Biomass Research and Development Board

Biofuel Feedstock Logistics:
Recommendations for Research and Commercialization

A Report by the Feedstock Logistics Interagency Working Group

The Feedstock Logistics Interagency Working Group of the Biomass Research and Development Board consisted of participants representing the following Federal agencies:

Department of Energy

Department of Agriculture
- Agricultural Research Service
- The National Institute of Food and Agriculture
  (formerly known as the Cooperative State Research, Education, and Extension Service)
- Economic Research Service
- Forest Service
- National Agricultural Statistics Service

Department of Transportation

Environmental Protection Agency

National Science Foundation

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Executive Summary

Achieving the cellulosic biofuel targets set forth in the Energy Independence and Security Act (EISA) of 2007 will require a very large increase in harvested cellulosic biomass feedstocks from agricultural, forest, and other resources. By 2022, it is estimated that nearly 180 million dry tons of biomass will be needed annually to produce the 16 billion gallons of cellulosic biofuels called for by EISA.[1] Supplying this volume of material will necessitate the development of an industry comparable to current agricultural supply chains for commodity crops and hay. While machines and systems capable of performing each biomass supply chain operation (harvest and collection, storage, preprocessing, and transportation) are already in place, they are not designed for the scale and efficiency required. The costs of supplying biomass using currently available technologies are too high for market acceptance of alternative fuels. Reducing logistics costs is therefore essential to create an economically sustainable biofuels industry.

The National Biofuels Action Plan (NBAP) released in 2008 by the Biomass Research and Development Board (Board) outlines seven action areas, including feedstock logistics, in which interagency cooperation is needed to support the establishment of a competitive cellulosic biofuels industry. The Board formed the Feedstock Logistics Interagency Working Group (FLIWG) in August of 2008, and charged the group with preparing a report outlining barriers to developing biomass logistics systems capable of supplying 180 million dry tons of biomass feedstock annually. These barriers are broken down into two categories: (1) logistics system design and management and (2) technology development. Logistics issues affect the assembly of a biomass supply system and impact its ability to deliver needed quantities of biomass in a cost-effective and sustainable manner. Technology issues must be addressed in the design of new machines and systems to develop and sustain biomass feedstock supply chains. This report focuses on two major categories of biomass feedstock resources: agricultural resources and forest resources, as well as several other resources, including municipal solid waste (MSW), livestock manure, and algae.

Barriers to commercialization of biofuel feedstock logistics systems include:

- *Biomass feedstocks from agricultural and forest resources have low mass and energy density with current harvest and collection technologies*. The low density of these feedstocks makes them cost-prohibitive to transport, handle, and store.

  Recommendation: Conduct research that will enable the development of densification and other preprocessing technologies to achieve higher bulk and/or energy densities so that transportation, storage, and other logistics operations become economically feasible.
- *The moisture content of biomass at the time of harvest or collection—whether agricultural, forest, MSW, manure, and algae—is higher than desired and leads to degradation and decreased system efficiency***.** High moisture content can cause aerobic instability during

[1] Biomass Research and Development Board, *Increasing Feedstock Production for Biofuels: Economic Drivers, Environmental Implications, and the Role of Research*, December 2008; p.85, figure 6.1.

storage and reduce the efficiency of transportation and preprocessing operations.

Recommendation: Conduct research to develop strategies and equipment to deal with high-moisture biomass.

- *Currently available equipment for biomass feedstock logistics systems is inefficient.* Existing equipment has insufficient capacity to efficiently and economically harvest, store, and deliver feedstocks for biofuel production.

  Recommendation: Conduct research in collaboration with industry partners that will enable the development of innovative equipment and systems designed specifically for cellulosic biofuel feedstocks. Such equipment should possess higher throughput capacity than currently available machines. New methods of integrating system components are also needed to increase efficiency and reduce costs.

- *Quality characteristics of biomass feedstocks are variable and inconsistent*. Biomass attributes vary with feedstock source and season, creating inefficiencies in handling and conversion systems. To optimize biofuel production, biorefineries will require feedstocks of consistent quality, particle size, and moisture content; more uniform feedstocks will have greater market potential; however there is a tradeoff between developing processes that are robust for a wide range of feedstock characteristics and producing feedstocks with consistent properties.

  Recommendation: Develop logistics operations that maximize uniformity and consistency of delivered feedstock attributes. Develop quality standards for delivered feedstocks and instrumentation to determine feedstock quality quickly at point of sale.

- *Transportation of biomass is costly and can strain transportation networks.* Currently available technology for biomass transportation involves truck traffic that is costly, is often damaging to roadways, and can be socially undesirable. Both agricultural and forest materials are distributed over large areas, making collection costly. A key determinant for biomass supply is an infrastructure that ensures economically viable feedstock logistics and handling from farm to plant.

  Recommendation: Conduct research to improve understanding of the impacts of increased payload regulations used to reduce costs and the effects of increases in heavy traffic on rural road networks. Develop new transportation technology, including improved containers and lighter vehicles to reduce truck traffic and transportation costs, reduce impacts on roads and bridges, and reduce undesirable social impacts.[2] [3]

Development of viable domestic biomass feedstock production systems will require combined public and private efforts. The government's role includes helping to define national energy goals and to provide appropriate policies and support where needed. The actions recommended in this report should be integrated with the work of the Production, Conversion, Distribution Infrastructure, and Sustainability Interagency Working Groups to help ensure

[2] The Biomass R&D Board tasked another Working Group, the Distribution Infrastructure Working Group, to evaluate existing transportation technologies and means and related challenges, as well as impediments to different modes of transportation for biofuels. See forthcoming reports, which provide analyses of technical, market, regulatory, and other barriers and recommendations on what actions to take regarding transportation infrastructure modifications. In addition, Congress required similar evaluations in EISA that are also forthcoming (summer 2010).

[3] In-depth discussion of greenhouse gas emissions (including methane, nitrous oxide, off-gassing, and carbon dioxide emissions) from transportation are beyond the scope of this research effort and could be addressed in the future in collaboration with the Department of Transportation.

sustainable production and management systems for delivering biofuel feedstocks to biorefineries. Ultimately, specific research will depend on the feedstock type; regional and site characteristics; and the goods, services, and values required to develop and maintain reliable biomass logistics supply systems.

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Foreword

The Biomass Research and Development Board (Board) was originally created by Congress as part of the Biomass Research and Development Act of 2000 and amended "to coordinate programs within and among departments and agencies of the Federal Government for the purpose of promoting the use of biobased fuels and biobased products by: maximizing the benefits derived from federal grants and assistance and bringing coherence to federal strategic planning.[4] The Board is co-chaired by senior officials from the Department of Energy (DOE) and the Department of Agriculture (USDA) and has consisted of senior decision makers from DOE, USDA, Environmental Protection Agency (EPA), National Science Foundation (NSF), the President's Office of Science and Technology Policy (OSTP), and the Departments of the Interior, Transportation (DOT), Commerce, and Defense (DOD). Staff from the Office of Management and Budget have also served as ex officio members.

In October 2008, the Board released the *National Biofuels Action Plan* (NBAP). The NBAP outlines areas in which interagency cooperation will help evolve biobased fuel production technologies from promising ideas to competitive solutions. The Board used a five-part supply-chain framework—Feedstock Production, Feedstock Logistics, Conversion, Distribution, and End Use—to identify Board action areas and develop interagency teams to better coordinate activities. In addition, the Board identified two crosscutting action areas (Sustainability and Environment, and Health and Safety) into which the other working groups will provide future input. The NBAP outlines the interagency coordination of federally sponsored research and development (R&D) efforts necessary to make biofuels a more prominent element in the national energy mix.

As identified in the NBAP Board Action Area 3, feedstock logistics are an important part of a sustainable biofuel supply chain. The NBAP concludes that feedstock logistics have received limited attention and will need additional R&D in two main categories to achieve national goals:

- Logistics system design and management: Consider and design complete feedstock logistics systems based on feedstock type, geography, and system interfaces.
- Technology development: Develop and deploy creative approaches to support efficient, economic, and sustainable biomass harvest and collection, storage, preprocessing, and transport.

This report addresses the NBAP call to action to create a Feedstock Logistics Interagency Working Group (FLIWG) consisting of members from USDA, DOE, and other agencies to lead a planning process for the development of recommendations for the successful implementation of logistics systems. The purpose of this report is primarily to inform Federal program managers and officers of the most essential R&D and engineering barriers and challenges to the commercialization of economically viable biofuel feedstock logistics systems, and to recommend R&D and other

[4] Pub. L. No. 106-224, 114. Stat. 431, Sec. 305, repealed by 2008 Farm Bill, Pub. L. No. 110-246, 122 Stat. 1651 (enacted June 18, 2009, H.R. 6124) (codified at 7 U.S.C. § 8108).

actions to overcome these barriers and challenges. The report generally focuses on agricultural and forestry feedstocks, and to a lesser extent municipal solid wastes, livestock manure and algae. The report was substantially completed in November 2009 and underwent minor revisions through June 2010.

I. Introduction

Logistics Background

Commodity, specialty crops, and forestry logistics systems have been developed over decades to improve efficiencies and reduce costs, ultimately benefiting the consumer. One of the strengths of commodity crop systems is their uniformity; for example, during the delivery of corn grain for biofuel, nearly all components of the logistics system—from harvest through delivery to the biofuel refinery—are similar regardless of agro-region. In contrast, woody biomass is less uniform because it is produced in forests composed of different combinations of species across variable terrain in different regions of the country. As the United States diversifies its sources of biofuel feedstocks to include cellulosic materials, it is clear that logistics systems are needed to handle large quantities of different types of biomass efficiently and in an economically viable and sustainable manner.

Logistics systems have developed in regions of the country to handle specific biomass. Today, systems are being developed to harvest and supply virtually all of the potential types of biomass feedstocks needed to support the country's cellulosic biofuels industry, including agricultural and forest residues and energy crops. In addition, the efficiency and sustainability of these niche biomass logistics systems are insufficient for large-scale biomass production. Therefore, a fundamental challenge is to develop systems that effectively and economically channel diverse cellulosic materials into a standardized supply system that meets biorefinery needs for quantity and quality.

The Energy Independence and Security Act (EISA) of 2007 mandates the use of an increasing volume of renewable fuels in our country's transportation sector, a large fraction of which is to be derived from cellulosic sources; EISA requires the production of 16 billion gallons of cellulosic biofuels by the year 2022.[5] (*See* Pub. L. 110-140, 121 Stat.1522). Assuming that all 16 billion gallons would come from domestic biomass and a conversion rate of 90 gallons of biofuel per dry ton of biomass, 180 million dry tons of cellulosic material will have to be available annually by 2022 (Figure 1). This quantity is roughly equivalent to the country's entire hay harvest for 2007 (USDA, 2008). While technology is expected to improve the efficiency and decrease the cost of logistics systems, the amount of biomass required is not expected to change significantly due to physical limits on conversion rate.

The buildup and expansion of the country's cellulosic biofuels industry will be constrained by the lack of a standardized supply system infrastructure. Demonstration and deployment of a uniform feedstock system supply is critical for achieving the national biofuels utilization targets mandated by EISA. This uniformity is important not only for biomass logistics supply system operators, but also for conversion biorefineries, which will demand reliably consistent feedstocks to maximize their efficiency, productivity, and profitability.

Although variable, the cost for biomass collection, storage, preprocessing, and transport to the biorefinery gate can cost 35%–65% of the

[5] Pub. L. No. 110-140, 121. Stat. 1522.

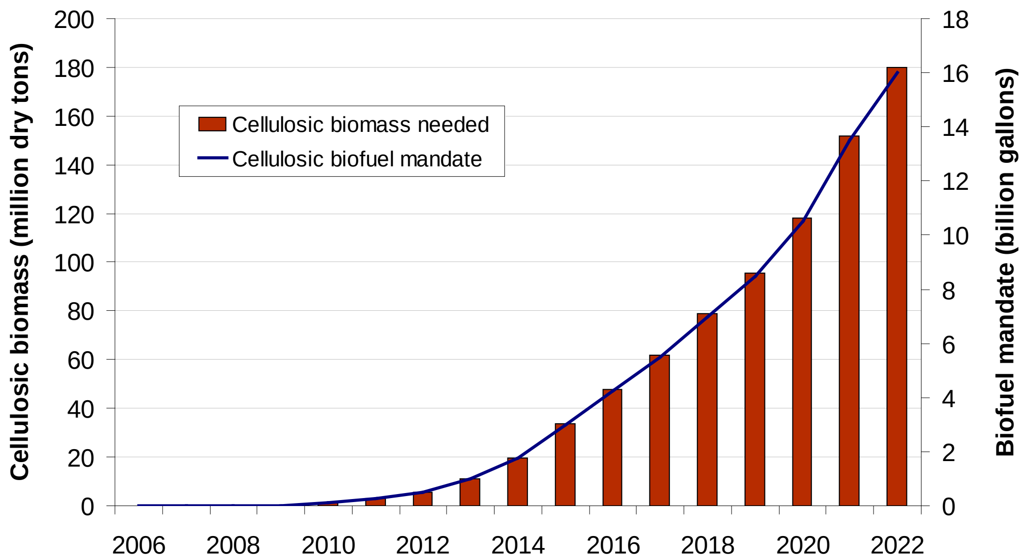


Figure 1. Cellulosic biomass feedstock quantities needed to meet federally mandated biofuel goals.

total production costs of cellulosic ethanol.[6] By contrast, feedstock logistics costs associated with the harvest, transportation, and storage of corn grain contribute roughly 7%–19% of the total cost of producing fuel ethanol.[7] Therefore, improving biomass feedstock logistics efficiency and economics would reduce the cost of biomass feedstocks while providing profit incentives for needed biomass logistics operations.

Major Logistics Components

Biomass logistics lies at the interface between biomass production and conversion (Figure 2). This interface involves planning, implementing, and controlling the efficient, effective flow and storage of biomass feedstocks between supply and use. Without assurance of efficient feedstock flow from point of origin to point of use, biofuels production can be limited by capacity and cost-prohibitive factors.

Four major unit processes contribute to a successful and sustainable biomass feedstock logistics system:

- **Harvest and collection**—Operations to acquire biomass from the point of origin and move it to a storage or queuing location. Examples include cutting, harvesting, collecting, hauling, and often some form of densification such as baling.
- **Storage**—Operations essential for holding biomass material in a stable form until preprocessing or transport to the biorefinery. Storage could be at locations near the harvesting areas, at the biorefinery, or both.
- **Preprocessing**—Processes that physically, chemically, or biologically transform biomass into a state more suitable for transport or conversion to liquid fuels. Examples include densifying, (e.g., pellets or torrefied material), on-site pyrolysis, grinding, drying, chemically treating, ensiling, fractionating, and blending.

[6] Fales et al, 2007.

[7] Shapouri and Gallagher 2002; Duffy and Smith 2008; Rapier 2008.

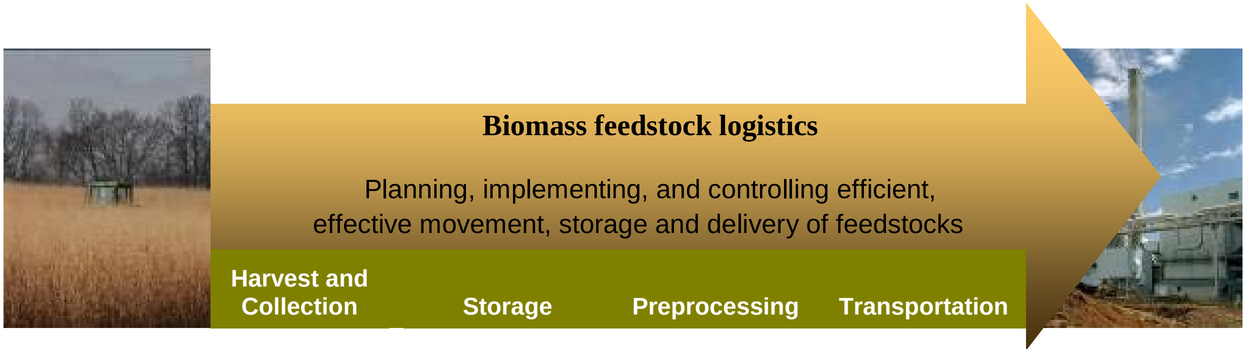


Figure 2. Biomass feedstock logistics systems include harvest and collection, storage, preprocessing, and transportation operations to deliver material from the field or forest to the biorefinery.

- **Transportation**—Movement of biomass through the logistics system from harvest and collection to the biorefinery. Biomass transport options are generally constrained to existing transportation infrastructure such as truck, rail, barge, or pipeline.

Specific research activities target the overarching operational and engineering challenges associated with each unit process. These challenges are widespread across types of biomass feedstock, including the feedstocks discussed in this report; a summary of challenges is presented in Table 1.[8]

Regardless of the specific type of biomass feedstock or particular logistics system process, the overall efficiency, cost, and sustainability of operation could be considered the ultimate challenge for logistics engineers and operators. During progression through the supply system, equipment use efficiency may decline due to harvest windows and other daily operational constraints. Furthermore, energy costs can rise due to more limited options with mobile equipment, such as specialty harvesters. Such operational and economic challenges add to the various technical barriers identified in this report.

Biomass logistics systems must be able to maintain, and in some cases enhance, the characteristics and properties of the biofuel feedstock as it moves from the field or forest to the biorefinery. Such systems must also account for numerous biomass parameters while delivering biomass with low inorganic contamination and proportionally desirable percentages of carbon and moisture. Logistics systems must strive to mitigate and minimize feedstock variability to reduce impacts on downstream conversion processes. A summary of the key biofuel feedstock parameters and their impact on the logistics system is shown in Table 2. Maximizing the operational efficiency of logistics systems is critical to driving down the overall costs of delivering biomass to the biorefinery.

The research and development (R&D) programs of the DOE's Office of the Biomass Program (OBP) and USDA have ongoing efforts focused on developing and optimizing cost-effective, integrated systems for harvesting, collecting, storing, preprocessing, and transporting a range of biomass feedstocks, including agricultural

[8] Hess et al., 2007

Table 1. Regardless of feedstock type, biomass logistics systems share many of the same operational and engineering challenges

Major Operational and Engineering Challenges for Biomass Logistics Systems		Crosscutting Example
Harvest and Collection	• Equipment capacity • Composition • Pretreatment requirements • Environmental impacts • Increase drying efficiency	Existing or conventional harvesting equipment may not be optimized for biomass energy crops such as grasses or short-rotation woody crops.
Storage	• Shrinkage • Compositional impacts • Pretreatment impacts • Soluble sugar capture	Moisture-induced biological degradation can lead to a loss of feedstock dry matter and quality over time.
Preprocessing	• Equipment capacity • Equipment efficiency • Material bulk density • Compositional impacts • Pretreatment impacts	On-site preprocessing, such as grinding and/or chemical pretreatment, is generally more energy intensive than processing at stationary facilities.
Transport	• Truck capacity • Loading density • Loading and unloading efficiencies • Social impacts	Low bulk density significantly reduces transportation efficiency and increases cost.

Table 2. Key biofuel feedstock attributes* to be considered in designing feedstock logistic systems that meet cost and quality targets

Biomass Attributes Impacting Cost and Performance	Logistics System Impact
Ash composition	• Equipment wear
Particle size and shape	• Grinding efficiency • Storage capacity
Material density	• Feeding and handling efficiency • Transportation economics • Storage capacity
Permeability	• Drying efficiency
Moisture content	• Grinding efficiency • Transportation economics • Feeding and handling efficiency • Storage stability

* *These attributes were determined by DOE experts, DOE national laboratory experts, and their USDA counterparts, informed by our industry partnerships and ongoing discussions.*

residues, forest resources, and dedicated biomass energy crops. OBP is working with national laboratories, the DOE Office of Science, and other partners to develop and deploy new technologies that overcome barriers to better recover and handle various feedstocks and integrate their production and use, as are USDA's Agricultural Research Service, National Institute for Agriculture,[9] Forest Service, and their partners. Working jointly, USDA and DOE are advancing technologies to ensure sufficient quantities of high-quality feedstocks are available for biofuels production.[10]

[9] Formerly the Cooperative State Research, Education, and Extension Service.

[10] USDA's Biomass Crop Assistance Program, as part of the 2008 Farm Bill's Section 2011, also intends to provide both grower payments and collection, harvest, storage, and transport payments to help cover these associated costs.

II. Agricultural Resources – Residues and Herbaceous Crops

Achieving EISA mandates requires significant expansion of second-generation, nonfood, cellulosic feedstocks. These feedstocks include, but are not limited to, agricultural residues and dedicated herbaceous crops, markets, and environmental concerns.

Agricultural residues (i.e., biomass that remains in the field following harvest) include corn stover (stalks, leaves, and cobs) and wheat, oats, or barley straw left after harvest. Agricultural residues can be found throughout the United States, but are most abundant in the Midwest due to the extensive availability of corn stover. Some residues cannot be removed either for environmental reasons (e.g., reducing erosion or maintaining soil carbon) or because their recovery may not be economical. The amount of corn stover and other residues that will be available for conversion to transportation fuels will depend heavily on technological advances in the supply chain that minimize environmental impacts and improve producer revenue.

Using current technologies, feedstock supply systems for agricultural residues and herbaceous crops are similar. As the biomass industry advances, new technologies are envisioned particularly for harvest and collection that take advantage of a particular feedstock's characteristics (e.g., single-pass harvesting systems for corn stover). In practice, the choice among various cellulosic feedstocks will primarily depend on regional issues such as climate, land availability.

Agricultural processing wastes are another potential source of feedstocks for biofuel production. These materials are byproducts of generally low value that result from the

Figure 3. Sustainable removal of agricultural residues such as corn stover and cereal straws will likely serve as primary feedstocks for initial cellulosic biorefineries.

processing of agricultural commodities and include cotton gin trash, bagasse, nutshells, grain hulls, and corncobs. These wastes are generally produced at centralized facilities and, therefore, do not need to be collected.

Dedicated herbaceous energy crops, primarily perennial grass crops such as switchgrass, have been identified as potential bioenergy feedstocks. Switchgrass—a native prairie grass—is well adapted to the Midwest, Southeast, and Great Plains. Switchgrass is relatively high yielding compared to crop residues. Adoption of switchgrass or other perennial grasses by producers will be based primarily on revenue potential relative to other crops and proximity to existing or potential biorefineries. Annuals, such as sorghum, could be another energy crop. Cover crops that reduce erosion potential can also be used as an energy crop. Combining the cover crop and another energy crop in one annual cropping cycle can produce high yields of biomass.

Figure 4. Herbaceous energy crops that exhibit high yields and meet other plant material and conservation requirements will likely become significant feedstock resource supplies as the industry matures.

Logistics System Design and Management

While the existing agricultural commodity logistics system could accommodate second-generation biofuel feedstocks, the design, development, and deployment of economically viable and sustainable biomass logistics systems require many fundamental design changes from the traditional, vertically integrated commodity systems. Biomass logistics systems must be able to mobilize millions of tons of low-density biomass through the country's existing roads and rails. Transporting low-density, high-moisture biomass is not optimal and will tax the current infrastructure by significantly increasing system demands. Therefore, at its core, biomass logistics poses a material science and handling problem.

Research and development efforts must overcome the feedstock supply system barriers for both conventional and advanced, commodity-scale designs; increase mass and energy density; reduce moisture content; and increase the reliability and quality of material delivered to the biorefinery. Integrated cellulosic biomass supply systems have two primary functional objectives: 1) integrate conventional technologies for biorefineries, and 2) develop commodity-scale supply systems for cellulosic biomass for a biorefining industry capable of producing 16 billion gallons of biofuel per year.

Biofuel feedstock yield per unit of land area is low. Feedstocks must be gathered from large areas to meet biorefinery requirements. The biorefinery footprint (the radius of feedstock acquisition) could be as great as 50 to 100 miles. The number of truck cycles required to move this material might increase the need for maintenance of local roads and bridges, and increased truck traffic through town centers may pose nuisance and health and safety concerns that will need to be managed.

Harvest management practices must balance competing expectations. Maximizing yields often reduces costs by improving production and harvest efficiency. Competing factors need to be carefully balanced to ensure sustainability while reducing the costs. Excessive residue removal may also jeopardize resource conservation, potentially leading to depletion of soil carbon, soil erosion and/or runoff. Late-fall harvest of perennial grasses takes wildlife habitat into consideration during harvest cycles; however, delayed harvest may decrease biomass yield and increase harvesting difficulty.

A lack of understanding regarding the physical requirements of biofuel feedstock hinders development of equipment. Processes that change feedstock physical properties (e.g., size-reduction or densification) can increase the saleable value of feedstock for the producer. However, value-added processes cannot be engineered into harvesting, handling, and preprocessing equipment until there is a clear understanding of the required physical properties.

There is a lack of information about biofuel feedstock storage requirements. This hinders the design and operation of biofuel feedstock storage facilities and overall logistics systems. For example, single-pass harvesting of grain and crop residues requires management of both grain and biomass transport. If biomass can be stored at the field edge, then biomass transport bottlenecks could be avoided; however, field-edge storage systems must be practical and economical for the whole feedstock logistics system, including storage, transport, and year-round availability.

Complete system cost and benefit analysis is required. Current equipment models do not accurately account for the costs associated with biomass harvest that are needed to support logistics system design and management. To develop realistic models, more data is required on the costs of owning and operating biomass harvesting and handling machines for the range of production conditions expected.

Biofuel feedstock logistics supply chain models are inadequate and data is insufficient for effective use of supply chain models. System modeling is complex and requires new and updated data. Biomass logistics supply chain optimization requires comprehensive simulation models to optimize both economic and environmental sustainability. Some specific barriers include:

- Lack of data on biomass variability and how variability affects storage and processing yields
- Scalability of current systems
- Understanding of how existing transportation infrastructure and regulations could limit transport options

Technology Development

Currently, commercially available machines exist to perform every operation required within a biomass supply chain; however, supply systems using existing technologies do not meet cost or capacity targets because these machines were not designed as a component of a biomass supply chain (e.g., the machines are not capable of efficiently handling fibrous, low-density material). Furthermore, the development of new technologies creates the opportunity to reduce environmental and social impacts.

Harvest and Collection

Existing agricultural harvesting equipment may not be adapted to characteristics, quantities, and harvesting requirements of cellulosic biomass feedstock. As crop yields increase due to genetic and management improvements, the capability of existing harvesting machines to handle large biomass quantities may be inadequate. Existing machines may also be unable to produce feedstocks with characteristics suitable for energy production.

Physical and chemical property standards for biofuel feedstocks are not clearly defined. Different conversion processes may require feedstocks with differing physical and chemical characteristics. Feedstock characteristics such as particle size, density, and moisture content influence conversion into biofuels, and may necessitate preprocessing.[11] Adapting harvest systems to utilize a variety of feedstocks with different characteristics will increase development time and costs. Conversely, rigid feedstock standards may limit development of equipment capable of meeting multiple regional feedstocks requirements.

Storage

Variable moisture content of biomass feedstocks at harvest adds difficulty and cost to storage. Generally, harvested crops with moisture content lower than about 15 to 20% can be stored under aerobic conditions. Most, but not all, crops harvested in a single-pass system will have moisture content higher than 15 to 20% and therefore will require drying or storage by anaerobic ensiling. Ensiling may create fermentation products that are detrimental during conversion.

Biological activity during storage can cause variable physical and chemical changes in feedstock properties. Although some changes in physical and chemical properties can be beneficial (e.g., partial delignification during fermentation), most will have negative consequences. The most important change is dry-matter loss due to microbial respiration. Quantification of these losses under a wide variety of storage schemes and environments is required. Technology and practices to manage change in feedstock properties during storage are needed.

Feedstocks can be susceptible to certain risks. The potential flammability of dry, stored material will require mitigation strategies to reduce the potential for fire. Innovative preconditioning technology, better stacking and handling techniques, and improved monitoring systems are needed.

Requirements and information about design and operation of effective large-scale biomass feedstock storage facilities is limited. Most storage cost estimates use information developed for storage of forage for ruminant animals. Although these models are good starting points, there are substantial differences in storage requirements of biomass used for animal forage and biomass used for biofuel feedstock. Research on storage characteristics of biomass feedstocks under large-scale conditions is needed to develop optimized equipment and cost models.

Preprocessing

Insufficient knowledge about properties of cellulosic biomass with regard to its use as a biofuel feedstock inhibits the design of preprocessing equipment. Methods and instruments to measure biomass properties must

[11] http://bioenergy.ornl.gov/main.aspx.

be developed to increase the understanding of biomass properties that influence conversion to biofuel.

Current preprocessing technology is expensive, inefficient, and adds little value. In general, cellulosic biomass must be modified to ease handling, storage, transport, and conversion to biofuel. Because preprocessing will alter biomass physical properties, systems must generate final products that are stable during long-term storage and are relatively free of fouling impurities. Specifically, drying and grinding operations must be able to handle a variety of biomass types and moisture levels efficiently and effectively. The energy required to grind or chop biomass increases exponentially as desired particle size decreases. Since some conversion processes—thermochemical conversion in particular—require small biomass particles, size reduction technology must reduce energy requirements and subsequent cost. Although densification, from simple baling to on-site pyrolysis or torrefaction, reduces the costs of handling, transporting, and storing biomass, densification itself is complicated and costly because it requires multiple steps.

Transport

Handling and transporting low-density materials is expensive. The low energy density of biomass requires moving large volumes of material, which increases loading, unloading, and transporting expenses. Improvements in size reduction and densification technologies are needed to reduce handling and transportation costs. Existing package-based equipment and facilities are projected to be incapable of handling the large volumes required. New material-handling systems capable of efficiently moving materials of variable particle shape, size, and texture are needed.

Environmental and Socioeconomic Impacts

There are many points of interaction between logistics operations and the environment and society along the biomass supply chain. As the biomass supply industry develops, there are opportunities to design systems with minimal, and perhaps even positive, environmental and socioeconomic impacts. This section includes examples of potential impacts from logistics systems for biomass feedstocks from agricultural resources.

Use of biomass for energy production can provide environmental benefits. Chief among environmental benefits is reduction of net carbon emissions associated with fossil fuel use. Perennial herbaceous crops in long-term rotations (i.e., 10 years or more) can decrease soil erosion compared to conventional rotations with primarily annual crops that leave soil exposed for several months each year. Annual crops combined with the use of a cover crop will greatly reduce the soil erosion potential. Perennial grasses can also improve wildlife habitat, especially when they are harvested only once a year, when harvest is delayed until late winter, or when grass cover is left to provide permanent habitat. At the same time, energy use for biomass transportation and processing can release GHGs and air pollutants that offset some of the benefits of displacing fossil fuels. Improvements in technology can help reduce the fossil usage in the production and delivery of biomass.

Biomass production must be environmentally sustainable. Ensuring a long-term feedstock supply requires sustainable crop production, which is a direct function of producers' ability to maintain soil productivity. This, in turn, requires management practices that maintain soil organic carbon and fertility and minimize erosion. For example, excessive harvest of crop residues such as corn stover can decrease a carbon source typically used to maintain soil organic matter and can increase the risk of erosion due to greater soil exposure. Erosion and runoff of crop inputs such as fertilizer, herbicides, and pesticides can lead to adverse impacts on water quality. The use of cover crops can reduce soil erosion potential and add to the organic carbon content of the soil. Management practices such as no-till seeding or land application of alternative carbon sources like manure, compost, or other agricultural wastes may help offset crop residue removal. The reduced use and precision applications of chemicals can reduce risks to water quality. Acceptable crop and residue harvest levels must be determined and incorporated into management practices that maintain soil productivity. Cropping systems must sustainably use production inputs of fuel, fertilizer, pesticides, and water. Minimizing these inputs will increase production efficiency and profitability and will reduce negative environmental impacts such as nutrient and pesticide pollution.

Biomass feedstock logistics could create significant socioeconomic benefits for rural communities by creating opportunities for business development and related jobs for the following:

- *Development of technology for equipment and systems to harvest, process, and transport cellulosic biomass.* Examples include harvesters that cube herbaceous crops or fractionate them into stems and leaves, or machines that treat harvested crops with acid or lime as they are put into on-farm storage.
- *Manufacture, sale, and service of required equipment.* Integrating such new equipment into rural economies will require sales and service personnel and infrastructure throughout the rural landscape. New opportunities will be created for custom harvest, transport, and processing businesses.
- *Construction and operation of facilities to preprocess feedstock and add value prior to storage, transportation, and delivery to the biorefinery*. High-value co-products from herbaceous crops can increase commodity and risk-management opportunities for producers. For example, harvest fractionation of alfalfa can separate stems for energy production from the higher-valued leaves for animal feed. New herbaceous crops can provide farmers with diversification opportunities, which can help to manage risks of fluctuating markets and stabilize farm income.

Biomass production may diversify operations compared to conventional, commodity crop production which may impact local communities and economies. The promise of biomass production alone will not necessarily entice new producers. Further, support services (e.g., equipment repair) and downstream operations (e.g., biomass handlers) may need to modify their traditional operations to support biomass production.

Some feedstock logistics operations may provide unsafe conditions for workers and the community. Potential concerns include dust, gaseous emissions, and falling objects during storage, increased traffic, and equipment safety. These risks are similar to other agricultural commodities because energy crops are agricultural commodities that utilize similar equipment.

Biomass production must be energy efficient. To achieve cost-effective greenhouse gas reductions, significantly more energy must be produced than is required to generate energy from biomass.

Figure 5. Dry-matter losses occurring during each logistics operation are one factor that prohibits feedstock supply systems from reaching cost targets.

Assessment of Work Underway

To date, development of logistics systems for biomass feedstocks has primarily been based on technologies designed for traditional commodity and forage crops. University and Government researchers and engineers have evaluated the collection of bioenergy feedstocks such as corn stover and switchgrass based on the performance of machines designed to cut and bale forage crops. Several factors such as yield, material mechanical properties, moisture, and bulk density can be considerably different for bioenergy feedstocks than for traditional crops. Numerous field studies have assessed the effects that these differences can have on the costs to collect feedstocks, the environmental impacts, and the quality of the biomass delivered to the biorefinery.

The agricultural equipment industry has extensive experience and capability designing and producing equipment for harvesting and handling herbaceous biomass. Equipment manufacturers are aware of the enormous market potential that biofuels production could provide their industry. There is reason to believe that these manufacturers should be able to provide the equipment necessary to meet the feedstock logistics needs of the proposed, large-scale cellulosic biofuel industry. Although considerable research has been done and many demonstration and commercial-scale projects have been proposed and are underway, the commercial cellulosic biofuels industry has not reached commercialization.

A mature bioenergy feedstock supply industry will include new machines and systems designed specifically for bioenergy feedstocks. A number of studies are underway at universities and government research labs to identify supply chain design decisions that lead to less expensive, higher quality feedstocks delivered to the biorefinery. Using specially developed computer simulations of the feedstock supply chain, researchers and engineers explore issues such as the best location (field or refinery) for comminuting biomass, where biomass should be stored and for what duration, and how the cost of densification compares to reductions in transport costs.

Based on simulations, new machines and processes can be designed to improve the supply chain. Field studies are already underway to test single-pass harvest systems for collecting both corn grain and stover. In one study, a grain combine was modified to produce single-pass, whole plant corn harvesting with two crop streams: grain and stover. In another study, the single-pass harvesting system comprised three machines—one to gather the crop and prepare the residue for no-till seeding, a second to thresh and clean the crop, and a third to separate the grain by density and quality. There also is research underway to design pneumatic bulk handling systems for biomass.[12] If successful, such a system could be a significant improvement over current biorefinery feedstock-handling systems.

The design of feedstock logistics supply chains can have significant environmental impacts. In particular, excessive removal of agricultural residues can degrade soil quality and reduce future crop productivity. Work is underway to prepare an assessment of the impact of corn stover removal on future soil quality and crop productivity in the Corn Belt region.

Recommendations

Advances in feedstock logistics technologies and developments in feedstock supply system design strategies are needed to establish the cellulosic biofuel industry and achieve future EISA-mandated targets. With present technology, a supply system for agricultural residues or herbaceous crops would likely be a bale-based system. Development of future feedstock logistics technologies will address the limitations of bale systems (identified in this section) to reduce feedstock delivered costs.

Harvest and Collection

Increase equipment throughput capacity. Genetic improvements to increase yield and improve the economic viability of bioenergy crops are already underway. To maximize the productivity of a bioenergy supply chain, harvesting and preprocessing equipment should be designed to take advantage of these greater yielding crops.

Reduce operational dry-matter losses. New machines developed for harvesting and processing biomass should minimize material losses. Each time an operation occurs, a portion of the material is lost. Currently, in a bale-based feedstock supply system, it is estimated that 14 operations employing 21 different types of machines are performed on biomass. New

Figure 6. Mitigating material degradation during storage is critical for supplying the needed tonnages of specified feedstocks to the biorefineries.

12 Hess, Wright, Kenney, Searcy, 2009.

feedstock supply chains should seek to minimize the number of operations performed on biomass.

Storage

Develop strategies for high-moisture biomass. Many agricultural residues—corn stover in particular—are quite moist at the time of harvest. Quantification of losses and feedstock quality degradation under a wide variety of storage schemes and environments is required. Further research is needed to develop strategies to deal with high-moisture biomass. Technology and practices to manage change in feedstock properties during storage are needed. Where ambient conditions for field drying are not favorable, mechanical drying systems that are energy efficient and cost effective may be needed. Another strategy for dealing with high-moisture material is to design harvesting and preprocessing systems that handle biomass in a way that promotes drying.

Preprocessing

Develop systems to deliver biomass at desired quality and particle size. Feedstock suppliers are likely to be compensated for high-quality material that meets biorefinery specifications and/or penalized for low-quality material. Feedstock quality can be affected at any point throughout the supply chain, but storage and preprocessing are the operations most likely to impact quality and particle size. Research is needed to develop operations that produce feedstocks with desired characteristics.

Increase feedstock bulk density. By far, the most critical factor affecting feedstock logistics cost is bulk density. New, cost-effective densification technologies are needed to reduce logistics costs. Bulk-density targets have recently been identified. These targets are the bulk densities at which logistics operations (i.e., transport, handling, and storage) cease to be a limiting factor. These bulk-density targets are 16 dry pounds per square foot (lbs/ft^3) for transportation and 30 dry lbs/ft^3 for handling and storage (Hess et. al, 2003).

Define required feedstock properties. Methods and instruments for measuring biomass properties must be developed to increase the understanding of the biomass properties that influence conversion to biofuel.

Develop biomass preprocessing technologies. Research is needed to develop low-cost densification technologies. Technology, other than simple size reduction or densification, may also be needed to increase the saleable value of feedstock. One possibility is pretreatment of biomass with acid, lime, or ozone during storage to enhance physical breakdown, which in turn reduces pretreatment costs at the biorefinery.

Transport

Develop technology to reduce infrastructure and social effects of transporting biofuel feedstocks. Research is needed to assess the effects of increased heavy vehicle traffic on rural roads and networks. Also, transportation of biomass by rail should be studied as an alternative that could reduce truck traffic and offset transport costs. These issues will affect both feedstock supply and biorefinery siting.

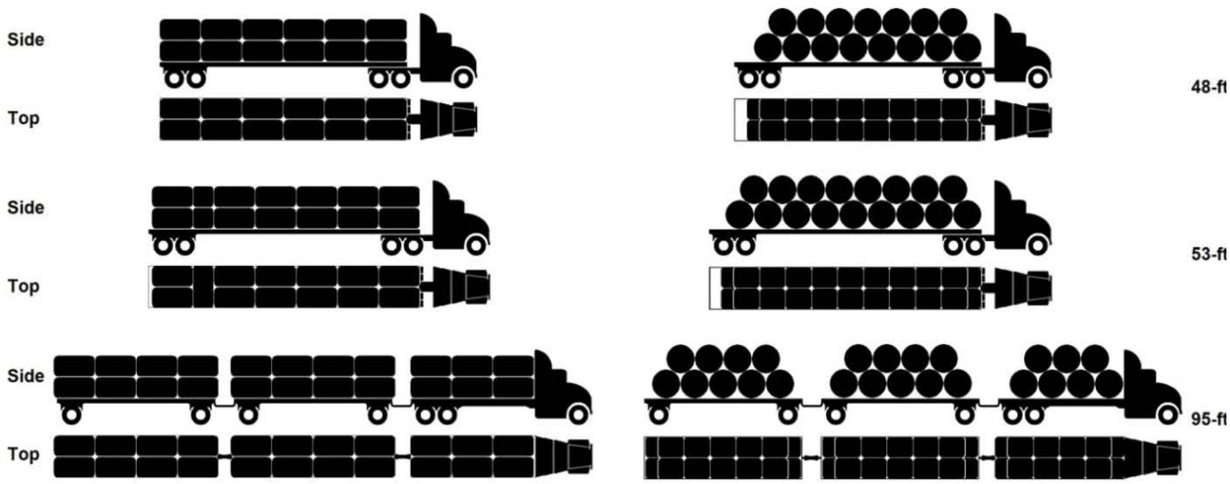
Develop efficient biofuel feedstock transportation equipment and systems. New material-handling systems capable of efficiently moving material of variable particle shape, size, and texture are needed.

Socioeconomic Factors

Develop technologies and practices to reduce environmental impacts. Operations not only need to be cost effective, but also should have limited or no long-term impacts on the soil, water quality and quantity, and associated ecological functions to help ensure sustainability.

Determine how producers can be influenced to incorporate cost-effective biomass production and logistics into their existing operations, and when it is appropriate to do so. Research on factors that influence a producer's decision to invest in new technology will provide valuable insight and guidance for improving the accuracy of logistics models that estimate costs and environmental impacts.

Define potential health and safety concerns of workers and the surrounding community during feedstock collection, preprocessing, storage, and transportation. Research is needed to better understand the health and safety implications of feedstock logistics operations. Standards and guidelines are needed to protect



Truck Configurations	Load Limits		Payload			Maximum Load Bulk Density (DM lb/ft^3)
	Length (ft)	GVW (lb)	Max (lb)	Square Bale Count	Round Bale Count	
48-ft Flatbed Trailer	48[a]	80,000[a]	51,100	24 – 4×4×8-ft 36 – 3×4×8-ft	30 – 4×5.5-ft	16.6 – 4×4×8-ft 14.8 – 3×4×8-ft 18.3 – 4×5.5-ft
53-ft Flatbed Trailer	53[b]	80,000[a]	50,800	26 – 4×4×8-ft 39 – 3×4×8-ft	34 – 4×5.5-ft	15.3 – 4×4×8-ft 13.6 – 3×4×8-ft 16.1 – 4×5.5-ft
24-ft Flatbed Tractor with two 30-ft Flatbed Trailers	95[c]	105,500[d]	59,500	44 – 4×4×8-ft 66 – 3×4×8-ft	50 – 4×5.5-ft	10.6 – 4×4×8-ft 9.4 – 3×4×8-ft 12.8 – 4×5.5-ft

a. Federal minimum trailer length or gross vehicle weight (GVW) that states must allow on National Network (NN) highways.

b. Common state maximum trailer length allowable on National Network (NN) highways.

c. Common allowable trailer length in AK, AZ, CO, FL, ID, IN, IA, KS, MA, MO, MT (93-ft), NE, NV, NY, ND, OH, OK, SD, and UT for two trailing units on non-NN highways.

d. Common allowable GVW limit in AZ, CO, ID, IN, IA, KS, MA, MI, MO, NE, NV, NY, ND, OH, OR, SD, UT, WA, and WY for two trailing units on non-NN highways.

Figure 7. Maximizing load capacity configurations to accommodate load limits on rural roads and networks will impact cost and tonnage targets and influence a host of other decisions, such as interim supply depots and biorefinery siting (Hess et.al, 2009).

workers and the community from dust, gaseous emissions created during storage, increased traffic, and hazardous equipment.

Develop technologies that increase biofuel feedstock production without requiring more land. Technological advances in crop breeding and production systems that increase herbaceous crop yields can help address the "Food versus Fuel" issue.

Develop accurate life-cycle analyses for biofuel feedstock logistics. Greater attention and focus on climate change from government, industry, and the public has increased the demand for accurate and complete life-cycle analyses that can help ensure that practices are sustainable. For feedstock logistics, this highlights a continuing need for new and improved data on fuel use and equipment needs and performance, especially as new technologies are introduced. For example, some research suggests that energy efficiency is maximized if mixed-species perennial grasses are used instead of monocultures, and if feedstocks are grown on marginal lands; however, both of these options may reduce yields, significantly affecting logistics costs. Comprehensive studies are needed to compare these trade-offs.

Develop technologies and practices to reduce environmental impacts. Operations need to be cost effective, but to help ensure sustainability, they should have limited or no long-term impacts on the soil and associated ecological functions. More research is needed to understand key factors limiting sustainable crop production (e.g., erosion, soil carbon, nutrients), and crop systems that could mitigate the adverse impacts of these limiting factors, using crop residue harvest and energy crop production scenarios.

III. Forest Resources—Residues, Energy Crops, and Energy Wood

Woody biomass from forests is a substantial source of potential feedstock for energy production. This feedstock ranges from residues to energy crops. It includes forest residues left after timber harvesting; the current nonmerchantable stand and stem components removed during harvests for merchantable products; woody energy crops that are planted and managed specifically for biomass production; and small-diameter trees, cull trees, or brush removed for stand treatments. Descriptions of these systems are shown in Table 3. There are significant technical, economic, and environmental barriers to expanded biofuel and bioenergy production from woody biomass. Forest operations for biomass recovery must conform to constraints imposed by stand and operating conditions (e.g., piece size, terrain, distribution of material) and by the end product the system will produce (e.g., ground-up particles, clean chips, bundled residue). The wide range of conditions across the United States results in distinct variants of biomass and wood-production systems.

(Photo courtesy of Tim Volk, SUNY)

Figure 8. Three-year-old willow biomass crops being harvested with a forage harvester and a cutting head that has been designed for short-rotation woody crops by Case New Holland.

Logistics System Design and Management

The material handling challenges for biomass from woody resources are similar to those for biomass obtained from agricultural residues and herbaceous crops: the costs to harvest or collect, transport, handle, process, and store low bulk-density biomass with high moisture content is often prohibitive. For biomass obtained from agricultural resources, systems that can be assembled with current technologies to obtain biomass from forest resources do not currently meet industry and government standards. Most commercially available forestry machines are designed for timber collection and preprocessing. Assembling a cost effective, sustainable, biomass supply chain from forests or energy-wood plantations poses unique challenges. This section includes some of the technical barriers regarding system-level design and management that must be addressed in order to develop a woody biomass supply.

Woody biomass harvest, preprocessing, and transportation systems are not integrated with basic forest-resource management plans, leading to overall inefficiency. Forest

Table 3. Feedstock logistics considerations* for different woody biomass supply resources

Woody Biomass Production System	Supply System Logistics Considerations
Forest residue collection Ground based Steep terrain	• Byproduct of other forest operations. • One of the largest sources of woody biomass. • Biomass scattered or piled in the forest or concentrated in piles at roadside. • Loose biomass can be bundled or baled before forwarding to improve handling. • Chipping can be performed on site or at the landing. • Steep terrain significantly increases difficulty of residue recovery. Cable logging systems or helicopters of whole trees may be necessary.
Integrated biomass harvesting Whole trees Multiple pass	• Integrated whole-tree operations recover woody biomass as part of the timber harvesting operation. • Chip transport often limits the economic viability of biomass from this system. • In a multiple-pass, integrated operation, woody biomass may be separated from conventional products in the woods. This increases costs.
Biomass energy crops Willow or brush Larger woody energy crops	• Planted stands may be managed for multiple wood products and benefits or as single-purpose stands for biomass production. The systems may be short-rotation energy crops like shrub willow or longer rotation stands of other types with intermediate thinnings. • Common features of this biomass production system are controlled spacing, shorter rotation lengths, and more intensive weed control and nutrient management. • At present, the best approach for short-rotation harvesting is a self-propelled forage harvester with a purpose-built header. This system cuts and chips the stems in one pass. Other prototype options include tractor-mounted systems that cut and chip stems in a single pass or a harvester pulled by a tractor that cuts, bundles, wraps, and cuts the stems into uniform lengths. • For larger trees, conventional forestry equipment is employed. Feller bunchers cut and pile the trees, which are collected by front-end loaders or grapple skidders and delivered to roadside for chipping and transport.
Understory or brush harvesting	• Woody biomass in forest understory or shrub lands is not utilized for conventional products and may be removed to reduce fire risk, control vegetative competition, or to restore rangelands. • Conventional logging machines—feller bunchers and skidders—are typically used to harvest smaller understory trees. Prototype swath harvesters are being developed to harvest shrubs and small trees more effectively.

* *These considerations were determined by DOE experts, DOE national laboratory experts and their USDA counterparts, informed by our industry partnerships and ongoing discussions.*

management decisions affect critical operational variables like piece size, volume per acre, and accessibility.

Regional variations of forest type, terrain, soils, and climate preclude single optimal-system solutions. Recovery of woody biomass involves operations on both gentle and steep slopes, firm or soft soils, big trees, small trees, hardwoods, softwoods, brush, winter weather, hot summer conditions, heavy precipitation, and other variables that influence operating efficiency.

(Photo courtesy of Dennis Dykstra, US Forest Service)

Figure 9. Recovery of slash from forests with steep slopes, as for the cable-logging operation shown above, can be quite costly and dangerous.

Integration of biomass recovery into conventional forest product operations involves complex product separation decisions. When biomass is a co-product, the harvest and processing system for separating high-value timber from slash must be cost-effective. The optimum operating strategy varies with a host of site, market, and material characteristics.

(Photo courtesy of Jason Thompson, U.S. Forest Service)

Figure 10. Residues from logging operations, or slash, removed from timber can be collected at the roadside landing and used for biofuel production. Operations to separate slash from high-value timber can be expensive.

Complexity of determining the optimum arrangement of preprocessing and transport. Preprocessing (i.e., delimbing or chipping) closer to the stump improves transport density and reduces costs, but can also adversely affect the efficiency of recovery and can increase total processing cost.

Complexity of system balance and work-in-process inventory. Biomass recovery systems can operate with little work-in-process inventory between concurrent functions (i.e., a hot system), but these must be carefully balanced to keep all the functions effectively utilized. Separated functions (i.e., cold systems) require inventory and storage but allow for different production schedules and flexibility in system balance. Management is critical for concurrent functions to reduce costs while the separated functions have costs associated with inventory and storage.

Woody biomass systems are dependent on collaboration among multiple parties. Efficiency and cost are affected by the landowner, resource manager, contractor, fiber procurement strategies, product specification decisions, and others. For the most part these parties act independently.

The organizational structure of forest operations contractors impacts efficiency. Most contractors are small business enterprises with constraints on capitalization.

(Photo courtesy of Barry Wynsma, U.S. Forest Service)

Figure 11. Handling small-diameter trees with conventional logging equipment is expensive.

Technology Development

Technological advances are needed for all operations along the woody biomass feedstock supply chain in order to deliver sufficient material that meets specified quality standards in a cost effective and sustainable way. New machines will be designed specifically to collect and handle small-diameter woody material for producing cellulosic materials, reduce overall system costs, and minimize environmental impacts.

Harvest and Collection

Current machines, systems, and procedures for logging are not designed to remove woody biomass from the forest efficiently. Equipment designed for harvest and removal of conventional forest products is often ill suited for handling smaller stems or residuals, resulting in higher feedstock costs.

Collection of forest residues in steep terrain presents special problems. Forestry operations in steep terrains substantially increase costs and, therefore, reduce the supply of biomass available for bioenergy or biofuel production.

Specialized woody biomass harvesters are not available for all forms of material (e.g., shrubs, small trees, etc.). First-generation harvesters have been developed for smaller-diameter (<3–4 in.) woody crops like willow, but do not work effectively in larger-diameter (>3–4 in.) or less uniform woody material. Terrain chippers are costly and their efficiency is sensitive to volume per acre.

Conventional harvesting equipment does not take advantage of all the characteristics of short-rotation energy crops. Most logging machines are designed to operate with randomly spaced trees on rough terrain. Energy crops are

(Photo courtesy of Rafaelle Spinelli)

Figure 12. Feller bunchers and other conventional logging equipment are not designed for the uniform stands of poplar plantations (as shown above). Significant improvements in harvesting efficiency can be made with machines designed to take advantage of the characteristics of short-rotation woody energy crops.

typically managed in uniform stands with controlled spacing and less variable terrain.

In-woods transport of woody biomass is inefficient with low-density materials. Some efforts have been made to find methods of densifying biomass prior to transport (e.g., baling, bundling, and chipping; on-site pyrolysis or torrefaction) but an optimum technology has not been identified and may vary under different conditions. For example, current research efforts by the U.S. Forest Service include exploration of the use of an in-woods portable pyrolysis unit to convert forest biomass to bio-oil as a method to reduce the need for long haul distances of woody biomass and reduce transportation costs.[13]

Environmental impacts of equipment operation in forests limit biomass recovery. Using large machines in forest stands can damage soil and the residual stand. Extensive traffic with heavy loads can compact soil. Ground-based operations on steep slopes can lead to soil erosion.

Storage

Comminuted wood has finite storage life due to biological degradation. Woody biomass undergoes continuous changes in moisture and condition. This leads to loss of feedstock quality over time—ranging from a few months for chipped material to a year for whole stem material—with implications for delivery schedules and inventory requirements. In addition, the continuous change in feedstock condition through storage requires active management to control changing properties.

Seasonal variation in wood harvest and accessibility impose inventory and storage requirements. This has been acknowledged in fiber procurement as mills have developed inventory levels in anticipation of weather-related, seasonal, harvesting variations. Woody biomass users must develop similar sourcing and storage strategies to minimize total cost.

Preprocessing

In-woods preprocessing is not as effective in meeting feedstock specifications as stationary facility operations (e.g., debarking, chipping). Densifying woody biomass using in-woods preprocessing can increase transport efficiency; however, in-woods processing is generally more energy intensive and results in poorer quality feedstock (e.g., poor size control, higher foreign matter content) than stationary processing facilities.

[13] Page-Dumrose, et al, 2009.

Mismatch between harvesting and preprocessing systems leads to equipment underutilization and higher costs. Woody biomass harvesting systems are generally less productive (in tons per hour) than chippers or grinders. This leads to underutilized equipment capability and increased costs.

Transport

Low density of whole-tree materials makes transport of woody biomass expensive. Unprocessed woody biomass is very low in density and may not make full highway-legal payloads when using conventional transport equipment. This means that the cost per unit is higher than it would be if the total load weight was near the maximum allowed. The high cost of transport limits the feasible haul distance.

Lack of standard transport forms for compressed woody biomass. Transport systems need to have some standardization for loading, unloading, and hauling equipment. There is currently no accepted standard form of baled or bundled woody biomass in the United States, making it difficult to find trucks and loaders for unique applications.

Forest roads are not designed for biomass. transports. Many forest roads, particularly in the western United States, have sharp corners and steep grades that are difficult for chip vans to navigate. This limits access to many sources of forest residues.

Environmental and Socioeconomic Impacts

The design and management decisions made in developing logistics systems for woody biomass feedstocks have direct, and in many cases long-term, effects on the environment and local community. With adequate understanding of these systems and their interactions within the environment and local socioeconomic systems, woody biomass supply systems that are both economically and environmentally sustainable can be developed. Some examples of interactions between biomass supply chains and environment and socioeconomic systems are listed below.

The unknown effect of biomass removal on site productivity leads to conservative allowances for biomass recovery. Because there is little consensus on how much material is necessary for nutrient cycling, the conservative approach is to restrict biomass removals. In addition to limiting amounts of material

(Photo courtesy of Jason Thompson, U.S. Forest Service)

Figure 13. In-woods transportation of low-density woody biomass (e.g., forwarding slash as shown above) is cost prohibitive.

removed, the timing of removals may be restricted to minimize removal of nutrients in leaf litter.

The effects of woody biomass removal on alternative forest ecosystem services are not well understood. Forests provide a wide range of ecosystem services and values, including recreation, wildlife habitat, esthetics, and water supply**.** Biomass recovery can have adverse impacts on some of these factors that must be addressed as part of environmental considerations. To better address adverse impacts, a better understanding and the development of mitigation practices are needed.

Forest resource management prescriptions may be developed that use biomass removal to accomplish objectives. For example, forest health or fire risk reduction can be achieved through better use of woody biomass removal practices.

Biorefineries will likely be required to complete Environmental Impact Assessments of their feedstock supply chains. This includes inputs and emissions for all phases of harvest, preprocessing, collection, and transport. Energy inputs, efficiency, and emissions of alternative technologies must be evaluated to identify the parts of existing or developing systems with the greatest potential for improvements.

The development of best management practices based on sound science should be developed for biomass-harvesting systems in different regions of the country. For example, acceptable woody biomass recovery criteria, like volume removal per acre, need to be developed.

A woody biomass industry will potentially create rural employment. Woody biomass recovery could create jobs in rural, forest-dependent areas. The effect on rural economies such as wage levels, industrial competition, economic multiplier effects, and training and workforce development need to be examined.

Forest work is generally regarded as one of the most dangerous industrial occupations in the United States. Potential jobs created to meet the increases in woody biomass feedstock demand must contend with potentially dangerous working conditions caused by dust exposure and hazardous equipment and terrain.

Assessment of Work Underway

There is a long history of research and development associated with woody biomass production for energy. Current activities build on this foundation of government, academia, and industry programs to advance forest operations technology. Below are some examples of United States and international activities. In the United States there are national research groups in USDA, through Forest Service Research and Development and in DOE through teams at national labs including Idaho National Laboratory (INL), National Renewable Energy Laboratory (NREL), and Oak Ridge National Laboratory (ORNL). University researchers working on woody biomass are found across the country, including biosystems and agricultural engineering programs, as well as focused programs in forest operations at several institutions. University research is often organized around special topic areas through consortia. Current research topics in these groups include developments in single-pass, cut-and-chip harvesters for short-rotation woody crops; alternative forms of woody biomass transport; harvest and delivery cost estimates; new residue-harvesting equipment; and improvements in woody biomass comminution efficiency.[14]

In Europe, there are similar research and development participants. National forest operations and technology research groups have programs to advance woody biomass utilization. Universities with forest operations and technology programs are active partners. Developments are motivated by national energy plans, industrial technology development, and environmental management. In addition, the European Union (EU) provides direction and support for some research activities through joint efforts like EUBionet and Intelligent Energy Europe. Similarly, Canada works extensively through the Forest Engineering Research Institute (FERIC), part of FP Innovations. Current developments in forest biomass utilization are shared among these groups through the International Energy Agency (IEA) Task 31. Key research areas currently highlight logistics and transport, harvesting technology, and sustainability implications of large scale biomass utilization

Specific technology development for woody biomass harvest and delivery is also being pursued by equipment manufacturers and individual innovators. Some large companies have internal technology development teams that are investigating potential breakthrough equipment like combine harvesters or walking machines. For example, one company, has developed a slow-running shredder that shreds all types of wood to a chosen particle size. Others are actively developing harvesting systems for energy crops. For example, researchers with the USDA Forest Service and Auburn University are adapting an existing bundling unit to capture otherwise non merchantable woody material.[15] Smaller companies are actively developing niche equipment to fill immediate needs for more efficient cutting, collection, and transporting processes. Some innovations are coming from individual contractors who see better ways to operate or adapt existing technology. The Small Business Innovation Research Program at USDA and the Forest Products Lab (FPL) USDA Biomass Grants program have funded some of these efforts. While some of this private effort is proprietary, there has been public disclosure of new biomass transport (roll-off bins), new field chipping systems for pinyon-juniper, new understory harvesting equipment, and baling and bundling systems.

Figure 14. New methods for measuring woody biomass properties are essential to the development of feedstock control and management systems.

[14] A summary of Forest Operations Research Unit regarding biomass is available from the Forest Service Southern Research Station: http://www.srs.fs.usda.gov/pubs/biomass_cd/

[15] Meadows, Gallagher, and Mitchell 2009.

Recommendations

Foundational and Baseline Developments

Develop methods for measuring woody biomass properties. Technologies need to be developed for rapid assessment of biomass properties such as moisture content, inorganic content, size, density, mass, and volume at various stages of harvest and collection. Such measures are essential to develop control and management systems that can optimize production.

Define baseline information on the operating costs, environmental impacts, and handling properties of conventional logging equipment used to handle biomass-sized material. This is necessary as a comparative measure of any future improvements.

(Photo courtesy of Bob Rummer, USDA Forest Service)

Figure 15. A bundler operating in northern Idaho demonstrates a potential solution to the high cost of handling loose, low-density biomass.

Harvesting Systems

Develop standard forms of compacted residues (bales, bundles) for in-woods operations. Standardized forms are needed to allow the development of related material-handling components. This requires market consensus as well as the development of feasible processes.

Develop biomass harvesting systems for steep slopes and understory. New technologies are needed to access many forest areas and increase potential volume. Helicopter adaptations and modified cable systems may be developed for steep slopes. For understory (i.e., fire treatment), swath cutters or modified mowers should be designed to cut an area, rather than individual stems.

Develop decision-support tools to model the cost and production of alternative woody biomass operations. This will help biomass users and producers match operations to the variety of potential feedstock situations.

Improve throughput capacity of forestry equipment. New technologies such as continuous-travel feller bunchers would significantly increase productivity and improve output, particularly in plantations.

Develop biomass-specific harvesting equipment for natural forests. Conventional operations should be resized to match smaller stems and shorter pieces more appropriately in order to reduce operating costs.

Develop harvesting systems for short-rotation energy crops. New systems are needed that cab take advantage of uniform rows and spacing of energy crops, such as automated single-pass, cut-and-chip operations, bundling or baling technology, and machines designed for larger materials.

Preprocessing

Develop systems to deliver biomass at desired quality and particle size. More energy-efficient comminution equipment with better feedstock quality control is needed to reduce costs and enable new conversion processes. The separation of wood from bark is a critical capability for feedstock preparation, and in-woods preprocessing is essential to the facilitation of more cost-effective transport.

Develop technology to manage the moisture content of woody biomass. This includes field-drying and forced-drying processes. Moisture content is a critical conversion process variable that affects costs from the time the material is harvested until it is converted into value-added products.

Develop mobile conversion technologies to take initial processing closer to the woods. This includes operations like conversion to liquid forms, densification, fractionation, and other basic separation methods that will reduce transportation costs.

Transport

Define costs of biomass transportation and develop improved payload technology. Develop reduced tare weights of transport equipment while optimizing transportation systems and conducting research to determine the impact of increased payload regulations on transportation costs.

Develop improved, two-stage transportation systems. Intermodal, chip-reloading, and containerized loads are possible developments that could increase economic transport distance to large facilities.

(Photo courtesy of the National Renewable Energy Laboratory [NREL])

Figure 16. Strategies for reducing the costs of transporting woody feedstocks are needed.

Socioeconomic Factors

Define potential health and safety concerns of workers and the surrounding community during collection, preprocessing, storage, and transport of woody biomass. Increasing employment in this sector calls for additional research on safety and health issues including dust exposure, traumatic injury, and organizational safety.

Improve understanding of the effects of woody biomass removal on forests. Research is needed to quantify the impacts of woody biomass removal on soil conditions, recreational opportunities, wildlife habitat, esthetics, and water quality and life cycle analysis.

IV. Municipal Solid Waste, Livestock Manure, and Algae

This section of the report on other biomass resources focuses on organic municipal solid waste (MSW), manure, and the emerging potential of algae. Several other potential feedstocks, including animal fats and renderings, used vegetable oils, process residues (e.g., distiller grains, food processing wastes), and biosolids (i.e., solids recovered from municipal wastewater treatment) have potential but do not have the size or volume of those addressed in this report. Algae are included as an emerging biomass source that is receiving increased attention as it undergoes continued evaluation and research.

(Photo courtesy of NREL)

Figure 17. Wastepaper (as shown above) is one of many potential feedstocks for biofuel production.

Logistics System Design and Management

Municipal Solid Waste

Municipal solid waste (MSW) could be a valuable biofuels feedstock because it is a readily available, domestic source of renewable biomass generated in large volumes and collected in centralized processing facilities. Between 250 and 350 million metric tons of MSW are generated in the United States per year. It is already collected in a vast, integrated collection system and transported to centralized locations for further processing and/or disposal. This system could be readily adapted to handle food and yard waste for biofuels production. However, only 25% of all MSW is both available and in the form of food and yard waste that would meet the statutory definition of renewable biomass and the current MSW logistics system is not designed to separate out this portion of MSW and may or may not be available in certain municipalities. In some locations wood pallets from contractors are also a useable resource. Certain cities have organized collection of these wood pallets. If the 25% available MSW was realized at current estimated yields for similar materials, this would roughly translate to 4.5 billion gallons of biofuel.[16]

[16] For more information on the conversion rate used to estimate gallons of ethanol, please see U.S. Department of Energy, Energy Efficiency and Renewable Energy, Office of the Biomass Program. *Table B-5 Unit Operation Cost Contribution Estimates (2007$) and Technical Projections for Biochemical Conversion to*

Existing efforts to separate the yard and food waste components from MSW are focused on providing materials suitable for composting. Little effort is underway to design a system for collecting, separating, and transporting yard and food waste to biofuels production facilities. A few jurisdictions in the United States (e.g., San Francisco) provide curbside separation of biomass from raw MSW, but no logistical system exists for collection and transport of these materials to biofuels production plants. However, MSW is collected and concentrated in materials handling facilities across the country, and this readily exploitable infrastructure could be re-designed to separate and transport the renewable biomass in MSW to biofuels production facilities.

Actual production of biofuels from MSW biomass is limited in the United States. No large-scale infrastructure exists to produce a significant volume of biofuel from this feedstock. The logistics system to feed MSW biomass to biofuels production facilities does not exist; however, conversion systems such as pyrolysis, gasification, and autoclaving could be adapted to produce biofuels from MSW.

Livestock Manure

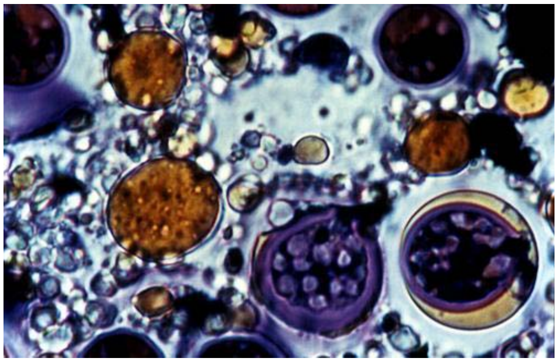
The use of manure for biofuels may conflict with the traditional use of manure as a fertilizer. Manure contains substantial amounts of plant nutrients—particularly nitrogen (N), phosphorous (P), and potassium (K)—plus minor elements. Manure has substantial value as a fertilizer and normally it can be used on crop or pastureland near the location where it is generated. If manure is treated through anaerobic digestion, the plant nutrients are still available in the effluent. However, other processes may alter the availability of these nutrients. Greater attention should be paid to determining the fate of these nutrients through thermochemical conversion processing.

(Photo courtesy of the USDA Agricultural Research Service [ARS])

Figure 18. Livestock manure is a potential feedstock for biofuel production.

More than 15,000 animal operations across the nation are concentrated in rural areas and are individually owned; this makes it difficult to establish standard systems for converting manure to energy. The use of manure for thermochemical conversion to energy could create many new private-sector jobs and provide additional income options for livestock producers. Very few companies will design, install, and operate manure-to-energy systems, and most livestock producers are not capable of managing an on-farm manure-to-energy facility. It may therefore be necessary to identify companies that will finance and operate on-farm manure-to-energy systems and potentially pay the livestock producer for the manure.

Ethanol Baseline Process Concept. Biomass Multi-Year Program Plan. March 2010.



(Photo courtesy of NREL)

Figure 19. Microalgae (shown above) are organisms from which a diesel-like fuel can be derived.

Algae

Algae processes have advantages over more cellulosic systems because algal oils have similar characteristics that are closer to the final biofuel product, and the algae can be 50%–60% lipids. Algae proponents also claim much greater yields than other oil-producing crops, with estimates from 10 to 100 times greater yield per acre than canola. Commercial development of algae biodiesel is nonexistent, and no viable, pilot-scale demonstration facility has been developed. There continue to be major concerns about dewatering and the large infrastructure that would be required for even minimal biomass production. Estimates of feasibility and viability are also disparate.

Technology Development

Municipal Solid Waste

Collection

MSW is a mixture of materials collected in a centralized system. Therefore, collection of MSW itself is not a particular barrier. For example, if a local jurisdiction required curbside separation of food and yard wastes, the existing collection system could be readily adapted to collect such materials for processing. If local jurisdictions decide to establish centralized separation systems at Municipal Recycling Facilities (MRFs), collection could occur in a specialized location. Barriers to overcome include:

- Curbside separation policies to segregate usable biomass from other recyclables and nonrecyclable materials are not well established nationally.
- The lack of specialized biomass separation units in jurisdictions that choose to bring raw MSW to centralized materials recovery facilities
- The absence of a specialized transportation system for MSW biomass to be carried to biofuels production facilities

Storage

MSW is generated and collected on a continuous basis at high volumes. Storage of MSW falls under the jurisdiction of local and state solid waste management authorities. Virtually all MSW is either processed or disposed of immediately; little storage occurs. Any storage of separated food and yard waste would be regulated by local authorities under permit. The EPA has issued “Guidelines for Storage and Collection of Residential, Commercial, and Institutional Solid Waste” that can be used by local or state authorities, but is not binding.[17] Thus, a potential barrier to an MSW for biofuels system would be the varied requirements for storage established by a state or municipality.

Preprocessing

EISA identifies “separated yard waste or food waste, including recycled cooking and trap

[17] 40 CFR Part 243.

grease" as part of the definition of renewable biomass.[18] About 25% of MSW meets this definition and would qualify for renewable fuels production under the statute. Perhaps the major logistics barrier to successful use of MSW as a biofuel feedstock is the necessity to separate food and yard waste from raw MSW. This separation is being done selectively in the United States, mostly to support efforts to compost the material; however, a very large percentage of food and yard waste ends up in landfills.

Preprocessing (i.e., separation) technologies are not currently in use in the United States. Separated organic waste materials can potentially be contaminated by unwanted solids or from the mixing of metals and/or organic toxicants into the feedstock.

Transport

The separated food and yard waste component of MSW has high moisture content and is therefore expensive to transport. Specialized transportation vehicles are not currently in use, but could be readily adapted from the existing MSW transportation system.

Livestock Manure

Collection

The typical forms of animal manure are relatively dry from beef feedlots and broiler litter; semisolid from scrape floor dairies and swine manure storage; and liquid from dairy, beef, and swine lagoons. Specific barriers facing harvest and collection include:

- Development and commercialization of specialized equipment to gather heterogeneous manures and overcome low energy densities.
- Livestock operations are widely distributed in rural areas throughout the United States.

Storage

Biological degradation may occur during storage. In most cases, the moist or wet manure undergoes biological activity, which can result in the release of gases and odors. This is a potential nuisance and air quality issue. The release of methane from anaerobic manure storage can also have global warming impacts. Livestock manures would ideally be stored in a biologically inert form, such as pyrolysis oil or charcoal; however, this technology is still in the research stage. Manure stored at low moisture contents (approximately 15%), such as beef feedlot and poultry litter, will have minimal biological degradation.

Proper storage for manure is critical to prevent water quality problems. Manure should be stored (in a liquid, semisolid, or solid state) with adequate safeguards to prevent pollution of surface and groundwater supplies by nutrients or pathogens.

Preprocessing

Liquid-solid separation will allow more options for techniques for energy recovery. High-moisture solids can be used for energy recovery while the liquid portion and its nutrients can be used as a fertilizer. Wastewater treatment and reuse is an important R&D area to minimize overall water usage.

Moisture removal is necessary for the thermochemical conversion of manure for energy. Excess heat from thermochemical conversion of manure can be used to dry the manure.

Manure with high moisture content is suitable for anaerobic digestion. In some

[18]Pub. L. No. 110-140, 121 Stat.1521.

cases, water will be added to produce a liquid (95% moisture) for anaerobic digestion and for producing methane. Normally, water will not be added because this would require the transport and management of additional volumes of wastewater. Furthermore, combined thermochemical processes can be used to convert remaining solids to additional high-energy gases and nutrient-rich ash.

Transport

The high moisture content of most manure makes transportation costs high. Widely distributed livestock operations and high moisture contents preclude the transport of manure to a centralized energy conversion facility. In most cases, large operations will have an on-site energy conversion and recovery facility (anaerobic digestion and electrical generation) to eliminate transportation costs.

Low energy content and low energy density of semi-dry manure limits transportation distances. Manure from broiler litter and from beef feedlots in the Southwest is relatively dry, but also relatively low in energy content. Therefore, it will be difficult to justify transporting these materials to centralized energy conversion facilities.

Pumping versus hauling manure. An assessment of pumping versus hauling manure will require modeling analysis to include the cost of transport, truck capacities, and regulatory impediments.

Algae

An exhaustive summary of technical barriers and recommendations is in development based on the results of the “Algal Biofuels Technology Roadmap Workshop” sponsored by the DOE Biomass Program in December 2008. For more information, see the workshop website at http://www.orau.gov/algae2008/.

Harvest and Collection

Algae are a group of simple, aquatic eukaryotes capable of autotrophic photosynthesis. Algae have great potential as an oil feedstock, theoretically capable of producing 10,000 gallons of oil per acre. However, there are many challenges associated with algae that have prevented commercial deployment. Dewatering remains the overwhelming barrier in terms of energy and capital costs. Keeping production rates high requires extensive infrastructure.

Storage

It is unlikely that any long-term storage of algae will occur. Rather, the feedstock may be processed on- or near-site to algal oil, which will presumably be converted to fuel via transesterification or hydrotreating.

Preprocessing

While R&D is underway to engineer algae microorganisms to excrete oils with little intervention, the short-term challenge of dewatering algae from the liquid growth substrate will remain the most significant collection and pre-processing barrier.

Transport

Transportation is largely considered by experts as impractical, except perhaps by pipeline after concentration to 10% solid. Higher concentrations are too viscous and tend to degrade.

Environmental and Socioeconomic Impacts

Municipal Solid Waste

From an environmental perspective, it would be desirable to establish a national system for converting separated MSW into biofuels. Most of the food and yard wastes found in MSW are currently being discarded in landfills. When in landfills, these types of waste undergo biodegradation and generate methane and other gases. Some of this methane is collected and used for energy generation; however, much of the methane is lost to the atmosphere where it contributes to climate change. EPA estimated that methane from landfills accounts for 24% of the anthropogenic methane released to the atmosphere each year.[19] Methane is 21 times more potent as a greenhouse gas (GHG) than carbon dioxide (CO_2). Removing some of the putrescent materials from the MSW currently in landfills is desirable from a climate change perspective.

There is potential for contamination of MSW biomass. Raw MSW is a complex and varied mixture of materials, some of which could contribute both organic and inorganic contaminants to the biomass fraction. Organic contaminants would theoretically be destroyed in the production process, particularly in a thermal conversion system.

Livestock Manure

The use of manure as an energy source may conflict with the traditional use of manure as a "natural" fertilizer. Manure contains substantial amounts of plant nutrients—particularly nitrogen (N), phosphorous (P), and potassium (K)—plus minor elements. Manure has substantial value as a fertilizer and normally it can be used on crop or pastureland near the location where it is generated. If manure is treated through anaerobic digestion, the plant nutrients are still available in the effluent. If manure is treated through thermochemical processes (e.g., direct combustion, gasification, or pyrolysis) most or all of the nitrogen will be lost to the atmosphere.

Biogas from anaerobic digestion can be burned directly to produce electricity via an engine-generator set. This will reduce the GHG load by converting methane to CO_2. Many livestock operations get carbon trading credits for producing CO_2 rather than methane.

Algae

The southwestern United States is considered by some to be the most promising area of the country for large-scale algae production because of large tracts of unused or underutilized land and potential for using brackish water with favorable sunlight conditions. However, this area already suffers from depleted water resources and an ever-increasing tension among water users. In light of these factors, algae production could use saline and other marginal water sources to limit its impact on the environment and surrounding communities.

Assessment of Work Underway

Municipal Solid Waste

There is no current national research program for converting biomass from MSW into biofuels in the United States. The MSW-derived organic materials currently being managed in the United States are almost always composted.

[19] Biocycle, 2005

Some private U.S. companies are researching the conversion technologies and infrastructure necessary for commercial-scale plants to produce biofuel from MSW. A number of pilot-scale projects researching MSW-to-biofuel are underway, but there is no commercial scale MSW-to-biofuels industry.

Some jurisdictions (e.g., Alberta, Canada) have plans to construct full-scale plants to convert raw MSW to biofuels, but the facilities are not yet operational.

Livestock Manure

There are about 150 anaerobic digesters currently operating on farms, and most of the biogas generated is used in stationary engines to drive electrical generators. The electricity is used directly on the farm or delivered to the electrical grid. Most of the biomass for these farm generators is animal manure combined with some other biological waste material. Some farms generate income with on-farm digesters; food-processing plants will pay farms to take waste products at a lower cost than landfill disposal fees.

Research and demonstration projects on converting livestock and poultry manure to energy have been taking place for several decades. The technical aspects of digestion are fairly well understood. There have not been many commercial operations running for a long period of time, mainly because of the on-farm management required and/or economic viability of such an investment. Several European countries have subsidized large-scale anaerobic-digestion systems in order to manage the concentration of livestock and poultry manure more efficiently.

There has been research on converting manure into liquid and gaseous fuels, but there are no commercial facilities currently operating, although methane digesters are operating to generate electricity.

Algae

The inaccessibility of economically affordable vegetable oil feedstock for biodiesel production, in combination with the availability of new and exciting molecular tools, has sparked a renewed interest in algae R&D. Current efforts are concentrating on algae species selection and development to achieve high lipid content and relatively high growth rates. The infrastructure varies widely, from natural lagoons and greenhouses to elaborate mazes of pipes, solar collectors, and processing equipment. The amount of peripheral equipment depends on the removal of phosphorous (P), nitrogen (N), and CO_2, especially if used in conjunction with a scrubber for a fossil fuel power plant. The massive water handling is challenging, although water usage can be considerably smaller than some terrestrial feedstocks.

(Photo courtesy of Bob Rummer, USDA Forest Service)

Figure 20. Cellulosic material in MSW (such as the pallets shown above) could be available for biofuel production if properly separated from other wastes.

Recommendations

Municipal Solid Wastes

Separation of usable biomass from municipal solid waste. Develop technologies and programs to enable curbside separation of usable biomass from other recyclable and nonrecyclable materials.

Develop MSW storage systems. Develop engineered, long-term MSW biomass storage facilities at municipal recycling facilities.

Develop MSW preprocessing technologies. Develop technology to process separated food and yard waste into usable feedstock for biofuels production.

Develop MSW biomass collection vehicles for long-haul transport. Design MSW collection vehicles into food and yard waste feedstock long-haul transporters.

Livestock Manure

Develop cooperatives or networks for collecting manure from farms. Establish a network of service providers for collection and treatment so that farmers do not have to invest in and operate a manure energy recovery operation.

Develop guidelines for sustainable storage facilities. Research is needed to establish construction standards for storage to prevent air and water quality pollution.

Develop moisture removal systems for manure. Develop technologies to remove excess moisture from manure prior to energy recovery.

Reduce, or eliminate, manure transportation costs. Develop on-farm energy-recovery systems, thereby reducing transportation costs.

Algae

Detailed recommendations for the development of algal biofuels will be available in the upcoming *Algal Biofuels Technology Roadmap* currently under development by the DOE Biomass Program (2008).

Develop dewatering technologies for algae and other aquatic species. Develop effective dewatering techniques for different algal species—natural or farmed—and salt, fresh, or brackish water using filtration, centrifugation, or flotation.

Develop storage containers for short-term algae storage. Some stainless-steel tanks may be necessary for short-term storage before oil extraction. There are only minor issues for algal oil storage.

Develop environmentally friendly oil-extraction technologies. Improve oil extraction using environmentally favorable solvents or enzymes; or, develop a mechanical process that effectively utilizes secondary byproducts.

Develop drying systems to remove excess water and reduce transportation costs. Design effective dryers for further water extraction of byproducts.

V. Summary of Recommendations

Overarching Recommendations

- Conduct research that will enable development of densification and other preprocessing technologies to achieve higher bulk and/or energy densities such that transportation, storage, and other logistics operations become economically feasible.
- Conduct research to develop strategies and equipment to deal with high-moisture biomass.
- Conduct research and collaboration with industry that will enable the development of innovative equipment and systems designed specifically for cellulosic biofuel feedstocks.
- Develop logistics operations that maximize uniformity and consistency of delivered feedstock attributes.
- Develop quality standards for delivered feedstocks and instrumentation to quickly determine feedstock quality at point of scale.
- Conduct research to better understand the impacts of increased payload regulations used to reduce costs and effects of increases in heavy traffic on rural road networks.

  Develop new transportation technology including improved containers and lighter vehicles to reduce truck traffic and transportation costs, reduce impact on roads and bridges, and reduce undesirable social impacts.

Agricultural Resources

- Increase equipment throughput capacity.
- Reduce operational dry-matter losses.
- Develop strategies for high-moisture biomass.
- Develop systems to deliver biomass at desired quality and particle size.
- Increase feedstock bulk density.
- Define required feedstock properties.
- Develop biomass preprocessing technologies.
- Develop technology to reduce infrastructure and social effects of transporting biofuel feedstocks.
- Develop efficient biofuel feedstock transportation equipment and systems.
- Determine how producers can be influenced to incorporate cost-effective biomass production and logistics into their existing operations, and when it is appropriate to do so.
- Define potential health and safety concerns of workers and the surrounding community during feedstock collection, preprocessing, storage, and transportation.
- Develop technologies that increase biofuel feedstock production without requiring more land.
- Develop accurate life-cycle analyses for biofuel feedstock logistics.

Forest Resources

- Develop methods for measuring woody biomass properties.
- Define baseline information on the operating costs, environmental impacts, and handling properties of conventional logging equipment handling biomass-sized material.
- Develop standard forms of compacted residues (e.g., bales, bundles) for in-woods operations.
- Develop biomass harvesting systems for steep slopes and understory.
- Develop decision-support tools to model the cost and production of alternative woody biomass operations.
- Improve throughput capacity of forestry equipment.

- Develop biomass-specific harvesting equipment for natural forests.
- Develop harvesting systems for short-rotation energy crops.
- Develop systems to deliver biomass at desired quality and particle size.
- Develop technology to manage moisture content of woody biomass.
- Develop mobile conversion technologies to take initial processing closer to the woods.
- Define costs of biomass transportation and develop improved payload technology.
- Develop improved two-stage transportation systems.
- Define potential health and safety concerns of workers and the surrounding community during collection, preprocessing, storage, and transport of woody biomass.
- Improve understanding of effects of woody biomass removal on forests.

Municipal Solid Wastes

- Separate usable biomass from municipal solid wastes (MSW).
- Develop MSW storage systems.
- Develop MSW preprocessing technologies.
- Develop MSW biomass collection vehicles for long-haul transport.

Livestock Manure

- Develop cooperatives or networks for collecting manure from farms.
- Develop guidelines for sustainable storage facilities.
- Develop moisture removal systems for manure.
- Reduce or eliminate manure transportation costs.

Algae

- Develop dewatering technologies for algae and other aquatic species.
- Develop storage containers for short-term storage of algae.
- Develop environmentally friendly oil-extraction technologies.
- Develop drying systems to remove excess water and reduce transportation costs.

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