to facilitate the functioning of the entire value chain. The conversion interface area primarily addresses the effect of algae processing operations on conversion technology performance characteristics. Compositional analysis of the intermediate also helps to evaluate water and nutrient recycle efficiency. These efforts will help to develop and optimize conversion process input specifications so that process economic targets can be achieved.

Integration and Scale-Up

Integrating analysis, biomass production, logistics, and conversion is particularly important to advancing algal systems R&D. Biomass properties (such as cell size, media composition, and carbohydrate/protein/lipid content) can affect downstream processes of harvesting and conversion. As methods to improve upon algal biomass production, harvesting, and conversion are developed, techno-economic and life-cycle analyses need to be run in parallel to bolster research focus to those processes with the best and most sustainable economic outcomes. Therefore, the Office continues to fund integrated projects that coordinate algal strain improvement for biomass production with harvesting and conversion processes with direct data feeding into techno-economic and life-cycle analyses, in order to select pathways that are successful at all stages of the production chain.

Scaling-up algal technologies, considered one of the largest challenges in the commercialization of algal biofuels, is necessary to demonstrate and validate algae systems. High biomass productivities or effective harvesting processes at small scales do not always translate to success in outdoor environments or at large scales. This is due to multiple factors including engineering constraints, pond ecology and pathology, and other issues. Scaling up nutrient sources that are inexpensive at small scales may be economically prohibitive at commercial scales. To address the pervasiveness of issues related to scale, in 2013, the Office invested in “open source” test bed facilities, the Algae Testbed Public-Private Partnership (ATP^3), with 5 locations in the United States. ATP^3 provides open testbed facilities for collaborative research, development, and deployment of algal technologies, productions, analysis, and commercialization processes. Small-scale lab research closely tied to performance of large-scale experiments is a priority to provide an iterative learning process that will expedite lessons learned before scaling to larger pilot facilities. Scaling to larger pilot and demonstration facilities may involve extensive capital deployment, construction management, and independent engineering monitoring. Pilot- and larger-scale projects are handled by the DMT program area (Section 2.3).

Table 2-6: Algal Feedstocks R&D Activity Summary

WBS Element	Description	Barrier(s) Addressed
Analysis and Sustainability	Analyze availability, cost, and sustainability of algal feedstock production and logistics systems through development of techno-economic analysis and life-cycle analysis models and collection of life-cycle analysis and SOT data. - Assess and quantify the geospatial volumetric supply potential of algal feedstocks and aggregate to national scale, incorporating technical, environmental, economic, and sustainability factors. Analyze factors that determine multiple and competing uses of algal feedstocks. - Analyze and model the performance of algal feedstock production and logistics systems. - Analyze impacts of algal feedstock production and logistics systems on human, animal and plant health, and biodiversity.	Aft-A: Biomass Availability and Cost Aft-B: Sustainable Production Aft-D: Sustainable Harvesting Aft-G: Feedstock Characterization, Quality, and Monitoring Aft-H: Storage Systems Aft-J: Material Properties Aft-M: Integration and Scale-Up Aft-N: Algal Feedstock Processing
Production	Develop productive and robust algal feedstocks, and develop, test, and demonstrate sustainable algal feedstock production systems. - Develop algal germplasm and enable development of genetic technologies. - Explore and identify underlying biological phenomenon and traits in algae that convey desirable characteristics for large-scale cultivation. - Discover, breed, or engineer productive and robust algae strains for increased production scales and lower operational costs. - Develop laboratory tools and technologies to expedite the development of algal strains for large-scale cultivation. - Develop materials, systems, and strategies to utilize advanced algal feedstock development to sustainably grow algal biomass suitable for downstream conversion. - Develop, test, and demonstrate open, closed, hybrid, and/or offshore cultivation system technologies for improved productivity and reduced costs. - Develop technologies and management strategies for efficient use of system resource requirements, such as water, nutrients, CO_2, and light. - Integrate fundamental learning from community and systems ecology into cultivation design and practice to maximize productivity and resilience.	Aft-A: Biomass Availability and Cost Aft-B: Sustainable Production Aft-C: Feedstock Genetics and Development
Logistics	Develop, test, and demonstrate technologies for harvesting and processing cultivated algae. - Develop, test, and demonstrate algal harvesting (dewatering) technologies with improved efficiency and reduced costs. - Develop, test, and demonstrate technologies that process algal biomass into products or intermediates through lysis, fractionation, extraction, and/or separation methods with improved efficiency and reduced costs. Investigate systems that integrate and/or circumvent these steps. - Develop, test, and demonstrate systems to store and handle whole and post-processed algal feedstocks with improved efficiency and reduced costs.	Aft-D: Sustainable Harvesting Aft-G: Feedstock Characterization, Quality, and Monitoring Aft-H: Storage Systems Aft-J: Material Properties Aft-M: Integration and Scale-Up Aft-N: Algal Feedstock Processing
Conversion Interface	Identify key algal feedstock characteristics and standards for downstream processes. - Analyze multiple pre- and post-processed algal feedstocks and determine physical properties and chemical composition (lipids, carbohydrates, proteins, inorganics, and water) for efficient lipid upgrading, nutrient recycling, biochemical or thermochemical conversion, or transformation into bioproducts or biopower. - Investigate effects of feedstock characteristics in conversion experiments to develop an understanding of the correlation between feedstock preprocessing and conversion yields and selectivity. - Deliver feedstocks and feedstock measurement procedures for conversion R&D.	Aft-B: Sustainable Production Aft-J: Material Properties
Integration and Scale-Up	Conduct pre-pilot-level demonstration and validation of all key technologies to produce algal feedstocks for biofuels. - Integrate algae production and logistics system technologies, identify system scale-up issues, and validate technoeconomics and environmental impacts at R&D scale. - Integrate algae production and logistics system technologies, identify system scale-up issues, and validate technoeconomics and environmental impacts at pre-pilot scale.	Aft-A: Biomass Availability and Cost Aft-B: Sustainable Production Aft-M: Overall Integration and Scale-Up

2.1.2.5 Prioritizing Advanced Algal Systems Research and Development Barriers

The key barriers to the development of algal feedstocks are the cost, quality, and volume of available sustainably-grown biomass to supply the growing biobased industry for biofuels, bioproducts, and biopower. Design cases and accompanying state-of-technology reports are used to describe discreet barrier areas to achieving large volumes of low-cost, high-quality algal biofuel intermediates. Analysts use modeled scenarios, developed in close collaboration with researchers, to perform conceptual evaluations termed "design cases." These design cases provide a detailed basis for understanding the potential of conversion technologies and help identify technical barriers where research and development could lead to significant cost improvements (please refer to Appendix A for full details of cost projections and targets). The following are critical emphasis areas identified as a result of these analyses:

- Developing biology and culture management approaches to unlock algal biomass productivity potential and stable cultivation.
- Developing low-cost, scalable cultivation systems that maximize reliable annual biomass yield and quality and minimize energy use, water consumption, land use, and nutrient additions.
- Developing low-cost, high-throughput harvest technologies that can be integrated with cultivation systems.
- Performing integrative analysis to identify critical barriers and evaluate impacts on overall yield to developments in biology, cultivation, and processing.
- Developing higher-value co-products that can be produced and recovered along with biofuel intermediates
- Demonstrating feasible routes and developing rigorous models to decouple the final upgrading of hydrocarbon-based biofuel intermediates to finished fuels and/or blendstocks to take advantage of existing depreciated refining infrastructure.

The Office has developed two design cases for algae, each supplied by a common nth plant algae farm model to provide algal biomass, followed by two separate conversion pathways that take the delivered algal biomass and produce advanced biofuels. The conversion designs are combined algae processing (CAP) and whole algae hydrothermal liquefaction and upgrading (HTL).

Algae Farm

The algae farm design and SOT analysis[8] establishes a set of process, design, and cost goals projected to be achieved through R&D for the cultivation and harvesting/dewatering of algal biomass grown photosynthetically in open, well-mixed, CO_2 enriched, low-cost ponds. Costs goals are expressed in minimum biomass selling prices (MBSPs). The algae farm design assumes process integration with the conversion facility but models a standalone MBSP. While this arrangement of a standalone biomass price may not reflect business models of actual algal

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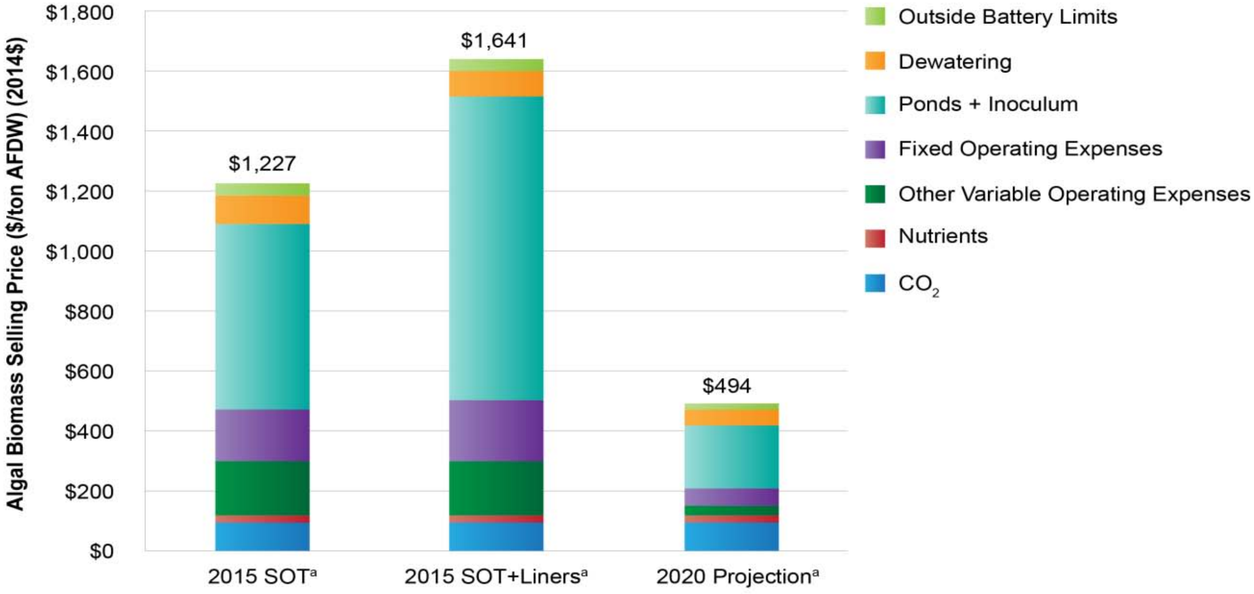
[8] R. Davis, et al. (2015), *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, National Renewable Energy Laboratory, NREL/TP-5100-64772.

biofuel operations, separately tracking biomass and biofuel minimum selling price aligns with standard Office assumptions and more easily allows consideration of a variety of conversion processes to both high-value products and fuels.

Figure 2-16 and Table 2-7 show nth plant MBSP projections for the algae farm, with accompanying technical targets shown in Appendix A, Table A-2. The 2015 MBSP SOT is based on cultivation data furnished by the ATP^3 test-bed consortium[9] and harvest data from literature and vendor sources described in the algae farm design report.[10] A liner case is included in the 2015 SOT because while unlined, saline media ponds are in domestic commercial operation today, it is unclear to what extent the siting considerations (e.g., suitable native soils) may limit the domestic resource potential; therefore, both cases are presented. The analysis clearly indicates that to achieve the future design case targets of <$5/GGE MFSP without high-value co-products, the capital cost of pond liners cannot be justified using standard Office design case conventions.



[a] 2015 MBSP projections are derived using cultivation data from the ATP^3 test-bed consortium with 2015 Algae Farm design report assumptions.

Figure 2-16: Cost contribution for algal biomass selling price by process area

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[9] ATP^3 Algae Testbed Public-Private Partnership, http://en.openei.org/wiki/ATP3.

[10] R. Davis, et al. (2015), *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, National Renewable Energy Laboratory, NREL/TP-5100-64772, http://www.nrel.gov/docs/fy16osti/64772.pdf.

Table 2-7: Summary of Key Cost Contributions for Algal Biomass Production Models

Burdened production cost breakdown, $/ton (2014$)[b]	2015 SOT[a]	2015 SOT + Liners[a]	Design Case
Cultivation + Inoculum System	$945	$1,359	$289
CO_2 + nutrient demands[c]	$124	$124	$120
Remainder	$158	$158	$85
Total	**$1,227**	**$1,641**	**$494**

[a] 2015 MBSP projections are derived using cultivation data from the ATP^3 test-bed consortium11 with 2015 Algae Farm design report assumptions.
[b] Values represent burdened costs including capital costs plus allocated fixed + variable operating costs. Note that ponds are not fully lined in the SOT or projection base cases.
[c] Does not include CO_2/nutrient recycle credits from downstream conversion operations (varies by conversion pathway).

Combined Algae Processing Pathway

The combined algae processing (CAP) conversion pathway in its current embodiment represents a variety of processing options for conversion of algal carbohydrates and lipids to fuel and blendstock products. This current pathway configuration focuses on fermentation of sugars and extraction/upgrading of lipids with high fractional energy yield to hydrocarbon products (e.g., renewable diesel), supplemented by additional energy yield to ethanol as a representative fermentative product from sugars—primarily to demonstrate a means to achieve a modeled minimum fuel selling price of roughly $5/GGE by 2022. Priority areas, technical targets, and accompanying cost projections for conversion of algal biomass to fuels and coproducts are documented in the 2014 algal lipid upgrading (ALU) design report.[12] The CAP pathway combines conversion cost projections from the 2014 ALU case with algae production cost projections from the recent algae farm design. The CAP design case describes one *single, feasible* conversion pathway to transparently document the assumptions and details that went into its design. It is not meant to provide an exhaustive survey of process alternatives, although a number of such alternatives exist for a fractionation-based pathway which may be well-suited for production of high-value coproducts (e.g., from algal sugars, lipids, or protein fractions isolated from the native biomass). Future work in the CAP pathway will investigate such coproduct opportunities, in support of presenting a path towards achieving $3/GGE fuel cost goals.

Figure 2-17 and Table 2-8 show projected minimum fuel selling prices for algae-based biofuel produced via the CAP pathway based on the yields and accompanying technical projections described in Appendix A, Table A-3. Four scenarios are presented here: (a) current SOT benchmarks based on an nth plant unlined base case pond design, (b) the same SOT case assuming the use of fully-lined ponds, (c) original 2022 targets based on the 2014 design report, and (d) revised 2022 targets based on adjusting the design case model to match up with the

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[11] ATP^3 Algae Testbed Public-Private Partnership, http://en.openei.org/wiki/ATP3.
[12] Davis, R. et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal iomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products*, National Renewable Energy Laboratory, NREL/TP-5100-62498, http://www.nrel.gov/docs/fy15osti/62498.pdf.

biomass composition, yields, and cost targets projected from the newer 2015 algae farm design report (both 2022 cases assume the use of unlined ponds).

The elemental and compositional analysis of the biomass assumed in the 2015 SOT and revised 2022 cases is shown in Table 2-8. The economics of the CAP process are highly sensitive to the biomass composition and the cost impact of meeting these specifications on the MBSP described above is not known at this time. The MBSP SOT is based on an algae strain and composition that, due to the high protein content, is not suitable for the CAP process. In the future, it may be valuable to utilize consistent biomass specifications for the algae farm output and conversion pathways input, but that is not feasible right now.

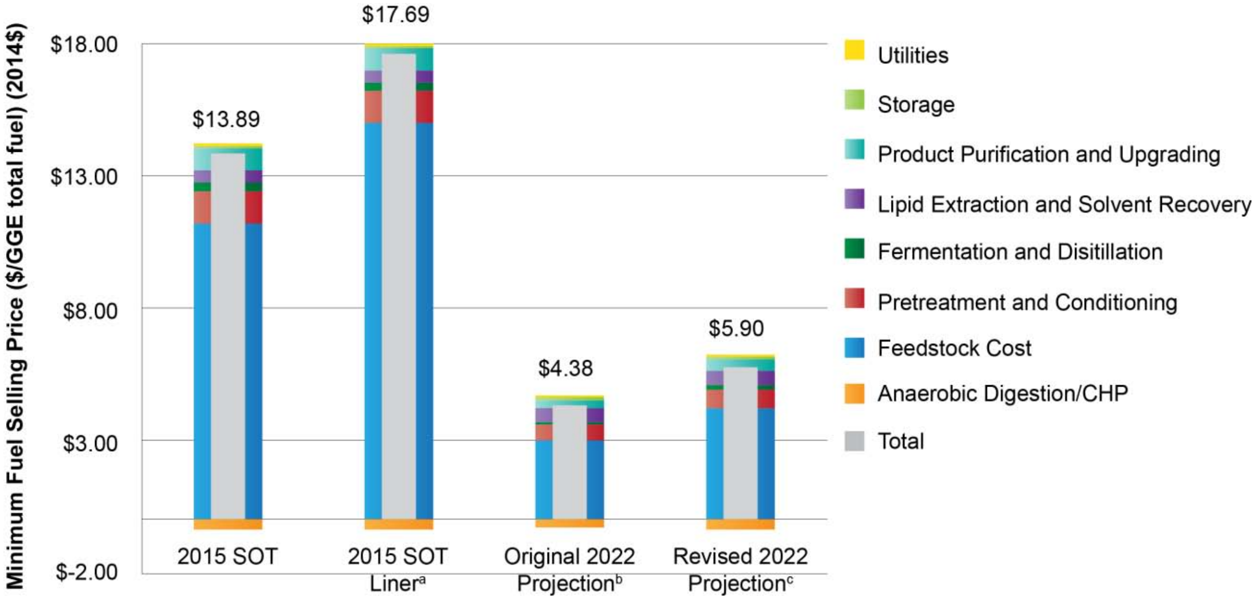
Table 2-8: Elemental and Component Composition for Mid-Lipid *Scenedesmus* Strain Assumed for Both the SOT and Revised 2022 Projections in the CAP Pathway

Elemental (AFDW wt%)[a]	
C	54.0
H	8.2
N	1.8
O	35.5
S	0.2
P	0.22
Total	100.0

Component (dry wt%)	
Ash	2.4
Fermentable carbohydrates	47.8
Other carbohydrates [b]	5.0
Protein	13.2
Lipids (fuel-relevant lipids as FAME)	27.4
Non-fuel polar lipid impurities	2.7
Cell mass	1.6
Total	100.0

[a] Original analytical data as measured achieved 100.2% mass closure including ash; adjusted here to AFDW basis and 100% closure.

[b] Original analytical data as measured achieved 89.5% mass closure including ash; adjusted here to 100% closure.



[a] 2015 MBSP projections are derived using cultivation data from the ATP^3 test-bed consortium with 2015 Algae Farm design report and 2014 ALU design case assumptions.
[b] Original 2022 projection based on 2014 ALU design report (assumed biomass feedstock)[13]
[c] Revised 2022 projection based on modified ALU design case (modeled biomass feedstock)[14]

Figure 2-17: Cost contribution by process area for CAP Pathway

Table 2-9: Summary of Cost Contributions for CAP Pathway

Production Cost Breakdown, $/GGE (2014$)	2015 SOT[a]	2015 SOT + Liners[a]	Original 2022 Projection[c]	Revised 2022 Projection[d]
Feedstock	$11.25	$15.05	$3.06	$4.23
Conversion	$1.95	$1.95	$1.14	$1.35
Hydrotreating	$0.81	$0.81	$0.30	$0.46
Anaerobic Digestion [b]	($0.27)	($0.27)	($0.20)	($0.25)
Balance of Plant	$0.15	$0.15	$0.08	$0.11
Total	**$13.89**	b **$17.69**	**$4.38**	**$5.90**

[a] 2015 MBSP projections are derived using cultivation data from the ATP^3 test-bed consortium with 2015 Algae Farm design report and 2014 ALU design case assumptions.
[b] AD contribution includes coproduct credits attributed to nutrient + CO_2 recycles back to production ponds
[c] Original 2022 projection based on 2014 ALU design report (Appendix A, Table A-3)
[d] Revised 2022 projection based on adjusting ALU design case model for consistency with 2015 algal biomass design report outputs (Appendix A, Table A-2)

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[13] R. Davis et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products*, National Renewable Energy Laboratory, NREL/TP-5100-62498, http://www.nrel.gov/docs/fy15osti/62498.pdf.
[14] R. Davis et al. (2015), *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, National Renewable Energy Laboratory, NREL/TP-5100-6477, http://www.nrel.gov/docs/fy16osti/64772.pdf.

Algal Hydrothermal Liquefaction Pathway

The algal hydrothermal liquefaction (HTL) design report [15] documents a pathway for converting whole algae, rather than the extracted lipids, to fuel and other products. Dewatered algae (20 wt% on an ash-free basis) is pumped to the HTL reactor. Condensed phase liquefaction then takes place through the effects of time, heat, and pressure. The resulting HTL products, oil, solid, aqueous phase, and gas are separated, and the HTL oil is hydrotreated to form diesel and some naphtha-range fuels. The HTL aqueous phase contains significant levels of nitrogen and carbon that must be recovered for their value as nutrients. The HTL aqueous phase is sent to catalytic hydrothermal gasification to convert all organics to carbon dioxide and methane before recycling the treated water back to the ponds to reduce the demand for fresh nutrients during cultivation. Process off-gas may be used to generate hydrogen, heat and/or power. A hydrogen source is included as hydrotreating is assumed to be co-located with the algae ponds and HTL conversion. Nutrients are recovered by recycling treated water containing dissolved carbon dioxide and ammonia, carbon dioxide containing flue gas, and phosphorus recovered from treated HTL solids back to the algae ponds.

Figure 2-18 and Table 2-11 show projected minimum fuel selling prices for algae-based biofuel produced via the HTL pathway based on the yields and accompanying technical projections described in Appendix A, Table A-4.

The composition for the SOT and for the target case are shown in Table 2-10. The HTL process is less sensitive to biomass composition than the CAP process; however, biomass composition still significantly affects the MFSP. Although biomass specifications will likely differ between CAP and HTL pathways, the same MBSP SOT is currently used for both cases. In the future, it may be valuable to better understand the dynamics between biomass composition, MBSP, and MFSP for conversion pathways. As with the CAP pathway, the cost to produce biomass is the single most significant factor affecting the final fuel cost.

This analysis demonstrates a strategy for achieving an overall fuel selling price near $4.50/GGE, on-par with published targets for algal hydrothermal liquefaction processing. However, additional improvements will be required to further improve economics and meet the Office's $3/GGE performance goal. The key conversion improvements needed are improvements in separation of the HTL oil from the aqueous phase and ensuring that the highest value is obtained from the HTL aqueous phase.

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[15] Jones et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading*, Pacific Northwest National Laboratory, PNNL- 23227, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf

Table 2-10: Elemental and Component Composition Details for SOT and 2022 Target Strains*

	2015 SOT	2022 Target
Ultimate Analysis, wt%		
C	38.6%	52%
H	5.3%	7.5%
O	27.5%	22%
N	5.0%	4.8%
S	1.6%	0.6%
ash	22.0%	13%
P	0.4%	0.6%
Total	**100.4%**	**100.5%**
Proximate Analysis		
ash	23.4	14.2
other	6.7	14.5
carbohydrates	28.1	19.1
protein	28.1	31.3
total lipids	11.8	20.8
Total	**98.1**	**99.9**
% of total lipids as FAME	5	17.4

Note: Only ultimate analysis, normalized, is used in the models.

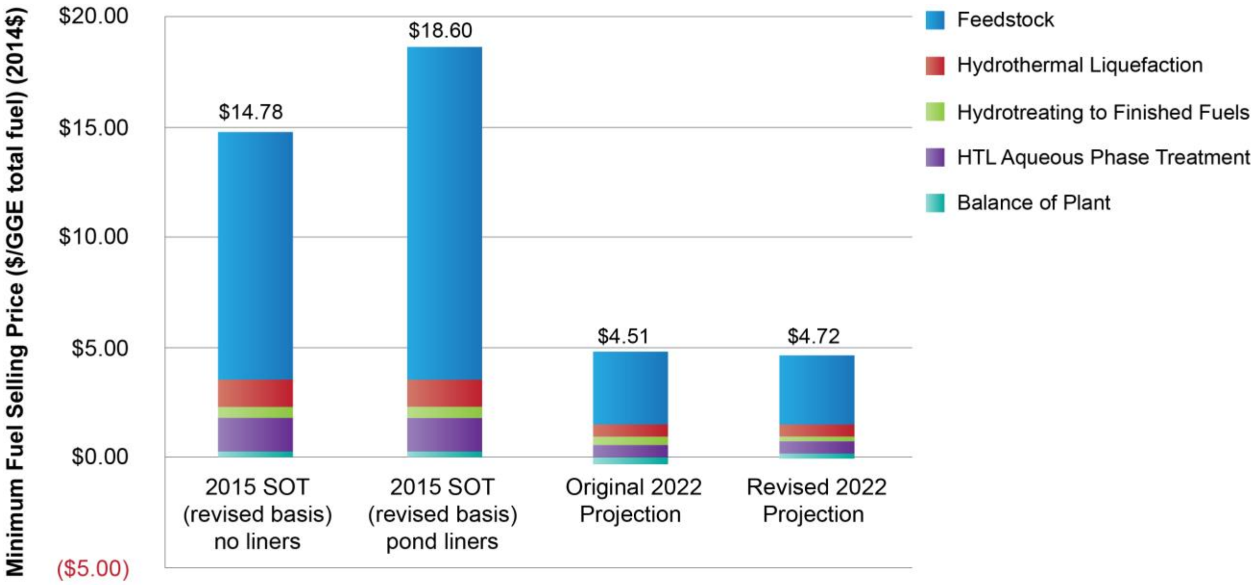

Figure 2-18: Cost contribution by feedstock and conversion process area for HTL Pathway

Table 2-11: Summary of Cost Contributions for HTL Design Case and SOT

Production Cost Breakdown, $/GGE (2014$)	2015 SOT [a]	2015 SOT [a]pond liners	Original 2022 Projection[b]	Revised 2022 Projection[c]
Feedstock	$11.33	$15.15	$3.33	$3.18
Hydrothermal Liquefaction	$1.18	$1.18	$0.61	$0.49
Hydrotreating Upgrade to Finished Fuels	$0.44	$0.44	$0.35	$0.31
Catalytic Hydrothermal Gasification	$1.54	$1.54	$0.61	$0.57
Balance of Plant	$0.29	$0.29	($0.38)	$0.17
Total	$14.78	$18.60	$4.51	$4.72

[a] 188 tpd AFDW algae @ $1222/ton; naphtha valued at production cost
[b] 1340 tpd AFDW algae @ $430/ton; naphtha values at $3.25/gal (design case reference)
[c] 568 tpd AFDW algae @ $491/ton; naphtha valued at production cost.

Pathway Sustainability Metrics

Supply chain sustainability analyses were performed on both pathways to quantify the GHG reduction potential of the finished fuel and provide a method to track other sustainability metrics such as water consumption. While the metrics presented are inclusive of the entire biomass and conversion supply chain, these 2015 SOT sustainability metrics do not include the recent Algae Farm design case and instead are based on the 2014 design cases.

Combined Algae Processing:

Supply chain and sustainability analysis on life-cycle energy use and GHG emissions was not yet available on the entire CAP pathway detailed above. However, it was performed on the process documented in the ALU design case (e.g. the “original” 2022 ALU targets) with a system boundary encompassing nutrient production, biomass and biofuel production, transportation of fuel to terminal and station, and combustion in a passenger vehicle.[16] As shown in Table 2-12, the ALU design required 0.5 MJ of fossil fuel and 0.07 MJ of petroleum per MJ of renewable diesel produced. GHG emissions were 35 gCO_2e per MJ of total fuel (combining renewable diesel and ethanol on an LHV energy basis).

Table 2-12: Sustainability Metrics for 2014 ALU Design Case, 2022 Design Case Basis

ALU Sustainability Metric	
Fossil energy consumption (MJ/MJ fuel)	0.5
Petroleum use (MJ/MJ fuel)	0.07
GHG emissions (g CO_2e/MJ fuel)	35
GHG emissions (g CO_2e/GGE LHV)	4100

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[16] Argonne National Laboratory, *Manuscript in Preparation*.

Hydrothermal Liquefaction:

Supply chain and sustainability analysis on life-cycle energy use and GHG emissions was performed on the algae hydrothermal liquefaction design.[17] The system boundary was comparable to that used for the ALU design case LCA and does not include the recent algae farm design. This LCA study utilized a previously validated Excel-based model of biomass production plus Aspen based mass and energy balances from the HTL design case for biomass processing and fuel production, including drying and storage of excess summer biomass for use during the winter. As shown in table 2-13, the pathway required 0.45 MJ of fossil fuel and 0.02 MJ of petroleum per MJ of renewable diesel produced. GHG emissions were 37 gCO_2e per MJ of total fuel (combining renewable diesel and naphtha on an LHV energy basis). Table 2-14 shows the water consumption from eight representative sites as described in referenced resource assessment.

Table 2-13: Sustainability Design Basis Metrics for Algal Hydrothermal Liquefaction Processing Pathways, 2022 Design Basis (2014 HTL Design Case)[18]

HTL Sustainability Metrics	
Fossil energy consumption (MJ/MJ fuel)	0.45
Petroleum use (MJ/MJ fuel)	0.02
GHG emissions (g CO_2e/MJ fuel)	37
GHG emissions (g CO_2e/GGE)	4,400

Table 2-14: Water Consumption from Eight Representative Sites in Texas, Louisiana, and Florida

	ALU	HTL
Representative Site	**Water use,[a] including farming (gal / GGE LHV)**	
1 (TX)	150	160
2 (TX)	100	100
3 (TX)	64	63
4 (LA)	11	9
5 (FL)	16	14
6 (FL)	20	19
7 (FL)	33	31
8 (FL)	36	35

[a] Evaporative minus rainfall plus consumptive use during conversion

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[17] A. K. Pegallapati, J. B. Dunn, E. D. Frank, S. Jones, Y. Zhu, L. Snowden-Swan, R. Davis, and C. M. Kinchin (2015), *Supply Chain Sustainability Analysis of Whole Algae Hydrothermal Liquefaction and Upgrading*, Argonne National Laboratory, ANL/ESD-15/8, http://www.osti.gov/scitech/biblio/1183770.

[18] Jones et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading*, Pacific Northwest National Laboratory, PNNL- 23227, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf.

2.1.2.6 Algal Feedstocks Research and Development Milestones and Decision Points

The key upcoming milestones and decision points for Advanced Algal Systems R&D over the next several years in support of the R&D approach to achieve the program area's 2022 performance goal are described above in Section 2.1.2.2 and illustrated below with accompanying decision points in Figure 2-19.

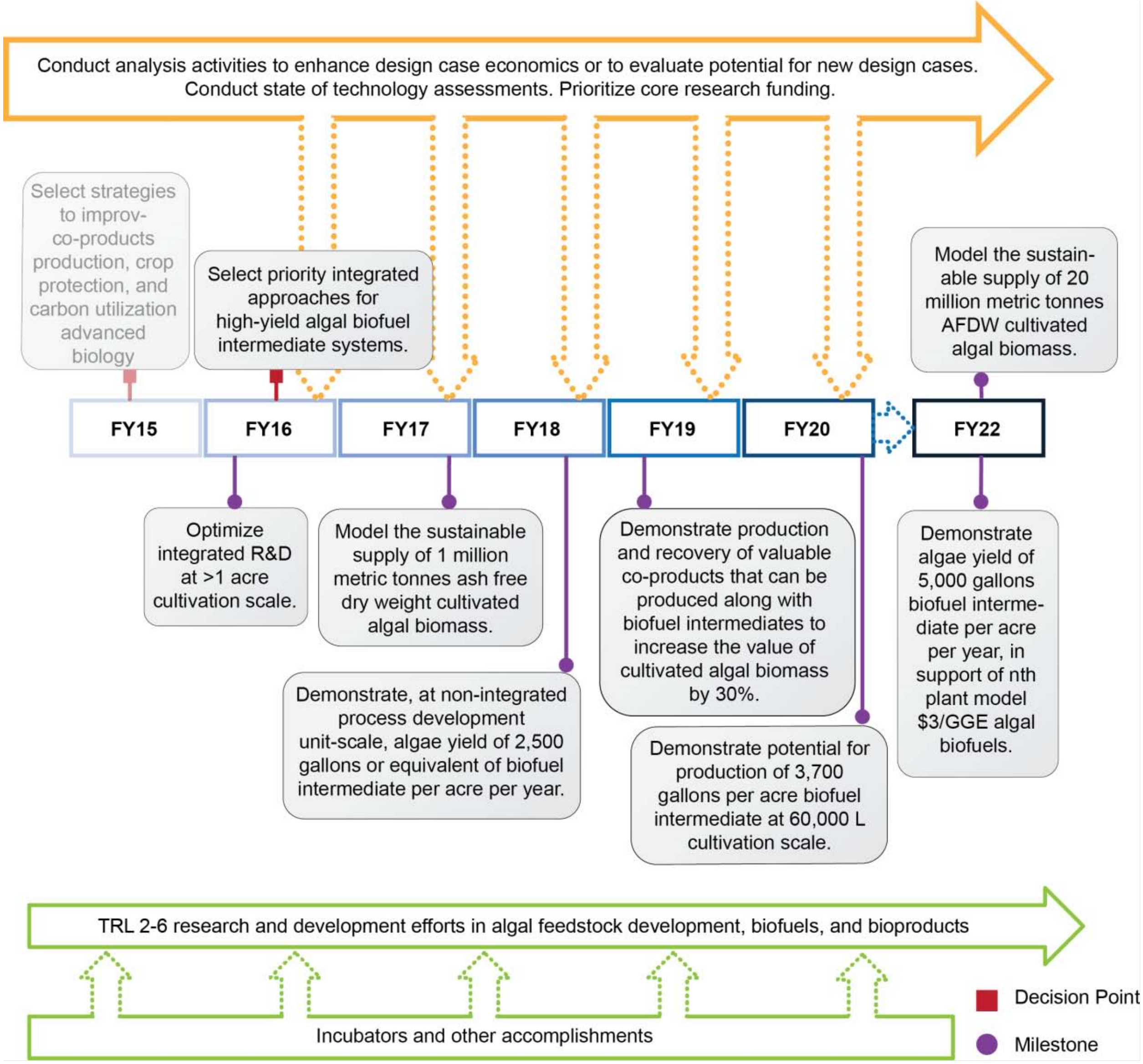

Figure 2-19: Advanced Algal Systems R&D key milestones and decision points

2.2 Conversion Research and Development

The strategic goal of Conversion Research and Development (R&D) is to *develop commercially viable technologies for converting biomass feedstocks via biological and chemical routes into energy-dense, fungible, finished liquid transportation fuels such as renewable gasoline, diesel, and jet fuel, as well as bioproducts or chemical intermediates and biopower*. To achieve this goal, a variety of conversion technologies are being explored that can be combined into pathways from feedstock to product (Figure 2-20). Historically these pathways have been roughly classified as either biochemical or thermochemical to reflect the primary catalytic conversion system employed as well as the intermediate building blocks produced. Generally, biochemical conversion technologies involve pathways that use sugars and lignin intermediates, while thermochemical conversion technologies involve pathways that use bio-oil and gaseous intermediates. Moving forward, however, the traditional division between biochemical and thermochemical conversion technologies does not encompass the diversity of innovative technologies, and this strategy reflects a shift to a simpler process flow in which the polymeric feedstock is deconstructed into intermediates that are then upgraded into products (Figure 2-20).

The conceptual block flow diagram in Figure 2-20 outlines the main process steps and materials in the feedstock-to-end products process. This figure depicts a high-level view of the primary unit operations within the scope of conversion R&D to create desired biomass-derived products. Each conversion technology involves at least two main steps: deconstruction of feedstock into relatively stable chemical building blocks through the breaking of chemical bonds followed by the controlled recombination of those building blocks into a slate of desired products.

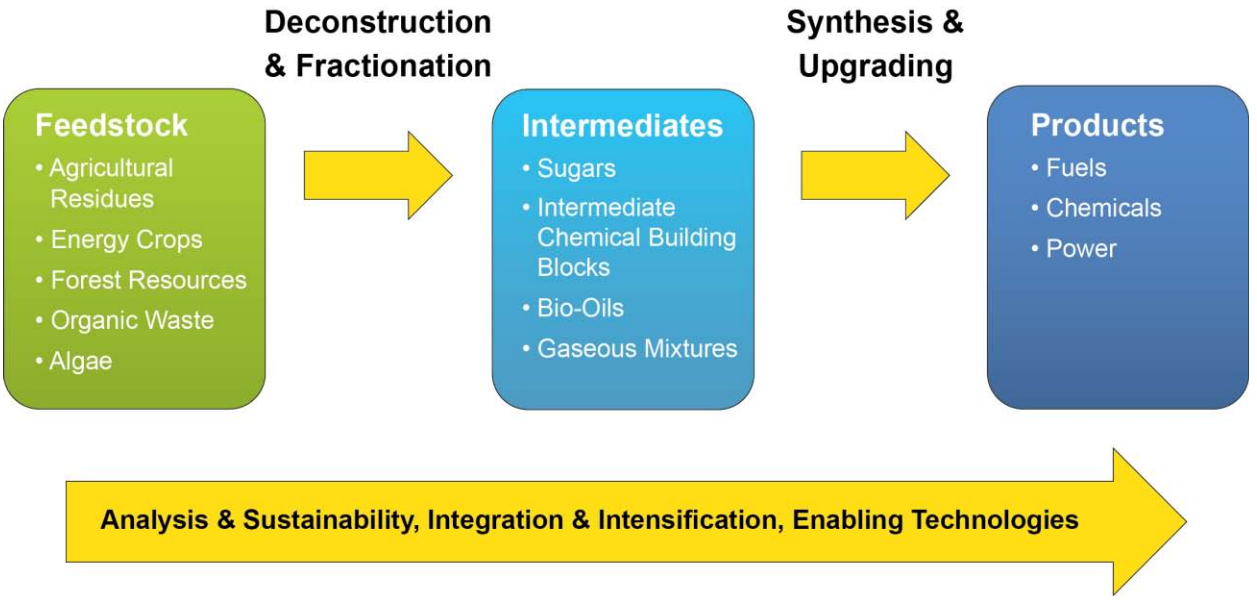

Figure 2-20: Generalized conversion route for biomass-derived feedstocks to renewable products

These renewable products can include finished fuels, fuel precursors, high-quality intermediates, such as sugars, syngas, or stabilized bio-oils, and high-value, bio-based chemicals that enable fuels production. Specific process operating conditions, inputs, and outputs vary within and between each step. These process variations impact key performance outcomes (such as titer, rate, selectivity and yield), which in turn determine economic viability. Potential environmental impacts are also assessed for conversion pathways by evaluating sustainability metrics and conducting life-cycle assessments.

Conversion Process Steps

Conversion can be broken down into two areas: Deconstruction and Fractionation, and Synthesis and Upgrading. Figure 2-21 highlights key technologies within Deconstruction and Fractionation as well as Synthesis and Upgrading, which can be linked to form a complete conversion pathway from feedstock to products. The arrows represent the transition of organic matter from feedstock to intermediates to end products, showing the diversity of accessible conversion options. Multiple technologies along several pathways are under development to address the broad range of physical and chemical characteristics of various feedstocks and to reduce the risk that any specific technology could fail to reach commercial viability. Additionally, each linked set of conversion technologies results in the production of a unique product slate with value that will vary depending on market size and demand.

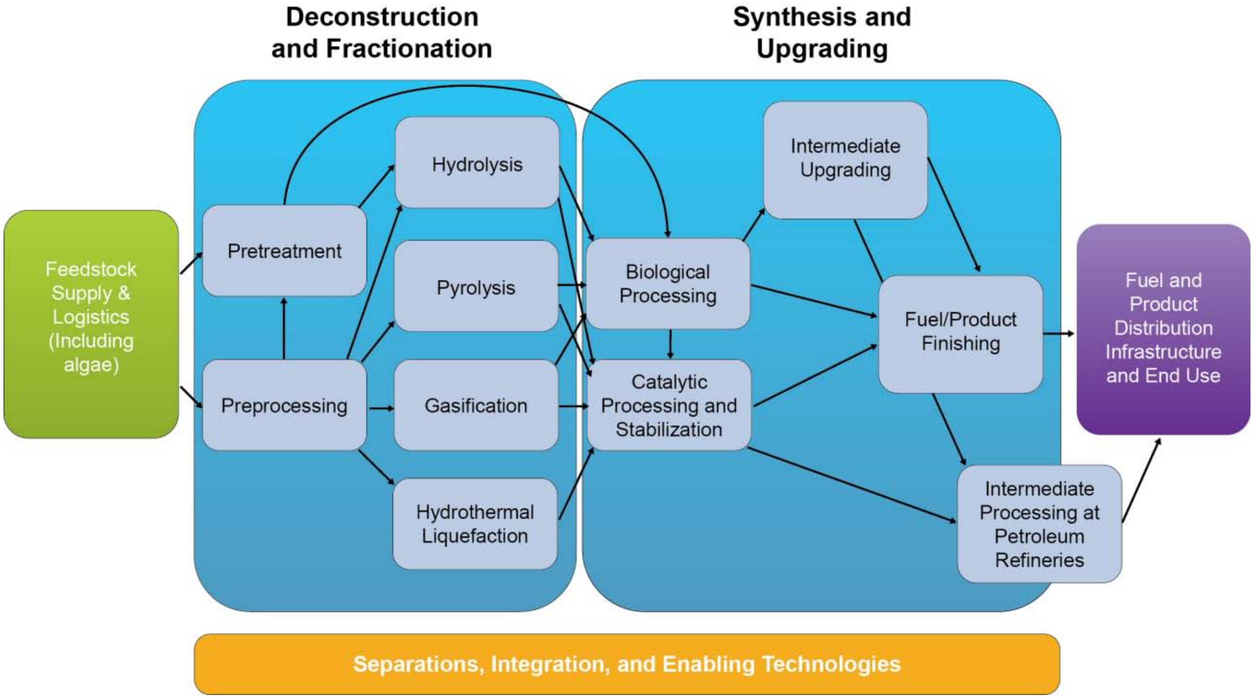

Figure 2-21: Conversion pathways from feedstock to products

Many combinations of unit operations can result in conversion strategies that have the potential for commercial success. The Office cannot pursue all possible permutations, and, ultimately, industry will select the technology combinations that provide them the strongest market advantage. To have the most significant impact on the largest number of alternatives, the Office is performing R&D on a variety of technical building blocks that can be combined and used by industry in various ways to convert biomass to products including fuels. Through analysis of various reference configurations and based on industry feedback, Conversion R&D identifies priority unit operations or key processing components that form the technology building blocks that may contribute the most significant price improvements. Progress is measured against a number of example or reference configurations that are called technology pathways. Technologies will be periodically assessed for economic viability, and pathways will be experimentally validated when technologies are deemed sufficiently advanced to contribute to the Office's $3/GGE performance goal in 2017, 2022, and 2030.

The following section provides a high-level overview of current conversion technologies. The barriers to progress in those areas are outlined in Section 2.2.3.

Deconstruction and Fractionation: Deconstruction and fractionation processes break biomass-derived polymeric feedstock down into tractable intermediate streams. After preprocessing and/or pretreatment, deconstruction processes can be divided into two categories: (1) high-temperature deconstruction and (2) low-temperature deconstruction. High-temperature deconstruction refers to processes performed at or above 200°C and includes deconstruction processes such as pyrolysis, hydrothermal and solvent liquefaction, and gasification. Low-temperature deconstruction refers to processes performed below 200°C and includes deconstruction processes such as enzymatic and acid hydrolysis.

> *Preprocessing:* Development of a variety of conversion technologies is necessary to address the broad range of physical and chemical characteristics of various biomass feedstocks as discussed in Section 2.1, Feedstock Supply and Logistics R&D. Depending on the conversion strategy, a variety of feedstock preprocessing and handling steps may be employed.
>
> *High-Temperature Deconstruction:* High-temperature deconstruction encompasses pyrolysis, gasification, and hydrothermal liquefaction (HTL).
>
>> *Pyrolysis* is the thermal and chemical decomposition of feedstock without the introduction of oxygen to produce a bio-oil intermediate. The bio-oil produced contains hydrocarbons of various lengths but contains more oxygenated compounds than petroleum crude oils and must undergo upgrading before it can be finished into a fuel or used in a refinery. There are several pyrolysis variations that require different catalysts and reaction conditions.
>>
>> *Hydrothermal liquefaction* is a deconstruction process that utilizes a wet feedstock slurry under elevated temperature and pressure to produce a HTL bio-oil. The feedstock is treated with water before entering the reactor and is particularly applicable to algal feedstocks (For more information on the application of HTL to algal feedstocks, see Section 2.1.2); other variations include solvothermal liquefaction where a non-water solvent, such methanol, is used to make the feedstock slurry.
>>
>> *Gasification* is the thermal deconstruction of biomass at high temperature (typically > 700ºC) in the presence of sub-stoichiometric air or an oxygen carrier and sometimes steam followed by gas cleanup and conditioning. In these

processes, feedstock is partially oxidized to form a synthesis gas (syngas), which contains a mixture of light gases such as CO_2, CO, H_2, CH_4, as well as heavier species.

Low-Temperature Deconstruction: Low-temperature deconstruction is the breakdown of feedstock into intermediates by pretreatment followed by hydrolysis. Pretreatment is the preparation of feedstock for hydrolysis via chemical or mechanical processing and separation of feedstock into soluble and insoluble components. This process opens up the physical structure of plant and algae cell walls, revealing sugar polymers and other components. Hydrolysis is the breakdown of these polymers either enzymatically or chemically into their component sugars and/or aromatic monomers.

Synthesis and Upgrading: Intermediates can include crude bio-oils, gaseous mixtures such as syngas, sugars, and other chemical building blocks as outlined in Figure 2-20. These intermediates are upgraded using various techniques to produce a finished product. These finished products could be fuels or bioproducts ready to sell into the commercial market, or could be stabilized intermediates suitable for finishing in a petroleum refinery or chemical manufacturing plant.

Biological Processing: Microorganisms (including, but not limited to, bacteria, yeast and cyanobacteria) can convert sugar or gaseous intermediates into fuel blendstocks and chemicals. Metabolic engineering of these microbes allows for maximum sugar utilization, robustness, and selection of the product slate.

Catalytic Processing and Stabilization: Sugars and other intermediate streams such as bio-oil and syngas are generally upgraded to minimize the effect of reactive compounds to improve storage and handling properties. Liquid sugar streams are filtered and concentrated and can then be catalytically upgraded in an aqueous phase reforming process to generate a range of hydrocarbons. For bio-oil, stabilization may involve hydroprocessing such as hydrodeoxygenation to transform oxygen-rich biomass into a mix of compounds more similar to hydrocarbon-rich petroleum. It may also involve separation and fractionation steps to remove water, coke, catalyst, char, and ash particulates, or metals and oxygenated species. For syngas streams, stabilization involves removal of contaminants from crude biomass-derived synthesis gas. Gas cleanup and conditioning involves the removal of problematic heteroatom compounds, metals, and particulates as well as adjusting the hydrogen-carbon monoxide ratio. Gaseous intermediate upgrading is the conversion of clean gaseous intermediates to fuels or mixed oxygenates via biological organisms (e.g., syngas fermentation) or catalytic processes (e.g., Fischer-Tropsch synthesis or fuel synthesis of mixed alcohols).

Intermediate Upgrading: Intermediate upgrading involves a variety of technologies to transform intermediate streams into crude product streams. Actual upgrading and separations processes will vary greatly according to the identity of the intermediate streams. Streams with tight chemical distributions such as algal lipids, fatty acids, or other products from biological processing may require less complex processes than streams involving more varied compounds. Chemical rearrangement into the final fuel blendstock or product can involve biological or chemical processing.

Fuel/Product Finishing: After upgrading, final product streams must conform to standards for off-take agreements. This may involve removing problematic contaminant compounds and further finishing to attain correct product specifications. For complex bio-oil mixtures, the finishing process may involve balancing various hydrocarbon components, whereas for single compound products the process may only involve removing impurities.

Intermediate Processing at Petroleum Refineries: Certain product streams may be transported to refineries at a more crude stage for upgrading. Placement of this box on the edge of Synthesis and Upgrading and Products in Figure 2-21 represents the interface of conversion technologies with refiners.

Conversion Research and Development Interfaces

Analysis and Sustainability Interface: Conversion technologies are evaluated by techno-economic analysis (TEA) and life-cycle assessment (LCA) not only to determine the cost and carbon footprint of the resulting products, but also to identify the portions of the process that provide the greatest leverage point for R&D. This necessitates interfaces between research and analysis activities, and the crosscutting Sustainability and Strategic Analysis program areas (Sections 2.4.1 and 2.4.2). TEAs and LCAs inform strategic planning on optimal R&D areas and document progress toward achieving program goals. Data generated from conversion R&D on greenhouse gas emissions, as well as energy and water use, also inform the Office's sustainability and analysis activities.

Feedstocks Supply and Logistics Interface: Close coordination between Conversion and the Terrestrial Feedstocks Supply and Logistics R&D (Section 2.1.1) and Advanced Algal Systems R&D (Section 2.1.2) program areas is required to understand the tradeoffs between feedstock cost, quantity, and quality to meet the conversion specification requirements of the biorefinery, and to identify positive synergies to improve efficiencies and reduce production costs.

Demonstration Interface: Demonstration of conversion processes in facilities of increasing scale provides information relevant to process integration and commercial plant design. Additionally, some challenges encountered during demonstration at pilot, demonstration, and pioneer scales can be addressed through R&D performed at bench scale.[1,2,3] The impacts of

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[1] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (2012), "INEOS New Planet BioEnergy Commercializes Bioenergy Technology in Florida," http://www1.eere.energy.gov/bioenergy/pdfs/ibr_arra_ineos.pdf.

[2] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (2012), "Logos Technologies Inc. and Edeniq, Inc. Pilot Corn-to-Cellulosic Migration Biorefinery," http://www1.eere.energy.gov/bioenergy/pdfs/ibr_arra_logos.pdf.

[3] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (2012), "Myriant Succinic Acid Biorefinery (MySAB)," http://www1.eere.energy.gov/bioenergy/pdfs/ibr_arra_myriant.pdf.

conversion technologies on wastewater treatment and heat and power integration are especially significant. Research, development, and demonstration (RD&D) accomplishments are incorporated into the design of the pioneer-scale integrated biorefineries, as demonstrated by the success of projects within the Office's Demonstration and Market Transformation portfolio (see section 2.3).

Intermediate Distribution and Refining: Three general distribution strategies exist for intermediates and final products from conversion processes. The first strategy involves fully upgrading to finished fuel blendstock specifications for gasoline, diesel, jet fuel, or other product (collectively "products") within an integrated biorefinery. The second strategy involves intermediate stabilization, which occurs at several distributed locations, and then stabilized intermediates are transported to a centralized upgrading biorefinery for finishing to product specifications (commonly referred to as the "hub and spoke" model). The third strategy involves production of stable, upgraded intermediates that are suitable for use in a petroleum refinery and can be blended with petroleum-derived streams, thus leveraging existing infrastructure for product finishing. Information regarding the physiochemical properties, reactivities, and compatibilities of intermediates for product finishing is required to successfully implement any of these strategies.

Biofuels Distribution Infrastructure Interface: To be accepted into existing petroleum infrastructure, bioproducts must meet regulated fuel and intermediate specifications. It is particularly critical to understand not only the technical parameters of finished bio-oils but also the behavior of biofuels when blended with petroleum-derived fuels and fuel-handling systems and engines.

2.2.1 Conversion Research and Development Support of Office Strategic Goals

The strategic goal of the Conversion R&D is to *develop commercially viable technologies for converting feedstocks via biological and chemical routes into energy-dense, fungible, finished liquid transportation fuels, such as renewable gasoline, diesel, and jet fuel, as well as bioproducts or chemical intermediates and biopower.*

Activities in this area directly address and support the production of gasoline, diesel, jet fuels, and other enabling products from on-specification feedstock that may be comprised of algae, woody biomass, energy crops, agricultural residues, sorted, dry municipal solid waste (MSW), wet wastes (e.g. biosolids), and other biomass including blends of these various feedstocks. These conversion technologies also support the production of biochemicals and biopower.

2.2.2 Conversion Research and Development Support of Office Performance Goals

The overall goal of Conversion R&D is to develop technologies that enable a reduction in the estimated mature technology processing cost[4] of converting algae or lignocellulosic biomass to

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[4] Estimated mature technology processing cost means that capital and operating costs are assumed to be for an "nth plant" where several plants have been built and are operating successfully, so additional costs for risk financing, longer startups, under performance, and other costs associated with pioneer plants are not included.

hydrocarbon fuels while maximizing the renewable carbon in the desired products. There are many different combinations of unit operations that could result in a successful conversion strategy. In order to track the maturity of these processes as well as evaluate the R&D hurdles for each, several design cases, with cost targets and technical goals, outline how performance goals might be achieved via continued RD&D over the near-, mid-, and long-term. To benchmark the progress of a few representative pathways that link conversion technologies, the Office funds R&D to overcome barriers to support the following cost goals:

- By 2017, validate an nth plant modeled minimum fuel selling price (MFSP) of $3/GGE (2014$) via a conversion pathway to hydrocarbon biofuel with GHG emissions reduction of 50% or more compared to petroleum-derived fuel.
- By 2022, validate an nth plant modeled MFSP of $3/GGE (2014$) for two additional conversion pathways to hydrocarbon biofuel with GHG emissions reduction of 50% or more compared to petroleum-derived fuel.

These performance goals were developed alongside technical design cases that represent possible paths from biomass to fuels and renewable chemicals. Descriptions of these design cases can be found in Section 2.2.5, along with links to the published technical reports.

Milestones towards achieving these goals, related to specific technologies, are graphically represented in Section 2.2.6 and are listed below:

- By 2016, based on techno-economic analysis and available data, select a vapor phase upgrading catalyst and process that can cost-effectively generate refinery-ready intermediates for the 2017 pyrolysis verification.
- By 2017, deliver feedstocks and complete verification operations at pilot scale with fuel production cost modeled at $3/GGE for 2,000 tonnes of feedstock/day.
- By 2018, select an integrated bench-scale lignin deconstruction and upgrading strategy for valorization of lignin in a hydrocarbon fuel production process.
- By 2020, provide enabling capabilities in synthetic biology for industrially relevant, optimized chassis microorganisms and Design-Built-Test-Learn cycles for fuel and chemical production that reduces time-to-scale-up by at least 50% compared to the current average of ~10 years.
- By 2021, complete the R&D necessary to set the stage for a 2022 verification that produces both fuels and high-value chemicals to enable a biorefinery to achieve a positive return on investment.
- By 2022, deliver feedstocks and complete verification operations at pilot scale for an alternate conversion pathway with fuel production cost modeled at $3/GGE for 2,000 tonnes of feedstock/day.

2.2.3 Conversion Research and Development Challenges and Barriers

The challenges and barriers listed in this section highlight areas in which improvements to processes are crucial to advancing the Office’s mission. The aim for all processes is an increase in both carbon and energy efficiency relative to the theoretical maximum. The challenges are categorized into five areas: (1) deconstruction and fractionation, (2) separations, cleanup, and conditioning, (3) synthesis and upgrading, (4) integration and intensification, and (5) crosscutting challenges.

Deconstruction and Fractionation Challenges

Ct-A. Feedstock Variability: Significant variability in feedstocks reduces conversion rates and product yields, negatively impacting process economics. More information is needed on how feedstock variability and characteristics affect overall conversion performance. Feedstock characteristics can vary widely in terms of physical parameters (e.g., particle size, shape, bulk density, surface area, pore volume, thermal-specific heat, thermal diffusivity, etc.) and chemical composition (e.g., moisture, ash, carbohydrate, lignin, problematic contaminants, etc.), even within a single species. This variability can make it difficult and costly to reliably supply biorefineries with formatted feedstocks of consistent, acceptable quality throughout the whole year and to maintain adequate process control.

Ct-B. Reactor Feed Introduction: It is challenging to efficiently introduce cohesive and inconsistent feedstocks with a high percentage of solids into a pressurized reactor at large scale. In addition to challenges of introducing dry feedstocks, new reactor processes and designs are needed for feeding wet cellulosic and wet algal biomass slurries into reactors and for feeding lipids extracted from algae into upgrading systems.

Ct-C. Efficient Preprocessing: Current preprocessing operations such as chemical, mechanical, and thermal treatments limit yield of deconstruction technologies if problematic components are not removed. For high-temperature deconstruction, more cost- and energy-efficient methods for the removal of ash and other problematic components are needed to preserve catalyst performance.

Ct-D. Efficient Pretreatment: Current pretreatment methods for low-temperature deconstruction are often costly, have low yields, or produce too many problematic components. Improved pretreatment methods are needed to increase the availability of sugar polymers for subsequent hydrolysis. Improved methods will maximize yields as well as remove problematic components from the intermediate streams. Developing cost efficient methods for overcoming the natural resistance of lignocelluosic material to deconstruction requires a better fundamental understanding of cell wall architecture and composition. An improved understanding of how each cell wall polymer is modified and interconnected will lead to new and innovative strategies for efficient low temperature pretreatment and subsequent deconstruction.

Ct-E. Efficient Low-Temperature Deconstruction: Current low-temperature deconstruction methods have some combination of low yields, high enzyme costs, low productivity rates, or a lack of robustness. Improved methods are needed for cost-effective and high-yielding deconstruction of pretreated feedstock into tractable intermediate streams. Currently known hydrolytic enzymes that are capable of converting sugar-based polymers into intermediates are not optimized, and new, more-efficient enzymes must be identified. Work is needed to decrease the mass of enzyme required to solubilize a given quantity of feedstock either through increased specific activity toward the substrate or by increasing enzyme robustness. Developing these improved enzymes requires a better fundamental understanding of the biochemical mechanisms underlying enzymatic hydrolysis, including the impact of feedstock architecture and inhibitors.

Previous work on corn stover deconstruction will be leveraged as different feedstocks and blends are investigated. Other goals include improving enzyme temperature tolerance so that pretreated materials do not have to be cooled before enzyme introduction. In addition to hydrolytic enzymes, new enzymes and pathways capable of deconstructing lignin and funneling it into central metabolism or into a stream of tractable intermediates need to be identified to improve the yield of useful carbon from feedstock.

Ct-F. Efficient High-Temperature Deconstruction to Intermediates: High-temperature deconstruction of biomass to both syngas and bio-oil is hindered by common efficiency issues of reliability, low yields, inconsistent quality, and high operating costs. The integration of biomass gasifiers into a biorefinery that produces intermediates will need to overcome the barriers of feeding issues, gas cleanup, and materials capability and gain a better understanding of gasification reactions and reactor behavior. To produce a higher yield of bio-oil, new methods for direct liquefaction technologies (including fast pyrolysis, catalytic fast pyrolysis, hydropyrolysis, or solvent liquefaction) and process parameters must be developed. An understanding is needed of the tradeoffs for producing a higher quality versus higher quantity of bio-oil as well as how this parameter is affected by various biomass blends and formats.

Separations, Cleanup, and Conditioning Challenges

Ct-G. Efficient Intermediate Cleanup and Conditioning: Impurities in intermediates such as sugar/aromatic streams, syngas, and crude bio-oil inhibit the function of downstream biological and chemical catalysts, limiting catalyst turnover and yields of biofuel. Low-cost purification technologies need to be developed to remove contaminants and provide concentrated, clean intermediate streams from which biofuels and biobased chemicals can be manufactured.

For sugar streams, impurities of interest include acetic acid released during hemicellulose hydrolysis; lignin-derived phenolic compounds solubilized during pretreatment; inorganic acids or bases; salts, ash, hexose, and pentose sugar degradation/transglycosylation products; and other compounds introduced during pretreatment.

Syngas cleanup and conditioning were validated in a 2012 demonstration (Appendix C). However, syngas cleanup still requires research into development of reliable and economical tar mitigation, methane reforming, and hot gas filtration in order to provide information relevant to process integration and commercial plant design.

Crude bio-oil is acidic and unstable due to the presence of a complex mixture of reactive species (such as carboxylic acids, aldehydes, ketones, and olefins) that can cause viscosity-increasing polymerization reactions and thus limit bio-oil quality. New characterization methods are needed for identifying highly reactive components of bio-oil that readily polymerize and reduce stability. Increased knowledge of these problematic components and how they are formed under certain reaction conditions will aid in identifying optimum bio-oil production and upgrading technologies.

Synthesis and Upgrading Challenges

Ct-H. Efficient Catalytic Upgrading of Sugars/Aromatics, Gaseous and Bio-Oil Intermediates to Fuels and Chemicals:

Challenges associated with hydrogen sourcing, cost, and utilization as well as reaction mechanisms, must be addressed to enable the development of more efficient, highly active, selective, and durable biological and inorganic catalysts. These catalysts need to transform sugar streams and biomass-derived oils and gases into desired products such as advanced biofuels, chemicals, and fuel intermediates. Cost-effective process intensification and/or smaller scales that are commensurate with biomass feedstock supply are also needed. Improving process economics depends upon other system improvements listed below:

> **Sugars and Aromatics:** Across biological catalysis, new metabolic pathways are critical that more efficiently convert intermediates to products with less carbon loss in conjunction with more robust host organisms that can tolerate greater feedstock variability and accumulation of inhibitory compounds. Novel durable transition metal catalysts are needed that are capable of selective sugar upgrading via hydrogenation, deoxygenation, and C-C coupling reactions. Catalysts are also needed that are capable of funneling lignin into streams of tractable intermediates for incorporation either into central metabolism or direct upgrading.
>
> **Gaseous Intermediates:** More robust chemical and biological processes are needed for producing oxygenated intermediates from syngas with further processing to hydrocarbons. These processes need to be capable of selectively generating products of the desired chain lengths and overcoming challenges related to fouling from syngas contaminants.
>
> **Bio-Oil Intermediates:** Oxygen removal strategies, condensation reactions, and improved hydrotreating catalysts are needed that are highly selective to desired end products and are stable in the presence of impurities. Greater understanding is needed regarding the tradeoffs between the amount and quality of bio-oil produced after hydrodeoxygenation and the impact on additional downstream catalytic hydroprocessing steps required to meet a finished fuel or refinery feedstock specification. In addition, it is essential to understand catalyst coking and contamination as well as to understand how to control the distribution of products formed.

Ct-I. Product Finishing Acceptability and Performance: Fuels and chemicals produced from biomass contain different quantities of impurities than those found in fuels and chemicals from petroleum. Improved knowledge of these impurities and methods for how their effects can most easily be ameliorated is necessary for biofuels and bioproducts to efficiently integrate into current markets.

Integration and Intensification Challenges

Ct-J. Process Integration: Feed and process variations can cause fouling, plugging, corrosion, or other disruptions in biorefinery operations. The lack of operational data on fully integrated systems over the extended periods of time required for successful commercialization presents large engineering scale-up risks. An improved understanding of process integration is essential for (1) characterizing the complex interactions that exist between unit operations, (2) identifying impacts of inhibitors and fouling agents on catalytic and processing systems, and (3) enabling the generation of predictive engineering models that can guide process optimization or scale-up efforts and enable process control.

Ct-K. Petroleum Refinery Integration of Intermediates: Bio-oil and other bio-intermediates are composed of mixtures different than those found in petroleum refineries, and there is a lack of information about how bio-oils will affect petroleum processing after blending. Information is needed about the physiochemical properties, reactivities, and compatibilities of bio-oil intermediates for fuel finishing within an existing petroleum refinery.

Ct-L. Aqueous Phase Utilization and Wastewater Treatment: Current wastewater treatment techniques are not cost effective or are not thoroughly developed for wastewater generated from biorefineries. The aqueous phase from high-temperature deconstruction and upgrading may contain organic acids, aldehydes, ketones, and phenolics, which require conversion or removal before the water can be released. Additionally, research is needed to characterize these aqueous phase mixtures and to convert the organics present to hydrogen, biochemicals, or hydrocarbon fuels to improve overall process yield.

Crosscutting Challenges

Ct-M. Cost-Effective Hydrogen Production and Utilization: Current methods for generation of hydrogen are not cost efficient at biomass scales, and externally produced hydrogen is a major contributor to operating costs. For hydrogen production from feedstock to become more viable, improvements are needed in conversion technology, catalyst development, waste stream characterization, and process integration. Hydrogen (or another reductant) is essential for conversion of oxygenated organic compounds to drop-in-ready fuels that contain much less oxygen.

Ct-N. Materials Compatibility and Reactor Design and Optimization: Current reactors are not designed to handle many harsh conditions inherent to converting feedstock, from a lack of compatibility with highly corrosive bio-oil to cost-effective handing of harsh pretreatment conditions for low-temperature deconstruction. Current reactors must be improved to cost effectively deliver an environment in which catalysts can be most efficient. This involves development of reactors with cost-effective materials that are optimized for process conditions.

2.2.4 Conversion Research and Development Approach for Overcoming Challenges and Barriers

The approach for overcoming conversion technical challenges and barriers is outlined in the work breakdown structure (WBS) depicted in Figure 2-22.

The Office's current Conversion activities generally fall into six broad groupings:

- *Analysis and Sustainability:* To understand the impact of technologies with respect to environmental sustainability, economic metrics, and the current state of technology (SOT)
- *Deconstruction and Fractionation:* To develop technologies to produce useful intermediates from biomass feedstock and better understand the impact of feedstock quality on conversion efficiency and economics
- *Synthesis of Intermediates, and Upgrading:* To convert intermediates to stable mixtures, fuels, and chemicals
- *Integration and Intensification:* To optimize for systems-level performance
- *Enabling Technologies:* To apply new knowledge and tools to innovate beyond current conversion technologies
- *Oversight and Support:* To support planning and execution of conversion activities and demonstrate improvements in technologies, sustainability, and economics.

Technical challenges in each of these areas are identified from technology road mapping, TEAs, stakeholder meetings, industry lessons learned from demonstration and market transformation activities, and through active project management of historical and existing projects. Research addressing key technical challenges is performed by national laboratories, industry, universities, and multi-disciplinary consortia. The relevance, impact, and progress of the R&D portfolio toward industrial and commercial applications are ensured via merit reviews prior to award, project stage-gate and biennial portfolio reviews with a panel of external experts, partnering with industry as appropriate, and disseminating the results.

The WBS illustrated in Figure 2-22 is described below. Table 2-15 summarizes each task as it relates to specific R&D activities, challenges, and DOE-funded performers.

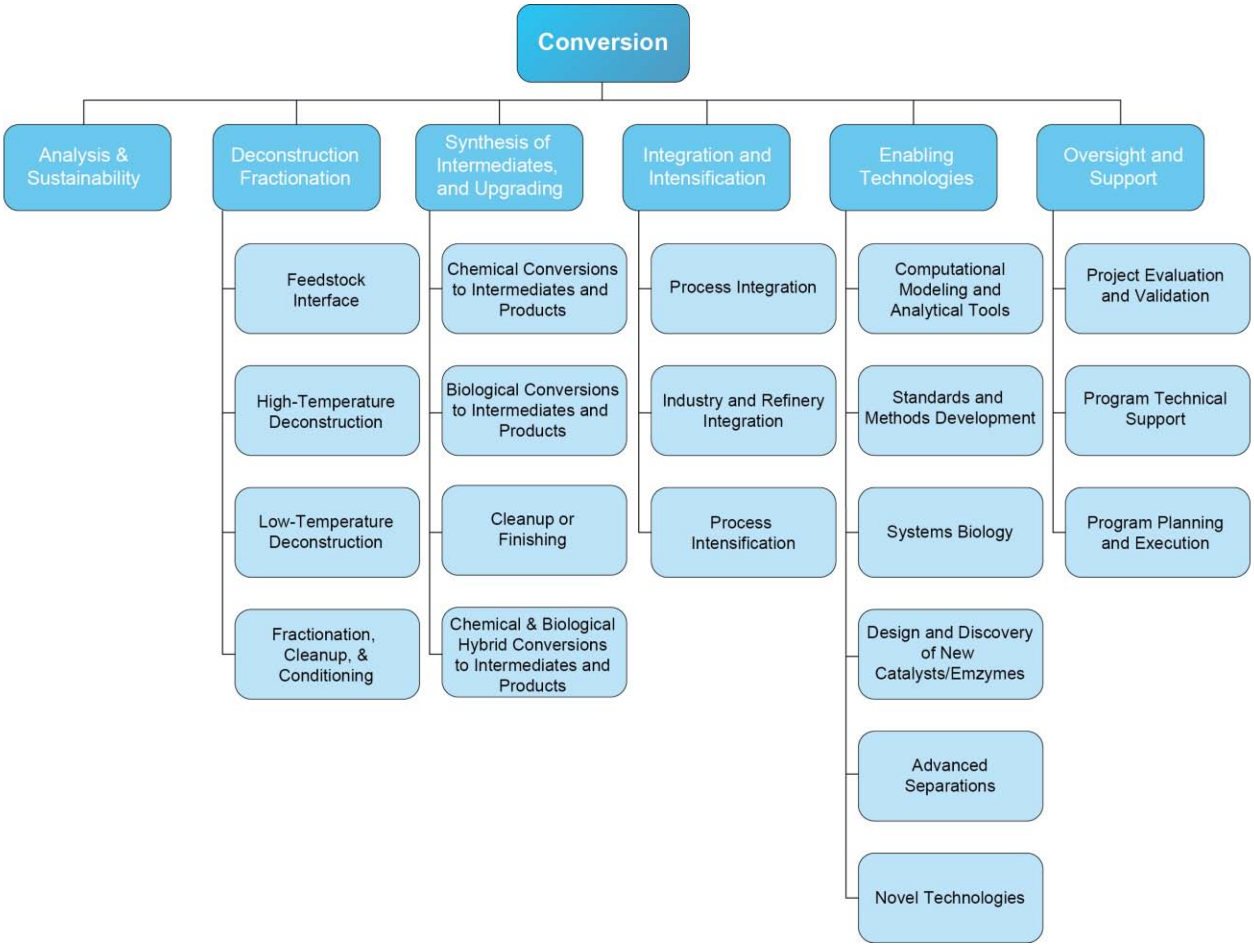

Figure 2-22: Conversion R&D work breakdown structure

Analysis and Sustainability

Analysis and sustainability activities play a critical role in understanding the feasibility, sustainability, and scalability of new conversion routes to renewable hydrocarbon fuels and biobased chemicals. Analysis and Sustainability activities such as process simulation, environmental sustainability assessments, techno-economic analysis, and life-cycle models are used to establish baselines, identify the highest impact areas of research, develop performance targets, monitor the progress of the research portfolio, and aid in understanding the tradeoffs among technology options within a systems context. Examples of environmental sustainability metrics include life-cycle greenhouse gas emissions, fossil energy consumption, consumptive water use, wastewater generation, air pollutant emissions, biomass carbon-to-fuel efficiency, renewable energy production, value of additional products, and total fuel yield.

Deconstruction and Fractionation

Deconstruction and fractionation activities seek to produce tractable intermediate streams from feedstock amenable to upgrading. This area breaks down into four broad categories as described hereafter:

Feedstock Interface
Conversion and feedstock interface activities include the R&D necessary to determine a desirable specification range for feedstocks intended for conversion processes. Additionally, this area includes the tasks necessary to produce the required volumes of feedstock at the optimal format and material specifications to support R&D and other scale-up activities. Linking feedstock logistics with conversion processes allows for the evaluation of technology options and tradeoffs on both sides of the processing interface, ensuring a fully integrated supply chain from stump or field to fuel. Additionally, the Office is investigating the development of preprocessing options (e.g., densification, blending of an expanded pool of feedstocks, and physical formats such as pellets, shredded material, and slurries) and simultaneously assessing the impact on conversion efficiency when such preprocessed feedstocks are introduced into a conversion process.

High-Temperature Deconstruction
The primary focus of R&D for high-temperature deconstruction is on improving technologies for thermochemical deconstruction of biomass to form a gaseous or bio-oil intermediate. Key focus areas include developing a better understanding of the fundamentals of gasification, pyrolysis, and hydrothermal liquefaction processes (including reaction mechanisms); improving reactor designs; improving the quality of deconstructed intermediates; developing more robust catalysts and catalyst regeneration processes; and developing catalysts with improved specificity.

Low-Temperature Deconstruction
The Office is developing technologies to create more efficient hydrolysis and cleaner separation of intermediate streams at lower cost. Specific areas of interest include developing better pretreatment conditions; creating lower cost hydrolytic enzymes; developing new hydrolytic enzymes with improved substrate scope; limiting the formation of contaminants; and creating a tractable lignin stream.

Fractionation, Cleanup, and Conditioning
The Office is developing technologies to purify intermediate streams to improve yield from catalytic upgrading in subsequent steps. The focus is on removal of problematic inhibitory compounds; fractionation into different intermediate streams; and other novel separations methods.

Synthesis of Intermediates and Upgrading

Activities within Synthesis of Intermediates and Upgrading seek to transform intermediate streams into stable product streams that meet off-take standards. This task breaks down into four broad categories described below:

Chemical Conversions to Intermediates and Products
The Office is developing technologies for cheaper and more efficient cleanup, conditioning, and stabilization for upgrading intermediate streams of bio-oil or syngas to finished fuels and chemicals. This R&D focuses on mitigating the effects of reactive compounds to improve storage and handling properties and producing a higher-quality bio-oil through removal of water, char, and ash particulates, as well as destabilizing components such as metals and

oxygenated species. Research on bio-oils focuses on hydroprocessing and similar thermal-catalytic processing techniques to reduce total oxygen and acid content, thereby increasing stability. Research on syngas intermediates upgrading and conditioning focuses on removing or reforming tars, capturing alkali metal, and removing particulates.

Biological Conversions to Intermediates and Products
Conversion R&D's primary objective with biological upgrading is identifying and developing robust microorganisms capable of converting complex intermediates to desired target molecules in the presence of inhibitors at high rates, titers, selectivity, and yields.

Cleanup or Finishing
The Office is pursuing technologies to enable product streams to conform to standards for off-take agreements. This research involves the removal of problematic contaminant compounds and further finishing. For complex bio-oil mixtures, the finishing process may involve balancing various hydrocarbon components, whereas for single compound products, it may only involve removing impurities.

Chemical and Biological Hybrid Conversions to Intermediates and Products
The Office is pursing technologies to improve conversion routes that involve metabolism of syngas by microorganisms and other hybrid technologies that combine the best of chemical and biological approaches. The primary objectives of this R&D are development of specific and durable inorganic catalysts with appropriate selectivity, improved capacity to regenerate, catalyst supports, and optimization of process conditions to improve conversion rates and yields.

Integration and Intensification

Activities within Integration and Intensification seek to ensure seamless transition between unit operations and improve whole plant efficiency. This task breaks down into three broad categories described below:

Process Integration
The Office supports R&D investigating the interaction of pretreatment and deconstruction technologies together with downstream upgrading technologies. This R&D aims to identify issues at operation interfaces and opportunities for better integration. The Office funds several pilot facilities that seek to address this area. Through their use, overall process efficiency and costs can be improved in a systems context, which is a necessary precursor for scale-up activities. In addition, the effect of feed and process variations must be understood to ensure robust, efficient biorefineries that produce fuels and chemicals on a consistently cost-effective basis. Integrated facilities can also help to better understand how best to generate hydrogen for conversion operations and how to best manage wastewater.

Industry and Refinery Integration
Conversion R&D is working to establish clear product specifications that will enable bio-oil, bio-intermediates, fuel-blendstocks, finished fuels, and products to seamlessly integrate with existing infrastructure, and will encourage industry acceptance of bio-based replacements. This activity involves R&D in coordination with refiners to understand how a bio-oil blend

will perform when integrated into their existing operations and ultimately seeking to provide additional value to refineries.

Process Intensification
The Office is pursing R&D on novel methods for reducing the number of process steps required to produce product-improving process economics through reduced capital and operating costs. One line of research pursued is consolidated bioprocessing, which seeks to combine deconstruction and fuel synthesis in one reactor, eliminating the need for extensive pretreatment and enzymatic saccharification.

Enabling Technologies

Enabling technologies activities seek to improve process efficiency across multiple R&D areas. This task breaks down into six broad categories described below:

Computational Modeling and Analytical Tools
Conversion R&D is developing new analytical and modeling tools that enable more efficient production of fuels and products across conversion. For low-temperature deconstruction, metabolic modeling of new and modified organisms, enzyme modeling, and development of novel analytical tools increase understanding of fundamental biological processes and suggest new avenues for engineering.[5] For high-temperature deconstruction, modeling of reaction mechanisms and kinetics, as well as improved tools to determine the composition and reactivity of bio-oils, are of paramount importance.

Standards and Methods Development
Conversion R&D is developing standards and protocols to increase researchers' ability to replicate experiments both within and between laboratories and to better characterize intermediate and final material provided to industry.

Systems Biology
The Office is investing in R&D to improve understanding of how entire organisms function to improve yields for both low-temperature deconstruction and biological upgrading under industrially relevant conditions. Researchers are working to understand how the engineering of a new metabolic pathway into a host organism perturbs other cellular functions. Understanding the changes that occur while improving the ability to predict the effect of future changes through modeling is very impactful for future cellular engineering efforts.

Design and Discovery of New Catalysts/Enzymes
Conversion R&D is developing new and improved catalyst and enzyme systems under industrially relevant conditions to reduce the cost of both deconstruction and upgrading. Specific areas of interest are catalysts offering improved yield, productivity, and product slate. Investment in early stage catalyst development ensures a consistent pipeline for

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[5] S. Chundawat, G. Beckham, et al. (2011), "Deconstruction of Lignocellulosic Biomass to Fuels and Chemicals," *The Annual Review of Chemical and Biomolecular Engineering* 2(1), http://www.annualreviews.org/doi/abs/10.1146/annurev-chembioeng-061010-114205.

breakthroughs in Conversion and is crucial to improving the economics of fuel and product production.

Advanced Separations
Conversion R&D is pursuing improved separations processes to enhance yields and intermediate/product purity in all steps of the conversion pathway. Specific areas of interest include solid/gas separation (e.g., hot gas filtration), solids/liquid separation, gas/liquid separation, and liquid/liquid separation.

Novel Technologies
The Office also pursues research on innovative technologies that can broadly enable conversion of feedstock to fuels and products and that do not readily fall into other areas.

Oversight and Support

Activities within Oversight and Support underpin project validation and technical and program planning. This task breaks down into two broad categories as described below:

Project Evaluation and Validation
Validation involves actual demonstration of a scaled-up route from feedstock to renewable fuels and products. The Office leverages feedback from industry to understand emerging issues and R&D opportunities. Integration and scale-up efforts are at the bench and pilot scale, and generate data that are used to assess progress against technical and cost targets, as well as environmental sustainability metrics. The operational data are also used to model nth plant costs and technical projections for each conversion pathway.

Program Technical Support & Program Planning and Execution
The Office regularly consults external experts from national laboratories, academia, and industry to help inform strategic decision-making, often via review panels. Additionally, the Office employs non-federal experts and staff to assist with the internal planning and execution of program activities.

Table 2-15: Conversion R&D Activity Summary

WBS Element	Description	Barrier(s) Addressed
Analysis and Sustainability	Develop, refine, and utilize conversion route LCAs and TEAs - Evaluate and identify sustainability performance improvements to technology pathways. - Develop and update process analyses, design cases, and annual, including technical, cost, and environmental sustainability metrics, SOT assessments for routes to hydrocarbon fuels and biobased chemicals.	Ct-J Process Integration At-A: Comparable, Transparent, and Reproducible Analyses At-C. Data Availability across the Supply Chain St-C: Sustainability Data across Supply Chain St-D: Implementing Science-Based Indicators and Methodology for Evaluating and Improving Sustainability St-E: Best Practices and Systems for Sustainable Bioenergy Production
Deconstruction and Fractionation	Develop technologies for converting biomass into intermediates, including sugars or other soluble carbon intermediates, bio-oil, and syngas intermediates for subsequent conversion to hydrocarbon fuels, upgraded intermediates, or chemicals. - Understand how feedstock specifications affect conversion. - Develop cost-effective pretreatment options. - Develop cost-effective hydrolysis options. - Develop novel deconstruction options. - Develop gasification technologies. - Develop pyrolysis technologies. - Develop solvent or HTL technologies.	Ct-A. Feedstock Variability Ct-B. Reactor Feed Introduction Ct-C. Efficient Preprocessing Ct-D. Efficient Pretreatment Ct-E. Efficient Low-Temperature Deconstruction Ct-F. Efficient High-Temperature Deconstruction to Intermediates Ct-G. Efficient Intermediate Cleanup and Conditioning Ct-N. Materials Compatibility and Reactor Design and Optimization Ft-I: Overall Integration and Scale-Up Ft-G: Biomass Physical State Alteration St-C: Sustainability Data across the Supply Chain Ft-E: Terrestrial Feedstock Quality Monitoring and Impact on Conversion Performance Im-E: Cost of Production
Synthesis of Intermediates, and Upgrading	Develop technologies to optimize and maximize the utilization of the carbon from deconstructed biomass to synthesize desired products. - Develop cost-effective biological synthesis technologies. - Develop cost-effective, low-temperature chemical synthesis technologies. - Develop gas cleanup technologies, bio-oil stabilization technologies, and improved catalysts for hydrotreating and fuels synthesis. - Explore new and/or improved reactor designs.	Ct-G. Efficient Intermediate Cleanup and Conditioning Ct-H. Efficient Catalytic Upgrading of Sugars/Aromatics, Gaseous and Bio-Oil Intermediates to Fuels and Chemicals Ct-I. Product Finishing Acceptability and Performance Im-E: Cost of Production
Integration and Intensification	Develop strategies that enable integration and/or process intensification. - Develop technologies for separation/purification of intermediates and chemicals. - Integrate and optimize deconstruction and product synthesis processes across interfaces. - Develop process intensification technologies. - Develop technologies to meet manufacturing specifications of innovative bio-derived materials, such as carbon fibers. - Optimize aqueous phase utilization.	Ct-G. Efficient Intermediate Cleanup and Conditioning Ct-J. Process Integration Ct-K. Petroleum Refinery Integration of Intermediates Ct-L. Aqueous Phase Utilization and Wastewater Treatment Ct-M. Cost Effective Hydrogen Production and Utilization Im-E: Cost of Production It-A: End-to-End Process Integration
Enabling Technologies	Enable the understanding of feedstock interface, deconstruction, and fuel synthesis processes to develop advanced technologies. - Develop and apply new analytical methods and tools. - Develop and apply systems biology tools. - Accelerate the design of catalysts in real world systems. - As needed, study reaction mechanisms of complex, real world systems - Develop advanced separations to enable efficient fuel blendstock production systems. Explore novel hydrogen production technologies. - Develop advanced pretreatment technologies.	Ct-A. Feedstock Variability Ct-D. Efficient Pretreatment Ct-E. Efficient Low-Temperature Deconstruction Ct-G. Efficient Intermediate Cleanup and Conditioning Ct-H. Efficient Catalytic Upgrading of Sugars/Aromatics, Gaseous and Bio-Oil Intermediates to Fuels and Chemicals Ct-I. Product Finishing Acceptability and Performance Ct-L. Aqueous Phase Utilization and Wastewater Treatment Ct-N. Materials Compatibility and Reactor Design and Optimization Im-D: Lack of Industry Standards and Regulations
Oversight and Support	Validate technical improvements of the integrated conversion technologies for the priority pathways. - Conduct integrated operations to validate conversion pathways.	Ct-J. Process Integration Ct-N. Materials Compatibility and Reactor Design and Optimization

2.2.5 Prioritizing Conversion Research and Development Barriers

All of these challenges and barriers need to be addressed in order to achieve Office goals. However, the following issues are considered critical and will be emphasized within near- to mid-term Conversion R&D efforts:

- Develop innovative biomass deconstruction approaches to lower the cost of intermediates
- Enable high-performance separations technologies to increase product yields and decrease cost
- Understand the relationship between feedstock quality and conversion performance
- Develop strategies for conserving carbon and hydrogen in conversion and upgrading processes
- Work with petroleum refiners to address integration of biofuels into refinery processes.

The progress and future direction of the Office's R&D is monitored and evaluated to determine the annual R&D priorities necessary to overcome technical barriers. Prioritization of R&D is based on periodic evaluation of the Conversion R&D portfolio, as well as information on technologies being developed without government involvement. These technology assessments help prioritize which conversion pathways could support program goals. From now through 2022, Conversion R&D activities will focus on developing and validating additional feedstock and conversion processes that can help meet the $3/GGE price goal to maximize biofuels production in conjunction with value-added chemicals.

Design Case

The following section provides brief descriptions of design case models detailing six pathways that exemplify how Conversion R&D is progressing toward the Office's performance goal for biofuels. These cases focus on terrestrial feedstocks; for cases focused on algal feedstocks, please see Section 2.1.2. Each design case includes conversion cost projections and technical targets, as well as environmental sustainability metrics. It is important to recognize that each of these pathways is at varying technical maturity levels and will require more or less R&D and validation efforts to achieve the Office goal and reach commercial readiness over differing time frames as determined by industry adoption. Design reports undergo rigorous peer review prior to publication.[6] Annual SOT updates will be conducted to track progress and serve as "on ramps" and "off ramps" for conversion pathways or technologies to ensure they are aligned with Office goals.

Cost Projections and Technical Targets

Each design case includes modeled cost projections and technical targets through at least 2017 and are based on an nth plant model. As the technologies are at varying levels of technological maturity these targets are not meant to be directly comparable. The projections through 2017 are based on extensive technical considerations around the expected progress of existing and future R&D. The projections past 2017 are a linear interpolation of costs between 2017 and the 2022

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[6] See Appendix B for details on design cases and setting program cost targets.

design case model, and the increased level of uncertainty of these projections is denoted by the solid green bar.

Sustainability Metrics

In addition to technical targets and cost projections, key sustainability metrics for each pathway are also evaluated. Results for the conversion stage are shown in tables for each pathway, and more detail can be found in each design case report. The environmental sustainability metrics that are currently quantified are greenhouse gas emissions, fossil energy consumption, fuel yield, biomass carbon-to-fuel efficiency, water consumption, and wastewater generation.

This set of environmental sustainability metrics is not intended to be all-inclusive and will be expanded and updated as more experimental data become available. Work is in progress to quantify additional metrics, including criteria air pollutant emissions and wastewater quality. The environmental sustainability metrics fit within the framework of sustainability indicators published by Oak Ridge National Laboratory.[7] Section 2.4.1.5 provides more information on the Office's approach to establishing environmental sustainability targets.

Full LCAs are also conducted using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET™) model.[8] While the Energy Independence and Security Act of 2007 requires the EPA to conduct its own greenhouse gas assessments to determine fuel qualification, it is essential that LCA be performed during the development of these pathways to predict and facilitate improvement of environmental performance. These analyses will better enable conversion technologies to meet legislated goals, such as greenhouse gas reductions required by the Renewable Fuel Standard, and achieve other social and environmental benefits.

Pyrolysis Pathway Variations

Three variations of the fast pyrolysis pathway are presented here: (1) conventional fast pyrolysis, (2) *in situ* catalytic fast pyrolysis, and (3) *ex situ* catalytic fast pyrolysis.

Conventional fast pyrolysis does not include a catalyst in or directly after the pyrolysis reactor. *In situ* catalytic fast pyrolysis involves introduction of a catalyst in the pyrolysis reactor, and *ex situ* catalytic fast pyrolysis involves introduction of a catalytic vapor phase upgrading step directly after the pyrolysis reactor. Development of design cases for multiple pathway variants is a risk abatement strategy and helps to give a more complete picture of potential routes to commercialization.

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[7] A.C. McBride and V.H. Dale et al. (2011), "Indicators to Support Environmental Sustainability of Bioenergy Systems," *Ecological Indicators* 11(5), http://web.ornl.gov/sci/ees/cbes/Publications/McBride%20et%20al%202011%20EI.pdf.

[8] For more detail on the GREET model see Section 2.4.2 and http://greet.es.anl.gov/.

Fast Pyrolysis Conversion Pathway

The updated fast pyrolysis design case, which uses a blended, formatted woody feedstock to produce gasoline and diesel blendstock fuel in 2017, is an example of how the $3/GGE cost goal can be achieved by 2017.[9] Cost projections for the fast pyrolysis design case are shown in Figure 2-23 and Table 2-16, and corresponding feedstock costs are presented in Section 2.1.1.5 (Figure 2-10 and Table 2-4). More details are provided in Appendix A, Table A-5.

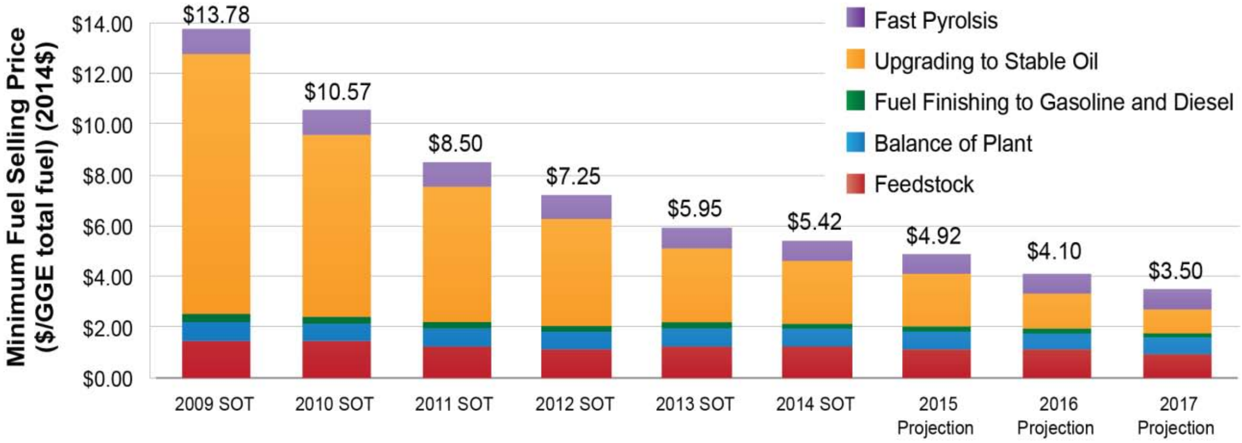

Figure 2-23: Cost projection breakdown for the fast pyrolysis design case

Based on the 2013 design case for fast pyrolysis, Figure 2-23 shows that a total potential cost reduction of 75% can be achieved between 2009 and 2017 with improvements in all four R&D areas shown in the legend.

Table 2-16: Cost Projection Breakdown for the Fast Pyrolysis Design Case)

Total Fuel $/GGE (2014$)	2009 SOT	2010 SOT	2011 SOT	2012 SOT	2013 SOT	2014 SOT	2015 SOT	2016 Projection	2017 Projection
Fast Pyrolysis	$1.00	$0.97	$0.95	$0.93	$0.81	$0.81	$0.80	$0.79	$0.78
Upgrading to Stable Oil	$10.32	$7.21	$5.36	$4.27	$2.95	$2.45	$2.07	$1.34	$0.96
Fuel Finishing to Gasoline and Diesel	$0.25	$0.25	$0.24	$0.24	$0.25	$0.24	$0.24	$0.25	$0.14
Balance of Plant	$0.75	$0.74	$0.73	$0.72	$0.70	$0.70	$0.69	$0.67	$0.64
Feedstock Cost	$1.45	$1.40	$1.23	$1.08	$1.24	$1.23	$1.12	$1.05	$0.97
MFSP	**$13.78**	**$10.57**	**$8.50**	**$7.25**	**$5.77**	**$5.95**	**$4.92**	**$4.10**	**$3.50**

Table 2-17 shows the environmental sustainability metrics for the conversion stage of the fast pyrolysis design case. Supply chain sustainability analysis indicates that, on a life-cycle basis, pyrolysis-derived gasoline and diesel produced from a blended woody feedstock may offer a 70% reduction in greenhouse gas emissions compared to conventional gasoline and diesel in the

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[9] S. Jones, E. Tan, and J. Jacobson et al. (2013), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Fast Pyrolysis and Hydrotreating Bio-oil Pathway*, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, and Idaho National Laboratory, PNNL-23053, NREL/TP-5100-61178, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf.

2017 projected case.[10] The 2015 SOT case has estimated greenhouse gas reductions of 52%. While the 2015 SOT case has supply chain water consumption of 6.0 gal/gge, the 2017 design case consumes 3.8 gal/GGE. Estimates of water consumption and greenhouse gas emissions will be updated as changes in process steps are considered in the analysis.

Table 2-17: **Environmental Sustainability Metrics Limited to the Fast Pyrolysis Conversion Process**

	2009 SOT	2012 SOT	2013 SOT	2014 SOT	2015 SOT	2017 Projection
Fossil GHG Emissions ($g\ CO_2e/MJ$ fuel)	22.1[*]	19.81	20.5	19.4	22.2	18.9
Fossil Energy Consumption (MJ fossil energy/MJ fuel)[**]	0.3261	0.2941	0.321	0.310	0.359	0.301
Total Fuel Yield (gal/dry ton wood; GGE/dry ton wood)	74; 78	74; 78	84; 87	83; 87	83; 87	84; 87
Carbon-to-Fuel Efficiency (C in fuel/C in biomass)	38%	38%	47%	47%	48%	47%
Water Consumption (m^3/day; gal/GGE fuel)[***]	998; 1.5	998; 1.5	1124; 1.5	1088; 1.5	1125; 1.6	1050; 1.4
Wastewater Generation (m^3/day; gal/GGE fuel)[c]	917; 1.4	917; 1.4	948; 1.3	975; 1.3	932; 1.3	932; 1.3

[*] Minor changes only to GHG and fossil energy consumption from 2009 to 2012 resulting from increased catalyst life.
[**] Fossil energy consumption does not include grinding of the feedstock prior to the pyrolysis step.
[***] Water consumption and wastewater generation include only direct use/emissions and do not include water associated with upstream production of materials and energy used at the plant. Water consumption is net water consumed during the biorefinery operation. Water consumption + wastewater generation = water withdrawal.

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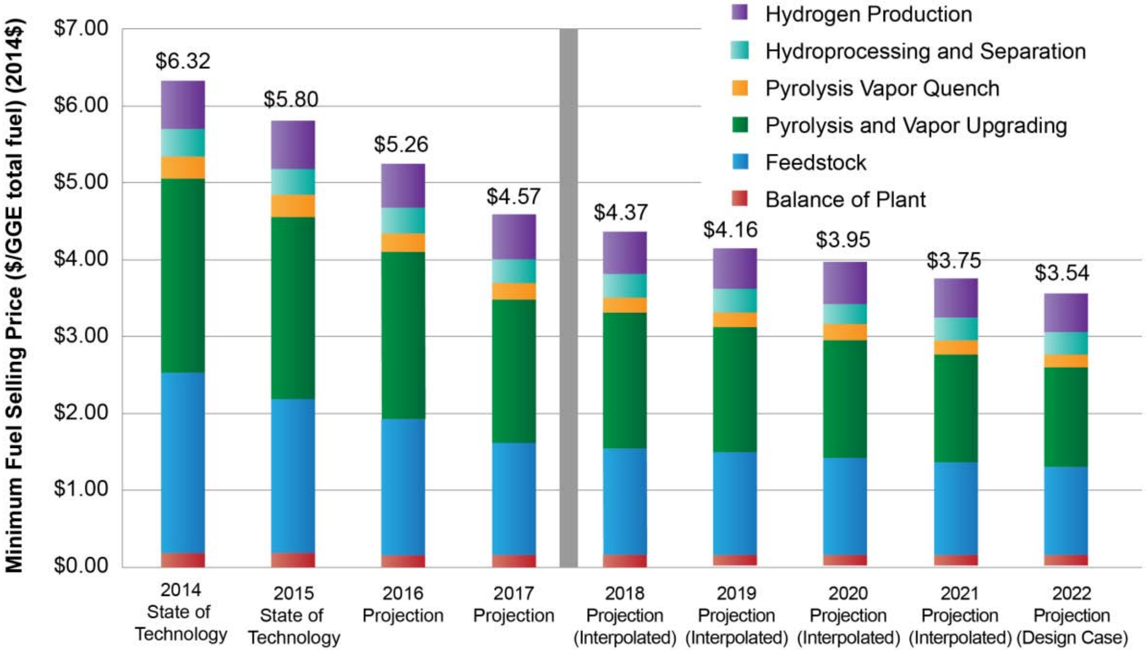
[10] F. Adom et al. (2016), "Supply Chain Sustainability Analysis of Fast Pyrolysis and Hydrotreating Bio-Oil to Produce Hydrocarbon Fuels," Argonne National Laboratory, ANL/ESD-15/2 Rev. 1, https://greet.es.anl.gov/publication-fast-pyrolysis-SCSA.

In Situ and *Ex Situ* Upgrading of Fast Pyrolysis Vapors Pathways

The design case model for *in situ* and *ex situ* upgrading of fast pyrolysis vapors details two designs based on projected product yields and quality improvements via catalyst development and process integration.[11] The two conversion pathways detailed are (1) *in situ* (also referred to as catalytic fast pyrolysis), where catalytic vapor upgrading happens within the fast pyrolysis reactor, and (2) *ex situ* (also referred to as vapor phase upgrading), where catalytic vapor upgrading happens in a separate reactor following the fast pyrolysis reactor. While the base case conceptual designs and underlying assumptions outline performance metrics for feasibility, it should be noted that these are only two of many other possibilities in this area of research. Other promising process design options emerging from the research will be considered for future techno-economic analysis. More details are provided in Appendix A, Tables A-5 and A-6.

In situ Upgrading of Fast Pyrolysis Vapors Pathway

Cost projections for the *in situ* upgrading of fast pyrolysis vapors design case are shown in Figure 2-24 and Table 2-18 and in Appendix A, Table A-7. Environmental sustainability metrics for the conversion stage of the *in situ* Upgrading of Fast Pyrolysis Vapors design case are shown in Table 2-19. Corresponding feedstock costs are presented in Section 2.1.1.5 (Figure 2-10 and Table 2-4). The 2015 projections for this pathway have been adjusted to 2014$ but 2015 SOT metrics were not reported for this pathway.



*Note: The projections for 2018–2021 are based solely on an interpolated linear reduction in costs between 2017 and 2022.

Figure 2-24: Cost projections for the *in situ* upgrading of fast pyrolysis vapors design case

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[11] A. Dutta, A. Sahir, E. Tan, D. Humbird, L. Snowden-Swan, P. Meyer, J. Ross, D. Sexton, R. Yap, and J. Lukas (2015), “Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels - Thermochemical Research Pathways With In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors,” National Renewable Energy Laboratory, NREL/TP-5100-62455, PNNL-23823, http://www.nrel.gov/docs/fy15osti/62455.pdf.

Table 2-18: Cost Projections for the *in situ* Upgrading of Fast Pyrolysis Vapors Design Case

Total Fuel $/GGE (2014$)	SOT	Projection			Projection*				Design Case Projection
	2014	2015	2016	2017	2018	2019	2020	2021	2022
Feedstock	$2.35	$2.02	$1.77	$1.46	$1.40	$1.33	$1.27	$1.20	$1.14
Pyrolysis and Vapor Upgrading	$2.52	$2.36	$2.16	$1.86	$1.75	$1.64	$1.53	$1.41	$1.30
Pyrolysis Vapor Quench	$0.29	$0.27	$0.25	$0.22	$0.21	$0.20	$0.19	$0.18	$0.17
Hydroprocessing and Separation	$0.36	$0.35	$0.33	$0.32	$0.31	$0.31	$0.30	$0.29	$0.28
Hydrogen Production	$0.63	$0.61	$0.58	$0.56	$0.55	$0.53	$0.52	$0.51	$0.49
Balance of Plant	$0.17	$0.18	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16
MFSP	**$6.32**	**$5.80**	**$5.26**	**$4.57**	**$4.37**	**$4.16**	**$3.95**	**$3.75**	**$3.54**

*Note: The projections for 2018–2021 are based solely on an interpolated linear reduction in costs between 2017 and 2022.

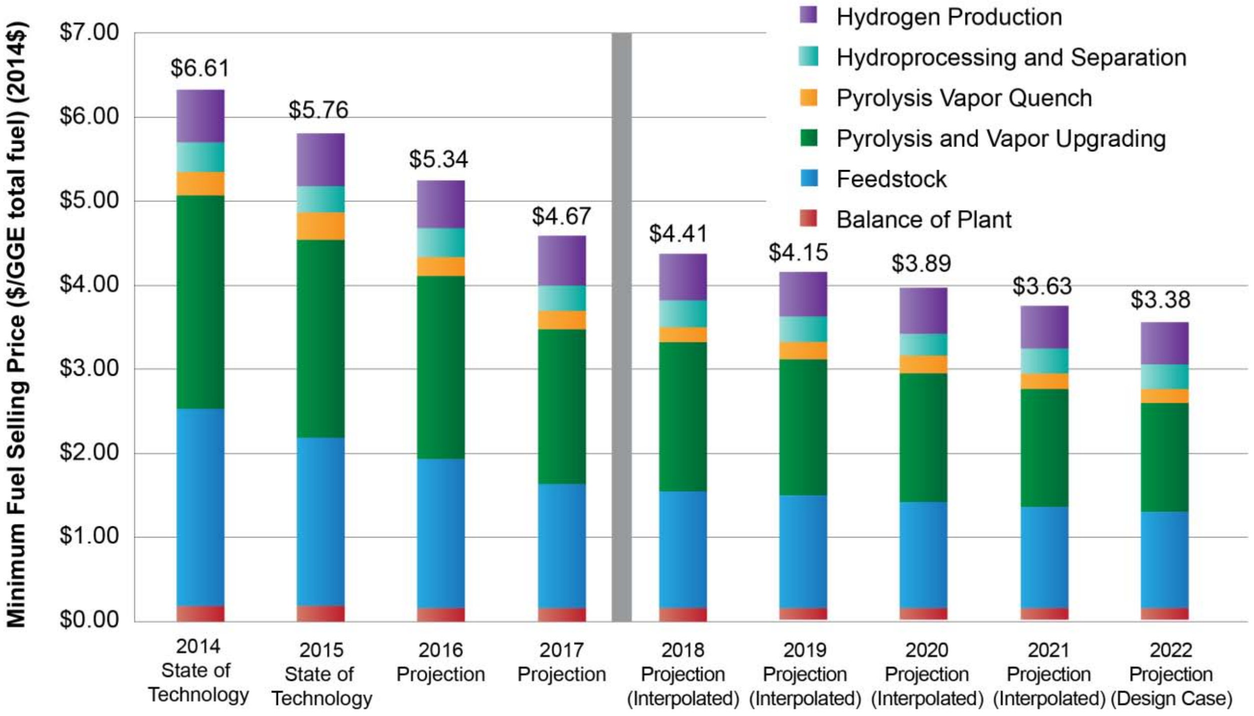
Table 2-19: Environmental Sustainability Metrics for the *in situ* Upgrading of Fast Pyrolysis Vapors Conversion Processes

	SOT	Projection							
	2014	2015	2016	2017	2018	2019	2020	2021	2022
Fossil GHG Emissions (g CO$_2$e/MJ fuel)[a]	-32.8	-28.6	-23.8	-16.1	-13.4	-10.7	-8	-5.3	-2.6
Fossil Energy Consumption (MJ fossil energy/MJ fuel)[a]	-0.37	-0.32	-0.27	-0.18	-0.15	-0.12	-0.09	-0.06	-0.03
Total Fuel Yield (GGE/ton)	46	49	52	59	62	65	68	72	75
Carbon Efficiency to Fuel Blendstock (%C in feedstock)	25.8	27.3	29.2	32.6	34.1	35.7	37.3	38.8	40.4
Water Consumption (gal H$_2$O/GGE fuel blend)	1.3	1.2	1.1	0.9	0.9	0.9	0.8	0.8	0.8
Electricity Production (kWh/GGE)	18.5	16.8	14.9	12.2	11.1	10.1	9.1	8.1	7.0
Electricity Consumption (for entire process, kWh/GGE)	11.7	10.9	10	8.7	8.2	7.7	7.2	6.8	6.3

[a] Includes electricity credit

Ex situ Upgrading of Fast Pyrolysis Vapors Pathway

Cost projections for the *ex situ* upgrading of fast pyrolysis vapors design case are shown in Figure 2-25 and Table 2-20, and in Appendix A, Table A-7. Environmental sustainability metrics for the conversion stage of the *ex situ* upgrading of fast pyrolysis vapors design case are shown in Table 2-21. Corresponding feedstock costs are presented in Section 2.1.1.5 (Figure 2-10 and Table 2-4).



Note: The projections for 2018–2021 are based solely on an interpolated linear reduction in costs between 2017 and 2022.

Figure 2-25: Cost projections for the *ex situ* upgrading of fast pyrolysis vapors design case

Table 2-20: Cost Projections for the *ex situ* Upgrading of Fast Pyrolysis Vapors Design Case

Total Fuel $/GGE (2014$)	**SOT**		**Projection**		**Projection***				**Design Case Projection**
	2014	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Feedstock	$2.58	$2.14	$1.87	$1.54	$1.45	$1.36	$1.27	$1.18	$1.09
Pyrolysis and Vapor Upgrading	$2.48	$2.16	$2.09	$1.86	$1.75	$1.63	$1.52	$1.41	$1.29
Pyrolysis Vapor Quench	$0.38	$0.36	$0.31	$0.27	$0.25	$0.23	$0.22	$0.20	$0.18
Hydroprocessing and Separation	$0.35	$0.33	$0.33	$0.30	$0.29	$0.28	$0.27	$0.25	$0.24
Hydrogen Production	$0.67	$0.61	$0.62	$0.57	$0.55	$0.53	$0.50	$0.48	$0.45
Balance of Plant	$0.16	$0.17	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12
MFSP	**$6.61**	**$5.76**	**$5.34**	**$4.67**	**$4.41**	**$4.15**	**$3.89**	**$3.63**	**$3.38**

*Note: The projections for 2018–2021 are based solely on an interpolated linear reduction in costs between 2017 and 2022.

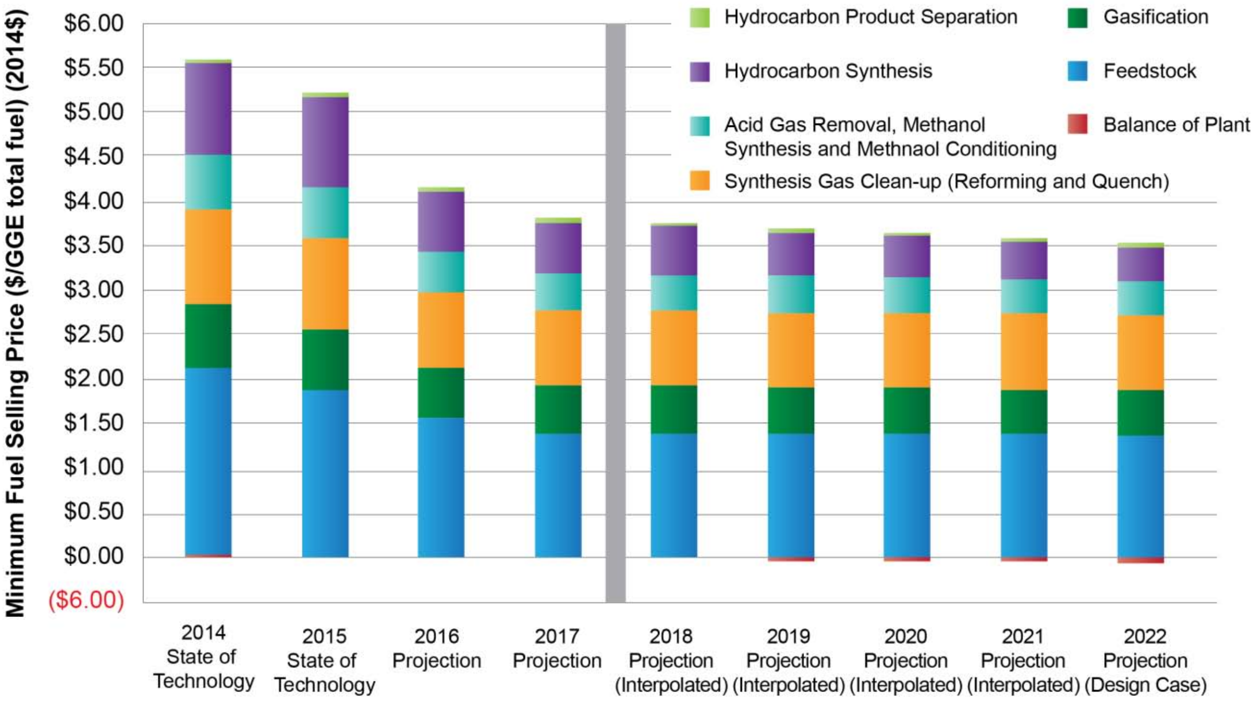
Table 2-21: Environmental Sustainability Metrics for the *ex situ* Upgrading of Fast Pyrolysis Vapors Conversion Processes

	SOT		Projection						
	2014	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Fossil GHG Emissions (g CO_2e / MJ fuel)[a]	-41.5	-35.5	-27.9	-19.3	-15.7	-12	-8.4	-4.8	-1.2
Fossil Energy Consumption (MJ fossil energy / MJ fuel)[a]	-0.47	-0.40	-0.31	-0.22	-0.17	-0.13	-0.09	-0.05	-0.01
Total Fuel Yield (GGE/ton)	42	46	50	56	60	64	69	73	78
Carbon Efficiency to Fuel Blendstock (%C in feedstock)	23.5	25.9	27.6	30.6	32.8	34.9	37.1	39.3	41.5
Water Consumption (gal H_2O/GGE fuel blend)	1.4	1.4	1.2	1.1	1.0	0.9	0.8	0.8	0.7
Electricity Production (kWh/GGE)	21.0	18.0	16.0	13.1	11.7	10.3	8.9	7.6	6.2
Electricity Consumption (for entire process, kWh/GGE)	12.7	11.0	10.4	9.1	8.4	7.8	7.1	6.4	5.7

[a] Includes electricity credit

Hydrocarbons via Indirect Liquefaction Pathway

The process design and economics model for the hydrocarbons via indirect liquefaction (IDL) pathway[12] leverages technologies previously demonstrated with the production of mixed alcohols from biomass in 2012. The new method involves much lower-severity operating conditions in the fuel synthesis area of the plant design making it considerably more economically competitive than the demonstrated mixed alcohols pathway. In the IDL pathway, a methanol intermediate is produced by indirect gasification followed by gas cleanup, and methanol synthesis. Methanol is then converted to a dimethylether (DME) intermediate and then further to high-octane, highly branched seven carbon-rich gasoline blendstock via modified beta-zeolite catalyst in three parallel fixed-bed reactor trains. The resulting blendstock is high in branched paraffin content, similar to alkylates from petroleum refineries, and has a highly desirable octane number. A summary of the costs contributing to the total high octane selling price is presented in Figure 2-26 and Table 2-22 and in Appendix A, Table A-8. Corresponding feedstock costs are presented in Section 2.1.1.5 (Figure 2-10 and Table 2-4).



*Note: The projections for 2018–2021 are based solely on an interpolated linear reduction in costs between 2017 and 2022.

Figure 2-26: Cost projections for the hydrocarbons via indirect liquefaction design case

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[12] E. Tan, M. Talmadge, A. Dutta, J. Hensley, J. Schaidle, M. Biddy, D. Humbird, L. Snowden-Swan, J. Ross, D. Sexton, and J. Lukas (2015), *Process Design for the Conversion of Lignocellulosic Biomass to High Octane Gasoline - Thermochemical Research Pathway With Indirect Gasification and Methanol Intermediate*, National Renewable Energy Laboratory, NREL/TP-5100-62402, PNNL-23822, http://www.nrel.gov/docs/fy15osti/62402.pdf.

Table 2-22: Cost Projections for the Hydrocarbons via Indirect Liquefaction Design Case

Total Fuel $/GGE (2014$)	**SOT**		**Projection**		**Projection***				**Design Case Projection**
	2014	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Feedstock	$2.10	$1.88	$1.56	$1.39	$1.39	$1.38	$1.38	$1.38	$1.37
Gasification	$0.71	$0.68	$0.57	$0.54	$0.53	$0.53	$0.52	$0.51	$0.50
Synthesis Gas Cleanup (Reforming and Quench)	$1.08	$1.03	$0.84	$0.84	$0.84	$0.84	$0.84	$0.84	$0.84
Acid Gas Removal, Methanol Synthesis Conditioning	$0.60	$0.56	$0.44	$0.43	$0.42	$0.41	$0.41	$0.40	$0.39
Hydrocarbon Synthesis	$1.02	$1.01	$0.68	$0.57	$0.53	$0.50	$0.46	$0.42	$0.38
Hydrocarbon Product Separation	$0.05	$0.05	$0.05	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04
Balance of Plant	$0.04	$(0.01)	$(0.01)	$(0.01)	$(0.02)	$(0.03)	$(0.04)	$(0.05)	$(0.06)
MFSP	**$5.60**	**$5.20**	**$4.13**	**$3.80**	**$3.74**	**$3.67**	**$3.60**	**$3.54**	**$3.47**

*Note: 2018-2021 projections based on interpolated linear reduction in costs between 2017 and 2022.

The environmental sustainability metrics for the conversion stage of the hydrocarbons via indirect liquefaction design case are shown in Table 2-23. Supply chain sustainability analysis indicates that, on a life-cycle basis, IDL-derived high octane gasoline produced from a blended woody feedstock may offer an 84% reduction in greenhouse gas emissions compared to conventional gasoline in the 2022 projected case.[13] The 2015 SOT case has estimated reductions of 50%. While the 2015 SOT case has supply chain water consumption of 11.5 gal/gge, the 2022 target case consumes 2.8 gal/gge. Estimates of water consumption and greenhouse gas emissions will be updated as changes in process steps are considered in the analysis.

Table 2-23: Environmental Sustainability Metrics for the Hydrocarbons via Indirect Liquefaction Conversion Process

	SOT		**Projection**						
	2014	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Fossil GHG Emissions (g CO_2e/MJ fuel)[a, ○]	1.64	1.65	1.19	0.96	0.88	0.81	0.74	0.67	0.6
Fossil Energy Consumption (MJ fossil energy/MJ fuel)[a]	0.023	0.022	0.011	0.013	0.011	0.01	0.009	0.007	0.006
Total Fuel Yield (GGE/ton)	39.7	39.9	61.8	64.2	64.4	64.5	64.6	64.8	64.9
Carbon Efficiency to Fuel Blendstock (%C in feedstock)	28.2	28.3	29.9	31.0	31.0	31.0	31.1	31.1	31.2
Water Consumption (gal H_2O/GGE fuel blend)	12.4	7.4	5.8	5.2	4.5	3.8	3.1	2.4	1.7

[a] Includes electricity credit.

○ FY 2015 SOT values for fossil GHG emissions and energy consumption are negative due to electricity export from higher hexamethylbenzene (HMB) production relative to target. Higher overall selectivity to gasoline-range products relative to target.

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[13] H. Cai et al. (2016), *Supply Chain Sustainability Analysis of Indirect Liquefaction of Blended Biomass to Produce High Octane Gasoline*, Argonne National Laboratory, ANL/ESD-15/4 Rev. 1, https://greet.es.anl.gov/publication-scsa-idl-hog.

Hydrolysis Pathway Variations

Two low-temperature pathways involve hydrolysis to intermediate sugar streams followed by different upgrading methods. Although both pathways rely on a co-product stream to enable cost-competitive fuel production, the very different upgrading technologies employed by each highlights the need for research on diverse technologies. Similar to the approach described for pyrolysis above, examination of these pathway variants is a risk mitigation strategy.

Low-Temperature Deconstruction and Fermentation Pathway

The design case model for biological production of diesel blendstock through a fatty acid intermediate details a model process that includes unit operations such as pretreatment, enzymatic hydrolysis, solid/liquid separations, and aerobic fermentation (biological conversion), followed by hydroprocessing.[14] To meet aggressive near-term cost targets of roughly $5/GGE by 2017, the update to the 2013 design case[15] includes production of a high-value coproduct, succinic acid, from the C5 stream along with fatty acid production from the C6 stream. The strategy envisioned here is flexible in terms of the high-value coproduct and showcases how products can enable fuels. To meet the 2022 cost goal of $3/GGE, adipic acid, a representative high-value co-product derived from lignin will be utilized, and the C5 stream will again be devoted solely to fuel production.[16] Cost projections for the low-temperature deconstruction and fermentation design case are shown in Figure 2-27 and Table 2-24 and Appendix A, Table A-9. Corresponding feedstock costs are presented in Section 2.1.1.5 (Figure 2-12 and Table 2-5).

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[14] Davis et al. (2013), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons*, National Renewable Energy Laboratory, NREL/TP-510060223, http://www.nrel.gov/docs/fy14osti/60223.pdf.

[15] R. Davis et al., Update to NREL/TP-510060223, *Manuscript in Preparation*.

[16] R. Davis et al., Update to NREL/TP-510060223, *Manuscript in Preparation*.

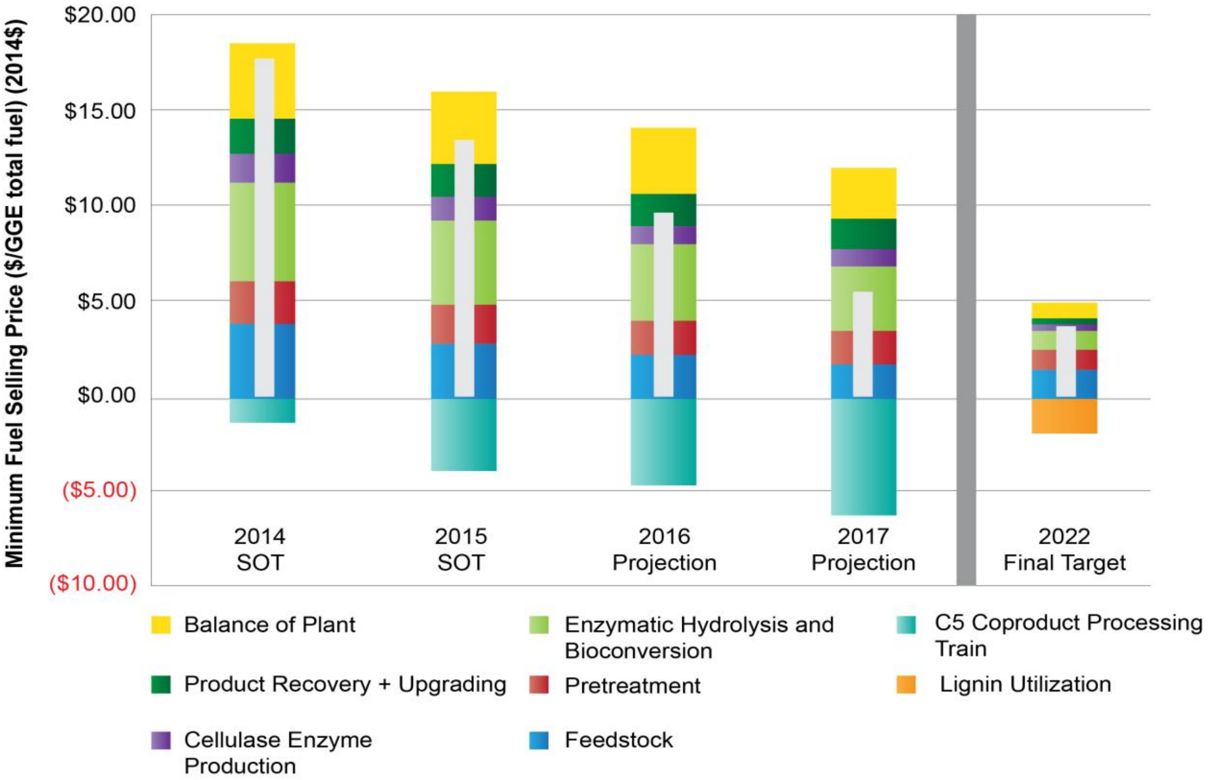

Figure 2-27: Cost projections for the low-temperature deconstruction and fermentation design case

Table 2-24: Cost Projections for the Low-Temperature Deconstruction and Fermentation Design Case

Total Fuel $/GGE (2014$)	**SOT**	**Projections**			**Target**
	2014	**2015**	**2016**	**2017**	**2022**
Feedstock	$3.80	$2.79	$2.19	$1.74	$1.41
Pretreatment	$2.33	$2.06	$1.87	$1.73	$1.05
Enzymatic Hydrolysis and Bioconversion	$5.14	$4.43	$3.96	$3.40	$0.95
Cellulase Enzyme Production	$1.56	$1.21	$0.96	$0.88	$0.41
C5 Coproduct Processing Train	-$1.37	-$3.92	-$4.68	-$6.20	$0.00
Lignin Derived Adipic Acid	NA	NA	NA	NA	-$1.88
Product Recovery + Upgrading	$1.77	$1.76	$1.72	$1.58	$0.34
Balance of Plant	$3.93	$3.79	$3.46	$2.68	$0.86
MFSP	**$17.16**	**$12.11**	**$9.47**	**$5.81**	**$3.14**

The environmental sustainability metrics of both approaches to sugar upgrading (fermentation and catalytic upgrading) for the 2022 projections include offsets from the displacement of petroleum-derived products now produced from lignin. This displacement is accomplished in a manner similar to exported electricity in other scenarios, with lignin-derived co-products (adipic acid) treated as avoided products using a previously established product displacement method.[17]

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[17] Wang, M., H. Huo, and S. Arora (2011), “Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the US context,” *Energy Policy* 39(10): 5726–5736.

Environmental sustainability metrics for the conversion stage of the low-temperature deconstruction and fermentation design case are shown in Table 2-25.

Table 2-25: Environmental Sustainability Metrics for the Low-Temperature Deconstruction and Fermentation Conversion Process

	SOT		Projection		
	2014	**2015**	**2016**	**2017**	**2022**[c]
Fossil GHG Emissions (g CO_2e/MJ fuel)	247.7	261.9	244.7	184.7	24.4
GHG credits (g CO_2e/MJ fuel)[b]	-226.5	-367.4	-348.2	-336.3	-325
Net GHG (g CO_2-e/MJ Fuel)	-78.7	-105.4	-103.6	-151.6	-301
Net Fossil Energy Consumption (MJ fossil energy/MJ fuel)	-1.2	-1.6	-1.6	-2.1	-1.30
Total Fuel Yield (GGE/ton)	15.6	17.4	19.1	20.7	44.0
Biomass Carbon-to-Fuel Efficiency (C in fuel/C in biomass)	8.9%	9.9%	10.9%	11.8%	25.6%
Biomass Carbon-to-Coproduct Efficiency (C in succinic acid coproduct/C in biomass)	11.6%	14.6%	15.2%	15.9%	NA
Water Consumption (gal/GGE fuel) [a]	44	36	31	28	12.3
Net Electricity Import (KWh/GGE)	14.4	16.5	15.6	6.4	0.29

[a] Note: The gal/GGE water metric is fully allocated to the fuel product (not distributed to a coproduct train).
[b] Note: The succinic acid life-cycle inventory is based on maleic anhydride proxy.[18] Maleic anhydride is the precursor to petroleum-derived succinic acid.
c Note: The large decrease in fossil emissions from the 2017 projection to the 2022 projection reflects (1) different sustainability metrics for succinic acid vs. adipic acid, (2) the use of the C5 sugar train for fuel production increasing fuel yield per ton of feedstock, and (3) increases in conversion efficiency.

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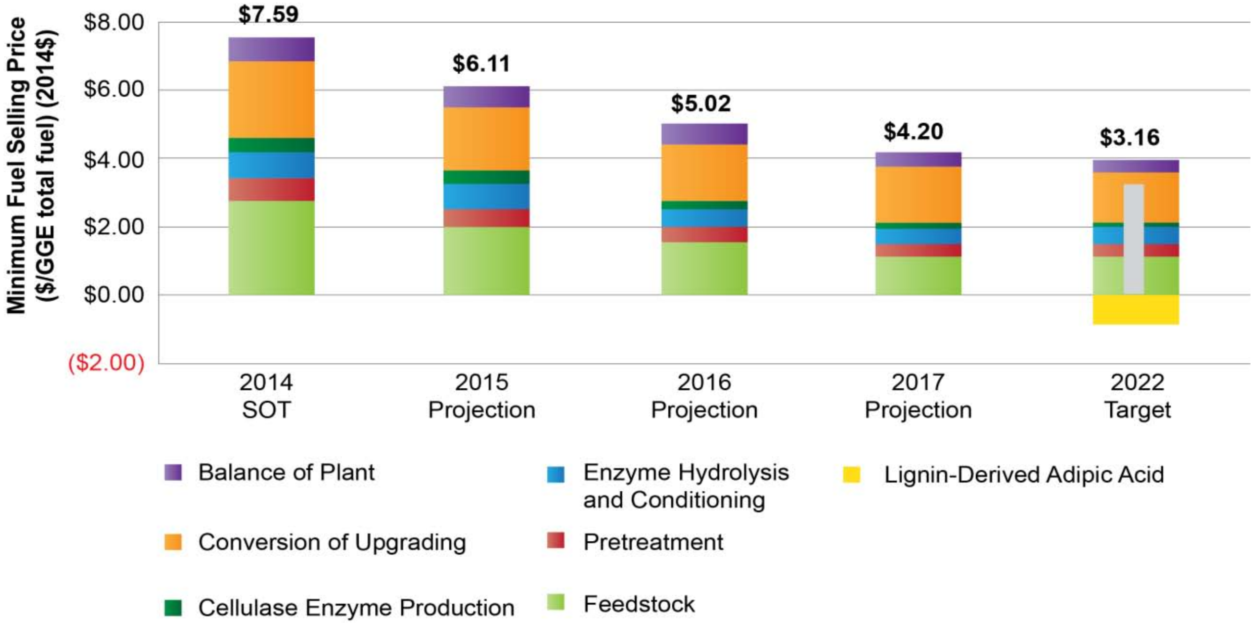
[18] Ecoinvent v.2.2. Duebendorf, Switzerland: Swiss Center for Life Cycle Inventories, 2010.

Low-Temperature Deconstruction and Catalytic Sugar Upgrading Pathway

This design case details enzymatic deconstruction to a sugar intermediate followed by chemocatalytic upgrading of sugars to fuels.[19] The design begins with feedstock preprocessing (deacetylation) and concurrent dilute-acid pretreatment, followed by enzymatic hydrolysis of the remaining cellulose, then by hydrolysate conditioning and catalytic conversion, and finally, upgrading of the resulting hydrolysate soluble carbon components to naphtha- and diesel-range fuel products.

Cost projections for the low-temperature deconstruction and catalytic sugar upgrading design case using externally purchased hydrogen are shown in Figure 2-28 and Table 2-26. Cost projections for 2017 are shown along with projected sustainability metrics in Table 2-27, highlighting the interconnectedness of sustainability and cost targets. The process economics and sustainability metrics vary widely with assumptions about the source of hydrogen used for catalytic upgrading, resulting in three different scenarios, shown in Table 2-28, which source hydrogen either externally, *in situ*, or through gasification of part of the feedstock. In particular, there is a tradeoff between additional fossil fuel consumption for externally purchased hydrogen and overall MFSP. More details are provided in Appendix A, Table A-10. The 2015 projections for this design case were adjusted to 2014$ but were not updated to 2015 SOT results. Corresponding feedstock costs are presented in Section 2.1.1.5 (Figure 2-12 and Table 2-5).



Note: Projections assume externally purchased hydrogen

Figure 2-28: Cost projections for the low-temperature deconstruction and catalytic sugar upgrading design case

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[19] R. Davis, L. Tao, C. Scarlata, and E.C.D. Tan et al. (2015), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons*, National Renewable Energy Laboratory, NREL/TP-5100-62498, http://www.nrel.gov/docs/fy15osti/62498.pdf.

Table 2-26: Cost Projections for the Low-Temperature Deconstruction and Catalytic Sugar Upgrading Design Case*

Total Fuel $/GGE (2014$)	SOT	Projection			Target
	2014	2015	2016	2017	2022
Feedstock	$2.72	$2.03	$1.48	$1.08	$1.08
Pretreatment	$0.72	$0.61	$0.53	$0.45	$0.49
Enzymatic Hydrolysis and Conditioning	$0.72	$0.60	$0.52	$0.46	$0.41
Cellulase Enzyme Production	$0.46	$0.34	$0.26	$0.22	$0.22
Conversion and Upgrading	$2.18	$1.87	$1.65	$1.50	$1.44
Balance of Plant	$0.79	$0.67	$0.57	$0.49	$0.34
Lignin-Derived Adipic Acid	$0.00	$0.00	$0.00	$0.00	-$0.82
MFSP	**$7.59**	**$6.11**	**$5.02**	**$4.20**	**$3.16**

*Projections shown assume externally purchased hydrogen.

As with the fermentation case, environmental sustainability metrics (Table 2-27) for the catalytic sugar upgrading case include offsets from the displacement of petroleum-derived products now produced from lignin.

Table 2-27: Environmental Sustainability Metrics for the Conversion Stage of the Low-Temperature Deconstruction and Catalytic Sugar Upgrading Conversion Process*

	SOT	Projection			
	2014	2015	2016	2017	2022[b]
Fossil GHG Emissions (g CO_2e/MJ fuel)	64.8	61.4	58.9	57.3	64.5
GHG credits (g CO_2e/MJ fuel)	-25.0	-18.6	-13.1	-8.3	-134
Net GHG (g CO_2e/MJ fuel)	39.8	42.7	45.8	49.1	-69.4
Fossil Energy Consumption (MJ fossil energy/MJ fuel)	1.0	1.0	0.9	0.9	1.0
Total Fuel Yield (GGE/ton)	50	59	68	78	76
Biomass Carbon-to-Fuel Efficiency (C in fuel/C in biomass)	29%	34%	39%	45%	44%
Total Carbon-to-Fuel Efficiency (C in fuel/C in biomass + NG [a])	25%	28%	32%	36%	35%
Water Consumption (gal/GGE fuel)	12.0	9.4	7.6	5.8	5.3
Net Electricity Export (KWh/GGE)	4.7	3.5	2.5	1.5	0.63

[a] NG = natural gas (used for off-site H_2 production via SMR at 0.44 mol NG/mol H_2).

[b] Note: The large decrease in fossil emissions from the 2017 projection to the 2022 projection reflects the introduction of lignin-derived adipic acid, which carries significant GHG credits for the displacement of petroleum-derived adipic acid.

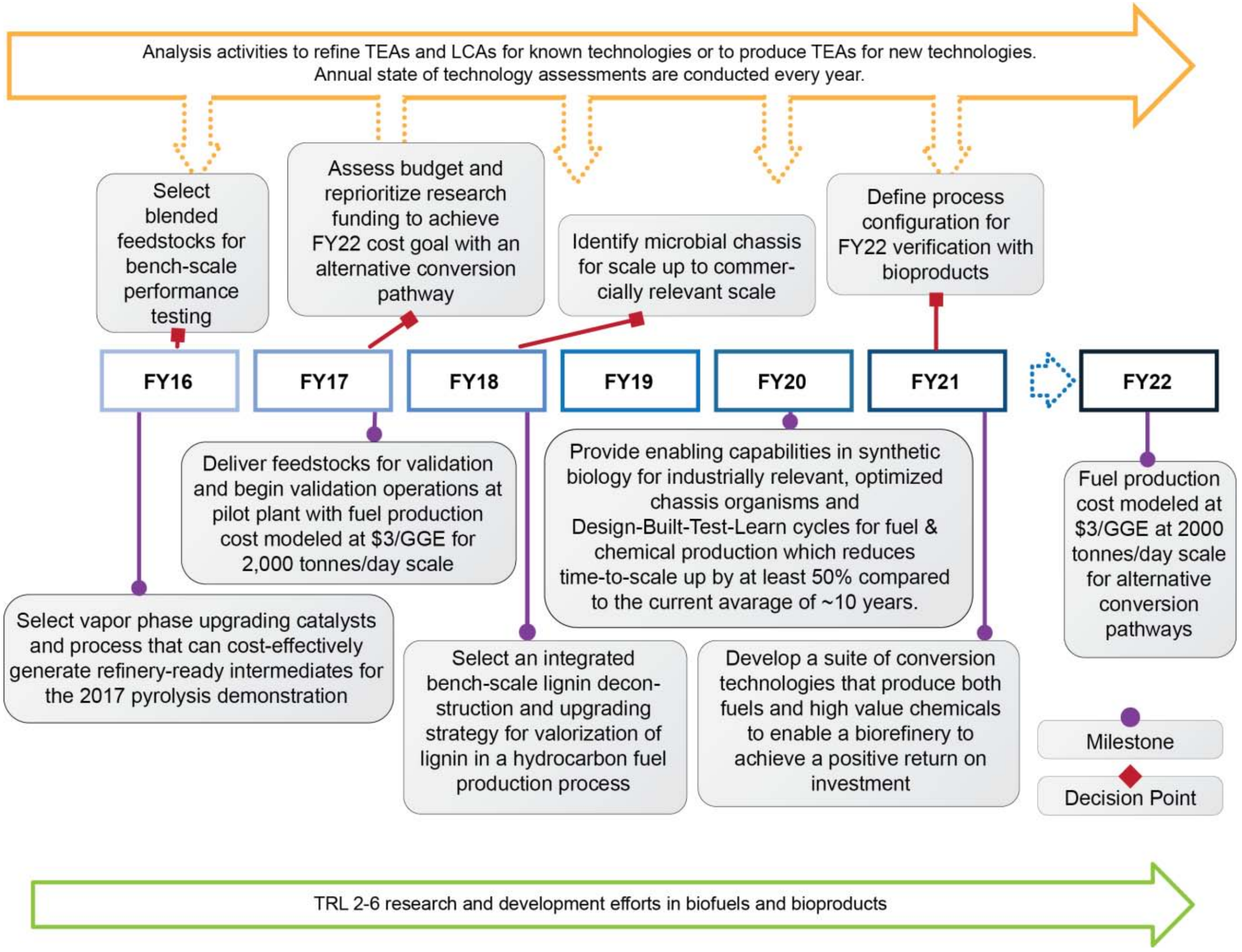
Table 2-22: Sustainability and Cost Projections for Different Sources of Hydrogen for Sugar Upgrading in the Low-Temperature Deconstruction and Catalytic Sugar Upgrading Conversion Process

Environmental Sustainability Metric	**2017 Projected**		
Hydrogen Source	**Purchased H_2**	***In situ* H_2**	**Gasification H_2**
Fossil GHGs (g CO_2e/MJ fuel)	49.2	15.3	7.5
Fossil energy consumption (MJ fossil energy/MJ fuel product)	0.8	0.2	0.1
Total fuel yield (GGE/dry ton feedstock)	78.3	45.3	50.1
Biomass carbon-to-fuel efficiency (C in fuel/C in biomass) [a]	45%	26%	28%
Water Consumption (gal/GGE)	5.8	9.8	11.4
MFSP (2014$)	**$4.20**	**$5.68**	**$5.13**

[a] Based only on C in starting biomass; when also including C implicit in NG for off-site H_2 production, “purchased H_2” case decreases to 36%.

2.2.6 Conversion Research and Development Milestones and Decision Points

The high-level Conversion R&D strategy program decision-making process, including milestones and decision points, is summarized in Figure 2-29.



TRL = technology readiness level

Figure 2-29: Conversion R&D key milestones and decision points

2.3 Demonstration and Market Transformation

The goal of Demonstration and Market Transformation (DMT) is to de-risk bioenergy production technologies through validated proof of performance at the pilot, demonstration, and pioneer scales and to conduct activities that will transform the biofuels market by reducing or removing commercialization barriers. This is achieved through public-private partnerships that build and operate integrated biorefineries (IBRs) and through projects focused on infrastructure and end-use market barriers and opportunities. These activities are essential to resolving key issues in the construction and scale-up of IBR systems, primarily by reducing risk to help overcome the commercial financing barriers that currently face the bioenergy industry. By creating a pathway to market, DMT helps address the final links of the bioenergy supply chain and works to enable a robust demand for end products.

The advanced bioenergy industry includes production of biofuels, bioproducts, and biopower. Similar to other process industries, the advanced bioenergy industry faces significant challenges and risks in the scale-up to pilot, demonstration, and pioneer scales. These include risks related to technology, construction, environmental impact, feedstock supply, operations, market offtake, and financing.[1] The specific risks of feedstock supply and market offtake are more pronounced for advanced biofuels than for other renewable sources of energy because of the variability inherent in biomass and the lack of long-term offtake agreements in the fuel and chemicals markets. Advanced infrastructure-compatible fuels require an extra level of certification for end use, such as in automotive and jet engines, as well as infrastructure compatibility testing for integration into refinery equipment, pipelines, rail cars, and storage tanks. DMT activities focus on reducing these barriers for the private sector by facilitating large-scale projects that address these risks and catalyze the transformation in the U.S. transportation fuel supply from fossil-based to renewable.

The Office is uniquely positioned to leverage both its legislative authority for financial assistance and DOE's successful track record in technology commercialization to assist developers through validated proof of performance at pilot, demonstration, and pioneer scales. A study that assumed a standard biorefinery size of 40 million gallons of ethanol equivalent fuel per year determined that meeting the goals of the Energy Independence and Security Act of 2007 will require more than 500 new biorefineries.[2] Of the approximately 200 U.S. companies currently working to develop advanced biofuels, only a fraction have progressed beyond in-house laboratory or very small-scale pilot testing.[3] Of these, an even smaller number have been able to raise the funds to move into the full pilot or demonstration phase of development without some form of government financial assistance.[4] During the Office's June 2015 Program Management Review,

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[1] S.E. Koonin, Gopstein, A.M. (2011), "Accelerating the Pace of Energy Change," *Issues in Science and Technology*.

[2] U.S. Department of Agriculture (2010), *USDA Biofuels Strategic Production Report*, http://www.usda.gov/documents/USDA_Biofuels_Report_6232010.pdf.

[3] Advanced Ethanol Council (2012), *Cellulosic Biofuels Industry Progress Report 2012-2013*, http://ethanolrfa.3cdn.net/d9d44cd750f32071c6_h2m6vaik3.pdf.

[4] D. Bacovsky, N. Ludwiczek, M. Ognissanto, M. Wörgetter (2013), *Status of Advanced Biofuels Demonstration Facilities in 2012: A Report to IEA Bioenergy Task 39*, http://task39.org/2013/12/report-on-the-status-of-advanced-biofuels-demonstration-facilities-in-2012/.

experts from the refining, chemical, and financial industries made similar conclusions, stating that "DOE should provide grant money to encourage the most successful, and potentially commercially viable, pilot plant projects to proceed to the next scale."[5]

The DMT program area is investigating high-potential feedstock resources, including agricultural and forest resides; herbaceous and woody energy crops; sorted, dry municipal solid waste (MSW); and algal feedstocks and intermediates. DMT also investigates a wide range of conversion pathways, including biochemical, thermochemical, and hybrid processes; advanced anaerobic digestion; and other waste-to-energy technologies. Potential product slates include, for example, biofuels, renewable home heating oil, and bioproducts (such as succinic acid) that can replace petroleum-derived products. Each of these alternative resources and conversion pathways must be proven and validated at larger scales in order to sufficiently reduce risk and reach market acceptance, as illustrated in Figure 2-30.

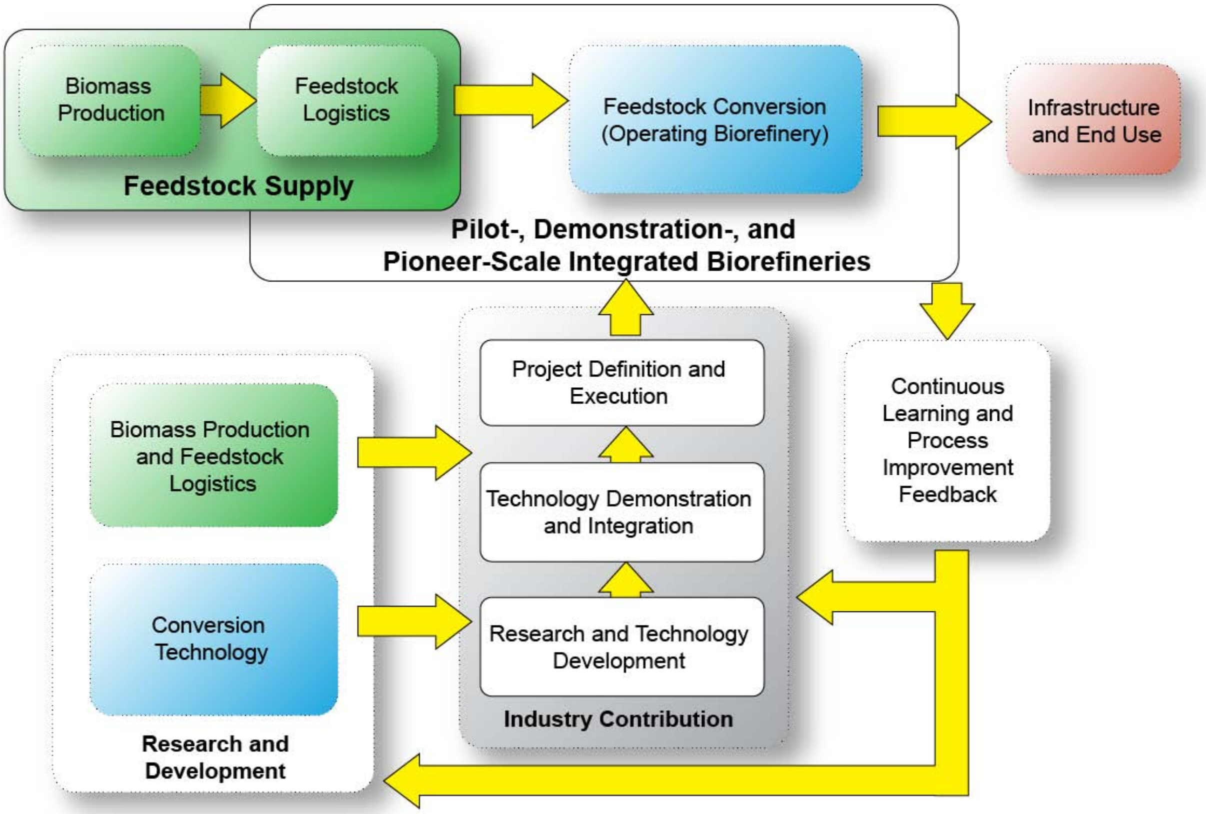

Figure 2-30: DMT scope and connection to R&D efforts

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[5] Visit the Office's 2015 Project Peer Review Web page for the most recent peer review report: http://energy.gov/eere/bioenergy/2015-project-peer-review.

Integrated Biorefinery Definitions and Objectives

An IBR facility is defined by its objectives and operational scale. These definitions were developed by a large group of stakeholders including biomass suppliers; technology developers; engineering, procurement, and construction (EPC) companies; and financial firms such as venture capitalists, angel investors, and large commercial banks.

Pilot-scale facilities verify the integrated technical performance of the given suite of technologies from feedstock in through product out at production capacities equal to or greater than one dry ton of feedstock per day. A pilot-scale facility integrates key recycle streams to validate the process and techno-economic model, but it is not intended to produce cost-competitive fuels due to its small scale of operation. Any problems identified in the pilot stage must be corrected prior to further scale-up or it is unlikely that the next plant will achieve its design capacity, operability factor, and profitability.[6] Integrated pilot testing also generates the performance data and equipment specifications required to design a demonstration-scale facility, as well as to determine process sustainability metrics such as water use and greenhouse gas emissions. Successful integrated pilots strengthen projects at larger scales and encourage private investment.

Demonstration-scale facilities verify performance at a scale sufficient to provide data and equipment specifications required to design a pioneer-scale facility. Demonstration facilities, typically between one-fiftieth and one-tenth of the pioneer scale, prove all recycle streams and heat integration for more than 1,000 hours of operations. This length of testing validates process robustness across the variability of biomass feedstock and operating conditions while still meeting the product specifications. Demonstration-scale operational data is used to validate commercial equipment specifications and design factors for the pioneer-scale facility. This data is used to balance sustainability performance across economic, social, and environmental dimensions, such as balancing the feedstock availability with site infrastructure and workforce requirements, or balancing emissions through heat integration or wastewater treatment. Demonstration-scale projects are not meant to produce positive cash flow, but instead to identify process design improvements and develop more precise cost estimates for the pioneer plant. In some cases, 1,000 hours of continuous operational data is sufficient to allow for a performance guarantee on the pioneer facility from a major EPC firm. An EPC performance guarantee is an important step in obtaining commercial financing for larger-scale facilities. To determine if a project is ready for demonstration-scale, integrated pilot testing of all critical process steps must have been successfully completed.

Pioneer-scale, or "first-of-a-kind" facilities prove economical production at commercial volumes on a continuous basis with a reliable feedstock supply and production distribution system, and verify environmental and social sustainability performance. These facilities have a higher capital cost than subsequent plants, which reflects the uncertainty and flexibility required in a first-of-a-kind process. Future plants benefit from refinements due to pioneer operations. Successful design, construction, and operation of a pioneer facility are greatly dependent on prior development of integrated pilot- and demonstration-scale facilities that have generated the

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[6] A. Marton (2011), "Research Spotlight: Getting off on the Right Foot – Innovative Projects*,"* *Independent Project Analysis Newsletter* 3(1).

necessary performance data and equipment specifications. Once the pioneer facility achieves operation at full design capacity and reaches positive cash flow, the technology application can be replicated through commercial debt or project financing.

Figure 2-31 depicts the progression of a conversion technology from pilot to demonstration to pioneer plant. The concentric ovals indicate that each stage is inclusive of the prior stage and builds upon its results, while the table below it describes the unique objectives at each stage.

Infrastructure and End Use

Once biofuels, bioproducts, or biopower are produced, distribution challenges remain for full market deployment. Biofuel use is constrained by the types of fuels produced (cellulosic ethanol, renewable diesel, or hydrocarbon intermediates or replacement), end-use applications, and the respective fuel blending limits that have been established. Additionally, biofuel use can also be constrained in some cases due to refinery process integration or existing pipelines and storage tank infrastructure. For instance, infrastructure-compatible hydrocarbon biofuels require extensive certification testing, especially for the jet fuel market. Beyond these constraints, opportunities exist to develop new fuels and engines that are co-optimized—that is, designed in tandem—to maximize performance and carbon efficiency.

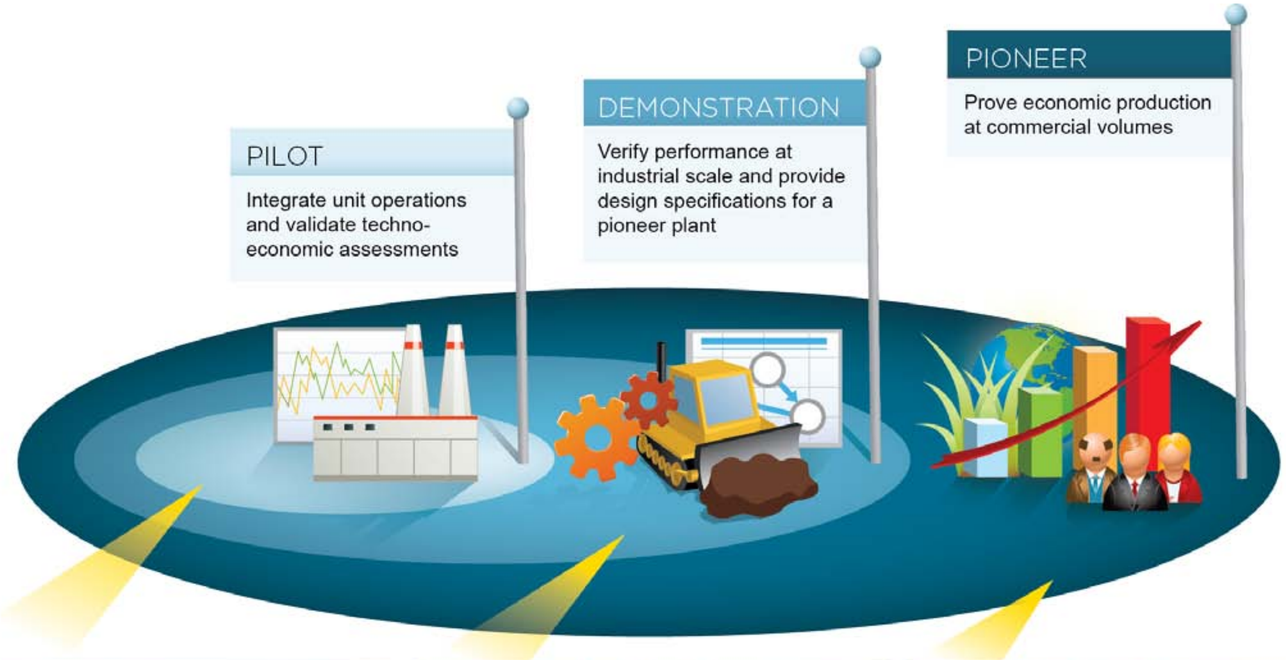
Market acceptance of renewable home heating oil faces similar challenges and constraints, including blending limits and compatibility with home furnaces and transport and storage equipment. Bioproducts, whether used to replace fossil-based products or in a completely new market, will need to consistently meet the associated specifications. In addition, any biopower generated at a biorefinery may require capacity upgrades or reliability improvements to the local electricity grid.

Demonstration and Market Transformation Interfaces

The Office’s R&D areas are focused on developing the scientific and engineering underpinnings of a bioenergy industry by understanding technical barriers and providing process and engineering solutions. The DMT projects then build upon these R&D efforts and create a feedback loop that uncovers additional barriers to commercial success at larger scale. The data and lessons learned from both R&D and DMT efforts are then used jointly for overall Office strategic planning.

Feedstock Research and Development

Successful commercialization of bioenergy technologies relies on a feedstock supply chain that can cost-effectively supply adequate volumes of a specified quality of feedstock to the biorefinery. Plant operations are dependent on a continuous, consistent feedstock supply of known quality attributes to achieve their performance targets. Feedstock cost, availability, variability, quality control, and storage are all parameters that greatly affect the performance of a facility. In addition to economic and technical parameters, feedstock handling and storage facilities must meet existing construction, safety, and fire codes that were not typically developed for large-scale lignocellulosic biomass operations. Updating these codes to address the



PILOT

Integrate unit operations and validate techno-economic assessments

DEMONSTRATION

Verify performance at industrial scale and provide design specifications for a pioneer plant

PIONEER

Prove economic production at commercial volumes

PILOT OBJECTIVES

- Technical Performance
  - Prove conversion efficiencies
  - Confirm mass and energy balance
- Operations
  - Determine feedstock and product specifications
  - Integrate technology from feedstock in through product out
  - Evaluate process sustainability metrics
- Scale-Up to Demonstration
  - Develop robust economic model

DEMONSTRATION OBJECTIVES

- Market Risk
  - Manufacture product for commercial acceptance testing
- Operations
  - Generate more than 1,000 hours of continuous operational data
  - Balance sustainability performance across environmental, social, and economic dimensions
- Scale-Up to Pioneer
  - Validate commercial equipment specifications and performance

PIONEER OBJECTIVES

- Financial Risk
  - Prove technology is profitable to support robust replication of commercial facilities
- Feedstock Supply and Logistics
  - Demonstrate robust feedstock supply and offtake value chain
- Operations
  - Validate performance data and equipment design specifications
  - Verify sustainability performance across environmental, social, and economic dimensions

Figure 2-31: Description of key objectives at each integrated biorefinery scale

Conversion Research and Development

Continued R&D to improve the conversion of biomass to biofuel, bioproducts, and biopower is necessary to increase conversion efficiency and lower costs. These efforts reduce the technological risk of the process and increase the probability of commercial success. Several existing DMT projects have been directly supported, and most have indirectly benefitted from the Office's past and current conversion R&D efforts.

2.3.1 Demonstration and Market Transformation Support of Office Strategic Goals

The strategic goal of the DMT program area is to *develop commercially viable biomass utilization technologies through public-private partnerships that build and validate pilot-, demonstration-, and pioneer-scale integrated biorefineries; and develop supporting infrastructure to enable a fully operational and sustainable biomass-to-bioenergy value chain in the United States.*

The biorefinery and infrastructure projects are testing advanced biofuels, bioproducts, and biopower from high-impact feedstocks, including herbaceous, woody, and algal feedstocks, as well as from MSW. DMT focuses on reducing risk to the consumer and the private sector and helping overcome challenges to financing the follow-on expansion of the industry, which is required to make a major contribution to our nation's energy independence. DMT also focuses on developing novel methods for expanding the end use market for biofuel.

2.3.2 Demonstration and Market Transformation Support of Office Performance Goals

Specific DMT goals in support of Office performance goals are as follows:

- By 2017, validate a mature technology modeled cost of cellulosic ethanol production, based on actual integrated biorefinery performance data, and compare to the target of $2.65/gallon ethanol (2014$).
- By 2027, validate a mature technology modeled cost of infrastructure-compatible hydrocarbon biofuel production, based on actual integrated biorefinery performance data, and compare to the target of $3/GGE (2014$).

The objective of validating these technologies is to prove techno-economic viability and enable commercial production facilities. The 2017 goal reflects the validation efforts of the existing pioneer cellulosic ethanol facilities in the DMT portfolio; the goals for 2018 and beyond reflect the focus on infrastructure-compatible hydrocarbon biofuels. Table 2-23 contains the projects expected to contribute to the 2017 performance goal.

Table 2-23: Estimated Project Contribution for 2017 Performance Goal

Project	Production Capacity (million gallons)	Fuel	Conversion Route	Feedstock
Abengoa	25	Cellulosic Ethanol	Biochemical	Agricultural Residue
POET-DSM	25	Cellulosic Ethanol	Biochemical	Agricultural Residue
INEOS New Planet Bioenergy	8	Cellulosic Ethanol	Thermochemical/ Biochemical Hybrid	Green Waste and MSW

In the past, DMT performance goals were focused on validating production capacity in a given year. Because the capacity of a pioneer project can be more than 100 times the capacity of a pilot project, these capacity goals relied on a disproportionately small number of pioneer projects. These pioneer projects face significant barriers outside the control of the Office, such as securing financing or long delays in construction and start-up. Also, the efforts to validate technology and reduce risk at pilot and demonstration-scale were not reflected. Therefore, future performance goals and milestones focus on validating a specific number of technologies at various scales instead of a projection of production capacity.

DMT interim milestones toward reaching these goals, to be accomplished in three cycles, include the following:

Cycle 1:

- By 2022, validate successful runs of two biofuels and/or bioproducts manufacturing processes at pilot-scale
- By 2022, validate successful runs of one biofuels manufacturing process using a hydrocarbon fuels pathway at demonstration-scale. By 2023, this successful demonstration of the technology enables the submission of a package for external funding sources (for example, loan guarantee) for the design and construction of a pioneer-scale facility on trajectory to market.

Cycle 2:

- By 2025, validate successful runs of one biofuels manufacturing process utilizing an additional pathway to fuels at pilot-scale
- By 2025, validate successful runs of one biofuels and/or bioproducts manufacturing process incorporating another compatible hydrocarbon biofuels/bioproducts pathway at demonstration-scale. By 2026, this successful demonstration of the technology facilitates the submission of a package for external funding (for example, loan guarantee) for the design and construction of a pioneer-scale facility on trajectory to commercialization.

Cycle 3:

- By 2030, validate successful runs of one biofuels and/or bioproducts manufacturing process based on a different conversion pathway at demonstration-scale. By 2031, this successful demonstration of the technology enables the submission of a package for external funding (for example, loan guarantee) for the design and construction of a pioneer-scale facility on trajectory to market.

More detail on interim milestones is shown in Table 2-24:

Table 2-24: Interim DMT Milestones

Cycle	Step (see Notes)	Accomplished By	Number of Pilot Projects	Number of Demonstration Projects	Number of Pioneer Projects
1	Initiation (BP-1)[a]	2017	10	4	-
	Down-select (BP-2)[b]	2019	5	2	-
	Select for next scale-up (end of BP-3)	**2022**	-	**2 from Pilot**	**1 from Demo**
2	Initiation (BP-1)	2020	5	4	-
	Down-select (BP-2)[c]	2022	3	2	-
	Select for next scale-up (end of BP-3)	**2025**	-	**1 from Pilot**	**1 from Demo**
3	Initiation (BP-1)	2025	2	4	-
	Down-select (BP-2)	2027	1	2	-
	Select for next scale-up (end of BP-3)[d]	**2030**	-	**-**	**1 from Demo**

Note: Refer to "Integrated Biorefinery Project Management Framework" and Figure 2-33 for the definition of Budget Period (BP) and Critical Decision (CD) Point.

[a] Initiation (BP-1 and CD-2) involves selecting pilot- and demonstration-scale projects for Technical Due Diligence, Design and Verification

[b] Down-select (BP-2, and CD-3 and CD-4) comprises the successful completion of Technical Due Diligence, Design and Verification and selecting pilot- and demonstration-scale projects to advance to Construction and Operations.

[c] Selection for the next scale-up step (end of BP-3) entails validating successful runs by pilot- and demonstration-scale projects and selection to advance to the next scale-up level (i.e., successful pilot-scale projects advance to demonstration-scale implementation and successful demonstration-scale projects advancing to pioneer-scale implementation).

2.3.3 Demonstration and Market Transformation Challenges and Barriers

Market Challenges and Barriers

Im-A. Inadequate Supply Chain Infrastructure: The development of a sustainable feedstock supply chain is impacted by the variability in feedstock and its limited infrastructure. Variable composition, geographical diversity, and diverse physical characteristics (such as particle size) impact supply chain costs. Difficulties in securing a reliable, sustainably produced feedstock supply also presents risks and additional costs. Producing and delivering a feedstock that meets the conversion specifications and cost targets of the biorefinery in sufficient volumes to support a commercial, advanced biofuels industry will require incentive programs to stimulate the large capital investments needed for feedstock production, preprocessing, storage, and transport to commodity markets. Feedstock infrastructure, such as handling and storage facilities, also must meet existing construction, safety, and fire codes, which, in most cases, were not developed for large-scale lignocellulosic biomass operations.

Im-B. High Risk of Large Capital Investments: Once emerging biomass technologies have been developed and tested, they must be commercially deployed. Financial barriers are the most challenging aspect of technology deployment. Capital costs for commercially viable facilities are relatively high, and securing capital for an unproven technology at scale is extremely difficult. Lenders are hesitant to provide debt financing for first-of-a-kind facilities where the process performance cannot be adequately guaranteed. Government assistance to validate proof of performance at the pilot, demonstration, and pioneer scales is critical to successful deployment. Another significant challenge for debt financing of first-of-a-kind pioneer facilities is the absence of long-term, consistent federal policies. Lenders will not account for federal incentives and subsidies as income in the consideration of loan applications if they perceive that federal (and state) policies and financial support mechanisms are subject to change.

Im-C. Codes, Standards, and Approval for Use: New biofuels and biofuel blends must comply with federal, state, and regional regulations before being introduced to the market. Codes and standards are adopted by federal, state, and regional jurisdictions to ensure product safety and reliability and reduce liability. Limited data and technical information can also delay approvals of technical codes and standards for biofuels and related infrastructure components, including pipelines, storage tanks, and dispensers. The long lead times associated with developing and understanding new and revised regulations for technology can impede commercialization and full market deployment.

Im-D. Cost of Production: The inability to compete—in most applications—with established fossil energy supplies and supporting facilities and infrastructure is an overarching market barrier for biomass technologies. Previous analysis has shown that doubling cumulative industrial capacity leads to an average reduction of 24% in cost[7] for process technologies. The accelerated industrial learning that occurs during this capacity growth also has been successful in reducing cost in the fuels and chemicals industry over the past several decades.[8] Reductions in production costs along the entire biomass supply chain—including feedstock supply, conversion processes, and product distribution—are needed to make advanced biofuels, bioproducts, and biopower competitive with petroleum-derived analogs.

Im-E. Offtake Agreements: Production costs—and therefore, selling price and profits—of commodity fuels and chemicals derived from crude oil are dependent on a fluctuating market. Generally, companies in these markets offer products on a contract basis; however, they often sell to the market on the spot to generate the greatest return on investment. Offtake agreements can often take the form of fixed-price contracts for 1–2 years, followed by contracts fixed to a specific index (such as the Chicago Board of Trade pricing). The producer then must adjust its *pro forma* accounting and variable cost structure to account for such market fluctuations. Another challenge with fuel offtake agreements is that the industry standard is 1–2 years, in contrast to the longer term of debt financing, which can range from 7–15 years or longer. The providers of long-term debt generally require the duration of the offtake agreement to match the length of the loan, which is a difficult challenge when the product selling price is dependent on a fluctuating market.

Im-F. Uncertain Pace of Biofuel Availability: The slow pace of development and commercialization of new biofuel technology contributes to a limited supply and availability of biofuels. Additionally, uncertainty about which types of biofuels will be produced at what volumes over the short and long term, adds risk to investing in biofuels infrastructure. Other factors, such as the price of oil, the pace of economic recovery, climate legislation, and other policy measures, also complicate investment decisions.

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[7] E.W. Merrow (1989), *An Analysis of Cost Improvement in Chemical Process Technologies*, RAND R-3357-DOE.

[8] E. Gummerman and C. Marnay (2004), *Learning and Cost Reductions for Generating Technologies in the National Energy Modeling System (NEMS)*, Lawrence Berkeley National Laboratory, University of California Berkeley, LBNL-52559, http://eetd.lbl.gov/sites/all/files/publications/report-lbnl-52559.pdf.

Im-G. Biofuels Distribution Infrastructure: The infrastructure required to distribute and dispense large volumes of ethanol does not currently exist. This puts this biofuel at a disadvantage compared to conventional liquid transportation fuels that have mature infrastructure. These infrastructure challenges may not apply to renewable hydrocarbon fuels. In the United States, ethanol is currently transported predominantly by rail and truck. These transportation modes will need to be substantially enhanced with concomitant capital investments to avoid congestion issues over the coming decades, especially in the Midwest. Higher-level ethanol blends, such as E85 (and other less-compatible biofuels), require separate storage tanks and dispensers, and may require other material modifications at refueling stations. Most refueling stations are privately owned with relatively thin profit margins, and owners have been reluctant to invest in new infrastructure until the market is more fully developed. Petroleum-compatible biofuels may also require distribution infrastructure investment.

Im-H. Lack of Acceptance and Awareness of Biofuels as a Viable Alternative: To be successful in the marketplace, biomass-derived fuels and chemical products must perform as well or better than comparable petroleum- and fossil-based products. Industry partners and consumers must believe in the quality, value, sustainability, and safety of biomass-derived products and their benefits relative to the risks and uncertainties that widespread changes will likely bring. Levels of consumer acceptance and awareness of biofuels and bioenergy technologies vary more widely compared to other renewable energy technologies. The availability of impartial, reliable information regarding the economic and environmental benefits and impacts of increased bioenergy use is currently limited.

Technical Challenges/Barriers

It-A. End-to-End Process Integration: Successful deployment of the biorefinery business model is dependent on advances in integrated conversion process technologies. The biorefinery concept encompasses a wide range of technical issues related to collecting, storing, transporting, and processing diverse feedstocks, as well as the complexity of integrating new and unproven process steps. The demonstrating and validating total process integration—from feedstock production to end-product distribution—is crucial, as it impacts both performance and profitability.

It-B. Risk of First-of-a-Kind Technology: Pioneer biorefineries will incorporate a variety of new technologies. Studies have shown that the number and complexity of new process steps implemented in pilot- and demonstration-scale projects are a strong predictor of the challenges to be encountered with reliable performance and operations of a commercial-scale facility. Heat and mass balances, along with the implications, are not likely to be well understood in new technologies. In addition, start-up and commissioning equipment may take longer than expected due to issues that were not observed at smaller scales, including buildup of impurities in process recycle streams, degradation of chemical or catalyst performance and abrasion, fouling, and corrosion of plant equipment.

It-C. Technical Risk of Scaling: Commercially viable biofuel production requires large-scale, complex, capital intensive biorefinery process technologies. Unit operations proven at small scale under laboratory conditions need to be scaled up and integrated at pilot-scale to validate process performance. Given the magnitude of capital investment required, scaling from pilot to full commercial-scale—as much as a 500–1,000x increase in scale—involves a level of technical risk that few investors are willing to undertake. Best practices from other process industries suggest more modest scaling factors of 50x from pilot to demonstration-scale and of 10–20x from demonstration to first-of-a-kind pioneer scale.[9] This step-wise scaling enables full integration of unit operations including all recycle streams, more complete validation and optimization of process operations, and development of equipment specifications that may enable process performance guarantees.

It-D. Engines Not Optimized for Biofuel: Transportation vehicle manufacturers are encouraged to design vehicles with lighter weight and higher overall fuel efficiency to meet the Corporate Average Fuel Economy (CAFE) standards at the same time as biofuels and biofuel blends enter the market place. In current motor vehicle engines, some biofuels result in decreased fuel economy on a miles per gallon basis, relative to petroleum fuels. For instance, ethanol has a lower energy density than gasoline, approximately 76,000 British thermal units (Btu) per gallon of ethanol in comparison to 115,000 Btu per gallon of gasoline,[10] but it also has a higher octane rating of 115 compared to 85–88 for regular gasoline. The actual fuel economy impact is dependent on a variety of factors; however, the negative effects from reduced energy density may be mitigated through optimizing engines to use higher octane fuels with higher renewable content. Co-development of fuels and engines has proved successful for controlling criteria pollutants and has the potential to drive increased vehicle engine efficiency and reduced GHG emissions. Vehicle manufacturers are considering the impact that the specification of new fuel mixtures and vehicle system optimizations can achieve, although no timeline has been established for introducing these changes to the vehicles market.

2.3.4 Demonstration and Market Transformation Approach for Overcoming Challenges and Barriers

The approach for overcoming DMT challenges and barriers is outlined in the work breakdown structure (WBS) depicted in Figure 2-32 and Table 2-25. The current activities generally fall into five categories: Analysis and Sustainability, Technology Interface, Feedstocks, Integrated Biorefineries, and Infrastructure and End Use. DMT activities are performed primarily by industry partners with national laboratories and universities also making significant contributions.

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[9] M.S. Peters, K.D. Timmerhaus, and R.E. West (2003), *Plant Design and Economics for Chemical Engineers*.

[10] U.S. Department of Energy (2007), "Biofuels in the U.S. Transportation Sector, Table 11," *Annual Energy Outlook 2007*, http://www.eia.doe.gov/oiaf/analysispaper/biomass.html.

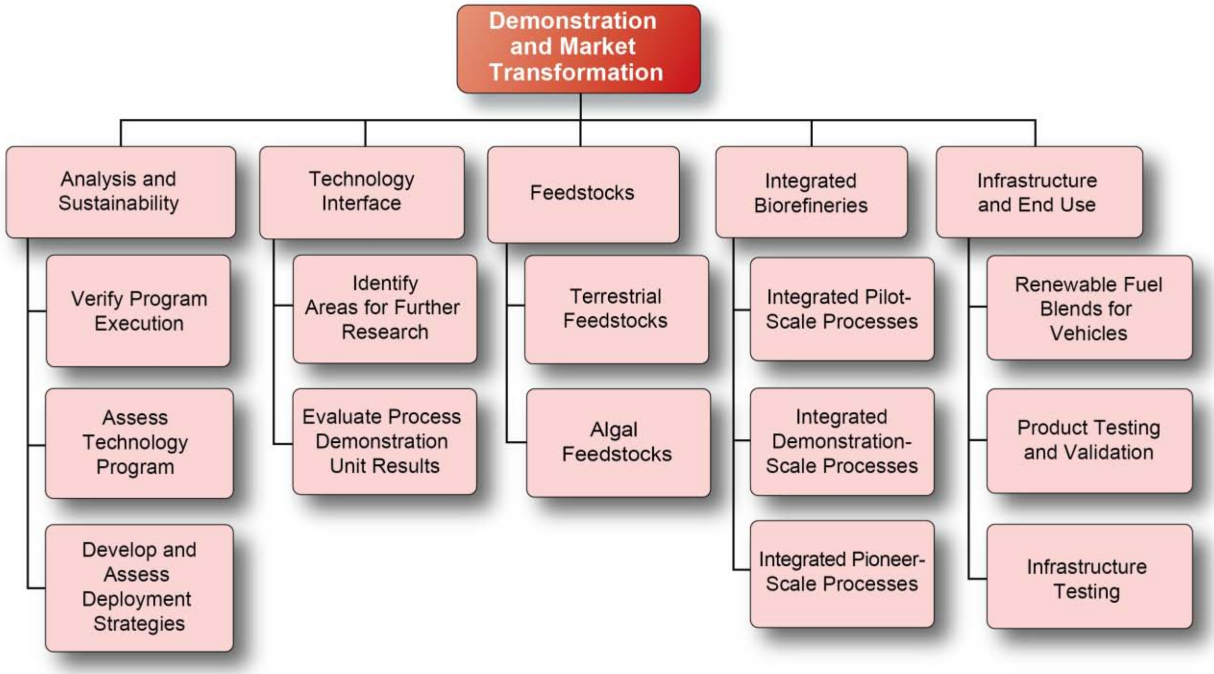

Figure 2-32: Demonstration and Market Transformation work breakdown structure

Analysis and Sustainability

Both project-specific and portfolio-wide evaluations assess progress toward objectives and sharpen the focus of DMT strategies on the areas with the highest potential impact to the industry. These evaluations, which encompass a broad range of technical performance and economic, social, and environmental sustainability metrics, are updated annually to reflect developments within each project and the industry. Specific metrics include process performance by unit operation; financial data, including pro forma and actual capital and operating costs; and sustainability metrics, including water usage, life-cycle greenhouse gas emissions, and jobs created. This data is used to monitor progress against goals, assess the current state of technology for various biomass utilization technologies, and determine the projected commercial impact of various projects.

Technology Interface

DMT projects integrate broad sets of technologies from the Feedstock Supply and Logistics and Conversion R&D program areas. Technology interface activities help identify (1) times when technologies are ready for piloting and scale-up, (2) entirely new feedstock logistics systems or conversion technologies, or (3) improvements to a smaller set of unit operations. In addition, new challenges discovered during scale-up are shared in a feedback loop with R&D areas.

Feedstocks

Every IBR uses biomass feedstock as an input, and efforts to improve the supply and logistics system are essential for commercial operations. These activities span both terrestrial feedstock systems and algal feedstock systems to identify areas for improvement in feedstock supply and logistics systems and in the development of advanced feedstock logistics systems.

Integrated Biorefineries

Validating performance at integrated pilot, demonstration, and pioneer scales is essential to de-risk technology and enable financing that will catalyze the transition to large-scale renewable fuel production. Operation at each of these scales systematically addresses many of the market and technical barriers previously identified. Integrated pilots prove the end-to-end process and develop engineering modeling tools. Demonstration-scale facilities then allow for more optimized equipment specifications and can manufacture product for commercial acceptance that can lead to offtake agreements for the pioneer plant. Finally, pioneer plants prove continuous economic operation with large-scale supply chains. Operational data at each scale is also used to address many other barriers, including sustainability.

The success of IBR projects is expected to provide assurances that offtake agreements for biofuels, bioproducts, and biopower can be managed for future commercial financing. Analogous to the petrochemical industry's development of refinery infrastructure, biorefinery projects showing success should translate into better financing potential.

Infrastructure and End Use

In addition to the significant risks involved with scaling-up new biorefinery technology, other market barriers related to infrastructure and end use also limit advanced biofuel production. Efforts in this area focus on enabling higher rates of renewable fuel usage in current markets while addressing barriers for expansion into new markets, such as home heating oil. Specific efforts in this area are to establish linkages early in the R&D cycle of both fuels and engines. Co-development of fuels and engines could result in expanded markets for renewable fuels, improvements in vehicle engine efficiency, and reductions in life-cycle GHG emissions. The Office works closely with DOE's Vehicle Technologies Office to identify the opportunities and challenges associated with the development of new fuel specifications and to assist stakeholders in the development and deployment of optimized vehicle systems, new fuel compositions, and compatible infrastructure needed to achieve increased advanced biofuels use in the U.S. transportation system.

Table 2-25: DMT Activity Summary

WBS Element	Description	Barrier(s) Addressed
Analysis and Sustainability	Verify progress of projects toward objectives, assess development of overall technologies across the "Valley of Death," and develop strategies to focus on the most promising areas. - Verify technology deployment, including Independent Engineer evaluations of each project. - Assess progress of biorefineries though TEA. - Deploy models and planning processes to assess the impact of DMT projects on overall bioindustry development.	Im-A: Inadequate Supply Chain Infrastructure Im-C: Codes, Standards, and Approval for Use It-B: Risk of First-of-a-Kind Technology St-C: Sustainability Data across the Bioenergy Supply Chain St-D: Implementing Indicators and Methodology for Evaluating and Improving Sustainability St-F: Systems Approach to Bioenergy Sustainability
Technology Interface	Maintain a feedback loop with R&D on new technologies ready for piloting and in identifying additional barriers and research needs at larger scale. - Monitor progress of emerging technologies within R&D areas, incubators, and outside sources. - Identify additional barriers and research needs at larger scale through biorefinery projects.	Ft-D: Sustainable Harvesting Mm-A: Lack of Understanding of Environmental/Energy Tradeoffs It-A: End-to-End Process Integration
Feedstocks	Deploy technologies to provide a secure, reliable, affordable, high-quality, and sustainable cellulosic and algal biomass feedstock supply for the U.S. bioenergy industry. - Demonstrate pioneer-scale terrestrial feedstock supply systems. - Demonstrate algal feedstock supply systems to validate technology performance.	Ft-A: Terrestrial Feedstock Availability and Cost Ft-E: Terrestrial Feedstock Quality and Monitoring Im-A: Inadequate Supply Chain Infrastructure Im-D: Cost of Production It-A: End-to-End Process Integration It-B: Risk of First-of-a-Kind Technology
Integrated Biorefineries	Demonstrate and validate IBR technologies at pilot, demonstration, and pioneer scale. - Pilots integrate unit operations from feedstock-in through product-out at ≥ 1 dry tonne per day. - Demonstrations prove all recycle streams and heat integration and develop equipment specifications for larger-scale facilities. - Pioneers, or first-of-a-kind plants, prove economical production at commercial volumes on a continuous basis along with a reliable feedstock supply and production distribution system.	Ft-E: Terrestrial Feedstock Quality and Monitoring Ft-F: Biomass Storage Systems Im-A: Inadequate Supply Chain Infrastructure Im-B: High Risk of Large Capital Investments Im-D: Cost of Production Im-E: Offtake Agreements It-A: End-to-End Process Integration It-B: Risk of First-of-a-Kind Technology It-C: Technical Risk of Scaling
Infrastructure and End Use	Enable higher rates of renewable fuel usage and define the needs for biofuels infrastructure and market use through 2030 and beyond. - Address barriers to renewable fuel use in new, existing, and future automobile engines and other areas, such as replacing home heating oil. - Investigate the potential for high-octane fuels to improve near-term conventional spark ignition engine efficiency. Characterize impact of biofuel properties such as heat of vaporization, burn rate, viscosity, volatility, and energy density on optimized engines. - Investigate the potential for advanced biofuel blends to improve thermal efficiencies and reduce GHG and criteria-pollutant emissions in advanced compression ignition engines, which includes kinetically-controlled and low-temperature combustion approaches.	Im-F: Uncertain Pace of Biofuel Availability Im-G Availability of Biofuels Distribution Infrastructure Im-H. Lack of Acceptance and Awareness of Biofuels as a Viable Alternative Im-C: Codes, Standards, and Approval for Use It-D: Engines Not Optimized for Biofuel

Integrated Biorefinery Project Management Framework

The Office has established a project management framework with additional project management, verification, and oversight procedures to effectively manage its large-scale, capital-intensive IBR activities. The project management framework incorporates DOE standards for management of capital assets as well as industry best practices–including use of an independent engineer (IE). The framework, shown in Figure 2-33, is divided into four main sections that correlate contractual budget periods (BP) to the critical decision (CD) points identified in DOE Order 413.3B.[11]

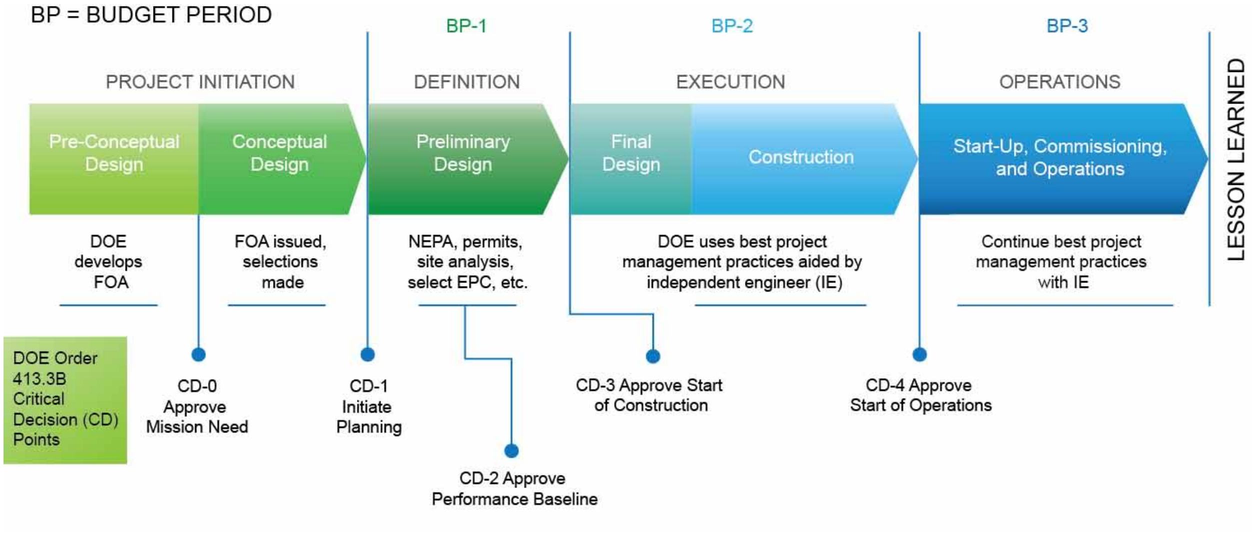

Figure 2-33: Framework for executing DOE project management for integrated biorefinery projects

Critical Decision Points

CD-0 is an internal DOE activity to appropriate funds, determine the nature of a funding opportunity announcement, and execute the competitive selection process. CD-0 effectively ends once the selections are made.

CD-1 begins with the award negotiation and continues with approval of the performance baseline for project scope, schedule, cost, and risk analysis. This corresponds to stage 1 in Front-End Loading (FEL-1) project management practices.

CD-2 occurs when the Project Management Plan (PMP) is put under DOE change control and the project locks down its performance baseline. The PMP forms the more detailed basis for the project scope (Statement of Project Objectives) that becomes the contractual basis for the obligation of BP-1 funds to the award. CD-2 also corresponds to an FEL–2 with a -15%/+ 30% cost estimate accuracy for EPC.

CD-3 requires completing the project financing, submitting the design for bids to EPC contractors, and meeting -5%/+15% cost estimate accuracy (FEL-3). Approval of CD-3 releases

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[11] U.S. Department of Energy, DOE Order 413.3B, Program and Project Management for the Acquisition of Capital Assets, https://www.directives.doe.gov/directives-documents/0413.3-BOrder-b/view.

the federal funds for BP-2, which typically has the highest associated cost of the three budget periods because of the procurement and construction components.

CD-4 is executed when the project has demonstrated readiness to begin operations. For demonstration and pioneer plants, CD-4 is based on meeting design performance objectives and usually occurs after the performance test has been completed. For some pilot plants, the performance test is what sets the baseline performance targets, so CD-4 is sometimes authorized as part of BP-3 during the start-up/commissioning of the plant.

Independent Engineer Role

The Office retains the services of an IE to assess an awardee's capabilities to successfully execute major capital projects and identify the risks associated with each IBR project. The IE's independent external reviews provide detailed analysis of the technical, organizational, financial, engineering, environmental, economic, and project-related risks at each CD point. The IEs monitor the IBR projects throughout all phases, are called upon to independent validate technical stage gates, and complete formal IBR performance tests. Using an IE firm to perform due diligence reviews is a best practice in many industries, including bioenergy, and a major component of investment decisions by private equity, venture capital firms, and commercial banks.

Lessons Learned Activity

The Office regularly captures project lessons learned with the goals of reducing the repetition of common costly mistakes and in order to develop best practices to share with the industry. This information indicates where the public/private partnership between DOE and private enterprise has been successful in reducing technology, project, and market risk, as well as where risk remains. This information can benefit the emerging bioindustry by educating the bioindustry to help minimize mistakes, reduce costs, and help accelerate market transformation of these technologies. Additionally, this information can be shared with the financing community to help inform its understanding of the risks DOE has reduced and improve the opportunities for private investment for commercialization.

2.3.5 Prioritizing Demonstration and Market Transformation Barriers

All of the primary barriers faced in the DMT program area must be successfully addressed to produce high volumes of advanced biofuels, bioproducts, and biopower. The following areas are critical and will be emphasized in DMT efforts:

- Validate proof of performance at integrated pilot, demonstration, and pioneer scales
- Reduce biorefinery capital and operating costs
- Product specification, qualification testing, and offtake agreements.

Financial barriers are the most challenging aspect of technology deployment. Capital costs for commercially viable facilities are relatively high, and securing capital for an unproven technology is extremely difficult. Lenders typically will not provide debt financing for pioneer facilities where the process performance cannot be adequately guaranteed. The Office is uniquely positioned to leverage both legislative authority for financial assistance and DOE's successful track record in commercialization to assist developers in de-risking technologies through validated proof of performance at the pilot, demonstration, and pioneer scales. This assistance is critical to enable equity holder and lender confidence to invest in facility construction and replication at the commercial-scale.

Demonstration projects that use federal cost-share funding have shown greater success when the basic technology principles were already proven at smaller scales.[12] In addition, the use of a pilot plant led to an increase of almost 50% in the average actual rate of production and a reduction of almost 30% in the start-up duration for a pioneer project—based on a database of more than 1,000 similarly innovative projects.[13] The Office supports commercialization in the bioprocessing industry through developing a portfolio of a larger number of integrated pilot scale projects, a smaller number of demonstration-scale projects, and an even smaller number of pioneer-scale plants.

Prioritizing efforts requires extensive stakeholder input from industry; national laboratories; academia; and other government agencies, such as USDA and the U.S. Department of Defense. Estimating the effects of these efforts requires consistent assumptions across a range of market variables, including, for example, national biomass cost and supply curves; biomass logistics systems; projected demand for biofuel, bioproducts, and biopower; learning rates of various conversion technology pathways; and government and tax policies; in addition to correlations between these variables.

The Biomass Scenario Model[14] uses consistent assumptions across a range of market variables to provide insight into the impact of different scenarios. Figure 2-34 illustrates the modeled potential fuel production[15] for the current reference oil price and the high oil price cases.[16] The panels titled "Baseline" provide the modeled production through 2040 using the state of the industry in 2015.[17]

The DMT milestones discussed in Section 2.3.2 project that reaching the 2027 DMT goal will require the validation of two pilot- and one demonstration-scale projects by 2022, and one additional pilot- and one additional demonstration-scale projects by 2025 in order to have one pioneer-scale project ready for external funding by 2026 and an additional pioneer-scale project ready for external funding by 2029. Additionally, to achieve wider deployment of IBRs beyond 2030, these milestones focus on validating one additional demonstration-scale project by 2030 enabling one more pioneer-scale project by 2034. The panels in Figure 2-34 titled "Baseline + DMT Milestones" illustrate the potential modeled impact of expanding the DMT portfolio to

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[12] W.S. Baer et al. (1976), *Analysis of Federally Funded Demonstration Projects*, RAND Corporation, Santa Monica, CA, RAND R-1925-DOC, http://www.rand.org/content/dam/rand/pubs/reports/2006/R1925.pdf.

[13] A. Marton (2011), "Research Spotlight: Getting off on the Right Foot – Innovative Projects," *Independent Project Analysis Newsletter* 3(1).

[14] For more detail on the Biomass Scenario Model, see Section 2.5

[15] L. Vimmerstedt et al. (2016), *Effects of Deployment Investment on the Growth of the Biofuels Industry: 2016 Update*, National Renewable Energy Laboratory, NREL TP-6A20-65903, www.nrel.gov/docs/fy16osti/65903.pdf.

[16] U.S. Energy Information Administration (2015), *Annual Energy Outlook 2015 with Projections to 2040,* http://www.eia.gov/forecasts/aeo/.

[17] Schwab, A., et al. (2016), *2015 Survey of Non-Starch Ethanol and Renewable Hydrocarbon Biofuels Producers*, National Renewable Energy Laboratory, NREL/TP-6A10-65519, http://www.nrel.gov/docs/fy16osti/65519.pdf.

meet those 2017–2034 DMT goals and milestones.[18] Figure 2-34 shows how meeting DMT milestones is projected to enable a substantial increase in biofuel production by 2040. Figure 2-35, which presents the same information from the lower right panel of Figure 2-34 (Baseline + DMT milestones) with an expanded Y-axis, shows the full effect, in a high oil price case, of the Baseline + DMT milestones scenario.

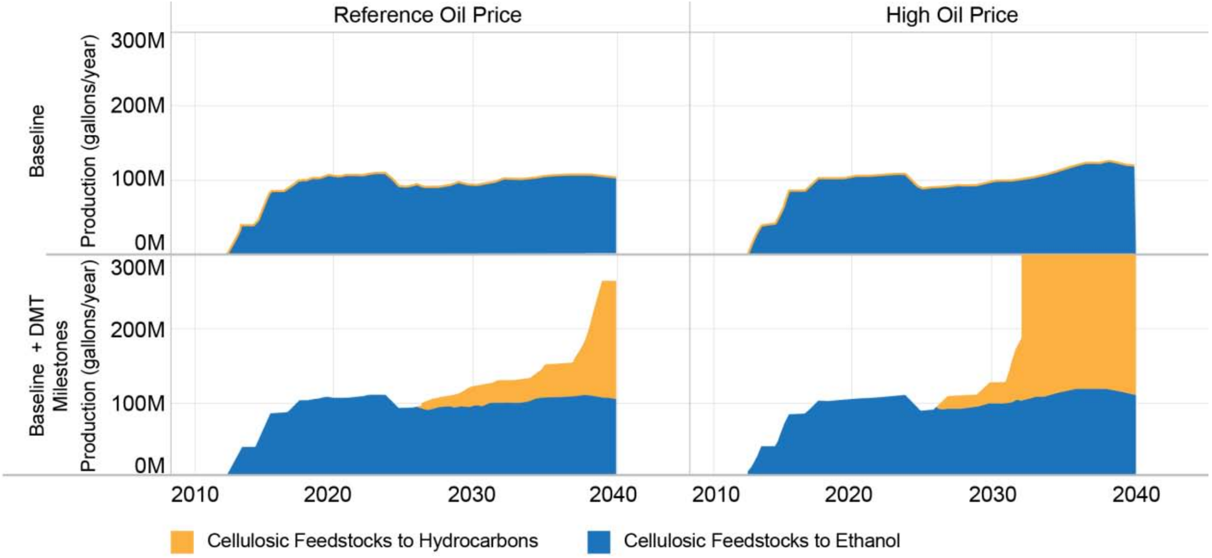

Figure 2-34: Biomass Scenario Model projection of the production volumes of renewable biofuels enabled by the Office's DMT efforts

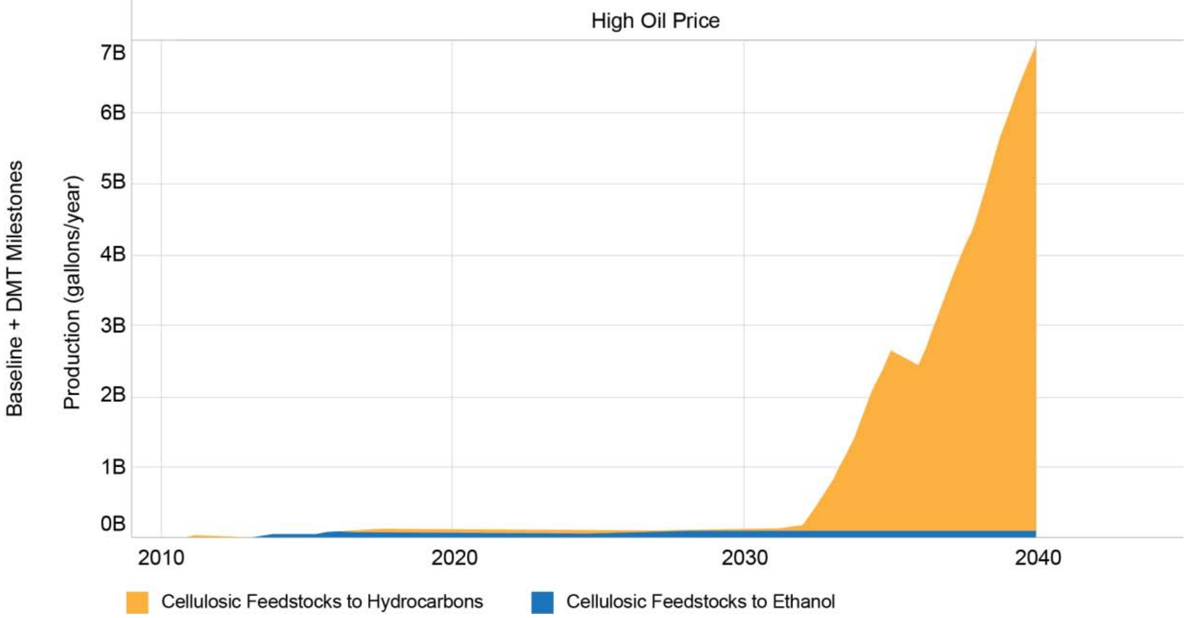

Figure 2-35: Biomass Scenario Model full projection of the production volumes of renewable biofuels enabled by the Office's DMT efforts in a high oil price case

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[18] This scenario included nine additional modeled pilot-scale projects, six additional modeled demonstration-scale projects, and three additional modeled pioneer-scale projects, implemented according to the milestone timeline.

Figures 2-36 and 2-37 illustrate the modeled potential reduction in the GHG emissions for the current reference oil price and the high oil price cases[19] used in Figures 2-34 and 2-35. The panels on Figure 2-36 titled "Baseline" provide the modeled reduction in GHG emissions through 2040 using the state of the industry in 2015[20] and the panels titled "Baseline + DMT Milestones" illustrate the potential modeled impact of expanding the DMT portfolio. Figure 2-37, which is an expanded view of the lower right panel from Figure 2-36, illustrates the full effect on GHG emissions reduction of meeting the DMT milestones in the high oil price case.

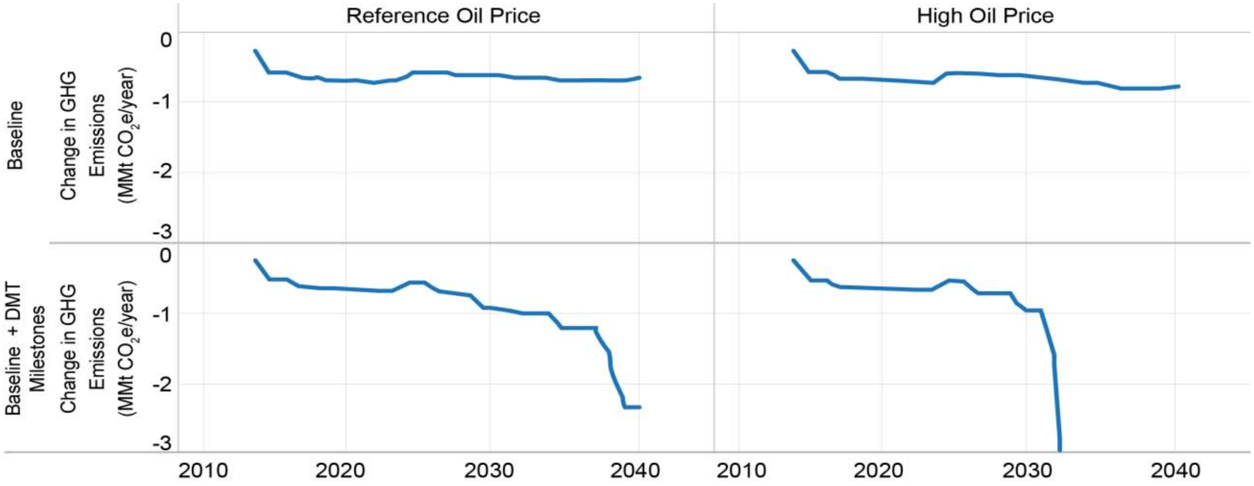

Figure 2-36: Biomass Scenario Model projection of the potential reduction in GHG emissions enabled by the Office's DMT efforts

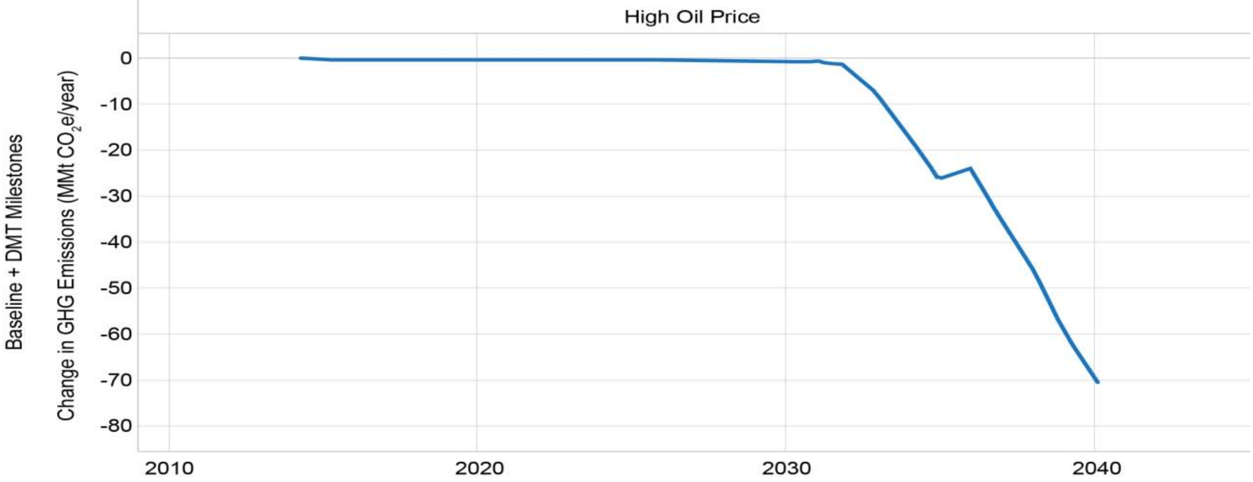

Figure 2-37: Biomass Scenario Model projection of the full potential reduction in GHG emissions enabled by the Office's DMT efforts in a high oil price case

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[19] U.S. Energy Information Administration (2015), *Annual Energy Outlook 2015 with Projections to 2040,* http://www.eia.gov/forecasts/aeo/.

[20] A. Schwab et al. (2016), *2015 Survey of Non-Starch Ethanol and Renewable Hydrocarbon Biofuels Producers*, National Renewable Energy Laboratory, NREL/TP-6A10-65519, http://www.nrel.gov/docs/fy16osti/65519.pdf.

2.3.6 Demonstration and Market Transformation Milestones and Decision Points

The key DMT milestones and decision points to complete the tasks described in Section 2.3.4 are summarized in Figure 2-38. The validation of integrated conversion technologies includes tracking and reporting the demonstrated performance metrics for each project. Milestones and go/no-go decisions are used to evaluate the progression of each biorefinery award at several stage gates, including the baseline of results achieved prior to award and through project initiation, construction, start-up, and operations.

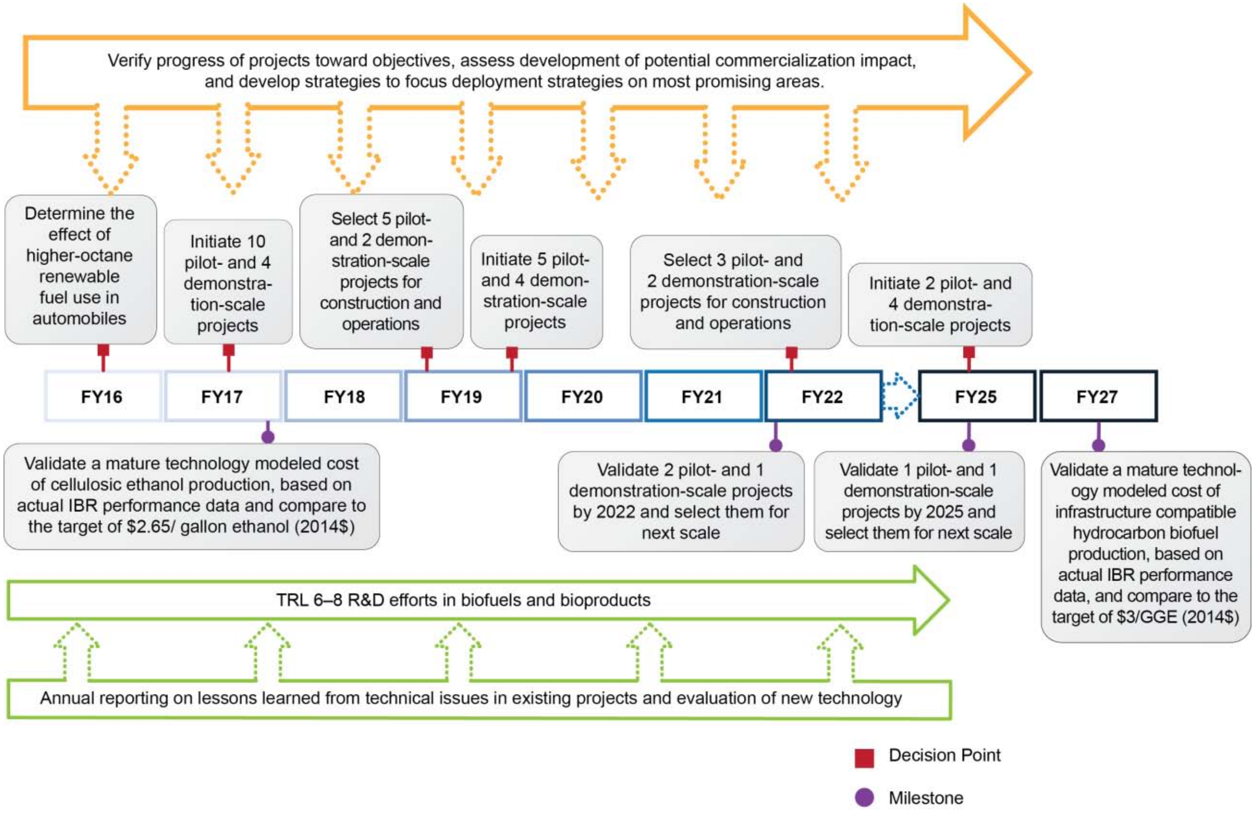

Figure 2-38: Demonstration and Market Transformation key milestones and decision points

2.4 Crosscutting Sustainability, Analysis, and Communications

Delivering on the promise of clean, renewable energy requires proactively considering complex policy, socioeconomic, market, and environmental factors, and developing beneficial collaborative solutions with diverse stakeholders. The Office is committed to supporting the development of a bioenergy industry that is economically self-sustaining, protects natural resources, and maximizes economic, social, and environmental benefits. The Office recognizes the value of and need for crosscutting capabilities and tools to support science-based policy, industry, and environmental decision-making. Maintaining these capabilities at the cutting edge ensures that the Office provides the most efficient and complete responses to internal and external stakeholders regarding a variety of supply chain viability and sustainability questions.

Three crosscutting areas—Sustainability, Strategic Analysis, and Strategic Communications—work together to support a holistic body of knowledge and tools related to the economic, environmental, and social dimensions of advanced bioenergy. Sustainability and Strategic Analysis contribute crosscutting science-based quantification of the economic, environmental, and social sustainability of advanced bioenergy to support an industry that delivers improved environmental performance and social benefits relative to conventional energy systems. Sustainability and Strategic Analysis work with program areas' analysis and sustainability efforts to conduct integrative analyses that facilitate higher-level insights across the bioenergy supply chain. This includes analyses that integrate economic and environmental dimensions to understand trends, synergies, and tradeoffs. Strategic communications activities help ensure that the tools and information are accessible and effectively communicated.

2.4.1 Sustainability

The Office is committed to developing the resources, technologies, and systems needed to support a thriving bioenergy industry that protects natural resources and advances environmental, economic, and social benefits. The Sustainability program area proactively identifies and addresses issues that affect the scale-up potential, public acceptance, and long-term viability of advanced bioenergy systems; as a result, this area is critical to achieving the Office's overall goals. The existing and emerging biofuels industry will need to develop systems that are not just based on economic viability and market needs, but also on environmental and social aspects such as resource availability and public acceptance. To that end, the Sustainability program area supports analysis, research, and collaborative partnerships to develop and promote practices and technologies that enhance the benefits of bioenergy production activities while mitigating environmental, economic, and social concerns.

Sustainability is not an end state or specific goal; rather, the Office is committed to developing and applying scientific approaches to quantifying bioenergy sustainability and promoting continuous improvements across multiple environmental, economic, and social objectives. The Office collaborates with other government agencies and diverse stakeholders from industry, nongovernmental organizations, research institutions, and international bodies to define those goals and priorities.

Executive Order 13514 (Federal Leadership in Environmental, Energy, and Economic Performance) defines sustainability as follows: "To create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations." Consistent with this mandate, the Office's sustainability efforts span environmental, economic, and social dimensions—the three core aspects of sustainability (see Figure 2-39). Maintaining the benefits and services provided by natural resources, promoting economic development, and providing conditions that support human and societal health are all critical components of a sustainable bioenergy industry.

Figure 2-39: Bioenergy Technologies Office sustainability scope

The Office works closely with other federal and international agencies that have missions that incorporate bioenergy, including USDA and EPA. While several federal agencies play important roles along the bioenergy supply chain—such as biomass production within USDA and environmental impacts within EPA—the Office addresses the integration of multiple dimensions of sustainability across all supply chain elements. These efforts include collaborating with relevant research and regulatory entities to enhance the benefits of emerging bioenergy technologies and feedstock varieties, as well as anticipating and mitigating unintended consequences.

The Office also engages in international dialogues on sustainable bioenergy. In coordination with the U.S. State Department and USDA, the Office participates in the Global Bioenergy Partnership to contribute technical expertise and communicate the U.S. experience in evaluating and enhancing bioenergy sustainability. The Office also contributes technical expertise to sustainability efforts led by the International Energy Agency, the Intergovernmental Panel on Climate Change, and the International Organization for Standardization. These international engagements accelerate R&D on sustainable bioenergy production through mutually beneficial technical exchanges and sharing research results. These collaborations also enable the Office to stay informed of international market developments that affect the U.S. bioenergy industry, as well as help ensure that the U.S. perspective and scientific contributions are represented.

Environmental, Economic, and Social Sustainability across the Bioenergy Supply Chain

Environmental, economic, and social implications are relevant across the full bioenergy supply chain (see Figure 2-40). Evaluating effects and promoting improvements in each sustainability component necessitates different measures and types of activities depending on the supply chain element in question. For example, certain environmental categories—such as soil quality and biological diversity—are most relevant to biomass production, while others—such as water and air emissions—are monitored across most or all supply chain elements.

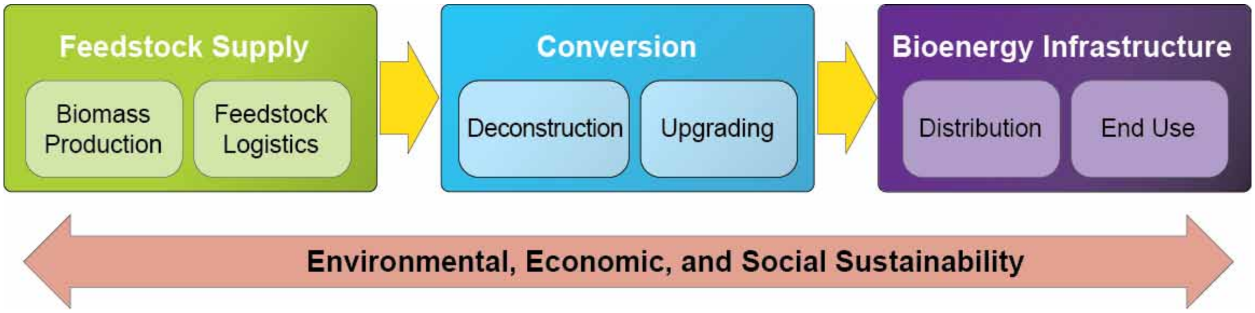

Figure 2-40: Sustainability across the bioenergy supply chain

Environmental Sustainability

Environmental categories of interest are based on the primary effects that many bioenergy systems have or are likely to have on environmental sustainability. These categories and the associated objectives are as follows:

- *Greenhouse Gas Emissions*: Reducing greenhouse gas emissions and enhancing climate benefits
- *Soil Quality*: Maintaining or improving soil quality
- *Water Quality and Quantity*: Maintaining or improving water quality, improving water-use efficiency, and avoiding negative impacts on water resources
- *Air Quality*: Minimizing air pollutants and maintaining or improving air quality
- *Biological Diversity*: Conserving plant and animal diversity and protecting habitat and ecological systems
- *Land Use and Productivity*: Enhancing beneficial land-use management and maintaining or improving land productivity.

Economic Sustainability

The primary goal of the Office is to promote a commercially viable bioenergy industry in the United States; therefore, economic sustainability is interwoven into the Office's strategic goals. Several economic sustainability categories are critical for measuring progress toward this goal. When assessing and documenting the SOT for promising bioenergy pathways, the primary measurements include return on investment, net present value, process efficiency, and yield of desired products. The interaction between economic sustainability and the other two core components of sustainability (environmental and social) is also considered in depth.

Social Sustainability

Social sustainability is critical to ensure that development of the bioenergy industry aligns with societal values and promotes social goals. Social sustainability categories and the associated objectives are as follows:

- *Social Acceptability:* Improving public opinion through science-based information, minimizing risks, maximizing transparency, and ensuring effective stakeholder participation
- *Social Well-Being:* Maintaining or improving prosperity, safety, health, and food security
- *Energy Security and External Trade:* Reducing dependence on foreign oil, increasing access to affordable energy, demonstrating a positive net energy balance relative to fossil fuels, and improving the balance of trade between imports and exports for energy-related materials
- *Resource Conservation:* Minimizing use of non-renewable resources relative to renewable resources and enhancing the energy return on investment
- *Rural Development and Workforce Training*: Creating job opportunities, enhancing rural livelihoods, and developing a skilled bioenergy workforce.

System-Level Sustainability

System-level sustainability considers the relationship within and between the sustainability component categories described above. System-level sustainability, for example, could focus on optimizing a technology for both economic and environmental factors to find the most beneficial outcome.

2.4.1.1 Sustainability Support of Office Strategic Goals

Sustainability is an integral part of the Office's vision and strategic goal. The strategic goal of the Sustainability program area is *to understand and promote the positive environmental, economic, and social effects and reduce the potential negative impacts of bioenergy production activities.*

The Sustainability program area supports the Office's strategic goals by providing science-based quantification of the sustainability of advanced bioenergy and promoting improved environmental performance and social benefits of bioenergy relative to conventional or business-as-usual energy systems. The Sustainability program area interfaces with and impacts all elements of the biomass-to-bioenergy supply chain and each stage of technology development. Considering sustainability early in technology development—rather than after systems are finalized and replicated—enhances the future economic and technical viability of those technologies. Sustainability activities closely align with the feedstock and technology pathways pursued under the Office's research, development, demonstration, and market transformation areas.

2.4.1.2 Sustainability Support of Office Performance Goals

The Sustainability program area's goals and milestones will be met by evaluating bioenergy systems and demonstrating continuous improvements, or the potential for improvement, across multiple sustainability categories and bioenergy production systems. This includes the feedstocks, logistics systems, and conversion technologies pursued through the Office's R&D and DMT areas.

The overall performance goals for the Sustainability program area are as follows:

- By 2017, identify conditions under which at least one technology pathway for hydrocarbon biofuel production, validated above R&D scale at a mature modeled price of $3/GGE, reduces greenhouse gas emissions by 50% or more compared to petroleum fuel and meets targets for consumptive water use, wastewater, and air emissions.[1]
- By 2022, validate landscape design approaches for two bioenergy systems that, when compared to conventional agricultural and forestry production and logistics systems, increase land-use efficiency and maintain ecosystem and social benefits, including biodiversity and food, feed, and fiber production.[2]
- By 2022, evaluate environmental and socioeconomic indicators across the supply chain for three cellulosic and algal bioenergy production systems. Environmental indicators will validate GHG reduction of at least 50% compared to petroleum, water consumption equal to or less than petroleum per unit of fuel produced, and that air emissions meet

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[1] Targets for water consumption will be based on potential process and plant design improvements. Targets for wastewater and air emissions will be based on water quality standards, pollutant discharge regulations, and federal air quality regulations.

[2] Here, landscape design refers to a holistic management process that incorporates bioenergy into existing land uses while maintaining or enhancing the environmental, economic, and social benefits that the landscape provides. Increasing land-use efficiency refers to integrating bioenergy systems in a manner that generates more services relative to required inputs.

federal regulations. Socioeconomic indicators will validate socioeconomic benefits including job creation.

Milestones for the pathways under investigation are as follows:

Sustainability Analysis and Communication

- By 2016, evaluate environmental sustainability indicators for updated assessment of potentially available feedstock supplies and identify conditions or conservation practices under which feedstock production scenarios are likely to maintain or improve soil quality, biodiversity, and water quality in major feedstock production regions while meeting projected demands for food, feed, and fiber production.
- By 2016, coordinate with feedstock logistics and conversion R&D areas to set targets for greenhouse gas emissions, consumptive water use, wastewater, and air emissions for at least three renewable hydrocarbon pathways to be validated in 2017 and 2022.
- By 2019, quantify and clearly communicate the environmental and socio-economic benefits of emerging advanced bioenergy pathways through at least three case studies that apply Office-supported analysis tools including but not limited to GREET, WATER, and the Landscape Environmental Assessment Framework (LEAF). Disseminate findings through technical publications and public outreach.

Sustainable System Design

- By 2016, apply LEAF to model three distinct cropping systems to analytically demonstrate the potential for integrated landscape management to increase biomass availability (energy crop production and agricultural residue removal) by 50%, increase soil quality by at least 25%, reduce nutrient loss by 10%, and reduce the risk to surface water quality by 10% as measured by the Water Quality Index, as compared to current agricultural management (conventional row crop practices).[3]
- By 2018, using available field data, validate case studies of feedstock production systems that reduce greenhouse gas emissions and maintain or improve water quality and soil quality compared to conventional agriculture and forestry systems; identify strategies to translate beneficial practices into broader applications.

2.4.1.3 Sustainability Challenges and Barriers

St-A. Scientific Consensus on Bioenergy Sustainability: While there is agreement on the general definition of sustainability, more agreement is needed on its specific definition and ways to quantitatively measure bioenergy sustainability (such as approaches, system boundaries, and time horizons).

St-B. Consistent and Science-Based Message on Bioenergy Sustainability: The prevalence of misrepresentations of the effects of bioenergy—including assumptions, scenarios, and model

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[3] Soil quality improvements refer to a 25% increase in soil organic carbon and soil erosion less than half of the T-value (soil loss tolerance). Risk to surface water will be measured by the NRCS Water Quality Index for Agricultural Lands. This milestone will not include field validation of landscape designs, as the primary objective is to enhance and apply LEAF to more diverse cropping systems and to show analytical potential to simultaneously meet economic and environmental goals.

projections that lack empirical underpinnings—creates confusion about the costs and benefits of bioenergy production and leaves the industry vulnerable to criticism.

St-C. Sustainability Data across the Bioenergy Supply Chain: A fundamental hurdle to improving the sustainability of bioenergy production is the lack of consistent data to evaluate sustainability and compare one biofuel or bioenergy pathway with another. Generating adequate and accessible temporal and spatial data for measuring sustainability supports industry investments and other critical activities, such as establishing baselines, determining targets for improvement, recommending best practices, and evaluating tradeoffs.

St-D. Implementing Indicators and Methodology for Evaluating and Improving Sustainability: Significant progress has been made in developing a science-based framework for evaluating bioenergy sustainability through environmental and socioeconomic indicators and conducting LCAs to determine the impacts of bioenergy relative to other energy alternatives. It is now critical to implement that framework to assess and improve sustainability with appropriate consideration of spatial, temporal, and other context-specific factors.

St-E. Best Practices and Systems for Sustainable Bioenergy Production: Because bioenergy production from cellulosic and algal feedstocks is relatively new, few “best practices” and sustainable systems are defined for all components of the bioenergy supply chain. Improved practices must be developed and deployed and their effectiveness demonstrated at larger scales and in a variety of contexts.

St-F. Systems Approach to Bioenergy Sustainability: The sustainability of the entire supply chain is not adequately considered in assessments of technical feasibility and economic optimization. Tools must be developed and maintained to allow researchers to consider the potential synergies and tradeoffs among different goals (such as energy security, biodiversity protection, or low-cost commodities) and different types of bioenergy systems.

St-G. Land-Use and Innovative Landscape Design: The limitations of existing data sources to capture the dynamic state of land use and management, as well as an incomplete understanding of the drivers of land-use and management changes, have undermined efforts to assess the environmental and social effects of bioenergy production and consumption. Science-based, multi-stakeholder strategies are needed to proactively design and manage landscapes to enhance benefits and minimize negative impacts.

2.4.1.4 Sustainability Approach for Overcoming Challenges and Barriers

The approach for overcoming biomass sustainability technical challenges and barriers is outlined in the Sustainability program area’s WBS, as shown in Figure 2-41. The WBS is organized around two broad groupings: Sustainability Analysis and Communication, and Sustainable System Design.

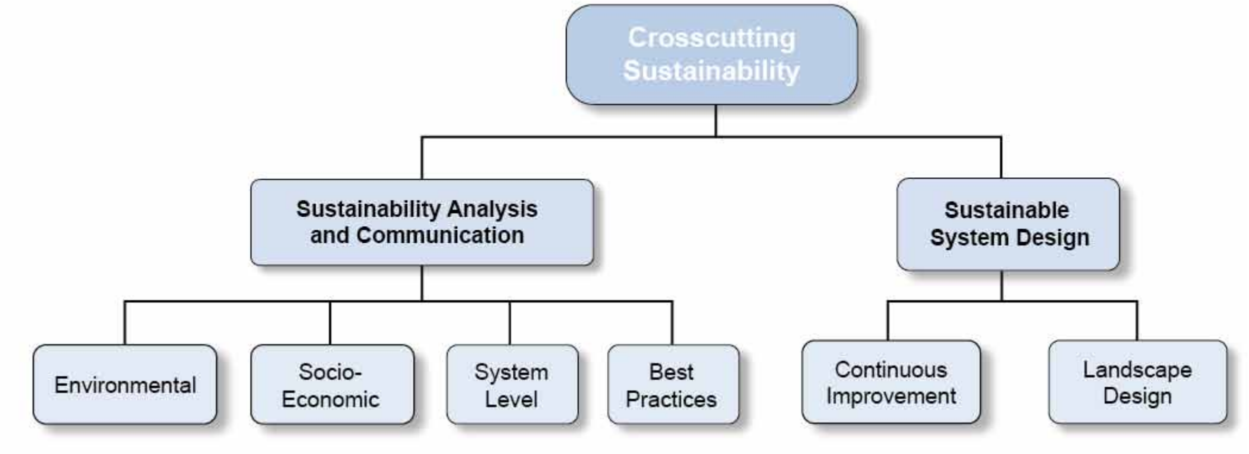

Figure 2-41: Sustainability work breakdown structure

The approach of each Sustainability WBS task grouping is described below and in Table 2-26. Each grouping is defined by its primary objectives; however, the two are interconnected, and outcomes in one inform activities in the other. Both groupings seek to quantify the environmental and socio-economic effects of bioenergy production, assess opportunities for improvement, disseminate technical information, and promote adoption of better practices through outreach and communication.

Each WBS grouping contains linkages with the Office's other program areas. This includes collecting and evaluating technology-specific data and developing strategies to improve the environmental performance, resilience, and sustainability of bioenergy systems.

Sustainability Analysis and Communication

Sustainability analysis and communication focuses on collecting and integrating data, developing analyses and decision-support tools, and synthesizing and communicating information on the environmental, economic, and social effects of bioenergy production. Activities include measuring and evaluating sustainability through appropriate indicators and metrics, as well as integrative and spatial analyses of bioenergy production scenarios at different geographic scales (field, regional, national, and global) and across multiple supply chain components and sustainability categories. These activities provide unbiased, science-based tools for quantification that the Office and diverse stakeholders can use, as well as peer-reviewed analyses and case studies on benefits, trends, and possible tradeoffs. Analyses reflect the latest empirical and modeled data from within and outside the Office's portfolio. Comparing new bioenergy technologies with current and evolving global bioenergy systems is also important and enables the Office to assess performance against benchmark systems from other major bioenergy-producing countries.

Results generated from sustainability analysis and communication activities are used by the Office to inform technology RD&D to maximize beneficial outcomes. Results and best practices are also disseminated and promoted through publications, interagency interactions, and outreach to non-governmental organizations and other stakeholders. This includes providing scientific input to bioenergy-relevant certification schemes and standards, such as the Roundtable on

Sustainable Biomaterials and the International Organization for Standardization. International collaborations enable the Office to stay informed of international market developments that affect the U.S. bioenergy industry, as well as help ensure that the U.S. perspective and scientific contributions are represented.

Sustainable System Design

Sustainable system design focuses on performing sustainability field research and data generation, testing innovative concepts, and developing strategies that maintain or improve the environmental and socioeconomic sustainability of bioenergy. Activities include developing innovative methods for spatial and multi-metric optimization, developing and testing landscape design approaches for bioenergy, and demonstrating continuous improvements over time. As better practices are developed and validated, they are incorporated into the Office's technology evaluation approach, encouraged within the Office's RD&D portfolio, and promoted through interagency coordination and domestic stakeholder interactions.

Table 2-27: Sustainability Activity Summary

WBS Element	Description	Barrier(s) Addressed
Sustainability Analysis and Communication	Collect and analyze data, develop decision-support tools, identify trends, and evaluate tradeoffs among different indicators and pathways. Use results to inform technology RD&D, best practices, and outreach activities. Disseminate findings through publications, interagency interactions, and stakeholder outreach.	
Environmental	- Assess baselines and targets across environmental categories (greenhouse gas emissions, water, soil quality, air quality, and biodiversity) for cellulosic and algal feedstock production, logistics, and conversion technologies. - Evaluate indicator values across technology types and over time. - Conduct integrative and spatial analyses to investigate environmental effects at various scales.	AFt-B. Sustainable Algae Production Ft-A. Terrestrial Feedstock Availability and Cost Ft-B. Production Mm-A: Lack of Understanding Environmental/Energy Tradeoffs St-A: Scientific Consensus St-B: Consistent, Evidence-Based Message St-C: Sustainability Data across the Supply Chain St-D: Indicators and Methodology St-G: Land-Use and Innovative Landscape Design
Socioeconomic	- Identify relevant socioeconomic sustainability indicators and evaluate indicator values across technology types and over time. - Conduct integrative and spatial analyses to investigate effects at various scales.	AFt-B. Sustainable Algae Production Ft-A. Terrestrial Feedstock Availability and Cost Ft-B. Production Mm-A: Lack of Understanding Environmental/Energy Tradeoffs St-A: Scientific Consensus St-B: Consistent, Evidence-Based Message St-C: Sustainability Data across the Supply Chain St-D: Indicators and Methodology St-G: Land-Use and Innovative Landscape Design
System-Level Sustainability	- Complete multivariate assessments that integrate environmental, social, and economic indicators to assess system-level sustainability.	At-B. Analytical Tools and Capabilities for System-Level Analysis At-C. Data Availability across the Supply Chain Ft-J Overall Integration and Scale-Up Mm-A: Lack of Understanding Environmental/Energy Tradeoffs St-C: Sustainability Data across the Supply Chain St-D: Indicators and Methodology St-F: Systems Approach to Bioenergy Sustainability St-G: Land-Use and Innovative Landscape Design Ct-O. Process Integration
Promoting Best Practices	- Identify and communicate best practices across Office portfolio, through interagency coordination, and through domestic and international stakeholder interactions.	St-C: Sustainability Data across the Supply Chain St-D: Indicators and Methodology St-E: Best Practices St-F: Systems Approach to Bioenergy Sustainability St-G: Land-Use and Innovative Landscape Design

WBS Element	Description	Barrier(s) Addressed
Sustainable System Design	Develop and test innovative concepts, practices, and technologies that maintain or enhance environmental, economic, and social sustainability of bioenergy.	
Continuous Improvement	- Develop processes by which sustainability measurement and evaluation leads to changes in practices and behavior. - Develop iterative, empirically based mechanisms that support continuous improvements in sustainability.	St-D: Indicators and Methodology St-E: Best Practices St-F: Systems Approach to Bioenergy Sustainability St-G: Land-Use and Innovative Landscape Design
Landscape Design	- Identify optimized bioenergy production strategies across environmental, economic, and social factors. - Conduct field research on best management practices, develop and test landscape design approaches for bioenergy, and demonstrate more sustainable practices at larger scales.	Ft-J Overall Integration and Scale-Up Im-A. Inadequate Supply Chain Infrastructure St-C: Sustainability Data across the Supply Chain St-D: Indicators and Methodology St-E: Best Practices St-F: Systems Approach to Bioenergy Sustainability St-G: Land-Use and Innovative Landscape Design

2.4.1.5 Prioritizing Sustainability Barriers

The following issues are critical and will be emphasized within near- to mid-term sustainability efforts:

- Advancing scientific methods and models for measuring and understanding bioenergy sustainability across the full supply chain
- Disseminating practical tools for analyses, decision making, and technology development that enhance sustainable bioenergy outcomes
- Quantifying improved environmental performance and social benefits of bioenergy relative to conventional or business-as-usual energy systems
- Developing landscape design approaches that increase bioenergy production while maintaining or enhancing ecosystem and social benefits.

To enable data-driven prioritization of sustainability efforts, the Office follows a framework that can be applied to biomass and bioenergy production systems at different scales and contexts, as illustrated in Figure 2-42. This framework helps guide activities for data generation, data collection, and evaluation of current and future scenarios. The framework also is used to develop practices and technologies that maintain or improve environmental performance and socioeconomic benefits.

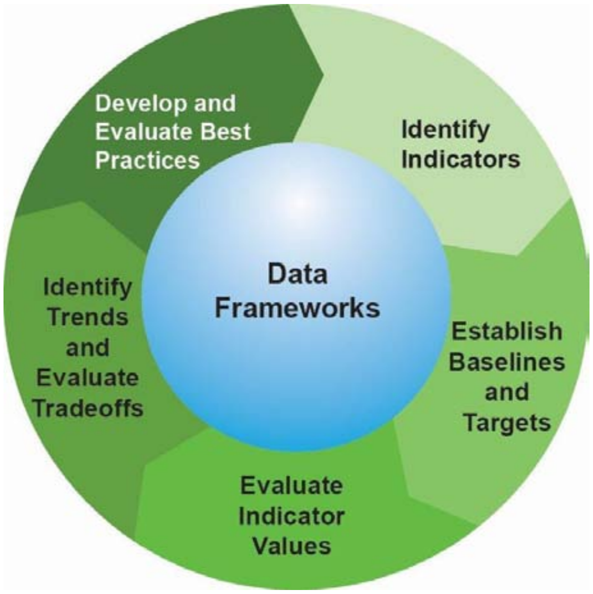

Figure 2-42: Sustainability activities

Implementation of this framework, as described in the following steps, primarily focuses on the categories shown in Figure 2-43. These categories are meant to illustrate the predominant sustainability considerations addressed through Office activities, but they are not exhaustive.

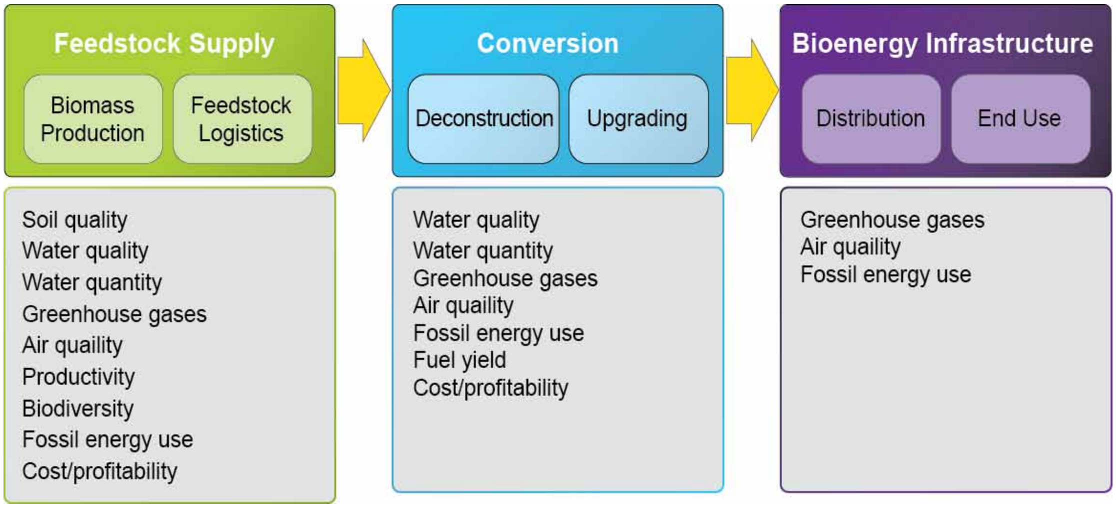

Figure 2-43: Sustainability considerations by supply chain component

***Identify appropriate indicators and metrics**:* Indicators and metrics are identified based on the spatial context and type of biomass/bioenergy system, as well as sustainability goals and selection criteria (e.g., cost of data collection and verification, attribution, comparability across pathways, consistency across agencies, etc.). Sustainability indicators for bioenergy are described in McBride et al. 2011 and Dale et al. 2012.[4,5]

Establish baseline and target conditions: Baselines and target conditions are established consistent with the goals and scales (temporal and spatial) of effects to be measured. Baselines may represent the current state, "business as usual" conditions, or non-optimized systems. Relevant sustainability targets are based on acceptable, improved, or optimized outcomes. Sustainability targets in the Office's portfolio include the following:

> *Scenario Analysis Targets*: Analysis projects develop regional or national scenarios of biomass/bioenergy production to investigate aggregate impacts. Targets reflect beneficial and/or optimized future scenarios and can help guide what technology improvements are necessary to best enable meeting intended objectives.
>
> *Pathway-Specific Targets*: Within the feedstock logistics and conversion R&D areas, sustainability metrics are being assessed alongside the techno-economic parameters and, as more data are available, will be increasingly incorporated into SOT assessments (see Conversion R&D, Section 2.2). Similar to the cost and technical targets, setting targets for greenhouse gases, air emissions, water

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[4] A. McBride, V.H. Dale, L. Baskaran, M. Downing, L. Eaton, R.A. Efroymson, C. Garten, K.L. Kline, H. Jager, P. Mulholland, E. Parish, P. Schweizer, and J. Storey (2011), "Indicators to support environmental sustainability of bioenergy systems," *Ecological Indicators* 11(1).

[5] V.H. Dale, R.A. Efroymson, K.L. Kline, M.H. Langholtz, P.N. Leiby, G.A. Oladosu, M.R. Davis, M.E. Downing, and M.R. Hilliard (2013a), "Indicators for assessing socioeconomic sustainability of bioenergy systems: A short list of practical measures," *Ecological Indicators* 26(1).

consumption, and other relevant sustainability metrics helps promote technologies that achieve multiple technical, environmental, economic, and social goals.

Site/Project-Specific Targets: Research and field projects establish site-specific targets that reflect acceptable conditions (e.g., maintain or improve level of soil organic carbon) or potential for improvement (e.g., reduce nitrogen runoff by X%). These targets help define practices or guide development of new practices that promote viable operations.

Evaluate indicator values**:** Indicator values are evaluated based on established monitoring protocols and consideration of relationships among each supply chain element and indicator. Evaluation includes documenting status of factors that induce changes in indicator values and the presumed degree to which Office intervention can impact indicator values.

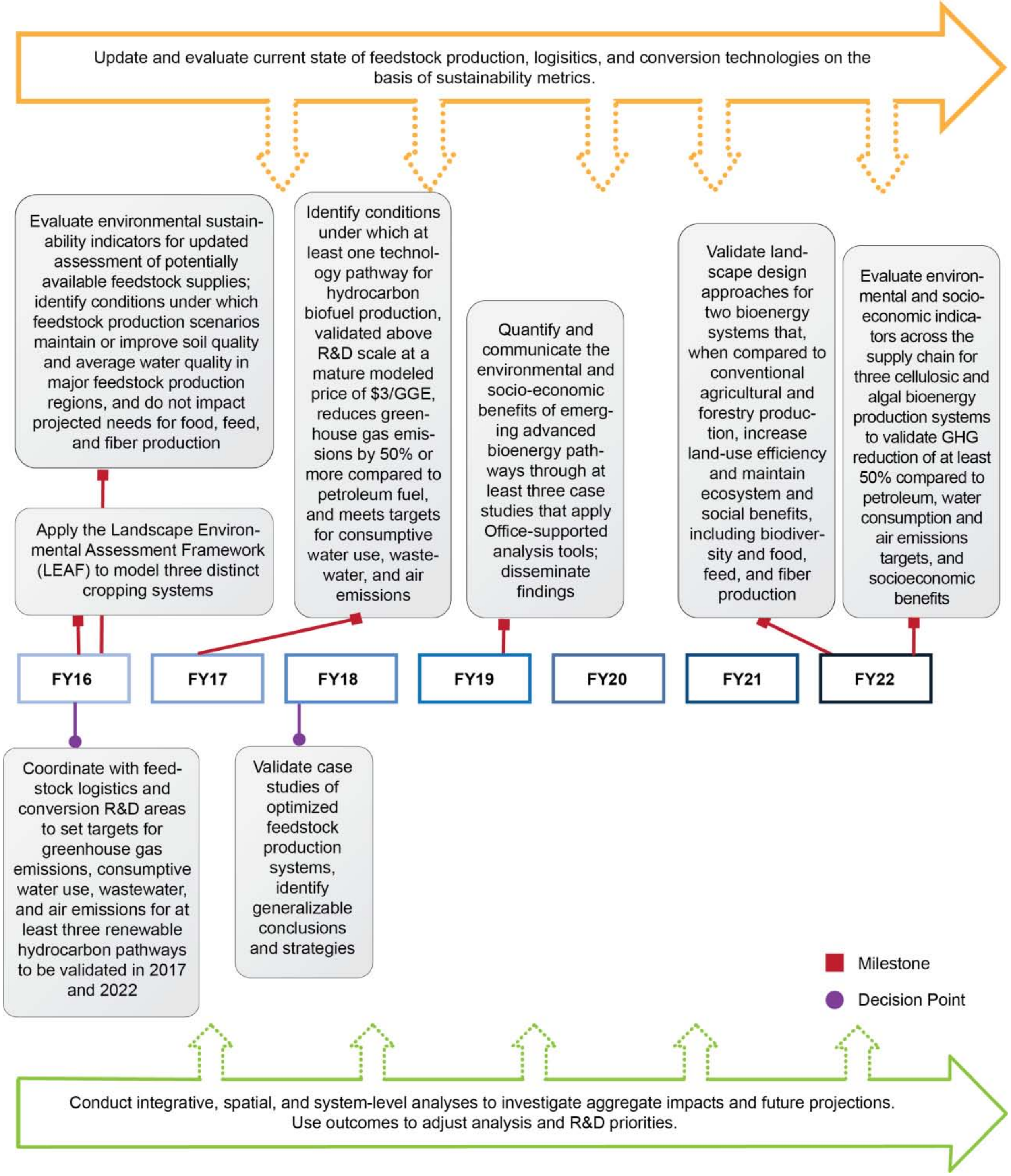
Identify trends and evaluate tradeoffs: Trends refer to changes in values of sustainability indicators over time. Hypotheses can be developed for forces influencing those trends and tested against relevant empirical data. Tradeoffs between different indicators and pathway elements or between achieving different targets can be explored as a way to improve sustainability.

Develop and evaluate best practices**:** Best practices are developed and evaluated based on monitoring, field data, and modeling results. This includes comparing practices with empirical data to support continuous improvement in sustainability and reviewing objectives, indicator values and definitions, and best practices based upon changing conditions, priorities, and new knowledge. As practices are evaluated for effectiveness, they can be applied to additional projects, locations, and production systems.

Maintain data frameworks**:** Frameworks for data collection, integration, and visualization support analysis, research, and adaptive management.

2.4.1.6 Sustainability Milestones and Decision Points

The key milestones and decision points to complete the tasks described in Section 2.4.1.4 are summarized in Figure 2-44.



Update and evaluate current state of feedstock production, logisitics, and conversion technologies on the basis of sustainability metrics.

Evaluate environmental sustainability indicators for updated assessment of potentially available feedstock supplies; identify conditions under which feedstock production scenarios maintain or improve soil quality and average water quality in major feedstock production regions, and do not impact projected needs for food, feed, and fiber production

Apply the Landscape Environmental Assessment Framework (LEAF) to model three distinct cropping systems

Identify conditions under which at least one technology pathway for hydrocarbon biofuel production, validated above R&D scale at a mature modeled price of $3/GGE, reduces greenhouse gas emissions by 50% or more compared to petroleum fuel, and meets targets for consumptive water use, wastewater, and air emissions

Quantify and communicate the environmental and socio-economic benefits of emerging advanced bioenergy pathways through at least three case studies that apply Office-supported analysis tools; disseminate findings

Validate landscape design approaches for two bioenergy systems that, when compared to conventional agricultural and forestry production, increase land-use efficiency and maintain ecosystem and social benefits, including biodiversity and food, feed, and fiber production

Evaluate environmental and socioeconomic indicators across the supply chain for three cellulosic and algal bioenergy production systems to validate GHG reduction of at least 50% compared to petroleum, water consumption and air emissions targets, and socioeconomic benefits

Coordinate with feedstock logistics and conversion R&D areas to set targets for greenhouse gas emissions, consumptive water use, wastewater, and air emissions for at least three renewable hydrocarbon pathways to be validated in 2017 and 2022

Validate case studies of optimized feedstock production systems, identify generalizable conclusions and strategies

🟥 Milestone

● Decision Point

Conduct integrative, spatial, and system-level analyses to investigate aggregate impacts and future projections. Use outcomes to adjust analysis and R&D priorities.

Figure 2-44: Sustainability key milestones and decision points

2.4.2 Strategic Analysis

Strategic Analysis helps determine overall Office goals and priorities and covers issues that cut across all program areas. System-level analyses inform strategic direction and planning efforts; they also help the Office focus its technology development priorities and identify key drivers and hurdles for industry growth. Technology-specific analyses explore sensitivities and identify areas where investment may lead to the greatest impacts.

The Strategic Analysis program area plays four main roles in the Office's decision-making process:

- Provides the analytical basis for planning and assessing progress
- Defines performance targets and strategy for validating biomass technologies and systems
- Conducts system-level policy, industry, and environmental analyses relevant to bioenergy
- Reviews and evaluates external analyses and studies.

Maintaining these capabilities at the cutting edge ensures that the analysis provides the most efficient and complete answers to internal and external stakeholders. Coordinated multi-lab efforts and continued partnerships with the biomass industry and scientific community help ensure that the Office's analysis results are peer reviewed, transferable, and comparable.

The majority of Strategic Analysis activities are designed to support Office decision-making processes and track milestones. They validate decisions, ensure objective inputs, and respond to external recommendations. Supporting activities in the Strategic Analysis portfolio strive to advance the state of the science within areas such as land-use change modeling, life-cycle assessment, and bioenergy impact analysis. The Office provides ongoing analysis and policy support to other U.S. government agencies and legislative bodies. Emerging issues, interests, and trends raise new questions from a wide variety of stakeholders, including DOE management, members of Congress, other federal agencies, and state governments. Scholarly articles, popular media, and other broader forums are additional sources of questions for analysis.

Figure 2-45 shows how the Strategic Analysis program area supports all elements of the biomass-to-bioenergy supply chain.

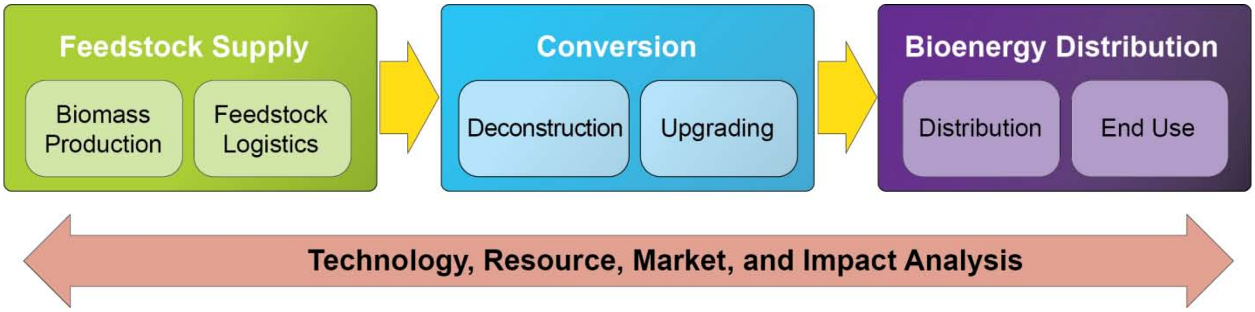


Figure 2-45: Strategic Analysis supports the entire supply chain

2.4.2.1 Strategic Analysis Support of Office Strategic Goals

The strategic goal of the Strategic Analysis program area is *to provide context and justification for decisions at all levels by establishing the basis of quantitative metrics, tracking progress toward goals, and informing portfolio planning and management*.

2.4.2.2 Strategic Analysis Support of Office Performance Goals

The overall performance goals for the Strategic Analysis program area are as follows:

- Ensure high-quality, consistent, reproducible, peer-reviewed analyses.
- Develop and maintain analytical tools, models, methods, and datasets to advance the understanding of bioenergy and its related impacts.
- Convey the results of analytical activities to a wide audience, including DOE management, Congress, the White House, industry, other researchers, other agencies, and the general public.

Strategic Analysis activities are ongoing; however, the following key milestones will provide the analytical basis for out-year targets and R&D activities for meeting those targets:

- By 2016, develop and deploy a consistent methodology for including co-products in TEAs and design cases.
- By 2016, hold a workshop and publish a whitepaper on the techno-economic analysis of aviation biofuels pathways.
- By 2017, complete supply chain sustainability analyses for at least four technology pathways to hydrocarbon biofuels to facilitate comparison of life-cycle energy use and greenhouse gas (GHG) emissions across biofuel pathways.
- By 2018, complete analysis on impact of advanced biofuels use on gasoline and diesel prices.
- By 2022, identify near-term technology pathways for the Office based on reassessment of current state of technology development and improved understanding of pathway LCA.

2.4.2.3 Strategic Analysis Challenges and Barriers

Several factors impact the understanding of key drivers and implications for developing and sustainably deploying new biomass technologies. These include the following:

At-A. Comparable, Transparent, and Reproducible Analyses: Analysis results are strongly influenced by the datasets employed, as well as by the assumptions and guidelines established to frame the analysis. Standardized datasets, assumptions, and guidelines are needed to compare and integrate analysis results.

At-B. Analytical Tools and Capabilities for System-Level Analysis: High-quality analytical tools and models are needed to enable the understanding of broader bioenergy supply-chain-wide systems, linkages, and dependencies. Models need to be developed and refined to improve understanding of these issues and their interactions. Improvements in model components and in linkages are necessary to improve utility and consistency.

At-C. Data Availability across the Supply Chain: Understanding the biomass-to-bioenergy supply chain and its economic, environmental, and other impacts requires complete and comparable data. Filling data gaps and improving data accessibility would improve efforts to understand all relevant dimensions of bioenergy production and use.

2.4.2.4 Strategic Analysis Approach for Overcoming Challenges and Barriers

The WBS shown in Figure 2-46 and Table 2-27 shows the types of analysis activities undertaken by the Office. Strategic Analysis activities are inherently crosscutting and interface with all other program areas within the Office. The descriptions below discuss the models and methods used for the various types of analysis conducted by national laboratories, universities, and DOE.

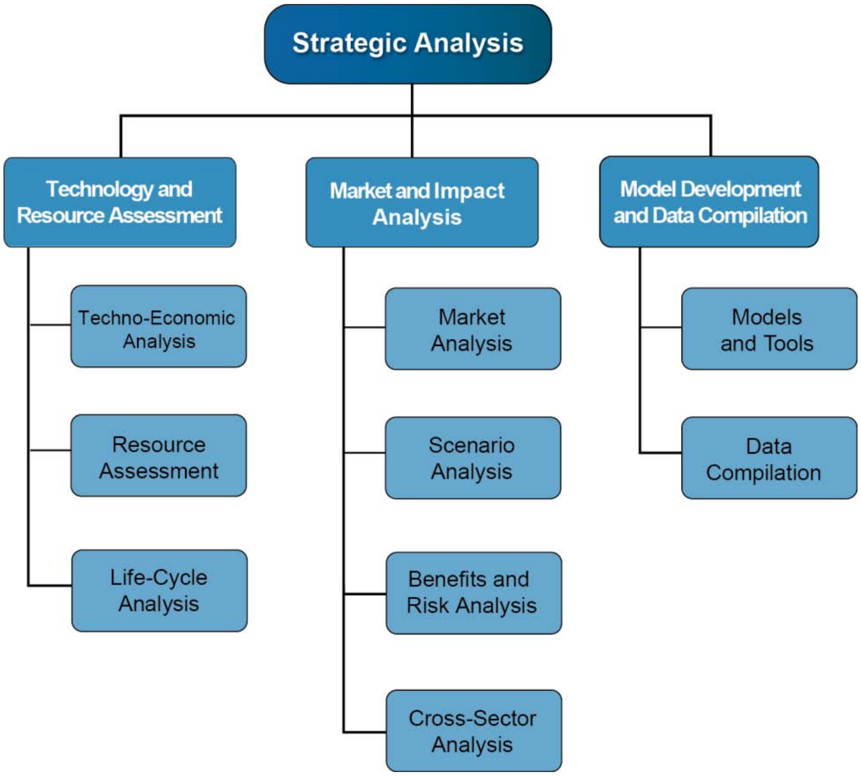


Figure 2-46: Strategic Analysis work breakdown structure

Technology and Resource Assessment

Techno-Economic Analysis: The Office assesses the technical and economic viability of new processes and technologies, identifies the potential for cost reduction, assesses cross-pathway and cross-technology progress, and provides input into portfolio development and technology validation. Technology and economic analysis methods and tools used include unit operation design flow and information models, process design and modeling (e.g., Aspen

Plus®[1]), capital costs (e.g., Aspen Capital Cost Estimator®[2]) and operating cost[3] determination, discounted cash-flow analysis, and Monte Carlo sensitivity analysis/risk assessment. The Office also assesses the potential cost reductions that can be achieved as the advanced biofuels industry develops and increases capacity beyond first-of-a-kind pioneer facilities. This ongoing analysis effort applies learning rates from relevant, more established industries to estimate the range of possible cost reductions as conversion technologies are commercialized and replicated.

Resource Assessment: Feedstock supply resource assessments identify the geographic location, price, and environmental sustainability of accessing existing and potential future feedstock resources, as well as projecting future supply availability and prices. Strategic Analysis activities utilize these data to understand price effects of competition from various biomass utilization technologies (e.g., biofuel versus biopower), as well as to assess cross-technology impacts of feedstock cost, quantity, and quality.

Life-Cycle Analysis: The Strategic Analysis program area supports Office sustainability efforts through developing and maintaining life-cycle and land-use change models to estimate the environmental impacts of biomass production and utilization technologies. LCA models identify and evaluate the emissions, resource consumption, and energy use of various processes, technologies, or systems to help understand the full impacts of existing and developing technologies and prioritize efforts to mitigate negative effects. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model[4] is used to estimate fuel-cycle energy use and emissions associated with alternative transportation fuels and advanced vehicle technologies. Strategic Analysis supports updates and enhancements to the GREET model to continually reflect new and evolving bioenergy technologies. Strategic Analysis also supports efforts to better understand and characterize the complex drivers of land-use change and gather more accurate land-use data.

Market and Impact Analysis

***Market Analysis*:** Market assessment helps the Office focus its technology development priorities in the near, mid, and long term by analyzing the potential cost, commercialization time, and market demands for candidate biofuels, biopower, and bioproducts. This analysis draws on a broad range of other analyses, including fossil fuel cost projections; future energy demand forecasts; infrastructure assessments; state of biomass utilization technology development; national and local sustainability analysis; and consumer, economic, and policy scenarios. This analysis also helps identify current and future market attractiveness, gaps, strengths, and risks that may impact producer, investor, and consumer decision making.

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[1] Aspen Plus® is a process modeling tool for steady-state simulation, design, performance monitoring, optimization, and business planning widely used in the chemicals, specialty chemicals, petrochemicals, and metallurgy industries. More information is available at http://www.aspentech.com/.

[2] For information, see http://www.aspentech.com.

[3] As an example, chemical supply costs are taken from *The Chemical Marketing Report* and labor costs from related industries, such as corn ethanol production.

[4] For information, see http://greet.es.anl.gov/.

Scenario Analysis**:** Understanding the impacts of changes and development of various elements of the biomass-to-bioenergy supply chain is the key to informing technology portfolio planning and monitoring progress toward national goals. To help understand which supply chain modifications have the greatest potential to accelerate deployment of biofuels, the Office has supported development of the Biomass Scenario Model (BSM). The BSM is a systems dynamics model for conducting biofuels policy analysis through investigation of the systemic effects, linkages, and dependencies across the biomass-to-biofuels supply chain. Figure 2-47 shows the conceptual structure of the model and an overview of the module for each supply chain component. The model considers pathways from starch, lignocellulosic, oilseed, and algal feedstocks to ethanol, butanol, gasoline, diesel, and aviation fuel.

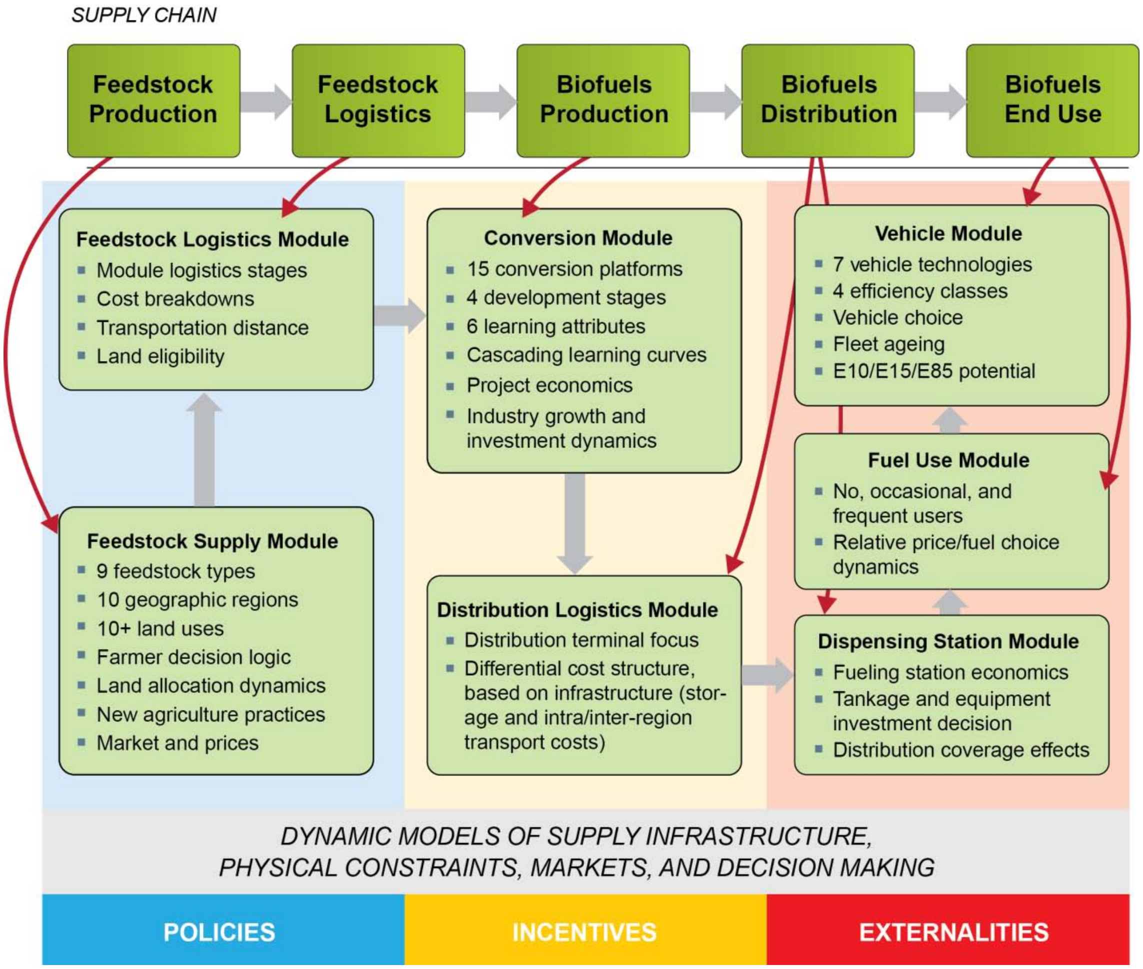

Figure 2-47: Conceptual schematic of the Biomass Scenario Model

Benefits and Risk Analysis**:** Benefits analysis helps the Office quantify and communicate the long-term benefits of biomass RD&D (e.g., imported oil displacement and greenhouse gas mitigation). The scenarios developed and the quantified costs and benefits are used to evaluate the most viable biomass utilization technologies and routes. Results are also used in crosscutting benefits analysis and are a key input to EERE renewable technology portfolio decision making. Risk analysis helps the Office quantify the impact of investments on technology risk over time.

Cross-Sector Analysis: A growing bioenergy industry affects and is affected by other renewable energy and transportation efficiency technologies. Cross-sector analysis includes collaborations with other EERE offices and federal agencies to explore future scenarios for transportation sector growth.

Model Development and Data Compilation

Models and Tools: The Office supports the development and deployment of new analytical tools and methods and guides the selection of assumptions and methodologies to be used for all analyses to ensure consistency, transparency, and comparability of results.

Data Compilation: Many disciplines and sectors are involved in bioenergy RD&D. Developing, compiling, maintaining, and providing easy access to the best available, credible data, models, and visualization tools is critical to supporting sustainable commercialization of biomass utilization technologies. To serve this need, the Office developed the Bioenergy Knowledge Discovery Framework (KDF),[5] a Web-based data repository, visualization tool, and library. The goal of the Bioenergy KDF is to facilitate planning, development, and management decisions by providing a means to synthesize, analyze, and visualize vast amounts of information in a relevant and succinct manner. The Bioenergy KDF's GIS-based data analysis, mapping, and visualization components draw from dynamic and disparate databases of information to enable users to analyze economic, social, and environmental impacts of various biomass utilization technologies for biomass feedstocks, biorefineries, and infrastructure.

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[5] Bioenergy Knowledge Discovery Framework, U.S. Department of Energy, http://www.bioenergykdf.net.

Table 2-28: Strategic Analysis Activity Summary

WBS Element	Description	Barrier(s) Addressed
Technology and Resource Assessments	- Assess quantity and associated costs of biomass resources. - Assess life-cycle greenhouse gas and air quality impacts of new biofuel pathways and integrate into technical and economic assessments. - Comparative technical and economic assessment of biofuels. - Support the comprehensive integration of annual SOT assessments. - Support feedstock-pathway-wide TEA.	At-A: Comparable, Transparent, and Reproducible Analysis At-B: Analytical Tools and Capabilities for System-Level Analysis At-C: Data Availability
Market and Impact Analysis	- Determine the cost, timing, and market demands for candidate biofuels and biocrudes. - Assess impacts of changes and development of various elements of the biomass-to-bioenergy supply chain and identify impacts of supply chain modifications on deployment of biofuels. - Evaluate and document impact of biofuels on U.S. economies and environment. - Identify, quantify, and evaluate uncertainty and risk of biofuels.	At-A: Comparable, Transparent, and Reproducible Analysis At-B: Analytical Tools and Capabilities for System-Level Analysis At-C: Data Availability
Model Development and Data Compilation	- Ensure results of analytical and research activities are available through the Bioenergy KDF. - Develop new analytical tools and methods, as needed, to address emerging needs. - Establish and maintain standardized assumptions and methods.	At-B: Analytical Tools and Capabilities for System-Level Analysis At-C: Data Availability

2.4.2.5 Strategic Analysis Milestones and Decision Points

The key milestones and decision points to complete the tasks described in Section 2.4.2.4 are summarized in Figure 2-48.

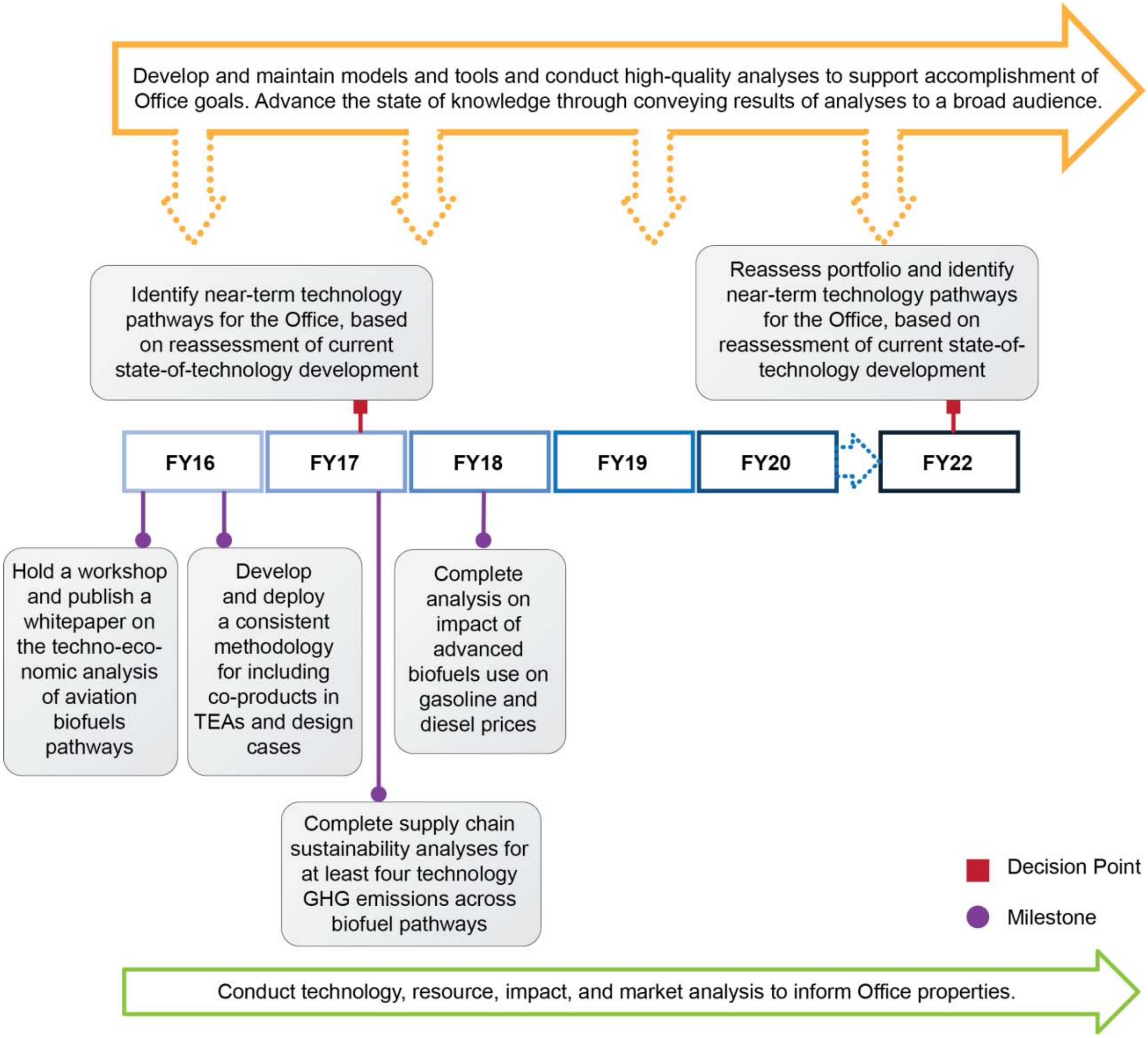

Figure 2-48: Strategic Analysis key milestones and decision points

2.4.3 Strategic Communications

The Office's Strategic Communications program area consistently creates and curates relevant and valuable content to assist stakeholders to better understand and embrace new concepts, technologies, and products. Informing targeted audiences about the Office's work and promoting the benefits of sustainable bioenergy strengthens support for supplying and consuming bioenergy products to develop a thriving bioeconomy. Strategic Communications engages a broad range of stakeholders in meaningful collaborations, promotes the accomplishments of Office funded advanced technologies, increases consumer awareness and acceptance of biofuels and bioproducts, and amplifies the expansion of bioenergy production and use across the bioenergy supply chain. Strategic Communications promotes outcomes of research, development, and demonstration projects and technologies developed in the Office's program areas—Terrestrial Feedstock Supply and Logistics, Advanced Algal Systems, Conversion, and Demonstration and Market Transformation—and for the crosscutting areas of Sustainability and Strategic Analysis.

In addition, Strategic Communications focuses on identifying and addressing non-technical barriers to bioenergy adoption and utilization in an effort to reach full-scale market penetration. This is accomplished by educating audiences and increasing awareness through a combination of internal and external communication methods. The Office aligns its messaging and outreach with the U.S. Department of Energy (DOE) and Office of Energy Efficiency and Renewable Energy (EERE) mission, strategic goals, and vision. Successful internal communications will improve the flow of accurate and consistent information throughout the DOE community and ultimately result in crosscutting collaborations, increased market transformation, and mission and vision alignment with other DOE transportation programs.

Successful coordination of internal and external communications strategies will improve the following:

- Knowledge of advanced bioenergy and biomass feedstocks research and development (R&D), funding opportunities, technologies, and policies
- Collaborative efforts to educate stakeholders and improve market penetration
- Dissemination of accurate and consistent information, which dispels inaccurate information clutter while also diffusing conflicts and conflicting messaging
- Understanding of the economic, environmental, social, and U.S. competitive advantage benefits of bioenergy as a viable alternative and complement to fossil fuels.

In response to misconceptions about bioenergy, Strategic Communications is focused on amplifying facts, based on sound science about bioenergy, the Office, and partnership successes, along with identifying and addressing market and other non-technical barriers to bioenergy adoption and utilization.

Environmental, Economic, Social, and U.S. Competitive Advantage Awareness across the Bioenergy Supply Chain

Strategic communications activities are relevant across the full bioenergy supply chain and support all of its elements, from biomass production to end use. For activities throughout the supply chain, the Office disseminates sound science as well as increases awareness of the economic, environmental, social, and U.S. competitive advantage benefits of bioenergy and how cutting-edge R&D can give the United States a competitive advantage in the bioenergy industry (See Figure 2-49).

Figure 2-49: Strategic Communications across the Bioenergy Supply Chain

Target audiences include scientists, engineers, and researchers; industry and investors across the bioenergy supply chain; policy makers at all levels of government (including members of Congress and their staff); U.S. Department of Energy staff; educators and students; members of rural and farming communities; and the general public who are potential users of biofuels and bioproducts. These key audiences vary greatly in terms of their level of understanding and opinions about the benefits of sustainable bioenergy. Strategic Communications efforts include distributing technical and non-technical information to internal and external stakeholders through a number of channels; including but not limited to traditional and digital media; website content; Facebook, Twitter, and LinkedIn; as well as conferences and other events.

2.4.3.1 Strategic Communications Support of Office Strategic Goals

The strategic goal of Strategic Communications is *to support and enhance the Office's mission by conducting outreach to target audiences to promote the research, development, and demonstration successes achieved through Office funding and to promote opportunities for, and benefits of, sustainable bioenergy production, highlighting the role that a thriving bioeconomy plays in improving economic and community stability, spurring innovation, and achieving U.S. competitive advantage in renewable energy.*

2.4.3.2 Strategic Communications Support of Office Performance Goals

Strategic Communications goals will result in the Office's messages and technical accomplishments being shared with a broader range of audiences, helping to increase awareness of and support for its research, initiatives, and technologies. Reaching the Office's goals also means a higher potential for new partnerships where more entities may apply for the Office's competitive funding opportunities, allowing for the advancement of existing technologies and the initiation of new, innovative technologies. Ultimately, Strategic Communications allows for a faster, more effective dissemination of bioenergy-related information to accelerate the growth of the bioenergy industry. It also enhances government accountability by transparently sharing with the public the technical progress that the Office is making toward its goals.

Strategic Communications strives to accomplish the following performance goals:

- Increase awareness of and support for the Office's advanced biomass RD&D and technical accomplishments, highlighting their role in achieving national renewable energy goals.
    - From 2016 through 2022, create and execute an annual communication strategy that incorporates synchronized messaging through the DOE national laboratories and other collaborative networks to highlight the Office's contributions to the development of new technologies and key milestones.
    - From 2016 through 2022, continually develop and implement Office messaging that provides clear, consistent, and accurate information about bioenergy and the industry. The messaging will be aligned with DOE's and EERE's missions and with individual Office program goals.
- Educate audiences about the environmental and economic opportunities and social benefits of biofuels, bioproducts, and a growing bioenergy industry.
    - From 2016 through 2022, in conjunction with EERE Sustainable Transportation Offices, develop and implement initiatives to raise awareness about the benefits of sustainable transportation technologies. Leverage these partnerships to educate new stakeholders on the benefits of biofuels and bioproducts.

Milestones towards reaching these goals include:

- From 2016 through 2022:
    - Develop infographics to demonstrate the economic and environmental impacts of biofuel technologies in development.
    - Identify and set goals for outreach strategies to address stakeholder concerns and recommendations on technological advancements and for how the Office is meeting national energy goals. Keep metrics to track progress toward these efforts.
    - Continually update existing outreach to consumers on the benefits of biofuels and bioproducts.
    - Develop or update education and communications products to address inaccurate information about bioenergy using science-based data.
    - Develop and implement a comprehensive education and workforce development program for K-Grey (elementary, middle, high school, college; grey represents non-traditional education, informal education; and veterans).
- From 2017 through 2022, support information sessions for agriculture, algae, and forestry communities regarding the economic, environmental, and social benefits of participating in the bioeconomy.

- By 2016, begin to implement the Office's new strategic plan communication and outreach activities to increase awareness of bioenergy to the general public as well as to educate decision makers on the benefits of a bioeconomy.
- By 2016, expand outreach efforts focused on the benefits of greenhouse gas emission reductions resulting from biomass-derived alternative fuels.
- By 2016, begin to develop and implement a robust communications and stakeholder engagement strategy around efforts to co-optimize the development of fuels and engines.
- By 2018, produce communication products to support conversion RD&D pathway validation of modeled nth plant and minimum fuel selling price.
- By 2018, notify and educate BETO stakeholders about validation of efficient, low-cost, and sustainable terrestrial feedstock supply and logistics systems.
- By 2019, develop a multi-agency strategy to convey the results of analytical activities to a wide audience, including DOE senior management, Congress, the White House, industry, RD&D stakeholders, and the public.
- By 2022, amplify technologies that produce sustainable algal biofuel intermediate feedstocks that perform reliably in conversion processes to yield renewable diesel, jet, and gasoline fuels in support of the Office's advanced biofuels goal.

2.4.3.3 Strategic Communications Challenges and Barriers

Accelerating the growth of the bioenergy economy requires addressing market barriers and opportunities at local, state, and federal levels. Strategic Communications' activities are focused on addressing the following market challenges and barriers.

Sct-A. Increase Acceptance and Awareness of Biofuel and Bioproducts as Viable Alternatives for Petroleum-Based Fuels and Products: To succeed in the marketplace, biomass-derived fuels and chemical products must perform as well as or better than comparable fossil-based products. Industry partners and consumers must perceive the quality, value, sustainability, and safety of biomass-derived products and their benefits, relative to the risks and uncertainties that widespread changes will likely bring. Compared with other renewable technologies, stakeholder acceptance and awareness of biofuels and bioenergy technologies are varied. Vehicle and engine manufacturers are a particularly influential stakeholder group, as future sustainable transportation designs that work well with biofuels can increase market penetration significantly.

Current misconceptions about biofuels offer opportunities to provide stakeholders and the public with accurate, science-based, and up-to-date information. Consistent, accurate information will educate and reassure the public that there are sufficient resources[1] to produce biofuel and bioproducts, sustainably and economically, while benefitting the environment and continuing to meet society's demand for food, feed, and fiber.

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[1] U.S. Department of Energy (2011), *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*.

Sct-B. **Understand Role of Government versus the Role of Industry**: Government-funded R&D focuses on a broad range of emerging technologies. This approach supports a diverse technology portfolio and identifies the most promising targets for industry to pursue in follow-on, industrial-scale demonstration. Through grants and partnerships with private industry, universities, national laboratories, and research groups, the Office helps support applied research that would be too risky for any one private entity to pursue, while advancing the state of technology development for the entire biomass industry. The Office funds technology maturation for all steps in the biofuels value chain, through funding of development for individual conversion steps as well as for integrated pilot and demonstration scale operations. Once technologies have been supported by the Office and partners at the demonstration scale, they are ready for proving at pioneer commercial scale through privately funded resources or with government assistance by a loan guarantee program. Once a technology reaches maturity, private industry entities typically take the lead in deploying that technology to end users.

Stakeholders and the general public often do not understand these distinct, necessary, and interdependent roles of government and private industry. For example, after cellulosic ethanol achieved the Office's $2.65 per gallon cost target (see Appendix C) and reached commercial scale, the Office shifted its R&D focus to less-developed technologies such as hydrocarbon fuels where a government role is still needed. Strategic Communications emphasized this transition. Now, the Office is working with stakeholders to pursue a bioeconomy concept, which integrates fuels and chemicals to maximize the benefits of a billion tons of biomass. Technological developments in renewable chemicals can accelerate the commercial development of advanced biofuels by improving economics and diversifying market risks. Strategic Communications can emphasize this focus to stakeholders, showing how a government role in the bioeconomy can accelerate biofuel technology adoption by private industry.

Sct-C. **Support Evolving Policy Landscape and Priorities**: The Office continues to support new, emerging technologies throughout a constantly changing policy, tax, and economic landscape. Communicating these shifting priorities effectively, accurately, and proactively is an opportunity. The Office must communicate its repositioning as a necessary step in the advancement of technology to meet national energy and environmental goals, including Energy Independence and Security Act of 2007 goals, which will require a diverse array of biobased fuels and products.

Sct-D. **Develop a Multi-Pronged Messaging Strategy**: As established energy commodities, conventional fossil fuel markets have extensive and compelling national communication campaigns promoting their products. There are also numerous new communication channels that are developing rapidly. While the "Information Age" increases the reach of traditional media and targets new audiences, it also represents resources to address specific audience needs, expectations, and sensitivities in order for communication efforts to be effective.

2.4.3.4 Strategic Communications Approach for Overcoming Challenges and Barriers

Strategic Communications uses a variety of communication channels and tactics to aid the Office in disseminating its messages, promoting accomplishments, and leveraging opportunities to address misconceptions. The approach for leveraging Strategic Communication opportunities is outlined in Figure 2-50 and described below. Strategic Communications activities are also summarized in Table 2-29.

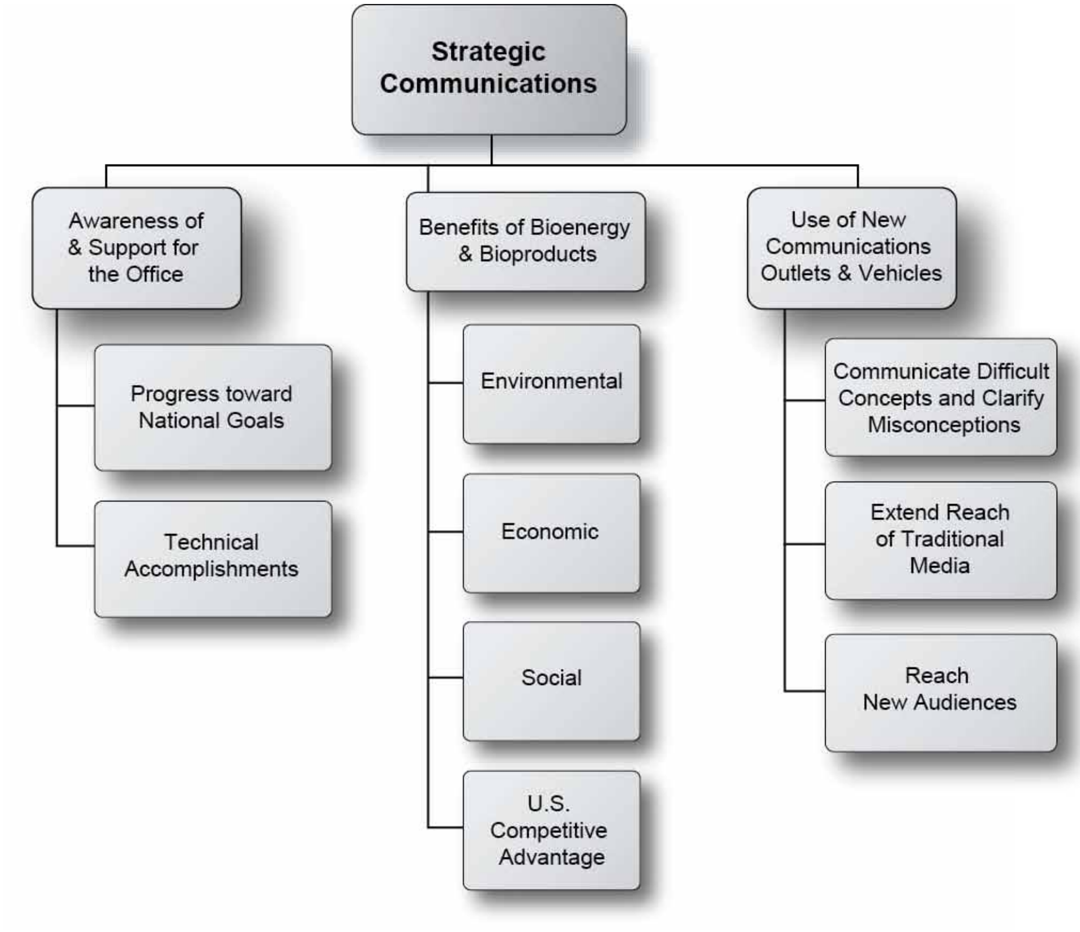


Figure 2-50: Strategic Communications work breakdown structure

Increasing Awareness of and Support for the Office

These activities focus on informing target audiences about Office accomplishments, strategies, and technologies, while calibrating expectations of near- and medium-term RD&D achievements. Near-term efforts include identifying highest-value media and audiences and setting strategies, goals and metrics for targeted outreach. Ongoing efforts include promoting small and large technological achievements, from laboratory breakthroughs to milestones of advanced demonstration-scale biorefineries. To disseminate this key messaging, the Office will expand its communication with target audiences through various outreach channels, including email announcements (e-blasts) and the monthly email newsletter (news blast), the Office's website, DOE press releases and EERE progress alerts, and social media.

Communicating the Benefits of Bioenergy and Bioproducts

These activities focus on deepening audiences' understanding of the economic, environmental, social, and U.S. competitive advantage benefits of bioenergy and bioproducts. Near-term efforts include outreach focused on greenhouse gas emission reductions resulting from biomass-derived alternative fuels and outreach focused on future consumers and workforce development. Mid-term activities will targeting vehicle and engine manufacturers directly through communication efforts. The Office will continue its use of regularly scheduled webinars, fact sheets and other publications, social media, the annual conference, industry and partner events, and education and workforce development efforts.

Using New Communications Vehicles and Outlets

In addition to using traditional media, the Office plans to make more effective use of digital communication vehicles and outlets to address the challenges surrounding bioenergy and draw attention to positive perceptions, results, and accomplishments. Near-term efforts include strengthening communication about the Office and its project portfolio to target audiences, such as decision makers, industry, end users, and educators, through regular social media, blogs, e-blasts, and website updates. For example, updating the online educational toolkit will allow educators to convey the latest, accurate information on bioenergy to their students. Other activities include disseminating messaging through graphical and interactive formats, including infographics and animations.

Table 2-29: Strategic Communications Activity Summary

WBS Element	Description	Barrier(s) Addressed
Awareness of & Support for the Office	Use various traditional and emerging media channels to inform stakeholders of the latest cutting-edge science and technology to stimulate the trajectory to market.	
Progress Toward National Goals	- Highlight the role the Office plays in achieving national goals, such as meeting EISA requirements for alternative fuels, creating new green jobs, and reducing the nation's dependence on foreign oil by replacing the whole barrel of petroleum-based fuels and products.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct-B. Understand Role of Government versus the Role of Industry
Technical Accomplishments	- Complete outreach efforts focused on promoting specific Office contributions to new technologies, pathways, and directions as Office-supported projects achieve important milestones and deliverables.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct-B. Understand Role of Government versus the Role of Industry
Benefits of Bioenergy and Bioproducts	Use various traditional and emerging media vehicles and outlets to increase education of the many facets of bioenergy and bioproducts across the supply chain.	
Environmental Benefits	- Educate audiences about the environmental benefits of biomass as a viable alternative to fossil fuels, such as outreach efforts focused on the greenhouse gas emission reductions resulting from biomass-based alternative fuels.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct-C. Support Evolving Policy Landscape and Priorities are Inconsistent Im-H. Lack of Acceptance and Awareness of Biofuels as a Viable Alternative
Economic Benefits	- Educate audiences about the economic benefits of a strong bioenergy industry, including the contribution to gross national product and keeping U.S. dollars within the United States.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct C: Support Evolving Policy Landscape and Priorities
Social Benefits	- Educate audiences about the social benefits of a strong bioenergy industry, including the creation of new, green jobs.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct-C: Support Evolving Policy Landscape and Priorities
U.S. Energy Benefits	- Educate audiences about the U.S. energy benefits of a strong bioenergy industry, including offsetting imported oil and resources expended securing availability of imported oil.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct-C: Support Evolving Policy Landscape and Priorities
Use of New Communications Vehicles and Outlets	Implement new communications vehicles and outlets to disseminate clear and consistent, targeted Office messaging that will increase the Office's reach beyond current stakeholders, while maintaining costs.	
Communicate Difficult Concepts and Clarify Misconceptions	- Strategically use new communications vehicles and outlets to create and distribute products that communicate difficult concepts and clarify misconceptions.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct-B. Understand Role of Government versus the Role of Industry Sct-C: Support Evolving Policy Landscape and Priorities Sct-D. Develop a Multi-Pronged Messaging Strategy
Extend Reach of Traditional Media	- Strategically use new communications vehicles and outlets to increase the distribution of traditional Office communications products.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct-B. Understand Role of Government versus the Role of Industry Sct-D. Develop a Multi-Pronged Messaging Strategy
Reaching New Audiences	- Strategically use new communications vehicles and outlets, in conjunction with traditional communication efforts, to reach new audiences and targeted demographics.	Sct-A. Increase Acceptance and Awareness of Biofuels and Bioproducts as Viable Alternatives for Fuel and Products Sct-B. Understand Role of Government versus the Role of Industry Sct-D. Develop a Multi-Pronged Messaging Strategy

2.4.3.5 Prioritizing Strategic Communications Challenges and Barriers

Success of the Office's Strategic Communications efforts is founded on accurate and timely outreach to key stakeholder audiences and communication of key messages. Office efforts must increase stakeholder confidence in the value and viability of a bioeconomy while also prioritizing investment in the development of the bioenergy industry.

Identifying and understanding the role of key stakeholders in industry expansion is essential to developing goals and measuring the progress of communications efforts. Table 2-30 shows the four classes of key stakeholders the Office has identified.

Table 2-30: Strategic Communications Key Stakeholders

Stakeholder Group	Role in Industry Expansion	Communication Goals
Policymakers	• Enable industry expansion through investment in risk reduction	• Craft consistent policy and prioritize development funding for bioenergy; give equal consideration of bioenergy alongside other renewable energy resources
Investors	• Enable industry expansion through development and commercialization of bioenergy infrastructures	• Increase investment in RD&D and market transformation activities all along the bioenergy supply chain through partnering with public and private entities and demonstrating a reduction in technical risk.
Future partners: Agencies and research institutions	• Partner in development of technologies that enable industry expansion and enable full supply change	• Increase support and promotion of strategic direction and tactical activities to accomplish larger goals; inspire partners to activity in an inclusive grand challenge. • Increase research institution engagement in strategic direction of the Office and leverage existing capabilities.
General public: Constituents and consumers, educators, students	• Drive demand for bioenergy industry development and products. • Partner in workforce development to support industry expansion. • Serve as future leaders and consumers of bioenergy products.	• Communicate projection of impacts and outcomes from investing tax dollars, time, and learning in bioenergy • Increase student engagement in bioenergy development, commercialization, and technology adoption by consumers • Better understand the diversity of bioenergy solutions and related issues; champion bioenergy development and open to opportunities and use.

It is also critical to develop and amplify consistent, simple, and clear messages such as the following:

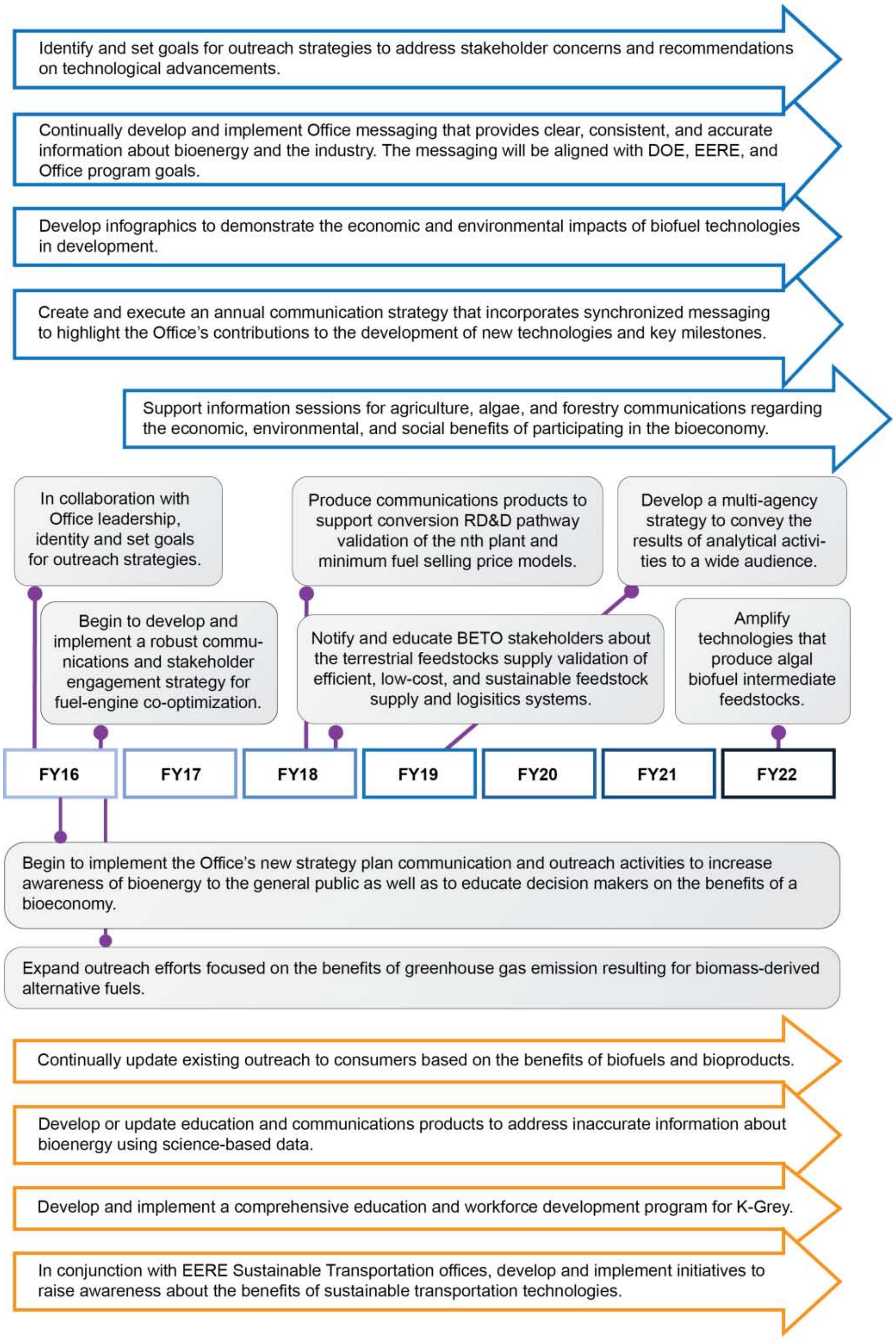
- Biomass is a low-carbon, renewable energy source that can help to diversify transportation fuels in the United States.
- The Bioenergy Technologies Office is developing technologies to enable the sustainable, nationwide production of biofuels compatible with today's transportation infrastructure.
- The Energy Department and the bioenergy community are now leveraging cellulosic ethanol research, development, and demonstration successes to accelerate advanced and

algal “drop-in” biofuel technologies that can replace petroleum-based gasoline, diesel, and jet fuel.
- An important component of the Bioenergy Technology Office’s work is to leverage partnerships between the private and public sectors to advance cleaner energy technologies, including advanced biofuels in the transportation sector.

With regular use, key messages will amplify communication efforts and resonate with stakeholders. These messages reflect what is important to the Office and will help to engage the bioenergy community. The Office’s key messages will show its priorities and help keep communication content accurate, relevant, and impactful.

2.4.3.6 Strategic Communications Milestones and Decision Points

The key milestones and decision points to complete the tasks described in Section 2.4.3.4 are summarized in Figure 2-51.



Identify and set goals for outreach strategies to address stakeholder concerns and recommendations on technological advancements.

Continually develop and implement Office messaging that provides clear, consistent, and accurate information about bioenergy and the industry. The messaging will be aligned with DOE, EERE, and Office program goals.

Develop infographics to demonstrate the economic and environmental impacts of biofuel technologies in development.

Create and execute an annual communication strategy that incorporates synchronized messaging to highlight the Office's contributions to the development of new technologies and key milestones.

Support information sessions for agriculture, algae, and forestry communications regarding the economic, environmental, and social benefits of participating in the bioeconomy.

In collaboration with Office leadership, identity and set goals for outreach strategies.

Produce communications products to support conversion RD&D pathway validation of the nth plant and minimum fuel selling price models.

Develop a multi-agency strategy to convey the results of analytical activities to a wide audience.

Begin to develop and implement a robust communications and stakeholder engagement strategy for fuel-engine co-optimization.

Notify and educate BETO stakeholders about the terrestrial feedstocks supply validation of efficient, low-cost, and sustainable feedstock supply and logisitics systems.

Amplify technologies that produce algal biofuel intermediate feedstocks.

Begin to implement the Office's new strategy plan communication and outreach activities to increase awareness of bioenergy to the general public as well as to educate decision makers on the benefits of a bioeconomy.

Expand outreach efforts focused on the benefits of greenhouse gas emission resulting for biomass-derived alternative fuels.

Continually update existing outreach to consumers based on the benefits of biofuels and bioproducts.

Develop or update education and communications products to address inaccurate information about bioenergy using science-based data.

Develop and implement a comprehensive education and workforce development program for K-Grey.

In conjunction with EERE Sustainable Transportation offices, develop and implement initiatives to raise awareness about the benefits of sustainable transportation technologies.

Figure 2-51: Strategic Communications key milestones and activities

Section 3: Office Portfolio Management

This section describes how the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office develops and manages its portfolio of research, development, and demonstration (RD&D) activities. It identifies and relates different types of portfolio management activities, including portfolio decision-making, analysis, and performance assessment.

Overview

The Bioenergy Technologies Office manages a diverse portfolio of technologies across the spectrum of applied RD&D. Management of the Office's technology portfolio is vital and demanding, made even more challenging by the dynamic context of changing federal budgets and administrative priorities.

To meet this challenge, the Office has developed a coordinated framework for managing its portfolio of RD&D projects. The framework is based on systematically investigating, evaluating, and down-selecting the most promising opportunities across a diverse spectrum of emerging technologies and technology readiness levels (TRLs) (see Table 3-1). This approach is intended to support a diverse technological base in applied research and development (R&D) while identifying promising earlier stage technologies and targeting the most favorable technologies for follow-on industrial-scale demonstration. As illustrated in Figure 3-1, this ensures a steady flow of evolving technologies through the RD&D pipeline while providing on-ramps for new technologies and off-ramps for technologies no longer meeting portfolio criteria.

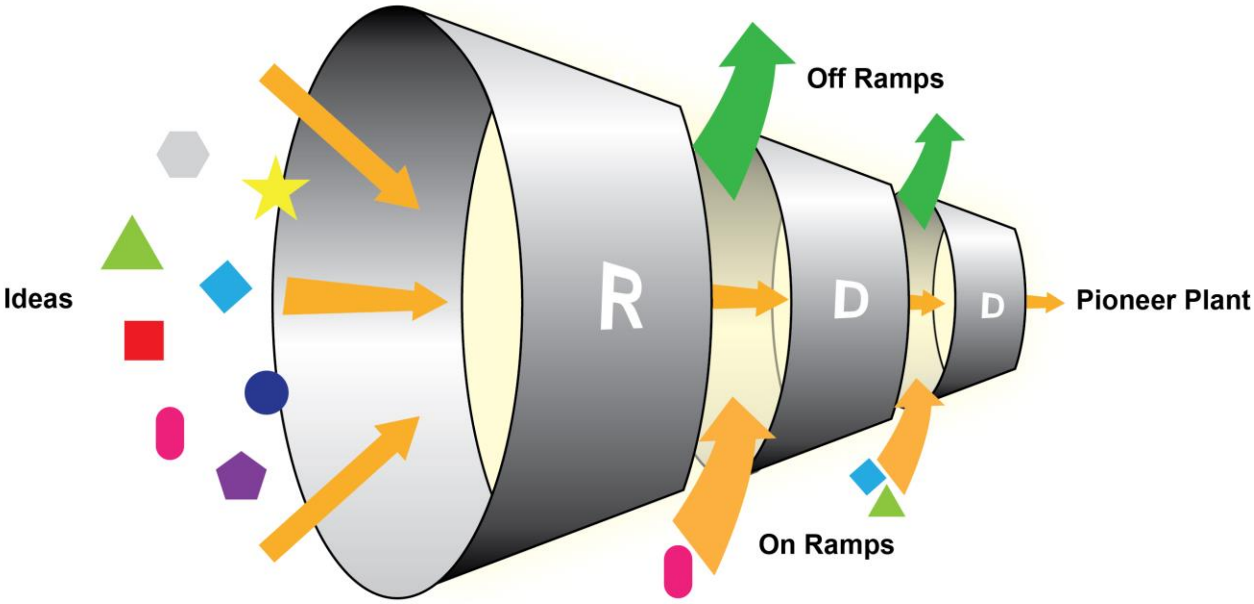


Figure 3-1: The RD&D pipeline concept

Table 3-1: Technology Readiness Level (TRL) Definitions

TRL 1	**Basic principles observed and reported:** Scientific problem or phenomenon is identified. Essential characteristics and behaviors of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research.
TRL 2	**Technology concept and/or application formulated—applied research activity**: Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
TRL 3	**Analytical and experimental critical function and/or characteristic proof of concept:** Proof of concept validation has been achieved at this level. Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions.
TRL 4	**Component and/or process validation in laboratory environment—alpha prototype (component):** Standalone prototyping implementation and testing in laboratory environment demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility.
TRL 5	**Component and/or process validation in relevant environment—beta prototype (component):** Thorough prototype testing of the component/process in a relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces.
TRL 6	**System/process model or prototype demonstration in a relevant environment—beta prototype (system):** Prototyping implementations are partially integrated with existing systems. Engineering feasibility is fully demonstrated in actual- or high-fidelity system applications in an environment relevant to the end user.
TRL 7	**System/process prototype demonstration in an operational environment—integrated pilot (system):** System prototype demonstrated in an operational environment. System is at or near full scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near production quality prototype.
TRL 8	**Actual system/process completed and qualified through test and demonstration—pre-commercial demonstration:** End of system development with full-scale system fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization.

The Office's approach to portfolio management has several distinct advantages:

- It ensures that the Office will examine diverse feedstocks and conversion technologies for producing biofuels, biopower, and bioproducts
- It brings new ideas and projects into the technology development cycle from applied research through commercial demonstration
- It provides structured decision-making for down-selection to ensure focus on the most most promising technologies and highest priority challenges
- It successfully identifies gaps within the portfolio, as well as crucial linkages between the stages of RD&D
- It is adequately flexible to accommodate new ideas and approaches, as well as various combinations of feedstock and process in real biorefineries
- It incorporates a structured management process, which guarantees a series of periodic technology reviews to help inform decision-making.

3.1 Office Portfolio Management Process

The Bioenergy Technologies Office manages its portfolio based on the approach recommended under the Office of Energy Efficiency and Renewable Energy (EERE) Program Management Initiative[1] and supplemented by Active Project Management and other structured systems approaches. The four major steps in the Office portfolio management process are shown in Figure 3-2 and are described on the following pages.

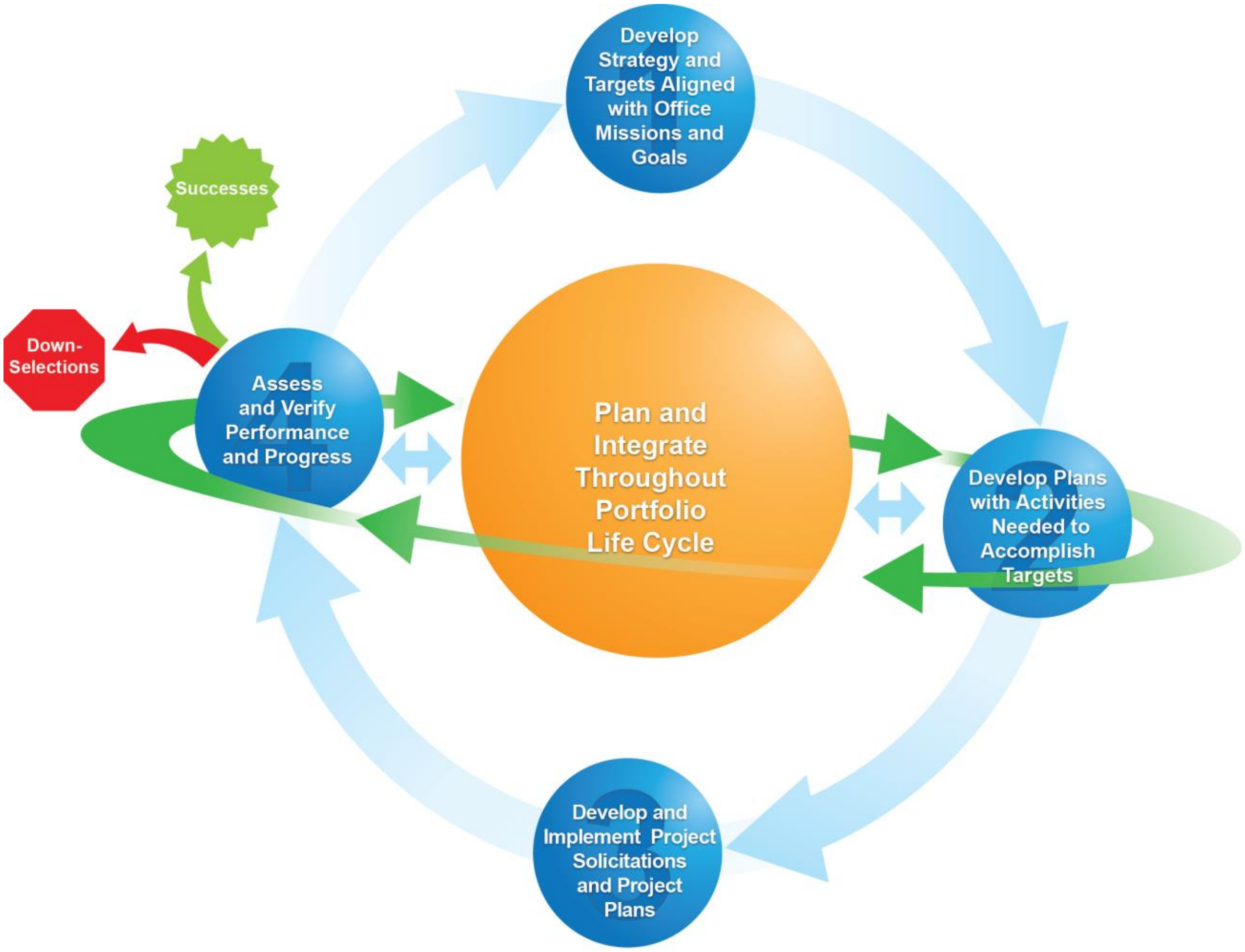


Figure 3-2: Office portfolio management process

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[1] The EERE Program Management Initiative was launched in 2003 to address stakeholder expectations, the President's Management Agenda, DOE and EERE strategic plans, findings and recommendations by the National Academy of Public Administration, and the Government Performance and Results Act. Complete information is available at http://energy.gov/eere/downloads/eere-program-management-initiative-pmi-brochure.

Step 1: Develop Office Strategy and Targets Aligned with Office Mission and Goals

Step 1 encompasses the process of developing the Office mission and goals (outlined in Section 1), both of which are developed from a combination of the Office's strategic goal hierarchy (see Figure 1-5) based on national goals, administrative and legislative priorities, and DOE and EERE strategic goals and priorities. The mission and goals are also developed in alignment with the goals of other federal agencies. The Office is currently undertaking a strategic planning process to update the Office's strategic goals and objectives.

The Office portfolio logic diagram (see Figure 1-7) outlines how the mission and goals fit within the planning and budgetary framework of the Office. Combining that Office portfolio logic with an understanding of market needs and technical scenarios leads to a definition of Office technical targets consistent with government objectives. Targets are allocated to Office program areas responsible for managing and funding research related to the targets. As shown in Figure 1-6, those program areas are organized around the two broad categories of RD&D and Crosscutting activities. RD&D is split into four technical areas: Terrestrial Feedstock Supply and Logistics R&D, Advanced Algal Systems R&D, Conversion R&D, and Demonstration and Market Transformation. Crosscutting areas include Sustainability, Strategic Analysis, and Strategic Communications.

Portfolio decision-making at the strategic level is based on three main criteria:

1. Does the portfolio balance the correct elements and priorities across the spectrum of RD&D and crosscutting activities to meet the technical and/or market targets required to achieve Office goals?
2. Does the portfolio support diverse technologies that can buy down the risk of producing competitively priced bioenergy and bioproducts?
3. Does the portfolio support the establishment of the bioenergy industry in the United States?

Step 2: Develop Plans with Activities Needed to Accomplish Targets

Step 2 guides how the Office develops its multi-year plans to outline the path to achieving the high-level Office technical and market targets defined in Step 1.

Based on overall Office goals, priorities, and relationships with other agencies, each program area develops performance goals and barriers through internal evaluation and public-private collaborative meetings. Based on the performance goals and barriers, programs develop long-term plans that inform budget priorities. To ensure alignment with Office goals and enable integration with other program area efforts, programs have used a structured resource loaded planning (RLP) process to detail activities required to meet strategic objectives and develop funding projections for achieving program targets. Each program area prioritizes and sequences activities for addressing challenges and barriers while considering the needs, developments, and driving forces behind the emerging industry within the context of inherently governmental activities. RLPs—integrated across program areas—identify gaps and linkages so gaps can be addressed and so linkages and interfaces between programs can be strengthened.

Future updates of program area RLPs may be based on updated Office strategies and goals. Updated plans align with and inform the activities described here in the Multi-Year Program Plan (MYPP). This MYPP is reviewed and updated annually to incorporate technology advances, cross-program learning, and changes in direction and priorities. Program plans are used to inform budget development process and are updated iteratively based on actual funding.

Program area priorities are informed by the five EERE core questions:[2]

- **Impact**: Is this a high-impact problem?
- **Additionality:** Will EERE funding make a large difference relative to existing funding from other sources, including the private sector?
- **Openness:** Are we focusing on the broad problem we are trying to solve and open to new ideas, approaches, and performers?
- **Enduring Economic Impact:** How will EERE funding result in enduring economic impact for the United States?
- **Proper Role of Government:** Why is this investment a necessary, proper, and unique role of government rather than something best left to the private sector?

Step 3: Develop and Implement Project Solicitations and Project Plans

Step 3 involves defining specific activities and goals required to meet strategic objectives, soliciting performers either competitively or non-competitively, and defining work scope of projects to meet those goals. Projects selected through competitive awards, as well as national laboratory projects developed through Annual Operating Plans (AOPs) and selected through the AOP merit review process, develop Project Management Plans (PMPs) that align with the MYPP and program area plans. PMPs outline the projects' approaches for achieving project objectives and aligning to technical and market targets and program barriers and milestones. At the initiation of a project, a PMP is prepared for the entire project duration, with special attention to the activities planned for the upcoming year. PMPs are updated annually based on actual progress, results of interim reviews, and updates to the Office MYPP.

Step 4: Assess and Verify Performance and Progress

As program area plans are implemented, Step 4 involves a system of performance assessments held on multiple levels to monitor and evaluate performance and progress (described in detail in Section 3.2). Individual projects are managed using Active Project Management (APM) practices required under EERE guidance. APM ensures that project progress is managed against program goals, the statement of work, and agreed upon milestones. APM includes a prescribed series of activities and reporting based on a graded approach that provides more oversight to projects with larger funding and higher risks.

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[2] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2016), *2016–2020 Strategic Plan and Implementing Framework*, http://www.energy.gov/eere/downloads/eere-strategic-plan.

The Office also monitors project performance on a quarterly basis against baseline schedule, scope, and cost provided in the AOP and PMP. Project assessments also inform program portfolio assessments. Program areas regularly assess their project portfolios to identify changes needed to more effectively achieve program and Office goals and targets. Within the program portfolio context, individual projects' scope, cost, schedule, risks, and potential benefits are assessed in comparison to other projects and based on their relevance towards addressing barriers and challenges and on reaching program area goals. Portfolio assessments identify overlaps and gaps and identify changes needed to better implement existing program plans while informing future plan updates.

The Office conducts biannual program area peer reviews and an overall Office peer review to provide input to decision making for future funding and direction. Project validations, go/no-go, and comprehensive project reviews are also conducted at the individual project level to assess technical, economic, environmental, and market potential, as well as risk.

In large-scale demonstration projects and pioneer conversion facilities involving public-private partnerships, independent expert analysis, project management processes such as DOE's Critical Decision process, and on-going evaluation by the Office contribute to project risk assessments and go/no-go decisions. BETO has adopted a modified approach of the acquisition-focused Critical Decision structure described in DOE O 413.3B, Program and Project Management for the Acquisition of Capital Assets,[3] to be more applicable to the Financial Assistance projects in the portfolio. The Critical Decision process is very similar to Front-End Engineering Design more commonly used by industry.

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[3] U.S. Department of Energy, Office of Information Resources, "DOE O 413.3B, Program and Project Management for the Acquisition of Capital Assets," https://www.directives.doe.gov/directives-documents/400-series/0413.3-BOrder-b.

3.2 Performance Assessment

The Office assesses its progress, decisions, goals, and approaches by monitoring and evaluating program and project performance. The performance assessment activities outlined in Table 3-2 provide avenues for input from other government agencies, stakeholders, and independent expert reviewers on program effectiveness and progress towards Office mission and goals.

Table 3-2: Office and Project-Level Assessments that Support Decision Making

Assessment Type		Assessment Synopsis	Documentation
Performance Monitoring	*External Monitoring*	DOE's Annual Performance Target Tracking System	Annual Performance Target Reports
	Internal Monitoring	Quarterly Portfolio Reviews	Quarterly Portfolio Review Reports
		Active Project Management and project monitoring with quarterly reports	Project Management Database and Quarterly Assessment and Site Visit Memos
		Project validations, integrated biorefinery (IBR) technical performance tracking	Biomass Database and IBR Performance data base and Annual ComPASS Report
		Independent Engineer evaluations and Comprehensive Project Reviews (CPRs)	Office Internal Reports
Office Evaluation	*Peer Reviews*	Conducted by independent experts outside of the Office portfolio to assess quality, productivity, and accomplishments, as well as relevance of Office success to EERE and Office strategic goals and to management[4]	Public Summary Documents (including Office Response)
	General Office Evaluation Studies	Conducted by independent external experts to examine process, quantify outcomes or impacts, identify market needs and baselines, or quantify cost-benefit measures as appropriate[5]	Public Reports and Documentation
Performance Monitoring and Office Evaluation	*Technical Office Reviews*	EERE Senior Management	EERE Internal
		Biomass R&D Technical Advisory Committee	Report to Congress (including Office Response)
	Technical Project Reviews	Project validations and go/no-go reviews conducted by DOE and other technical experts for select competitively awarded R&D and all public/private demonstration projects. Reviews are conducted by DOE plus independent industry, academia, or other government for pre-competitive R&D projects.	Internal reports for select competitively awarded R&D and all public-private demonstration projects.

Performance Monitoring

External Performance Monitoring

The Office of Management and Budget monitors Office performance against technical annual performance targets. Each EERE office is responsible for establishing and monitoring quarterly milestones, as well as meeting annual performance targets established in congressional budget requests.

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[4] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2004), *Peer Review Guide*, http://www1.eere.energy.gov/analysis/pdfs/2004peerreviewguide.pdf.

[5] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2006), *EERE Guide for Managing General Program Evaluation Studies: Getting the Information You Need*, http://www.seachangecop.org/sites/default/files/documents/2006%2002%20EERE%20-%20EERE%20Guide%20for%20Managing%20General%20Program.pdf.

Internal Performance Monitoring

The Office utilizes Quarterly Portfolio Reviews (QPRs) to summarize and report project schedule and cost performance for over 300 projects in the Office portfolio. Along with Active Project Management and other standardized processes, this review ensures on-going monitoring of project status, early identification of project issues, and notification of significant variances enabling a timely response.

Active Project Management and other standardized processes used to monitor and manage project performance include the following:

- Project Management Plans (PMPs) provide details of work planned throughout the entire project duration, as well as to establish measures for evaluating performance. The plans include multi-year descriptions, milestones, schedules, cost projections, and also identify other project subcontractors or partners. The PMPs are updated annually.
- Annual Operating Plans (AOPs) outline the scope of work, milestones, risks, and funding details of projects performed by national laboratories. These one- to three-year plans detail activities that have been selected through a merit review process or directly selected by program areas to focus on specific program or Office objectives, as appropriate based on the core capabilities of each national laboratory.
- Quarterly project progress reports are submitted by the funded organizations, outlining financial and technical status, identifying problem areas, and highlighting achievements. The Office performs a quarterly assessment of project progress against the planned scope and schedule and financial performance against the cost projection and documents the assessment in a quarterly management report.
- The performance of large-scale demonstration projects is also monitored through annual comprehensive project reviews and ongoing performance monitoring and analysis. The results of the reviews and performance monitoring are used for portfolio management and planning.
- Face-to-face meetings are held between DOE technical project officers and contractors with the project principal investigator or project team at least two times per year.

The Office uses structured systems approaches including interface management, project validation, independent performance verification, and information management tools to monitor overall progress toward achieving technical targets and to track lessons learned.

Office Evaluation

Peer Reviews

The Bioenergy Technologies Office uses an external peer review process to assess program area performance, as well as overall Office and portfolio performance. The Office implements the peer review process through a combination of program area peer reviews and an overall Office peer review, which are conducted at least biennially. The emphasis of the Office peer review is on the MYPP and the overall portfolio to determine whether or not it is balanced, organized, and performing appropriately. In contrast, the emphasis of the program area reviews is on the performance and execution of individual projects that comprise that program area and whether those projects are performing appropriately and contributing to program area goals as well as on the program area's overall portfolio balance.

The program area peer reviews evaluate the RD&D contributions of each program area toward the overall Office goals, as well as the processes, organization, management, and effectiveness of the Bioenergy Technologies Office. The review is led by an independent steering committee that selects independent experts to review both the Office and program area portfolios. The results of the review provide feedback on the performance of the Office and its portfolio and identify opportunities for improved Office management, as well as gaps or imbalances in funding that need to be addressed. By addressing these gaps and imbalances, the Office ensures focus on the highest priorities.

The program area peer reviews are conducted prior to the Office review. Information and findings from the program area peer reviews are incorporated into the comprehensive Office peer review process. The objectives of the program area peer review meetings are the following:

- Review and evaluate RD&D accomplishments and future plans of projects in each program area portfolio following the process guidelines of the EERE Peer Review Guide and incorporating the project evaluation criteria used in Office decision-making and project assessment processes
- Define and communicate Office strategic and performance goals applicable to the projects in that portfolio
- Provide an opportunity for stakeholders and participants to learn about and provide feedback on the projects in that portfolio to help shape future efforts so that the highest priority work is identified and addressed
- Foster interactions among industry, universities, and national laboratories conducting the RD&D, thereby facilitating technology transfer.

Technical experts from industry and academia are selected as reviewers based on their experience in various aspects of bioenergy technologies under review, including project finance, public policy, and infrastructure. The reviewers score and provide qualitative comments on RD&D based on the presentations given at the meeting and the background information provided. The reviewers also are asked to identify specific strengths and weaknesses as related to technical progress, project relevance, project approach, critical success factors, future work, and technology transfer plans.

The Office analyzes all of the information gathered at the review and develops appropriate responses to the findings for each program. Individual projects are given the opportunity to provide responses to the reviewers' comments. This information, including the Office response, is documented and published in a review report that is made available to the public through the Office website.[6]

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[6] Visit the 2015 Project Peer Review Web page for the most recent peer review report: http://energy.gov/eere/bioenergy/2015-project-peer-review.

General Office Evaluation Studies

The Office sponsors several activities and processes that are aligned with the program evaluation studies described in the EERE Guide for Managing General Program Evaluation Studies. The Office is conducting general program evaluations based on this guide, including the following:

- Needs/Market Assessments
- Outcome Evaluations
- Impact Evaluations
- Cost-Benefit Evaluations.

<u>Needs/Market Assessments</u>: In the past several years, the Office has held a number of workshops that have brought together stakeholders from federal and state government agencies, industry, academia, trade associations, and environmental organizations. These workshops have identified the key needs and opportunities for biobased fuels, power, and products in the United States. Recent workshops have focused on advanced feedstock supply systems, bioproducts, waste-to-energy, advanced conversion technologies, and advanced algal supply systems.

<u>Outcome, Impact, and Cost/Benefit Evaluations</u>: These types of evaluations are carried out by the EERE Office of Planning Budget and Analysis and were described previously in the Benefits Analysis portion of Section 2.4.2.

Performance Monitoring and Office Evaluation

The Office uses several forms of technical review to assess Office and program area progress and promote improvement. These include the Biomass R&D Technical Advisory Committee Office reviews, EERE strategic office reviews, the project validation and go/no-go processes, and comprehensive project reviews.

Technical Reviews

The Biomass Research and Development Technical Advisory Committee annually reviews the joint USDA/DOE Biomass R&D Initiative processes and portfolio and also provides recommendations to the Secretary of Energy and Secretary of Agriculture concerning the technical focus and future biofuels and bioproduct directions. The Committee provides periodic briefings to the Biomass R&D Board. Internally, DOE-EERE senior management meets frequently with the Bioenergy Technologies Office Director on strategic issues, including preparation of congressional budget submissions and evaluation of strategic direction.

Technical Project Reviews

The Office conducts project-level technical reviews. R&D projects are subject to review via three main processes: (1) project-level validations, (2) go/no-go reviews, and (3) comprehensive integrated biorefinery project reviews.

Project-level validations, performed by independent subject matter experts, verify technical and economic performance related to technical data provided in FOA applications and provide benchmarks and targets for interim and final reviews.

Go/no-go reviews, conducted either by BETO staff or external, independent reviewers, provide recommendations to inform go/no-go project decisions. Go/no-go reviews are generally aligned with the budget periods defined in the contractual Assistance Agreement or Annual Operating Plan for each project. Milestones and associated completion criteria are set at the beginning of a budget period or project. Projects are required to present not only progress to date, but also plans for the remainder of the project. At a pre-determined point in the project, progress is evaluated against these review criteria resulting in one of three possible outcomes: (1) review criteria are met resulting in a "go" decision to continue with the project as originally scoped, (2) review criteria are not met resulting in project termination ("no-go"), or (3) review criteria are partially met, resulting in required changes to the project; for example, by changing the scope of the effort or by extending the timeline to completion.

Figure 3-3: Office portfolio management process

The Office conducts annual comprehensive reviews on each of its large-scale demonstration- and pioneer-scale facility projects throughout the period of performance to monitor progress, identify key risks, and assess commercial viability. These in-depth reviews consider company structure and project management, technical performance, financial health, and commercial viability. Table 3-3 shows the key areas being assessed. These reviews also identify critical lessons learned to inform future DOE program activities. In conjunction with these reviews, key performance metrics for each major demonstration project are monitored, and the results are compiled and analyzed at least annually.

Table 3-3: Comprehensive Project Review Evaluation Criteria

Evaluation Category	Illustrative Evaluation Criteria
COMPANY STRUCTURE AND PROJECT MANAGEMENT	
1A: Project Management	• Project team is aligned to manage completion of performance baseline (cost/schedule) • Risks identified and mitigated • Key expertise and staff retained • Intellectual property secured/licensed
1B: Performance Against Baseline Scope, Budget, and Schedule	• Execution plans for operations are complete or appropriate for project stage • Performance baseline is well defined and complete • Earned value management metrics consistent with expectations, variances are addressed, plans for baseline are credible and achievable
1C: Risk Mitigation	• Risks adequately identified and risk mitigation plan maintained
TECHNICAL PERFORMANCE	
2A: Process Operations and Technical Targets	• Minimal new or untested technologies and process integrations • Technical performance appropriate for current stage and technical targets met • Environmental sustainability issues considered, measured, and addressed
2B: Feedstock Supply	• Feedstocks supply demonstrated at adequate scale to support commercial applications • Project feedstock(s) same as experimentally demonstrated and future commercial applications • Feedstock secured at reasonable cost to support long-term operations and feedstock supply logistics addressed • Environmental implications of feedstock production, logistics, and procurement assessed and addressed
FINANCIAL HEALTH AND MARKETING APPROVAL / COMMERCIALIZATION PLANS	
3A: Marketing Approval and Commercialization Plans	• Off-take agreements secured, production volumes aligned, and achievable path to market penetration defined • Marketing plan including fuel testing and approval coordinated with long-term project plans • Commercialization plans developed
3B: Project Financing	• Adequate access to financing and cost-share secured • Post-construction working capital sources defined • Future financing needs supported by performance baseline and critical path • Financing risks adequately addressed in contingency plans
3C: Project Economics	• The projected *pro forma* for the envisioned first commercial plant incorporates achievable performance targets and cost goals adequate for financial returns and debt coverage required for future commercialization.

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Appendix A: Technical Projection Tables

Table A-1: Biomass Volume and Price Projections through 2030 (Minus Allocations for Losses, Chemicals, and Pellets) at an Estimated $84/Dry Ton Delivered Feedstock Cost[1] (2014$)

Feedstock Category	**Feedstock Resource**	**Feedstock Available for Cellulosic Fuel Production (MM Dry Tons/Year)**							
		SOT	**Projection**						
		2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2022**	**2030**
Agricultural Residues	Corn Stover	70.7	83.2	106.7	131.8	138.1	150.7	154.1	172.5
	Wheat Straw	11.2	12.9	13.9	15.9	17.1	18.7	13.9	35.6
Energy Crops	Herbaceous Energy Crops	-	0.5	1.9	3.3	6.4	9.2	10.7	50.2
	Woody Energy Crops	-	-	-	-	-	0.2	5.0	22.9
Forest Residues	Pulpwood	0.8	1.2	1.6	2.1	2.7	3.3	1.7	31.4
	Logging Residues and Fuel Treatments	60.6	56.6	55.1	34.0	50.2	50.5	67.1	60.9
	Other Forestland Removals	0.6	0.8	0.4	0.6	1.3	1.2	0.9	2.9
	Urban and Mill Wood Wastes	32.3	31.3	31.0	27.0	29.9	29.7	31.0	33.8
Totals (MM Dry Tons/Year)		**176.1**	**186.5**	**210.6**	**214.7**	**245.7**	**263.4**	**284.5**	**410.2**

Note: Transport distance and other factors impact feedstock logistics cost, and therefore, the biomass volumes at $84/dry ton is an estimate (Idaho National Laboratory (2014), "Feedstock Supply System Design and Analysis," INL/EXT-14-33227).

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[1] Volumes presented estimate quantities available at $84/dry ton delivered to the throat of a conversion reactor. This cost is calculated based on current and projected biomass availability at a given stumpage fee/grower payment, combined with logistics cost estimated for the various feedstocks. The estimated logistics costs are based on a 2017 design.

Table A-2: Unit Operation Cost Contribution Estimates (2014$) and Technical Projections for Algae Farm[2]

Processing Area Cost Contributions & Key Technical Parameters	Metric	2015 SOT [a]	2015 SOT (Fully Lined) [a]	2022 Projection
Biomass Selling Price	$/ton AFDW	$1227	$1641	$494
Production Cost	$/ton AFDW	$1069	$1483	$409
Harvest/Dewatering Cost	$/ton AFDW	$116	$116	$64
Other Cost (Facility Circulation, Storage)	$/ton AFDW	$42	$42	$21
Gross Biomass Production Yield	ton AFDW/acre-year	12.4	12.4	37.5
Total Farm Power Demand	KWh/ton AFDW	860	860	407
Production				
Total Cost Contribution	$/ton AFDW	$1069	$1483	$409
Capital Cost Contribution	$/ton AFDW	$629	$1015	$213
Operating Cost Contribution	$/ton AFDW	$440	$468	$196
Cultivation Productivity (Annual Average)	g/m^2/day AFDW	8.5	8.5	25
Max Seasonal Production Variability	max:min productivity	2.3:1	2.3:1	3:1
Lipid Content	dry wt% as FAME	27.4%	27.4%	27.4%
N Content	AFDW wt%	1.8%	1.8%	1.8%
CO_2 Utilization Efficiency	% utilized for biomass	90%	90%	90%
Gross CO_2 + Nutrient Cost Contributions[b]	$/ton AFDW	$124	$124	$120
Operating Days Per Year	days/year	330	330	330
Biomass Concentration at Harvest	g/L AFDW	0.27	0.27	0.5
Dewatering				
Total Cost Contribution	$/ton AFDW	$116	$116	$64
Capital Cost Contribution	$/ton AFDW	$93	$93	$52
Operating Cost Contribution	$/ton AFDW	$23	$23	$12
Gross Dewatering Efficiency [c]	%	87%	87%	87%
Net Dewatering Efficiency [c]	%	99%	99%	99%
Final Concentration of Dewatered Biomass	g/L AFDW	200	200	200
Dewatering CAPEX	$/MGD from cultivation	$18	$18	$6
Dewatering OPEX	$/MM gal from cultivation	$4	$4	$1
Balance of Plant				
Total Cost Contribution	$/ton AFDW	$42	$42	$21
Capital Cost Contribution	$/ton AFDW	$31	$31	$15
Operating Cost Contribution	$/ton AFDW	$11	$11	$6

[a] Base case assumes nth-plant facility utilizing low-cost unlined ponds; alternative SOT scenario considers fully lined ponds
[b] Included as part of “operating cost contribution”; gross cost does not account for CO_2/nutrient recycling from conversion
[c] “Gross” efficiency = product of individual operations’ dewatering efficiencies. “Net” efficiency = rate of algal biomass recovered in dewatered product to conversion relative to biomass produced from cultivation (including recycle of clarified effluent streams)

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[2] R. Davis et al. (2015), *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, National Renewable Energy Laboratory, NREL/TP-5100-64772, http://www.nrel.gov/docs/fy16osti/64772.pdf.

Table A-3: Unit Operation Cost Contribution Estimates (2014$) and Technical Projections for Combined Algae Processing

Processing Area Cost Contributions & Key Technical Parameters	**Metric**	**2015 SOT**	**2015 SOT (Fully Lined)**	**2022 Projection (ALU design case)**[a]	**Revised 2022 Projection (2015 Farm Design)**[b]
Fuel Selling Price	$/GGE fuel	$13.89	$17.69	$4.38	$5.90
Conversion Contribution	$/GGE	$2.64	$2.64	$1.32	$1.67
Diesel Production	mm GGE/year	3.3	3.3	45.4	13.0
Naphtha Production	mm GGE/year	1.1	1.1	0.9	0.3
Ethanol Production	mm GGE/year	2.4	2.4	16.1	8.6
Diesel Yield (AFDW algae basis)	GGE/U.S. ton algae	53	53	103	69
Naphtha Yield (AFDW algae basis)	GGE/U.S. ton algae	17	17	2	2
Ethanol Yield (AFDW algae basis)	GGE/U.S. ton algae	39	39	36	46
Total Fuel Yield from Algae Farm	GGE/acre-year	1,352	1,352	6,235	4,380
Natural Gas Usage (AFDW algae basis)	scf/U.S. ton algae	1,800 (3,642 including NG for off-site H_2)	1,800 (3,642 including NG for off-site H_2)	2,698 (4,337 including NG for off-site H_2)	1,396 (2,486 including NG for off-site H_2)
Feedstock					
Total Cost Contribution	$/GGE fuel	$11.25	$15.05	$3.06	$4.23
Feedstock Cost (AFDW algae basis)	$/U.S. ton algae	$1227	$1641	$433	$494
Feedstock Solids Content	wt% AFDW	20%	20%	20%	20%
Feedstock Lipid/Carb/Protein Content	dry wt%	27%/53%/13%[c]	27%/53%/13%[c]	41%:38%:9%	27%/53%/13%
Conversion					
Total Cost Contribution	$/GGE fuel	$1.95	$1.95	$1.14	$1.35
Capital Cost Contribution	$/GGE fuel	$1.08	$1.08	$0.66	$0.83
Operating Cost Contribution	$/GGE fuel	$0.87	$0.87	$0.48	$0.52
Pretreatment Solids Loading	wt% AFDW	20%	20%	20%	20%
Pretreatment Acid Loading	wt% of water feed	2%	2%	1%	1%
Pretreatment Fermentable Sugar Yield	%	74%	74%	90%	90%
Carbs to Degradation Products	%	1.5%	1.5%	0.3%	0.3%
Fermentation Batch Time	hr	<18	<18	72	72
Fermentation Total Solids Loading	wt%	20%	20%	20%	20%
Sugar Diversion to Organism Growth	%	6%	6%	4%	4%
Fermentable Sugar Utilization	%	98.5%	98.5%	95%	95%
Extraction Solvent Loading	g/g solvent/dry biomass	5.9	5.9	5.0	5.0
FAME Lipid Extraction Yield	%	87%	87%	95%	95%
Polar Lipid Impurity Partition to Extract	%	<11.5%	<11.5%	33%	33%
Lipid Hydrotreating to Finished Fuels					
Total Cost Contribution	$/GGE fuel	$0.81	$0.81	$0.30	$0.46
Capital Cost Contribution	$/GGE fuel	$0.51	$0.51	$0.21	$0.31
Operating Cost Contribution	$/GGE fuel	$0.30	$0.30	$0.09	$0.15
Hydrotreating Diesel Yield	wt% of oil feed	66%	66%	80%	80%
Hydrotreating Naphtha Yield	wt% of oil feed	22%	22%	2%	2%
Hydrotreating H_2 Consumption	wt% of oil feed	5%	5%	2%	2%

Processing Area Cost Contributions & Key Technical Parameters	**Metric**	**2015 SOT**	**2015 SOT (Fully Lined)**	**2022 Projection (ALU design case) [a]**	**Revised 2022 Projection (2015 Farm Design) [b]**
Anaerobic Digestion + Combined Heat & Power					
Total Cost Contribution	$/GGE fuel	($0.27)	($0.27)	($0.20)	($0.25)
Capital Cost Contribution	$/GGE fuel	$0.16	$0.16	$0.09	$0.12
Operating Cost Contribution	$/GGE fuel	$0.05	$0.05	$0.02	$0.03
AD N/P Nutrient Coproduct Credits	$/GGE fuel	($0.15)	($0.15)	($0.10)	($0.13)
AD CO_2 Coproduct Credit	$/GGE fuel	($0.26)	($0.26)	($0.15)	($0.20)
AD Power Coproduct Credit	$/GGE fuel	($0.06)	($0.06)	($0.05)	($0.06)
AD Digestate Fertilizer Credit	$/GGE fuel	($0.01)	($0.01)	($0.01)	($0.01)
Balance of Plant					
Total Cost Contribution	$/GGE fuel	$0.15	$0.15	$0.08	$0.11
Capital Cost Contribution	$/GGE fuel	$0.11	$0.11	$0.04	$0.07
Operating Cost Contribution	$/GGE fuel	$0.04	$0.04	$0.04	$0.04
Models: Case References		*HCSD + Store SOT*	*HCSD + Store SOT + Liners*	*HLSD + Store*	*HCSD + Store (Revised)*

[a] Original 2022 projection based on 2014 ALU design report [3] assumed targets for biomass cost, yield, and composition

[b] Revised 2022 projection based on running the ALU design model for biomass cost, yield, and composition details consistent with outputs from 2015 algal biomass design report[4]

[c] SOT case assumes algal biomass feedstock composition consistent with revised 2022 target case.

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[3] R. Davis et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products*, National Renewable Energy Laboratory, NREL/TP-5100-62498.

[4] R. Davis et al. (2015), *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, National Renewable Energy Laboratory, NREL/TP-5100-64772.

Table A-4: Unit Operation Cost Contribution Estimates (2014$) and Technical Projections for Whole Algae Hydrothermal Liquefaction and Upgrading to Diesel[5]

Processing Area Cost Contributions & Key Technical Parameters	Metric	2015 SOT[2] No Pond Liners	2015 SOT[2] Pond Liners	Original 2022 Projected[3]	Revised 2022 Projected[4]
Fuel Selling Price	$/GGE	$14.78	$18.60	$4.51	$4.72
Conversion Contribution	$/GGE	$3.45	$3.45	$1.19	$1.54
Production Diesel	mm gallons/year	5	5	54	23
Production Naphtha	mm gallons/year	2	2	11	5
Diesel Yield (AFDW Algae Basis)	gal/U.S. ton algae	77	77	122	122
Naphtha Yield (AFDW Algae Basis)	gal/U.S. ton algae	25	25	25	25
Natural Gas Usage-Drying (AFDW Algae Basis)	scf/U.S. ton algae	3,291	3,291	2,946	3,126
Feedstock					
Total Cost Contribution	$/gge fuel	$11.33	$15.15	$3.33	$3.18
Feedstock Type		Field Grown	Field Grown	14% ash; 20% total lipid	mid-lipid Scenedesmus
Feedstock Cost (AFDW Algae Basis)	$/U.S. ton algae	$1,227	$1,641	$433	$494
HTL Biocrude Production					
Total Cost Contribution	$/GGE fuel	$1.18	$1.18	$0.61	$0.49
Capital Cost Contribution	$/GGE fuel	$0.64	$0.64	$0.45	$0.00
Operating Cost Contribution	$/GGE fuel	$0.55	$0.55	$0.16	$0.49
Liquid Hourly Space Velocity (LHSV)	vol/h/vol	4.0	4.0	4.0	8.0
HTL Biocrude Yield (AFDW)	lb/lb algae	0.40	0.40	0.59	0.59
HTL Biocrude Hydrotreating to Finished Fuels					
Total Cost Contribution	$/GGE fuel	$0.44	$0.44	$0.35	$0.31
Capital Cost Contribution	$/GGE fuel	$0.24	$0.24	$0.13	$0.00
Operating Cost Contribution	$/GGE fuel	$0.21	$0.21	$0.22	$0.31
Mass Yield on Dry HTL Biocrude	lb/lb AHTL oil	0.86	0.86	0.83	0.83
HTL Aqueous Phase Treatment					
Total Cost Contribution	$/GGE fuel	$1.54	$1.54	$0.61	$0.57
Capital Cost Contribution	$/GGE fuel	$0.81	$0.81	$0.35	$0.00
Operating Cost Contribution	$/GGE fuel	$0.72	$0.72	$0.26	$0.57

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[5] Jones et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading*, Pacific Northwest National Laboratory, PNNL- 23227, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf.

Processing Area Cost Contributions & Key Technical Parameters	Metric	2015 SOT[2] No Pond Liners	2015 SOT[2] Pond Liners	Original 2022 Projected[3]	Revised 2022 Projected[4]
Balance of Plant					
Total Cost Contribution	$/GGE fuel	$0.29	$0.29	($0.38)	$0.17
Capital Cost Contribution	$/GGE fuel	$0.25	$0.25	$0.17	$0.00
Operating Cost Contribution	$/GGE fuel	$0.23	$0.23	$0.04	$0.22
Credits	$/GGE fuel	($0.20)	($0.20)	($0.58)	($0.05)
Models: Case References		T-021716-15SOT-14$-NL	T-021716-15SOT-14$-WL	030114P-14$	N-120815-22P-14$

[1] The table may contain very small (≤ $0.01) rounding errors due to the difference between the way that rounded values.
Microsoft Excel™ displays and calculates

[2] New Basis: 188 tpd AFDW algae @ $1222/ton; naphtha valued at production cost

[3] Original Basis: 1340 tpd AFDW algae @ $430/ton; naphtha values at $3.25/gal (Jones 2014a)

[4] New Basis: 568 tpd AFDW algae @ 491/ton; naphtha valued at production cost

Table A-5: Unit Operation Cost Contribution Estimates (2014$) and Technical Projections for Fast Pyrolysis Conversion to Gasoline and Diesel Baseline Process Concept[6]

(Process Concept: Woody Feedstock, Fast Pyrolysis, Bio-Oil Upgrading, Fuel Finishing)*

Processing Area Cost Contributions & Key Technical Parameters	**Metric**	**2009 SOT†**	**2010 SOT**	**2011 SOT**	**2012 SOT**	**2013 SOT**	**2014 SOT**	**2015 SOT**	**2016 Projection***	**2017 Projection***
Conversion Contribution	$/gal gasoline blendstock	$12.71	$9.45	$7.50	$6.36	$4.62	$4.12	$3.73	$2.99	$2.49
	$/gal diesel blendstock	$13.36	$9.93	$7.88	$6.68	$5.14	$4.58	$4.16	$3.32	$2.76
Conversion Contribution, Combined Blendstocks	$/GGE	$12.33	$9.17	$7.27	$6.17	$4.71	$4.19	$3.80	$3.05	$2.53
Performance Goal	$/GGE	-	-	-	-	-	-	-	-	$3
Combined Fuel Selling Price	$/GGE	$13.78	$10.57	$8.50	$7.25	$5.95	$5.42	$4.92	$4.10	$3.50
Production Gasoline Blendstock	mm gallons/year	30	30	30	30	29	29	29	29	29
Production Diesel Blendstock	mm gallons/year	23	23	23	23	32	32	32	32	32
Yield Combined Blendstocks	GGE/dry U.S. ton	78	78	78	78	87	87	87	87	87
Yield Combined Blendstocks	mmBTU/dry U.S. ton	9	9	9	9	10	10	10	10	10
Natural Gas Usage	scf/dry U.S. ton	1,115	1,115	1,115	1,115	1,685	1,742	1,774	1,685	1,685
Feedstock										
Total Cost Contribution	$/GGE fuel	$1.45	$1.40	$1.23	$1.08	$1.24	$1.23	$1.12	$1.05	$0.97
Capital Cost Contribution	$/GGE fuel	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Operating Cost Contribution	$/GGE fuel	$1.45	$1.40	$1.23	$1.08	$1.24	$1.23	$1.12	$1.05	$0.97
Feedstock Cost	$/dry U.S. ton	$112.86	$108.68	$95.60	$84.14	$107.80	$107.09	$97.34	$91.54	$84.45
Fast Pyrolysis										
Total Cost Contribution	$/GGE fuel	$1.00	$0.97	$0.95	$0.93	$0.81	$0.81	$0.80	$0.79	$0.78
Capital Cost Contribution	$/GGE fuel	$0.85	$0.82	$0.80	$0.78	$0.69	$0.68	$0.68	$0.67	$0.67
Operating Cost Contribution	$/GGE fuel	$0.15	$0.15	$0.15	$0.15	$0.12	$0.12	$0.12	$0.12	$0.11
Pyrolysis Oil Yield (dry)	lb organics/lb dry wood	0.60	0.60	0.60	0.60	0.62	0.62	0.62	0.62	0.62

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[6] S. Jones et al. (2013), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway*, Pacific Northwest National Laboratory, PNNL-23053, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf.

Processing Area Cost Contributions & Key Technical Parameters	**Metric**	**2009 SOT†**	**2010 SOT**	**2011 SOT**	**2012 SOT**	**2013 SOT**	**2014 SOT**	**2015 SOT**	**2016 Projection***	**2017 Projection***
Upgrading to Stable Oil via Multi-Step Hydrodeoxygenation/Hydrocracking										
Total Cost Contribution	$/GGE fuel	$10.32	$7.21	$5.36	$4.27	$2.95	$2.45	$2.07	$1.34	$0.96
Capital Cost Contribution	$/GGE fuel	$0.72	$0.69	$0.68	$0.67	$0.60	$0.63	$0.49	$0.46	$0.43
Operating Cost Contribution	$/GGE fuel	$9.59	$6.52	$4.68	$3.60	$2.34	$1.82	$1.57	$0.88	$0.53
Annual Upgrading Catalyst Cost, mm$/year	Annual cost is a function of WHSV,[2] number of reactors, catalyst replacement rate, and $/lb	525	352	249	188	133	100	82	41	19
Upgraded Oil Carbon Efficiency on Pyrolysis Oil	wt%	65%	65%	65%	65%	68%	68%	68%	68%	68%
Fuel Finishing to Gasoline and Diesel via Hydrocracking and Distillation										
Total Cost Contribution	$/GGE fuel	$0.25	$0.25	$0.24	$0.24	$0.25	$0.24	$0.24	$0.25	$0.14
Capital Cost Contribution	$/GGE fuel	$0.16	$0.16	$0.15	$0.15	$0.17	$0.16	$0.16	$0.16	$0.07
Operating Cost Contribution	$/GGE fuel	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.08	$0.08	$0.07
Balance of Plant										
Total Cost Contribution	$/GGE fuel	$0.75	$0.74	$0.73	$0.72	$0.70	$0.70	$0.69	$0.67	$0.64
Capital Cost Contribution	$/GGE fuel	$0.38	$0.36	$0.35	$0.35	$0.31	$0.31	$0.31	$0.31	$0.30
Operating Cost Contribution	$/GGE fuel	$0.38	$0.38	$0.38	$0.38	$0.38	$0.38	$0.38	$0.37	$0.34
Models: Case References		2009 SOT 090913	2010 SOT 090913	2012 SOT 090913	2012 SOT 090913	2013 SOT 122013	2014 SOT 123014	2015 P 123013	2016 P 121913	2017 P 093013

*Pyrolysis conversion performance tests conducted through 2017 are based on dried, debarked pine that has been ground to a 2-mm particle size. As explained in Section 2.1.1.5, research funded by FSL aims to develop a blend that will support comparable conversion performance as a pure pine feedstock.
† SOT: State of Technology

1. Note: The table may contain very small (< $0.01) rounding errors due to the difference between the way that Microsoft Excel™ displays and calculates rounded values.
2. WHSV=weight hourly space velocity: weight of oil feed per hour per weight of catalyst.

Note that while the blend is under development, research will continue to expand the specification accepted by the pyrolysis process, making it more robust. Relying solely on pine as a feedstock will not only limit the amount of material available for fuel production via pyrolysis, but will also influence the delivered cost of feedstock to the throat of the conversion process (Figure A-1).

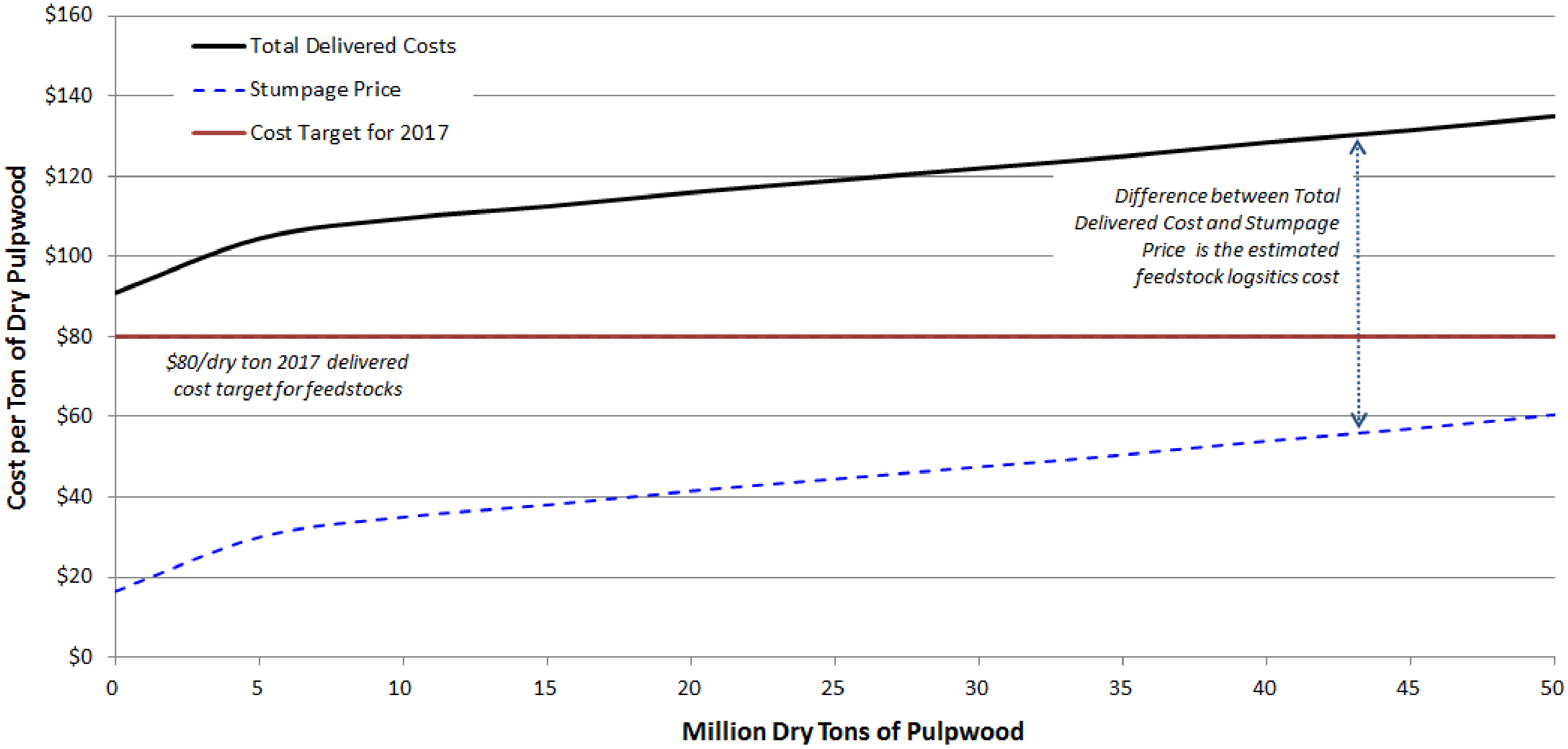

Figure A-1: Estimated total delivered cost of debarked, dried, ground pulpwood, delivered to the throat of the reactor and meeting the conversion specifications for pyrolysis. Pulpwood prices are based on values presented in the 2011 *U.S. Billion-Ton Update* for the year 2017

As demonstrated in Figure A-1, pulpwood resources are available for conversion in 2017; however, they are more expensive and available in lower volumes than the woody blend scenario presented in Table 2-4. The volumes presented in Figure A-1 are consistent with and are generated from the same data as those presented in Table A-1. However, the volumes presented in Table A-1 were constrained to those available at a low-enough stumpage price such that the total delivered cost target of $80/dry ton could be met.

Table A-6: Processing Area Cost Contribution (2014$) and Key Technical Parameters for In Situ Catalytic Pyrolysis Vapors to Gasoline and Diesel Baseline Process Concept[7]

(Process Concept: Hydrocarbon Fuel Production via In Situ Upgrading of Fast Pyrolysis Vapors)

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT†	2015 Projection	2016 Projection	2017 Projection	2018 Projection	2019 Projection	2020 Projection	2021 Projection	2022 Projection (Design Case)
		Pulp-wood	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**
Projected Minimum Fuel Selling Price▲	$/GGE*	$6.32	$5.80	$5.26	$4.57	$4.37	$4.16	$3.95	$3.75	$3.54
Conversion Contribution	$/GGE*	$3.97	$3.77	$3.49	$3.11	$2.97	$2.83	$2.69	$2.55	$2.40
Total Project Investment per Annual GGE	$/GGE/ year	$16.07	$15.20	$14.02	$12.44	$11.85	$11.26	$10.67	$10.08	$9.50
Plant Capacity (Dry Feedstock Basis)	metric tons/day	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Total Gasoline Equivalent Yield	GGE/dry U.S. ton	46	49	52	59	62	65	68	72	75
Diesel Product Proportion (GGE** basis)	% of fuel product	17%	17%	17%	17%	19%	21%	23%	25%	27%
Feedstock										
Total Cost Contribution	$/GGE	$2.35	$2.02	$1.77	$1.46	$1.40	$1.33	$1.27	$1.20	$1.14
Capital Cost Contribution	$/GGE	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Operating Cost Contribution	$/GGE	$2.35	$2.02	$1.77	$1.46	$1.39	$1.33	$1.26	$1.20	$1.14
Feedstock Cost	$/dry U.S. ton	$107.09	$97.34	$91.54	$84.45	$84.45	$84.45	$84.45	$84.45	$84.45
Feedstock Moisture at Plant Gate	wt% H_2O	10%	10%	10%	10%	10%	10%	10%	10%	10%

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[7] A. Dutta, A. Sahir, E. Tan, D. Humbird, L. Snowden-Swan, P. Meyer, J. Ross, D. Sexton, R. Yap, and J. Lukas (2015), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels - Thermochemical Research Pathways With In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors*, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, NREL/TP-5100-62455, PNNL-23823, http://www.nrel.gov/docs/fy15osti/62455.pdf.

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 Projection**	**2016 Projection**	**2017 Projection**	**2018 Projection**	**2019 Projection**	**2020 Projection**	**2021 Projection**	**2022 Projection (Design Case)**
Feed Moisture Content to Pyrolyzer	wt% H_2O	10%	10%	10%	10%	10%	10%	10%	10%	10%
Energy Content (LHV, Dry Basis)	BTU/lb	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000
Pyrolysis and Vapor Upgrading										
Total Cost Contribution	$/GGE	$2.52	$2.36	$2.16	$1.86	$1.75	$1.64	$1.53	$1.41	$1.30
Capital Cost Contribution	$/GGE	$0.74	$0.70	$0.64	$0.57	$0.54	$0.51	$0.48	$0.46	$0.43
Operating Cost Contribution	$/GGE	$1.78	$1.66	$1.51	$1.29	$1.21	$1.13	$1.04	$0.96	$0.87
Gas Phase	wt% of dry biomass	31%	30%	29%	27%	26%	25%	24%	24%	23%
Aqueous Phase	wt% of dry biomass	26%	26%	26%	27%	27%	28%	28%	28%	29%
Carbon Loss	% of C in biomass	3.2%	3.1%	2.6%	2.4%	2.3%	2.3%	2.2%	2.2%	2.1%
Organic Phase	wt% of dry biomass	19.5%	20.6%	21.6%	24.0%	24.9%	25.7%	26.6%	27.5%	28.3%
H/C Molar Ratio	ratio	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5
Oxygen	wt% of organic phase	15.6%	15.5%	14.4%	14.0%	13.3%	12.6%	11.9%	11.2%	10.5%
Carbon Efficiency	% of C in biomass	29%	31%	33%	37%	38%	40%	41%	43%	44%
Solid Losses (Char + Coke)	wt% of dry biomass	24%	24%	23%	23%	22%	22%	21%	21%	20%
Char	wt% of dry biomass	12%	12%	12%	12%	12%	12%	12%	12%	12%
Coke	wt% of dry biomass	12.0%	11.6%	11.2%	10.6%	10.1%	9.6%	9.1%	8.6%	8.1%
Pyrolysis Vapor Quench										
Total Cost Contribution	$/GGE	$0.29	$0.27	$0.25	$0.22	$0.21	$0.20	$0.19	$0.18	$0.17
Capital Cost Contribution	$/GGE	$0.18	$0.17	$0.15	$0.13	$0.13	$0.12	$0.11	$0.11	$0.10
Operating Cost Contribution	$/GGE	$0.12	$0.11	$0.10	$0.08	$0.08	$0.08	$0.07	$0.07	$0.07

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 Projection**	**2016 Projection**	**2017 Projection**	**2018 Projection**	**2019 Projection**	**2020 Projection**	**2021 Projection**	**2022 Projection (Design Case)**
Hydroprocessing and Separation										
Total Cost Contribution	$/GGE	$0.36	$0.35	$0.33	$0.32	$0.31	$0.31	$0.30	$0.29	$0.28
Capital Cost Contribution	$/GGE	$0.20	$0.20	$0.19	$0.18	$0.17	$0.17	$0.17	$0.16	$0.16
Operating Cost Contribution	$/GGE	$0.16	$0.16	$0.15	$0.14	$0.14	$0.13	$0.13	$0.13	$0.12
Carbon Efficiency of Organic Liquid Feed to Fuels	%	88%	88%	89%	89%	90%	90%	90%	91%	91%
Hydrotreating Pressure	psia	2,000	2,000	2,000	2,000	1960	1920	1880	1840	1,800
Oxygen Content in Cumulative Fuel Product	wt%	0.7%	0.7%	0.7%	0.7%	0.7%	0.6%	0.6%	0.5%	0.5%
Hydrogen Production										
Total Cost Contribution	$/GGE	$0.63	$0.61	$0.58	$0.56	$0.55	$0.53	$0.52	$0.51	$0.49
Capital Cost Contribution	$/GGE	$0.42	$0.41	$0.39	$0.37	$0.36	$0.35	$0.35	$0.34	$0.33
Operating Cost Contribution	$/GGE	$0.21	$0.20	$0.19	$0.19	$0.18	$0.18	$0.17	$0.17	$0.17
Additional Natural Gas**	% of biomass LHV	0.3%	0.0%	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%
Balance of Plant										
Total Cost Contribution	$/GGE	$0.17	$0.18	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16
Capital Cost Contribution	$/GGE	$0.81	$0.75	$0.68	$0.57	$0.53	$0.49	$0.45	$0.41	$0.37
Operating Cost Contribution	$/GGE	($0.65)	($0.58)	($0.51)	($0.41)	($0.37)	($0.33)	($0.29)	($0.25)	($0.21)
Electricity Production from Steam Turbine (credit included in operating cost above)	$/GGE**	($0.98)	($0.89)	($0.79)	($0.64)	($0.59)	($0.53)	($0.48)	($0.42)	($0.36)

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 Projection**	**2016 Projection**	**2017 Projection**	**2018 Projection**	**2019 Projection**	**2020 Projection**	**2021 Projection**	**2022 Projection (Design Case)**
Sustainability and Process Efficiency Metrics										
Fuel Yield by Weight of Biomass	% w/w of dry biomass	15.0%	15.8%	17.0%	19.0%	19.9%	20.9%	21.9%	22.8%	23.8%
Carbon Efficiency to Fuels	% C in feedstock	25.8%	27.3%	29.2%	32.6%	34.1%	35.7%	37.3%	38.8%	40.4%
Overall Carbon Efficiency to Fuels	% C in feedstock + NG	25.8%	27.3%	29.2%	32.6%	34.1%	35.7%	37.3%	38.8%	40.4%
Overall Energy Efficiency to Fuels	% LHV of feedstock + NG	33.2%	35.3%	37.9%	42.4%	44.8%	47.2%	49.6%	52.0%	54.3%
Electricity Production	kWh/GGE	18.5	16.8	14.9	12.2	11.1	10.1	9.1	8.1	7.0
Electricity Consumption (entire process)	kWh/GGE	11.7	10.9	10.0	8.7	8.2	7.7	7.2	6.8	6.3
Water Consumption	gal H_2O/GGE	1.3	1.2	1.1	0.9	0.9	0.9	0.8	0.8	0.8
Fossil GHG Emissions (with electricity credit)	g CO_2e/MJ fuel	(32.8)	(28.6)	(23.8)	(16.1)	(13.4)	(10.7)	(8.0)	(5.3)	(2.6)
Fossil Energy Consumption (with electricity credit)	MJ fossil energy/MJ fuel	(0.4)	(0.3)	(0.3)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	0.0
TEA Reference File		PyVPU-v218g IS - 2014 (2014$)-v03.xlsm	PyVPU-v218g IS - 2015 (2014$)-v03.xlsm	PyVPU-v218g IS - 2016 (2014$)-v03.xlsm	PyVPU-v218g IS - 2017 (2014$)-v03.xlsm					PyVPU-v218 IS - 2022 (2014$)-v03.xlsm

▲Conceptual design result with margin of error +/- 30%

† SOT: State of Technology

* Gallon Gasoline Equivalent (GGE) on a Lower Heating Value (LHV) basis

** A negligible stream was maintained in the model to allow natural gas use if necessary.

Table A-7: Processing Area Cost Contribution (2014$) and Key Technical Parameters for Ex Situ Pyrolysis Vapors Baseline Process Concept[8]

(Process Concept: Hydrocarbon Fuel Production via Ex Situ Upgrading of Fast Pyrolysis Vapors)

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT†	2015 SOT●	2016 Projection	2017 Projection	2018 Projection*	2019 Projection*	2020 Projection*	2021 Projection*	2022 Projection (Design Case)
		Pulpwood	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**
Projected Minimum Fuel Selling Price▲	$/GGE*	$6.61	$5.76	$5.34	$4.67	$4.41	$4.15	$3.89	$3.63	$3.38
Conversion Contribution	$/GGE*	$4.03	$3.62	$3.47	$3.13	$2.96	$2.79	$2.62	$2.45	$2.29
Total Project Investment per Annual GGE	$/GGE /year	$19.67	$17.49	$16.51	$14.55	$13.60	$12.66	$11.72	$10.78	$9.83
Plant Capacity (Dry Feedstock Basis)	metric tons/day	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Total Gasoline Equivalent Yield	GGE/dry U.S. ton	42	46	50	56	60	64	69	73	78
Diesel Product Proportion (GGE* basis)	% of fuel product	15%	15%	14%	14%	22%	30%	38%	47%	55%
Feedstock										
Total Cost Contribution	$/GGE	$2.58	$2.14	$1.87	$1.54	$1.45	$1.36	$1.27	$1.18	$1.09
Capital Cost Contribution	$/GGE	$0.01	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Operating Cost Contribution	$/GGE	$2.57	$2.13	$1.86	$1.53	$1.45	$1.36	$1.27	$1.18	$1.09
Feedstock Cost	$/dry U.S. ton	$107.09	$97.34	$91.54	$84.45	$84.45	$84.45	$84.45	$84.45	$84.45
Feedstock Moisture at Plant Gate	wt% H_2O	10%	10%	10%	10%	10%	10%	10%	10%	10%
Feed Moisture Content to Pyrolyzer	wt% H_2O	10%	10%	10%	10%	10%	10%	10%	10%	10%
Energy Content (LHV, Dry Basis)	BTU/lb	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000

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[8] A. Dutta, A. Sahir, E. Tan, D. Humbird, L. Snowden-Swan, P. Meyer, J. Ross, D. Sexton, R. Yap, and J. Lukas (2015), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels - Thermochemical Research Pathways With In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors*, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, NREL/TP-5100-62455, PNNL-23823, http://www.nrel.gov/docs/fy15osti/62455.pdf.

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT†	2015 SOT	2016 Projection	2017 Projection	2018 Projection*	2019 Projection*	2020 Projection*	2021 Projection*	2022 Projection (Design Case)
Pyrolysis and Vapor Upgrading										
Total Cost Contribution	$/GGE	$2.48	$2.16	$2.09	$1.86	$1.75	$1.63	$1.52	$1.41	$1.29
Capital Cost Contribution	$/GGE	$1.08	$0.94	$0.91	$0.81	$0.76	$0.71	$0.67	$0.62	$0.57
Operating Cost Contribution	$/GGE	$1.40	$1.23	$1.18	$1.05	$0.98	$0.92	$0.85	$0.79	$0.73
Gas Phase	wt% of dry biomass	35%	34%	32%	30%	29%	27%	26%	24%	23%
Aqueous Phase	wt% of dry biomass	25%	25%	25%	26%	27%	27%	28%	29%	30%
Carbon Loss	% of C in biomass	2.9%	2.9%	2.4%	2.3%	2.1%	1.9%	1.7%	1.5%	1.3%
Organic Phase	wt% of dry biomass	17.5%	18.6%	20.2%	22.0%	23.0%	24.1%	25.1%	26.2%	27.2%
H/C Molar Ratio	ratio	1.1	1.1	1.2	1.3	1.3	1.4	1.5	1.5	1.6
Oxygen	wt% of organic phase	15.0%	13.3%	14.0%	12.5%	11.3%	10.1%	8.8%	7.6%	6.4%
Carbon Efficiency	% of C in biomass	27%	29%	31%	34%	36%	38%	40%	42%	44%
Solid Losses (Char + Coke)	wt% of dry biomass	23%	21%	23%	22%	22%	21%	21%	20%	20%
Char	wt% of dry biomass	12%	11%	12%	12%	12%	12%	12%	12%	12%
Coke	wt% of dry biomass	11.0%	9.5%	10.5%	10.2%	9.8%	9.3%	8.9%	8.4%	8.0%
Pyrolysis Vapor Quench										
Total Cost Contribution	$/GGE	$0.38	$0.36	$0.31	$0.27	$0.25	$0.23	$0.22	$0.20	$0.18
Capital Cost Contribution	$/GGE	$0.23	$0.21	$0.19	$0.16	$0.15	$0.14	$0.13	$0.12	$0.11
Operating Cost Contribution	$/GGE	$0.15	$0.14	$0.12	$0.11	$0.10	$0.09	$0.09	$0.08	$0.07
Hydroprocessing and Separation										
Total Cost Contribution	$/GGE	$0.35	$0.33	$0.33	$0.30	$0.29	$0.28	$0.27	$0.25	$0.24
Capital Cost Contribution	$/GGE	$0.20	$0.18	$0.19	$0.17	$0.16	$0.16	$0.15	$0.14	$0.14
Operating Cost Contribution	$/GGE	$0.15	$0.14	$0.14	$0.13	$0.13	$0.12	$0.12	$0.11	$0.11

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 SOT**	**2016 Projection**	**2017 Projection**	**2018 Projection***	**2019 Projection***	**2020 Projection***	**2021 Projection***	**2022 Projection (Design Case)**
Carbon Efficiency of Organic Liquid Feed to Fuels ‡	%	88%	90%	89%	90%	91%	92%	93%	93%	94%
Hydrotreating Pressure	Psia	2,000	2,000	2,000	2,000	1900	1800	1700	1600	1,500
Oxygen Content in Cumulative Fuel Product	wt%	0.8%	0.8%	0.8%	0.7%	0.6%	0.6%	0.5%	0.4%	0.4%
Hydrogen Production										
Total Cost Contribution	$/GGE	$0.67	$0.61	$0.62	$0.57	$0.55	$0.53	$0.50	$0.48	$0.45
Capital Cost Contribution	$/GGE	$0.44	$0.41	$0.41	$0.38	$0.36	$0.35	$0.33	$0.31	$0.30
Operating Cost Contribution	$/GGE	$0.23	$0.21	$0.20	$0.19	$0.19	$0.18	$0.17	$0.16	$0.15
Additional Natural Gas**	% of biomass LHV	0.3%	0.1%	0.1%	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%
Balance of Plant										
Total Cost Contribution	$/GGE	$0.16	$0.17	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12
Capital Cost Contribution	$/GGE	$0.91	$0.80	$0.70	$0.58	$0.53	$0.48	$0.42	$0.37	$0.31
Operating Cost Contribution	$/GGE	($0.76)	($0.64)	($0.58)	($0.46)	($0.41)	($0.36)	($0.30)	($0.25)	($0.19)
Electricity Production from Steam Turbine (credit included in operating cost above)	$/GGE**	($1.12)	($0.96)	($0.85)	($0.69)	($0.62)	($0.54)	($0.47)	($0.39)	($0.32)
Sustainability and Process Efficiency Metrics										
Fuel Yield by Weight of Biomass	% w/w of dry biomass	13.7%	15.0%	16.1%	17.9%	19.2%	20.6%	21.9%	23.2%	24.6%
Carbon Efficiency to Fuels	% C in feedstock	23.5%	25.9%	27.6%	30.6%	32.8%	34.9%	37.1%	39.3%	41.5%
Overall Carbon Efficiency to Fuels	% C in feedstock + NG	23.5%	25.9%	27.6%	30.6%	32.8%	34.9%	37.1%	39.3%	41.5%

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 SOT**	**2016 Projection**	**2017 Projection**	**2018 Projection***	**2019 Projection***	**2020 Projection***	**2021 Projection***	**2022 Projection (Design Case)**
Overall Energy Efficiency to Fuels	% LHV of feedstock + NG	30.4%	33.4%	36.0%	40.2%	43.5%	46.8%	50.0%	53.3%	56.6%
Electricity Production	kWh/ GGE	21.0	18.0	16.0	13.1	11.7	10.3	8.9	7.6	6.2
Electricity Consumption (entire process)	kWh/ GGE	12.7	11.0	10.4	9.1	8.4	7.8	7.1	6.4	5.7
Water Consumption	gal H_2O/ GGE	1.4	1.4	1.2	1.1	1.0	0.9	0.8	0.8	0.7
Fossil GHG Emissions (with electricity credit)	g CO_2e/MJ fuel	(41.5)	(35.5)	(27.9)	(19.3)	(15.7)	(12.0)	(8.4)	(4.8)	(1.2)
Fossil Energy Consumption (with electricity credit)	MJ fossil energy/MJ fuel	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	0.0
TEA Reference File		PyVPU-v218g ES - 2014 (2014$)-v03.xlsm	PyVPU-v218g ES - 2015 SOT (2014$)-r35.xlsm	PyVPU-v218g ES - 2016 (2014$)-v03.xlsm	PyVPU-v218g ES - 2017 (2014$)-v03.xlsm	Interpolated Values from 2017 and 2022 Target Cases.				PyVPU-v218g ES - 2022 (2014$)-v03.xlsm

▲Conceptual design result with margin of error +/- 30%

† SOT: State of Technology
* Note: The projections for 2018–2021 are based solely on an interpolated linear reduction in costs between 2017 and 2022.

* Gallon Gasoline Equivalent (GGE) on a Lower Heating Value (LHV) basis

** A negligible stream was maintained in the model to allow natural gas use if necessary.
‡ Interpolated value is based on Figure 8 in http://www.nrel.gov/docs/fy15osti/62455.pdf.
● Experiments for the FY 2015 SOT were completed using pulpwood with only minor variations from the woody feedstock specifications in the SOT model.

NG = natural gas; Psia = pounds per square inch absolute.

Table A-8: Processing Area Cost Contribution (2014$) and Key Technical Parameters for Indirect Gasification and Methanol Intermediate Conversion to High-Octane Fuels[9]

(Process Concept: Gasification, Syngas Clean-Up, Methanol/Dimethyl Ether [DME] Synthesis & Conversion to Hydrocarbons)

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT †	2015 SOT	2016 Projection§	2017 Projection	2018 Projection*	2019 Projection*	2020 Projection*	2021 Projection*	2022 Projection (Design Case)
		Pulp-wood	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**	**Woody Blend**
C_5+ Minimum Fuel Selling Price (per Actual Product Volume) ▲	$/gallon	$5.57	$5.11	$3.95	$3.63	$3.57	$3.50	$3.44	$3.37	$3.57
Mixed C_4 Minimum Fuel Selling Price (per Actual Product Volume) ▲	$/gallon	$3.69	$3.70	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Minimum Fuel Selling Price (per Gallon of Gasoline Equivalent) ▲	$/GGE	$5.60	$5.20	$4.13	$3.80	$3.73	$3.67	$3.60	$3.54	$3.47
Conversion Contribution (per Gallon of Gasoline Equivalent) ▲	$/GGE	$3.49	$3.49	$2.57	$2.41	$2.34	$2.28	$2.22	$2.16	$2.10
Total Capital Investment per Annual Gallon	$	$14.34	$14.42	$8.83	$8.36	$8.33	$8.30	$8.28	$8.25	$8.23
Plant Capacity (Dry Feedstock Basis)	tonnes/ dry	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
High-Octane Gasoline Blendstock (C_5+) Yield	gallons/ dry ton	39.7	39.9	61.8	64.2	64.4	64.5	64.6	64.8	64.9
Mixed C_4 Co-Product Yield	gallons/ dry ton	17.9	17.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feedstock										
Total Cost Contribution	$/GGE	$2.10	$1.88	$1.56	$1.39	$1.39	$1.38	$1.38	$1.38	$1.37
Capital Cost Contribution	$/GGE	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Operating Cost Contribution	$/GGE	$2.10	$1.88	$1.56	$1.39	$1.38	$1.38	$1.38	$1.38	$1.37

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[9] E. Tan, M. Talmadge, A. Dutta, J. Hensley, J. Schaidle, M. Biddy, D. Humbird, L. Snowden-Swan, J. Ross, D. Sexton, J. Lukas (2015), *Process Design for the Conversion of Lignocellulosic Biomass to High Octane Gasoline - Thermochemical Research Pathway With Indirect Gasification and Methanol Intermediate*, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, NREL/TP-5100-62402, PNNL-23822, http://www.nrel.gov/docs/fy15osti/62402.pdf.

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT †**	**2015 SOT**	**2016 Projection**	**2017 Projection**	**2018 Projection***	**2019 Projection***	**2020 Projection***	**2021 Projection***	**2022 Projection (Design Case)**
Feedstock Cost	\$/dry U.S. ton	\$107.09	\$97.34	\$91.54	\$84.45	\$84.45	\$84.45	\$84.45	\$84.45	\$84.45
Feedstock Moisture at Plant Gate	wt% H_2O	10%	10%	10%	10%	10%	10%	10%	10%	10%
In-Plant Handling and Drying / Preheating	\$/dry U.S. ton	\$0.55	\$0.54	\$0.73	\$0.73	\$0.73	\$0.72	\$0.72	\$0.72	\$0.72
Cost Contribution	\$/gallon	\$0.01	\$0.01	\$0.01	\$0.01	\$0.01	\$0.01	\$0.01	\$0.01	\$0.01
Feed Moisture Content to Gasifier	wt% H_2O	10%	10%	10%	10%	10%	10%	10%	10%	10%
Energy Content (LHV, Dry Basis)	BTU/lb	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000
Gasification										
Total Cost Contribution	\$/GGE	\$0.71	\$0.68	\$0.57	\$0.54	\$0.53	\$0.53	\$0.52	\$0.51	\$0.50
Capital Cost Contribution	\$/GGE	\$0.48	\$0.45	\$0.36	\$0.35	\$0.34	\$0.33	\$0.32	\$0.31	\$0.31
Operating Cost Contribution	\$/GGE	\$0.23	\$0.23	\$0.20	\$0.20	\$0.20	\$0.20	\$0.19	\$0.19	\$0.19
Raw Dry Syngas Yield	lb/lb dry feed	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Raw Syngas Methane (Dry Basis)	mole %	15.4%	15.4%	15.4%	15.4%	15.4%	15.4%	15.4%	15.4%	15.4%
Gasifier Efficiency (LHV)	% LHV	72.5%	72.5%	72.5%	72.5%	72.5%	72.5%	72.5%	72.5%	72.5%
Synthesis Gas Clean-Up (Reforming and Quench)										
Total Cost Contribution	\$/GGE	\$1.08	\$1.03	\$0.84	\$0.84	\$0.84	\$0.84	\$0.84	\$0.84	\$0.84
Capital Cost Contribution	\$/GGE	\$0.59	\$0.55	\$0.44	\$0.42	\$0.42	\$0.42	\$0.42	\$0.43	\$0.43
Operating Cost Contribution	\$/GGE	\$0.48	\$0.48	\$0.41	\$0.42	\$0.42	\$0.42	\$0.41	\$0.41	\$0.41
Tar Reformer (TR) Exit CH_4 (Dry Basis)	mole %	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%
TR CH_4 Conversion	%	80.0%	80.0%	80.0%	80.0%	80.0%	80.0%	80.0%	80.0%	80.0%
TR Benzene Conversion	%	99.0%	99.0%	99.0%	99.0%	99.0%	99.0%	99.0%	99.0%	99.0%
TR Tars Conversion	%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%
Catalyst Replacement	% of inventory /day	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%
Acid Gas Removal, Methanol Synthesis, and Methanol Conditioning										
Total Cost Contribution	\$/GGE	\$0.60	\$0.56	\$0.44	\$0.43	\$0.42	\$0.41	\$0.41	\$0.40	\$0.39
Capital Cost Contribution	\$/GGE	\$0.41	\$0.38	\$0.29	\$0.28	\$0.27	\$0.27	\$0.26	\$0.25	\$0.25
Operating Cost Contribution	\$/GGE	\$0.19	\$0.18	\$0.15	\$0.15	\$0.15	\$0.15	\$0.15	\$0.15	\$0.14
Methanol Synthesis Reactor Pressure	psia	730	730	730	730	730	730	730	730	730

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT †**	**2015 SOT**	**2016 Projection**	**2017 Projection**	**2018 Projection***	**2019 Projection***	**2020 Projection***	**2021 Projection***	**2022 Projection (Design Case)**
Methanol Productivity	kg / kg-cat / hour	3.4	3.7	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Methanol Intermediate Yield	gallons/ dry ton	156	156	145	145	144	144	143	143	142
Hydrocarbon Synthesis										
Total Cost Contribution	$/GGE	$1.02	$1.01	$0.68	$0.57	$0.53	$0.50	$0.46	$0.42	$0.38
Capital Cost Contribution	$/GGE	$0.66	$0.64	$0.46	$0.41	$0.37	$0.34	$0.30	$0.27	$0.24
Operating Cost Contribution	$/GGE	$0.37	$0.36	$0.22	$0.17	$0.16	$0.16	$0.15	$0.15	$0.14
Methanol to DME Reactor Pressure	Psia	145	145	145	145	145	145	145	145	145
Hydrocarbon Synthesis Reactor Pressure	Psia	129	129	129	129	129	129	129	129	129
Hydrocarbon Synthesis Catalyst	-	Commercially available beta-zeolite		NREL modified beta-zeolite with copper (Cu) and gallium (Ga) as active metals for activity and performance improvement						
Hydrogen Addition to Hydrocarbon Synthesis	-	No H_2 Addition	Supplemental H_2 added to hydrocarbon synthesis reactor inlet to improve selectivity to branched paraffins relative to aromatics							
Utilization of C_4 Reactor Products	-	Co-Product	Co-Product	Recycle	Recycle	Recycle	Recycle	Recycle	Recycle	Recycle
Single-Pass DME Conversion	%	15%	15%	20%	30%	32%	34%	36%	38%	40%
Overall DME Conversion	%	81%	85%	84%	88%	89%	90%	91%	92%	93%
Hydrocarbon Synthesis Catalyst Productivity	kg / kg-cat / hour	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
Carbon Selectivity to C_5+ Product	% C in reactor feed	46.2%	48.3%	86.1%	89.9%	90.5%	91.2%	91.8%	92.4%	93.1%
Carbon Selectivity to Total Aromatics (Including Hexamethylbenzene)	% C in reactor feed	25.0%	20.0%	8.0%	4.0%	3.3%	2.6%	1.9%	1.2%	0.5%
Carbon Selectivity to Coke and Pre-Cursors (Hexamethylbenzene Proxy)	% C in reactor feed	10.0%	9.3%	4.0%	2.0%	1.7%	1.4%	1.1%	0.8%	0.5%
Dimerization of C_4-C_8 Olefins to Jet / Kerosene-Range Hydrocarbons	-	Not considered	Production of jet / kerosene range hydrocarbons will be considered as sensitivity case or modified design case starting in FY 2015							
Hydrocarbon Product Separation										
Total Cost Contribution	$/GGE	$0.05	$0.05	$0.05	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04
Capital Cost Contribution	$/GGE	$0.04	$0.04	$0.04	$0.03	$0.03	$0.03	$0.03	$0.03	$0.03
Operating Cost Contribution	$/GGE	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT †**	**2015 SOT**	**2016 Projection**	**2017 Projection**	**2018 Projection***	**2019 Projection***	**2020 Projection***	**2021 Projection***	**2022 Projection (Design Case)**
Balance of Plant										
Total Cost Contribution	$/GGE	$0.04	($0.01)	($0.01)	($0.01)	($0.02)	($0.03)	($0.04)	($0.05)	($0.06)
Capital Cost Contribution	$/GGE	$0.48	$0.44	$0.35	$0.33	$0.32	$0.31	$0.30	$0.29	$0.27
Operating Cost Contribution	$/GGE	($0.44)	($0.45)	($0.35)	($0.33)	($0.33)	($0.33)	($0.33)	($0.33)	($0.33)
Sustainability and Process Efficiency Metrics										
Carbon Efficiency to C_5+ Product	% C in feedstock	20.7%	20.8%	29.9%	31.0%	31.0%	31.0%	31.1%	31.1%	31.2%
Carbon Efficiency to Mixed C_4 Co-Product	% C in feedstock	7.5%	7.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Overall Carbon Efficiency to Hydrocarbon Products	% C in feedstock	28.2%	28.3%	29.9%	31.0%	31.0%	31.0%	31.1%	31.1%	31.2%
Overall Energy Efficiency to Hydrocarbon Products	% LHV of feedstock	37.3%	37.4%	43.1%	44.6%	44.7%	44.8%	44.9%	45.0%	45.0%
Electricity Production	kWh/gallon C_5+	11.4	8.8	6.7	6.4	6.3	6.3	6.3	6.2	6.2
Electricity Consumption	kWh/gallon C_5+	11.4	8.8	6.7	6.4	6.3	6.3	6.3	6.2	6.2
Water Consumption	gal H_2O/gal C_5+	12.4	7.4	5.8	5.2	4.5	3.8	3.1	2.4	1.7
Fossil GHG Emissions	g CO_2e / MJ Fuel	1.64	1.65	0.81	0.96	0.88	0.81	0.74	0.67	0.60
Fossil Energy Consumption	MJ fossil energy/MJ fuel	0.023	0.022	0.011	0.013	0.011	0.010	0.009	0.007	0.006
TEA Reference File		2014 SOT Rev4a.xlsm	2015 SOT Rev5 Comm-HBEA.xlsm	2016 Target Rev4a.xlsm	2017 Target Rev4a.xlsm	Interpolated values based on 2017 and 2022 target cases.	H09G1e Rev4-Final1a Final5a.xlsm			

▲ Conceptual design result with margin of error +/- 30%

† SOT: State of Technology

§ Note: The 2016 projection is based on technology progression via advances in new catalytic tools from previously reported, commercially available materials utilized prior to 2016. These novel materials have shown improved performance over the current catalysts and are reflected in future projections.

● NREL will complete FY2015 SOT scenario for production of jet / kerosene range hydrocarbons in December 2015 and incorporate results into subsequent MYPP updates.

○ FY2015 SOT values for fossil GHG emissions and energy consumption are negative due to electricity export from higher hexamethylbenzene (HMB) production relative to target. Higher overall selectivity to gasoline-range products relative to target

LHV = lower heating value.

Table A-9: Unit Operation Cost Contribution Estimates (2014$) and Technical Projections for Low-Temperature Deconstruction and Fermentation Process Concept[10] [11]

(Process Concept: Dilute Acid Pretreatment, Enzymatic Hydrolysis, Biological Upgrading, Succinic Acid/Adipic Acid Co-Product)

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT†	2015 SOT†	2016 Projection	2017 Projection	2022 Projection
Process Concept: Hydrocarbon Fuel Production via Biological Upgrading of Sugars	**-**	**Stover**	**Stover**	**Blend**	**Blend**	**Blend**
Projected Minimum Fuel Selling Price	$/GGE	$17.16	$12.11	$9.47	$5.81	$3.14
Conversion Contribution[1]	$/GGE	$13.36	$9.32	$7.28	$4.07	$1.73
Plant Capacity (Dry Feedstock Basis)	metric tons/day	2,000	2,000	2,000	2,000	2,000
Total Gasoline Equivalent Yield	GGE/dry U.S. ton	15.6	17.4	19.1	20.7	44.0
Succinic Acid Yield	lb/dry ton biomass	256	323	336	351	0
Feedstock						
Total Cost Contribution	$/GGE	$3.80	$2.79	$2.19	$1.74	$1.41
Capital Cost Contribution	$/GGE	NA	NA	NA	NA	NA
Operating Cost Contribution	$/GGE	$3.80	$2.79	$2.19	$1.74	$1.41
Feedstock Cost[2]	$/dry U.S. ton	$137	$120	$100	$84	$84
Feedstock Moisture at Plant Gate	wt% H_2O	20%	20%	20%	20%	20%
Pretreatment						
Total Cost Contribution	$/GGE	$2.33	$2.06	$1.87	$1.73	$1.05
Capital Cost Contribution	$/GGE	$1.22	$1.10	$1.00	$0.92	$0.55
Operating Cost Contribution	$/GGE	$1.11	$0.96	$0.87	$0.81	$0.49
Solids Loading	wt%	30%	30%	30%	30%	30%
Xylan to Xylose (including conversion in C5 train)	%	73%	76%	78%	78%	>73%

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[10] Davis et al. (2013), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons*, National Renewable Energy Laboratory, NREL/TP-510060223, http://www.nrel.gov/docs/fy14osti/60223.pdf.

[11] Davis, R et al., Update to NREL/TP-510060223, *Manuscript in Preparation*.

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 SOT†**	**2016 Projection**	**2017 Projection**	**2022 Projection**
Hydrolysate Solid-Liquid Separation	-	Yes	Yes	Yes	Yes	No
Xylose Sugar Loss (into C6 stream after acid PT separation)	%	5.0%	4.0%	2.5%	1.0%	NA
Enzymatic Hydrolysis, Conditioning, Bioconversion						
Total Cost Contribution	$/GGE	$5.14	$4.43	$3.96	$3.40	$0.95
Capital Cost Contribution	$/GGE	$3.34	$2.92	$2.62	$2.26	$0.46
Operating Cost Contribution	$/GGE	$1.80	$1.51	$1.34	$1.13	$0.49
Total Solids Loading to Hydrolysis	wt%	15%	15%	17.5%	17.5%	20%
Enzymatic Hydrolysis Time	days	3.5	5.0	3.5	3.5	3.5
Hydrolysis Glucan to Glucose	%	77%	86%	85%	90%	90%
Hydrolysis Residual Xylan to Xylose	%	30%	93%	93%	93%	>30%
Glucose Sugar Loss (into solid lignin stream after EH separation)	%	5%	5%	5%	5%	1%
Bioconversion Volumetric Productivity	(g/L/hour)	0.29	0.34	0.35	0.40	1.30
Lipid Content	wt%	57%	60%	65%	70%	NA
Glucose to Product [total glucose utilization] [3]	%	73% [100%]	75% [100%]	78% [100%]	82% [100%]	87% [95%]
Xylose to Product [total xylose utilization] [3]	%	71% [98%]	44% [59%]	77% [98%]	80% [98%]	82% [86%]
C6 Train Bioconversion Metabolic Yield (Process Yield)	g/g sugars	0.24 (0.24)	0.25 (0.24)	0.26 (0.26)	0.27 (0.27)	0.34 (0.28)
Intermediate Product Recovery	%	90%	90%	90%	90%	97%
Carbon Yield to RDB from Biomass	%	8.9%	9.9%	10.9%	11.8%	25.6%
Cellulase Enzyme Production						
Total Cost Contribution	$/GGE	$1.56	$1.21	$0.96	$0.88	$0.41
Capital Cost Contribution	$/GGE	$0.32	$0.25	$0.23	$0.21	$0.10
Operating Cost Contribution	$/GGE	$1.23	$0.96	$0.73	$0.67	$0.31
Enzyme Loading	mg/g cellulose	14	12	10	10	10
Product Recovery + Upgrading						
Total Cost Contribution	$/GGE	$1.77	$1.76	$1.72	$1.58	$0.34
Capital Cost Contribution	$/GGE	$1.03	$0.99	$0.99	$0.92	$0.21
Operating Cost Contribution	$/GGE	$0.74	$0.76	$0.72	$0.67	$0.13
Natural Gas Usage[4]	scf/GGE fuel blendstock	11	10	10	10	18

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 SOT†**	**2016 Projection**	**2017 Projection**	**2022 Projection**
C5 Coproduct Processing Train						
Total Cost Contribution	$/GGE	($1.37)	($3.92)	($4.68)	($6.20)	$0.00
Capital Cost Contribution	$/GGE	$4.32	$4.52	$4.21	$3.50	$0.00
Operating Cost Contribution	$/GGE	($5.70)	($8.44)	($8.89)	($9.69)	$0.00
Bioconversion Volumetric Productivity	g/L/hour	0.3	1.45	1.5	2	NA
C5 Train Bioconversion Metabolic Yield (Process Yield)	g/g sugars	0.63 (0.59)	0.80 (0.62)	0.785 (0.63)	0.795 (0.74)	NA
Carbon Yield to Succinic Acid from Biomass	%	11.6%	14.6%	15.2%	15.9%	NA
Lignin Utilization						
Total Cost Contribution	$/GGE	$0.00	$0.00	$0.00	$0.00	($1.88)
Capital Cost Contribution	$/GGE	$0.00	$0.00	$0.00	$0.00	$0.31
Operating Cost Contribution	$/GGE	$0.00	$0.00	$0.00	$0.00	($2.19)
Balance of Plant						
Total Cost Contribution	$/GGE	$3.93	$3.79	$3.46	$2.68	$0.86
Capital Cost Contribution	$/GGE	$4.58	$4.11	$3.70	$3.10	$1.04
Operating Cost Contribution	$/GGE	($0.65)	($0.32)	($0.24)	($0.42)	($0.18)
Sustainability and Process Efficiency Metrics [5]						
Fuel Yield by Weight of Biomass	% w/w of dry biomass	4.8%	5.4%	5.9%	6.4%	13.6%
Carbon Efficiency to Fuels	% C in feedstock	8.9%	9.9%	10.9%	11.8%	25.6%
Overall Carbon Efficiency to Fuels	% C in feedstock + NG	8.8%	9.8%	10.8%	11.7%	25.6%
Net Electricity Import (Entire Process)	kWh/GGE	14.4	16.5	15.6	6.4	0.29
Water Consumption	gal H_2O/GGE	44	36	31	28	12.3
Fossil GHG Emissions	g CO_2e/MJ fuel	247.7	261.9	244.7	184.7	24.4
Fossil GHG Emissions Credits	g CO_2e/MJ fuel	-326.5	-367.4	-348.2	-336.3	-325
Net Fossil GHG Emissions	g CO_2e/MJ fuel	-78.7	-105.4	-103.6	-151.6	-301
Fossil Energy Consumption	MJ fossil energy/MJ fuel	2.9	3.1	2.9	2.2	0.40
Fossil Energy Consumption Credits	MJ fossil energy/MJ fuel	-4.1	-4.7	-4.4	-4.3	-1.70

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT†	2015 SOT†	2016 Projection	2017 Projection		2022 Projection
Net Fossil Energy Consumption	MJ fossil energy/MJ fuel	-1.2	-1.6	-1.6	-2.1		-1.30

[1] Cost breakdowns to feedstock vs. conversion cost contributions are re-allocated in new target case according to carbon efficiency to renewable diesel blendstock (RDB) fuel vs. succinic acid (feedstock contribution reflects cost allocated to “C6 train” for RDB production).

[2] Feedstock costs shown here based on a 5% “ash equivalent” basis for all years considered, consistent with values provided by Idaho National Laboratory for total feedstock costs and associated ash “dockage” costs for each year.

[3] First number represents sugar conversion to desired product (free fatty acids); values in parentheses indicate total sugar utilization (including biomass organism propagation).

[4] Represents natural gas (NG) demand implicit in H_2 usage delivered from off-site steam methane reformer

[5] Succinic acid life-cycle inventory based on maleic anhydride proxy.

† SOT: State of Technology

scf = standard cubic feet.

Table A-10: Unit Operation Cost Contribution Estimates (2014$) and Technical Projections for Low Temperature Deconstruction and Catalytic Sugar Upgrading Process Concept[12]

(Process Concept: Dilute Acid Pretreatment, Enzymatic Hydrolysis, Chemocatalytic Upgrading to Hydrocarbons)

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 Projection**	**2016 Projection**	**2017 Projection**	**2022 Projection**
Process Concept: Hydrocarbon Fuel Production via Catalytic Upgrading of Sugars		**Stover**	**Stover**	**Blend**	**Blend**	**Blend**
Projected Minimum Fuel Selling Price	$/GGE	$7.59	$6.11	$5.02	$4.20	$3.16
Conversion Contribution	$/GGE	$4.87	$4.07	$3.53	$3.12	$2.08
Plant Capacity (Dry Feedstock Basis)	metric tons/day	2,000	2,000	2,000	2,000	2,000
Total Gasoline Equivalent Yield	GGE/dry U.S. ton	50	59	68	78	76
Feedstock						
Total Cost Contribution	$/GGE	$2.72	$2.03	$1.48	$1.08	$1.08
Capital Cost Contribution	$/GGE	NA	NA	NA	NA	NA
Operating Cost Contribution	$/GGE	$2.72	$2.03	$1.48	$1.08	$1.08
Feedstock Cost[1]	$/dry U.S. ton	$137	$120	$100	$84	$84
Feedstock Moisture at Plant Gate	wt% H_2O	20%	20%	20%	20%	20%
Pretreatment						
Total Cost Contribution	$/GGE	$0.72	$0.61	$0.53	$0.45	$0.49
Capital Cost Contribution	$/GGE	$0.38	$0.33	$0.28	$0.25	$0.23
Operating Cost Contribution	$/GGE	$0.34	$0.28	$0.25	$0.21	$0.26
Solids Loading	wt%	30%	30%	30%	30%	30%
Xylan to Xylose Conversion (overall)[2]	%	81%	84%	87%	90%	90%

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[12] R. Davis, L. Tao, C. Scarlata, and E.C.D. Tan et al. (2015), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons*, National Renewable Energy Laboratory, NREL/TP-5100-62498, http://www.nrel.gov/docs/fy15osti/62498.pdf.

Processing Area Cost Contributions & Key Technical Parameters	**Units**	**2014 SOT†**	**2015 Projection**	**2016 Projection**	**2017 Projection**	**2022 Projection**
Enzymatic Hydrolysis and Conditioning						
Total Cost Contribution	$/GGE	$0.72	$0.60	$0.52	$0.46	$0.41
Capital Cost Contribution	$/GGE	$0.50	$0.41	$0.36	$0.31	$0.27
Operating Cost Contribution	$/GGE	$0.22	$0.19	$0.17	$0.15	$0.14
Solids Loading	wt%	20%	20%	20%	20%	20%
Enzymatic Hydrolysis Time	days	3.5	3.5	3.5	3.5	3.5
Glucan to Glucose Conversion[2]	%	77%	85%	85%	90%	90%
Sugar Loss in S/L Separation	%	5%	4%	2.5%	1%	1%
Microfiltration Soluble Retention Loss	%	10%	10%	10%	10%	10%
Cellulase Enzyme Production						
Total Cost Contribution	$/GGE	$0.46	$0.34	$0.26	$0.22	$0.22
Capital Cost Contribution	$/GGE	$0.10	$0.07	$0.06	$0.06	$0.05
Operating Cost Contribution	$/GGE	$0.36	$0.26	$0.19	$0.17	$0.17
Enzyme Loading	mg/g cellulose	14	12	10	10	10
Conversion and Upgrading						
Total Cost Contribution	$/GGE	$2.18	$1.87	$1.65	$1.50	$1.44
Capital Cost Contribution	$/GGE	$0.54	$0.47	$0.42	$0.37	$0.32
Operating Cost Contribution	$/GGE	$1.64	$1.39	$1.23	$1.13	$1.12
Hydrogen Feed Molar Ratio (H_2 : total APR feed)	-	9.8	9.8	9.8	9.8	9.8
Total Hydrogen Consumption (wt% vs APR feed)	%	4.6%	5.3%	5.9%	6.5%	6.5%
Hydrogenation WHSV	h^{-1}	0.7	0.85	1.0	1.2	1.2
APR WHSV	h^{-1}	0.7	0.8	0.9	1.0	1.0
Condensation WHSV	h^{-1}	0.7	0.85	1.0	1.2	1.2
Hydrogenation catalyst lifetime	years	0.5	0.6	0.8	1.0	1.0
APR catalyst lifetime	years	1.0	1.3	1.6	2.0	2.0
Condensation catalyst lifetime	years	1.0	1.3	1.6	2.0	2.0
Natural Gas Usage[3]	scf/GGE fuel blendstock	102	100	99	97	97
Overall C Yield to Fuels vs APR Feed Components	%	64%	70%	78%	86%	86%
Overall C Yield to Fuels vs Biomass C [vs Total C] [4]	%	29% [25%]	34% [28%]	39% [32%]	45% [36%]	44% [35%]

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT†	2015 Projection	2016 Projection	2017 Projection	2022 Projection
Lignin Utilization						
Total Cost Contribution	$/GGE	$0.00	$0.00	$0.00	$0.00	($0.82)
Capital Cost Contribution	$/GGE	$0.00	$0.00	$0.00	$0.00	$0.15
Operating Cost Contribution	$/GGE	$0.00	$0.00	$0.00	$0.00	($0.97)
Balance of Plant						
Total Cost Contribution	$/GGE	$0.79	$0.67	$0.57	$0.49	$0.34
Capital Cost Contribution	$/GGE	$1.06	$0.87	$0.73	$0.61	$0.46
Operating Cost Contribution	$/GGE	($0.27)	($0.20)	($0.16)	($0.12)	($0.12)
Sustainability and Process Efficiency Metrics						
Fuel Yield by Weight of Biomass	% w/w of dry biomass	16%	18%	21%	24%	24%
Carbon Efficiency to Fuels	% C in feedstock	29%	34%	39%	45%	41%
Overall Carbon Efficiency to Fuels	% C in feedstock + NG	25%	28%	32%	36%	35%
Net Electricity Export (Entire Process)	kWh/GGE	4.7	3.5	2.5	1.5	0.63
Water Consumption	gal H_2O/GGE	12.0	9.4	7.6	5.8	5.31
Fossil GHG Emissions	g CO_2e / MJ fuel	64.8	61.4	58.9	57.3	64.5
Fossil GHG Emissions Credits	g CO_2e / MJ fuel	(25.0)	(18.6)	(13.1)	(8.3)	(134)
Net Fossil GHG Emissions	g CO_2e / MJ fuel	39.8	42.7	45.8	49.1	(69.4)
Fossil Energy Consumption	MJ fossil energy / MJ fuel	1.0	1.0	0.9	0.9	1.0
Fossil Energy Consumption Credits	MJ fossil energy / MJ fuel	(0.3)	(0.2)	(0.1)	(0.1)	-0.7
Net Fossil Energy Consumption	MJ fossil energy / MJ fuel	0.7	0.8	0.8	0.8	0.3

[1] Feedstock costs shown here based on a 5% “ash equivalent” basis for all years considered, consistent with values provided by Idaho National Laboratory for total feedstock costs and associated ash “dockage” costs for each year.

[2] For this pathway, values represent glucan/xylan conversion to both monomeric and oligomeric sugars given flexibility in downstream conversion step.

[3] Values represent natural gas (NG) demand implicit in H_2 usage delivered from off-site steam methane reformer (SMR).

[4] “Total carbon” includes external natural gas carbon implicit in SMR-derived H_2 (0.44 mol C in natural gas/mol H_2 product).

† SOT: State of Technology

Appendix B: Calculation Methodology for Cost Goals

The two primary goals of this appendix are as follows:

1. Summarize the bases for the Bioenergy Technologies Office's performance goal
2. Explain the general methodology used to develop the cost goals and projections and adjust them to different year dollars.

Table B-1 describes the primary documents—including the Multi-Year Program Plan (MYPP)—that cover the evolution of technology design and cost projections for specific conversion concepts. Additional details for the technical performance targets and cost goals can be found in Appendix A.

Table B-1: Primary Source Documents for Office Cost Goals

Document	Design and Cost Information: Bases and Differences
2009 MYPP	• Introduction of first projection of woody feedstock costs. • Thermochemical conversion model included based on first design report for pyrolysis, pyrolysis-oil upgrading and stabilization, and fuel synthesis to gasoline/diesel blendstock. • All costs in 2007 dollars using actual economic indices up to 2007.
2010 MYPP	• Thermochemical conversion models updated based on first detailed design report for pyrolysis to hydrocarbon biofuels.[1]
2011 MYPP	• Thermochemical conversion models, including preliminary technical projections, provide further detail for pyrolysis to hydrocarbon fuels.
2012 MYPP	• The Office's 2017 performance goals are based on the EIA reference case projections for the wholesale price of gasoline, diesel, and jet fuel.[2] • All costs in 2011 dollars using updated cost indices. • Algae cost goals added for the Algae Lipid Upgrading pathway based on 2012 technical report.[3]
2014 MYPP	• Thermochemical conversion cost goals revised based on updated design report for fast pyrolysis and upgrading to hydrocarbon biofuels.[4] • Biochemical conversion interim cost goal based on first detailed design report for biological conversion of sugars to hydrocarbon biofuels.[5] • Feedstocks cost goals were revised to $80/DM ton, including both grower payment and logistics, based on updated cost projections that incorporate the need for higher volumes and the need to address feedstock quality. Grower payments were based on resource assessment analyses, rather than a fixed cost as in 2011.

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[1] S.B. Jones, C. Valkenburg, C.W. Walton, et al. (2009), "Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case," Pacific Northwest National Laboratory, PNNL-18284, http://www.pnl.gov/main/publications/external/technical_reports/pnnl-18284.pdf.

[2] U.S. Department of Energy (2012), *Annual Energy Outlook 2012: Table 131*, Washington: Government Printing Office, http://www.eia.gov/oiaf/aeo/supplement/suptab_131.xlsx.

[3] R. Davis et al. (2013), "Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model," Argonne National Laboratory, ANL/ESD/12-4, http://greet.es.anl.gov/publication-algae-harmonization-2012.

[4] S. Jones et al. (2013), "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway," Pacific Northwest National Laboratory, PNNL-23053, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf.

[5] R. Davis et al. (2013) "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons," National Renewable Energy Laboratory, NREL/TP-5100-60223, http://www.nrel.gov/docs/fy14osti/60223.pdf.

Document	Design and Cost Information: Bases and Differences
	• Algae design reports for the Lipid Extraction and Upgrading[6] and Hydrothermal Liquefaction[7] pathways were added and updated to reflect changes from the harmonized baseline.
2015 MYPP	• Combined Conversion R&D section cost goals for combined supported by additional design cases for *Ex Situ* and *In Situ* Upgrading of Fast Pyrolysis Vapors,[8] Low-Temperature Deconstruction and Catalytic Sugar Upgrading,[9] and Hydrocarbons via Indirect Liquefaction[10] pathways. • Fast Pyrolysis and Low-Temperature Deconstruction and Fermentation pathways updated. • 2014 woody feedstock costs updated from projection to actual modeled cost. • Herbaceous feedstock costs added to support biochemical conversion cost tables.
2016 MYPP	• All costs in 2014 dollars using updated cost indices. • Algae production design report added.[11]

Office's Performance Goal: Calculation Methodology

The Office's performance goals are based on commercial viability, specifically the Energy Information Administration's (EIA's) oil price outlook for future motor gasoline, diesel, and jet wholesale prices. The underlying assumptions include the following:

- Refinery gate production cost of gasoline can be compared to the biorefinery production cost of biomass-based renewable gasoline and ethanol (adjusted for Btu content). Similarly, refinery gate production cost of diesel and jet fuel can be compared to the biorefinery production cost of biomass-based renewable diesel and jet fuel.
- Downstream distribution costs are excluded as are subsidies and tax incentives.

The historical crude oil prices and EIA projections are presented in Figure B-1.

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[6] R. Davis, C. Kinchin, J. Markham, E. Tan, et al. (2014), *Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products*, National Renewable Energy Laboratory, NREL/TP-5100-62368, http://www.nrel.gov/docs/fy15osti/62368.pdf.

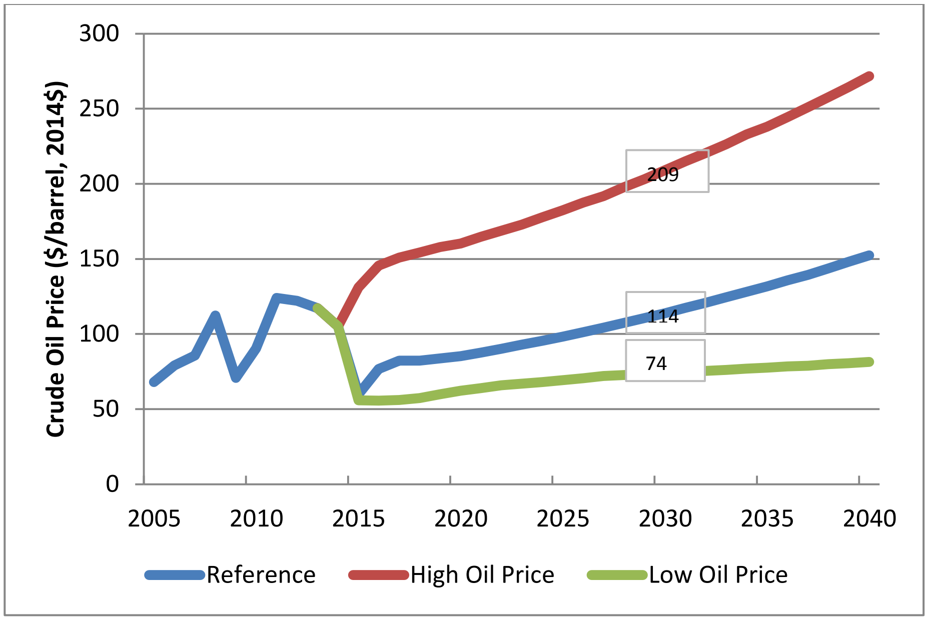
[7] S. Jones, et al. (2014), "Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading," Pacific Northwest National Laboratory, PNNL-23227, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf.

[8] A. Dutta, A. Sahir, E. Tan, D. Humbird, L. Snowden-Swan, P. Meyer, J. Ross, D. Sexton, R. Yap, J. Lukas (2015), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels - Thermochemical Research Pathways With In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors*, National Renewable Energy Laboratory, NREL/TP-5100-62455, Pacific Northwest National Laboratory, PNNL-23823.

[9] R. Davis et al. *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons*," National Renewable Energy Laboratory, NREL/TP-5100-62498, http://www.nrel.gov/docs/fy15osti/62498.pdf.

[10] E. Tan, M. Talmadge, A. Dutta, J. Hensley, J. Schaidle, M. Biddy, D. Humbird, L. Snowden-Swan, J. Ross, D. Sexton, and J. Lukas (2015), *Process Design for the Conversion of Lignocellulosic Biomass to High Octane Gasoline - Thermochemical Research Pathway With Indirect Gasification and Methanol Intermediate*, National Renewable Energy Laboratory, NREL/TP-5100-62402, Pacific Northwest National Laboratory, PNNL-23822, http://www.nrel.gov/docs/fy15osti/62402.pdf.

[11] R. Davis et al. (2015), *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, National Renewable Energy Laboratory, NREL/TP-5100-64772, http://www.nrel.gov/docs/fy16osti/64772.pdf.



Source: History: U.S. Energy Information Administration, "Petroleum & Other Liquids, Europe Bent Spot Price FOB," http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=D.
Projections: AEO2015 National Energy Modeling System, runs REF2015.D021915A, LOWPRICE.D021915A, and HIGHPRICE. D021915A.

Figure B-1: EIA projections for crude oil prices[12]

The crude oil, gasoline, diesel, and jet prices for EIA's reference and high oil cases are summarized in Table B-2.

Table B-2: EIA Oil Price Forecasts[14]

	Wholesale Prices in 2014$[15]	2017	2020	2022	2030	2035	2040
Reference Case							
	Crude oil ($/barrel)	82	85	90	114	132	152
	Diesel ($/gallon)	2.26	2.39	2.54	3.14	3.61	4.15
	Jet ($/gallon)	2.16	2.26	2.38	3.02	3.49	4.04
	Gasoline ($/gallon)	2.30	2.35	2.44	2.87	3.24	3.65
High Oil Price Case							
	Crude oil ($/barrel)	151	160	169	209	238	272
	Diesel ($/gallon)	4.00	4.32	4.55	5.66	6.39	7.24
	Jet ($/gallon)	3.77	4.12	4.35	5.48	6.2	7.02
	Gasoline ($/gallon)	3.67	3.88	4.06	4.85	5.5	6.24

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[12] U.S. Energy Information Administration (2015), *Annual Energy Outlook 2015 with Projections to 2040*, http://www.eia.gov/forecasts/aeo/section_prices.cfm.

[13] Note: Fuel prices are reported in 2013$ in the *Annual Energy Outlook 2015*. They have been adjusted from 2013$ to 2014$ by using the gross domestic product implicit price deflators (1.110 for 2010; 1.133 for 2011) obtained from the U.S. Department of Commerce, Bureau of Economic Analysis, "National Income and Product Accounts: Table 1.1.9," http://www.bea.gov/iTable/index_nipa.cfm.

[14] U.S. Energy Information Administration (2015), *Annual Energy Outlook 2015 with Projections to 2040*, http://www.eia.gov/forecasts/aeo/section_prices.cfm.

[15] Note: Fuel prices are reported in 2013$ in the *Annual Energy Outlook 2015*. They have been adjusted from 2013$ to 2014$ by using the gross domestic product implicit price deflators (1.07 for 2013; 1.09 for 2014) obtained from the U.S. Department of Commerce, Bureau of Economic Analysis, *National Income and Product Accounts: Table 1.1.9*, http://www.bea.gov/iTable/index_nipa.cfm.

Table B-2 shows that the Office performance goal of producing biofuels at around \$3/gallon by 2017 is between the EIA reference case and high oil case projections for diesel, jet, and gasoline prices.

Cost Goals and Projections

Specific cost goals and projections are based on published design cases and state of technology (SOT) reports as defined below.

Design Case: A design case is a techno-economic analysis that outlines a target case and preliminary identification of data gaps and research and development (R&D) needs and is used by the Office as a basis for setting technical targets and cost of production goals.

- Design cases and related goals and targets serve four purposes:
    1. Provide goals and targets against which technology progress is assessed
    2. Provide goals and targets against which processes are validated at increasing scale and integration
    3. Identify optimal R&D areas for prioritizing funding and focus
    4. Provide justification for budget requests.
- A design case is documented in a peer-reviewed design report that represents a particular example of a technology pathway and which encompasses a set of technologies across the entire biomass-to-bioenergy supply chain—from feedstock input through product production (i.e., total feedstock cost: harvest, collection, storage, grower payment, handling, size reduction, moisture control, and total conversion costs).
- Design case technical targets and cost goals must be adequately detailed to fully integrate across all supply chain elements in order to credibly represent a total finished product cost (excluding distribution, taxes, and tax credits).
- A design case is based on (1) best available information at date of the associated design reports and (2) current projections of nth plant capital and operating costs. Depending on the maturity of technology development of a particular technology pathway, design cases can range from high-level conceptual, literature-based process flows with material balances for earlier-stage technologies, to more fully detailed and specified processes with material and energy balances and capital and operating estimates based on actual, experimental data. In more mature forms, design cases are based on design reports that include detailed, peer-reviewed process simulation based on ASPEN, Chemcad, or other process models.
- As technology development progresses, design cases generally become more detailed and are reconfigured, which results in changes to technical targets and cost goals to reflect advances in the R&D knowledge base.
- Over the time span from initial to final design case for a given technology pathway, the range of uncertainty around the associated technical targets and cost estimates is expected to decrease.

State of Technology: An SOT assessment is a periodic (usually annual) assessment of the status of technology development for a biomass to biofuels/products pathway. An SOT assesses progress within and across relevant technology areas based on actual experimental results relative to technical targets and cost goals from design cases and includes technical, economic, and environmental criteria as available.

Table B-3 shows the cost breakdown of the projected cost goals for the fast pyrolysis pathway as a result of updating the dollar year, initially from 2007 to 2011 and now to 2014 and adjusting other key assumptions, as shown in Table B-4. It also shows the changes resulting from updates to the fast pyrolysis design reports.[16] The cost components are based on the first two major elements of the biomass-to-biofuels supply chain (delivered cost of feedstock production and feedstock conversion) and their associated sub-elements.

The costs for feedstock production are based on simulated feedstock supply curves developed and published in the *U.S. Billion-Ton Update*.[17] This analysis projects feedstock production scenarios based on a series of factors that impact feedstock production decisions. The supply curves project the amount of feedstock produced at various market prices for each of several feedstock categories identified in Table A-1. The grower payment in Tables A-4 through A-9 reflects the component of the total feedstock cost paid to the producer. This grower payment corresponds to the estimated average price required to procure total volumes available using U.S. Billion-Ton data (e.g., Figure 2-9).

The projected production cost goals represent mature technology processing costs, which means that the capital and operating costs are assumed to be for an “nth plant,” where several plants have been built and are operating successfully, no longer requiring increased costs for risk financing, longer startups, under-performance, and other costs associated with pioneer plants.

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[16] Jones et al. (2013), *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Fast Pyrolysis and Hydrotreating Bio-Oil Pathway*, Pacific Northwest National Laboratory, PNNL-23053, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf.

[17] U.S. Department of Energy (2011), *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224, Oak Ridge National Laboratory, Oak Ridge, TN, https://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf.

Table B-3: Change Over Time in 2017 Production Cost Targets for Wood/Pyrolysis to Hydrocarbon Fuel

Supply Chain Areas	Units	2009 Wood/ Pyrolysis to Hydrocarbon Fuel Design Report	2012 MYPP 2017 Goals/Targets	2014 MYPP 2017 Goals/Targets	2016 MYPP
Year $	Year	2007	2011	2011	2014
Feedstock Production					
Grower Payment	$/DT	$22.60	$26.25	$21.90	$23.12
Feedstock Logistics					
Harvest and Collection	$/DT	$18.75	$19.53	$10.47	$11.05
Landing Preprocessing	$/DT	$11.42	$11.73	$10.24	$10.81
Transportation and Handling	$/DT	$8.95	$6.37	$7.52	$7.94
Plant Receiving and In-Feed Preprocessing	$/DT	$17.65	$16.88	$29.87	$31.53
Logistics Subtotal	**$/DT**	**$56.77**	**$54.50**	**$58.10**	**$61.33**
Feedstock Total	**$/DT**	**$79.37**	**$80.75**	**$80.00**	**$84.45**
Fuel Yield	(gal gasoline + diesel)/DT	106	106	84 (87 DT/GGE)	87 GGE/DT
		$/gal total fuel	**$/gal total fuel**	**GGE**	**GGE**
Feedstock Production					
Grower Payment	-	$0.21	$0.25	$0.25	$0.26
Feedstock Logistics					
Harvest and Collection	-	$0.18	$0.18	$0.12	$0.13
Landing Preprocessing	-	$0.11	$0.11	$0.12	$0.13
Transportation and Handling	-	$0.08	$0.06	$0.09	$0.10
Plant Receiving and In-Feed Preprocessing	-	$0.17	$0.16	$0.34	$0.36
Logistics Subtotal	-	$0.54	$0.51	$0.67	$0.70
Feedstock Total	**-**	**$0.75**	**$0.76**	**$0.92**	**$0.97/GGE**
Biomass Conversion					
Fast Pyrolysis*	-	$0.34	$0.39	$0.76	$0.78
Upgrading to Stable Oil	-	$0.47	$0.55	$0.95	$0.96
Fuel Finishing to Gasoline and Diesel	-	$0.11	$0.13	$0.14	$0.14
Balance of Plant	-	$0.65	$0.75	$0.63	$0.64
Conversion Total	**-**	**$1.57**	**$1.83**	**$2.47**	**$2.52**
Fuel Production Total	-	***$2.32***	***$2.83***	***$3.39***	***$3.50***

* Fast pyrolysis costs in 2009 Design Report and 2012 MYPP cost targets include feedstock drying and sizing. 2014 MYPP and 2016 MYPP cost targets assume feedstock costs to the reactor throat.

Table B-4 outlines changes in the analysis assumptions for the fast pyrolysis pathway, as well as other conversion design reports.

Table B-4: 2012 Changes to Conversion Cost Assumptions

	Prior Values	2012 Updated Values
% Equity / % Debt Financing	100%	40% / 60%
Loan Terms (% Rate, Term)	N/A	8%, 10 years
Discount Factor	10%	10%
Year-Dollars	2007 dollars	2011 dollars
Depreciation Method, Time	MACRS 7 years general plant 20 years steam/boiler	MACRS 7 years general plant 20 years steam/boiler (if exporting electricity)
Cash Flow / Plant Life	20 years	30 years
Income Tax	39%	35%
Online Time	90%	90%
Indirect Costs (Contingency, Fees, etc.)	51% of total installed costs	60% of total direct costs*
Lang Factor	3.7	4.7 (fast pyrolysis case)

* Total direct costs include installed costs plus other direct costs (buildings, additional piping, and site development).

General Cost Estimation Methodology

The Office uses consistent, rigorous engineering approaches for developing detailed process designs, simulation models, and cost estimates, which in turn are used to estimate the minimum selling price for a particular biofuel using a standard discounted cash-flow rate of return calculation. The feedstock logistics element uses economic approaches to costing developed by the American Society of Agricultural and Biological Engineers. Details of the approaches and results of the technical and financial analyses are thoroughly documented in the Office's conceptual design reports[18] and are not included here. Instead, a high-level general description of how costs are developed and escalated to different year dollars is provided below.

Cost estimate development is slightly different between the feedstock logistics and biomass conversion elements, but generally both elements include capital costs, costs for chemicals and other material, and labor costs. The indices for plant capital chemicals and materials have increased significantly since 2003, while the labor index has shown a consistent and steady rise of about 2.5% per year.

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[18] S.B. Jones, C. Valkenburg, and C.W. Walton et al. (2009), *Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case*, Pacific Northwest National Laboratory, PNNL-1828, http://www.pnl.gov/main/publications/external/technical_reports/pnnl-18284.pdf.

The total project investment (based on total equipment cost), as well as variable and fixed operating costs, are developed first using the best available cost information. Cost information typically comes from a range of years, requiring all cost components to be adjusted to a common year. For the case shown in Appendix B, each cost component was adjusted based on the ratio of the 2011 index to the actual index for the particular cost component. The delivered feedstock cost was treated as an operating cost for the biomass conversion facility. With these costs, a discounted cash-flow analysis of the conversion facility was carried out to determine the selling price of fuel when the net present value of the project is zero.

Design reports added in the 2015 MYPP update have utilized updated published index values, which are summarized in each respective design report. This minor inconsistency across design cases will be resolved in future MYPP updates.

Total Project Investment Estimates and Cost Escalation

The Office design reports include detailed equipment lists with sizes and costs, as well as details on how the purchase costs of all equipment were determined. For the feedstock logistics element, some of the equipment, such as harvesters and trucks, do not require additional installation cost; however, other logistics equipment and the majority of the conversion facility equipment will be installed.

For the types of conceptual designs the Office carries out, a “factored” approach is used. Once the installed equipment cost has been determined from the purchased cost and the installation factor, it can be indexed to the project year being considered. The purchase cost of each piece of equipment has a year associated with it. The purchased cost year will be indexed to the year of interest using the Chemical Engineering Plant Cost Index.

Figure B-2 and Table B-5 show the historical values of the index. Notice that the index was relatively flat between 2000 and 2002 with less than a 0.4% increase, while there was a jump of nearly 18% between 2002 and 2005 and an additional increase of nearly 23% between 2005 and 2008. Changes in the plant cost indices can drive dramatic increases in equipment costs, which directly impact the total project capital investment.

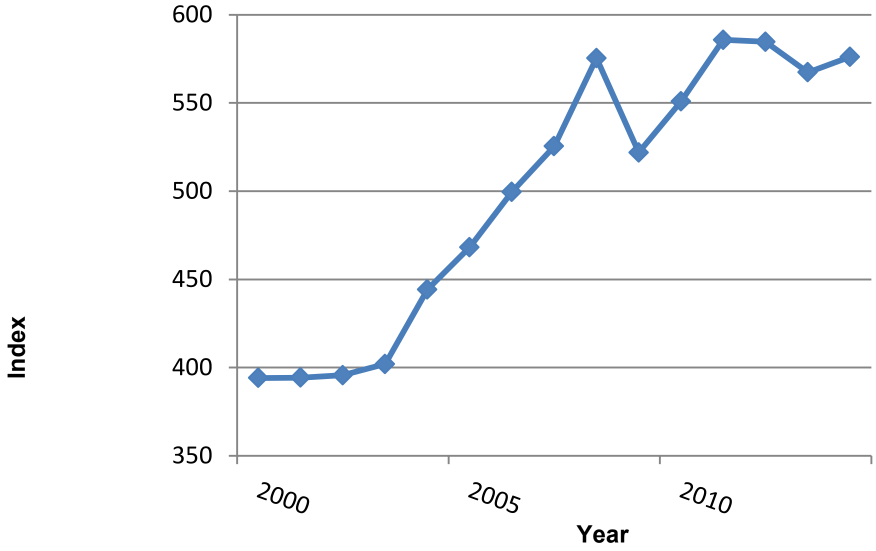

Figure B-2: Chemical Engineering Plant Cost Index (see Table B-5 for values)

Table B-5: Annual Values for the Plant Cost Index

Source	Year	Chemical Engineering Annual Index
(1)	2000	394.1
(2)	2001	394.3
(2)	2002	395.6
(3)	2003	402.0
(3)	2004	444.2
(3)	2005	468.2
(4)	2006	499.6
(4)	2007	525.4
(4)	2008	575.4
(4)	2009	521.9
(4)	2010	550.8
(4)	2011	585.7
(4)	2012	584.6
(4)	2013	567.3
(4)	2014	576.1

Sources (http://www.che.com/ei):

(1) *Chemical Engineering Magazine*, April 2002

(2) *Chemical Engineering Magazine*, December 2003

(3) *Chemical Engineering Magazine*, May 2005

(4) *Chemical Engineering Magazine*, July 2015

Any extrapolation of this data is extremely difficult. Trends prior to 2003 were nearly linear, followed by significant increases until an economic downturn in 2009. The index increased from 2009 until 2011 when it regained 2008 levels and, since then, the trend has been fairly flat.

For equipment cost items in which actual cost records do not exist, a representative cost index is used. For example, the U.S. Department of Agriculture (USDA) publishes Prices Paid by Farmers indexes that are updated monthly. These indexes represent the average costs of inputs purchased by farmers and ranchers to produce agricultural commodities and a relative measure of historical costs. For machinery list prices, the Machinery Index was used. The Repairs Index was used for machinery repair and maintenance costs. These USDA indices were used for all machinery used in the feedstock supply system analysis, including harvest and collection machinery (combines, balers, tractors, etc.), loaders and transportation-related vehicles, grinders, and storage-related equipment and structures.

Operating Cost Estimates and Cost Escalation

For the different design cases, variable operating costs—which include fuel inputs, raw materials, waste handling charges, and byproduct credits—are incurred when the process is operating and are a function of the process throughput rate. All raw material quantities used and wastes produced are determined as part of the detailed material and energy balances calculated for all the process steps. As with capital equipment, the costs for chemicals and materials are associated with a particular year. The U.S. Producer Price Index from SRI Consulting was used as the index for all chemicals and materials and can be seen in Figure B-3 and Table B-6.

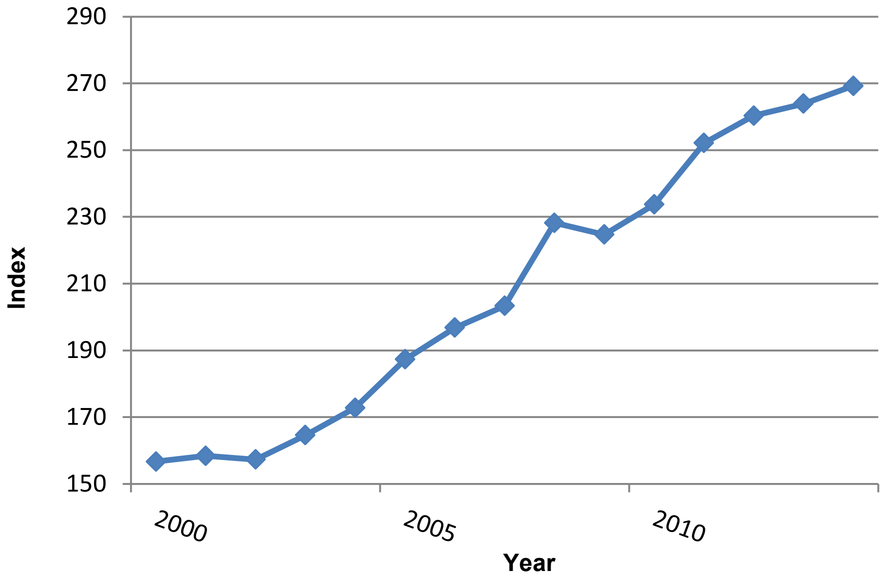

Figure B-3: U.S. Producer Price Index for chemicals and allied products (see Table B-6 for values)

Table B-6: Annual Values for U.S. Producer Price Index—Total, Chemicals and Allied Products

Year	U.S. Producer Price Index
2000	156.7
2001	158.4
2002	157.3
2003	164.6
2004	172.8
2005	187.3
2006	196.8
2007	203.3
2008	228.2
2009	224.7
2010	233.7
2011	252.1
2012	260.3
2013	263.9
2014	269.2

Source: Handbook, Economic Environment of the Chemical Industry 2011, http://chemical.ihs.com/CEH/Private/EECI/EECI.pdf.

Some types of labor—especially related to feedstock production and logistics—are variable costs, while labor associated with the conversion facility are considered fixed operating costs.

Fixed operating costs are generally incurred fully, whether or not operations are running at full capacity. Various overhead items are considered fixed costs in addition to some types of labor. General overhead is often a factor applied to the total salaries and covers items such as safety, general engineering, general plant maintenance, payroll overhead (including benefits), plant security, janitorial and similar services, phone, light, heat, and plant communications. Annual maintenance materials are generally estimated as a small percentage (e.g., 2%) of the total installed equipment cost. Insurance and taxes are generally estimated as a small percentage (e.g., 1.5%) of the total installed cost. The index to adjust labor costs is taken from the Bureau of Labor Statistics and is shown in Figure B-4 and Table B-7.

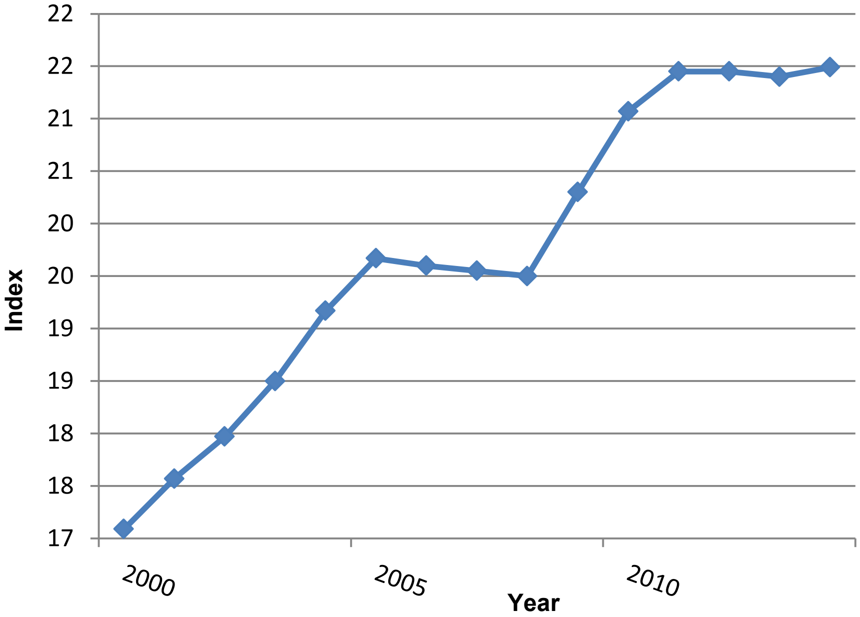

Figure B-4: Actual labor cost index—earnings of chemical production workers (see Table B-7 for values)

Table B-7: Annual Values for Labor Cost Index

Year	Labor Cost Index
2000	17.09
2001	17.57
2002	17.97
2003	18.50
2004	19.17
2005	19.67
2006	19.60
2007	19.55
2008	19.50
2009	20.30
2010	21.07
2011	21.45
2012	21.45
2013	21.40
2014	21.49

Source: Bureau of Labor Statistics, Series ID: CEU3232500008,
Chemicals Average Hourly Earnings of Production Workers, http://data.bls.gov/cgi-bin/srgate.

Discounted Cash-Flow Analysis and the Selling Price of Biofuels

Once the two major cost areas—total project investment and operating costs—have been determined, a discounted cash-flow analysis can be used to determine the minimum selling price per gallon of biofuel produced. The discounted cash-flow analysis program iterates on the selling price of the biofuel until the net present value of the project is zero. This analysis requires that the discount rate, depreciation method, income tax rates, plant life, and construction startup duration be specified. The Office has developed a standard set of assumptions for use in the discounted cash-flow analysis.

Appendix C: 2012 Cellulosic Ethanol Success

The Bioenergy Technologies Office has supported research, development, and demonstration for the production of cellulosic ethanol, focusing on three key areas: feedstock logistics, biochemical conversion, and thermochemical conversion. In September 2012, after 10 years of dedicated research and development (R&D) at the lab/bench and pilot[1] scales, the Office's research, development, and demonstration (RD&D) activities resulted in a four-fold reduction in cost and ultimately demonstrated two biofuels pathways that can produce cellulosic ethanol at a modeled nth plant cost of approximately $2.65 per gallon. This equates to a 77% reduction in the minimum ethanol selling price (MESP) from an estimated $10.92 (2014$U.S.) in 2001.

This achievement marks a critical milestone for the industry that was accomplished with strong bipartisan federal support across two presidential administrations. This milestone was achieved through U.S. Department of Energy (DOE) support of R&D at DOE national laboratories, academic institutions, and industry. RD&D was specifically focused on improving the efficiency and economics around biomass harvesting and feedstock supply system logistics, developing techno-economically viable process steps for both biochemical and thermochemical conversion processes, and through process integration. Reduced costs, technology improvements, and progress in scale-up and integration of processes represent major successes in cost-competitive cellulosic ethanol production. With conservative economic assumptions and proven process parameters, the technologies demonstrated at pilot scale[1] are modeled to produce cellulosic ethanol at commercial-scale costs that are competitive with gasoline production at $110/barrel of crude oil.

Many industry partners are also demonstrating their proprietary technology pathways to produce biofuel at pilot, demonstration, and commercial scales. Some of these technologies are similar to those demonstrated in the recent R&D accomplishment, while others demonstrate or commercialize newly developed technologies for cellulosic ethanol production.

Feedstock Logistics

Improvements in biomass harvesting and feedstock supply system logistics are crucial to meeting modeled 2,200 U.S. tons (2,000 tonne) per day refinery input/uptake/requirement for commercial-scale production costs of cellulosic ethanol. For 2012, research focused on corn stover as a model agricultural residue feedstock and purpose-grown trees as a model woody feedstock for biochemical and gasification routes, respectively.

Key advances in sustainable harvesting and collection include using the Residue Removal Tool[2] for accurate area assessments, improved storage strategies for preservation of biomass quantity and quality, and more energy- and cost-efficient mechanisms for preprocessing of biomass appropriate for introduction into the conversion processing system. Additional improvements included increased harvest efficiency, which contributes to higher sustainable yields, and improved biomass quality through ash content reduction. Higher bale density and reduced losses during handling and storage further contributed to meeting cost targets by lowering the cost of

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[1] Pilot throughput is defined as ½ to ≥ 1 dry ton per day.

[2] D. Muth and K.M. Bryden (2012), "An Integrated Model for Assessment of Sustainable Agricultural Residue Removal Limits for Bioenergy Systems," *Environmental Modelling and Software* 39(1).

transporting feedstocks. Other contributions to cost reduction include lower-cost storage methods, reduced uncertainty associated with storage losses through meeting a 59% carbohydrate preservation target, and direct improvements in grinder efficiency and capacity. These feedstock advancements, paired with increases in conversion yield/efficiency, resulted in a reducing production costs in 2012 by $0.48 and $0.58 per gallon for biochemical and thermochemical cellulosic ethanol, respectively.

Biochemical Conversion

Biochemical conversion route costs were significantly impacted through an approximate 90% reduction in enzyme cost (enabled by development of new enzymes and enzyme cocktails) and the engineering of microorganisms that can more effectively utilize multiple sugars produced from hydrolyzed plant cell wall cellulose and hemicellulose (i.e., glucose, xylose, and arabinose). A biochemical conversion pilot plant demonstrated a fully integrated suite of technologies capable of producing cellulosic ethanol from corn stover at a cost of $2.65 per gallon ethanol ($3.95 gasoline gallon equivalent [GGE]) when modeled at commercial scale.

Biochemical conversion of biomass to cellulosic ethanol can involve many steps, including pretreatment, conditioning, and enzymatic hydrolysis, followed by fermentation. Key breakthroughs in these process steps included the development of more efficient pretreatment processes, resulting in increased sugar yields; improved enzyme production method and enzymes that reduced enzyme loading and associated enzyme costs; and more robust fermentation organisms that were able to utilize sugars in the presence of biomass-derived inhibitors, ultimately achieving significantly higher ethanol yields. The deconstruction strategy, tested at bench and pilot scales, resulted in greater than 80% conversion of the xylan to desired xylose monomer in whole slurry mode while simultaneously lowering acid usage from 3.0% to 0.3%. An improved neutralization step reduced conditioning-related sugar losses from 13% to undetectable amounts. Increased enzyme efficiency resulted in reduced enzyme loading and cellulose-to-glucose yields of nearly 80%, contributing to an overall reduction in enzyme costs by 20-fold. Improvements in fermentation and microbial strain development resulted in the industrially relevant strains capable of converting cellulosic sugars at total conversion yields greater than 95% and tolerant of ethanol titers of approximately 72 gram/liter.

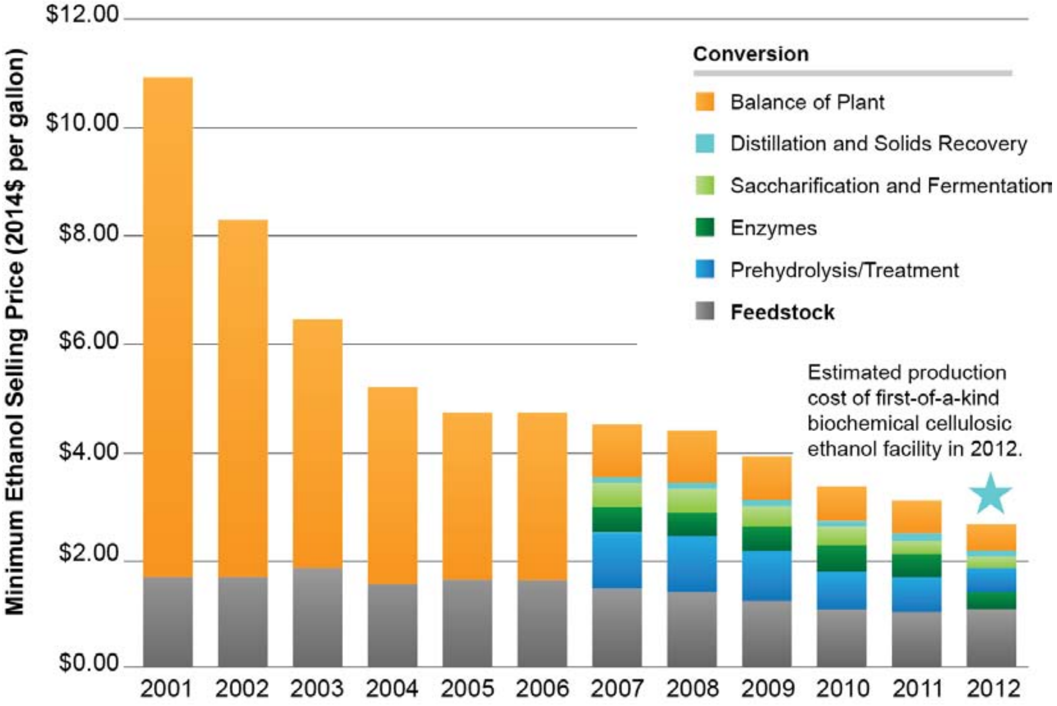

Figure C-1: Biochemical R&D impact on MESP from corn stover

Figure C-1 illustrates the R&D impact on MESP of corn stover to ethanol via biochemical conversion, from 2001 to 2012. The dotted line denotes success at varying scales: bench scale prior to 2007 and pilot and modeled nth plant scale thereafter, until 2012. The star represents the published production cost[3] expected at one of the first cellulosic ethanol facilities to come online.

Thermochemical Conversion

The thermochemical conversion process used for cellulosic ethanol production included a gasifier, syngas clean-up, and catalytic fuel synthesis reactors. Significant process engineering improvements were achieved within the gasifier and fuel synthesis steps, and technical improvements were achieved in the syngas cleanup and catalytic fuels synthesis steps.

After developing, improving, and down-selecting a variety of technologies for each process step, the Office demonstrated a configuration capable of producing cellulosic ethanol from a woody feedstock at a cost of $2.45 per gallon ethanol ($3.66 GGE) when modeled at commercial scale (using the pilot plant at its thermochemical users facility). The Office's notable technical breakthroughs included the optimization of its indirectly heated fluidized bed gasifier; the development of tar- and methane-reforming catalysts that increased methane conversion to syngas from 20% to more than 80%; and development of catalysts and operational strategies for the conversion of syngas to mixed alcohols production. These key improvements resulted in an increase in ethanol yield from 62 gallons to greater than 84 gallons per ton of biomass.
Figure C-2 illustrates the R&D successes contributing to the decrease in MESP for a gasification process between 2007 and 2012.

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[3] Chris Standlee (2014), "Advanced Ethanol: Coming Online," National Ethanol Conference, February 18, 2014, Orlando, Florida.

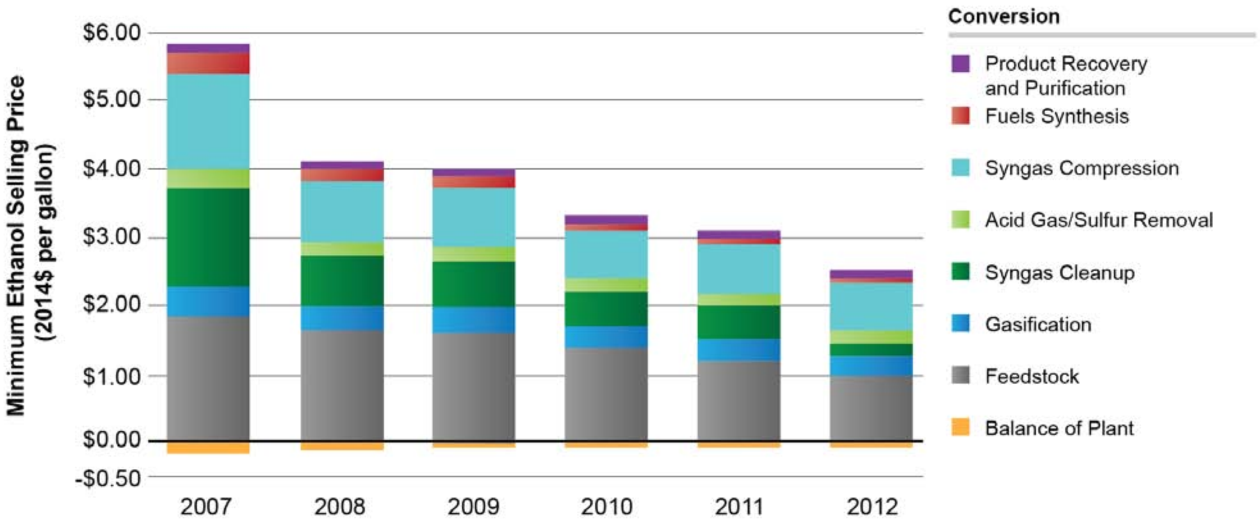

Figure C-2: Thermochemical R&D impact on MESP from woody feedstock

Figure C-2 illustrates the R&D impact on MESP of woody feedstocks to ethanol via thermochemical conversion, from 2007 to 2012.

Leveraging Success

More than 10 years of dedicated RD&D enabled the breakthroughs necessary for the production of cost-competitive cellulosic ethanol. Meeting cost-competitive production targets is important because cellulosic ethanol represents a very significant life-cycle reduction in greenhouse gas emissions compared to petroleum gasoline (roughly 80% and roughly 90% for fermentation and gasification pathways, respectively).[4] This does not suggest that these processes cannot be further improved. Updated design cases have shown that the escalation of costs to 2014 U.S. dollar bases increased the MESP and helps to identify further process efficiencies that could be addressed through additional R&D.

These R&D achievements demonstrated in 2012 and afterward for cellulosic ethanol production provide the groundwork for the development and optimization of biomass conversion technologies and techniques capable of producing hydrocarbon liquids that are virtually indistinguishable from gasoline, diesel, jet fuel, and other petroleum products, and that are fully compatible with existing fuel handling and distribution infrastructures. These breakthroughs will be repurposed and leveraged to accelerate the commercialization of new, renewable fuels and chemicals from biomass.

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[4] J.B. Dunn, M. Johnson, M. Wang (2013), "Supply Chain Sustainability Analysis of SOT Pathways," BETO Quarterly Meeting, January 17, 2013, Washington, D.C.

Appendix D: Matrix of Revisions

Section Name	Specific Reference	Revision	Version Change was Implemented
July 2014			
All Sections	Throughout	Major and minor updates to all sections	July 2014
Feedstock Supply and Logistics R&D	Section 2.1	Terrestrial Feedstocks and Algal Feedstocks separated into two sub-sections	July 2014
Thermochemical Conversion R&D	Section 2.2.2	Oils and Gaseous Intermediate Sections combined into Thermochemical Conversion R&D	July 2014
Demonstration and Deployment	Section 2.3	Combined Integrated Biorefinery and Distribution Infrastructure and End Use sections and redrafted/refocused D&D section	July 2014
November 2014			
Terrestrial Feedstock Supply & Logistics R&D	Section 2.1.1 and Appendix B	Updates to reflect volume revisions associated with goals and changes in blending strategies. Added feedstock logistics costs table to Appendix B	November 2014
Algal Feedstocks	Section 2.1.2	Inclusion of Algal Lipid Upgrading and Algal Hydrothermal Liquefaction design cases	November 2014
Thermochemical Conversion R&D	Section 2.2.2 and Appendix B	Added 2013 Sustainability metrics and feedstock costs to out-year projections	November 2014
March 2015			
Introduction to Research, Development, and Demonstration	Section 2	Inclusion of Wet Waste to Energy Feedstocks and change to Demonstration and Market Transformation	March 2015
Feedstocks Supply and Logistics	Section 2.1	Define Wet Waste to Energy Feedstocks	March 2015
Terrestrial Feedstocks Supply and Logistics	Section 2.1.1	Added herbaceous feedstocks cost tables	March 2015

Section Name	Specific Reference	Revision	Version Change was Implemented
Algal Feedstocks	Section 2.1.2	Minor clarifications	March 2015
Conversion R&D	Section 2.2	Integration of themo- and bio-chemical activities, strategic refocus on technology building blocks, additional technology pathways for hydrocarbon-based fuels, and addition of co-products to enable cost competitive biofuels	March 2015
Demonstration and Market Transformation	Section 2.3	Renamed	March 2015
Sustainability	Section 2.4	Milestone modifications	March 2015
Appendices	-	Former Appendix A removed and subsequent appendices renamed	March 2015
Technical Projection Tables	Appendix A	Tables added for new conversion pathways	March 2015
March 2016			
Entire Document	-	Updated to 2014 dollars and minor updates throughout; milestone additions throughout Section Two	March 2016
Office Vision and Mission	Section 1.2	Revised wording of vision statement and mission statement	March 2016
Algal Supply Systems	Section 2.1.2 and Appendix A	Renamed section and included Algae Farm Design Case	March 2016
Demonstration and Market Transformation	Section 2.3	Revised milestones and impact analysis	March 2016
Crosscutting	Section 2.4	Added crosscutting description; restructured Sustainability, Strategic Analysis, and Strategic Communications as sub-sections of Section 2.4	March 2016
Strategic Communications	Section 2.4.3	Revisions throughout; added a key milestones and activities chart and a table of key stakeholders	March 2016
Office Portfolio Management	Section 3	Revisions throughout	March 2016

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