Uniform Format Feedstock Supply System Design for Lignocellulosic Biomass

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DOE Biorefining Industry 2030 Goals

Displace a significant fraction of gasoline demand
~ 60 billion gallons/year by 2030

~1.3 Billion tons/yr Biomass Potential in the U.S.

Including Corn Grain, an Estimated 600 – 700 Million Tons of Biomass per Year is Needed for 60 B gal of ethanol.

http://bioenergy.ornl.gov
Feedstock Logistics R&D Scope

- Connect Feedstock Supply System to Feedstock Resources
- Improve Feedstock Supply Logistics
- Develop a Uniform Lignocellulosic Commodity Supply System
- Connect Feedstock Supply to Uniform Format Biorefinery Conversion Facilities
Biomass Feedstock Cost
Target and Metrics

\[
\frac{\text{$/ton}}{\text{ton}} = \left( \frac{\text{Grower Payment}}{\text{$/ton}} \right) + \left( \frac{\text{Efficiency [$/hr]}}{\text{Capacity [ton/hr]}} \right) + \frac{\text{Quality}}{\text{$/ton}}
\]

\[
\text{Therefore}
\]

\[
$35-75/\text{ton} = $10-$50/\text{ton} + $25/\text{ton}
\]

Feedstock Resource R&D Plan
Contributes:
- Analysis and characterization
- Projections based on technology development and supply demand assumptions
- Technology development through “Regional” and “Office of Science” Partnerships

Feedstock Supply System R&D Plan Contributes:
- Engineering Designs
- Technology Development

$25 Adjusted to 2006 Costs = $32.80
Characterize Feedstock Tonnages and Costs? (Resource Assessment)

- **Resource Tonnage (available)**
- **Feedstock Cost (throat of reactor)**
- **Feedstock Value (grower payment)**
- **Resource Tonnage (demand)**

**Increased tonnage due to advances in supply system technologies**

**Increased tonnage due to improved supply / conversion technologies (or policies) so that more can be paid for the feedstock resource**

Line represents tonnage needed for projected yearly ethanol demand
All feedstock supply curve analyses demonstrate changes in available feedstock quantities with increasing price paid. The difference between feedstocks and feedstock analyses are the rates of the supply SLOPES.

Analysis by Marie Walsh, UofTN, 2005 version of Polysis
Performance Metrics:
• Efficiency ($/hr)
• Equipment Capacity (ton/hr)
• Biomass Quality ($/ton)

Supply System Overview
Design Documents Completed:

- Pioneer Supply System Design
- Excel Spreadsheet Design Database
- Engineering Design Review and Permitting Analysis
- Business Plan / Structure Analysis

Documents Located at:
### Notable Parameters:
- 4’X4’X8’ bales
- 1100 lbs per bale
- 7.8 lbs/cuft
- 1.71 tons / acre
- Windrow from 25 ft swath

### Table:

<table>
<thead>
<tr>
<th>Installed Capital Costs</th>
<th>Capital Costs per Year</th>
<th>Operating Costs per Year</th>
<th>Labor Costs per Year</th>
<th>Total Costs per Year</th>
<th>Feedstock Costs ($/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$27,242,000</td>
<td>$6,111,356</td>
<td>$2,069,389</td>
<td>$989,749</td>
<td>$9,170,539</td>
<td>$12.52</td>
</tr>
</tbody>
</table>
Field side Stacking (Roadsiding)

Notable Parameters:
• Stinger Collects from Field and Drops at Stack
• Loader Builds Stack

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>$11,408,428</td>
<td>$2,753,751</td>
<td>$359,062</td>
<td>$699,780</td>
<td>$3,812,593</td>
<td>$5.21</td>
</tr>
</tbody>
</table>
Notable Parameters:

- Storage costs assumed by grower
- No payroll labor costs
- Operating costs include shrinkage for Southeast Idaho Climate
Bale Loading and Transport

Notable Parameters:

- Double 42’ flat bed trailers carrying 44 bales
- Truck net wt. = 44,000 lbs
- Loads strapped, but may need to tarp
- Two 8 hr shifts – six days/week

<table>
<thead>
<tr>
<th>Installed Capital Costs</th>
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<th>Labor Costs per Year</th>
<th>Total Costs per Year</th>
<th>Feedstock Costs ($/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8,329,836</td>
<td>$2,101,616</td>
<td>$1,467,077</td>
<td>$4,347,383</td>
<td>$7,916,076</td>
<td>$10.81</td>
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</tbody>
</table>
## Bale Receiving and Handling

<table>
<thead>
<tr>
<th>Installed Capital Costs</th>
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<th>Total Costs per Year</th>
<th>Feedstock Costs ($/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5,355,540</td>
<td>$835,792</td>
<td>$1,832,261</td>
<td>$1,302,350</td>
<td>$3,970,403</td>
<td>$5.42</td>
</tr>
</tbody>
</table>

**Notable Assumptions:**
- Bale storage per International Fire Code (~20 acres)
- 72-hr. inventory (14,000 bales)
- Manual unloading of bales via telehandlers, 14 hrs/day, 6 days/wk
- 3 grinders feeding plant 24 hrs/day, 7 days/wk
- 1 telehandler per grinder
### Description of System Design Scenarios

<table>
<thead>
<tr>
<th>Location</th>
<th>Installed Capital ($/dry ton)</th>
<th>Total Engineering Costs ($/dry ton)</th>
<th>Grower Payment Costs ($/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho Straw</td>
<td>$88.65</td>
<td>$33.48</td>
<td>$10.00</td>
</tr>
<tr>
<td>Kansas Straw</td>
<td>$75.48</td>
<td>$46.17</td>
<td>$10.00</td>
</tr>
<tr>
<td>Kansas Stover</td>
<td>$110.37</td>
<td>$57.22</td>
<td>$10.00</td>
</tr>
<tr>
<td>Virginia Straw</td>
<td>$173.90</td>
<td>$61.87</td>
<td>$10.00</td>
</tr>
<tr>
<td>Virginia Stover</td>
<td>$175.58</td>
<td>$65.47</td>
<td>$10.00</td>
</tr>
</tbody>
</table>

#### Virginia
- Biorefinery Size: 126,000 dry tons (Warrenton)
- Feedstock:
  - Wheat Straw, 12%
  - Corn Stover, 24%
- Avg. dist. to supply: 37.5 mi.
- Feedstock Cost
  - Wheat Straw: $71.87
  - Corn Stover: $75.47

#### Kansas
- Biorefinery Size: 255,000 dry tons (932 Solicitation)
- Feedstock:
  - Wheat Straw, 65%
  - Milo Stover, 25%
  - Corn Stover, 10%
- Avg. dist. to supply: 46.5 mi.
- Feedstock Cost
  - Wheat Straw: $56.17
  - Corn Stover: $67.22

#### Idaho
- Biorefinery Size: 800,000 dry tons (NREL Biorefinery)
- Feedstock:
  - Wheat/Barley Straw, 100%
- Avg. dist. to supply: 47.5 mi.
- Total Feedstock Cost
  - Wheat/Barley Straw: $46.05

Assumptions: Moisture = 15%, In-storage dry matter loss = 5%
Permitting/Policy Issues

Production
- Sustainability
- Water
- Soil Erosion
- Chemical / Fertilizer Applications
- Land Use
- Feedstock resources (Billion Ton)
- Forest land access
- Conservation

Harvest & Collection
- Compaction
- Residue Removal Rate
- No Till

Preprocessing & Transportation
- Land Use Right-of-Way
- Road Congestion
- Load Limits
- Dust

Storage & Queuing
- Fire
- Rodents
- Run off / leaching
- Waste disposal
- Odor
- Gases (NO$_x$ & CO$_2$)
Specific Permitting Examples

- Dust control for grinders, loading, and unloading systems

  2903.5 Dust collection. Where located within a building, equipment or machinery which generates or emits combustible fibers shall be provided with an approved dust-collecting and exhaust system. Such systems shall comply with Chapter 13 and Section 511 of the International Mechanical Code.

- Trucking load laws and limitations
  - Idaho: 105 ft., 115,500 GVW
  - Kansas: 85 ft., 85,500 GVW
  - Iowa: “No limit” (frost regulations)

Bale System
- Fire code regulations

  2903.4 Agricultural products. Hay, straw, seed cotton or similar agricultural products shall not be stored adjacent to structures or combustible materials unless a clear horizontal distance equal to the height of a pile is maintained between such storage and structures or combustible materials. Storage shall be limited to stacks of 100 tons (91 metric tons) each. Stacks shall be separated by a minimum of 20 feet (6096 mm) of clear space. Quantities of hay, straw, seed cotton and other agricultural products shall not be limited where stored in or near farm structures located outside closely built areas. A permit shall not be required for agricultural storage.
Uniform Feedstock Supply System Design

- **Feedstock**
  - Whole wood
  - Residue bundles
  - Conservation Reserve Program (CRP) grass
  - Corn stover
  - Cereal straw
  - Sorghum straw
  - Other crop residue
  - Dedicated energy crops

- **Harvest/Collection**
  - Round wood and bundles

- **Storage/Preprocessing**
  - Bales
  - Bulk
  - Loose Biomass

- **Transportation**
  - Bioenergy Entry Gate

- **Handling/Queuing**
  - Evenflow Feed System

- **Biochemical conversion process**

- **Thermochemical conversion process**

- **Bioenergy conversion infrastructure**

- **G2008-02**
Field side Grinding for Round Bales

Notable Parameters:

- Wet top/bottom bales and barley/wheat straw do not create capacity or product size problems
- Twine ground with bales
- Product bulk density = 12.87 lbs/cuft
- Capacity = 26 tons / hr
- Two 8 hr shifts – 6 days/week

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</thead>
<tbody>
<tr>
<td>$5,515,848</td>
<td>$1,447,251</td>
<td>$2,035,268</td>
<td>$1,283,568</td>
<td>$4,766,087</td>
<td>$6.51</td>
</tr>
</tbody>
</table>
Bulk Biomass Transportation

Notable Parameters:

- Double 42’ trailers with 4’ side extensions
- Truck volume = 4,739 cuft
- Truck net wt. = 60,984 lbs
- Loads always tarped
- Two 8 hr shifts – six days/week

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<th>Feedstock Costs ($/dry ton)</th>
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<tbody>
<tr>
<td>$6,009,404</td>
<td>$1,198,560</td>
<td>$924,766</td>
<td>$2,268,415</td>
<td>$4,391,741</td>
<td>$6.00</td>
</tr>
</tbody>
</table>
## Bulk Receiving and Handling

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<tr>
<td>$11,172,572</td>
<td>$844,436</td>
<td>$303,467</td>
<td>$599,295</td>
<td>$1,747,198</td>
<td>$2.39</td>
</tr>
</tbody>
</table>

### Notable Assumptions:

- 72-hr. inventory - 973,000 ft³
- Truck unloading 14 hrs/day, 6 days/wk
- Conveyor density 5.2 lb/ft³, bin density 14.1 lb/ft³
- Simultaneous fill and discharge during receiving hours
Description:
- Grinding occurs at the stack
- Current grinder performance:
  Capacity = 26 tons/hr, Bale Bulk Density = 8 lbs/ft³

Explanation of Difference: **Scale**
- Variability in operating times
- Equipment utilization (grinders are under-utilized in VA scenarios)

Needed Improvements:
- Increase grinder capacity >25% (32.4 tons/hr)

<table>
<thead>
<tr>
<th>Feedstock Type</th>
<th>Feedstock Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho Straw</td>
<td>$7.57</td>
</tr>
<tr>
<td>Kansas Straw</td>
<td>$7.53</td>
</tr>
<tr>
<td>Kansas Stover</td>
<td>$7.83</td>
</tr>
<tr>
<td>Virginia Straw</td>
<td>$8.14</td>
</tr>
<tr>
<td>Virginia Stover</td>
<td>$7.94</td>
</tr>
</tbody>
</table>

Costs in 2006 $/dry ton.
Description:
• Stinger Stackers
• Loaders and semi-trailers
• Grinder loading with self-unloading belt trailers

Explanation of Difference: _Scale & Logistics_
• Fixed transport costs
• State road limits:
  Idaho: 105 ft., 115,500 GVW
  Kansas: 85 ft., 85,500 GVW
  Virginia: 80 ft., 85,500 GVW

Needed Improvements:
• Increase loaded densities to gross-out vehicles (capacity)
• Decrease handling costs (efficiency)

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<td>$10.58</td>
</tr>
<tr>
<td>Kansas Stover</td>
<td>$11.24</td>
</tr>
<tr>
<td>Virginia Straw</td>
<td>$12.09</td>
</tr>
<tr>
<td>Virginia Stover</td>
<td>$11.64</td>
</tr>
</tbody>
</table>

Costs in 2006 $/dry ton.
### Transportation Costs

<table>
<thead>
<tr>
<th>Service</th>
<th>Fixed ($/ton)</th>
<th>Variable (cents/ton-mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP Bale Transporter</td>
<td>1.48</td>
<td>62.4</td>
</tr>
<tr>
<td>Semi - bulk</td>
<td>1.98</td>
<td>10.5</td>
</tr>
<tr>
<td>Semi - bales</td>
<td>4.80</td>
<td>13.6</td>
</tr>
<tr>
<td>Rail</td>
<td>17.10</td>
<td>1.7</td>
</tr>
</tbody>
</table>

### Distance vs. Cost Graph

The graph shows the relationship between distance (loaded mile) and cost for various transportation services, including fixed and variable costs. The graph includes data for different modes of transportation:
- Rail, fixed
- Rail, variable
- Semi-bale, fixed
- Semi-bale, variable
- Semi-bulk, fixed
- Semi-bulk, variable
- SP Bale Transporter, variable
- Stinger - Sq_bale, fixed
- Stinger - Sq_bale, variable
- Train - bulk, fixed
- Train - bulk, variable

The graph visually represents how costs vary with distance for each service type.
Initial moisture removal (above 25%) requires less energy and time than lower moisture content removal (below 25%).
Interface to Existing Woody Supply System Designs

1. Timber Harvest
2. Transport & Storage
3. Round Wood
4. Urban Wood Waste
5. Preprocess
6. Lumber/Industrial Processing
7. Preprocess
8. Mill Waste
9. Preprocess
10. Bundling/Gathering Methods
11. Preprocess
12. Slash

Uniform Format
Advanced Feedstock Supply System Design
Single-pass “high cut” harvested 72% of stover (12% more per acre than billion ton assumption)

- 70% removed with combine
  - Short soil half-life (Kumar and Goh, 2000; Eiland et al. 2001)
  - Reduced pretreatment severity
  - Low moisture

- 30% of stalk left behind
  - High moisture
  - Highly recalcitrant
  - Long soil half-life

- 40% removed with mow and rake – mostly stalk material
- Single-pass lends itself to bulk systems
- Possible $10-$20/dry ton savings

<table>
<thead>
<tr>
<th>Feedstock Type</th>
<th>Feedstock Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stover (traditional)</td>
<td>$22.97</td>
</tr>
<tr>
<td>Stover (single pass)</td>
<td>$5.26</td>
</tr>
</tbody>
</table>

Costs in 2006 $/dry ton.
R&D Path to the Uniform Feedstock Supply System Design

- Harvesting/Collection and Preprocessing are Key Unit Processes
- Harvesting addresses feedstock diversity
- Moving preprocessing forward in the supply system creates down-stream uniformity and increases system efficiencies
Bale Receiving, Handling, and Preprocessing (Grinding)

- Harvest & Collection
- Storage & Queuing
- Preprocessing
- Transportation & Handling
Feedstock Supply System Models, Business Elements and Interfaces

Bale-Based Feedstock Supply System

Bulk Feedstock Supply System

Distributed On-farm Storage

Centralized Agri-business Storage

Biomass

Agriculture

Farm Gate

Agri business

Plant Gate

Bales or other formats
**Supply System:**
- Crop physical/anatomical structure, rheological properties, fractionation properties, etc.

**Conversion:**
- Carbohydrate content, biomass recalcitrance, BTU content, etc.

- **Forest resources**
  - Logging residues (white pine, loblolly pine, etc.)
  - Forest thinnings (fuel treatments)
  - Fuelwood
  - Primary wood processing mill residues
  - Secondary wood processing mill residues
  - Pulping liquors
  - Urban wood residues

- **Agricultural resources**
  - Crop residues (corn, sorghum, wheat, barley, etc.)
  - Grains to biofuels (corn, sorghum, wheat, etc.)
  - Perennial grasses (switchgrass, prairie grasses, etc.)
  - Perennial woody crops (willow, popular, etc.)
  - Animal manures
  - Food/feed processing residues
  - MSW and landfill gases
**Current and Projected Biomass Reserves (EIA classification)**

- **Demonstrated Reserve** – In-place demonstrated resource from which reserve are estimated. (Does not include resources for food, feed, fiber, soil maintenance, etc.)
- **Estimated Reserve** – Portion that can be economically recovered with current and foreseeable technology.
- **Recoverable (or Market) Reserve** – Portion of the resource currently in the market.
- **Identified Resource** – Portion of the total resource that has the potential to become the reserve base.
- **Total Resource** – Entire resource volume (includes annual renewable and stock resources).
### Agronomic Factors Limiting Crop Potential

<table>
<thead>
<tr>
<th>Limiting factor</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of soil organic carbon</td>
<td>Supply/replenish SOC</td>
</tr>
<tr>
<td></td>
<td>Soil quality</td>
</tr>
<tr>
<td></td>
<td>Future production capacity</td>
</tr>
<tr>
<td>Soil erosion</td>
<td>Water erosion and runoff management</td>
</tr>
<tr>
<td></td>
<td>Wind erosion management</td>
</tr>
<tr>
<td></td>
<td>Off-site effects</td>
</tr>
<tr>
<td>Loss of plant nutrients</td>
<td>Increased fertilizer application and production costs or reduced crop</td>
</tr>
<tr>
<td></td>
<td>yield and producer income</td>
</tr>
<tr>
<td>Soil water and temperature dynamics</td>
<td>Complex interactions</td>
</tr>
<tr>
<td></td>
<td>Condition-specific solutions necessary</td>
</tr>
<tr>
<td>Soil compaction</td>
<td>Compaction of soil due to increase field traffic for residue removal</td>
</tr>
<tr>
<td></td>
<td>and/or transition to no-till cropping system</td>
</tr>
<tr>
<td>Environmental degradation</td>
<td>Off-site erosion impacts</td>
</tr>
<tr>
<td></td>
<td>Nutrient loss to surface water</td>
</tr>
</tbody>
</table>

- Spatial Variability of Combine Harvest Index
  - Data Range 0 (Lower) – 0.75 (upper)

- Hard Red Spring Wheat
  - Ashton, ID - 1996

Crop Organic Matter return rate recommendations (or biomass input) must be managed just like fertilizers and other crop production inputs
Resource Harvest / Collection (or access) Priority:

- First Priority – grain, dedicated lignocellulose crop.
- Second Priority – residues (crop or logging), CRP harvest.
- Third Priority – Processing residues and wastes.

<table>
<thead>
<tr>
<th>Priority</th>
<th>Today (190 MDT)</th>
<th>Estimated 320 (MDT)</th>
<th>Identified (1366 MDT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>24</td>
<td>24</td>
<td>576</td>
</tr>
<tr>
<td>2nd</td>
<td>35</td>
<td>165</td>
<td>510</td>
</tr>
<tr>
<td>3rd</td>
<td>131</td>
<td>131</td>
<td>278</td>
</tr>
</tbody>
</table>
Lignocellulosic Feedstock Supply Types

• Dry Herbaceous – Agriculture Residues/Crops at less than 15% moisture

• Wet Herbaceous - Agriculture Residues/Crops greater than about 50% moisture

• Energy Crops – Wet, Dry, and Woody

• Woody – Forest resources and woody energy crops
Contract Positions:

- **1st Position** – The crop is produced for a contracting buyer or market.
- **2nd Position** – The contract for the lignocellulosic biomass is in second position to another buyer/market for the grain, timber, etc.
- **3rd Position** – This contract position refers to processing and/or municipal wastes and by-products, wherein the contracting position is subservient to primary processes and biomass collection characteristics.
- **Commodity / Spot Market** – In the near-term, lignocellulosic biomass in this contracting category will be spot market, as no lignocellulosic biomass commodity yet exists.

The primary logistics concern of contracting position is access to and control of the resource.
National biofuel goals will not be achieved with multiple unique and site-specific supply system designs, nor accomplished with complex designs requiring multiple sets of unique equipment. Achieving national biofuel goals can only be accomplished through development of a highly efficient commodity-like feedstock supply system consisting of modularized harvesting and preprocessing equipment that can be adapted to the diversity of feedstocks and yet connect to uniform commodity-scale receiving systems of "standardized" and highly replicable biorefinery designs.
Biorefining Depends on Feedstock