Quadrennial Technology Review 2015

Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

Technology Assessments

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U.S. DEPARTMENT OF ENERGY

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Biomass Feedstocks and Logistics

Chapter 7: Technology Assessments

Introduction

The sustainable supply of quality, cost-effective feedstocks to future biorefineries is fundamental to growing the bioenergy industry. The Department of Energy (DOE) has made significant contributions to ensuring a sustainably supply of biomass. However, the inherently dispersed, highly-variable, aerobically unstable nature of biomass, among other characteristics, are still a challenge. Technologies need to be developed that can provide a sustainable, secure, and affordable biomass feedstock supply for the U.S. bioenergy industry. As the raw material for biofuels, bioproducts, and biopower production, reaching industrial scale will require availability of and access to a reliable supply of high-quality biomass. R&D is needed in two broad categories of feedstock: (1) terrestrial feedstocks, which include lignocellulosic feedstocks such as agricultural residues, forest resources, dedicated energy crops,[1] and municipal solid waste (MSW) resources; and (2) algal feedstocks.

Feedstocks are essential to achieving national goals because the cost, quality, and volume of feedstock available and accessible at any given time will determine the maximum amount of biomass-derived products that can be produced. The *U.S. Billion-Ton Update*[2] report provided biomass supply scenarios that show the potential biomass resource that could be developed, leading to a sustainable national supply of more than 1 billion tons of biomass per year by 2030. Sustainably supplying the required volumes for conversion to energy and products requires the transition from conventional logistics systems to more advanced systems.[3] New supply systems are needed to provide large amounts of biomass to various types of biorefinery conversion facilities for biofuels, biopower, and bioproducts in a growing bioeconomy.

Conventional 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 do not access the full volume of the diverse, nationally distributed U.S. biomass resource potential. Neither do they modify nor control the inherent moisture contents of either wet or dry systems in use today, which contributes to costs at conversion facilities. Conventional systems constrain biorefinery and biopower locations to areas where there are sufficient supplies of biomass within a limited distance, limit the scale-up capacity of the biorefinery or biopower plant, and expose the investors to increased risk from potential local feedstock disruptions.[4, 5]

Advanced Logistics Systems: Advanced logistics systems are designed to deliver infrastructure-compatible feedstocks with specified physical and chemical characteristics, longer-term stability during storage, and high-capacity bulk material handling characteristics that facilitate economic transport over longer distances.[6] These properties are 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 and bioproducts production can eliminate inefficiencies in conventional harvest and delivery systems. Reducing the number of operations, pieces of equipment, and labor required per delivered ton of feedstock would enable implementation of additional operations, such as pre-processing, that do not occur in conventional systems. Methods to estimate feedstock quality characteristics at critical points in the supply chain also need to be developed to help ensure bioenergy system performance.

Feedstock Barriers

To develop sustainable technologies that provide a secure and affordable feedstock supply for the U.S. bioenergy industry, challenges and barriers associated with biomass need to be prioritized and addressed. Those barriers include but are not limited to:

Terrestrial Feedstock Availability and Cost: Reliable and consistent feedstock supply is needed to reduce financial, technical, and operational risk to biomass supply and conversion investments. Reaching federally mandated national volumes of biofuels will require large amounts of sustainably available, quality-controlled biomass to enter the market at an affordable price. Conventional logistics systems restrict the amount of biomass that can be cost-effectively delivered to the bioenergy system, leaving large amounts of biomass that cannot cost-effectively enter the system (i.e., “stranded resources”) without being incentivized for their value in GHG reductions, energy security, and economic opportunity.[7, 8] These high costs for feedstocks are a significant barrier to expanding a bio-based economy.

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. Estimates of current and potential feedstock resources are limited in scope and do not adequately represent how major potential advances in genetics, production technologies, and supply chain strategies will impact future biomass availability, cost, quality, and processing characteristics.

Production: Another barrier is the lack of energy crop yields and the environmental effects of energy crop production. The range and improvements in energy crop yields have not been well-documented for deployment of energy crops at commercial scale. Reliable production data are needed over several growing seasons and across wide geographies to make well-substantiated productivity projections. Comprehensive data are also needed to measure the environmental effects of energy crop production and biomass collection systems to provide data for complete life-cycle analysis of biorefinery systems and address sustainability questions such as water and fertilizer inputs or establishment and harvesting impacts on soil. Production and sustainability gaps also exist for conventional crop residues.

Terrestrial Feedstock Genetics and Development: The productivity and robustness of terrestrial feedstock crops used for biofuel production could be increased by developing improved varieties through screening, breeding/selection, and genetic engineering. This will require extensive ecological, genetic, and biochemical information that is currently lacking and is a barrier to use of the dedicated perennial terrestrial energy crops.

Sustainable Harvesting: Current crop harvesting machinery is unable to selectively harvest preferred components of cellulosic biomass while maintaining acceptable levels of soil carbon and minimizing erosion. Actively managing biomass variability imposes additional functional requirements on biomass harvesting equipment. Current systems cannot meet the capacity, efficiency, or delivered price requirements of large cellulosic biorefineries. Neither can these current systems continue to protect and conserve soil structure over cumulative operations at massive scales.

Terrestrial Feedstock Quality and Monitoring: A better understanding of the physical, chemical, microbiological, and post-harvest physiological variations is needed to manage feedstock costs and reduce conversion costs and final product prices. Biomass is very heterogeneous in physical and chemical properties that arise from differences in genetics, degree of crop maturity, geographical location, climatic events, and harvest methods. This variability presents significant cost and performance risks, and is a barrier to cost-effective bioenergy and biopower systems. Processing standards and specifications for cellulosic feedstocks are not as well-developed as they are for mature commodities and are being developed.

Biomass Storage Systems: Biomass that is stored with high moisture content or exposed to moisture during storage is susceptible to spoilage, spontaneous combustion, odor problems, and rapid changes in quality. Therefore, a barrier is managing and controlling post-harvest biological processes to ensure a consistent, high-quality feedstock supply. Characterization and analysis of different storage methods and strategies are needed to better define storage requirements to preserve the volume and quality of harvested biomass over time and maintain its conversion yield. Low-cost options are need for high-capacity storage – storage options that are safe and not subject to fire and pests.

Biomass Material Properties and Variability: Available data and information are extremely limited on biomass quality and physical characteristics and how those properties influence conversion performance. Methods and instrumentation also are lacking for quickly, accurately, and economically measuring chemical, physical, and mechanical properties of biomass.

The inherent variability of biomass physical and chemical quality parameters is needed at more refined levels such as within a species and even between tissues of the same plant and require additional research. Acceptable ranges of quality parameters for different conversion processes are poorly understood, and few genetic or pre-processing strategies have been developed to limit or control variability in biomass quality. Since many quality factors vary independently, it is not clear what fraction of available biomass materials will actually be able to meet specifications for the various conversion processes being developed and commercialized.

Biomass Physical State Alteration: The initial sizing and grinding of cellulosic biomass affects conversion efficiencies and yields of all downstream operations, especially for biofuels conversion options, yet little information exists on managing these operations to improve the product yields or reduce costs. This is a barrier to designing high-performance supply systems. New technologies and equipment are required to economically process biomass to meet biorefinery and biopower facility specifications such as particle-size distribution. Managing these particle-size reductions operations to match the conversion process is paramount to improving overall efficiency.

Biomass Material Handling and Transportation: Raw herbaceous biomass is costly to collect, handle, and transport long distances because of its low density and fibrous nature. Existing 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 can be inefficient for bioenergy processes due to the costs and challenges of transporting, storing, and drying high-moisture biomass.

Overall Integration and Scale-Up: Conventional supply systems used to harvest, collect, store, handle, and transport biomass are not designed for the large-scale needs of a nationwide system of integrated bioenergy systems. The infrastructure for feedstock logistics has not been defined for the potential variety of locations, climates, feedstocks, storage methods, and processing alternatives which will occur at a national scale. Integration of one or more aspects of the feedstock supply system—either alone or in combination with bioenergy system 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, efficiency improvements, and reduction of technical and financial risks.

Although substantial progress has been made, there are many challenges and barriers associated with working with biomass, the following issues are considered most critical:

- Increase the volume of sustainable, acceptable, cost-effective feedstock available to bioenergy systems by developing advanced feedstock supply systems and strategies
- Incorporate sustainability and feedstock supply risk into the resource assessments

- Work with conversion technology areas to understand the range of acceptable physical and chemical specifications for the various conversion technologies
- Develop high-capacity, high-efficiency, low-cost, commercial-scale feedstock supply and logistics systems that deliver stable, dense, consistent, infrastructure-compatible feedstock.

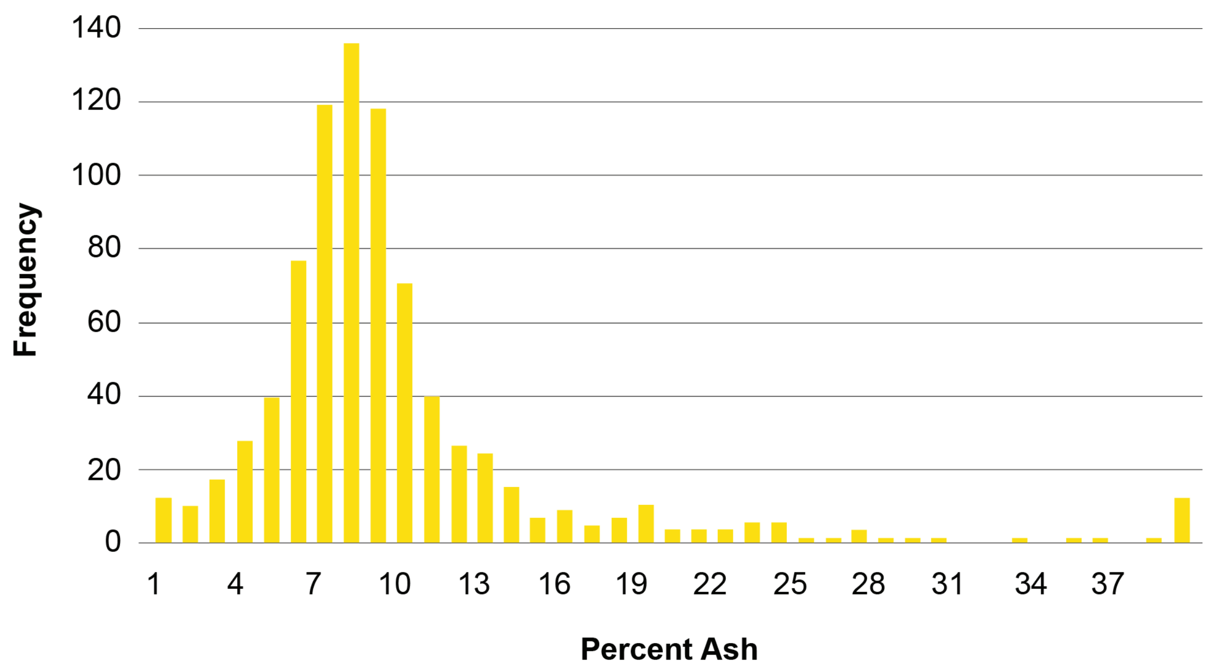
Strategies Moving Forward

Terrestrial feedstock research in the past has 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-yielding areas. Supplying feedstock to a growing bioenergy industry requires increasing the accessible volumes of lignocellulosic feedstock while increasing the emphasis on quality and reducing variability. This can be achieved by applying pre-processing techniques such as fracturing, drying, densifying, and blending.[9]

Terrestrial feedstock research is needed to: (1) reduce the delivered cost of sustainably produced feedstock, (2) preserve and improve the quality of harvested feedstock to meet the needs of biorefineries and other biomass users, and (3) expand the tonnages of feedstock materials accessible to the bioenergy industry. This is done by identifying, developing, demonstrating, and validating efficient and economical systems for harvest and collection, storage, handling, and pre-processing raw biomass from a variety of crops to reliably deliver high-quality, affordable feedstocks.

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 inherent variability of one aspect of biomass quality, namely ash, for Midwestern corn stover is illustrated in Figure 7.B.1.[10]

Figure 7.B.1 Example of the Variability of Corn Stover Characteristics such as Percent Total Ash Content[11]

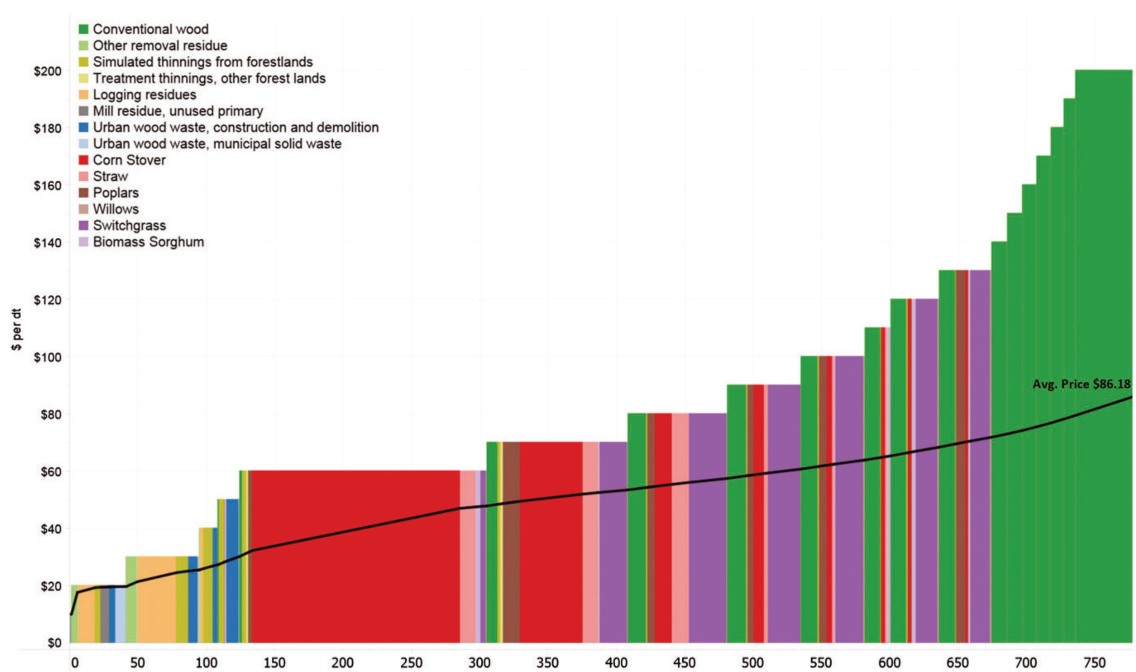


Ash is the inorganic or mineral content of biomass. Ash content varies considerably among and within biomass materials. Understanding biomass ash content, variability, and where it originates requires differentiation of the sources of ash, which include structural ash associated with the plant cell walls, 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 of pyrolysis oils, slagging in thermochemical equipment, and costs associated with ash disposal; it can similarly challenge power plant equipment. The proportion of convertible biomass content decreases with increasing ash content effectively increasing the cost per dry ton of feedstocks. The variability in ash and other biomass quality parameters highlights the need to rapidly quantify quality parameters and develop mechanisms for moderating changes to the final point of delivery.

Biomass price projections can be combined with quality information from the Bioenergy Feedstock Library[12] to determine supply characteristics for commercial bioenergy systems. Sufficient projected volumes can be made available at cost and bioenergy system specifications by transitioning to a blended feedstock approach. Figure 7.B.2—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.[13] These costs are marginal cost, i.e., the price for the "last" available ton of biomass on the market) to reflect total cumulative biomass at farm gate prices.

Feedstock blending allows a bioenergy system to collect less of any one feedstock and thus move down the cost versus supply curve enabling bioenergy systems to pay a lower average price. This does not change the supply versus cost curves for each resource but it describes a system where purchasers can use a combination of least-cost resources and blend them to reach the desired cost and quality specifications.[14] 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.

Figure 7.B.2 Biomass Supply Projections at Marginal Prices, Price of Last Ton at a Given Level of Supply,Between $20 and $200/dry ton in 2022[15, 16]



Using a least-cost formulation analysis, Table 7.B.1 illustrates that modeled feedstock cost and quality targets can be met for the bio-oil conversion pathway (fast pyrolysis).[17] This pathway is currently designed to process feedstocks with an ash content of less than 1% on a dry weight basis.[18] In this example, low-cost, low-quality logging residues; switchgrass; and construction and demolition (C&D) waste can be processed and blended with higher-cost, higher-quality debarked pine chips to meet conversion specifications. The exact quantity of each feedstock depends on the cost, quality characteristics of each feedstock, and the target requirements of the blended material. The modeled formulation uses 45% purpose-grown pine, 32% residues, 3% switchgrass, and 20% C&D waste as an example of this least-cost formulation strategy to obtain feedstocks that have an average delivered cost of $80/dry ton and cumulative ash content below 1% on a dry weight basis.

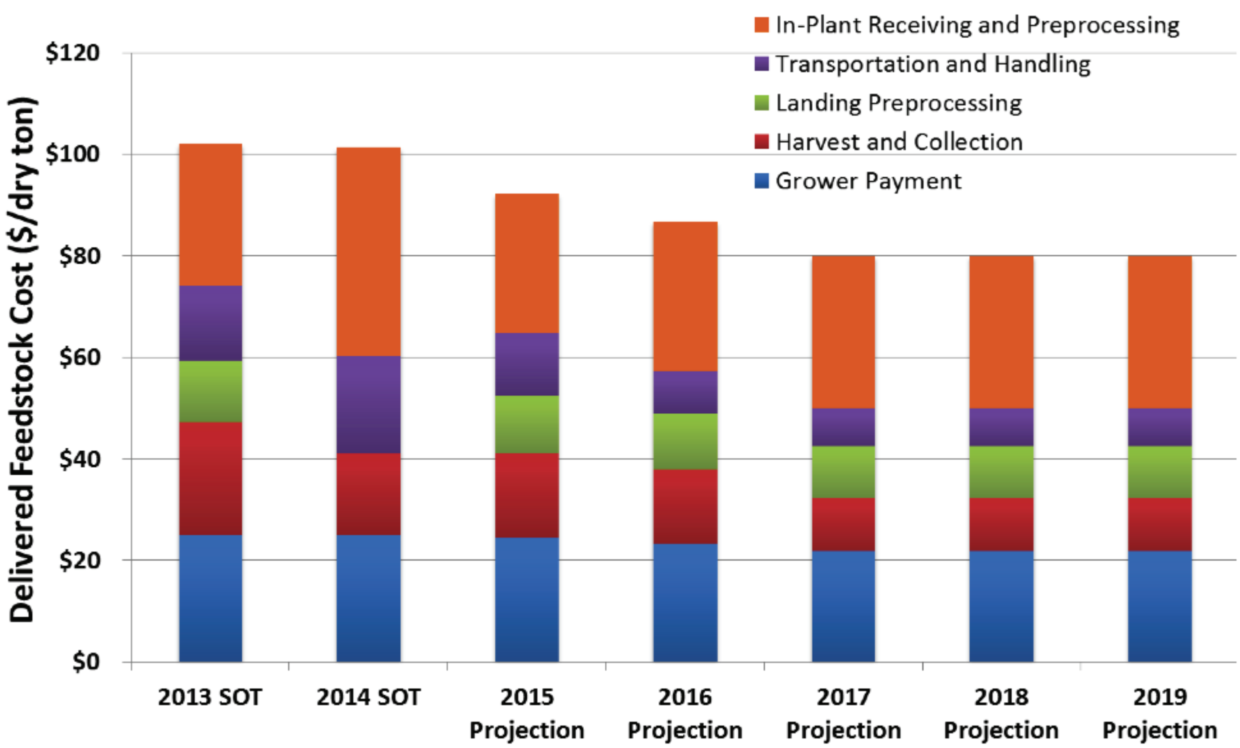
Table 7.B.1 Example of Modeled Costs and Specifications for Processed Woody Feedstocks and Blends for Fast Pyrolysis and Subsequent Upgrading to a Hydrocarbon Fuel[19]

Feedstock	Modeled Feedstock Cost to Reactor Throat (logistics cost + grower payment, $/dry ton)	Formulation Fraction (%)	Ash Content at Reactor Throat
Purpose-Grown Pine (Wood)	99.49	45	0.5
Logging Residues[20]	67.51	32	1.0
Switchgrass	66.68	3	4.0
C&D Waste	58.12	20	1.0
Delivered Formulation Totals	**80.00**	**100**	**<1.0%**

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 $80/dry ton target. While the 45% fraction of debarked purpose-grown pine in Table 7.B.1 exceeds the $80/dry ton cost target (at a modeled cost of nearly $100/dry ton), it provides very low-ash material that helps the feedstock meet the thermochemical conversion quality specifications. When blended, the formulation meets both cost and feedstock quality targets. Moving beyond 2017, the blending strategy would allow more resources to become economical with the appropriate quality for bioenergy production while still hitting the $80/dry ton cost target.

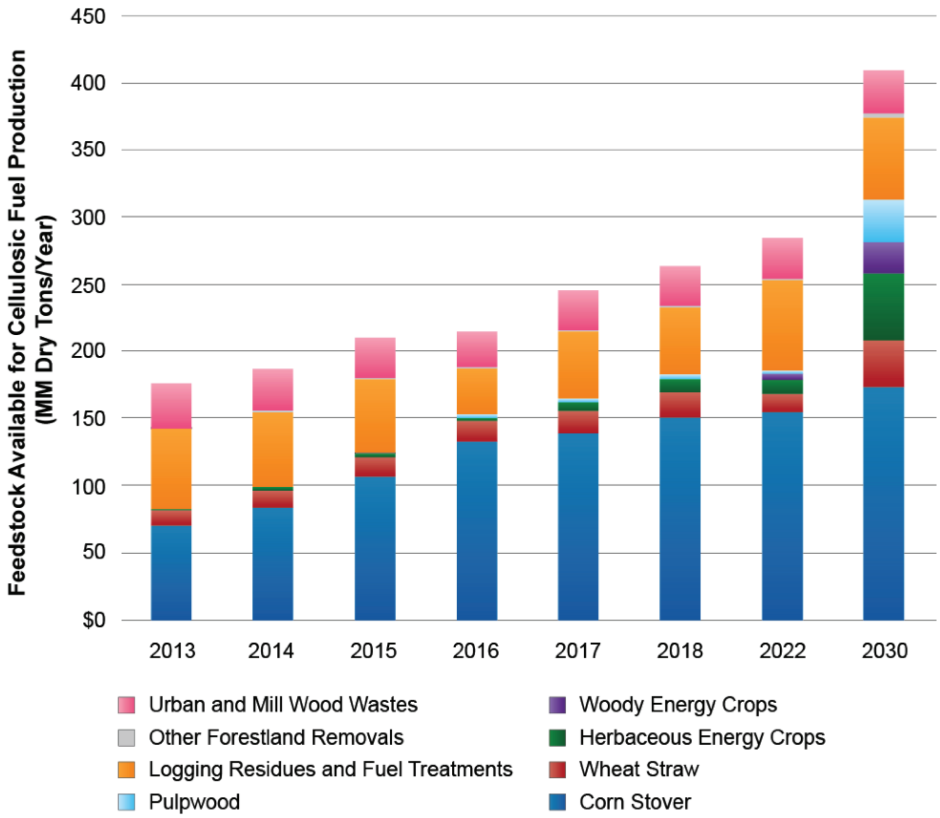
Prior to the transition to advanced systems that incorporate concepts such as blending, feedstock research was focused on improving conventional systems. Through 2012 conventional woody supply system costs were reduced by improving existing equipment efficiencies, adopting innovative ways of mitigating moisture content, and increasing grinder performance. The year 2013 marked the transition from conventional feedstock supply systems to advanced systems and non-ideal feedstock supply areas, based on the desire to increase the total volume of material that can be processed and to enable more biorefinery options. Moving beyond 2017, advanced systems could gradually bring in larger quantities of feedstock from a broader resource base and incorporate environmental impact criteria into availability determinations. Feedstock supplied after 2017 could continue to meet the $80/dry ton cost target and quality requirements of various conversion processes. Figure 7.B.3 shows potential reductions in the delivered woody feedstock costs from 2013 through 2019 for a fast pyrolysis conversion process.

Figure 7.B.3 Historical and Projected Delivered Woody Feedstock Costs Modeled for Pyrolysis Conversion[21]



Total modeled feedstock cost decreases through 2017 as the result of capacity and efficiency improvements, innovative design strategies (such as blending which reduces the harvest and collection cost), novel pre-processing approaches, and integrated landscape management strategies. The 2013 state-of-technology case ("2013 SOT" in Figure 7.B.3) 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 construction/demolition waste does not have a harvest cost. Therefore, blending these materials will reduce harvest and collection cost. The modeled costs do not decrease between 2017 and 2019, although there is an increase in the volume of biomass available at the $80/dry ton target (as indicated in Figure 7.B.4).

Figure 7.B.4 Historical and Projected Volumes of Biomass Available at a Delivered Cost of $80/dry ton for Various Biomass Types Accommodating Multiple Conversion Processes[22]



The higher tonnages in Figure 7.B.4 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. Research is needed on blending strategies, on the performance of blended material, and on other advanced design technologies to meet cost, quality, and volume targets.

Algae

Biofuels derived from algal biomass have the potential to contribute to the domestic advanced biofuel resource. Advantages of algae-derived biofuels include: the ability to cultivate algae on non-arable land, the ability to utilize brackish or saline water, and the possibility of using waste nutrients and effluents, including carbon dioxide from power plants. Algal species can accumulate significant amounts of lipids in their cell structure and thus are particularly well suited for conversion to hydrocarbon-based renewable diesel and jet fuel. The challenges associated with algae include the high cost of production, water requirements, and micro-nutrient requirements. Research and development activities are focused on reducing the cost of production of algal biomass and intermediates, developing cultivation and logistics systems for producing fuels and products at commercial scale, developing innovative and energy efficient drying technologies, and developing algal strains that can survive and maintain high productivity in large scale algae farming operations. Algal biomass includes micro- and macro-algae and 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.

Table 7.B.2 shows projected minimum fuel selling prices for algae-based biofuels based on reasonable yield assumptions derived from literature and technical projections for one baselined technology pathway which incorporates lipid extraction and upgrading. The projections show that the greatest opportunity to reduce costs is in the production systems through improved biomass yield and reduced cultivation capital costs. Significant cost improvements are also needed in feedstock harvest and pre-processing. The 2022 projection could be achieved if there could be: a five-fold improvement in biomass yield through increased productivity and extractable lipid content, a factor of two reduction in capital costs for pond construction (including removing pond liners from the design), and significant capital and operability improvements in the harvest and pre-processing steps. While the incorporation of co-products such as polymers or animal feed could reduce costs for these systems by increasing the value of the algal biomass, this strategy was not included in the literature design assumptions summarized below, but is included in the Department of Energy's overall strategy for reducing the price of algae-based biofuels.

Table 7.B.2 Summary of Cost Contributions for the Algal Lipid Upgrading Design[23]

Unit Operation	2010 State of Technology	2014 Projection	2018 Projection	2022 Projection
Feedstock	$16.50	$10.60	$5.19	$3.05
Conversion	$1.72	$1.56	$1.11	$1.11
Hydro-treating	$1.84	$1.84	$1.84	$0.29
Anaerobic Digestion	$0.68	$0.65	$0.47	-$0.18
Balance of plant	$0.00	$0.00	$0.00	$0.08
Total	**$20.74**	**$14.66**	**$8.61**	**$4.35**

Note: The 2022 anaerobic digestion cost is negative as the byproduct biopower production value exceeds the costs of algal conversion.

Strategies to meet and reduce the projected costs above are being investigated along the supply chain. 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 requires extensive ecological, genetic, and biochemical information. Any genetically modified organisms deployed commercially will also require regulatory approval by the appropriate federal, state, and local government agencies.

Research efforts are also focused on identifying key algal feedstock characteristics and standards for downstream conversion processes. A unique aspect of the conversion interface in these systems 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. The fundamental components (lipids, carbohydrates, and proteins) of algal biomass vary greatly, within strains, among strains, and in comparison to plants. These efforts will help to develop and optimize conversion process input specifications so that process economic targets can be achieved.

The integration of analysis, biomass production, logistics, and conversion is particularly important to advancing algal systems. 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 are run in parallel to bolster research focus on those processes with the best and most sustainable economic outcomes. Scaling-up algal technologies is considered one of the largest challenges in the commercialization of algal biofuels and 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. The scaling up of nutrient sources that are inexpensive at small scales may be economically prohibitive at commercial scales. 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.

Waste-to-Energy

In addition to purpose-grown crops, municipal, industrial, and agricultural waste streams constitute a potential resource for the production of fuels, product precursors, heat, and electricity. The "Biogas Opportunities Roadmap" issued jointly by the USDA, EPA, and DOE[24] estimates that the combination of biogas production from agricultural manure operations, landfills, and water resource recovery facilities could yield 654 billion cubic feet per year of biogas. If converted to electricity the roadmap projects potential generation of over 40 terra-watt-hours, more than 1% of total U.S. consumption according to the Energy Information Administration.[25] This figure is probably conservative as it does not include organic industrial wastes. The estimate incorporates currently available technologies for wastewater treatment facilities[26] thereby excluding the potential contribution of future research and development. Beyond electricity generation there are significant opportunities to produce heat for on-site use, and hydrocarbons for use in biofuels and bio-products, thereby avoiding greenhouse gas emissions from the use of fossil fuel feedstocks. There is interest in utilizing the potential from four kinds of organic feedstocks:

1. The non-recyclable organic fraction of landfill solid wastes. Food wastes from landfills constitute the largest single fraction of currently unrecovered wastes.[27]
2. Sludge from various stages of municipal wastewater treatment processes. While the wastewater industry is undergoing a shift towards viewing themselves as water resource recovery facilities[28] much work remains to realize this vision.
3. Manure slurries from concentrated livestock operations, particularly dairies.[29]
4. Organic wastes from industrial operations including but not limited to food and beverage production and biorefineries. Other industries such as pulp and paper, forest products, and pharmaceuticals also generate streams that might be suitable for incorporation.

There is also opportunity to combine two or more of the above streams in particular locations to attain regional economies of scale. These synergies may be particularly relevant in producing biofuels and bioproduct precursors as opposed to the onsite generation of combined heat and power (CHP) which is particularly suited to facilities that have a proximal beneficial use for the heat such as many wastewater treatment plants.

Producing biofuels and bioproducts from wastewater streams requires the conversion of often dilute (3-4% solids by weight) inputs into useful chemicals (e.g. butanol[30]) while minimizing the energy inputs for drying. There are a number of avenues to achieve these objectives including, but not limited to:

1. Hydrothermal processes, including hydrothermal liquefaction, that are capable of utilizing the unique properties of sub and supercritical water (and other solvents) to produce liquid fuel precursors, biogas, and beneficial solids.[31, 32] Some of these pathways could contribute to reductions in energy consumption for municipal wastewater treatment facilities.[33, 34]
2. Microbial and other biochemical processes that convert wastewater directly into higher hydrocarbons. There are two general categories: modification of existing anaerobic digestion processes to produce

either drop-in biofuels or bioproduct precursors rather than biogas; and microbial electrolysis and electro-synthesis cells that yield hydrocarbon compounds and in some cases could produce more electricity than they consume.[35, 36]

3. Enhanced anaerobic digestion and other biochemical processes to convert CO_2 in biogas into higher value products.[37, 38, 39]
4. Exploration of anaerobic membrane bioreactors (AnMBRs) in conjunction with other technologies such as microbial fuel cells. While AnMBRs have gained commercial acceptance in high organic load industrial processes they are not yet widely deployed for municipal wastewater applications. Minimization of fouling is a key challenge. AnMBRs could replace secondary aeration which tends to be the largest electricity consumer in wastewater treatment facilities and avoid the capital costs of anaerobic digesters, especially for smaller facilities.[40, 41]
5. Other processes for conversion of organic feedstocks into higher value biofuel and bioproduct precursors include fast pyrolysis and various pathways to gasification. Strategies that utilize waste heat to reduce the energy required for drying are of particular interest.
6. Research is needed in biological and chemical options to convert methane into hydrocarbons. ARPA-E's REMOTE solicitation is relevant, as strategies that work for natural gas could apply to biogas.[42] The possibility may also exist to co-develop biofuels and engines to exceed the performance of currently available internal combustion engines.
7. Systems integration is an important consideration. Detailed techno-economic analyses of the conditions under which it makes economic and environmental sense to pursue various renewable energy options could be valuable. For example, it would be useful to understand the parameters that guide the economics of biofuel production vs. localized combined heat and power in contrast to biogas upgrading to pipeline quality or fleet utilization of compressed natural gas or liquefied natural gas.

In summary, there are numerous opportunities to utilize organic "wastes" to produce bioenergy, biopower, and bioproducts. These pathways are not only renewable but also hold the potential of supplementing seasonal agricultural crops and residues with reliable year-round feedstock streams.

Endnotes

1 Energy crops are produced primarily to be feedstocks for energy 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 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

3 J. Richard Hess, Christopher Wright, et al. "Uniform-Format Solid Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass," Idaho National Laboratory, INL/EXT-08-14752 (2009), https://inldigitallibrary.inl.gov/sti/4408280.pdf.

4 J. Richard Hess, Christopher Wright, et al., as above.

5 Advanced Feedstock Supply System Validation Workshop Summary Report, Available at https://bioenergy.inl.gov/SitePages/Home.aspx

6 Lamers, Patrick, Eric C.D. Tan, Erin M. Searcy, Christopher J. Scarlata, Kara G. Cafferty, Jacob J. Jacobson,. 2015. Strategic supply system design – a holistic evaluation of operational and production cost for a biorefinery supply chain. This article is a U.S. Government work and is in the public domain in the USA. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd. | *Biofuels, Bioprod. Bioref.* (2015); DOI: 10.1002/bbb.

7 (see Section 1.1.6 for discussion of biomass benefits) Bioenergy Technologies Program - Multi-Year Program Plan. http://www.energy.gov/sites/prod/files/2015/03/f20/mypp_beto_march2015.pdf

8 Volume 2, Chapter 6, Renewable Electricity Futures Report. National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy12osti/52409-2.pdf

9 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." INL/EXT-13-30342. https://inlportal.inl.gov/portal/server.pt?open=512&objID=421&parentname=CommunityPage&parentid=4&mode=2.

[10] For a more in-depth discussion of biomass variability, see K. Kenney, W. Smith, G. Gresham, and T. Westover. 2013. Understanding Biomass Feedstock Variability. *Biofuels* 4(1).

[11] Data was extracted from the Bioenergy Feedstock Library (https://bioenergylibrary.inl.gov/Home/Home.aspx). The data set includes 840 samples, including corn stover, miscanthus, and wheat straw.

[12] Bioenergy Feedstock Library - https://bioenergylibrary.inl.gov/Home/Home.aspx

[13] Figure 7.B.2 shows both the marginal price and average price (white line). For the purpose of this study, farm-gate 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 farm-gate 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 farm-gate, forest landing, biomass depot, or conversion facility. "Average price" is used to convey the price to acquire biomass from the first to the last ton over a specific period of time. The average price is less than the marginal price for a single feedstock.

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[19] Table 7.B.1 is intended as a demonstration of the blending concept and does not represent future quality targets for ash. Values for pulpwood, residues, and C&D from: E. Lindström, S. Larsson, D. Boström, M. Ohman. 2010. "Slagging Characteristics During Combustion of Woody Biomass Pellets Made from a Range of Different Forestry Assortments." *Energy & Fuels* 24(6); Switchgrass value extracted from: Turn, S.Q., 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).

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Acronyms

AnMBRS	Anaerobic membrane bioreactors
BETO	Bioenergy technologies office
C&D wastes	Wood construction and deconstruction wastes
CHP	Combined heat and power
DOE	Department of energy
EPA	Environmental protection agency
GHG	Greenhouse gases
MSW	Municipal solid wastes
R&D	Research & development
SOT	State-of-technology
USDA	U.S. Department of Agriculture

Glossary[43]

Aerobic	Able to live, grow, or take place only where free oxygen is present.
Aerobic fermentation	Fermentation processes that require the presence of oxygen.
Agricultural residue	Agricultural crop residues are the plant parts, primarily stalks and leaves, not removed from the fields with the primary food or fiber product. Examples include corn stover (stalks, leaves, husks, and cobs), wheat straw, and rice straw.
Algae	Simple photosynthetic plants containing chlorophyll, often fast growing and able to live in freshwater, seawater, or damp oils. May be unicellular and microscopic or very large, as in the giant kelps.
Ash content	Residue remaining after ignition of a sample determined by a definite prescribed procedure.
Biobased product	The term 'biobased product' as defined by Farm Security and Rural Investment Act (FSRIA), means a product determined by the U.S. Secretary of Agriculture to be a commercial or industrial product (other than food or feed), that is composed in whole or in significant part, of biological products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials.
Bioconversion (or biochemical conversion)	A general term describing the use of biological systems to transform one compound into another. Examples are digestion of organic wastes or sewage by microorganisms to produce methane and the synthesis of organic compounds from carbon dioxide and water by plants.
Biodiesel	A biodegradable transportation fuel for use in diesel engines that is produced through the transesterification of organically derived oils or fats. It may be used either as a replacement for or as a component of diesel fuel.
Biofuels	Biomass converted to liquid or gaseous fuels such as ethanol, methanol, methane, and hydrogen.
Biogas	A gaseous mixture of carbon dioxide and methane produced by the anaerobic digestion of organic matter.
Biomass	Organic matter, including wood, agricultural waste, algae, and other material derived from living cells such as sewage or municipal solid wastes, that can be used as a feedstock to produce energy, products, or other commodities.

Biopower	The use of biomass feedstock to produce electric power or heat through direct combustion of the feedstock, through gasification and then combustion of the resultant gas, or through other thermal conversion processes. Power is generated with engines, turbines, fuel cells, or other equipment.
Bioproduct	Materials that are derived from renewable feedstocks. Examples include paper, ethanol, and palm oil.
Biorefinery	A facility that processes and converts biomass into value-added products. These products can range from biomaterials, to fuels such as ethanol, or important feedstocks for the production of chemicals and other materials. Biorefineries can be based on a number of processing platforms using mechanical, thermal, chemical, and biochemical processes.
Carbon dioxide	A colorless, odorless gas used by plants in the photosynthesis process and produced by the combustion of carbon-containing fuels, including biomass. Represented as CO_2.
Cellulose	A carbohydrate that is the principal component of wood. It is made of linked glucose molecules (a six-carbon sugar) that strengthen the cell walls of most plants. Cellulosic/woody biomass contains cellulose components.
Chips	Small fragments of wood chopped or broken by mechanical equipment. Total tree chips include wood, bark, and foliage. Pulp chips or clean chips are free of bark and foliage.
Co-firing	The use of a mixture of two fuels within the same combustion chamber.
Co-generation	The technology of producing electric energy and another form of useful energy (usually thermal) for industrial, commercial, or domestic heating or cooling purposes through the sequential use of the energy source.
Co-products	The resulting substances and materials that accompany the production of a fuel product.
Combined heat and power	An integrated system that generates both electricity and useful thermal energy simultaneously. More commonly referred to as CHP.
Combustion	A chemical reaction between a fuel and oxygen that produces heat (and usually light).
Energy crop	A commodity (crop) grown specifically for its fuel value. These include crops such as corn and sugarcane that are also grown for food, and nonfood crops such as poplar trees and switchgrass.

Fast pyrolysis	Pyrolysis in which reaction times are short, resulting in higher yields of certain fuel products, ranging from primary oils to olefins and aromatics, depending on the severity of conditions.
Feedstock	Any material used directly as a fuel, or converted to another form of fuel or energy product. Bioenergy feedstocks are the original sources of biomass. Examples of bioenergy feedstocks include corn, crop residues, and woody plants.
Fermentation	A biochemical reaction that breaks down complex organic molecules (such as carbohydrates) into simpler materials (such as ethanol, carbon dioxide, and water). Bacteria or yeasts can ferment sugars to ethanol.
Forestry residues	Includes tops, limbs, and other woody material not removed in forest harvesting operations in commercial hardwood and softwood stands, as well as woody material resulting from forest management operations such as pre-commercial thinnings and removal of dead and dying trees.
Greenhouse gas	A gas, such as water vapor, carbon dioxide, and methane, which contributes to the greenhouse effect.
Municipal solid waste (msw)	Any organic matter, including sewage, industrial, and commercial wastes, from municipal waste collection systems. Municipal waste does not include agricultural and wood wastes or residues.