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# Convergence of Agriculture and Energy: IV. Infrastructure Considerations for Biomass Harvest, Transportation, and Storage

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## Introduction

The United States is committed to expanding the role of biomass as an energy source to decrease imports of oil and gas and the production of greenhouse gases and to foster the growth of agriculture, forestry, and rural economies. The Energy Independence and Security Act (EISA) of 2007 mandates the production of 136 billion liters of renewable fuels by 2022 including 79 billion liters of advanced biofuels and cellulosic ethanol. In addition to transportation fuels, biomass can be used to generate electricity or steam. During the past several years, research and development activities have focused on the collection and use of agricultural crop residues and the production of dedicated agricultural biomass crops for use in energy and biofuel production.

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Biomass includes all plant and plant-derived materials. The first generation of biofuels has been produced primarily from starches, plant oils, and sugars that have been used historically for food. This paper focuses on agricultural cellulosic biomass crops that are generally inedible for humans. The primary agricultural cellulosic feedstocks for

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biofuels include crop residues, perennial grasses, perennial woody crops, and forest management residues. The use of *Life Cycle Analyses* (LCA)[1] to assess biomass feedstock production, production of cellulosic ethanol, and the use of ethanol in liquid transportation fuels has been modeled by several laboratories (Farrell et al. 2006). Broad scientific consensus supports claims that the use of dedicated biomass crops and residues provides significant decreases in greenhouse gas emission and in the need for fossil fuels.

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The sustainable collection of biomass feedstocks is an important consideration for cellulosic ethanol production. The sustainable amount of biomass that can be removed from the field is directly related to the amount of carbon in the soil, the amount of macronutrients removed in the biomass, and the mass left in the field to protect the soil from erosion. More than 700 million metric tons (MT) of biomass feedstocks can be harvested economically and sustainably for biofuels in the United States (West et al. 2009).

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## Biomass Collection

Collection options for agricultural biomass crops and residues encompass three methods: baling (dry), chopping (wet), and loafing (dry), as summarized by Kumar and Sokhansanj (2007). (Similar technologies exist for forest residues and woody biomass.)

Baling is the most common option; the biomass is mowed, field-dried, raked into a windrow, and then baled into round or rectangular bales. The production of round bales involves the use of a tractor, pickup head, crop processor, baler, and bale wagon. Large round bales are approximately 1.5 meters (m) diameter by 1.8 m long and weigh more than 580 dry kilograms (kg). Rectangular bale systems use a tractor, rectangular baler, and bale wagon. Large rectangular bales typically are 1.2 m square by 2.7 m long and weigh more than 588 dry kg. Rectangular bale production is slightly more efficient than large round bales, but with most equipment this method is limited to a lower number of bales per bale wagon (10) and flatbed truck (26) compared with 17 round bales per wagon and 28 per truck. After baling, bales can be left in the field, brought to the field edge, or taken directly to an on-farm or secondary storage site (Perlack and Turhollow 2002).

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Procedures for wet chopping of corn *stover* and hay crops are well established. Wet chopped biomass can be packed in bunkers and stored on-farm at the same dry matter density level as baled. Forage harvesters chop the stover or hay and throw it into a forage wagon. This process is accomplished with a self-propelled forage chopper and forage wagon or a tractor-pulled harvester and wagon. Silage collection of corn stover and hay is slower than baling and requires an expensive forage harvester and further compression to increase density (Perlack and Turhollow 2002). Switchgrass and other biomass crops can be direct-cut and chopped, which involves one trip over the field and no field drying time, making it a much faster harvest option than baling.

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Loafing is a process in which the biomass is picked up from a windrow and large stacks are created. The stacking compresses the biomass and leaves a dome-shaped top that sheds water. It may be possible to densify biomass at farm sites to 240 kg per cubic meter using roll compaction, allowing the transport of 22.5 MT-truckloads (Morey, Tiffany, and Kaliyan 2009).

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[1] Italicized terms (except genus and species names) are defined in the Glossary.

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Harvest of a dedicated biomass crop typically occurs once a year. Harvest timing is dependent on factors such as weather, market conditions, and environmental targets. The harvest window for agricultural biomass is typically 3 to 6 weeks in the fall or winter, depending on the location and crop.

Technologies under development for corn stover collection involve single pass, combined stream harvesting or single pass, dual stream harvesting, which are expected to lower overall harvest costs compared with baling (Birrell et al. 2006). With the single pass, combined stream method a whole-plant harvester is used, eliminating the need for a combine. The single pass, dual stream system is based on a conventional harvester with two harvest streams—grain and biomass.

## Biomass Storage

Storage requirements will vary depending on the length of the storage period and the density of the biomass unit.

Once biomass feedstocks have been collected and processed into bales or accumulated as silage in pits or above ground, storage requirements will vary depending on the length of the storage period and the density of the biomass unit (bales versus compacted loose material). Generally, pelletization is not an economical option for biomass feedstocks because of its cost. However, pelletization may be economical depending on the distance of transportation, storage facility requirements, downstream use, and market value.

On-farm storage can decrease overall costs and give the biorefinery greater flexibility.

On-farm storage can decrease overall costs and give the biorefinery greater flexibility. This storage can be accomplished either on an unmodified surface (soil) or a modified surface (crushed stone, concrete, or asphalt). Biomass bales can be stored uncovered or can be covered to decrease storage losses. Biomass feedstock weight loss during storage is projected to be 5 to 10% of harvested dry weight. Most on-farm options are open storage and do not use enclosed structures. Biomass must be at or below the appropriate moisture content when stored and must be properly ventilated. Research on fire hazard management is required for long-term storage of some types of biomass because of the dangers of spontaneous combustion.

Storage requirements at the biorefinery are based on the usage rate, local availability of biomass, and the quality of biomass.

Storage requirements at the biorefinery are based on the usage rate, local availability of biomass, and the quality of biomass. Biorefineries likely will maintain some on-site storage, with the balance of storage located on-farm. Storage facilities at the biorefinery consist of gravel, crushed stone, or concrete floors with good drainage and adequate spacing to allow machinery to retrieve bales or loose biomass feedstock efficiently. Biorefineries will need to further process (mill) the biomass to a small particle size for use in the production of cellulosic ethanol.

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A well-defined system of on-farm bins, grain elevators, transportation equipment, and commodity markets exists to supply corn grain ethanol plants. This system does not yet exist to supply biomass feedstocks for energy and industrial use in small-scale markets and micro-markets across the United States. Biomass feedstocks generally have a low density compared with grains and fill the available space (*cube out*) before reaching the container or road maximum weight limit (*weigh out*). Even with on-farm *densification*, specialized over-the-road equipment may be necessary to lower transportation costs and minimize the number of trips to the plant. Vehicle width, height, or weight waivers may be desirable but might not be feasible in heavily trafficked areas. Physical constraints such as low clearances or narrow bridges also present transportation obstacles.

Large-scale biomass processing plants may require intermediate storage or biomass aggregation sites.

Large-scale biomass processing plants may require intermediate storage or biomass aggregation sites. Storage sites need access to all-weather roads with a minimum of load and axle weight restrictions. Storage sites must be secure areas or structures with a prepared base, drainage, road access, and an area for loading. Storage sites will require loading equipment, scales, office space and, possibly, densification equipment. If there are a number of offsite storage facilities, work crews and equipment such as loaders and scales may be shared and moved between sites as needed.

It will be necessary to be able to track each lot of biomass from the farm into the processing plant and through any intermediate storage locations.

It will be necessary to be able to track each lot of biomass from the farm into the processing plant and through any intermediate storage locations so that the processor can pay for desired quality attributes and optimize plant operations. Knowledge of characteristics such as bulk density, carbohydrate levels, *kilojoule (kJ) content*, moisture level, and ash content are essential.

## Costs of Producing Biomass

A major cost to perennial biomass producers is the “opportunity cost” of multiyear commitments because producers cannot respond as rapidly to changing market conditions as they can with annual crops.

The costs of producing biomass vary by crop; cropping practices; and collection, storage, and transportation scenarios. Regardless of crop and approach, biomass producers will expect to cover their costs and generate a profit from the sale of biomass to the biorefinery. Biorefineries may contract directly or through aggregators to obtain biomass. Cost and risk structures differ for producers who grow crops specifically for biomass (switchgrass or woody biomass) and producers of byproducts (cobs and corn stover). A major cost to perennial biomass producers is the “opportunity cost” of multiyear commitments because producers cannot respond as rapidly to changing market conditions as they can with annual crops.

Production costs for crops grown specifically for biomass are incurred to establish the crop.

Production costs for crops grown specifically for biomass are incurred to establish the crop. These costs include seed or propagules, seedbed tillage, starter fertilizer, and weed control. In subsequent years there will be costs for fertilizer applications and possible costs for weed control.

Collection and harvesting costs for dedicated biomass crops include mowing, chopping, and conditioning.

Collection and harvesting costs for dedicated biomass crops include mowing, chopping, and conditioning. Crop residue suppliers have costs to collect the residues during grain harvest or for a dedicated harvest. Transportation costs are incurred to move the harvested materials to storage locations in or near the field or farm, to intermediate sites if used, and to the biomass processing plant. Handling costs, which may include loading, unloading, inspection and sampling, densification, and weighing, will occur at each storage site.

Inventory carrying costs are incurred because most biomass crops are harvested annually but processing plants operate year round.

Inventory carrying costs are incurred because most biomass crops are harvested annually but processing plants operate year round. To operate throughout the next year, it will be necessary to have approximately one year’s supply of feedstock in storage at the completion of harvest. (Uncertainties due to weather and yield variability may require an additional safety stock.) The total inventory carrying cost for a year is equal to the value of the average inventory times the cost of money to the inventory owner. If the producer is paid at harvest, the inventory carrying cost will be borne primarily by the processing plant. If the biomass is purchased at the time of processing, most of the inventory carrying cost will fall to the producer.

Storage costs include depreciation and maintenance of structures, rents, taxes, and security costs. If structures are not used, there may be costs for tarps or other covers for at least part of the inventory. Dry matter and quality losses also are storage costs.

Biomass stored under poor conditions for 12 months can lose more than 10% of its dry matter and value. Even biomass stored under ideal conditions has some loss of dry matter and quality. Storage costs will be incurred over the season even if storage is left to the producer.

Storage costs include depreciation and maintenance of structures, rents, taxes, and security costs.

The total costs of producing and delivering biomass at the farm gate or to a processing facility vary by crop and region. One study found that the total cost of round bales of corn stover to end users in Minnesota would be $85 per MT. This cost included replacing the nutrients removed from the soil, hauling to a local storage site, transloading, and transporting the bales 32.2 kilometers to a processing plant (Morey, Tiffany, and Kaliyan 2009). In preparation for their Project LIBERTY, a 95 million liter cellulosic ethanol plant in Emmetsburg, Iowa, POET, LLC, expects their costs of corn cobs to be $50 to $72 per MT in 2010.This is based on a four-year commitment between POET and the farmer for a minimum of 680 MT per year. Pricing to farmers will also be dependent on the quality of the cobs and the form in which they are delivered to the plant (Project LIBERTY 2010).

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Estimates of the annualized delivered costs of switchgrass and *Miscanthus* in Illinois using 2003 prices were $64.84 and $49.58 per MT, respectively, before the opportunity cost of land and $98.19 and $59.24 per MT including the opportunity cost of land (Khanna, Dhungana, and Clifton-Brown 2008).

## Case Study: Cobs

POET has selected corncobs as its first feedstock for the production of cellulosic ethanol. Corncobs offer advantages for technical, environmental, and economic reasons. Corncobs, which are typically left in the field after the harvest of the corn kernels, are rich in sugars and contain approximately 16% more total carbohydrates than corn stalks. They are twice as heavy as corn stalks, which makes separation easy. Cobs can be removed from the field with little environmental impact because they have little fertilizer value (they do, however, have organic matter value to soil). They can be collected relatively easily by the farmers who provide the ethanol plant with corn grain. POET estimates that the volume of cobs available in the United States is sufficient to produce about 19 billion liters of cellulosic ethanol per year, about 25% of the EISA mandate.

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In 2007, 2008, and 2009 POET harvested more than 10,000 MT of corncobs from more than 10,000 hectares (ha) of corn in Iowa, South Dakota, and Texas. In this test POET had excellent farmer participation and feedback. POET has worked with 15 equipment manufacturers using three cob harvest concepts: (1) a corn and cob mix (CCM), (2) a single pass towable corn stover-cob separator, and (3) second pass cob bales. With the CCM system, corn kernels and cobs are collected and stored in the combine hopper while the stalks are returned to the field; both corn and cobs are transferred to a grain cart in the field, then transported off the field to be separated with a grain separator to create a grain pile and a cob pile. With the combine and towable stover-cob separator, grain is collected in the combine hopper and the stover from the combine is received by the towable separator. The towable separator collects the cobs and drops the stalks on the ground to provide cover for erosion control and nutrients for soil fertility. Second pass bales are produced in either round or square forms by collecting and baling corncobs and stalks from the ground after corn harvest.

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POET hosted a Field Day in November 2009 to showcase equipment, brief farmers on the process, and provide opportunities for farmer and equipment suppliers to discuss equipment performance and pricing. By 2012, POET expects to collect more than 227,000 MT of corncobs from more than 121,400 ha (300,000 acres) working with approximately 400 farmers in the Emmetsburg, Iowa, area to produce more than 95 million liters of cellulosic ethanol.

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## Case Study: Switchgrass

A comprehensive research program for switchgrass as a dedicated energy crop is part of a $70.5 million demonstration and pilot-scale cellulosic ethanol biorefinery funded by the state of Tennessee. The University of Tennessee contracted with farmers to produce Alamo switchgrass and is developing an integrated supply chain for the biorefinery.

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Switchgrass has characteristics that make it attractive as a dedicated feedstock for biorefineries. Yields of lowland and upland ecotypes of the warm-season perennial grass averaged 12.9 MT and 8.7 MT per ha based on 1,190 observations from 39 field trials in 17 states. The lowland ecotype is found in wetter and more southern habitats, and the upland ecotype is found in drier and more northern latitudes. Existing hay and forage equipment can be used for harvesting (Wullschleger et al. 2010).

Farmers signed contracts for 2,400 ha of switchgrass production. Participating farms have wide ranges of cropping histories, fertility, physical characteristics, equipment, and management experience. The first year's production, harvested in November 2008, yielded approximately 4.5 MT per ha at 18 to 20% moisture content. Yields are expected to increase to approximately 11 MT per ha in the second year and higher in subsequent years.

The first year's production, harvested in November 2008, yielded approximately 4.5 MT per ha at 18 to 20% moisture content. Yields are expected to increase to approximately 11 MT per ha in the second year and higher in subsequent years.

Farmers harvest the switchgrass in the fall or early winter after the first frost. This practice improves the quality of the switchgrass by allowing the translocation of nitrogen and other nutrients to the root, which decreases the overall nutrient use and ash production. Delay in harvesting decreases harvest yields (Khanna, Dhungana, and Clifton-Brown 2008; McLaughlin and Ksozos 2005). Bales are staged at the field's edge, tagged for tracking, picked up from the farms, transported to a central storage site, stored on a gravel pad in pyramid rows with a 3-bale base, and covered with 5-mm plastic tarps. The storage site is equipped with permanent truck scales. Weight and moisture are recorded at the time of unloading at the storage site. In 2009, participating farmers were offered separate storage contracts for on-farm storage of bales under a covered structure or an approved tarp cover.

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Key insights from the first year of production and handling include the following:

- One-on-one technical expertise provided by University Extension specialists and county agents was critical in establishing and handling a brand new crop and developing a new crop system.
- Although farmers' existing harvesting and handling equipment works for switchgrass, it is not designed for long-term use with such a high-yielding biomass crop. Better equipment for harvesting and handling will be required.

- Current contracts are a fixed price per ha. Future contracts will require a yield and quality-based payment. Additional specifications from the biomass processor with desired feedstock characteristics and specifications (e.g., acceptable moisture content range, chemical composition, particle size, packaging, age, etc.) are needed to develop efficient contracts.
- Round bales were better than square bales for on-farm storage because their shape and structure is better at shedding water. Covering bales shortly after baling is critical for keeping moisture content low, which prevents degradation and loss of biomass.
- Significant gains in efficiency occurred when bale loading, transport, and unloading from the farm to the storage location were provided by an independent service provider rather than by the producer.
- Switchgrass bales must be stored off the ground, at a minimum on a well-drained gravel pad, to prevent moisture-related degradation and loss.
- Feedstock quality was highest when storage stacks were configured in a 3-2-1 pyramid; loss and degradation increased when stored in a larger footprint (e.g., 4-3-2-1).

## Conclusions

There is broad scientific consensus that biomass crops and residues can replace fossil fuels, which should decrease the need to import petroleum and also decrease greenhouse gas emissions. To accomplish this, however, it is necessary to develop new methods and systems to routinely and reliably harvest, handle, store, and transport large quantities of bulky materials of varying characteristics. These needs contrast with the well-developed logistics, grading, and marketing systems for grain biofuel feedstocks and fossil fuels. There have been a number of research activities aimed at providing solutions to specific unit processes within the feedstock provision value chain. The case studies show that substantial efforts have been made toward the development of machines for harvesting and collecting agricultural biomass. Several projects also have been initiated to investigate the effective harvesting of dedicated perennial energy crops. Many possibilities have been considered, and some have been tested, within each of the tasks of biomass harvest, transportation, and storage. Many of these infrastructure issues are under study by both the public and private sectors, as illustrated by the case studies. But the case studies also demonstrate that continued research and innovation are needed to develop the reliable infrastructure necessary to meet the nation's ambitious goals for energy from cellulosic biomass.

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## Glossary

**Cube out.** To fill the volume capacity of a truck or container before reaching its weight capacity or limit.

**Densification.** To increase the density of a material by compaction or compression; to decrease the volume of material that must be transported, stored, or handled.

**Kilojoule (kJ) content.** A measure of agricultural energy production (kJ/kg) used to describe the heat content of fuels. One kilojoule is approximately the amount of solar radiation received by one square meter of the Earth in one second.

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**Life Cycle Analyses (LCA).** A method to measure and record environmental impacts from “cradle to grave” or production to final disposal/recycling. Two of the most used types of LCA for bioenergy and biofuels are those used to determine net energy and net greenhouse gas emissions. Other types include water usage or toxicological effects of fertilizers and pesticides.

**Stover.** Mature stalks of plants with the grain heads removed.

**Weigh out.** To load a truck or container to the maximum weight allowed for safety or legal requirements before reaching its capacity or volume limits.

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