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

U.S. Department of Energy (DOE)
Bioenergy Technologies Office (BETO)

2017 Project Peer Review

1.2.1.1000:
Development of a Wet Logistics System for Bulk Corn Stover

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Lynn Wendt, PI
Idaho National Laboratory

March 7, 2017
Feedstock Supply & Logistics

Goal Statement

The goal in this project is to design a wet, bulk logistics system that protects corn stover from loss in storage and is cost competitive with the existing herbaceous (dry bale) SOT

- Project Outcome: A wet, bulk logistics system provides solutions for high-moisture corn stover
  - Secures feedstock supply from dry matter loss and fire loss
  - Enables mobilization of the high-moisture portions of the nation’s billion tons of biomass
  - Compatible with the existing logistics operations and conversion technology, leading to a quick entry into the marketplace
- Background:
  - Research efforts were previously only focused on dry systems to realize cost savings in not transporting water
  - This project is a response to feedback from academia and industry
    - Industrial interest in wet systems to mitigate fire risk and improve handling
    - 2013 Peer Reviewer’s suggestions to expand logistics systems to provide a solution for wet biomass

Quad Chart Overview

Timeline

- Project start date: Oct 1, 2014
- Project end date: Sept 30, 2017
- Percent complete: 80%
- *Ongoing Project*

Budget

	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date)
DOE Funded	$385K	$327K	$385K

Barriers

- Ft-H. Biomass Storage Systems
- Ft-G. Quality and Monitoring
- Ft-L. Biomass Material Handling and Transportation

Partners

- DOE partners
  - ORNL, LBNL ABPDU
- Abengoa Bioenergy

Project Overview

A wet, bulk system solves multiple logistics problems

Wet Storage

- Reduces dry matter loss due to microbial degradation
- Mitigates catastrophic loss of bales to fire
- Reduces storage footprint and costs
  - Buffer strips increase land use and handling costs
- Moisture-affected bales lose physical structure
  - Increased losses in handling and transportation

Harvest & Collection

- Eliminates dependence on field drying for stability
- Enables double cropping
- Forage chopping results in size reduction
  - Low fines, narrow particle size range

Project Overview

Unaccounted costs exist in conventional feedstock supply system

- Fines are created during size reduction of dry bales
  - Occur from overprocessing in conventional systems
  - Result in mechanical loss
  - Increase fire risk in preprocessing
  - Increase environmental regulations
  - Over-pretreat in conversion, produce fermentation inhibitors
- Bale twines are problematic
  - Bale de-stringers require operator attention, increase operating costs
  - Twines that pass through de-stringer into grinder can cause fires
  - Twines in moisture-affected bales often are not cut
  - Twines require either disposal cost or preprocessing if inserted into boiler
- Size reduction through forage chopping followed by size classification reduces preprocessing at biorefinery, reduces issues related to fines and twines
- Wet feedstock that meets the size spec will lead to higher reliability, operability, and higher yield in conversion

Technical Approach

Design a wet logistics system that is cost competitive

- Anaerobic storage, or ensiling, has been used for centuries to preserve high-moisture biomass for livestock
  - Anaerobic conditions created mechanically and biologically
  - Acid fermentation lowers pH and stabilizes biomass
  - Dry matter losses of <5% possible compared to losses of 12% for bales entering storage at 30% moisture (2015 SOT)
- Wet storage can compliment existing dry systems
  - Dry logistics systems apply when stover can be baled dry
  - Long-term wet storage at biorefinery used for “at-risk” material
- Utilize industrial-scale storage within the biorefinery gate
  - Eliminates a transportation step
  - Eliminates on-site queuing (3-5 days of feedstock)
- Compare costs and performance for two systems capable of wet industrial-scale storage
  - Industrial-scale ensiling
  - Modified Ritter pile

Technical Approach

Proposed large-scale storage solutions

- Industrial-scale silage pile
  - 40 to 50% moisture w.b. during storage
  - Compacted by tractors or similar heavy machinery
- Modified-Ritter pile
  - Pile constructed and compacted with slurried biomass
  - Biomass 70 to 80% w.b. moisture content during storage, dewatered upon exit
  - Nutrients in runoff can provide cost benefit

Gaps exist in published wet storage research

- Mass closures of dry matter
- Individual structural sugars concentrations
- Conversion to sugars

INL 100 liter storage reactors fill research gaps

- Recreate field conditions to inform TEA
- Storage metrics include dry matter loss, greenhouse gas production, chemical composition, sugar release

Atchison, 2004 NREL/SR-510-33893

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

Technical Approach

Technoeconomic analysis (TEA) informs wet logistics system selection

Go/No-Go Milestone: successfully met 3/31/16

- Determine if wet logistics system is cost competitive (within 200% of costs) with existing three-pass dry bale SOT
- Choose <u>industrial-scale ensiling</u>, Ritter storage, or stop

Challenges

- Transportation costs: Transporting water increases costs
- Entire supply chain is impacted by wet biomass, not just storage
- Near-term industry adoption: Bulk corn stover in preprocessing operations is currently designed around dry bales

Success Factors

- Cost: TEA shows wet systems are competitive with dry systems
- Sustainability: analysis shows reduced energy and water consumption
- Demonstrates that wet logistics systems can solve handling and feed issues experienced at demonstration-scale biorefineries

Management Approach

Engage diverse national laboratory and industry capabilities

Initial logistics design based on:

- Logistics modeling of wet systems
  - Biomass Logistics Model / INL Analysis Team (Ag and Process Engineers)
- Engineering design of centralized preprocessing and storage operations
  - Harris Group design based on commercial vendor quotes, Aspen Plus®
- Laboratory research
  - INL Storage Team (Microbiologists, Environmental Scientists, Biological Engineers)

Final TEA includes data from the field and laboratory

- Field demonstration of a wet logistics system
  - Abengoa Bioenergy, INL
- Storage performance
  - INL, LBNL
- Logistics performance
  - INL, ORNL

Laboratory Storage

Goal: Compare performance of field-chopped corn stover in anaerobic INL storage reactors

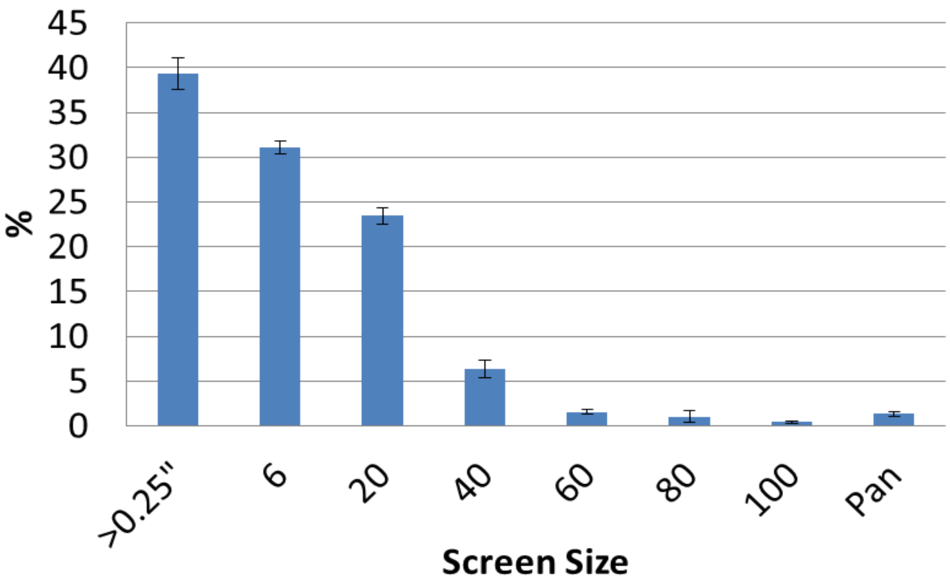
Method: Store for 110 days; simulate Ritter pile construction by washing with water prior to storage

Results:

	Silage	Ritter
Dry Matter Loss	5.9% ± 1.1%	10.1% ± 0.6%
Gas Production	CO_2, CO, H_2, and NO_X	3X more than silage
Organic Acids	3% lactic, 1% acetic, pH 4.6	5.5% acetic, 1.5% butyric, pH 5.2
Washing	No co-products	Removal of 40% of soil contamination, Potassium removed offsets $4/ton
Composition	Reduction in total extractives and non-structural glucan and xylan after storage, No significant change in structural sugars	

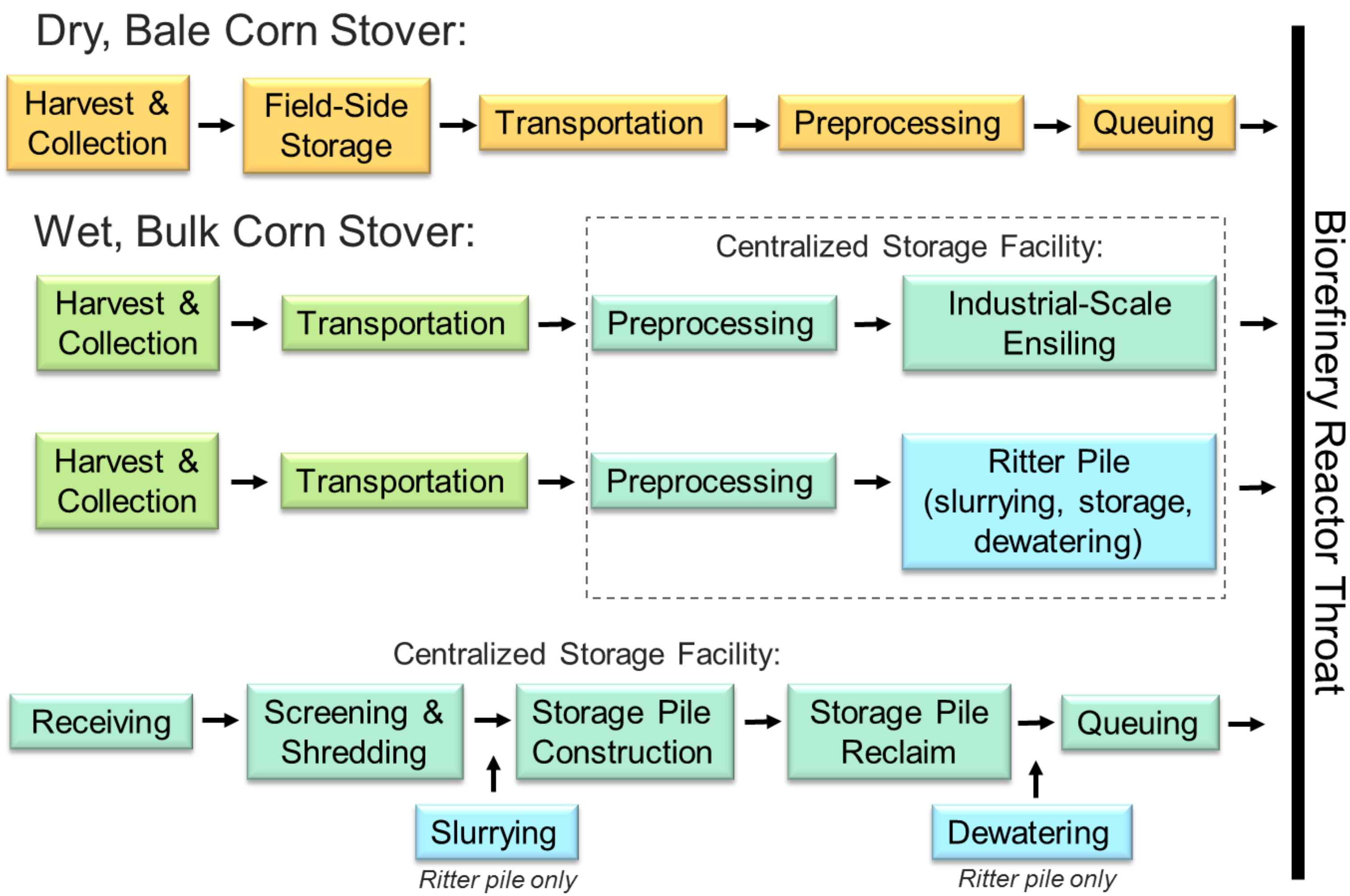
Size Reduction During Harvest

- Target Particle Size Distribution
  - Narrow distribution
  - All material under 1″
  - < 5% fines
- Direct forage chopping resulted in 60% of the stover meeting 1" spec with < 5% fines
- Size reduction in forage chopping results in cost savings in preprocessing:
  - Only 40% of the corn stover needs additional size reduction to meet size specification
  - Data input into engineering design



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

Logistics Systems Overview



- Define unit operations and costs for centralized storage facility
- Compare costs of wet logistics systems to dry bale system

Centralized Preprocessing and Storage Design

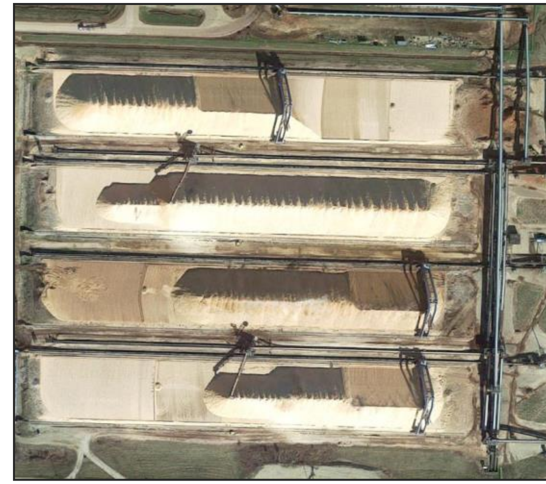
Centralized preprocessing and storage design based on vendor quotes

Truck Tipper

Vibratory Screen

Disk Screen for Fractionation

Shredder



Storage site with 4 150’ wide piles and Stackers (2) and Reclaimer (1)

Linear Stacker for Silage

Slurry Placing Boom for Ritter Pile

Linear Reclaimer

Techno-economic analysis

- Harvest, collection, transportation, and dry system costs (INL BLM Model)
- Centralized Preprocessing and Storage costs (Discounted Cash Flow Analysis using depot and chemical refinery installation and indirect costs)
  - Costs range due to assumptions on installation and indirect costs

	Wet Bulk Logistics System		Dry Bale Logistics System
	Industrial-Scale Ensiling	Ritter Pile	
Grower Payment	$31.34	$31.34	$31.34
Harvest & Collection	$13.50	$13.50	$21.49
Field-Side Storage	-	-	$4.97
Transportation	$23.53	$23.53	$13.68
Preprocessing			$33.23
Centralized Storage	$49.26-$81.75	$69.50-$112.61	-
Dockage			$17.94
Credits	($0.17)	($4.19)	-
Total	**$117.46-$149.95**	**$133.68-$176.79**	**$122.65**
% of Dry Logistics System	**96%-122%**	**109%-144%**	**-**

*Costs reported in 2015 dollars on a dry basis

- Result: both wet systems meet Go/No-Go criteria of 200% of 2015 dry bale SOT; industrial-scale ensiling most competitive
  - Drying ($7.19) and pelleting ($7.58) included in 2015 dry bale SOT. If removed, total costs are $107.94.

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

Energy Consumption

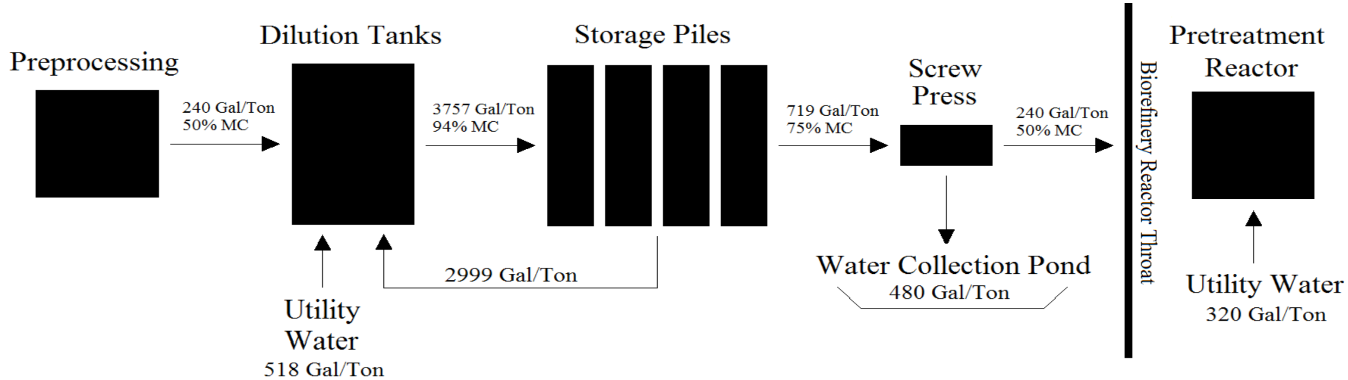
- Calculated contribution of diesel, electricity, and natural gas

	Wet Bulk Logistics System		Dry Bale Logistics System
	Industrial-Scale Ensiling	Ritter Pile	
Harvest & Collection	278,360	278,360	133,966
Field-Side Storage	-	-	99,346
Transportation	294,326	294,326	125,361
Preprocessing	169,592	266,710	1,846,109
Centralized Storage			-
Total	742,278	839,396	2,204,782
% of Dry Logistics System	**34%**	**38%**	-
Units are in MBTU/dry ton			

- Wet logistics systems reduce energy requirements
  - 34-38% of the dry bale system
- Wet systems eliminate drying energy requirements
  - If drying is not considered, wet systems are still within 2-15% of dry bale system
- Wet logistics systems reduce greenhouse gas released
  - Even when considering CO and NO_x detected in laboratory storage experiments

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

Water Consumption



- Ritter system requires significant water input, even with recycling
  - 157% of the dry bale system
- A wet logistics system using industrial-scale ensiling reduces water needs
  - 60% of the dry bale system

	Wet Bulk Logistics System		Dry Bale Logistics System
	Industrial-Scale Ensiling	Ritter Pile	
Ritter Pile construction	-	517.80	-
Makeup water required at biorefinery (assuming 30% solids in PT reactor)	320.13	320.13	533.55
Total	**320.13**	**837.93**	**533.55**
% of Dry System	**60%**	**157%**	**-**
Units are in gallons water/dry ton			

Field Demonstration

- 350-acre plot of corn stover collection; included shredding and forage chopping
- Time-in-motion study performed to validate logistics costs of harvest and collection
- Ensiling of 40% moisture corn stover to predict storage performance in field

Flail Shredding Windrower

Forage Chopping

40’ Walking Floor Trailer

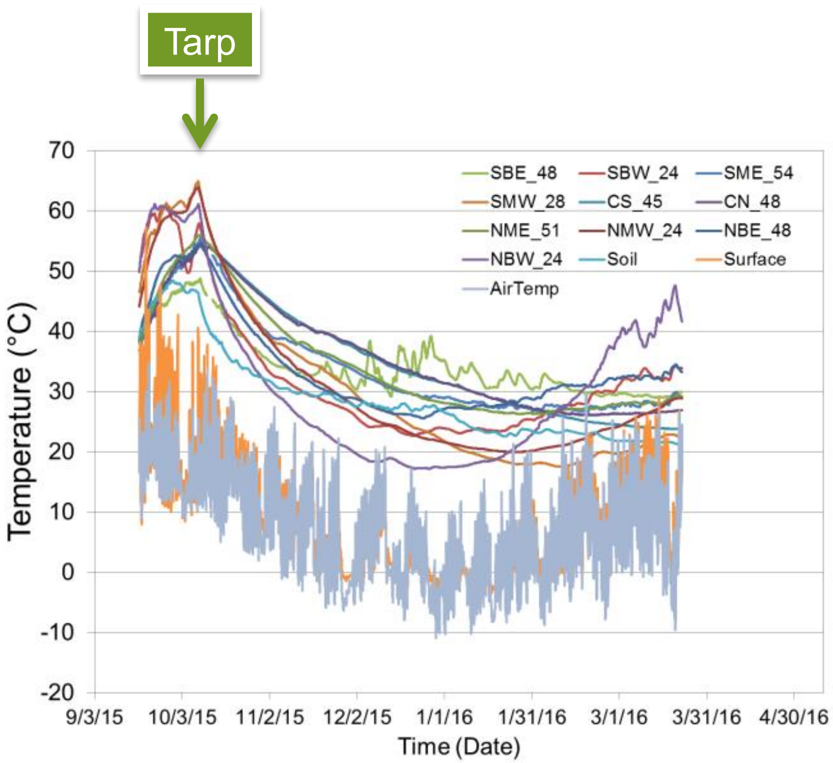
Pile formation and compaction

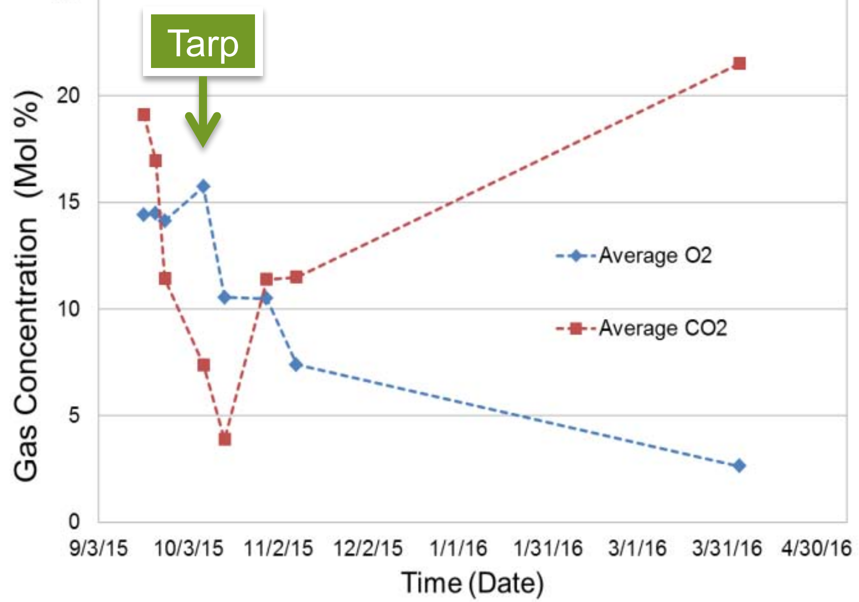
Data-logging equipment

300 dry ton, covered pile

Field Demonstration

- 10 zones in pile were monitored for temperature, gas production, moisture content, acid production, and composition
- Pile was uncovered for 3 weeks; self-heating observed initially
- Oxygen consumed in pile and carbon dioxide formed, signaling fermentation





Field Demonstration

Corn stover was successfully preserved over 6 months

- Average losses were 5%
- pH decreased
- Organic acids present signal fermentation, ~2-5%/dry matter
- Structural glucan and xylan was preserved in samples centrally located in pile and slightly reduced in outer regions

Sample Description	%DML	%Moisture	pH	Organic acids (% of DM) Succinic	Lactic	Formic	Propionic	Butyric	Total
SBE - 48"	6.1%	30.5	4.9	2.1	0.2	1.4	0.3	0.3	4.5
SBW - 28"	4.2%	36.5	5.2	1.1	0.3	0.3	1.4	0.5	4.1
SME - 54"	11.4%	47.0	4.8	0.6	0.7	0.4	0.9	0.2	3.2
SMW - 28"	1.1%	37.2	4.8	0.9	0.3	0.3	1.2	0.6	3.8
CS - 45"	3.4%	38.2	4.9	0.9	0.4	0.2	1.3	0.2	3.4
CN - 48"	6.5%	42.0	4.8	1.0	0.7	0.2	1.4	0.3	4.1
NME - 51"	2.8%	37.6	5.1	0.4	0.2	0.1	0.5	0.2	1.7
NMW - 24"	5.9%	42.3	4.6	0.5	1.0	0.2	1.4	0.6	4.3
NBE - 48"	3.5%	40.1	4.7	0.9	0.9	0.2	1.3	0.3	4.0
NBW - 24"	-2.2%	31.4	5.0	0.4	0.3	0.2	0.8	0.5	2.7

Relevance

Wet logistics systems can reduce risk of loss in the supply chain

- ~5% loss in anaerobic storage, compared to 12% loss in 30% moisture corn stover (SOT) (demonstrated in laboratory and field storage)
- Wet logistics system using industrial-scale ensiling ($117-150/dry ton) is cost competitive with 2015 SOT for 3-pass, dry-baled stover ($122/ton) (TEA results)

Contributes to BETO targets and milestones

- Reduces feedstock loss in the supply chain, enables wet portion of Billion Tons

Bioenergy Industry and Marketplace Impact

- Advances storage beyond current SOT by incorporating the logistics of wet bulk, not just dry baled, herbaceous biomass
- Provides alternative pathways to manage year-round supply risks
- Compatible with existing logistics operations and conversion technology, leading to quick market entry
- New profit opportunities for equipment manufacturers: Informs selection of equipment and new design
- New and improved profit opportunities for feedstock producers: Enables double cropping and increased profit; delivers biomass at peak conversion value for optimum feedstock payment

Future Work

Wet, bulk corn stover logistics, Year 3

- Incorporation of field data into TEA
- Impact of storage on convertibility
- Prediction of storage performance in large-scale piles
- End of Project Deliverable: 9/30/17
  - Final wet logistics designs, TEA, LCA
  - Overview of existing infrastructure available to support a wet logistics pathway
  - Recommendation to BETO on future wet logistics opportunities

Future wet logistics goals

- Reduce costs of wet logistics system to compete with dry system at $84/ton
  - High-yielding bioenergy crops (i.e. biomass sorghum, energy cane), MSW yard waste
  - Lower transportation costs through decreased distance and increased density
- Further define costs and risks of conventional dry compared to wet system
  - Additional costs of fire loss, satellite storage, and just-in time delivery of bales
  - Risk reduction of wet systems through companion markets (i.e. livestock feed)

Summary

Overview

- Design wet, bulk feedstock logistics system for corn stover that relies on storage at the biorefinery gate

Relevance

- Wet logistics systems protect feedstock from aerobic deterioration and risk of fire compared to dry systems and are necessary to mobilize our nation’s billion tons of biomass resource to support a thriving bioeconomy

Approach

- TEA informs wet logistics system selection, validated by lab and field data

Progress

- Dry matter losses in storage reduced to 5% over 6 months compared to target of 12% for dry bales
- TEA shows that a wet bulk logistics system for corn stover is competitive with existing bale logistics systems meanwhile reducing energy and water use

Future Work

- Final TEA, LCA on wet corn stover logistics (FY17)
- High-yield, high-moisture crops in wet logistics systems (FY18-FY20)

Acknowledgments

INL

William Smith
Quang Nguyen
Austin Murphy
Damon Hartley
Kastli Schaller
Allison Ray
Brad Thomas
Eric Fillerup
Karen Delezene-Briggs
Amber Hoover
Michelle Walton

ORNL

Erin Webb
Shahab Sokhansanj

LBNL

Ling Liang
Ning Sun

Independent Contractors

Thomas Robb
Kirk Spikes
Walter Beesley

Harris Group

Danielle Sexton
Jeff Ross
John Lucas

Additional Slides

Responses to Previous Reviewers’ Comments

- Reviewer: They will be estimating CAPEX and OPEX for these feedstock storage systems. Please make sure the energy inputs are all determined or estimated. BETO needs to consciously determine the net energy production of its systems.

- Reviewer: Encourage more sustainability examinations of the process.

- *Response: We recognize the need for sustainable solutions to feedstock logistics, especially in terms of water and energy consumption of a wet, bulk supply system. Initial estimates for water and energy consumption will be included in the techno-economic and life cycle assessment in order to inform the Go/No-Go decision in FY16. Furthermore, these estimates will be updated with measured performance from the large-scale field demonstration performed in collaboration with our industrial partner, which will be the final deliverable of this 3-year project.*

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

Responses to Previous Reviewers' Comments

- Reviewer: Good project that is exploring a relatively innovative concept for feedstock logistics. The SOA has mostly pursued dry material systems for well-recognized advantages. However this project re-opens the question and explores alternatives that may have some significant advantages beyond simply fire risk reduction.

- *Response: Wet storage of herbaceous feedstock is being explored as a means to provide a consistent feedstock for biorefineries that reduces the risk associated with feedstock loss, specifically the risk of catastrophic loss to fire and dry matter loss due to aerobic microbial degradation. A bulk, wet feedstock logistics supply chain that moves size reduction to the field and large-scale storage at the biorefinery has the possibility of being cost competitive with the current State of Technology, which is based on a dry bale feedstock. Two storage options are being explored, traditional ensiling using a drive-over pile and a modified-Ritter approach that is based on slurring to promote compaction in the storage pile. We recognize the need for sustainable solutions for feedstock logistics, especially in terms of water and energy consumption for the wet, bulk feedstock supply chain. Initial estimates for water and energy consumption will be included in the techno-economic and life cycle assessment in order to inform the Go/No-Go decision in FY16, which will determine which storage option to pursue. Furthermore, these estimates will be updated with measured performance from the large-scale field demonstration performed in collaboration with our industrial partner, which will be the final deliverable of this 3-year project. The cost of wet, bulk corn stover feedstock supply chain will be compared to the low-moisture system. However, the costs of insurance for dry bale storage have not yet been quantified by the industry. We will continue to follow advancements in this area in order to accurately describe the advantages of a high-moisture feedstock supply chain.*

Publications, Patents, Presentations, Awards, and Commercialization

- Wendt, L.M., J.A. Murphy, W.A. Smith, T. Robb, Q. Nguyen J.A. Ross, D.M. Sexton, J.C. Lukas. Performance and techno-economic analysis of corn stover in a wet, bulk logistics system. In process.

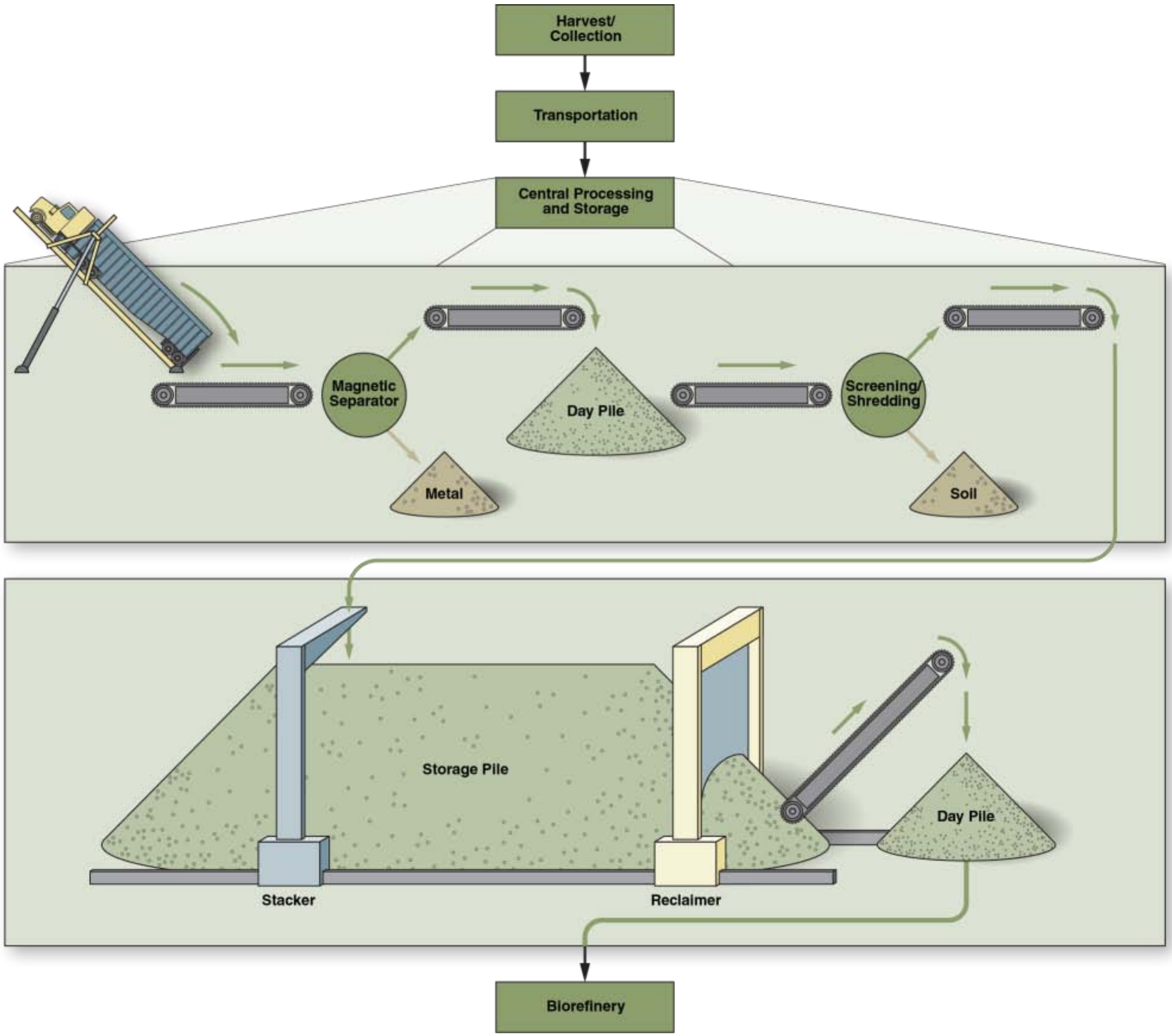
- Wendt, L.M., J.A. Murphy, W.A. Smith, T. Robb, Q. Nguyen, D. Hartley. Cost and performance estimates of corn stover in a wet logistics system. Poster Presentation. The 38th Symposium on Biotechnology for Fuels and Chemicals, Baltimore, MD. April 25-29, 2016.

- Wendt, L.M., J.A. Murphy, W.A. Smith, T. Robb, Q. Nguyen. Evaluation of bulk, high moisture corn stover performance in anaerobic storage. Poster Presentation. 2015 AIChE Annual Meeting, Salt Lake City, UT. November 8-13, 2015.

Centralized Preprocessing and Storage Design

Industrial-scale ensiling

- Truck tipper unloads
- Day pile allows 24 hr operations
- Screening/shredding system delivers corn stover at <1", <5% ash
- Automated storage pile formation
- Automated storage pile reclaim
- Day pile provides 24 hr supply to biorefinery, mixing for consistency
- Delivery to biorefinery



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

Centralized Preprocessing and Storage Design

Ritter pile storage

- Truck tipper unloads
- Day pile allows 24 hr operations
- Screening/shredding system delivers corn stover at <1", <5% ash
- Slurrying/pumping to 6% solids
- Automated storage pile formation
- Automated storage pile reclaim
- Screw press dewaters
- Day pile
- Delivery to biorefinery