U.S. Department of Energy (DOE)
Bioenergy Technologies Office (BETO)
2017 Project Peer Review

Development of Algal Biomass Yield Improvements in an Integrated Process Phase 2

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Global Algae Innovations

Goal Statement

The goal is

to develop ***improved strains and cultivation methods*** to increase the algal biofuel intermediate yield by at least 70% and

to develop ***new drying and extraction technology*** to reduce the energy for downstream processing by at least 50%

in an ***integrated outdoor system that reduces the projected minimum selling price*** (MSP) of algae biomass by 20%

Relevance to bioenergy industry

- Productivity is crucial to economic viability and sustainability of algal biofuel
- ABY1 solved harvesting & dewatering, so drying and extraction are now largest downstream energy use
- Fully-integrated system and cost metrics lead to commercially relevant new technologies

Quad Chart Overview

Timeline

10/2016 – 3/2019

18% Complete

(jump-started at-risk based on pre-award cost approval)

Budget

	Total Planned FY 17 + ($000)
DOE Funded	**5000**
Cost Share	**1250**
TSD	63
UCSD	204
GE	70
Other	200

Barriers

- Aft-B. Sustainable Algae Production
- Aft-C. Biomass Genetics and Development
- Aft-H. Overall Integration and Scale-Up
- Aft-I. Algal Feedstock On-Farm Preprocessing

MYPP targets addressed:

- 2022 algal yield of 5000 gal/ac-yr
- 2022+ nth plant algal biofuel at $3/GGE

Partners

Strain Improvement

- Hildebrand and Mayfield labs at the University of California, San Diego

Harvesting, dewatering & extraction

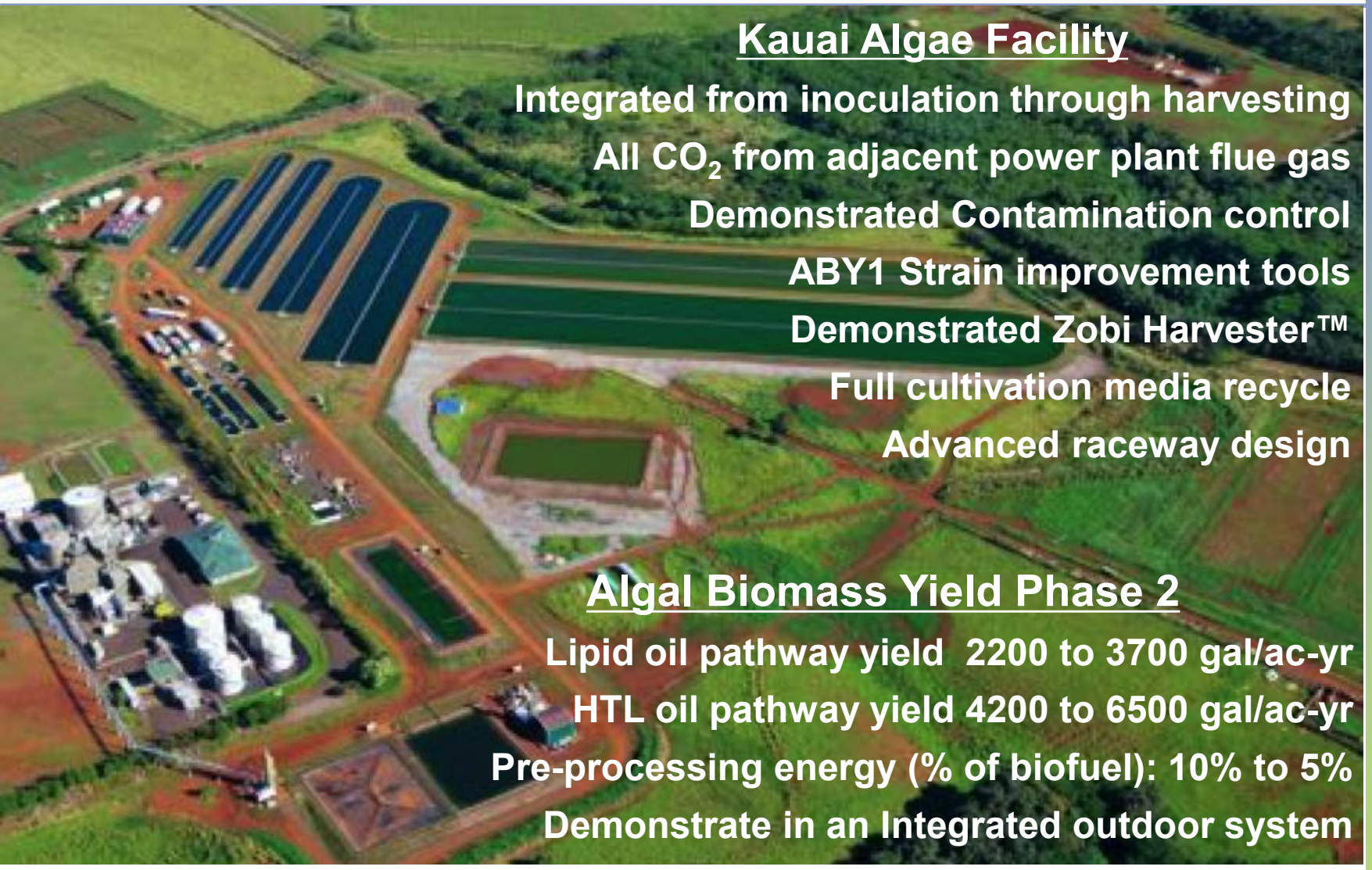
- TSD Management Associates
- General Electric
- PNNL

Techno-economic modeling

- NREL

GLOBAL ALGAE INNOVATIONS

1 - Project Overview History



Kauai Algae Facility

Integrated from inoculation through harvesting

All CO_2 from adjacent power plant flue gas

Demonstrated Contamination control

ABY1 Strain improvement tools

Demonstrated Zobi Harvester™

Full cultivation media recycle

Advanced raceway design

Algal Biomass Yield Phase 2

Lipid oil pathway yield 2200 to 3700 gal/ac-yr

HTL oil pathway yield 4200 to 6500 gal/ac-yr

Pre-processing energy (% of biofuel): 10% to 5%

Demonstrate in an Integrated outdoor system

1 - Project Overview Goals

Area	Lipid Pathway	Lipid Goals	HTL Pathway	HTL Goals
Productivity: (gal oil/acre-year)	2200	5000	4200	8000
Pre-processing: (% of the biofuel energy)	9.6%	4%	11.1%	9%
Integration: algae paste MSP ($/mt AFDW)	$597	$425	$437	$325
Integration: Protein (% protein in algae meal)	48%	40%	NA	NA
Integration: Farm energy (kwh/mt AFDW)	270	205	160	150
5. Integration: MFSP ($/GGE)	$3.33[a]	$3.00	$ 5.37[b]	$4.00

[a] Assumes $500/mt for the co-product algae meal
[b] Conversion cost from PNNL/NREL 2014 design report

2 – Approach (Management)

All technologies filtered through comprehensive cost model

- Economically viable
- Integration impacts and opportunities

$/ton

Technology development map

- Prioritize research
- Many options
- Quick advancement/early risk retirement
- Synergistic projects or opportunities

Technology	Yield	Cost
Adv. cultivation	70%	($4.70)
Fast lipid accum.	50%	($3.70)
O_2 Tolerance	25%	($0.90)
Constitutive lipid	87%	($4.30)

Frequent telecoms to discuss results and opportunities

- Rapid communication
- Synergistic projects and opportunities
- Cost and technology status/potential transparent to team

Go/No-go Metric on biofuel intermediate yield

gal/ac-yr

2 – Approach (Technical)

Biofuel Intermediate Yield

Strain Improvement

- Proven outdoor strains
- 3 labs, multiple green and diatom strains
- Non-GMO lipid & growth improvements
- Integral growth requirement

Cultivation

- Proven contamination control
- Advanced cultivation methods
- Control optimization

Preprocessing Energy

Harvesting & Dewatering

- Zobi Harvester™

Extraction & Drying

- Combined drying & extraction
- New separation unit operations
- Optimization of collets with commercial extractor
- MVR and waste heat dryers
- Improved HTL conversion

Top Challenges

- Complexity of abiotic and biotic variation
- Translating lab to large-scale outdoor cultivation
- Inability to achieve early risk retirement for strain optimization
- Producing sufficient material for downstream processing work

Milestone & Go/no-go approach

- **Set high, challenging technical milestones/objectives for specific strain and cultivation improvements (home runs)**
  - 25-50% success rate will achieve integration milestones
  - Ensures there are enough planned improvements to achieve goals
  - Encourages early risk retirement and moving resources into the most successful approaches rather than pouring into a single area that is lagging and may never work

- **Go/no-go is on yield, which is integration milestone, not an individual improvement milestone (score, not number of hits)**
  - 3100 gal/ac-yr for lipid oil pathway or
  - 5700 gal/ac-yr for the hydrothermal liquefaction pathway

Technical Progress - Yield Improvement

Strain improvements

- Achieved 75% higher growth rate with a new green strain relative to the best green strain from ABY1 in standard raceway
- Initial screening of nine diatom strains derived from GAI-229,

Cultivation improvements

- Developed for conceptual designs for simulating the large-scale advanced cultivation methods in small raceways (using 3-D printer for rapid prototyping and testing)
- Started media and control optimization

Technical Progress - Processing & Integration

Downstream processing

- Developed, validated, and applied for patents on an important Zobi Harvester™ system improvement
- Completed extensive testing of combined drying & extraction
  - Reduced time for separation from to 1 hr from 24 hrs
  - Found major issue, so eliminated this approach
- Alternative approach with new unit operations for drying/extraction
  - Successfully demonstrated two novel membrane processes
  - Testing in progress on two other new technologies

Integration

- Improved fluid mechanics and thermal modeling of cultivation
- Updating for TEA for new drying and extraction unit operations

4 – Relevance

Higher yield, lower energy use, lower cost algae biofuel intermediate production in a large-scale integrated outdoor facility

Directly Supports the BETO mission to "Develop and demonstrate transformative and revolutionary bioenergy technologies for a sustainable nation."

Goal aligned with three major Algal R&D targets:

- BETO MYPP 2022 yield target of 5000 ga/ac-yr
- BETO MYPP 2022-2030 goal of algal biofuel at $3/GGE

Technology advance objectives

- Advanced cultivation and strains: 100% higher biofuel intermediate productivity
- Lower energy, lower cost extraction and drying

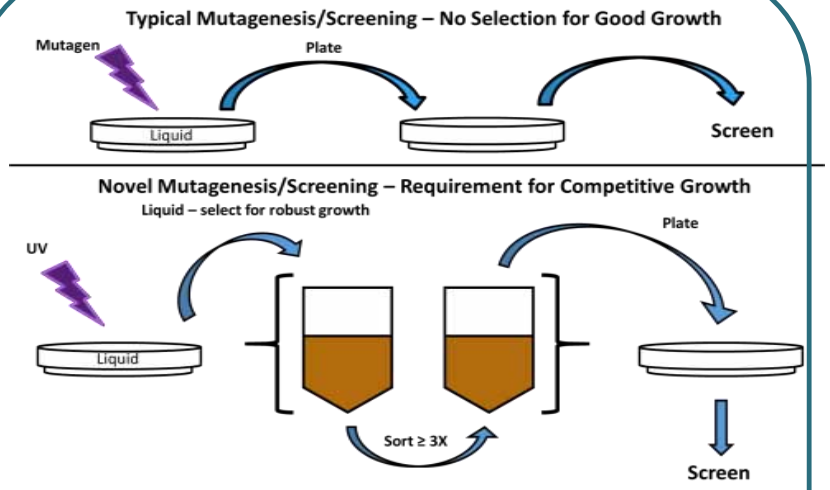
Tech Transfer/marketability

- Incorporate advances into integrated biorefinery
- Partnering/business structure for rapid, parallel implementation of algal commodity production
- Building IP portfolio that covers the entire process with dozens of innovations
- Building cultivation and processing database

5 – Future Work

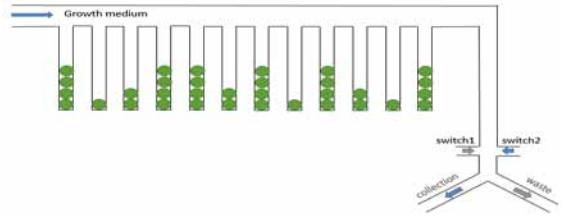
- **Strain improvement**
- **Cultivation improvement**
- **Pre-processing Energy**
  - Harvesting optimization
  - New extraction process
  - Higher conversion in hydrothermal liquefaction

Strain improvement



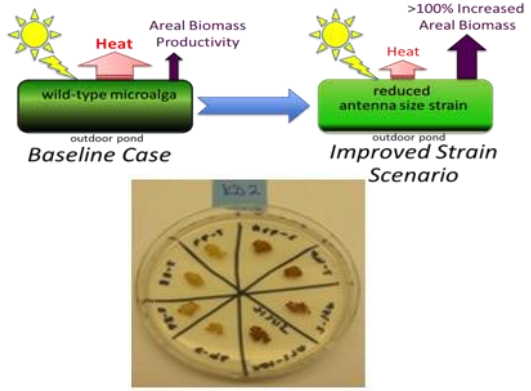
Novel mutagenesis/high throughput fluorescent activated cell sorting

- 3,600x's more efficient in viable mutants



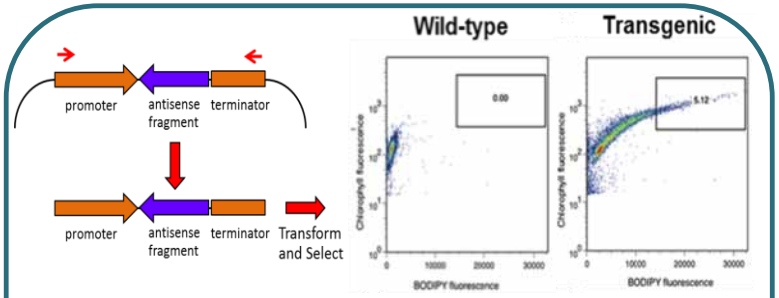
Microfluidics for individual cell analyses

- Sort for fastest growing cell lines



Reduced photosystem antenna size

- New strain lines started
- Reduced pigmentation lines on left



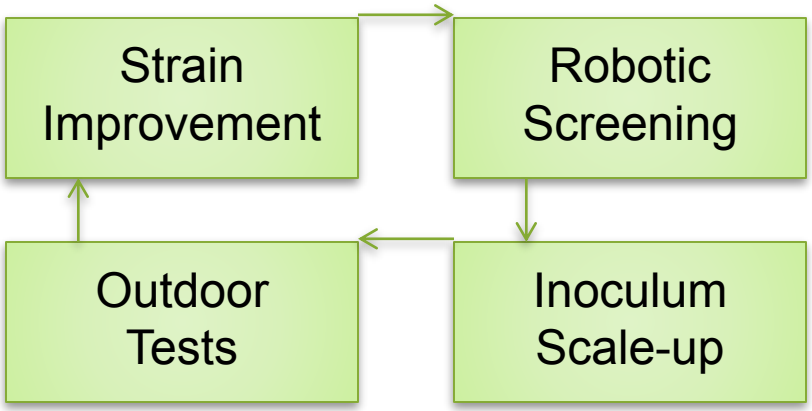
Native sequence genetic manipulation

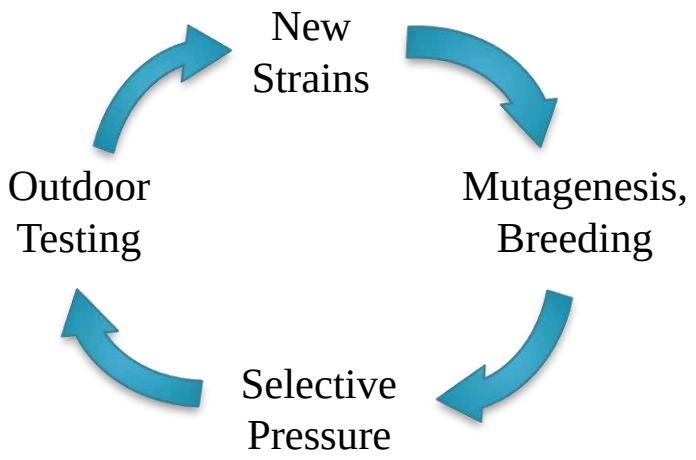
- Avoids GMO classification
- Demonstrated antisense knockdown of CGI-58 lipase improved TAG content
- Can target light-harvesting pigments

Strain Improvement

Rapid feedback

- New strains sets every 6 weeks





Directed Evolution

- Specialty PBRs for selective pressure
- High oxygen, high light, shallow, high concentration, temperature control

Cultivation Improvements

Move to prior cultivation advances to smaller scale

Advanced cultivation

- New set of advanced cultivation methods
- Control & media optimization for both growth & lipid formation
- Bacterial control strategies
- Cultivation system advances to amplify lipid trigger

Tests utilize best strains available and comparison to control methods

Pre-processing Energy

Fully integrated with cultivation, daily harvests

- Working with freshly harvested samples is essential
- Immediate identification of issues with new strains or cultivation
- Experience the diversity of culture conditions throughout year

Harvesting

- Finish longer term continuous operations
- Parametric studies to improve to enable further optimization

Lipid Extraction - Focus on early risk retirement

- Prioritize and test alternatives for each unit operation to attain a new low energy, low cost approach
- Develop the approach into robust process

Hydrothermal liquefaction

- Optimize cultivation/strain conditions for higher HTL yield without reducing the biomass productivity

Summary

1. **Overview:** Addresses key BETO targets - yield, energy use, cost
2. **Approach:** Comprehensive cost model and development map
   Early risk retirement with many technology options
   Rapid feedback to accelerate development
   Fully integrated outdoor operations
3. **Technical Accomplishments/Progress/Results:**
   - Cultivation: New strain with 75% higher growth rate in outdoor cultivation
   - Processing: Stopped 1 approach, demonstrated 2 new technologies
4. **Relevance**
   - Targeting MYPP 2022-2030 yield & cost goals
5. **Future Work**
   - Achieve many strain and cultivation improvements
   - Develop new extraction and drying technology
   - Improve HTL conversion

Additional Slides