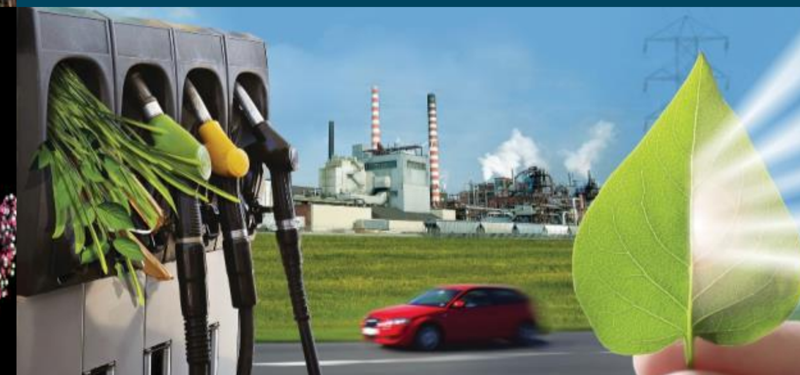

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U.S. Department of Energy (DOE)
Bioenergy Technologies Office (BETO)

2017 Project Peer Review

1.3.3.100:
Algal Feedstock Logistics and Handling

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

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March 7, 2017
Advanced Algal Systems

Goal Statement

The goal of this project is to manage seasonal variation in algal biomass production through stabilization to reduce conversion costs and to reduce ash to increase conversion yield

Project Outcomes

- A process that preserves harvested microalgal biomass over a six-month period and enables a biorefinery to run year round with a consistent feedstock supply
- A process for simultaneous ash reduction and stabilization of biomass derived from an algal turf scrubber that could be applicable to multiple high-ash algae species

Relevance

- Supports long-term goals of emerging algae industry
  - Seasonal variation in microalgae necessitates long-term storage
  - Wet storage eliminates natural-gas-based drying, reducing costs and GHGs
- Supports near-term goals of emerging algae industry
  - Stabilization methods allow for transportation to conversion facility
  - Blending can bridge the gap for utilizing algae biomass before dedicated algae conversion facilities are constructed

Quad Chart Overview

Timeline

- Task 1: 4/22/15-9/30/18
  - Percent complete: 50%
- Task 2, 3: 10/01/17-9/30/19
  - Percent complete: 15%
- *Ongoing Project*

Barriers

- Aft-F. Algae Storage Systems
- Aft-G. Algal Feedstock Material Properties
- Aft-H. Overall Integration and Scale-up

Budget

	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date)
DOE Funded	$150K	$340K	$2,000K

Partners

DOE partners

- NREL, PNNL, SNL

Collaborations

- ASU/AzCATi/ATP^3
- Univ. of Arizona
- Cal Poly-San Luis Obispo

Project Overview

Feedstock logistics studies are essential to ensure that the maximum amount of biomass harvested is convertible to valuable energy and co-products

Algae Production
Variable ash, moisture, viscosity

Feedstock Logistics
Stabilize feedstock, manage variability

Conversion
Depends on available, consistent, on-spec & economical feedstock

Scale-up lessons learned in cellulosic industry

Lack of integration of unit operations = slow start-up

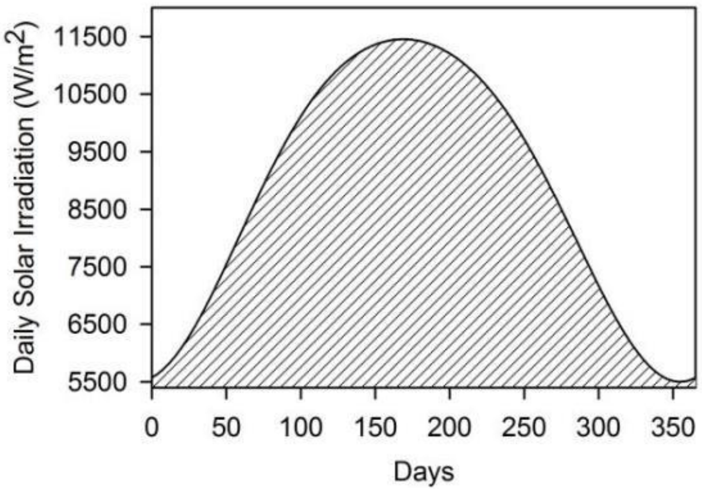
- Batch to continuous-feed operations lead to unforeseen problems
- Feed handling issues underestimated
- Soil contamination leads to abrasion of equipment and issues in conversion
- “Dry” biomass still contains 10-20% moisture, which migrates during long-term storage and causes degradation

Microalgae studies @ INL

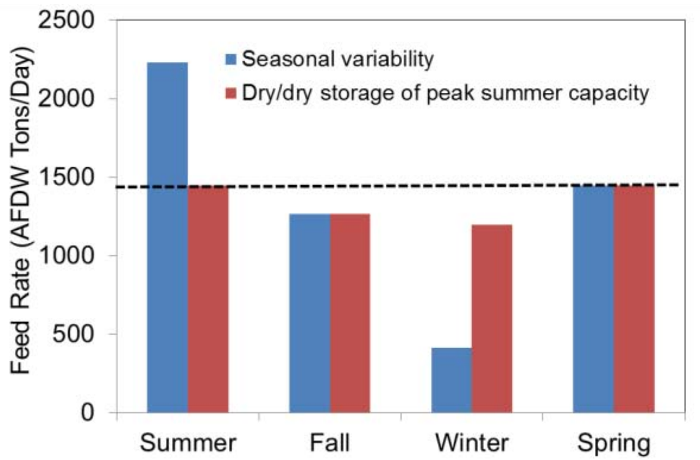
- Gas formation occurs in many types of harvested algae biomass
- Short-term dry matter loss is high; 2-3% loss per day measured
- Material properties vary widely for harvested microalgae at 20% solids

Project Overview

Productivity swings due to seasonal variation necessitates long-term stabilization to maximize conversion efficiency



Historical average from Beaumont, TX



Adapted from Davis et al. 2014

- DOE BETO Design Cases utilize drying to stabilize a portion of algae grown in summer for use in winter
- Drying is expensive: $136-158 per AFDW ton
- Dry storage stability is unknown in hot, humid environments

Technical Approach

Wet storage is an alternative to drying and dry storage of harvested algae

Commonly used for livestock feed

- Currently available infrastructure
- Field deployable and scalable
- <5% dry matter loss possible

Creates anaerobic, acidic conditions

- Mechanical exclusion of air
- Lactic acid fermentation lowers pH and stabilizes biomass

Goal: Determine if microalgae is preserved in wet storage

1. Determine if the properties of herbaceous biomass can be extended to microalgae through blending to stabilize biomass
2. Determine if algae can be stored by itself in wet storage systems
3. Determine if chemical treatment can upgrade biomass by reducing ash and provide stabilization

Technical Approach

Three tasks explore optimization of harvested algae from multiple angles

1. Stabilization through blending

2. Stabilization of algae alone

3. Ash reduction and subsequent stabilization

Management Approach

Task Overview

- **Year 1:** Optimization at bench scale
  - Laboratory-based screening at INL
- **Year 2:** Scale-up on performance metrics achieved, assess conversion potential
  - Leverage INL Biochemical and Thermochemical Conversion Interface Projects as well as partner national labs
- **Year 3:** Collaborate with conversion labs for full validation
  - NREL, PNNL, SNL

- Annual and Go/No-Go Milestones
- TEAs assist in comparing solutions to SOT
- Collaborations with industry and academia provide access to a wide range of biomass types and growth conditions

Technical Approach

Challenges

- Herbaceous biomass is inactive once harvested, algae is metabolically active
- Wet anaerobic storage must preserve dry matter and composition

Critical Success Factors

- Wet storage can compete with drying/dry storage in TEA and LCA
- Wet storage methods compatible with existing conversion approaches

How do we determine success in storage?

- Go/No-Go Milestone (3/30/17): Determine if wet storage of blends can reduce dry matter loss to less than 30% over 6 months
- 6-17% loss observed
- Goal: 10% loss or as indicated by TEAs

Technical Approach

Three tasks explore optimization of harvested algae from multiple angles

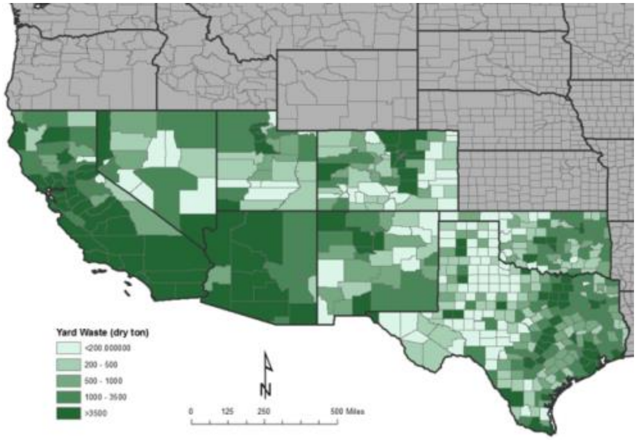
1. Stabilization through blending

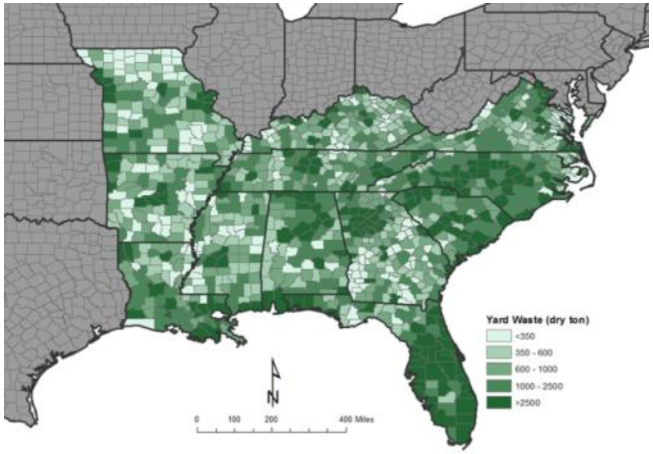
2. Stabilization of algae alone

3. Ash reduction and subsequent stabilization

Technical Approach - Task 1

- Low-cost logistics systems exist for herbaceous biomass
- Blending extends rheological properties of herbaceous biomass to algae
  - Up to 40% algae can be blended and maintain herbaceous properties
- Approach: Use low cost blending and storage to solve seasonal variation problem
- Herbaceous biomass used for blending must be
  - Compatible with algae conversion
    - Hydrothermal Liquefaction (HTL)
    - Combined Algal Processing: Fermentation, Lipid upgrading
  - Sufficiently available where algae industry is likely to emerge
    - Gulf coast, arid southwestern states





MSW yard waste in Southwest and Southeast US, estimated 5 million tons currently available annually

Accomplishments - Task 1

TEA comparing costs of dried algae to blended algae shows opportunities for wet storage

High Winter Productivity Scenario

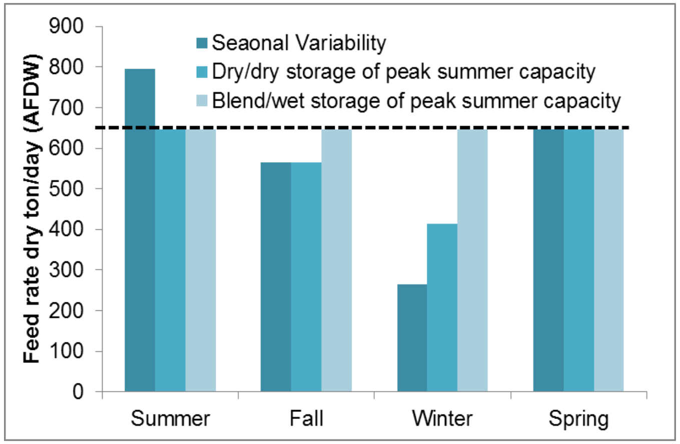
- 3:1 Summer-to-Winter Variation
- Blending and wet storage reduces cost of diesel by 25 to 42% compared to drying

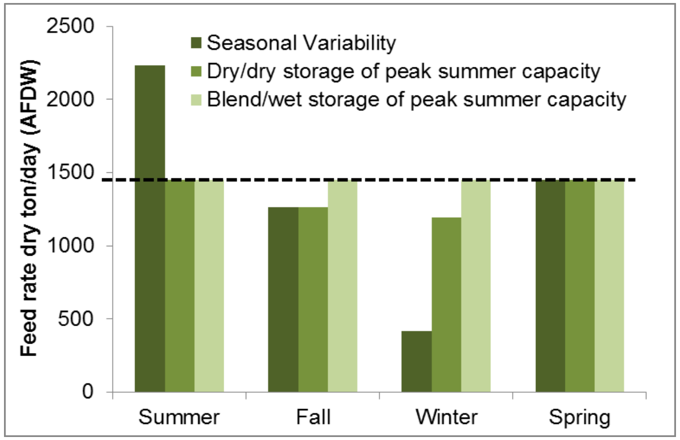
Low Winter Productivity Scenario

- 5:1 Summer-to-Winter Variation
- Blending and wet storage reduces cost of diesel by 0 to 18% compared to drying
- Algae production can be shut down during winter without impacting conversion throughput
- Expands algae production and conversion to northern latitudes

Blending and wet storage systems eliminate natural gas-based drying

- 90% reduction in energy consumption
- 75% reduction in greenhouse gas release



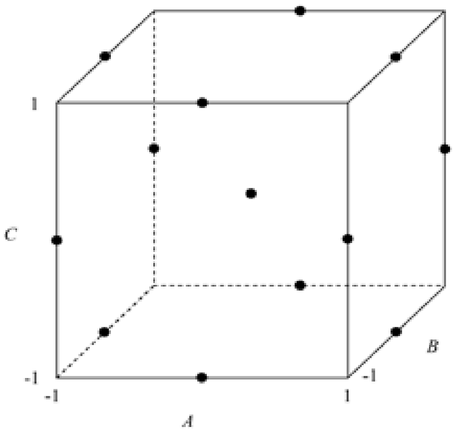


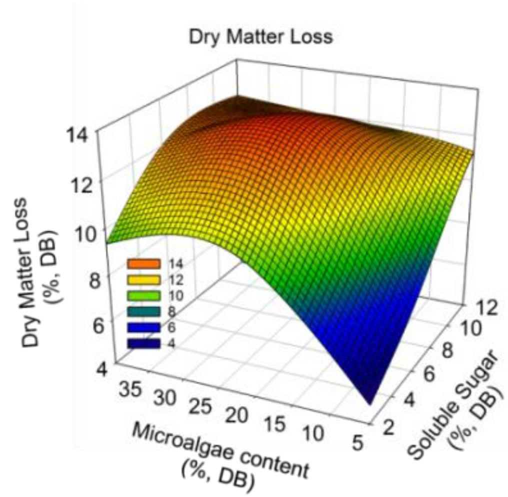
Accomplishments - Task 1

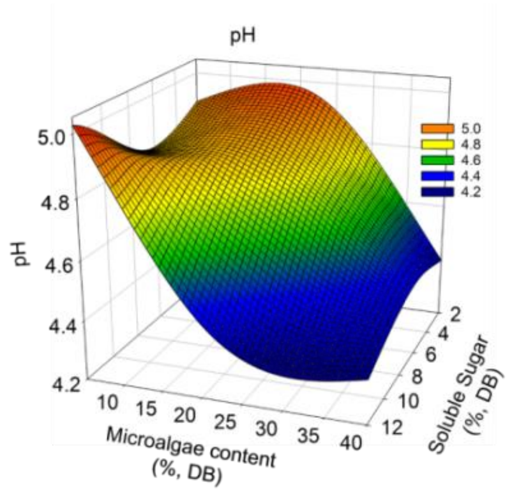
Blends of algae and herbaceous biomass are able to undergo ensiling in storage and are preserved

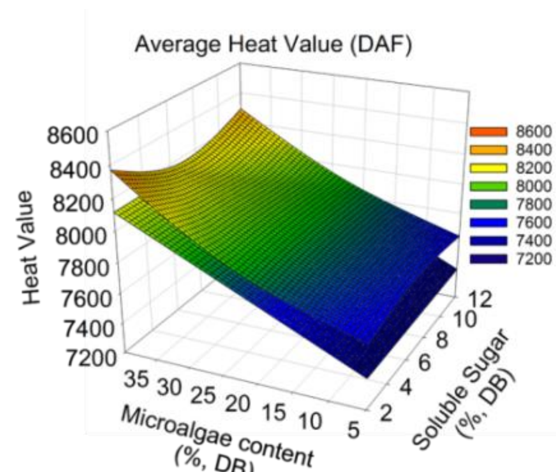
Storage Parameters

- Moisture content
- Blend ratios
- Sugar content
- 35 days of storage









Accomplishments - Task 1

Long-term storage study showed stability over 6 months

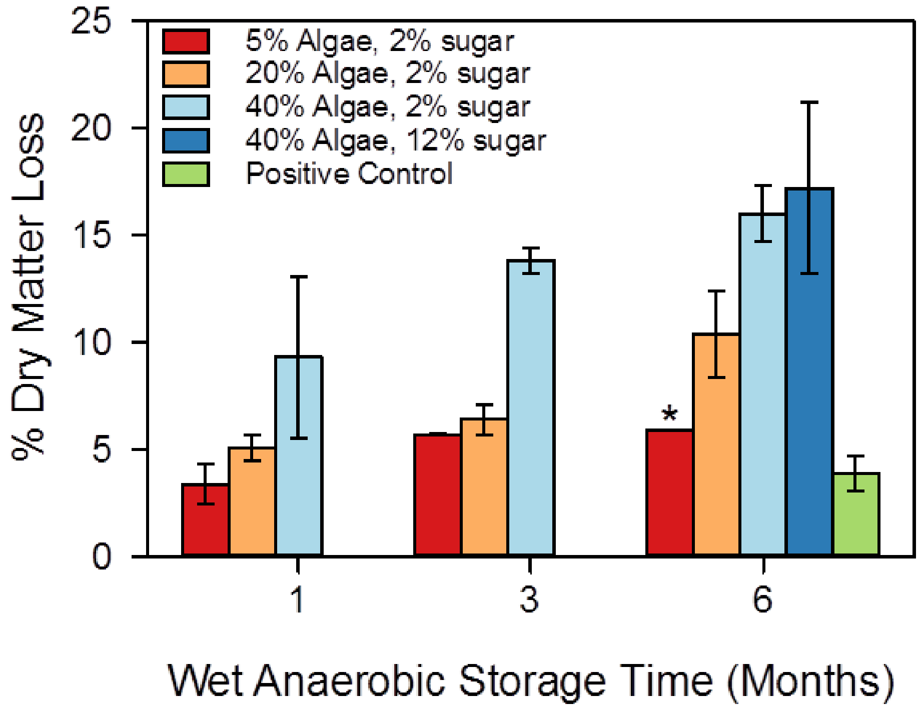
Go/No-Go Milestone (due 3/30/17)

Determine if wet storage can reduce dry matter loss to less than 30% over 6 months, which is a 50% improvement over wet algae stored aerobically

Result: *Scenedesmus obliquus*/corn stover blends were preserved over 6 months

Observed changes in composition

- Higher Heating Value (HHV) and Carbon increase
- Structural sugars are preserved over 6 months or decline proportionally with loss depending on blend ratio
- Protein preserved
- Lipid analysis underway



Future Work - Task 1

Investigate storage and conversion performance of additional blends

- *Scenedesmus acutus,* MSW yard waste: 4.8% ± 0.8% dry matter loss (DML)
- *Scenedesmus acutus,* sweet sorghum: 6.3% ± 3.1% DML
- Biomass from Algal Turf Scrubber, biomass sorghum:
  - Pioneer turf, primarily benthic diatoms: 4.6% ± 0.8% DML
  - Established turf, filamentous green algae: 6.2% ± 1.5% DML

Assess conversion potential for blends through INL interface projects

- HTL screening
- Dilute acid pretreatment, enzymatic hydrolysis, lipid extraction

Incorporate algae strains of industrial relevance

- *Chlorella zofingiensis*
- *Chlorella vulgaris*
- *Porphyridium purpureum*
- *Nannochloropsis gaditana*

FY18: Assess conversion of blends with partner labs, finalize TEA and LCA

Technical Approach

Three tasks explore optimization of harvested algae from multiple angles

1. Stabilization through blending

2. Stabilization of algae alone

3. Ash reduction and subsequent stabilization

Technical Approach - Task 2

Algae are stable during simulated ensiling

- Losses limited to 6-12% over 30 days

Ensiling doesn't occur as easily on its own as when blended with herbaceous biomass (preliminary results)

- Anaerobic storage, no treatment: 30% DML
- Anaerobic storage with lactic acid bacteria: 20% DML

Approach for stabilization

- Manipulate storage conditions to enable ensiling
- Explore value-added benefit of storage
  - Produce stabilizing co-products

Storage treatments under consideration

- Enzyme addition to release algal sugars for subsequent microbial fermentation
- Enzyme addition to produce preservatives
- Sulfuric acid treatment; compatible with dilute acid pretreatment
- Production of value-added organic acids for stability

Initial results promising

Scenedesmus acutus: 11% DML

Chlorella zofingiensis: 6.5% DML

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Technical Approach/Future Work - Task 2

Validation of storage approaches in multiple freshwater, saline, and filamentous strains over 1 and 6 months

- *Scenedesmus acutus*
- *Chlorella zofingiensis*
- *Chlorella vulgaris*
- *Porphyridium purpureum*
- *Nannochloropsis gaditana*
- Biomass from Algal Turf Scrubber-Corpus Christie, TX
- *Oedogonium* sp., filamentous algae grown on wastewater-Cal Poly-San Luis Obispo

- Assess storage performance and resulting composition-FY17
- TEA: Provide results to NREL to assess wet storage costs compared to the SOT of drying-FY17, Q2-Q3
- Down-select treatments, assess performance through collaboration with conversion labs as in Task 1, FY18-FY19

Technical Approach

Three tasks explore optimization of harvested algae from multiple angles

1. Stabilization through blending

2. Stabilization of algae alone

3. Ash reduction and subsequent stabilization

Technical Approach - Task 3

Ash reduction and subsequent stabilization solves seasonality aspect while upgrading biomass qualities

- Biogenic Ash: Diatoms in ATS biomass contain silica in the cell wall and intracellular silica
- Non-Biogenic Ash: Contamination from soil, silt, dissolved inorganics

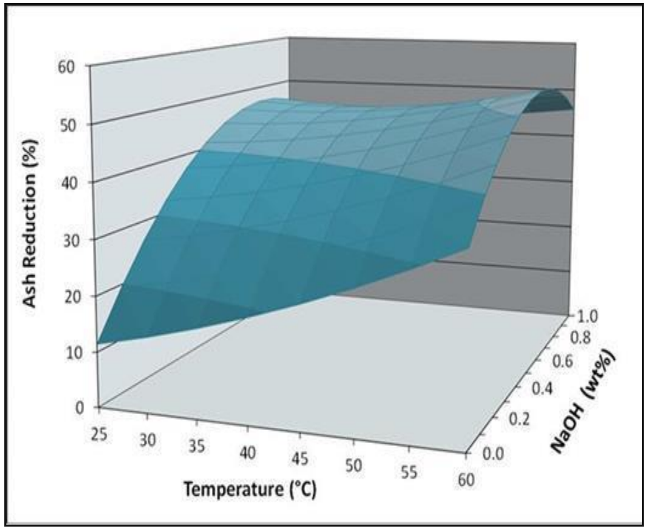
Algal Turf Scrubber (ATS)

- Approach
  - Reduce ash content in ATS biomass, which can be as high as 50 wt%
    - Alkaline extraction to solubilize silica
  - Determine short- and long-term stability of treated blend
    - Short-term stability addresses need for transportation to conversion facility
    - Long-term stability addresses seasonal variation in production

Technical Approach/Future Work - Task 3

Goal: Develop a robust process to reduce ash content while preserving organic material

- Alkaline extraction targets
  - 70% ash reduction with 90% organic recovery
  - Methods developed for corn stover could be more efficient for algae
- One-step method
  - Biogenic and non-biogenic removal combined
- Two-step method
  - Sequential biogenic and non-biogenic removal
- Investigate stability of alkaline-treated solids
  - Storage stability
  - Possibility of reduced pretreatment requirements
- Results will assist SNL in defining a logistics system for biofuel production from ATS biomass
- Results may be applicable to multiple high-ash algae species



Ash reduction through alkaline extraction in corn stover

Relevance

- Feedstock logistics bridges the gap between production and conversion
- Lack of integration across all operations led to issues for current cellulosic industry suffered during startup, costly repairs/replacement, low fuel yield
- Integrating feedstock logistics and conversion now will save in the future

- Wet storage offers opportunities to lower conversion costs and energy requirements through the elimination of drying in order to manage seasonal variation in production
- Ash reduction in ATS biomass can reduce conversion costs by increasing yield while stabilizing biomass

Relevance for the emerging algal biofuels industry

- Short-term storage can enable stable transport to a central conversion facility, mobilizing rural economic resources
- Blending offers an opportunity for utilization of algae biomass before a dedicated algae conversion facility is built

Summary

Overview

- Manage seasonal variation of produced algal biomass through high-moisture stabilization to reduce the risk of feedstock loss prior to conversion
- Reduce ash to increase conversion yield while stabilizing biomass

Relevance

- Optimization in feedstock logistics can assist in meeting or lowering conversion cost targets, integrates production and conversion

Approach

- Stability research addresses seasonal variation in production and optimization of properties prior to conversion

Progress

- Demonstrated losses 6-17% in algae/corn stover blends stored for 6 months and as low as 6.5% in algae stored alone over 1 month
- TEA shows that stabilization through blending and wet storage is competitive with drying, can eliminate winter production in low-yield scenarios

Future Work

- Optimize storage performance while preserving composition
- Assess conversion performance, TEA, and LCA

Acknowledgments

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Publications, Patents, Presentations, Awards, and Commercialization

Publications

L. Wendt, B. Wahlen, C. Li, G. Kachurin, K. Ogden, J.A. Murphy. Evaluation of a high-moisture stabilization strategy for harvested microalgae blended with herbaceous biomass: Part I – storage performance. Submitted to Algal Research.

L. Wendt, B. Wahlen, C. Li, J.A. Ross, D.M. Sexton, J.C. Lukas, D.S. Hartley, J.A. Murphy. Evaluation of a high-moisture stabilization strategy for harvested microalgae blended with herbaceous biomass: Part II – techno-economic analysis. Submitted to Algal Research.

Presentations

B.D. Wahlen, L.M. Wendt, K. Ogden, and J.A. Murphy. Stabilization of microalgae through blending and storage with herbaceous crops. Poster presentation at the Algal Biomass Summit, Glendale, AZ. October 24-26, 2016.

L.M. Wendt, B.D. Wahlen, C. Li, G. Kachurin, K. Ogden, and J.A. Murphy. Stabilization of microalgae through blending and storage with herbaceous crops. Oral Presentation at the 6th International Conference on Algal Biomass, Biofuels, and Bioproducts, San Diego, CA. June 26-29, 2016.

B.D. Wahlen, L.M. Wendt, C. Li, G. Kachurin, K. Ogden, J.A. Murphy. Evaluation of the potential for high-moisture, anaerobic storage to stabilize microalgae biomass. Oral Presentation at the 6th International Conference on Algal Biomass, Biofuels, and Bioproducts, San Diego CA. June 26-29, 2016.

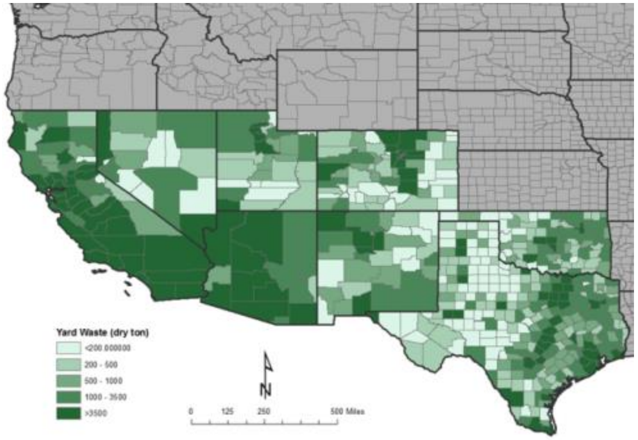
F.I. Seibel, L.M. Wendt, B.D. Wahlen, K. Ogden and J.A. Murphy. Stabilization of microalgae through blending and storage with herbaceous crops. Poster presentation at 2016 ASABE Annual International Meeting, Orlando, FL. July 17-20, 2016.

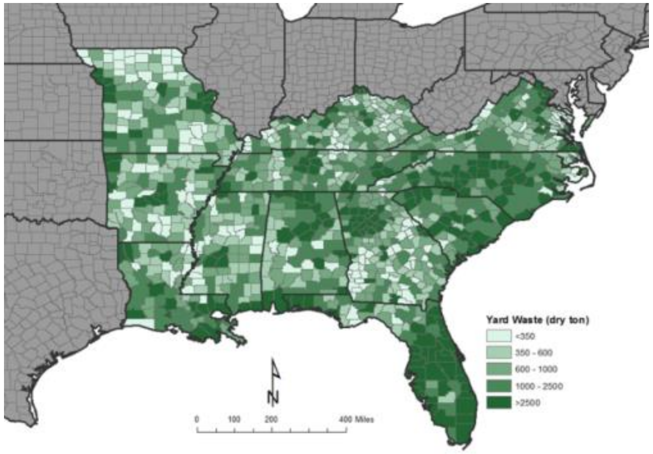
Two invention disclosures submitted in 2016

Accomplishments - Task 1

Resource assessment completed to identify herbaceous biomass available for blending during summer months in Southwest and Southeast US

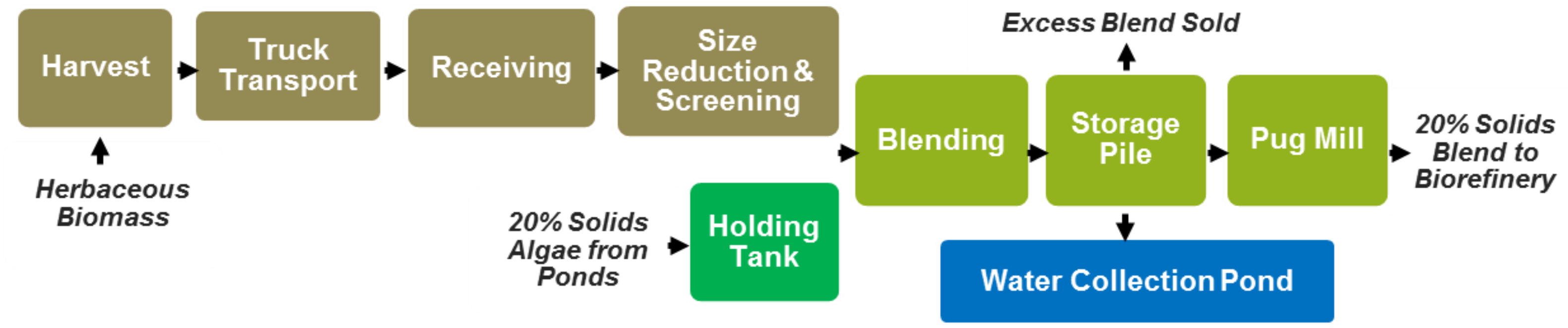
Feedstock	Annual Inventory, Southeastern U.S. (US ton)	Annual Inventory, Southwestern U.S. (US ton)	Total Annual Inventory (US ton)
Corn stover	27,958,773	11,187,082	39,145,855
Cotton stalks	4,174,541	4,064,226	8,238,767
Peanut hay	4,383,210	462,923	4,846,133
Rice straw	7,157,144	2,756,610	9,913,754
Sorghum	776,201	1,256,652	2,032,853
Haylage	934,803	2,866,954	3,801,757
Distillers grains	2,064,000	2,496,000	4,560,000
Sugar cane/energy cane	27,380,199	1,401,926	28,782,125
MSW Yard waste	2,439,955	2,588,903	5,028,858





Accomplishments - Task 1, TEA

Techno-economic analysis compares blending and wet storage to drying



Defined unit operations for wet storage of algae/terrestrial biomass blends at a reactor throat

- HTL is assumed conversion method
- Cost comparison includes
  – Feedstock cost
  – Drying or wet storage cost
- Total cost compared by estimating fuel yield and resulting cost/gallon

Accomplishments - Task 1, TEA

	3:1 Summer:Winter Variation 5,000 acre pond		5:1 Summer:Winter Variation 1,000 acre pond		
	3:1 Drying	3:1 Wet Storage	5:1 Drying	5:1 Wet A[a]	5:1 Wet B[a]
Feedstock Cost[b]					
Algae Produced	$5,995,808	$5,995,808	$3,446,820	$3,446,820	$3,446,820
Corn Stover Purchased	-	$1,790,719	-	$715,009	$715,009
Upgraded Blend	-	-	-	($907,651)	($466,982)
Stabilization Cost ($/ton)	$140.80	$81.84	$140.80	$112.13	$113.75
Stabilization Cost ($)	$1,719,368	$3,287,384	$988,416	$2,020,398	$2,049,587
Total Costs ($)	**$7,715,177**	**$11,073,911**	**$4,435,236**	**$5,274,575**	**$5,744,434**
Total Diesel Produced (Gallons)[c]					
From Algae	1,489,794	1,415,304	856,440	490,367	657,848
From Corn Stover	-	1,859,141	-	422,037	566,181
Total	**1,489,794**	**3,274,444**	**856,440**	**912,404**	**1,224,029**
% of Dry System		**219.8%**		**106.5%**	**142.9%**
Cost ($/gallon diesel)	**$5.18**	**$3.38**	**$5.18**	**$5.78**	**$4.69**
% of Dry System		**65.3%**		**111.6%**	**90.6%**

*All costs reported in 2011 dollars on an ash-free dry weight basis

[a]5:1 Wet A case assumes winter operation of algae ponds, while the 5:1 Wet B case assumes no algae is produced during winter

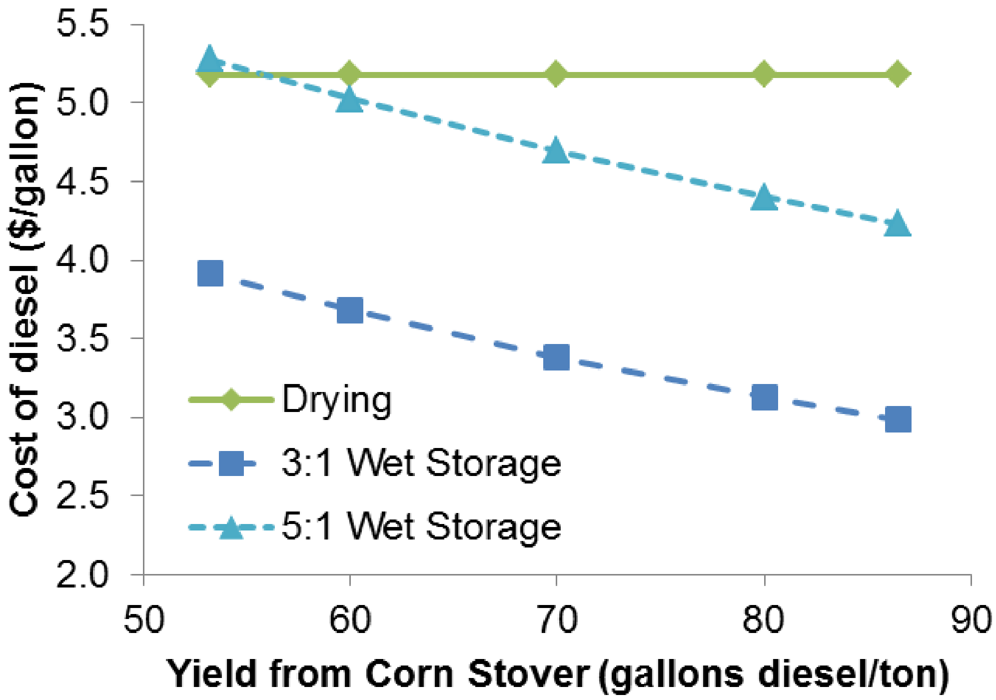
[b]Algae: $491/ton [Davis, 2016]; Corn stover 3:1: $64.05/ton; Corn stover 5:1: $65.01/ton; Upgraded Blend: ($128.40)/ton

[c]Algae: 122 gallons/ton [Jones, 2014]; Corn Stover: 70 gallons/ton

Accomplishments - Task 1, TEA

TEA comparing blending and wet storage to drying for the fraction of biomass needing preservation

- Fuel yield from algae was assumed at 122 gallons/ton biomass
- Fuel yield from corn stover was estimated at 53.2-87.5 gallons/ton biomass



Accomplishments - Task 1

Energy consumption and greenhouse gas release associated with blending and wet storage is reduced significantly compared to drying

	3:1 Summer:Winter Variation 5,000 acre pond		5:1 Summer:Winter Variation 1,000 acre pond		
	3:1 Drying	3:1 Wet Storage	5:1 Drying	5:1 Wet A[a]	5:1 Wet B[a]
Total Energy (kWh)	**49,420,000**	**4,956,000**	**28,410,000**	**2,292,000**	**2,328,000**
% of Drying Case	–	**10.0%**	–	**8.1%**	**8.2%**
GHG (kg CO_2 equiv/tonne)	993.25	40.30	993.25	41.19	41.69
Total GHG release (kg CO_2 equiv)	**11,003,280**	**2,763,713**	**6,325,473**	**1,252,734**	**1,271,014**
% of Drying Case	–	**25.1%**	–	**19.8%**	**20.1%**

*All tonnages reported on an ash-free dry weight basis

[a]5:1 Wet A case assumes winter operation of algae ponds, while the 5:1 Wet B case assumes no algae is produced during winter

[b]Data from Drying cases from Davis, 2016.