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

2016 BILLION-TON REPORT
Advancing Domestic Resources
for a Thriving Bioeconomy

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2016 BILLION-TON REPORT

Advancing Domestic Resources for a Thriving Bioeconomy

A Study Sponsored by U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Bioenergy Technologies Office

Volume 1:
Economic Availability of Feedstocks

July 2016

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for the
U.S. DEPARTMENT OF ENERGY

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Availability

This report, as well as supporting documentation, data, and analysis tools, can be found on the Bioenergy Knowledge Discovery Framework at bioenergykdf.net. Go to https://bioenergykdf.net/billionton2016/reportinfo for the latest report information and metadata.

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Additional Information

The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office and Oak Ridge National Laboratory provide access to information and publications on biomass availability and other topics. The following websites are available:

energy.gov
eere.energy.gov
bioenergy.energy.gov
web.ornl.gov/sci/transportation/research/bioenergy/

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DISCLAIMER

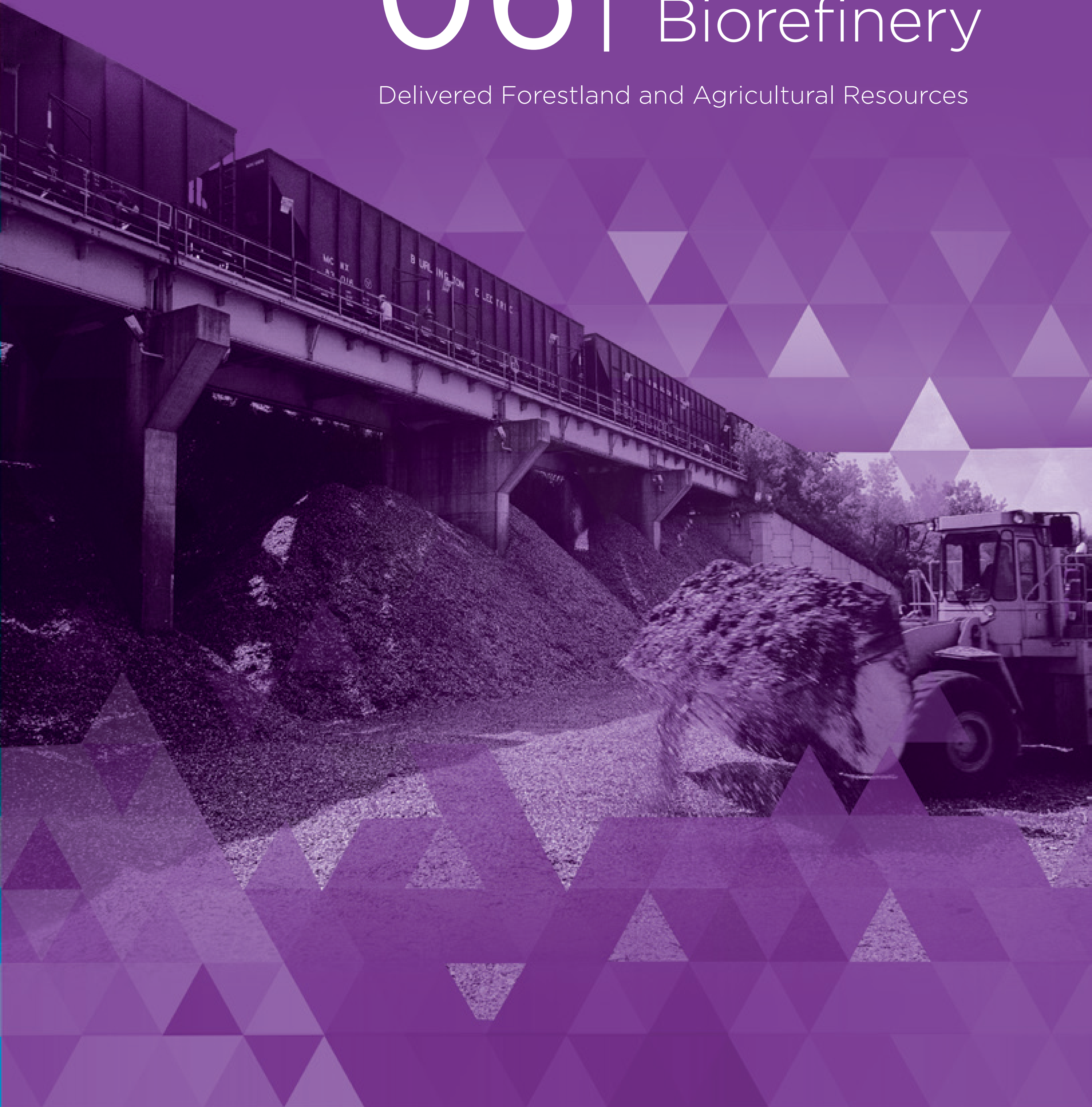
The authors have made every attempt to use the best information and data available, to provide transparency in the analysis, and to have experts provide input and review. However, the *2016 Billion-Ton Report* is a strategic assessment of potential biomass. It alone is not sufficiently designed, developed, and validated to be a tactical planning and decision tool, and it should not be the sole source of information for supporting business decisions. This analysis provides county by county estimates of the feedstocks at a selected cost, yet users should use associated information on the Bioenergy Knowledge Discovery Framework (bioenergykdf.net/billionton) to understand the assumptions and ramifications of using this analysis. The use of tradenames and brands are for reader convenience and are not, nor does their use imply, an endorsement by the U.S. Department of Energy or Oak Ridge National Laboratory.

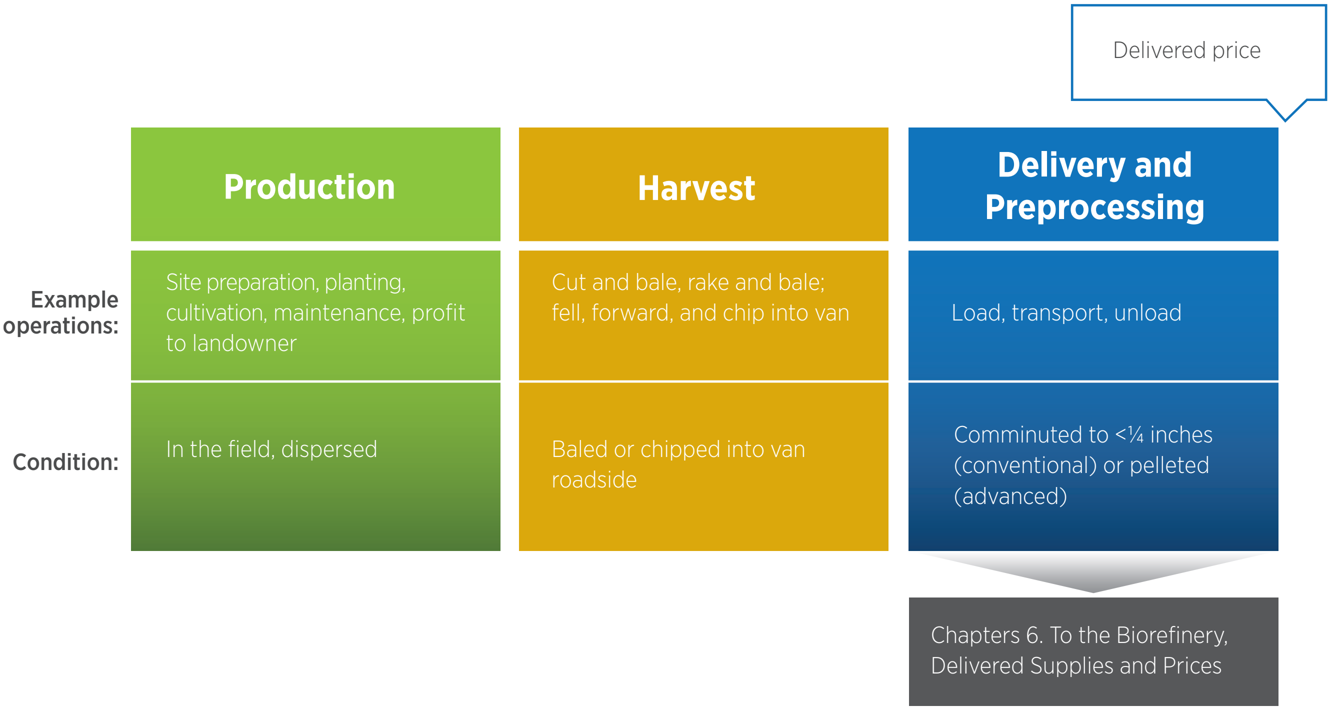
The foundation of the agricultural sector analysis is the USDA Agricultural Projections to 2024. From the report, "projections cover agricultural commodities, agricultural trade, and aggregate indicators of the sector, such as farm income. The projections are based on specific assumptions about macroeconomic conditions, policy, weather, and international developments, with no domestic or external shocks to global agricultural markets." The *2016 Billion-Ton Report* agricultural simulations of energy crops and primary crop residues are introduced in alternative scenarios to the 2015 USDA Long Term Forecast. Only 2015-2024 Billion-Ton national level baseline scenario results of crop supply, price, and planted and harvested acres for the 8 major crops are considered to be consistent with the 2015 USDA Long Term Forecast. Additional years of 2025–2040 in the *2016 Billion-Ton Report* baseline scenario and downscaled reporting to the regional and county level were generated through application of separate data, analysis, and technical assumptions led by Oak Ridge National Laboratory and do not represent nor imply U.S. Department of Agriculture or U.S. Department of Energy quantitative forecasts or policy. The forest scenarios were adapted from U.S. Forest Service models and developed explicitly for this report and do not reflect, imply, or represent U.S. Forest Service policy or findings.

The biomass supply projections presented in this report are policy independent and estimate the potential economic availability of biomass feedstocks using specified market scenarios and guiding principles intended to be conservative and to reflect certain environmental and socio-economic considerations. For example, some principles aim to maintain food availability and environmental quality, including improved tillage and residue removal practices, exclusion of irrigation, and reserved land areas to protect biodiversity and soil quality. In this sense, this report (volume 1) and related analyses on environmental effects (forthcoming in volume 2) may differ from other efforts seeking to depict potential biomass demand and related market, environmental and land use interactions under business-as-usual or specific policy conditions.

06 | To the Biorefinery

Delivered Forestland and Agricultural Resources





Delivered price

	Production	**Harvest**	**Delivery and Preprocessing**
Example operations:	Site preparation, planting, cultivation, maintenance, profit to landowner	Cut and bale, rake and bale; fell, forward, and chip into van	Load, transport, unload
Condition:	In the field, dispersed	Baled or chipped into van roadside	Comminuted to <¼ inches (conventional) or pelleted (advanced)

Chapters 6. To the Biorefinery, Delivered Supplies and Prices

Building a commercial-scale industry capable of achieving DOE cost and production targets for biofuels will require consideration of how feedstock supply systems impact the cost, quantity, and quality of feedstocks delivered to the biorefinery. This chapter adds transportation and logistics costs to the county-level feedstocks estimated in chapters 3, 4, and 5 to characterize the cost and quantity of feedstocks that could be available to biorefineries. The 2011 *BT2* was explicitly limited to analysis of feedstock costs at the farmgate and forest landing. Recognizing that commercialization of biomass-based industries requires a broader, systematic evaluation of feedstock supplies that accounts for the challenges of delivering feedstocks to the biorefinery, this scenario analysis has been added to illustrate how select feedstocks could be delivered from the roadside to the reactor throat.

6.1 Designing Commercial Feedstock Supply Systems

Mobilizing one billion tons of biomass to fully achieve a large-scale bioeconomy will require innovations along the feedstock supply chain. Much has been achieved in recent years to improve efficiency, reduce losses, and preserve quality. Further advances in biomass preprocessing to transform raw biomass into engineered feedstocks could revolutionize the industry and enable commercialization and expansion.

Biomass is a challenging feedstock on which to build industrial processes. Like all agricultural and forestry systems for production of food, feed, and fiber, supply systems designed to provide biomass for energy and other products must contend with material variability (both spatially and temporally), yield reductions caused by weather and pests, and degradation in storage. As supply systems for commodities and products, such as corn grain, produce, milk, livestock, and feed, have matured over time to preserve quality while reducing cost in the face of these external pressures, so, too, must cellulosic feedstock supply systems evolve by increasing efficiency, reducing material losses, and standardizing quality.

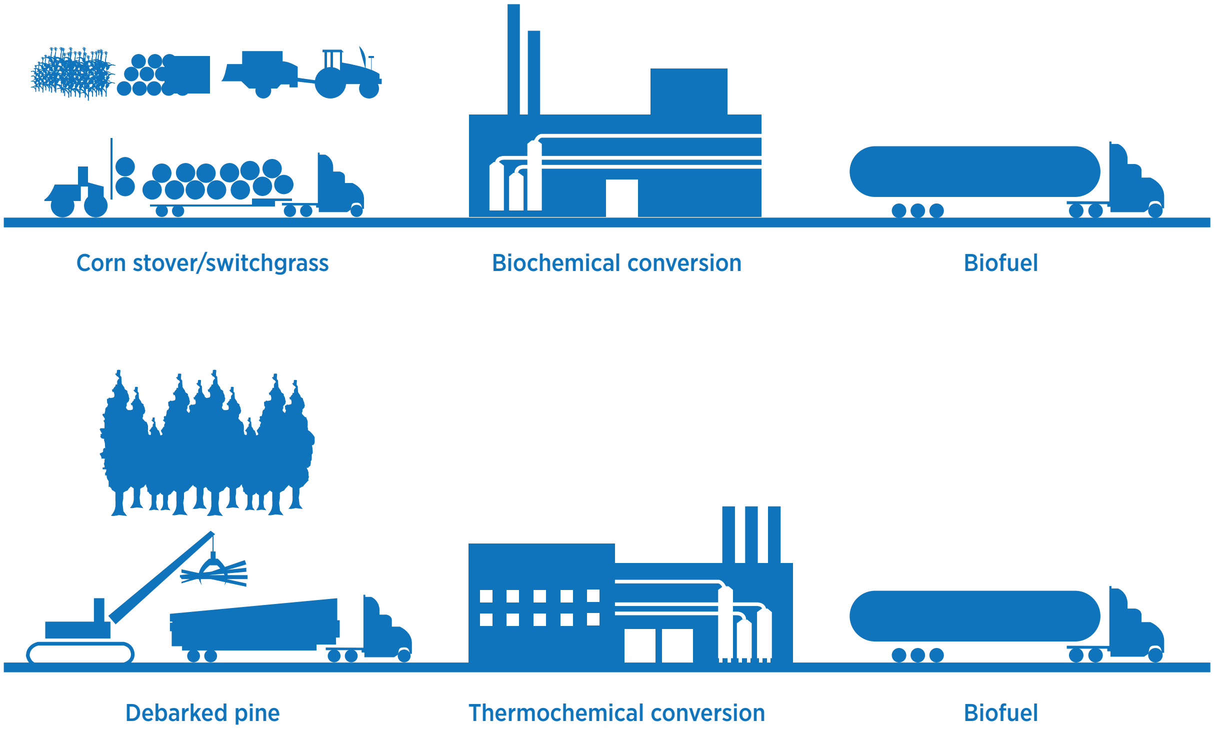
The following barriers to commercialization of feedstock supply systems were outlined by the Feedstock Logistics Interagency Working Group in its 2010 report (Biomass Research and Development Board 2010):

- Low mass and energy density with current harvest and collection equipment
- High biomass moisture content at the time of harvest, leading to degradation and decreased system efficiency
- Insufficient capacity and efficiency of currently available equipment for harvesting and preprocessing biomass
- Variable, inconsistent biomass quality upon arrival at the biorefinery
- Costly transportation options that can strain transportation networks.

The development of supply systems to overcome these challenges will enable mobilization of the more than one billion tons of biomass that was shown in chapters 3, 4, and 5 to be potentially available from agriculture, forestry, and waste resources.

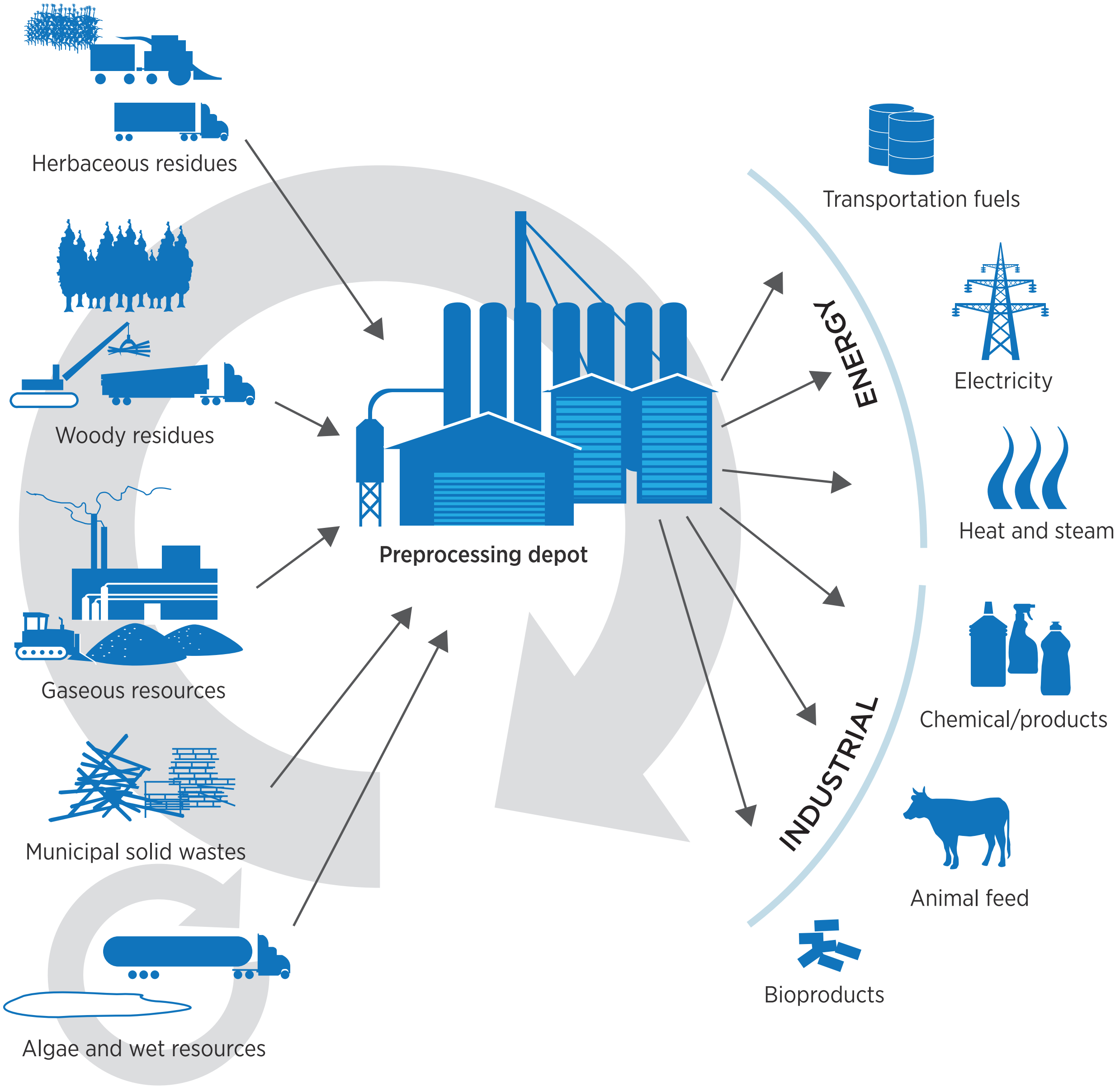
In the near term, design of conventional feedstock supply systems will continue to focus on supplying specified feedstock quantities at the lowest cost. Here, conventional supply systems use equipment that is designed for traditional agricultural and forestry systems. These passive systems have few to no active quality control strategies (an exception is debarking in some whole tree harvest systems). They rely on truck transport within a regional supply shed around the biorefinery. In conventional feedstock supply systems, as shown in figure 6.1, biorefineries accept only one feedstock type, either herbaceous bales (e.g., switchgrass or corn stover) or wood chips.

Figure 6.1 | Current feedstock supply systems are designed to deliver a single feedstock type (e.g., corn stover or switchgrass bales, or wood chips) to the biorefinery using technologies designed for traditional agricultural and forestry industries



(Image courtesy of Idaho National Laboratory)

Figure 6.2 | Proposed future feedstock supply system for transforming raw biomass into stable, tradeable commodities suitable for long-distance transport and handling in existing infrastructure



(Image courtesy of Idaho National Laboratory)

Success of the nascent cellulosic biofuel industry requires high-quality and consistent feedstock supplies to be competitive with more established biofuel and fossil fuel industries. Proposed advanced feedstock supply systems (example shown in fig. 6.2) are designed to meet those demands by transforming raw feedstocks that are aerobically unstable and highly variable into a high-density, flowable format that can be traded as a commodity. These commoditized feedstocks will be suitable for long-distance transportation by rail or barge, can be blended to meet custom requirements and handled in existing grain infrastructure, and have long-term stability in storage.

6.1.1 Improving Efficiency, Capacity, and Reliability

The first challenge to building a commercial-scale bioenergy feedstock supply industry is to develop supply systems capable of cost-effectively delivering increasing quantities of biomass as new biorefineries are constructed. Over the past decade, many modifications have been made to improve the efficiency and capacities of machines for feedstock supply systems, particularly in harvest, collection, preprocessing (including size reduction), handling, and transport. As the biofuel industry begins to expand, work continues to improve these machines—especially their reliability and productivity.

Harvesting biomass for energy is similar to harvesting other crops and resources, such as hay for animal feed, or saw logs. However, a few key differences make using conventional equipment to harvest, preprocess, and handle bioenergy feedstocks difficult and more expensive. Mowing and baling (packaging) high-yielding energy crops such as switchgrass or miscanthus—or corn stover, which has thick, stiff stalks and leaves—with machinery designed for traditional forage crops leads to high maintenance costs, increased downtime from plugging (Womac et al. 2012), shorter useful lifetimes, and expensive repairs. Machine capacities can also be limiting. Larger, faster machines with higher capacity, especially for operations such as collecting and hauling bales in the field or small-diameter trees in the forest, could reduce costs significantly.

Biomass, in both baled and ground form, is difficult to handle with conventional equipment. Picking up bales and placing them on a trailer individually is highly time-intensive and costly, particularly if the bale density is low. Conveying ground biomass has proved to be a significant challenge to biomass facilities. Moving raw biomass in ground or chopped form is difficult with conventional equipment and often results in significant maintenance costs and downtime.

Designing a cost-effective transportation system is also complicated, as suitable land on which biomass can be economically produced may not be concentrated near a utilization facility. Rather, many feedstocks are geographically dispersed, making transport to a biorefinery problematic and costly. Furthermore, the low-bulk density of cellulosic feedstocks exacerbates the transportation challenge, as trucks that are not fully loaded (by weight) travel long distances to deliver bioenergy feedstocks.

In recent years, manufacturers of forage and hay equipment have partnered with researchers from government and academia to modify balers, in-field bale-collection equipment, and trailers to better handle biomass, which can have significantly higher yields than conventional forage crops. Particularly notable improvements are increased bale density—which can significantly reduce transport, handling, and storage costs—and more efficient bale collection and loading. New technologies such as single-pass baling systems reduce machine and labor costs by eliminating operations and reducing the number of passes on the field during harvest. Similarly, forestry equipment manufacturers are responding to a need for equipment to better cut and remove small-diameter trees in thinning operations and to harvest trees purposely grown in plantations for energy.

High-Tonnage Logistics Demonstration Projects

In 2009, the DOE Biomass Program (now the Bioenergy Technologies Office) issued an announcement to fund five projects to develop and demonstrate supply systems for delivering high-tonnage biomass feedstocks (capable of supplying at least 100 million dry metric tons per year) for cellulosic ethanol production (see table 6.1). The primary goal of these projects was to reduce the logistics costs of bioenergy feedstocks delivered to the biorefinery. Projects were required to demonstrate feedstock harvest, collection, preprocessing, handling, transport, and storage and show the impact of these improvements on costs associated with logistics operations costs relative to a benchmark conventional system. These projects are just a sampling of how government-industry-academic partnerships are working together to reduce

Table 6.1 | Examples of How Recent Investments by the Bioenergy Technologies Office in Logistics Demonstration Projects Led to Significant Advances in Feedstock Supply Systems

Lead organization	Year awarded	Crop	Key technologies developed and demonstrated
AGCO Corp.	2010	Corn stover	• Single-pass harvesting • High-density baling • Trailer with automatic load securing
Auburn University	2009	Southern pine	• Tree-length harvesting • In-woods chipping • Transpirational drying • Tracked feller buncher with EPA-compliant engine • Skidder with extra-large grapple • Optimized chip trailer to maximize load weight
FDC Enterprises, Inc.	2010	Corn stover, switchgrass, miscanthus	• Self-propelled baler • High-density baling • Self-propelled bale pick-up truck • Self-loading/unloading trailer
TennEra, LLC	2010	Switchgrass	• Field chopping • Bulk handling • Bulk storage • Bulk compaction
State University of New York College of Environmental Science and Forestry	2010	Willow, poplar	• Single-pass cut-and-chip harvester • Chip handling • Rapid quality assessment methods

Table 6.1 *(continued)*

Lead organization	Year awarded	Crop	Key technologies developed and demonstrated
FDC Enterprises, Inc.	2013	Corn stover	• High-capacity bale movers • Improved harvest data collection and management • Rapid in-field quality assessment • High-density round balers • Horizontal grinder
University of Tennessee	2016	Southern pine, switchgrass	• Whole tree harvesting and delivery strategy • Merchandizing depot for trees • Online quality assessment • Feedstock blending to achieve quality specs
State University of New York (SUNY) College of Environmental Science and Forestry	2016	Willow, poplar	• Improved harvest and collection equipment utilization • Rapid quality assessment

feedstock logistics costs. There are many other efforts under way in companies, universities, and national laboratories across the United States with goals to improve feedstock logistics operations.

Teams led by AGCO and FDC Enterprises developed improved harvesting techniques for corn stover by increasing bale density, developing single-pass and self-propelled baling technologies, and developing advanced bale-collection and loading/unloading systems (see figs. 6.3 and 6.4). The AGCO and FDCE projects were successful in reducing the cost of baled corn stover by increasing the amount of biomass within each bale, reducing the number of operations required during harvest, and increasing the efficiency of loading bales onto trucks for transport out of the field and over the road. Implementing these new technologies is projected to reduce the delivered cost of corn stover by nearly 20%. AGCO project partners included Iowa State University, Stinger, Inc., Midwest Research Institute, Texas AgriLife Research, Oklahoma State University, Noble Foundation, and Idaho National Laboratory. Organizations working with FDC Enterprises included Antares Group, Inc., Kelderman Manufacturing, Inc., Allied Systems Company, MacDon, Inc., Abengoa Bioenergy New Technologies, Rotochopper, and Idaho National Laboratory.

A TennEra LLC-led team, including the University of Tennessee, Laidig Systems, and Marathon Equipment, developed an innovative system for harvesting, handling, transporting, and compacting forager harvester-chopped switchgrass. Bulk compaction, using equipment systems typically used for municipal and construction waste handling, achieved much improved bulk densities, and yet maintained the advantages of automated bulk flow. Although the cost of equipment to handle and store chopped switchgrass at the depot was significantly higher than the costs

Figure 6.3 | The single-pass corn stover baling system demonstrated by an AGCO-led team reduces baling costs by consolidating harvest operations, and reduces ash content by avoiding contact between the ground and the stover.

(Photo courtesy of Maynard Herron, AGCO)

Figure 6.4 | Advanced self-propelled baling technologies (top) coupled with new prototype bale-collection (middle) and loading/unloading equipment (bottom) developed by the FDC Enterprises team were successfully shown to improve baling and handling efficiency and reduce overall logistics costs.

(Photos courtesy of Kevin Comer, Antares Group, Inc.)

Figure 6.5 | In a project led by TennEra LLC, innovative technologies for (top) handling and (bottom) compacting forage harvester-chopped biomass increased bulk flow rates compared with tub-ground bales, resulting in reduced downstream processing and handling costs.

(Photos courtesy of Al Womac, University of Tennessee)

Figure 6.6 | A SUNY-led team developed a modified New Holland forage harvester and innovative wood chip field transport strategies to improve efficiency and reliability in harvesting willow and hybrid poplar.

(Photo courtesy of Tim Volk, SUNY College of Environmental Science and Forestry)

Figure 6.7 | An Auburn-led team developed improved equipment for felling (top), skidding (middle), chipping (bottom), and transporting wood chips from pine plantations

(Photos courtesy of Steve Taylor, Auburn University)

of on-farm bale storage, these costs were somewhat offset by increases in bulk flow rates and decreased investments and costs at the biorefinery (see fig. 6.5). The project provided a basis to further advance and optimally design dedicated equipment systems for economically supplying consistent-quality biomass feedstock to biorefineries.

Improving the reliability, capacity, and efficiency of harvesting and collecting wood chips from willow and hybrid poplar was the focus of a project led by the SUNY College of Environmental Science and Forestry working with Case New Holland, GreenWood Resources, and Mesa Reduction Engineering and Processing, Inc. The SUNY team modified equipment conventionally used for harvesting agricultural crops to efficiently deliver willow and poplar chips as bioenergy feedstocks (see fig. 6.6) and developed and demonstrated a short-rotation woody crop header for a commercially available forage harvester.

A team composed of Auburn University, the USDA Forest Service, Tigercat, and Corley Land Services, improved forestry equipment to reduce the costs of harvesting biomass from pine plantations by increasing the productivity of the feller buncher, skidder, and chipper, and increasing biomass transport efficiency (see fig. 6.7).

6.1.2 Preserving Feedstock Quality

As the feedstock supply industry expands and matures, biorefineries are expected to evolve from merely securing adequate quantities of feedstock as cheaply as possible to procuring feedstocks that meet quality specifications, so as to optimize feedstock handling and conversion performance. Feedstock quality is key to biorefineries' success, especially in the early years of their development, because meeting quality specifications consistently ensures high rates of conversion from biomass to biofuel, making refineries competitive with other biofuel producers (and even with fossil-fuel producers). Although cost and quantity will remain top priorities, it is expected that, like other agricultural and forestry-based industries, biorefineries will be willing to, within reason, pay more for feedstocks that are easier and less expensive to handle and convert.

Most analyses of bioenergy feedstock supply systems to date have focused on reducing delivered cost, with less emphasis on feedstock quality and consistency. This oversight has interfered with acquiring and handling adequate quantities of feedstock during system startup. As the priority of the bioenergy industries shifts from process development to deployment, attention will increasingly focus on meeting biomass quality specifications for such parameters as ash, carbohydrate, lignin, and moisture content and particle morphology (Kenney et al. 2013).

A guiding principle in the development of the proposed future feedstock supply system designs (DOE 2015) is incorporation of active quality-management technologies that transform raw, highly variable feedstocks into a tradeable commodity. Strategies for minimizing moisture and ash while preserving carbohydrates will be added along the supply chain, as will densification or conversion to liquids to produce intermediates that can be handled in existing storage, conveyance, and transportation infrastructure. The concept calls for the development of regional depots, typically 5 to 10 miles from production sites, where baled herbaceous biomass and/or wood chips would be converted to an intermediate commodity. Depots would be strategically located, with access to major highways, rail, or barges, to minimize long-distance transport to biorefineries or other appropriate markets. The commodities can then be transported to a biorefinery or other utilization facility. The improved handling characteristics of these intermediates make them suitable for blending with other feedstocks to produce custom recipes. Increased bulk density and handling characteristics make long-distance transport via rail or barge a more suitable option.

Bioenergy feedstock quality considerations are somewhat different from those of conventional uses of similar crops. Some biofuel conversion processes are highly sensitive to high ash content. Harvest techniques whereby biomass remains on the ground, as is the case in field drying, result in contamination by dirt, a significant source of ash in biomass. Harvest technique and soil type have a significant impact on the amount of ash (introduced as dirt) or other contaminants. For example, Bonner et al. (2014) observed that mean ash content of corn stover harvested from the same region varied from 11.5% to 28.2%. More aggressive collection techniques collect more of the available biomass, but cause greater soil disturbance. Thus, the benefits of increasing biomass throughput versus the effects of increasing the concentration of non-biological ash resulting from the entrainment of more soil and rocks must be considered when selecting harvest equipment and determining operational parameters.

Biomass moisture management during harvest and storage has significant impact on delivered biomass quality and dry-matter loss. Some bioenergy crops, such as energy sorghum, do not dry well in the field, so harvest, storage, and handling strategies in high-moisture environments are needed. In many regions, ambient weather conditions during harvest inhibit field drying. Field drying is not an option for new single-pass harvest technologies designed to reduce ash content and increase harvest efficiency.

Aerobic respiration during storage, which increases as available water increases, results in the loss of desired chemical components. Storage configurations that allow drying and prevent the entry of additional moisture reduce dry-matter losses. For example, in an untarped dry stack, moisture from precipitation is allowed to accumulate on the top bale. Over extended periods, this moisture accumulation results in high levels of biological activity, which causes loss of feedstock from degradation and bale instability. Dry matter loss also tends to destabilize bale stacks, causing them to topple.

Feedstock quality varies by genetics, location, year, weather, harvesting technology, anatomical fraction, and agronomic treatments. Optimizing the design of a particular feedstock supply system requires a detailed understanding of feedstock variability at a local level to assess the viability of specific feedstock resources for specified conversion processes. Such changing conditions as water availability, local production practices, and weather conditions further complicate matters and can have significant effects on quality.

6.1.3 Reducing Risk along the Feedstock Supply System

Risk is another increasingly important consideration for biorefineries. Risk associated with feedstock supply, financing availability, fire, and safety increases the likelihood of operational disruptions and exposes a biorefinery to higher insurance premiums and, in the case of fire and safety, potential litigation. Designing and operating feedstock supply systems to minimize risk will enable industry expansion. Neglecting risks will discourage investment in new facility construction and drive up costs by increasing operational disruptions and liability.

Feedstock supply uncertainty may limit financing options for a biorefinery, as this will be perceived as a major risk by investors (DOE 2015). Higher interest rates may be imposed, which could significantly increase biorefinery capital investment costs, resulting in higher biofuel production costs. Supply systems must be designed to contend with a number of risk factors associated with feedstock availability, including drought or other inclement weather events, pest damage, lack of producer participation, and competing demands. A pioneer biorefinery near a highly concentrated feedstock is particularly susceptible to feedstock availability risk, as its entire feedstock supply area would be affected by the same external risk factors.

Current options for addressing these risks include overcontracting to secure more feedstock than the biorefinery requires (which will help avoid outages) or downscaling production during feedstock shortages. Both options, although sometimes necessary in the mid-term, are cost-prohibitive for industry expansion. In the long term, advanced supply systems to develop a stable, tradeable commodity that can be transported long distances will alleviate many of these risks, as biorefineries will have more cost-effective options for purchasing feedstocks from beyond their immediate supply sheds (Hansen and Searcy 2015).

Fire is another risk facing bioenergy feedstock supplies; it may not only cause feedstock shortages, but, more importantly, can inflict harm on people and property at the biorefinery or in the surrounding community. The current strategies for minimizing fire risk include spacing biomass stacks and piles far from other structures to reduce the likelihood of fire spread, and securing the area to minimize arson, a leading cause of biomass fires. Research to better understand fire behavior in biomass storage stacks will lead to advanced storage systems—such as high-moisture storage—and biomass formats that reduce the risk of fire spread and minimize the threat of harm to people and property. The threat of fire can never be fully eliminated; rather, efforts to improve storage and handling design should concentrate on minimizing fire spread. Feedstock shortages due to fire can be reduced in the same manner as are other feedstock shortages—by improving access to feedstocks from a broader supply area.

6.2 Approach to Quantifying the Delivered Costs of Biomass Resources

To estimate the costs of biomass resources delivered to the biorefinery reactor throat, the Supply Characterization Model (SCM), a geographically based modeling system for allocating feedstock supplies to potential utilization facilities and calculating the delivered price and quantity of the supplies, was used to simulate feedstock transport from source to destination facility (Webb et al. 2014). Costs of unit operations (storage, size reduction, and handling) and dockage (additional charges incurred for disposal of feedstocks that do not meet quality specifications) were derived from previous studies (Cafferty et al. 2014; Kenney et al. 2014). Locations of utilization facilities are based on minimizing the average total feedstock cost. Facility locations are selected iteratively, in order of increasing total delivered cost, until all of the available supply is used.

For each feedstock, SCM requires five logistics cost estimates—(1) production costs, (2) other logistics costs (storage, handling, and preprocessing), (3) time transportation cost, (4) distance transportation cost loaded, and (5) distance transportation cost empty. Production costs include operations on the farm (corn stover and perennial grass), at the landing (pulpwood and woody residues), or at the sorting facility (construction, demolition, and yard waste), along with the grower payment (herbaceous feedstocks) or stumpage price (woody feedstocks). Transportation cost is divided into time- and distance-based components. Here, the distance component of transportation cost, namely fuel, varies by the distance traveled. The time cost accounts for the capital cost of the truck and labor cost. Fuel economy is known to change with payload, so distance transportation costs are estimated for fully loaded trucks going to the facility and for empty trucks on the backhaul. The other logistics cost parameter includes the costs of all other operations along the supply chain, such as storage, handling, and preprocessing.

The quantities of available feedstock for the SCM analyses presented here are the county-level biomass production estimates (dry tons/county for each feedstock) discussed in chapters 3, 4, and 5, for a near-term scenario (using the 2022 resource base) and a long-term scenario (2040 resource base). The production estimates for agricultural resources represent materials available at an offered farmgate price of $60 per ton. Production estimates for forestry resources are materials available with stumpage plus harvest costs of $60 per ton (or less) selected from the ForSEAM simulation results that had the highest demand level in all years of the simulation (see chapter 3). Associated with each production level was a roadside cost that includes production, harvest, and transport to the landing or field edge. An estimated profit (10% of production and harvest costs) was included for the agricultural resources.

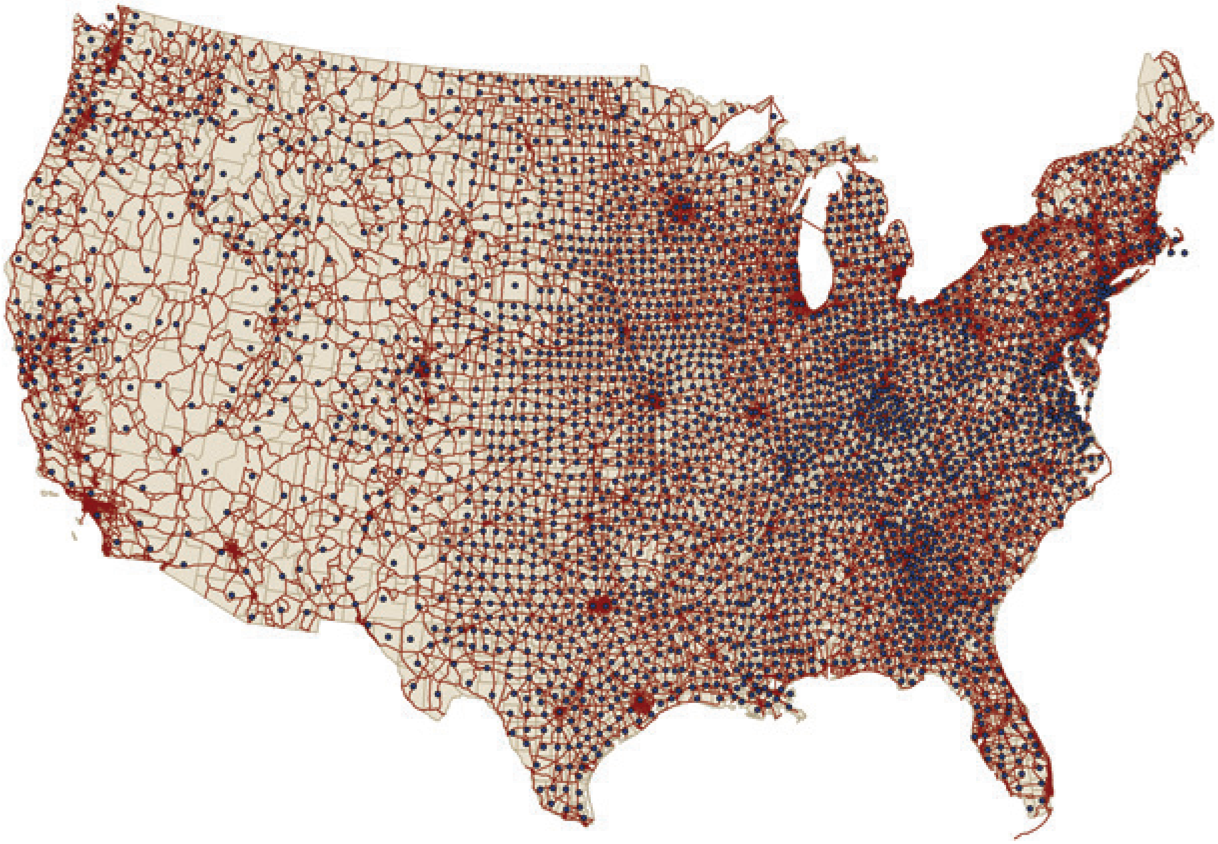
The road transportation network used for these analyses was version 11.09 of the 2013 National Highway Planning Network, a 1:100,000 scale geospatial database representing approximately 450,000 miles of principal arterial and rural minor arterial roads in the United States. Road speeds were assigned to each segment of the road network as described in Webb et al. (2014).

The county feedstock estimates used in the near-term and the stage 1 long-term scenarios (farm or forest to depot) were assigned to their county centroids. Potential facilities (depots and refineries) were restricted to points in a 50-mile spaced grid superimposed on the 2013 National Highway Planning Network road network. The corresponding grid points were then linked to the nearest node in the road network (as shown in fig. 6.8).

6.2.1 Near-Term Feedstock Supply System Modeling Assumptions

In this analysis, near-term or conventional feedstock supply systems use commercially available equipment. The primary goal is to supply the specified quantities at minimal cost. These systems do not include active quality-management strategies; rather, the challenges of dealing with feedstocks that do not meet quality specifications are accounted for in dockage fees applied to the total delivered cost to account for disposal of off-specification material. The model is designed to secure additional feedstock to compensate for off-specification biomass and to fully meet the biorefinery demand.

Figure 6.8 | Potential biorefinery and depot locations for these analyses derived by restricting utilization facilities to a 50-mile grid snapped to nearest highway network intersections



The SCM simulates the near-term scenario by modeling transport of baled herbaceous biomass or wood chips from the county centroid to a biorefinery by truck. For this analysis, the annual biorefinery demand is assumed to be 800,000 tons per year, based on analysis by Argo et al. (2013) and Muth et al. (2014), to optimize the cost per gallon of fuel by considering the tradeoffs between feedstock transport distance and biorefinery economy of scale. Logistics costs for storage, preprocessing, and handling are adapted from 2013 state of technology estimates by Kenney et al. (2014) and Cafferty et al. (2014). It should be noted that harvest and in-field transportation costs were accounted for in roadside cost estimates developed in chapters 3, 4, and 5.

It is assumed that biorefineries with no active quality control can accept only one feedstock type. Dockage fees are applied to delivered costs to represent the costs of disposing of feedstocks that do not meet quality specifications for moisture and ash. Tables 6.2 and 6.3 show estimated dockage fees by feedstock. The ash-dockage fee was calculated based on Bonner et al. (2014) and Bonner and Kenney (2013); moisture dockage fees for herbaceous feedstocks were derived from Kenney et al. (2014). Moisture dockage fees were not applied to woody feedstocks, because it was assumed that they would not be stored long term.

Table 6.2 | Estimating Dockage Fees for Herbaceous Feedstocks

	Corn stover	Switchgrass	Miscanthus	Sorghum	Yard trimmings
Initial ash (%)	7%	6%	4%	7%	10%
Ash dockage fee ($/dry ton)	$2.71	$2.33	$1.55	$2.71	$3.88
Moisture at harvest (%)	20%	15%	15%	40%	20%
Moisture dockage fee ($/dry ton)	$3.36	$3.36	$3.36	$6.72	$3.36

Table 6.3 | Estimating Ash Dockage Fees for Woody Feedstocks

	Whole tree chips	Logging residues	Urban wood waste	Woody energy crops	Construction and demolition waste
Initial ash (%)	1%	4%	4%	2%	1%
Ash disposal cost ($/dry ton)	$0.23	$1.55	$1.55	$0.78	$0.39

Costs for the near-term feedstock supply scenario are described below by operation for corn stover, switchgrass, miscanthus, and energy sorghum, and in tables 6.4 and 6.5.

- **Corn stover:** Following harvest, large, rectangular bales of corn stover are collected from the field and stacked along the farm edge, covered with tarps, and stored until needed by the biorefinery. It is assumed that stover is allowed to field dry to less than 20% moisture content before baling. In reality, weather conditions in some regions during corn harvest are not suitable for field drying, and high-moisture storage systems or mechanical dyers are needed. Future resource-assessment analyses will account for the regional impacts of moisture on the selection of stover harvest strategies. When stover bales are needed by the biorefinery, bales are removed from storage stacks, placed on flatbed trailers, and transported to the biorefinery. Bales are stored temporarily at the biorefinery (≤5 days) and passed through a grinder before entering the conversion process.
- **Switchgrass:** The switchgrass supply chain is much like that for stover, in that the large, rectangular bales of switchgrass are stacked, covered with tarps, and stored on the farm edge until called for by the biorefinery. Bales are transported by trucks with flatbed trailers to the biorefinery, where they are stored temporarily before being ground. It is assumed that the moisture content of switchgrass is 10% to15%, as harvest occurs after the first killing frost, when moisture content declines rapidly.

Table 6.4 | Logistics and Transportation Cost Assumptions for Herbaceous Feedstocks Supplied to a Biorefinery in the Near-Term Scenario

Corn stover		Switchgrass	
Logistics costs ($/dry ton)			
Storage on farm	$3.92	Storage on farm	$3.92
Loading/unloading truck	$3.24	Loading/unloading truck	$3.24
Storage at biorefinery	$1.57	Storage at biorefinery	$1.57
Grinding	$14.00	Grinding	$14.00
Dockage, moisture	$3.36	Dockage, moisture	$3.36
Dockage, ash	$2.71	Dockage, ash	$2.33
Total	**$28.80**	**Total**	**$28.41**
Transportation costs ($/dry ton)			
Time cost ($/dry ton/hour)			$3.90
Distance cost, loaded ($/dry ton/mile)			$0.038
Distance cost, empty ($/dry ton/mile)			$0.027
Biomass sorghum		**Miscanthus**	
Logistics costs			
Module building	$8.29	Storage on farm	$3.92
Storage	$3.92	Loading/unloading truck	$3.24
Loading/unloading truck	$7.17	Storage at biorefinery	$1.57
Storage at biorefinery	$1.57	Grinding	$14.00
Grinding	$8.29	Dockage, moisture	$3.36
Dockage, moisture	$6.72	Dockage, ash	$1.38
Dockage, ash	$2.71	**Total**	**$27.47**
Total	**$38.67**		

Table 6.4 ***(continued)***

Corn stover		Switchgrass	
Transportation costs			
Time cost ($/dry ton/hour)	$3.20	Time cost ($/dry ton/hour)	$3.90
Distance cost, loaded ($/dry ton/mile)	$0.033	Distance cost, loaded ($/dry ton/mile)	$0.038
Distance cost, empty ($/dry ton/mile)	$0.022	Distance cost, empty ($/dry ton/mile)	$0.027

Table 6.5 | Logistics and Transportation Cost Assumptions for Woody Feedstocks Supplied to a Biorefinery in the Near-Term Scenario

Whole tree chips		Logging residues	
Logistics costs ($/dry ton)			
Hammer mill (second-stage grind)	$19.14	Hammer mill (second-stage grind)	$19.14
Dockage, ash	$1.38	Dockage, ash	$1.55
Total	**$20.53**	**Total**	**$20.69**
Woody crops—coppice		**Woody crops—non-coppice**	
Hammer mill (second-stage grind)	$19.14	Hammer mill (second-stage grind)	$19.14
Handling	$3.25	Dockage, ash	$0.78
Dockage, ash	$0.78	**Total**	**$19.92**
Total	**$23.16**		
Urban wood waste		**Construction and demolition waste**	
Logistics costs ($/dry ton)			
Hammer mill (second-stage grind)	$19.14	Chipper	$6.83
Dockage, ash	$1.55	Hammer mill (second-stage grind)	$15.65
Total	**$20.69**	Dockage, ash	$0.39
		Total	**$22.87**

Table 6.5 *(continued)*

Transportation costs	
Time cost ($/dry ton/hour)	$4.24
Distance cost, loaded ($/dry ton/mile)	$0.046
Distance cost, empty ($/dry ton/mile)	$0.028

Note: Costs for chipping woody biomass at the source or landing are included in roadside costs estimates (see chapters 3, 4, and 5).

- **Miscanthus:** Supply systems for miscanthus bales (also large, rectangular bales) from storage to delivery at the conversion reactor are the same as for switchgrass and corn stover bales. The delivered costs, however, are lower than for stover and switchgrass, as the average miscanthus ash content is assumed to be 3.5%, which is lower than the 5% biorefinery specification.
- **Energy sorghum:** Unlike stover, switchgrass, and miscanthus, energy sorghum is not easily field-dried, making it a challenge to bale conventionally. This analysis assumed a promising system investigated by An and Searcy (2012) and Searcy, Hartley, and Thomasson (2014) for assembling field-chopped sorghum into large modules (similar to cotton modules) for storage and transport. The large, plastic-wrapped modules are stored along the field edge. When they are needed, a specialized module hauler loads two modules onto a flatbed trailer for transport to the biorefinery. The sorghum has been harvested by a field chopper; ergo, no grinding operation is needed at the biorefinery.
- **Woody resources:** Woody biomass is transported as wood chips from the landing or plantation edge to the biorefinery via chip truck.

A widely recognized weakness of current feedstock supply systems is their inability to deal with risk to feedstock availability (DOE 2015). Such risks include low crop yield due to drought or pests, crop losses during such extreme weather events as floods or hurricanes, fire, and competition for other uses. To address this risk, it is assumed here that biorefineries will secure contracts for a feedstock supply greater than their operational demand to minimize the likelihood of process downtime. This approach is supported by analysis by Golecha and Gan (2016), who demonstrated that biorefineries can mitigate the impacts of year-to-year variations in available stover by maintaining a supply region that is larger than exactly what is needed to feed the biorefinery under average yield conditions. Using U.S. corn yield data since 1975, Golecha and Gan determined that the optimal structure using current supply chain technologies is a supply region where, on average, only 63% of collectable stover is used to supply the biorefinery. The remaining supply area is available each year in case of reduced feedstock availability. A supply buffer of 25% was applied to herbaceous feedstocks supplied via a near-term supply chain in the SCM. This buffer was based on the study by Golecha and Gan (2016), along with the additional assumption that annual variability in perennial energy crop yields is less than that of stover (Langholtz et al. 2014).

It also took into consideration that in most years, a portion of the stover will be available for carryover to the following year. The 25% supply buffer means that no more than 75% of the available supply is used to feed the biorefinery. A supply buffer of 10% was applied to woody feedstocks, based on current estimates of the amount of feedstock that pulp and paper mills keep on hand to avoid supply disruptions.[1]

6.2.2 Long-Term Feedstock Supply Chain Modeling Assumptions

The long-term scenario considered for 2040 assumes that all feedstocks are delivered via advanced feedstock supply systems with regional depots that convert raw feedstocks into pellets. Although in reality long-term supply chain designs will vary depending on feedstock availability, regional conditions, and biorefinery design, a single future supply chain design was selected for simulation here. The model assumes that baled herbaceous feedstocks (stover, switchgrass, miscanthus, and sorghum) are baled and transported by flatbed trailer to a regional depot for drying and densification. Wood chips are similarly transported from the landing or plantation to the depot by chip truck. At the depot, feedstocks are dried and processed into pellets by a high-moisture pelletization process described by Lamers et al. (2015). While this pelletization technology is not yet viable at commercial scale, it provides a reasonable estimate of the costs of future depot-processing technologies. For the purposes of this analysis, pellets are transported by truck from depots to large biorefineries.

For this analysis, the SCM is used twice for each long-term supply chain: once for simulating the transport of raw feedstocks from the county centroid to the depot (with demand of 80,000 dry tons/year), and again for the transport of pelleted feedstocks from the depot to the biorefinery (with a feedstock demand of 800,000 dry tons/year); see tables 6.6, 6.7, and 6.8. Logistics costs for storage, preprocessing, and handling are adapted from the 2017 cost targets developed by Kenney et al. (2014) and Cafferty et al. (2014). Note that harvest and in-field transportation costs were accounted for in roadside cost estimates from chapters 3, 4, and 5.

The long-term feedstock supply systems include improvements over the near-term supply systems, described in section 6.2.1, to better address risk to feedstock availability and deal with biomass that does not meet quality specifications. A primary goal of the future feedstock supply chain presented here is to create commoditized feedstocks—with standard quality characteristics—that can be transported farther and traded in the same manner as commodities such as corn grain. Although advanced preprocessing operations at depots will require additional energy and add cost, active quality controls—such as drying and blending—will significantly reduce or eliminate dockage fees. This system should also eliminate the need for the supply buffer added in the SCM simulations of near-term systems to account for the additional feedstock contracts that biorefineries must secure to reduce the risk of feedstock supply shortages.

In the SCM analysis of long-term feedstock supply systems, biorefineries are designed to accept any pelleted feedstock. Recognizing that the chemical natures of some feedstocks are better suited for particular conversion processes, this analysis allows herbaceous feedstocks (stover, switchgrass, miscanthus, and sorghum) to be blended together for biorefineries with biochemical conversion processes, and woody feedstocks to be blended for thermochemical biorefineries. This is oversimplified, as some feedstocks, such as miscanthus, are suitable for both biochemical and thermochemical conversion processes, and there may be conversion designs that call for blend-

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[1] Steve Kelley, 2015, personal communication to Erin Webb, Oak Ridge National Laboratory. December 9, 2015.

Table 6.6 | Logistics and Transportation Cost Assumptions for Herbaceous Feedstocks Supplied to a Local Preprocessing Depot

Corn stover		Switchgrass	
	Logistics costs ($/dry ton)		
Storage on farm	$3.92	Storage on farm	$3.92
Loading/unloading truck	$3.24	Loading/unloading truck	$3.24
Dockage, moisture	$3.36	Dockage, moisture	$3.36
Total	**$10.52**	**Total**	**$10.52**
Biomass sorghum		Miscanthus	
	Logistics costs ($/dry ton)		
Module building	$8.29	Storage on farm	$3.92
Storage	$3.92	Loading/unloading truck	$3.24
Loading/unloading truck	$7.17	Dockage, moisture	$3.36
Dockage, moisture	$6.72	**Total**	**$10.52**
Total	**$26.10**		
	Transportation costs		
Time cost ($/dry ton/hour)			$3.83
Distance cost, loaded ($/dry ton/mile)			$0.037
Distance cost, empty ($/dry ton/mile)			$0.027

Table 6.7 | Logistics and Transportation Cost Assumptions for Woody Feedstocks Supplied to a Local Preprocessing Depot

Short-rotation woody crops	
Logistics costs ($/dry ton)	
Handling	$3.25
Transportation costs	
Time cost ($/dry ton/hour)	$4.24
Distance cost, loaded ($/dry ton/mile)	$0.046
Distance cost, empty ($/dry ton/mile)	$0.028

Table 6.8 | Logistics and Transportation Cost Assumptions for Densifying Feedstocks at a Depot and Delivering to a Biorefinery

Corn stover/switchgrass/miscanthus		Biomass sorghum	
Logistics costs ($/dry ton)			
Grinding	$14.00	Grinding	$8.29
Drying	$6.27	Drying	$6.27
Densifying	$4.93	Densifying	$4.93
Handling	$2.13	Handling	$2.13
Storage at biorefinery	$0.47	Storage at biorefinery	$0.47
Total	**$27.80**	**Total**	**$22.09**
Whole tree chips/logging residues/ non-coppice/energy crops/waste		**Coppice woody energy crops**	
Logistics costs ($/dry ton)			
Hammer mill (second-stage grind)	$19.14	Drying	$6.27
Drying	$6.27	Densifying	$4.93
Densifying	$4.93	Handling	$2.13
Handling	$2.13	Storage at biorefinery	$0.47
Storage at biorefinery	$0.47	**Total**	**$13.80**
Total	**$32.94**		
Transportation costs			
Time cost ($/dry ton/hour)			$3.35
Distance cost, loaded ($/dry ton/mile)			$0.032
Distance cost, empty ($/dry ton/mile)			$0.022

ing herbaceous and woody feedstocks. Here, these groupings of herbaceous and woody feedstocks are based primarily on minimizing the cost of receiving equipment to handle either baled or chipped biomass at the depot.

6.3 Results and Discussion

A scenario analysis was conducted using the SCM to estimate the delivered costs of herbaceous feedstocks (biomass sorghum, corn stover, miscanthus, switchgrass, and yard trimmings) for a biochemical conversion refinery and woody feedstocks (whole tree chips, logging residues, short-rotation woody crops, urban wood waste, and construction and demolition waste) for a thermochemical conversion refinery using primarily conventional systems in the near term and primarily advanced systems in the long term. In the near-term scenario, bales and wood chips are delivered directly to the biorefinery with no active quality management along the supply chain. Each biorefinery is limited in the types of feedstocks it can accept; a dockage fee is applied to feedstocks that do not meet specifications for ash and for losses due to higher-than-desired moisture content. The long-term scenario includes regional depots for transforming baled biomass and wood chips into a stable, tradeable commodity suitable for long-distance transport.

Table 6.9 and figure 6.9 show the marginal delivered costs and annual quantities of select herbaceous and woody bioenergy feedstocks using the available resources (from chapters 3, 4, and 5) for the base case (1% annual yield increase for agricultural and woody energy crop resources) and a high-yield (3% annual yield increase) scenario. For the purposes here of a scenario analysis to approximate delivered costs, logistics costs are based on 2013 feedstock supply system state-of-technology assessments for near-term systems and 2017 targets for future, advanced systems.

This analysis projects that with the base-case yield scenario, near-term systems could deliver approximately 139 million tons at a marginal cost below the DOE $84 per ton cost target (2014$) while long-term systems supply 249 million tons. Here, marginal cost is defined as the additional cost of incorporating feedstock from an additional county. Including delivered costs up to $100 per ton, still considered to be economically feasible given the uncertainty in simulation results and the potential for reducing logistics costs with technology improvements, brings the quantity up to 194 (near term) and 465 (long term) million tons. Adding the biomass resources of chapters 2, 3, 4, and 5 not considered in this logistics analysis, the total quantity of available feedstock increases to 710 and 981 million tons in the near and long term, respectively. Achieving the higher-yield scenario increases future availability to 742 million tons coming in below $100 per ton.

It may also be helpful to consider not only the marginal delivered costs, but also the quantity weighted running average as shown in figure 6.10 and table 6.10. The quantity weighted average provides an estimate of feedstock costs across all regions. Considering the quantity weighted average cost, 217 and 467 million tons are available at the DOE programmatic target of $84 per ton in the base-case scenario in 2022 and 2040, respectively. In the long-term high-yield scenario, total feedstock quantities less than $84 per ton increase to 825 million tons.

Figures 6.11, 6.12, and 6.13 summarize the quantities of feedstocks delivered to the reactor throat at less than $84 per ton, quantities delivered at between $84 and $100 per ton, and the portion available at the roadside that is unused. Unused portions are those that would be delivered at a cost greater than $100 per ton, are lost along the supply system because of biological degradation or mechanical losses, or are part of the overcontracting buffer included in near-term systems to mitigate supply variability. These diagrams also show the portions of each feedstock type considered that fall in these three delivered categories. In the near-term scenario (fig. 6.11), corn stover and forest resources are the only feedstocks that meet delivered cost targets. This is to be expected considering that dedicated energy crops (e.g., switchgrass, miscanthus, willow) are not planted in this analysis until 2019. Given the single-feedstock constraint imposed on near-term supply systems in this analysis, spatial density of dedicated energy crops in the near term leads to longer transport distances. In reality, energy crop plantings will be strategically clustered to reduce transport distance, a factor not accounted for here. In time, as production of these feedstocks expands, so does their contribution to the feedstocks that meet delivered cost targets, as shown in figure 6.12 for 2040. Their impact increases even more if higher yields can be achieved (fig. 6.13).

Table 6.9 | Feedstocks Available at Marginal Roadside Cost and Delivered Costs of $84 and $100 per Ton

	Herbaceous[a]		Woody[b]		Total	
	Near term	Long term	Near term	Long term	Near term	Long term
Base-case yield scenario (million tons)						
Roadside at ≤$60	184	497	126	182	310	679
Delivered ≤$84	51	198	88	52	139	249
Delivered ≤$100	99	367	95	98	194	465
Unused[c]	85	130	31	84	116	214
High-yield scenario (million tons)[d]						
Roadside at ≤$60	N/A	754	N/A	232	N/A	985
Delivered ≤$84		419		109		528
Delivered ≤$100		588		154		742
Unused[c]		166		77		243

Note: Including resources not accounted for in this delivered cost analysis brings the total available annual feedstock supply to more than one billion tons.

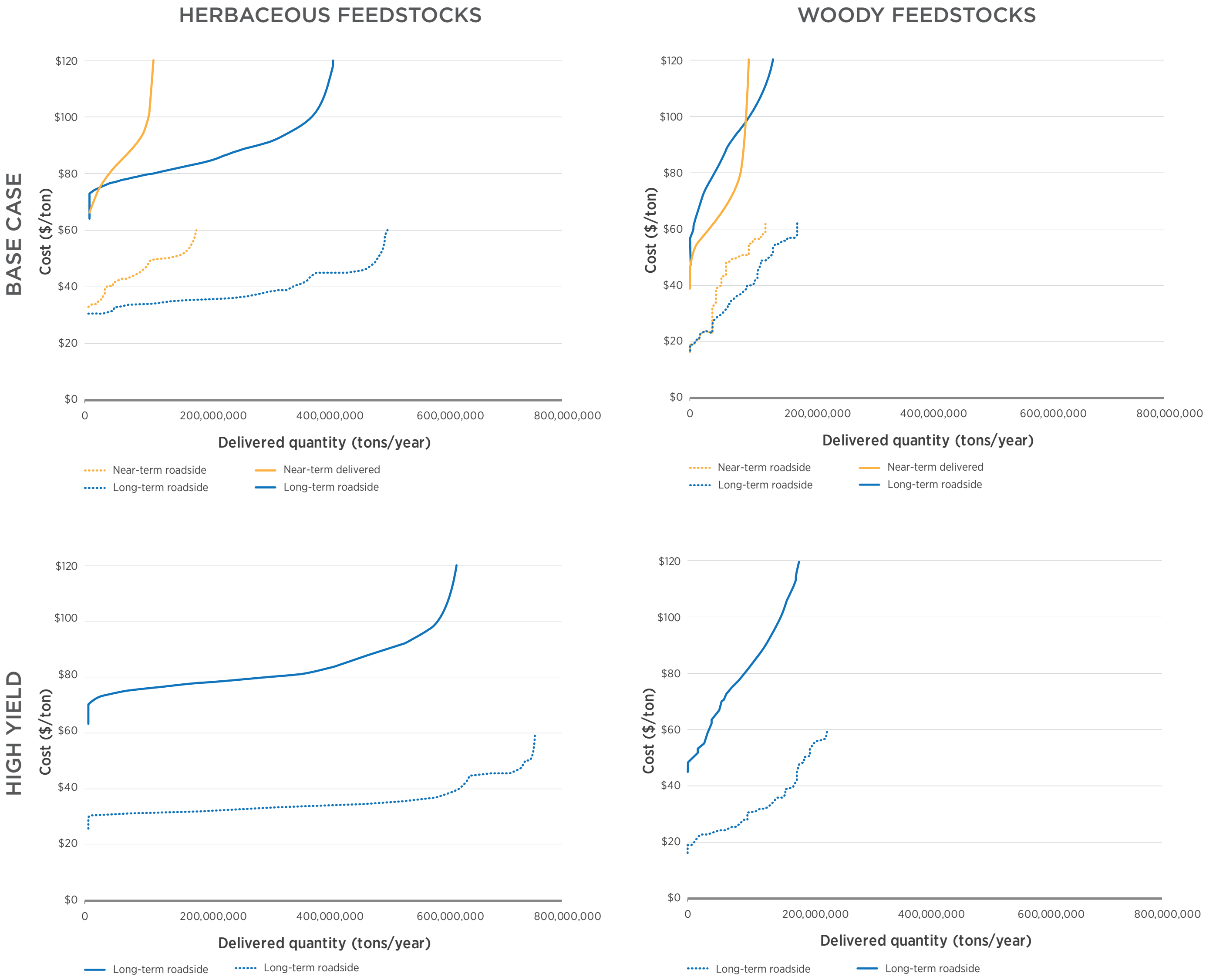
[a] Biomass sorghum, corn stover, miscanthus, switchgrass, and yard trimmings.

[b] Whole trees, logging residues, woody portions of C&D and MSW, and woody energy crops.

[c] Unused resources are those delivered at greater than $100 per ton, lost along the supply chain, or part of the overcontracting buffer included in the near-term systems to mitigate supply risk.

[d] A high-yield scenario was not considered for near-term resources, as there would be only minimal impact within such a short time frame.

Figure 6.9 | Marginal costs ($/dry ton) of select herbaceous (biomass sorghum, corn stover, miscanthus, switchgrass, and yard trimmings) and woody (whole trees, logging residues, woody portions of C&D and MSW, and woody energy crops) feedstocks at the roadside and delivered to the reactor throat



Note: Currently used resources from agriculture and forestry (chapter 2) and agricultural wastes (chapter 5) totaling 516 million tons for the base yield case (567 for high yield) are not included in this analysis.

Figure 6.10 | Marginal and weighted average costs ($/dry ton) of select herbaceous and woody feedstocks at the roadside and delivered to the reactor throat in the near and long term for a base yield scenario

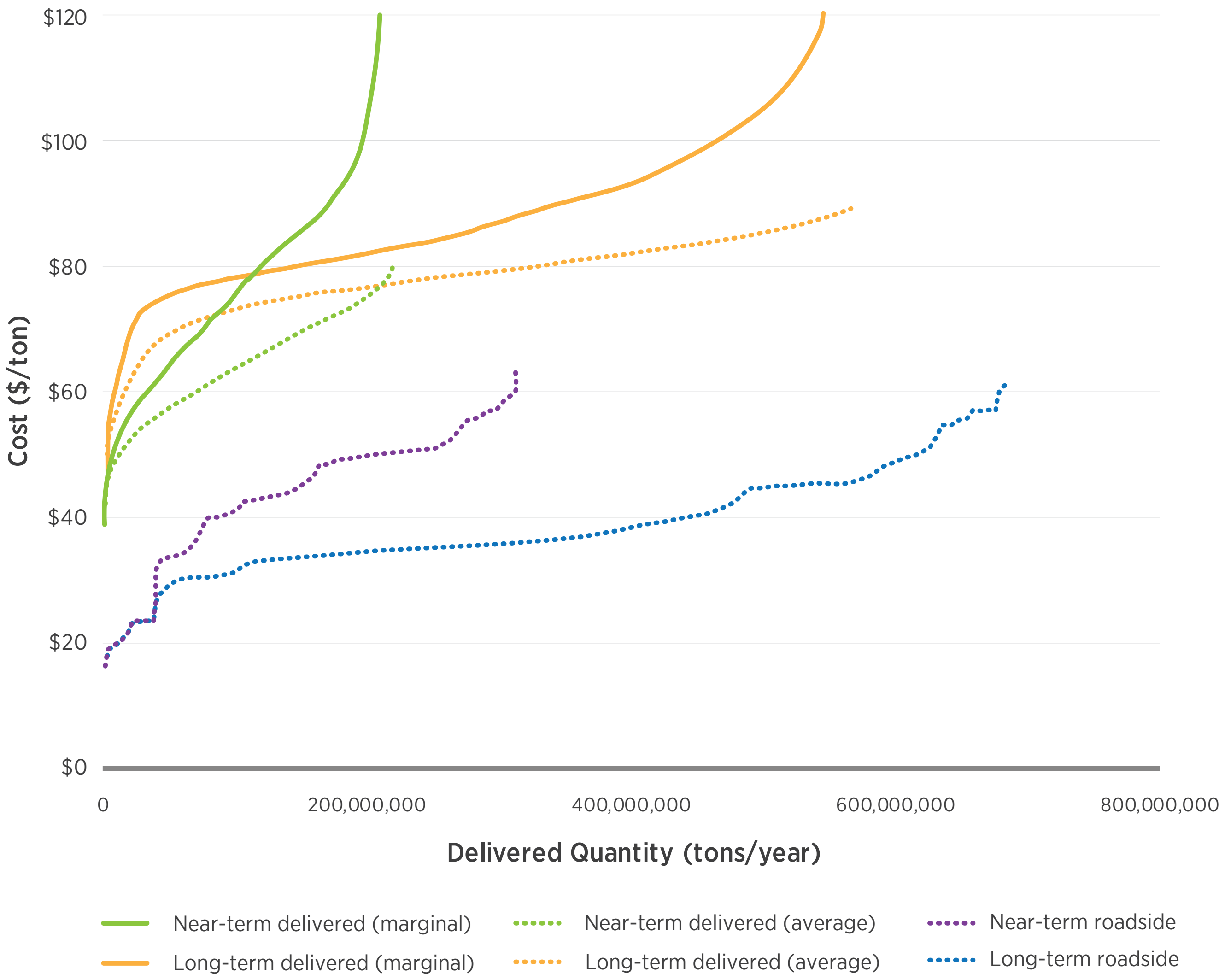
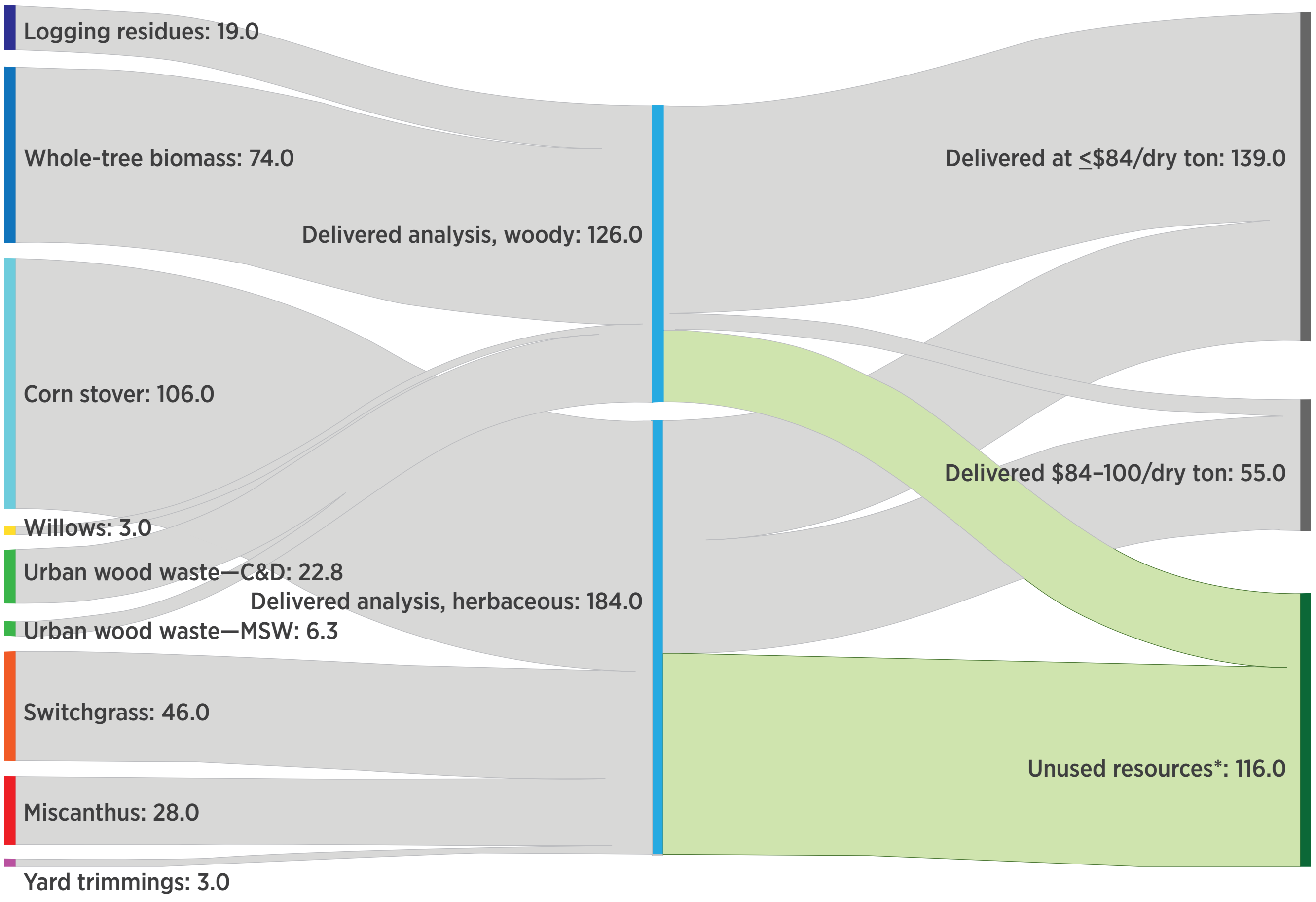


Table 6.10 | Total Feedstocks Available at Average Roadside Cost and Delivered Costs of $84 and $100 per Ton

	Near term	Long term
Base-case yield scenario (million tons)		
Roadside at ≤$60	310	679
Delivered ≤$84	217[a]	467
Delivered ≤$100	217	564
Unused	93	114
High-yield scenario (million tons)		
Roadside at ≤$60	N/A	985
Delivered ≤$84		825
Delivered ≤$100		825
Unused		160

[a] Near-term availability of feedstocks delivered at less than $84/ton diverges from DOE targets as (1) previous analyses were based on *BT2* roadside availability assessments and (2) this analysis does not include all biomass sources.

Figure 6.11 | Quantities (million tons) of select herbaceous and woody feedstocks delivered at less than $84 per ton, less than $100 per ton, and unused in a near-term scenario[2]



Note: Unused resources are those that are delivered at greater than $100 per ton, lost along the supply chain, or part of the over-contracting buffer included in the near-term systems to mitigate supply risk.

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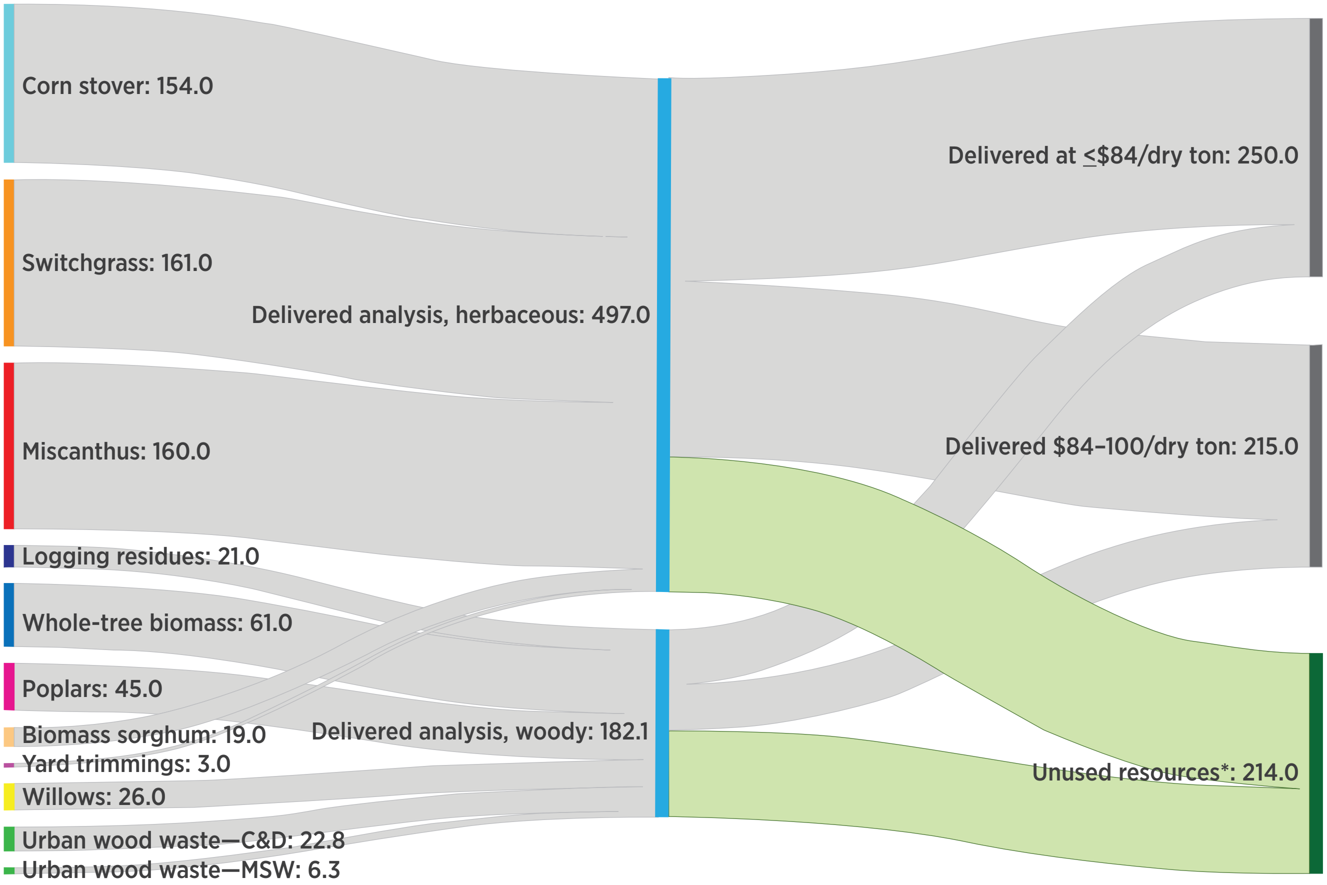
[2] Interactive visualization: https://bioenergykdf.net/billionton2016/6/3/bc-2022/sankey

Figure 6.12 | Quantities (million tons) of select herbaceous and woody feedstocks delivered at less than $84 per ton, less than $100 per ton, and unused in the long-term in a base-case yield scenario[3]



Note: Unused resources are those that are delivered at greater than $100 per ton, lost along the supply chain, or part of the over-contracting buffer included in the near-term conventional systems to mitigate supply risk.

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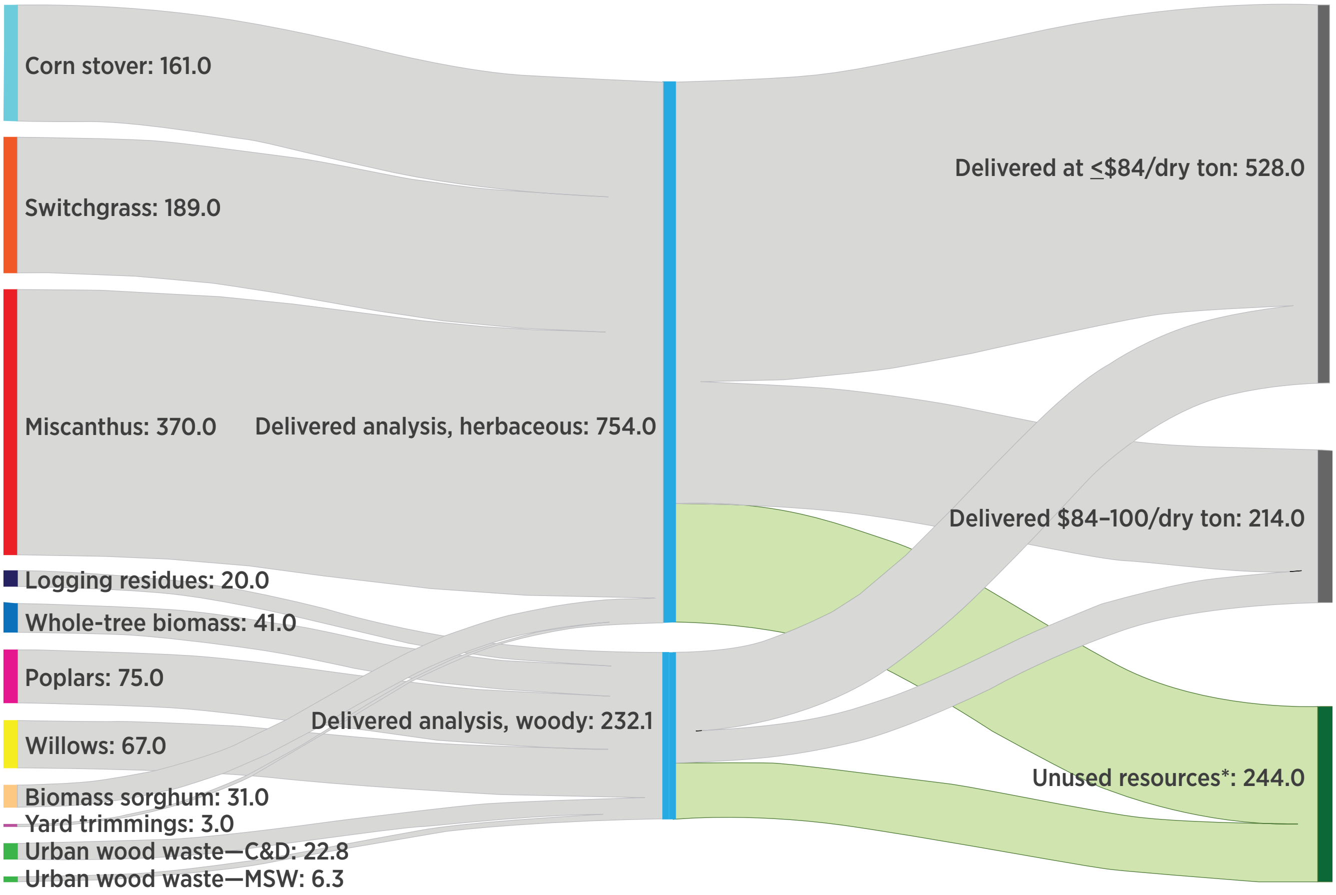
[3] Interactive visualizations: https://bioenergykdf.net/billionton2016/6/3/bc-2040/sankey

Figure 6.13 | Quantities (million tons) of select herbaceous and woody feedstocks delivered at less than $84 per ton, less than $100 per ton, and unused in the long term in a high-yield scenario



Note: Unused resources are those that are delivered at greater than $100 per ton, lost along the supply chain, or part of the over-contracting buffer included in the near-term systems to mitigate supply risk.

6.4 Summary and Future Research

Based on previous research and discussions with industry stakeholders, it is assumed that future feedstock supply systems will evolve to include advanced supply systems capable of transforming raw biomass into a tradeable commodity. Building on experiences currently being gained with conventional feedstock supply systems for pioneer biorefineries, further research to incorporate advanced depot-based preprocessing technologies will allow mobilization of more of the projected resource base. Ongoing advances in harvest operations to increase efficiency and capacity, better manage moisture, and minimize ash contamination will continue to reduce costs and provide higher-quality feedstocks. In the proposed system, feedstocks will be delivered to a regional processing facility where they will be transformed to multiple intermediate products for conversion to biofuel, biopower, or bioproducts. While these advanced preprocessing steps do increase cost and energy requirements, it is expected that these costs would be outweighed by the value added in improving quality and reducing risk.

In a near-term supply system scenario considered here, for a $60/ton offered price at the roadside, 217 million tons of biomass could be available at a delivered cost ≤$84/ton. In a long-term scenario, increasing yields, additional feedstocks, and improved supply systems increase this delivered quantity meeting cost targets to 467 and 825 million tons per year under the base-case and high-yield scenarios, respectively. It is worth noting that the delivered costs are simulated costs using an economic-engineering approach; they are not prices expected to be paid by biorefineries, as they do not account for profit beyond the roadside, transaction costs, or other business costs.

Future research to better represent and analyze feedstock supply systems will involve the following:

- Quantifying costs of risk and quality
- Quantifying the economic benefits that may be achieved through improved supply reliability, quality, and handling characteristics of advanced logistics systems
- Accounting for regional variation in moisture content at time of harvest on logistics cost estimates
- Adding rail as a transportation option in the SCM from depot to biorefinery.[4]

Future research to reduce the delivered costs of biomass feedstocks is also planned in the following areas:

- Lower-cost, higher-efficiency densification and drying systems
- Multi-feedstock, multi-product depots that share expensive depot infrastructure and energy requirements among a range of merchandisable intermediates
- Feedstock blending strategies to optimize biomass quality while making best use of local resources
- Further improvements in harvest efficiency and cost to increase the profitability of producers and encourage higher rates of energy crop production.

Expansion of biomass-based industries will be enabled, in part, by successful evolution across all of the feedstock supply system to better address risk and quality challenges. For simplicity, this analysis considered conventional and advanced supply systems independently. However, future analysis should consider industry evolution and how adopting advanced systems can enable industry expansion by creating favorable markets for feedstock production where conditions are unfavorable (e.g., low feedstock density, high risk of feedstock shortages, high feedstock variability).

[4] Interactive tools for exploring the SCM model results are at bioenergykdf.net/billionton2016/6/1/tableau and bioenergykdf.net/billionton2016/6/2/tableau.

6.5 References

An, H. J., and S. W. Searcy. 2012. "Economic and energy evaluation of a logistics system based on biomass modules." *Biomass & Bioenergy* 46: 190–202. doi: 10.1016/j.biombioe.2012.09.002.

Argo, A. M. et al. 2013. "Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs." *Biofuels Bioproducts & Biorefining* 7 (3): 282–302. doi: 10.1002/bbb.1391.

Biomass Research and Development Board. 2010. *Biofuel Feedstock Logistics: Recommendations for Research and Commercialization. A Report by the Feedstock Logistics Interagency Working Group*. U.S. Department of Energy, Washington, D.C.

Bonner, I. J., and K. L. Kenney. 2013. "Moisture sorption characteristics and modeling of energy sorghum (*Sorghum bicolor* (L.) Moench)." *Journal of Stored Products Research* 52: 128–36. doi: 10.1016/j.jspr.2012.11.002.

Bonner, I. J. et al. 2014. "Impact of Harvest Equipment on Ash Variability of Baled Corn Stover Biomass for Bioenergy." *Bioenergy Research* 7 (3): 845–55. doi: 10.1007/s12155-014-9432-x.

Cafferty, K. G. et al. 2014. *Feedstock Supply System Design and Economics for Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels - Conversion Pathway: Fast Pyrolysis and Hydrotreating Bio-oil Pathway, 2017 Design Case*. Idaho National Laboratory, Idaho Falls, ID.

DOE (U.S. Department of Energy). 2015. *Advanced Feedstock Supply System Validation Workshop*. Bioenergy Technologies Office, February 3–4, 2015, Denver, CO. Idaho National Laboratory and Oak Ridge National Laboratory, Idaho Falls, ID.

Golecha, R., and J. Gan. 2016. "Effects of corn stover year-to-year supply variability and market structure on biomass utilization and cost." *Renewable and Sustainable Energy Reviews* 57: 34–44. http://dx.doi.org/10.1016/j.rser.2015.12.075.

Hansen, J. K., and E. Searcy. 2015. "Managing risk at the cellulosic biorefinery." Manuscript in preparation.

Kenney, K. L. et al. 2014. *Feedstock Supply System Design and Economics for Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels - Conversion Pathway: Biological Conversion of Sugars to Hydrocarbons, 2017 Design Case*. Idaho National Laboratory, Idaho Falls, ID.

Kenney, K. L. et al. 2013. "Understanding biomass feedstock variability." *Biofuels* 4 (1): 111–27.

Lamers, P. et al. 2015. "Techno-economic analysis of decentralized biomass processing depots." *Bioresource Technology* 194: 205–13. http://dx.doi.org/10.1016/j.biortech.2015.07.009.

Langholtz, M. et al. 2014. "Climate Risk Management for the U.S. Cellulosic Biofuels Supply Chain." *Climate Risk Management* 3: 69–115. doi: 10.1016/j.crm.2014.05.001.

Muth, D. J. et al. 2014. "Investigation of thermochemical biorefinery sizing and environmental sustainability impacts for conventional supply system and distributed pre-processing supply system designs." *Biofuels Bioproducts & Biorefining* 8 (4): 545–67. doi: 10.1002/bbb.1483.

Searcy, S. W., B. E. Hartley, and J. A. Thomasson. 2014. "Evaluation of a Modular System for Low-Cost Transport and Storage of Herbaceous Biomass." *Bioenergy Research* 7 (3): 824–32. doi: 10.1007/s12155-014-9427-7.

Webb, E. et al. 2014. *Spatial Analysis of Depots for Advanced Biomass Processing*. Oak Ridge National Laboratory. ORNL/TM-2014/463.

Womac, A. R. et al. 2012. "Biomass Harvesting of High-Yield Low-Moisture Switchgrass: Equipment Performance and Miosture Relations." *Applied Engineering in Agriculture* 28 (6): 775–86. doi: 10.13031/2013.42469.