Idaho National Laboratory

Technical Memorandum

To:

Title: Integrated model analysis using field- and PDU-scale data to demonstrate feedstock logistics cost of $35.00 per dry ton for corn stover

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Platform: Feedstock

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Purpose: This Technical Memorandum communicates the results of Idaho National Laboratory's (INL's) Bioenergy Program's Department of Energy (DOE) FY12 Feedstock Joule Milestone, which was to achieve a modeled dry corn stover feedstock logistics cost of $35 per DMT in 2007 dollars, excluding grower payment.

1. MILESTONE COMPLETION SUMMARY

INL's Bioenergy Program undertook a DOE Office of Biomass FY12 Joule Milestone to achieve achieved an overall supply system cost of $35 per dry matter ton (DMT) or less in 2007 dollars for dry corn stover. The milestone was completed by implementing field- and PDU-scale data from harvest, collection, storage, preprocessing, handling, and transportation operations into INL's Biomass Logistics Model (BLM) and showing the achieved overall supply system cost target. The focus of this year's Joule milestone was to demonstrate the feasibility of meeting the $35 per DMT cost target through an integrated full-scale approach. The operating parameters that contributed to the cost savings where harvest efficiency through improved sustainable yields, reduced dry matter loss through cost-efficient storage practices, improved transport efficiencies through better loading and unloading practices and high bale densities, and improved preprocessing capacities and capital costs through grinder design changes. Other minor cost savings resulted from overall systemwide capacity and efficiency gains resulting indirectly from improvements made in all major operations. All improvements to the supply system reduced the cost of the supply system from FY11's state-of-technology (SOT) cost of $36.10 per DMT to $34.86 per DMT demonstrated through INL's BLM using actual field testing results.

The first quarter milestone, "Update the supply logistic design, equipment economic and performance parameters, and current system efficiency and capacities to deliver an FY11 state-of-technology (SOT) baseline dataset and BLM scenario for dry corn stover feedstock logistics" was achieved by finalizing the model used to capture FY11 research results. The purpose of this milestone is to establish the baseline system by which FY12 research would be compared and improvements demonstrated through field-scale research. The approval of FY11's Joule Milestone Report is evidence of first quarter completion.

The second quarter milestone, "Demonstrate a modeled harvest, collection, and storage cost of $18.00 per dry ton (farm gate) using field-scale test data for dry corn stover in 2007$" was achieved. Research identified that a 1.9 tons per acre sustainable removal rate allowed for a stalk chopping and windrowing

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operational efficiency of 75% and capacity of 18.5 DMT per hour. In addition, 3x4x8-ft large square bales with an average bulk density of 11.1 lb/ft^3 (dry matter) were produced at a rate 39 tons per hour and an in-field operational efficiency of 70%. Bales were moved to the roadside at a capacity of 62 bales per hour. A bale storage system was implemented where bales were stacked four-high and tarped immediately after stacking. Costs associated with tarps, labor, maintenance, and dry matter loss were calculated. A higher average dry matter loss of 7.7% was measured causing an increase in overall storage costs. However, the overall system from harvest through storage resulted in cost that met the $18 per DMT target.

The third quarter milestone "Demonstrate a modeled preprocessing, handling, and transport cost of $17.00 per dry ton (reactor throat) using PDU-scale data for dry corn stover in 2007$" was achieved. Through the use of DOE's Process Demonstration Unit, a 2-in. grinder screen and a conventional drag-chain discharge system was used to demonstrate a configuration capable of achieving the $17 per DMT cost target. This system produced an overall adjusted grinding capacity of 8.4 DMT per hour at 12% moisture based on the system's capacity versus moisture relationship. In addition, updated loading and unloading data for the transportation operation were modeled adding to the cost savings. Thus, the overall preprocessing, handling, and transportation system met the $17 per DMT cost target.

Finally, the fourth quarter milestone "Demonstrate through integrated model analysis using field- and PDU-scale data from dry corn stover a total feedstock logistics cost of $35.00 per dry ton (excluding grower payment, in 2007$)" was met as the entire system was integrated within the feedstock logistics model and a final cost was evaluated. Improvements to the transportation and preprocessing systems (third quarter), directly impacted by very good bale densities from the baling system, made up all of the demonstrated cost savings for the milestone. The final cost table is shown below.

FY12 Cost Summary ($/DM ton)					
	Installed Capital	**Ownership**	**Operating**	**DM Loss**	**Total**
Harvesting	19.00	1.08	2.20	0.00	3.28
Baling	33.51	2.73	4.20	0.00	6.93
Roadsiding	19.12	2.39	1.41	0.00	3.80
Total Harvest & Collection	**71.62**	**6.20**	**7.81**	**0.00**	**14.01**
Transportation #1	4.06	0.78	6.44	0.00	7.22
Total Transportation	**4.06**	**0.78**	**6.44**	**0.00**	**7.22**
Preprocessing #1	13.87	2.93	5.68	0.00	8.61
Total Preprocessing	**13.87**	**2.93**	**5.68**	**0.00**	**8.61**
Storage	6.88	2.56	0.00	1.38	3.94
Plant Handling & Queuing	0.95	0.19	0.89	0.00	1.08
Total Storage & Queuing	**7.83**	**2.75**	**0.89**	**1.38**	**5.02**
Total	**97.38**	**12.66**	**20.82**	**1.38**	**34.86**

2. EXECUTIVE SUMMARY

The current baseline delivered feedstock cost has been established as $36.10 per dry matter ton (DMT) (FY11 SOT). The feedstock Joule Milestone target is a modeled cost of $35.00 per DMT by the end of FY12 for a dry herbaceous corn stover supply system without the grower payment. To accomplish this milestone, full-scale demonstrations show that key cost and performance barriers to current feedstock supply system designs can be overcome. The overall barrier that has been identified as the focus of this Joule Milestone is a demonstrated integrated system at scale for all unit operations from harvesting to biorefinery in-feed. This includes data on harvesting and collection efficiencies, storage configuration and dry matter losses, handling and transportation efficiencies, and preprocessing capacity and efficiency.

The FY12 cost target is unique as it represents the culmination of the feedstock R&D pathway focused on improving conventional logistics systems. Rather than focusing on a specific element of the supply chain, the FY12 Joule will demonstrate through implementation of best management practices and proper selection of machinery and operating parameters within each unit operation that the $35 cost target is achievable throughout the entirety of the feedstock supply chain.

The objective of the first quarter Joule Milestone is to establish the baseline system by which FY12 technology improvements can be compared. This includes the supply system design and modeling framework that the technology improvements are placed within to arrive at an overall cost improvement. This modeling framework is the same as was used in the FY11 Joule Milestone. The FY11 baseline scenario implemented into this framework is the conventional bale feedstock supply system, which by definition is restricted to currently available technologies and existing infrastructure, regardless of the geographical region in which a biorefinery operates. This design will use corn stover, representing a crop residue, as the model feedstock and large, square (3×4×8-ft) bales as the baseline field format.

The objective of the second quarter Joule Milestone is to demonstrate a modeled harvest, collection, and storage cost of $18 per DMT to the farm gate using field-scale test data for corn stover in 2007 dollars. In collaboration with Iowa State University and DuPont Danisco, field-scale trials were performed and equipment performance parameters were measured. Bales were stacked and tarped to simulate best-possible on-farm storage conditions. Dry matter loss, which represents a storage cost since it decreases feedstock available for downstream use, was measured. The INL Biomass Logistics Model (BLM) was used to calculate unit operational costs based upon field performance results. Total costs (to the farm gate) from this demonstration are calculated to be $17.95 per DMT, which exceeds the goal of $18 per DMT. It should be noted, however, that this demonstration represents one possible path to this cost target and that operational (i.e., equipment selection) and environmental (i.e., weather) conditions have the potential to increase or decrease this average cost.

The objective of the third quarter Joule Milestone is to demonstrate a modeled preprocessing, handling, and transport cost of $17 per DMT to the throat of the conversion reactor using Process Demonstration Unit (PDU) scale test data for corn stover in 2007 dollars. In collaboration with Vermeer Manufacturing (CRADA) and Iowa State University, transport and PDU-scale trials were performed and equipment performance parameters were measured. The same bales used in the harvest, collection, and storage tests of the second quarter were used in this test to maintain complete consistency in the logistics demonstration and cost analysis. Like the modeled harvest, collection, and storage costs, INL's BLM was used to calculate the cost of each preprocessing, handling, and transportation unit operation based on specific data collected during scaled testing. Total costs (from the farm gate to the biorefinery reactor throat) from this demonstration are calculated to be $16.91 per DMT, which exceeds the goal of $17 per DMT. Again, it should be noted that this demonstration represents one possible preprocessing path to the cost target, and that feedstock quality and operational parameters (i.e., equipment selection) can increase or decrease this average cost.

Finally, the objective of the fourth quarter Joule Milestone is to integrate the results of FY12 research and show an overall cost improvement in the feedstock supply system of $1.10 per DMT from the FY11 SOT due to technical improvements made in all aspects of the supply system. These improvements are based on increased equipment capacities and efficiencies, and mitigation of dry matter loss. Thus, the combined results of FY12 demonstrated research reduced system costs by more than $1.10 per DMT meeting and exceeding the target of $35 per DMT in 2007 dollars excluding the grower payment. The final total cost of the demonstrated supply system is $34.86 per DMT in 2007 dollars, excluding grower payment.

2.1.1 Joule Scope and Purpose:

The FY12 Feedstock Joule Milestone is to achieve a modeled dry corn stover feedstock logistics cost of $35 per DMT in 2007 dollars, excluding grower payment. The conventional bale supply system design is the baseline for measuring and reporting supply system cost and performance improvements related to this Joule milestone. By definition, the conventional bale design represents the current state of technology with currently available biomass (e.g., corn stover), machinery and equipment, and management practices that can be implemented today (Hess et. al, 2009a and 2009b). The unit operations within this design include multi-pass harvest (windrowing and baling), collection of large, square bales (3x4x8-ft) from the field to field-side storage, delivery of bales from storage to a biorefinery, and preprocessing of bales at the biorefinery to particle size specification prior to insertion in the conversion process. Figure 1 illustrates the operations of the conventional bale supply system design.

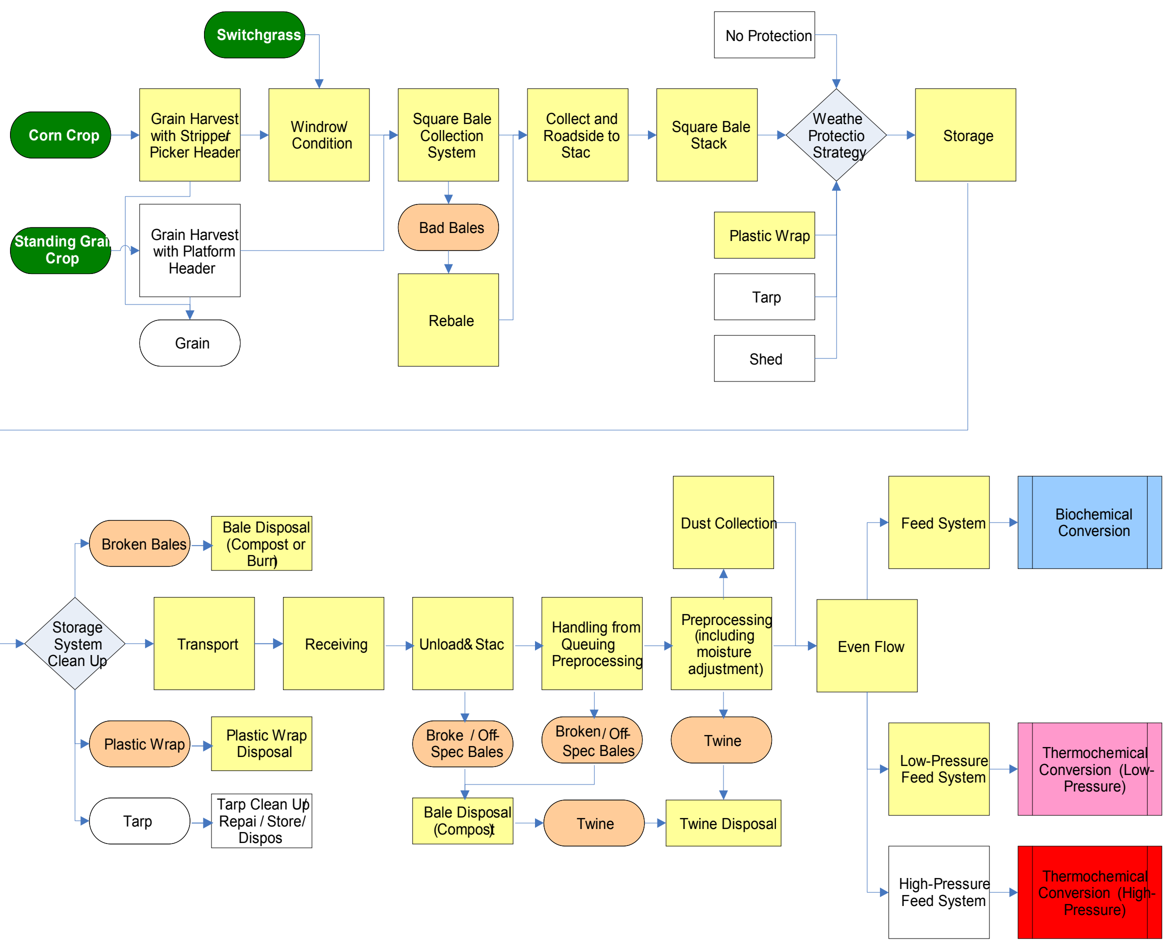

Figure 1. Conventional Bale feedstock supply system design process flow. Green ovals represent format intermediates, tan ovals represent potential waste streams, yellow rectangles represent individual modeled processes, and white rectangles represent alternate processes that were not modeled.

The purpose of the Feedstock Joule milestone is to document progress in reducing feedstock costs and achieving feedstock cost targets identified in the DOE Multi-Year Program Plan (MYPP). Previous years Joule milestones focused on specific improvements to the biomass supply chain that have contributed to feedstock cost reductions shown in Figure 2. These improvements were accomplished through R&D that focused on a particular barrier or element of the feedstock supply chain. As this figure illustrates, feedstock logistics improvements are categorized and documented according to the main unit operations that define the feedstock supply chain. The improvements represented in this figure are summarized as follows:

- Transportation/Handling – Indirect gains due to improved bale density and reduced losses (shrink)
- Preprocessing – Direct improvements in grinder efficiency and capacity
- Storage/Queuing – Lower cost storage methods, and reduce uncertainty of storage losses (e.g., preserve the 60% carbohydrate target)
- Harvest/Collection – Improved harvest/collection efficiency (i.e., a yield component) while not violating sustainability limits, and biomass quality (namely ash) targets

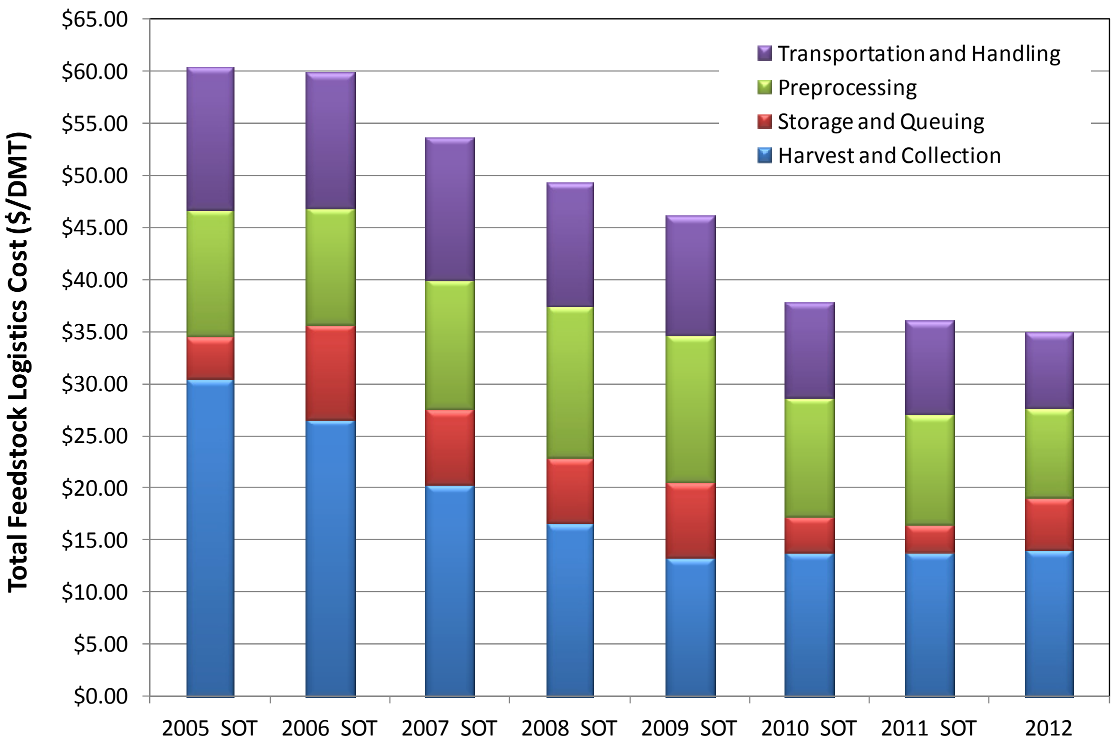

Figure 2. Historical (back cast) and projected total feedstock logistics costs from 2005 to 2012.

The FY12 cost target is unique in that it represents the culmination of the feedstock R&D pathway focused on improving conventional logistics systems. Rather than focusing on a specific element of the supply chain, the FY12 Joule will demonstrate through implementation of best management practices and proper selection of machinery and machinery operating parameters that the $35 cost target is achievable. Consistent with a working year-round supply system, this demonstration is staged throughout the fiscal year to accommodate fall harvest in Quarter 1, storage through Quarter 2, preprocessing in Quarter 3, and an integrated supply system analysis in Quarter 4. To accommodate this schedule, the quarterly Joule milestones are established as follows:

Qtr 1: Update the supply logistic design, equipment economic and performance parameters, and current system efficiency and capacities to deliver an FY11 state-of-technology (SOT) baseline dataset and modeled scenario for dry corn stover feedstock logistics.

Qtr 2: Demonstrate a modeled harvest, collection, and storage cost of $18.00 per dry ton (farm gate) using field-scale test data for corn stover in 2007$.

Qtr 3: Demonstrate a modeled preprocessing, handling, and transport cost of $17.00 per dry ton (reactor throat) using PDU-scale data for dry corn stover in 2007$.

Qtr 4: Demonstrate through integrated model analysis using field and PDU-scale data from dry corn stover a total feedstock logistics cost of $35.00 per dry ton (excluding grower payment, in 2007$).

2.1.2 Quarter 1: Base Model Scenario

A computer based model, the Biomass Logistics Model (BLM), will simulate the entire logistics system, and monitor, both temporally and spatially, the integrated impact of feedstock formats and machinery attributes on cost and performance. The model architecture is based on a continuous flow process which accomplishes the desired results by coupling all functions of major operations, including machine performance and material characteristics, with standard economic relationships. This model has been used to baseline current cost and performance values for the logistics system and will be used to document process improvements that lead to cost and performance targets associated with this milestone.

The modeled Conventional Bale feedstock supply system design will supply a biorefining facility with 800,000 DMT of biomass annually (Table 1). This supply system design is considered appropriate for both biochemical (Aden et al., 2002) and thermochemical (Phillips et al., 2007) conversion facilities that depend on a year-round biomass delivery schedule.

Table 1. Conventional Bale supply system design size annual capacity assumptions for corn stover and switchgrass.

	Corn Stover
Plant Operation Size (delivered tons[a])	800,000 DM ton/yr
Feedstock Harvested Annually[b]	868,600 DM ton
Acres Harvested Annually	527,000
Participating Acres	50%
Acres Available for Contract	1,054,000
Cultivated Acres	2,107,000
Feedstock Draw Radius[c]	45.8 miles
a. U.S. short ton = 2,000 lb. b. Extra tonnage harvested to account for supply system losses. c. Assume an equal distance distribution of acres throughout the draw radius.	

The process model used to analyze feedstock supply system designs is improved every year to include more functionality and a better user interface. Figure 3 shows the flow diagram and each major supply system operations from production to feeding the conversion facility that is included in the model. Navigation within the model can be done through the buttons on the left or by clicking the icons in the model flow diagram. The model architecture is designed around a series of sub-models that can be developed separately and then plugged into the overall model framework when ready. The result of this model design allow for broad collaboration among many research groups and will provide the INL with the means of assessing feedstock logistics and performance gains within DOE core research activities as well as throughout the research community.

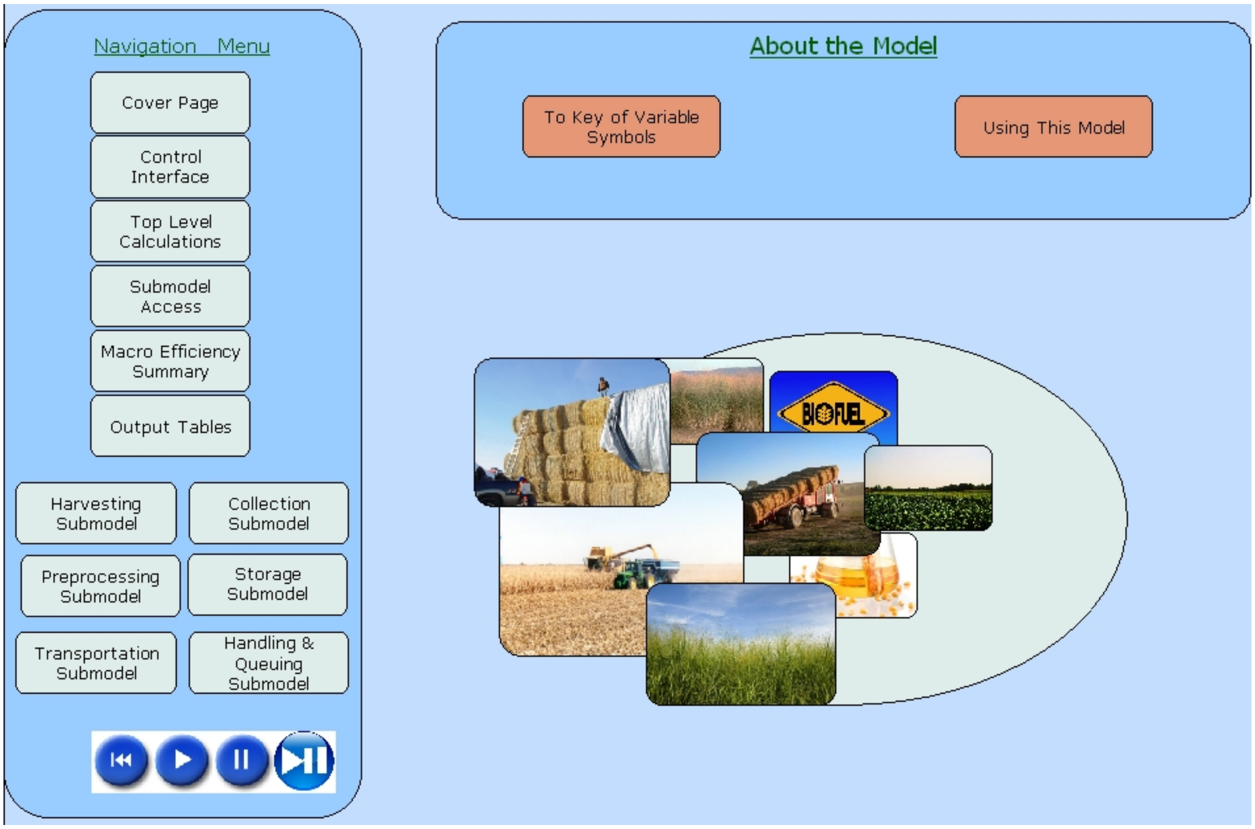

Figure 3. Diagram of the process model and navigation controls.

Figure 4 shows an example of the input screens for each of the operations; in this case the harvester inputs. For each choice of equipment there is a drop down box that pulls information from the INL equipment database. Data captured through R&D activities is archived in and accessed from the INL equipment performance database. To achieve each quarter's milestone, data pertaining to preprocessing characteristics, material bulk density, and other operational parameters (harvest and collection efficiencies, storage losses, etc.) will be captured in the database as inputs and evaluated for cost and logistics improvements to the system.

Improvements to the preprocessing performance parameters, material bulk density, and moisture mitigation will be accomplished primarily through INL's core R&D projects and the collaboration partners relevant to each improvement. This year's improvements will be very aggressive due to the strong research foundation and expertise developed within INL's Bioenergy Program and established research partners.

Finally, Figure 5 shows an example of the flow model and the relationship between variables in a typical process model. The round circles and diamonds are decision and control calculations, which normally contain data from laboratory-scale, bench-scale, and field-scale research activities that are entered directly or input from the equipment database described previously. The calculations can be as simple or as complex as needed and are time and spatially dependant so that the model can capture the behavior of an actual feedstock supply system.

Also included in the model are data and indices from online U.S. Department of Agriculture and U.S. Department of Labor statistics as well as actual diesel fuel costs from the Energy Information Administration so that accurate machine and labor costs can be calculated during a simulation. For the purpose of this Joule milestone, these data and indices are fixed in year 2007 values/dollars.

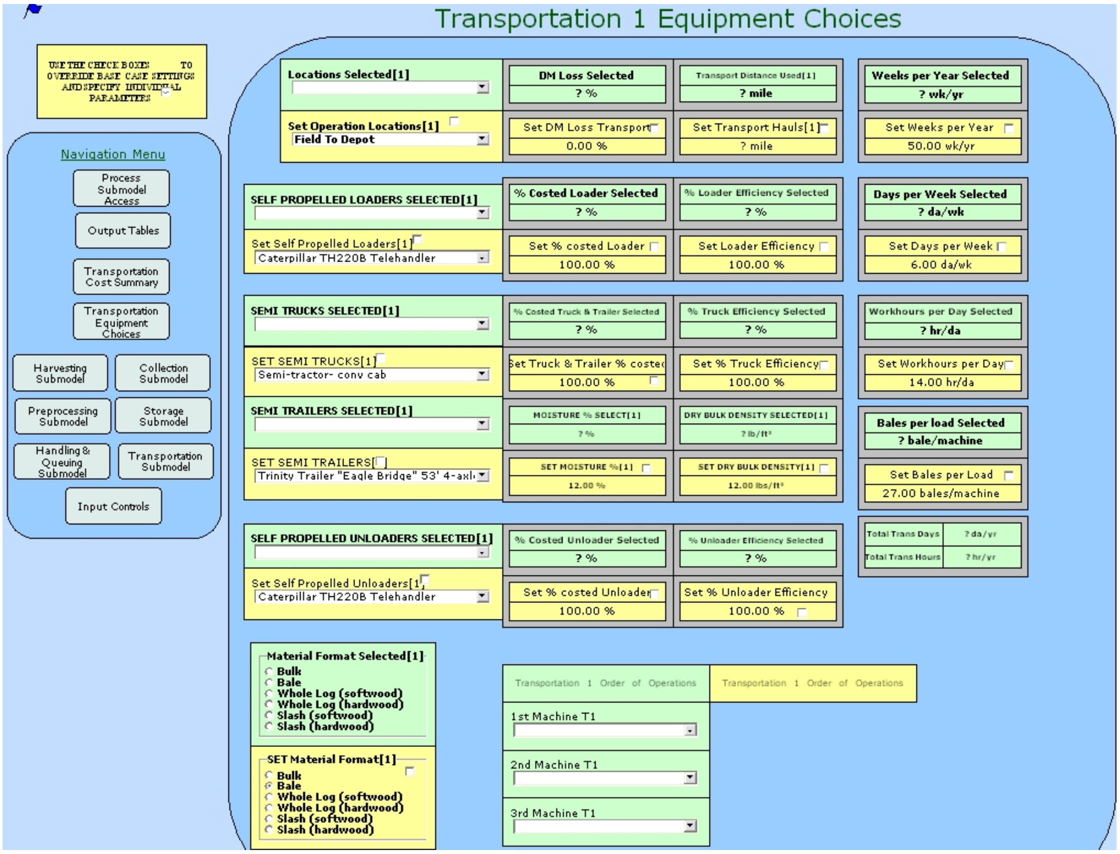

Figure 4. An example of the input screens available for each of the processes in the supply chain.

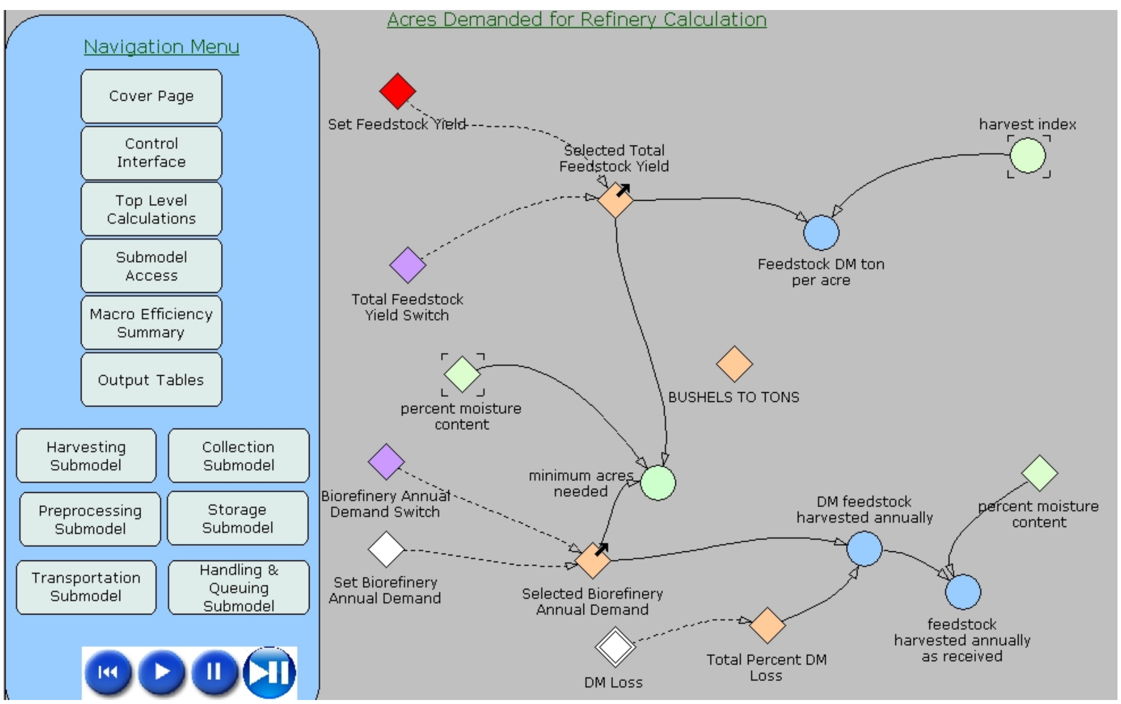

Figure 5. Process modeling structure for acreage demand. Calculations are tracked through stock and flow components and developed mathematical relationships.

Results

The current baseline cost has been established as $36.10 per DMT. The goal is to reach a modeled $35.00 per DMT by the end of FY12. In order to reach this goal we have to demonstrate that we can move past the barriers that are major impacts to current cost and performance. Those barriers are harvest efficiencies, dry matter loss in storage, grinding capacity, and handling efficiencies. Table 2 shows the FY11 SOT total cost as well as costs from each of the major unit operations within the biomass feedstock supply system. These costs are in year 2007 dollars and form the cost basis from which the final Joule Milestone report, each quarterly milestone report, and all system performance improvements will be measured.

To put the FY11 SOT costs and the FY12 Joule Milestone target into perspective, the total feedstock logistics costs back cast to 2005 and projected to 2012 are provided (Figure 6). These costs are again in 2007 dollars for proper comparison. The costs for each unit operation are also individually identified showing their relative contribution and improvements compared to other unit operations. Harvest and Collection and Preprocessing ultimately account for most of the costs in the supply system, both historically and in the future.

Table 2: Cost summary table for the FY11 SOT design with detailed costs reported for significant processes.

FY11 Cost Summary ($/DM ton)					
	Installed Capital	Ownership	Operating	DM Loss	Total
Harvesting	53.72	0.61	1.23	0.00	1.84
Baling	24.05	3.48	6.35	0.20	10.03
Roadsiding	7.69	1.12	0.83	0.00	1.95
Total Harvest & Collection	**85.46**	**5.21**	**8.41**	**0.20**	**13.82**
Transportation #1	4.59	1.50	7.50	0.00	9.00
Total Transportation	**4.59**	**1.50**	**7.50**	**0.00**	**9.00**
Preprocessing #1	11.44	1.81	8.83	0.00	10.64
Total Preprocessing	**11.44**	**1.81**	**8.83**	**0.00**	**10.64**
Storage	4.08	1.19	0.04	0.96	2.19
Plant Handling & Queuing	1.72	0.22	0.23	0.00	0.45
Total Storage & Queuing	**5.80**	**1.41**	**0.27**	**0.96**	**2.64**
Total	**107.29**	**9.93**	**25.01**	**1.16**	**36.10**

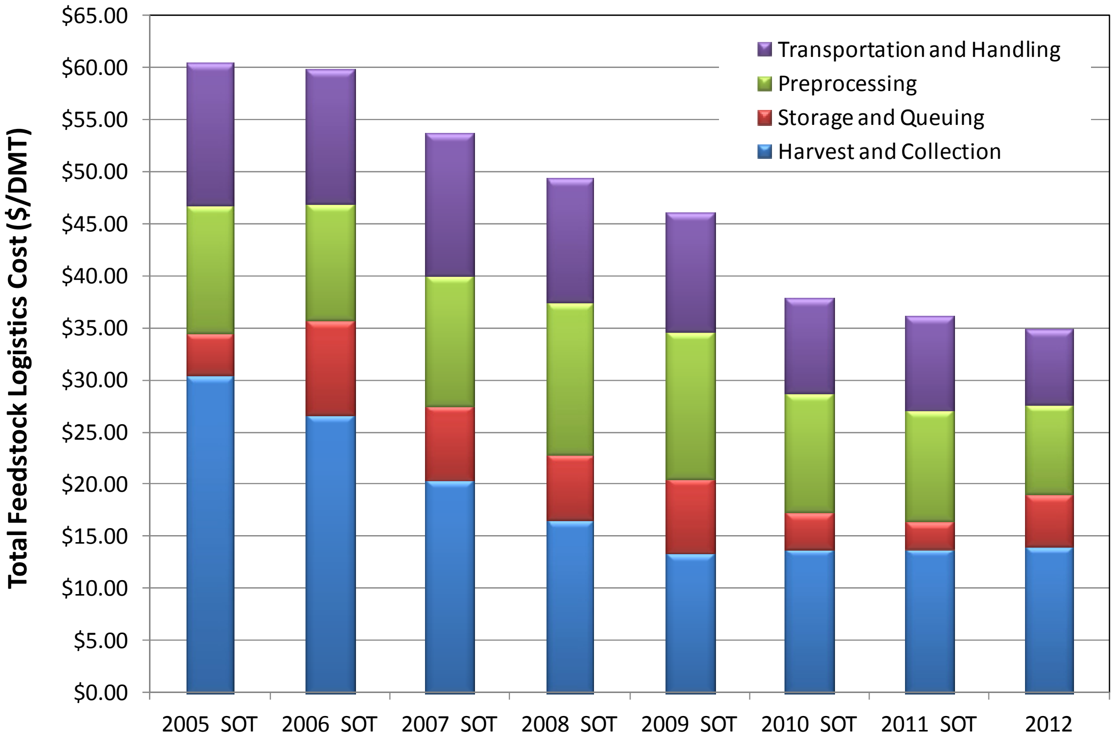

Figure 6. Historical (back cast) and projected total feedstock logistics costs from 2005 to 2012.

2.1.3 Quarter 2: Harvest, Collection, and Storage Costs

The second quarter milestone focuses on the biomass harvest, collection and storage elements of the biomass supply chain. Recommendations and best management practices developed by INL research over the last five years were assembled in a field test plan. Execution of this plan occurred in collaboration with Iowa State University who, through a contract with DuPont Danisco, has access to fields, machinery, labor, and facilities to carry out these studies on a production scale. This report describes the details of the harvest, collection, and storage activities and provides a comparison of supply system parameters measured through this work to those identified to achieve the Joule cost target.

2.1.3.1 Methods

Field Selection

A field was selected in Boone, Iowa at the discretion of ISU and DuPont Danisco that could sustainably support a removal rate greater than 50%. Field data (soil type, slope) and grower management data (cultivation and production practices) were collected for a sustainability analysis to be conducted using the DOE Residue Removal Tool.

Harvest

A Hiniker 5600 series 20-ft stalk chopping windrower, also commonly referred to as a flail shredder, was selected for windrowing the stover after grain harvest due to the flexibility to accommodate a wide range of stover removal rates. A flail shredder does not contact the ground and therefore soil contamination is less sensitive to removal rate compared to a ground-contacting windrower such as a wheel rake.

A Krone BiGPack™ 1290 HDP 3x4x8-ft large square baler was selected for baling due to its ability to produce bales of market-leading densities. Previous field testing conducted by INL and Abengoa (now the FDCE group) demonstrated the ability of the Krone HDP-1290 to produce corn stover bales with densities averaging 12.3 pounds (dry matter) per cubic foot. The results of this work was described in the FY10 second quarter Joule milestone report.

Collection

A Pro Ag 16k Plus Bale Runner tractor-pulled bale wagon was used to move the bales from the field to field side. A Stinger Stacker self-propelled bale wagon has previously been included in the conventional bale SOT supply system designs, but a Stinger was not available to ISU for conducting this work, so the Pro Ag bale wagon was used instead.

Storage

Bales were stored in a stack measuring 1-bale wide x 4-bales high x 9-bales long for a total of 36 bales. Two stacks were constructed, one to be removed for dry matter loss measurement at approximately 4-months of storage, and the second to be removed at approximately 6-months for shipment to INL for preprocessing in the third quarter. Both stacks were placed on well-drained ground to minimize moisture accumulation in the bottom bales, and each was also covered with a high-quality Western Ag hay tarp to protect the top bale from accumulation of moisture due to precipitation.

Data Collection

Data loggers were installed in all machines to collect machinery performance data that included travel speed and fuel usage. Machinery travel speed was used to calculate harvest rate for windrowing (tons/hour) and baling (bales/hour) as well as the collection rate (bales/hour) for roadsiding of bales.

2.1.3.2 Key Results

Corn stover windrowing and baling occurred on November 4, 2011 (Alliger Farms, Williams Field – F145; major soil types: Canisteo-42%, Okoboji-26%, Nicollet-18%). Previous year's (2010) corn grain yield was 175 bushels per acre. Available grain and stover (2011) averaged 178 bushels per acre and 4.99 ton (dry matter basis) per acre as determined by hand sampling prior to harvest.

In the conventional system, baled feedstock production costs begin with windrowing and baling; harvest costs remain with the grain collection. Harvest rate for the combination Case MX 140 tractor and Hiniker 5620 stalk chopper averaged 22.0 tons per hour; in-field operational efficiency was estimated at 75%. Stalk chopping and windrowing operational costs are shown in Table 3

Table 3. Cost summary table for windrowing operations.

Windrowing Cost			**$/ton**
Peak Capacity	ton/hr	18.5	
Machinery Eff.	%	75%	
Tractor &Windrowing Ownership Cost*	$/ton	$1.08	$0.96
Labor*	$/hr	$11.82	$0.76
Fuel Rate	gal/hr	6.13	$1.14
Fuel Cost*	$/gal	$2.50	
Lube Rate	%	15%	
Equipment Life	years	4	
Interest Rate	%	4%	
Working Days	day/yr	30	
Shift Time	hr/day	11	
Maintenance	%	10%	$0.30
T/I/H	%	2%	$0.12
Overhead	%	0%	$0.00
Total			$3.28

*Uses 2007 Values

A combination of a John Deere 8335R tractor and a Krone BiGPack™ 1290 HDP baler were used to produce 3x4x8-ft large square bales with an average bulk density of 11.1 lb/ft^3 (dry matter). Baling rate for this combination was 39 tons per hour; in-field operational efficiency was estimated at 70%. Baling operational costs are shown in Table 4. The total average stover removal rate was 1.9 tons per acre, resulting in collection efficiency 0f 38%.

Bales were collected and moved field side for stacking using a combination of a Case 225 tractor and a ProAg 16K Plus Bale Runner square bale picker/stacker (bale wagon). This unit is capable of picking up and stacking two 3x4x8-ft large square bales per cycle and can carry eight of these bales from the field to the stack landing per trip. Average operational capacity was 62 bales per hour (31 tons per hour). Operational costs for the bale wagon are shown in Table 5.

Table 4. Cost summary table for bailing operations.

Bailing Cost			$/ton
Peak Capacity	ton/hr	35	
Machinery Eff.	%	70%	
Tractor & Baler Ownership Cost*	$/ton		$2.43
Labor*	$/hr	$11.82	$0.52
Fuel Rate	gal/hr	9.86	$1.25
Fuel Cost*	$/gal	$2.50	
Lube Rate	%	15%	
String	$/ton	$2.00	$2.00
Equipment Life	years	6	
Interest Rate	%	4%	
Working Days	day/yr	30	
Shift Time	hr/day	10	
Maintenance	%	10%	$0.43
T/I/H	%	2%	$0.30
Overhead	%	0%	$0.00
Total			$6.93

*Uses 2007 Values

Table 5. Collection costs for feedstock collection operations.

Collection Cost			$/ton
Peak Capacity	ton/hr	31	
Machine Eff.	%	85%	
Tractor & Wagon Ownership Cost*	$/ton	$2	$2.15
Labor*	$/hr	$14.20	$0.60
Fuel Rate	gal/hr	10.51	$0.78
Fuel Cost*	$/gal	$2.50	
Lube Rate	%	15%	
Equipment Life	years	6	
Interest Rate	%	4%	
Working Days	day/yr	30	
Shift Time	hr/day	16	
Maintenance	%	10%	$0.03
T/I/H	%	2%	$0.24
Overhead	%	0%	$0.00
Total			$3.80

*Uses 2007 Values

Storage stacks for this demonstration were constructed within the bale storage yard at ISU BioCentury Farm. Bales were stacked four-high to optimize loading and unloading from the ProAg bale wagon. Bales were tarped immediately after stacking. Tarp, labor, and maintenance costs were calculated at $3.36 per ton. Tarps are assumed to be reusable for three years before requiring replacement. Land rent for stacking field side was priced at $85 per acre with a "stack multiplier" of two—stacks require additional area for loading and unloading operations. Truck loading costs for bale delivery to the biorefinery were calculated at $0.52 per ton.

Initial bale moisture content for these stacks was 21% ± 2% (wet basis); final moisture content after four months of storage was 18% ± 3%, indicating a net loss of moisture during storage. Final average moisture contents for bales in each stack position are shown in Figure 7. Red circles indicate individual bale moisture content values; blue circles indicate average values with error bars of one standard deviation above and below the mean. Bale locations within each column of the stack are indicated in Figure 8. Bottom bales (Location 1) had higher moisture contents than bales from the higher locations and tended to accumulate moisture in contact with the ground. Top bales appeared to have a thin wet layer (less than 6-in.) in contact with the tarp, but did not have significantly higher moisture contents than the middle bales.

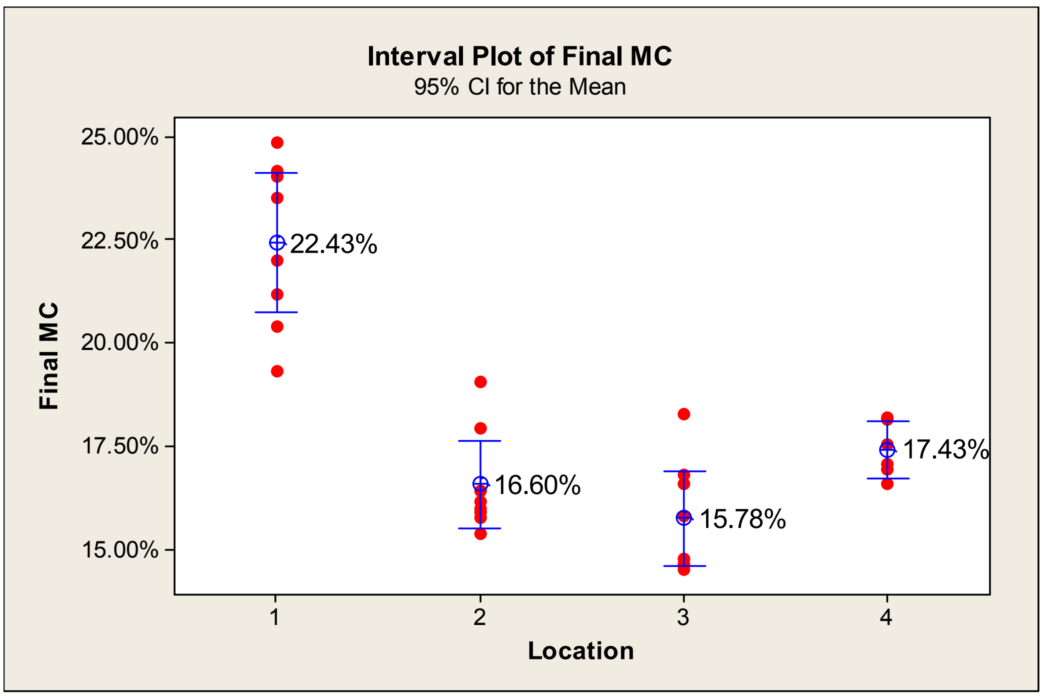

Figure 7. Final moisture content showing the increase moisture content in the bottom bales relative to the others in the stack.

Dry matter losses as a result of mechanical loss during handling and microbial and fungal degradation during storage were measured at an average of 7.7% and ranged from 0 to 14% on a starting dry matter basis. Summary statistics for dry matter loss among the test bales is shown in Figure 9. A summary of the storage costs is shown in Table 6.

A yield scenario of 1.9 tons per acre stover removal was used in the model analysis. This removal rate results in an estimated 3 tons per acre remaining of the initial 5 tons per acre available for removal. Total harvest, storage, and collection costs from this demonstration are calculated to be $17.95 per DMT, which exceeds the goal of $18 per DMT. Based upon the performance of this demonstration study, using machinery performance data, labor rates, and storage costs baselined to 2007 dollars, we have shown that we can meet our target milestone costs from harvest through storage.

Table 6. Summary of storage costs.

Storage Cost	$/ton
Tarp Ownership & Land Rent Cost*	$2.56
Dry Matter Loss	$1.38
Total	$3.94

*Uses 2007 Values

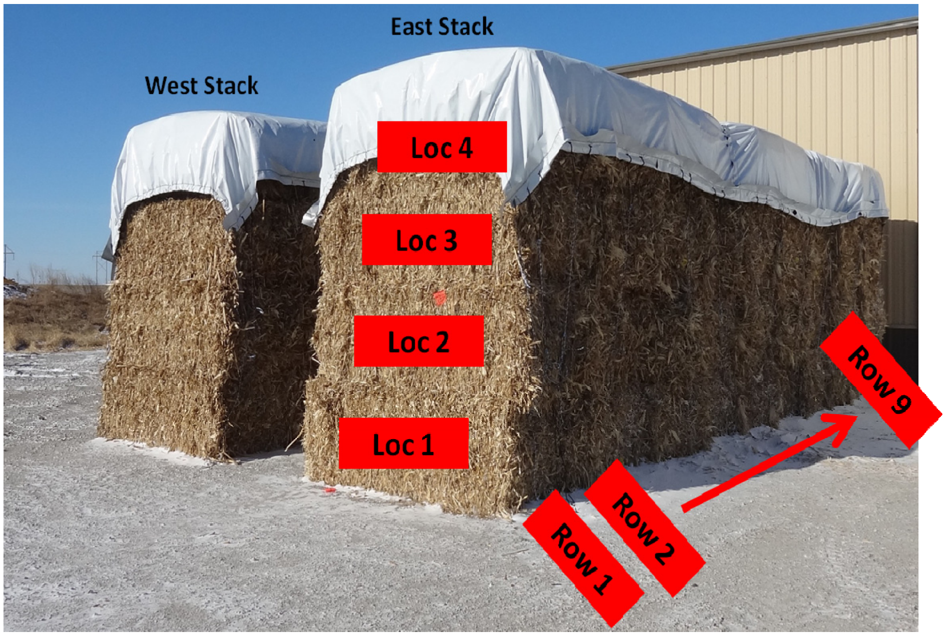

Figure 8. Stover bale stacks showing bale and row locations within the stacks.

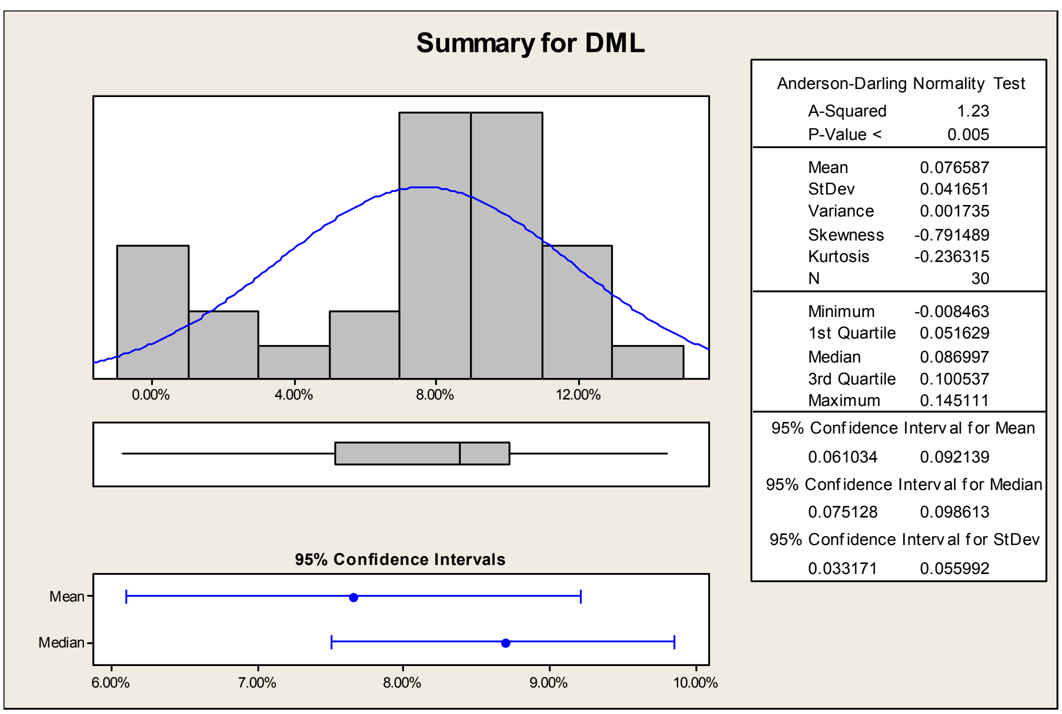

Figure 9. Summary of the dry matter loss data for this sampling period. Mean dry matter loss is 7.7%.

2.1.3.3 Discussion & Conclusions

It is important to note that the feedstock costs reported for this demonstration represent one set of conditions under which the goal of $18 per DMT can be met. Using different equipment—for instance a Stinger™ or Mil-Stak™ stacker—greater collection efficiency may be obtained in transporting bales from the field to field side storage due to the greater number of bales transported field side per trip. Additionally, a six-high stack would reduce both the tarping costs and the land needed to store the same quantity of feedstock. Alternatively, higher initial moisture contents—such as seen in Iowa and South Dakota in 2009—would increase transportation costs and produce greater dry matter losses than noted in this study, thus increase collection and storage costs.

The analysis conducted used average machinery rates and fuel use, bale densities, collection efficiencies, and storage dry matter losses measured in a field demonstration to determine average costs for corn stover harvest, collection, and storage given the conditions experienced in the Midwest corn belt in the fall 2011 through the spring of 2012. While these costs could vary given different conditions, this milestone demonstrates that the best management practices developed through INL research have had significant impact in reducing biomass harvest, collection, and storage costs compared to where we started back in 2005. Specifically, these costs have decreased from approximately $35 in 2005 to $18 today.

The average feedstock cost will represent a range of conditions under which feedstock is delivered, including different equipment combinations, storage conditions, and climate conditions existing from harvest to the time of delivery. Future sensitivity analysis of this design will be completed and introduced into the updated version of the feedstock design report to represent the range of costs that might be expected given the range and variability of supply system parameters.

2.1.4 Quarter 3: Preprocessing, Handling, and Transportation Costs

The third quarter milestone focuses on the preprocessing (size reduction), handling, and transportation elements of the biomass supply chain. Improvements in machine performance including capacity and efficiency as well as a reduction in capital costs for the herbaceous biomass size reduction equipment have been the focus of INL research over the last five years. The culmination of this research was assembled and executed at the INL PDU test site with the primary focus on a prototype bale grinder provided by Vermeer Corporation through a Cooperative Research and Development Agreement (CRADA). This report describes the details of the preprocessing, handling, and transportation activities and provides a comparison of supply system parameters measured through this work to those identified to achieve the Joule cost target.

2.1.4.1 Methods

Bale Staging

Fifty bales selected from the storage study identified in the report prepared for Quarter 2 were transported to the INL PDU test site one week prior to the execution of the preprocessing test plan. The bales were transported on two flatbed semi-trucks in a configuration not meant to represent the actual transport of material in an ideal supply system situation. This less than ideal configuration was to accommodate the 50 bales, which do not make up two full loads, and the long distance transport from Iowa to Idaho. The more ideal transport condition of 37 3×4×8-ft^3 bales, limited by weight due to bale moisture from storage, will be the configuration used in the model. Once the bales arrived in Idaho, they were staged in small stacks representative of stacks located at a biorefinery (1-bale wide x 3-bales high x 12-bales long). The stacks were tarped for the short period of time between delivery and preprocessing to preserve their storage condition as much as possible prior to inserting them into the grinding process.

Handling

A John Deere loader with bale spears was used to grab bales from the staged bale stacks and place them on a scale located at the beginning of the in-feed conveyor in order to determine the weight of each bale prior to grinding. The loader then placed the bale on the in-feed conveyor and returned to the stack for the next bale. The loader logistics of the PDU run are not ideal since they don't match the condition found at a modeled 2,000 ton a day biorefinery. Therefore, the equipment and operational parameters of loading a grinder are modeled according to previously determined operations within the model with refinement in the data being provided by Iowa State University.

Once the bales were process through the BG480E, the ground product was conveyed into a truck for post-testing storage. The truck represented the metering bin used in the model to control the feed of biomass into the conversion process. The actual meeting bin and in-feed system is modeled according to the conventional design and no additional data is collected or used from the current test plan.

Preprocessing (size reduction)

A Vermeer BG480E prototype grinder fitted with a 2-in. hexagonal screen was used to size-reduce the bales into a mean particle size of ¼-in. minus (Figure 10). This grinder has an in-feed conveyor capacity of four 8-ft long bales. Each bale is placed on the conveyor end-to-end to avoid inefficient gaps in material as the bales are presented to the grinding chamber. A 36-in.-wide out-feed conveyor is used to discharge the material from the bottom of the grinding chamber to the empty trucks acting as a surrogate of the metering bins used to feed the conversion process.

Figure 10. Vermeer BG480E prototype bale grinder used in this demonstration study.

Data Collection

The PDU is equipped with a data acquisition system to measure the time stamped power consumed by the entire grinding system including both the in-feed and out-feed conveyors as well as both motors running the duel rotor grinding drums. Manual logging of bale numbers and grinding times was performed as a backup and cross check for the automated system. Moisture samples were manually collected as the bales discharged from the grinding chamber to properly collect a uniform moisture sample and then determine the moisture content of each processed bale.

2.1.4.2 Key Results

In the conventional supply system, the preprocessing, handling, and transportation unit operations begin with the transport of baled material from the field-side storage locations to the biorefinery. These bales are stacked and queued for the grinding process. Loaders are used to both unload the trucks and place the bales into the bale yard and remove bales from the bale yard and insert them into the grinders. Conveying systems are then used to remove the ground material from the grinders and insert it into the conversion process. Pneumatic cyclone systems are used to control dust and capture airborne product that is reintroduced into the process.

A demonstration of this system began June 8, 2012 when the first of two loads of bales left Boone County, Iowa for Idaho. The bales in these loads are the same as those used in the harvest, collection, and storage studies reported in Quarter 2. These loads, as mentioned previously, were in a less than ideal or optimized configuration due to the small number of bales used and the distance they had to travel. Therefore, to be consistent with the target, a 53-ft flatbed trailer and semi-truck loaded with 37 bales is modeled. The bales are loaded and unloaded with a Caterpillar TH220B Telehandler. Current loading and unloading times were provide by Matt Darr at Iowa State University and used in the model. The final cost of transporting bales from field-side storage to the biorefinery is $7.22 per DMT. The specific parameters and final cost of performing the transportation unit operation is provided in Table 7.

Table 7. Cost summary table for transportation operations.

Transportation Cost			**$/ton**
Truck Peak Capacity	bales/load	37	
Truck Eff.	%	100%	
Truck & Trailer Ownership Cost	$/ton		$0.25
Truck Labor	$/hr	$17.48	$2.34
Trucking Equipment Life	Miles	1,000,000	
Truck & Trailer Maintenance	$/ton		$0.12
Loader Peak Capacity	ton/hr	42	
Loader Eff.	%	100%	
Loader Ownership Cost	$/ton		$0.14
Loader Labor	$/hr	$14.20	$0.63
Loader Equipment Life	Hrs	10,000	
Loader Maintenance	$/ton		$0.05
Unloader Peak Capacity	ton/hr	42	
Unloader Eff.	%	100%	
Unloader Ownership Cost	$/ton		$0.14
Unloader Labor	$/hr	$14.20	$0.63
Unloader Equipment Life	Hrs	10,000	
Unloader Maintenance	$/ton		$0.05
Transport Distance	Miles	35.1	
Fuel Cost	$/gal	$2.96	$2.62
Lube Rate	%	10%	
Interest Rate	4%		
Working Days	day/yr	300	
Shift Time	hr/day	14	
T/I/H			$0.25
Overhead	%	0%	$0.00
Total			$7.22

**Uses 2007 Values*

Preprocessing of the corn stover bales from Iowa occurred on June 22, 2012. The average bale wet weight was 1,163 pounds and the average bale moisture was 14.4%. Both of these parameters have a significant impact on the cost of the preprocessing operation. In combination, they determine the bulk density of the bales and, through correlation, the impact on grinding capacity.

The model uses a previously correlated data set to represent grinder capacity as a function of moisture (Figure 11). This correlation uses data from the Chariton Valley project and other grinder tests done in the field with a Vermeer HG6000. However, a lack of data in low and high moisture ranges still limits the broad application of this correlation. The data shown in Figure 11 represents 103 data points with a range of moisture between 7 and 33%. With data collected from this study, the correlation shown in Figure 11 is being refined (Figure 12). The new data provides a few more points in the higher moisture range, but does not provide data in the lower moisture range. Thus, more data is needed in order to have a robust correlation.

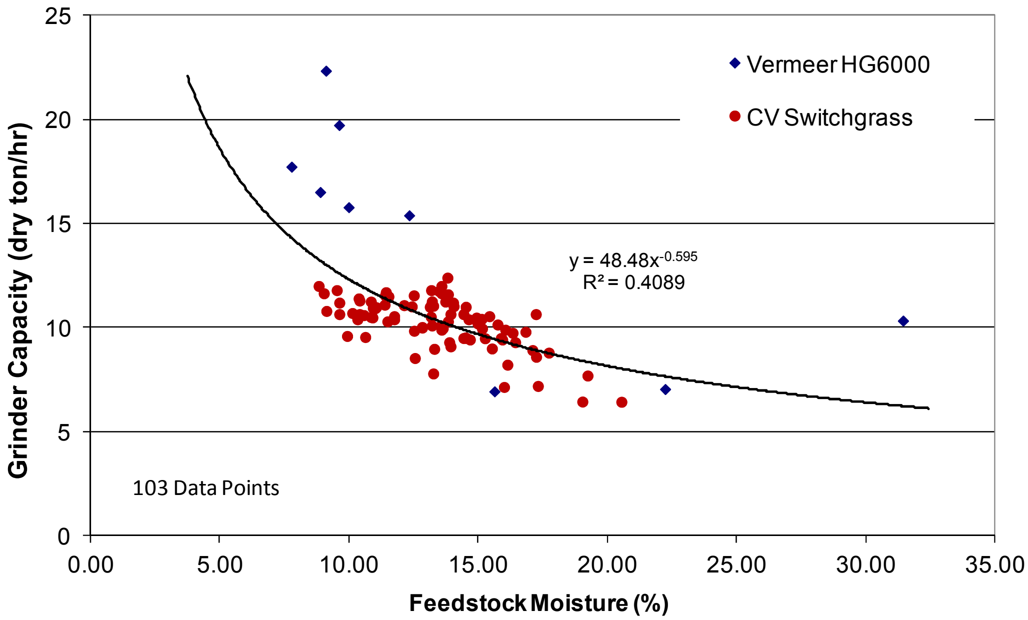

Figure 11. Relationship between grinder capacity and moisture for two separate data sets using a Vermeer HG6000 and the Chariton Valley grinder.

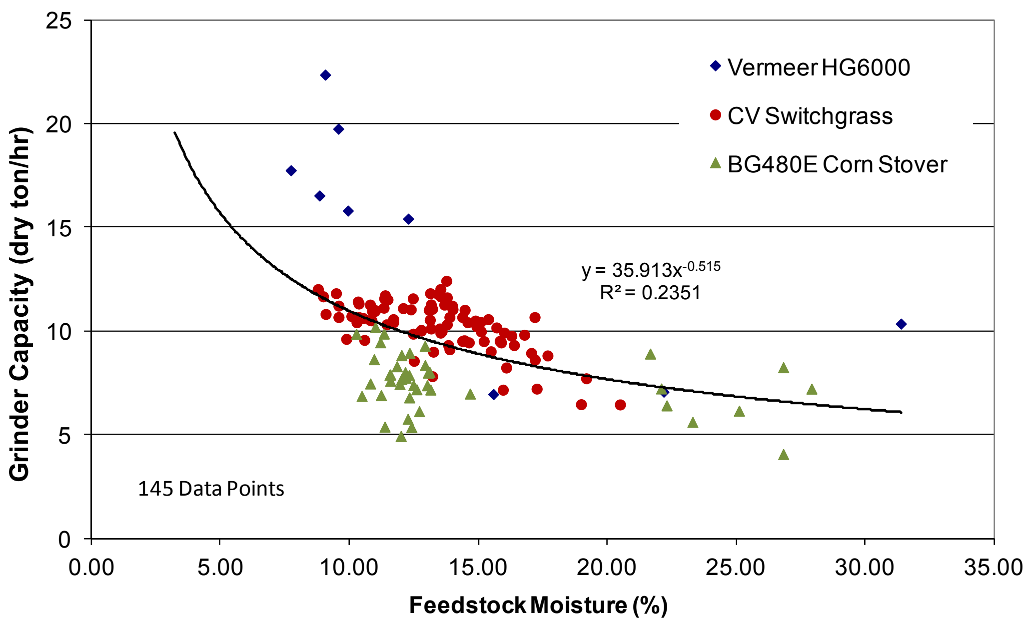

Figure 12. Relationship between grinder capacity and moisture with the added data from this test plan using a Vermeer BG480E prototype grinder.

A particularly significant trend in the data shown in Figure 12 is highlighted in Figure 13. This graph shows a decreasing trend in grinder capacity from the Vermeer HG6000 to the Vermeer BG480E prototype grinder. The cause of this decrease in capacity is the relative decrease in rated power of each test machine. The rated power of the Vermeer HG600, Chariton Valley grinder, and Vermeer BG480E are 720, 600 and 298 kW, respectively. Thus, the more power available to grind product increases the capacity of the machine. However, it also increases the energy consumption and the capital cost of the machine. The trade-off between these parameters will impact the total cost of the operation. But, these trade-offs also open the door to optimize the grinder performance. The relationship between all these parameters is complex, so further research is needed to realize the potential to optimize the system.

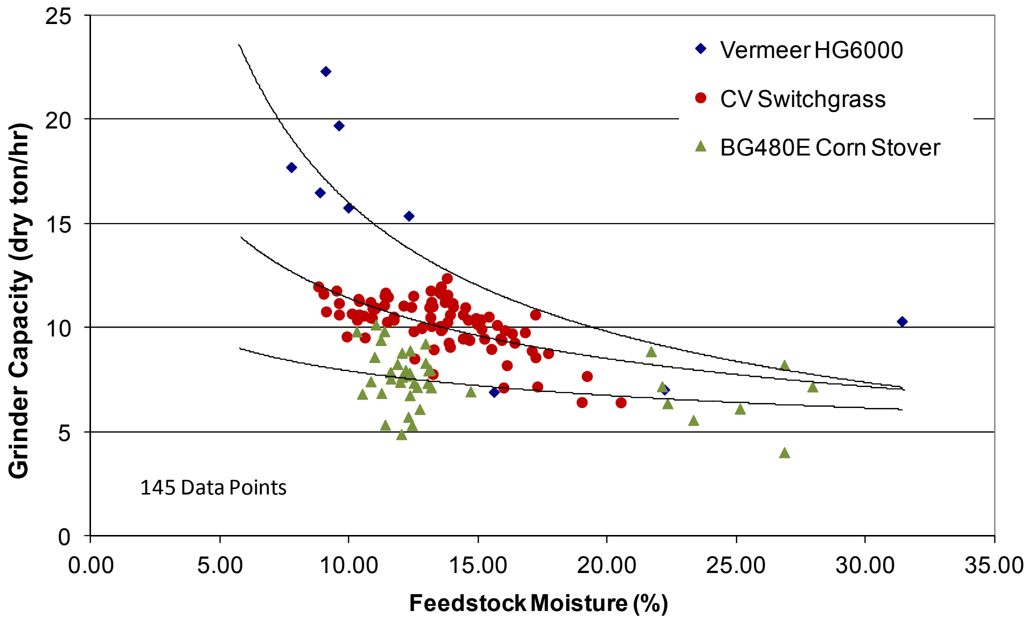

Figure 13. Comparison of capacity trends between the Vermeer HG6000, the Chariton Valley grinder, and the Vermeer BG480E prototype grinder.

The Chariton Valley grinder and Vermeer BG480E are electric grinders while the Vermeer HG6000 is a diesel grinder. This difference certainly has an influence on the efficiency of the grinding process, but might also have an influence on the capacity as well. The widest range in grinding capacity, 6.94 to 22.3 dry tons per hour, comes from the diesel HG6000 (Figure 14). The other two grinders, both with significantly more data points, have a much tighter capacity range; 6.44 to 12.4 dry tons per hour for the Chariton Valley grinder and 4.05 to 10.2 dry tons per hour for the BG480E. One possible reason for this difference might be the test conditions under which the three grinders were tested. The electric grinders were tested in a fixed, industrial-like setting while the diesel grinder was tested in the field. The significance of these testing conditions is not well understood, but worth further investigation.

Because of the rated power difference between the grinders, the correlation of grinder capacity and feedstock moisture data is skewed toward the grinder with the most data, in this case the Chariton valley grinder. Therefore, to maintain consistency and accuracy in the final cost and performance results from the current preprocessing, handling, and transportation unit operations, only the moisture impacted capacity and corresponding energy use of the Vermeer BG480E is used in the cost calculations of the system. The final modeled cost of the preprocessing operations is $8.61 per dry matter ton. A summary of the specific parameters and final cost of performing the preprocessing unit operation is provided in Table 8.

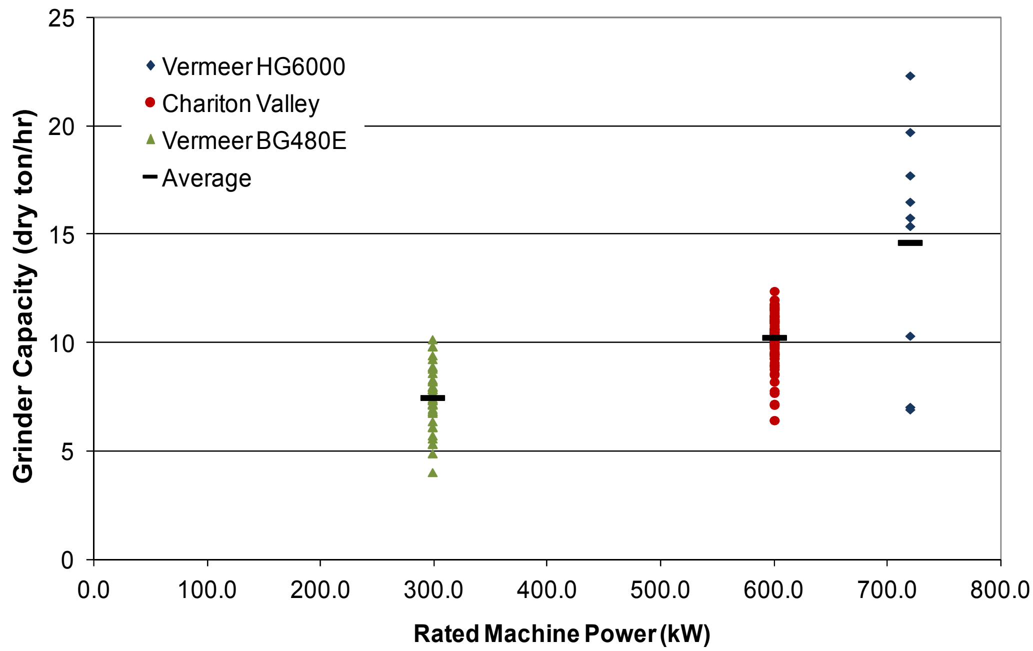

Figure 14. Comparison of capacity versus rated machine power between the Vermeer HG6000, the Chariton Valley grinder, and the Vermeer BG480E prototype grinder.

Table 8. Cost summary table for preprocessing operations.

Preprocessing Cost			$/ton
Grinder Peak Capacity	ton/hr	8.40	
Machinery Eff.	%	85%	
Grinder Ownership Cost	$/ton		$0.87
Grinder Labor	$/hr	$14.25	$0.94
Grinder Equipment Life	Hrs	15	
Grinder Maintenance	$/ton		$0.86
Grinder Energy Use	kWh/Ton	23.37	
Grinder Energy Cost	$/KWh	$0.055	$1.48
Lube Rate	%	10%	
Dust Collection Ownership Cost	$/ton		$0.39
Dust Collection Fuel Cost	$/ton		$2.16
Conveyors Ownership Costs	$/ton		$1.00
Conveyors Fuel Cost	$/ton		$0.12
Surge Bin Ownership Cost	$/ton		$0.24
Surge Bin Fuel Cost	$/ton		$0.06
Misc Equipment Ownership Cost	$/ton		$0.26
Misc Equipment Fuel Cost	$/ton		$0.06
Interest Rate	%	4%	
Working Days	day/yr	350	
Shift Time	hr/day	8	
T/I/H			$0.17
Overhead	%	0%	$0.00
Total			$8.61

**Uses 2007 Values*

Handling and queuing operations are represented by previously modeled systems including standard conveyors, metering bins and cyclone dust collection equipment. An improved gravel pad is modeled to provide sufficient space for a 3-day supply of bales necessary to feed the plant during times when trucks are not delivering fresh bales from field-side satellite storage. The primary cost to this system is the loaders that feed the grinder. The logistics of these loaders are strictly tied to the capacity of the grinders making the grinder of primary importance to the efficient operation of the handling and queuing equipment. The cost of this part of the supply system is modeled to be $1.08 per dry matter ton. A summary of the specific parameters and final cost of performing the handling and queuing unit operation is provided in Table 9.

Table 9. Cost summary table for handling and queuing operations.

Handling & Queuing Cost			**$/ton**
Machinery Eff.	%	100%	
Equipment Ownership Cost	$/ton		$0.06
Electricity Cost	$/KWh	$0.055	$0.04
Lube Rate	%	10%	
Equipment Life	Years	15	
Interest Rate	%	4%	
Working Days	day/yr	350	
Shift Time	hr/day	24	
Gravel Pad			$0.01
Loader Peak Capacity	ton/hr	48	
Loader Eff.	%	100%	
Loader Ownership Cost	$/ton		$0.12
Loader Labor	$/hr	$14.20	$0.50
Loader Equipment Life	Hrs	10,000	
Fuel Cost	$/gal	$2.96	$0.29
Maintenance	$/ton		$0.05
T/I/H			$0.01
Overhead	%	0%	$0.00
Total			$1.08

**Uses 2007 Values*

2.1.4.3 Discussion & Conclusions

It is important to note that the feedstock costs reported for this demonstration represent one set of conditions under which the goal of $17 per dry matter ton can be achieved. Using different equipment for preprocessing, handling, and transporting bales may allow the cost target to be met as long as there is comparable ranges in equipment capacity and efficiency, and the very important parameter of capital cost. The last five years, for example, have shown great gains in grinder capacity and efficiency. But these gains alone, without reductions in grinder capital costs, would not have been enough to demonstrate a total cost for all operations of less than the target of $17 per dry ton.

Of course it is critically important that the conditions in harvest, collection, and especially storage be met or the interface with the transportation and size reduction operations would cause too much of a decrease in capacity that any chance of meeting the cost target could not be met. In other words, all operations within the supply system must be considered together with all interface points being thoroughly understood and carefully controlled. In particular, the variables of bale moisture and density become paramount to an acceptable system efficiency and capacity. As reported in Quarter 2, higher initial moisture contents of the baled material would have increased transportation and grinder costs and produce greater dry matter losses such that the cost target would not have been met. The moisture content seen in the collection and storage part of the system were about as high as they could be and still allow the transportation and preprocessing operations meet the necessary costs.

The modeled analysis generally used average machinery capacities and fuel use, including average bale moisture for the transportation operation. However, the average grinder capacity and efficiency was directly influenced by the actual moisture of each bale. In fact, this study identified a critical need to understand bale moisture relative to grinder capacity. Though the average bale moisture seen by the grinder was 14.4%, an acceptable value for the assumed dry supply system of the conventional design, the range in bale moisture was 10.3 to 27.9%. The bales with this range of moisture were randomly processes such that very wet bales were mixed in with very dry bales. The result of this mixing was the intermittent plugging of the grinder screen by the wet bales requiring several dry bales, at a much reduced capacity, to be processed in order to clear the screen. Overall this reduced the potential capacity of the grinder if only dry bales were processed. Thus, a more optimized operation might either segregate bales with different moisture contents and run them in batches at significantly different capacities or implement an operation to ensure all bales are maintained at more consistent moisture content. However, each of these options goes beyond the assumptions of a conventional bale supply system and move toward an advanced system where feedstock consistency or quality is an important and controlled parameter.

Even though the inconsistency in bale moisture was a reality, the average bale moisture and resulting grinder capacity normalized to the modeled target of 12% was sufficient to meet the cost target. This would indicate that there is room to improve beyond what was demonstrated so long as material conditions are understood and controlled.

The final feedstock cost of the entire supply system will represent a range of conditions under which feedstock is harvested, collected, stored, transported, preprocessed, and inserted into the conversion process. These conditions can likely include different equipment combinations, storage conditions, climate conditions, preprocessing conditions, and requirements imposed by the conversion facility. Follow-on sensitivity analysis will be conducted as part of the updated feedstock design report that will show the range in unit operation and overall supply system costs identified in this milestone report.

2.1.5 Quarter 4: System Integration

One of the cost impacts on the total supply system is the relatively high feedstock yield reported in Quarter 2. This yield increased the harvest and collection efficiencies and reduced the transport distance, thus reducing each unit operation's cost. Improved bale loading and unloading logistics had an even higher impact on transport cost. This resulted in a comparatively lower transport cost from that reported in last year's Joule Milestone. However, the primary decrease in the total supply system cost came as a result of reduced preprocessing cost. This reduction balanced the slight increase in harvesting and storage costs which can be attributed to generally higher moisture content in the feedstock. Therefore, through system integration, the total supply system cost was reduced and the target was met.

The total net change in cost from FY11 to FY12 for each unit operation is:

- Harvesting +$1.44
- Collection –$3.10
- Storage +$3.60
- Transport –$1.78
- Preprocessing –$2.03
- Handing and Queuing +$0.63
- Total –$1.24

2.1.6 Overall Conclusion

The Feedstock Joule Milestone for FY12 was to achieve a modeled dry herbaceous feedstock logistics cost of $35 per DMT in 2007 dollars excluding grower payment. To meet this milestone, INL Bioenergy research needed to meet all integrated performance metrics reported in each quarterly milestone established at the beginning of FY12. These quarterly milestones were:

Qtr 1: Update the supply logistic design, equipment economic and performance parameters, and current system efficiency and capacities to deliver an FY10 state-of-technology (SOT) baseline dataset and IBSAL-SD modeled scenario for dry corn stover feedstock logistics.

Qtr 2: Achieve a storage dry matter loss improvement of 1.9% (7.9 to 6%) on field-side storage of baled corn stover.

Qtr 3: Achieve a grinder capacity improvement of 5.2 tons/hour (26 to 31.2) on dry corn stover feedstock utilizing 470 kilowatts of power.

Qtr 4: Achieve a modeled dry corn stover feedstock logistics cost of $36.10 per dry ton (excluding grower payment, in 2007$).

Based on the research performed in FY12, specifically that associated with harvest efficiency through improved sustainable yields, reduced dry matter loss through cost efficient storage practices, improved transport efficiencies through better loading and unloading practices and high bale densities, and improved preprocessing capacities and capital costs through grinder design changes, the target cost of $35 per DMT has been achieved. This cost is captured within the feedstock supply system model (BLM) as a conventional bale, dry herbaceous feedstock supply scenario. The final cost breakdown is shown in Table 10.

Table 10. Cost summary table for the FY12 Joule Milestone research results.

FY12 Cost Summary ($/DM ton)					
	Installed Capital	Ownership	Operating	DM Loss	Total
Harvesting	19.00	1.08	2.20	0.00	3.28
Baling	33.51	2.73	4.20	0.00	6.93
Roadsiding	19.12	2.39	1.41	0.00	3.80
Total Harvest & Collection	**71.62**	**6.20**	**7.81**	**0.00**	**14.01**
Transportation #1	4.06	0.78	6.44	0.00	7.22
Total Transportation	**4.06**	**0.78**	**6.44**	**0.00**	**7.22**
Preprocessing #1	13.87	2.93	5.68	0.00	8.61
Total Preprocessing	**13.87**	**2.93**	**5.68**	**0.00**	**8.61**
Storage	6.88	2.56	0.00	1.38	3.94
Plant Handling & Queuing	0.95	0.19	0.89	0.00	1.08
Total Storage & Queuing	**7.83**	**2.75**	**0.89**	**1.38**	**5.02**
Total	**97.38**	**12.66**	**20.82**	**1.38**	**34.86**

2.1.7 Acknowledgements

We thank Matthew Darr, Assistant Professor in the Department of Agriculture and Biosystems Engineering at Iowa State University and the students in his laboratory for information relating to the loading and unloading of baled corn stover and for their help collecting and compiling the results used in this report. We also thank a team of researchers at Vermeer Manufacturing in Pella, Iowa for their

contributions and research partnership in the last five years of grinder testing including the BG480E that is a staple in the DOE Feedstock Process Demonstration Unit used in this study.

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