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 I

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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 40% and

to develop ***new harvest and dewatering technology*** to reduce the energy for downstream processing by at least 88%

in an ***integrated outdoor system that reduces the projected minimum selling price*** (MSP) of algae biomass by 58%

The project outcome: Exceeded the goal and technology targets

Technologies demonstrated in an integrated large-scale facility that operated with power plant CO_2 and full media recycle

- A breakthrough cultivation method increased the growth phase productivity by 80% with 1/3 of the original energy input
- A breakthrough harvesting and dewatering technology that is commercially available now

Quad Chart Overview

Timeline

Validation: **10/13 - 10/14**
Project work: **11/14 - 6/16**
% complete: **99%**

Budget

	FY 12 – FY 14 Costs ($000)	FY 15 Costs ($000)	FY 16 Costs ($000)	Total Planned FY 17 + ($000)
DOE Funded	**159**	**2838**	**1997**	**3**
Cost Share	**40**	**709**	**499**	**1**
TSD	9	45	49	-
UCSD	-	22	20	-
Evodos	18	415	90	-
GE	-	125	93	-
Kuenhle	-	17	8	-
Other	2	49	31	

Barriers

- Aft-B. Sustainable Algae Production
- Aft-D. Sustainable Harvesting
- Aft-H. Overall Integration and Scale-Up

MYPP targets addressed:

- ✓2018 - algae yield of 2500 gal/ac-yr
- ✓2020 - algae yield of 3700 gal/ac-yr
- ✓2022 – 407 kWh/ton energy for farm
- ✓2022 - $494/ton algae for HTL pathway
- ✓2022 – $4.72/GGE for lipid pathway

Partners

Strain Improvement

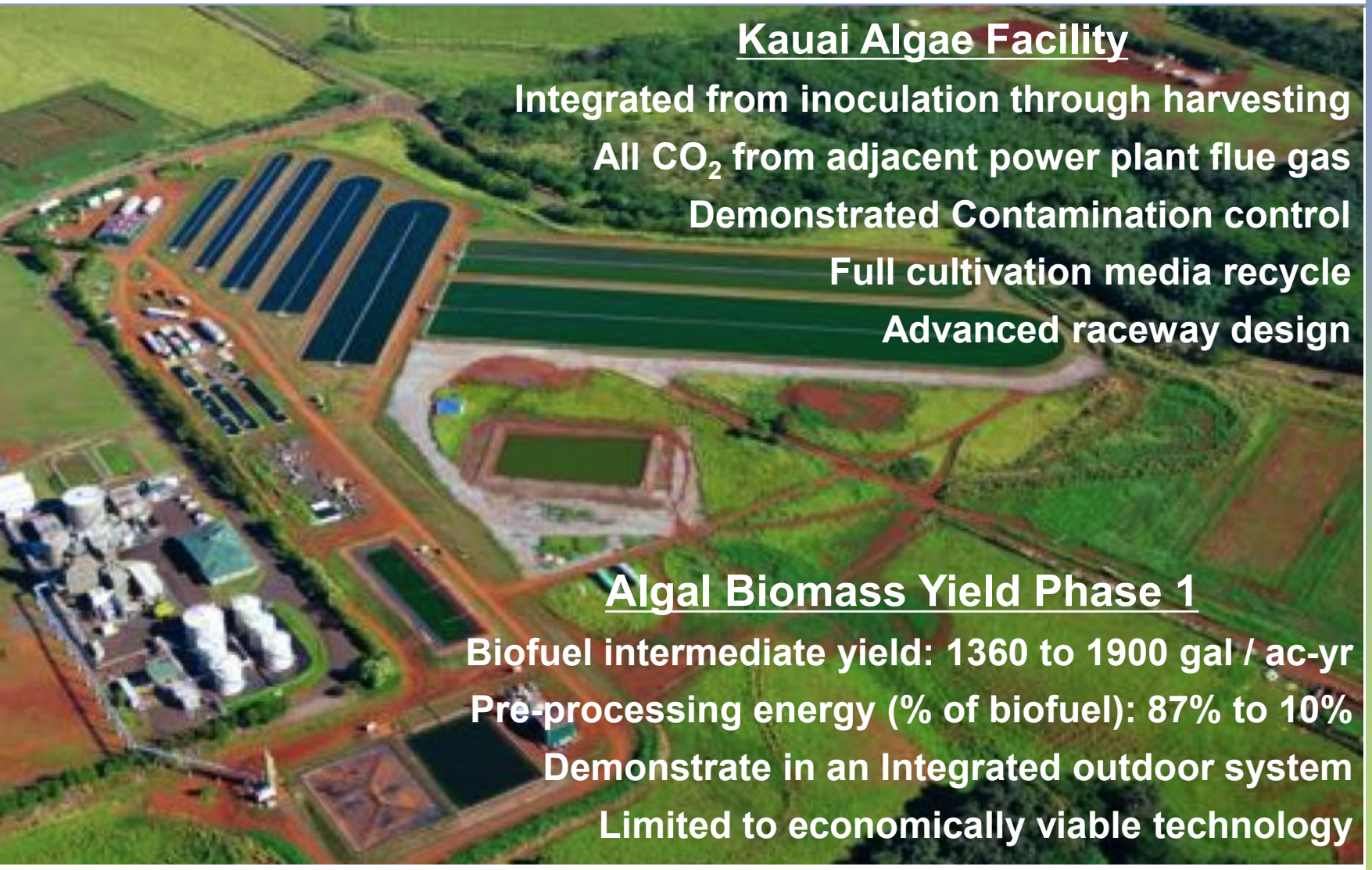
- University of California, San Diego
- Kuehnle AgroSystems
- Hamilton Robotics

Harvesting, dewatering & extraction

- TSD Management Associates
- General Electric, Evodos
- Texas A&M, Crown Iron works
- PNNL

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

Full cultivation media recycle

Advanced raceway design

Algal Biomass Yield Phase 1

Biofuel intermediate yield: 1360 to 1900 gal / ac-yr

Pre-processing energy (% of biofuel): 87% to 10%

Demonstrate in an Integrated outdoor system

Limited to economically viable technology

1 - Project Overview Summary

Area	Baseline	Phase 1 Goals	Lipid Pathway	HTL Pathway	MYPP 2022
Productivity: (gal oil/acre-year)	1360	1900	**2200**	**4200**	5000
Pre-processing: (% of the biofuel energy)	87%	10%	**9.6%**	**11.1%**	**10%**
Integration: algae paste MSP ($/mt AFDW)	$ 1536	$ 900	**$ 597**	**$ 437**	**$ 494**
Integration: Protein (% protein in algae meal)	15%	40%	**48%**	NA	NA
Integration: Farm energy (kwh/mt AFDW)	860[a,b]	NA	**270**	**160**	**407**
5. Integration: MFSP ($/GGE)	$ 17.69[a]	NA	**$ 3.33[c]**	**$ 5.37[d]**	**L: $ 5.90[a]** H: $ 4.72[a]

[a] From 2016 MYPP
[b] From 2016 MYPP, our model projected 1810
[c] Assumes $500/mt for the co-product algae meal
[d] 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

2 – Approach (Technical)

Biofuel Intermediate Yield

Strain Improvement

- Proven outdoor strains
- 2 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

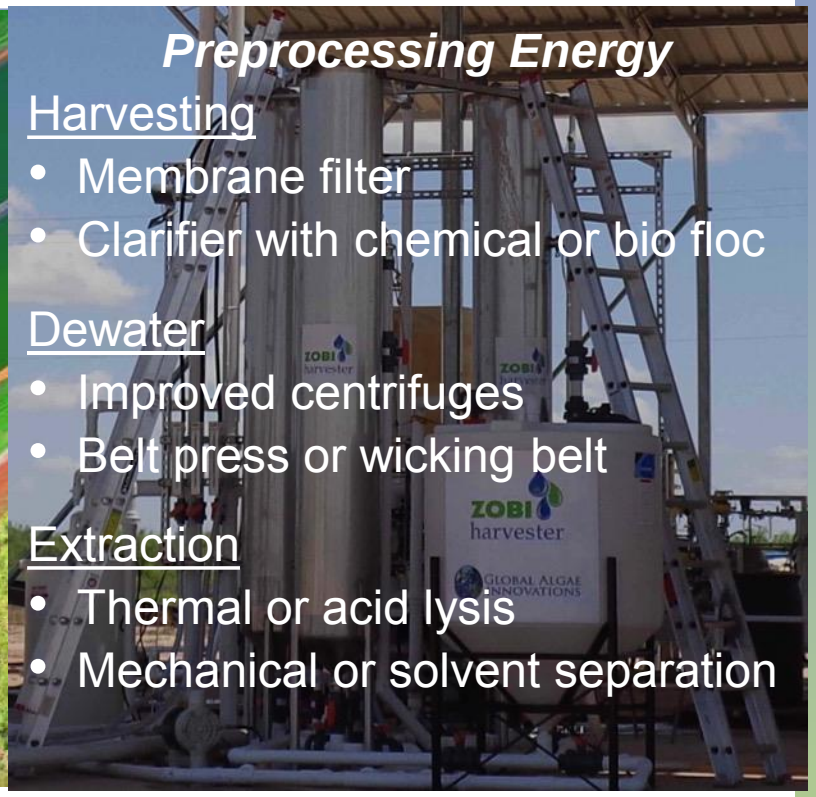
- Membrane filter
- Clarifier with chemical or bio floc

Dewater

- Improved centrifuges
- Belt press or wicking belt

Extraction

- Thermal or acid lysis
- Mechanical or solvent separation

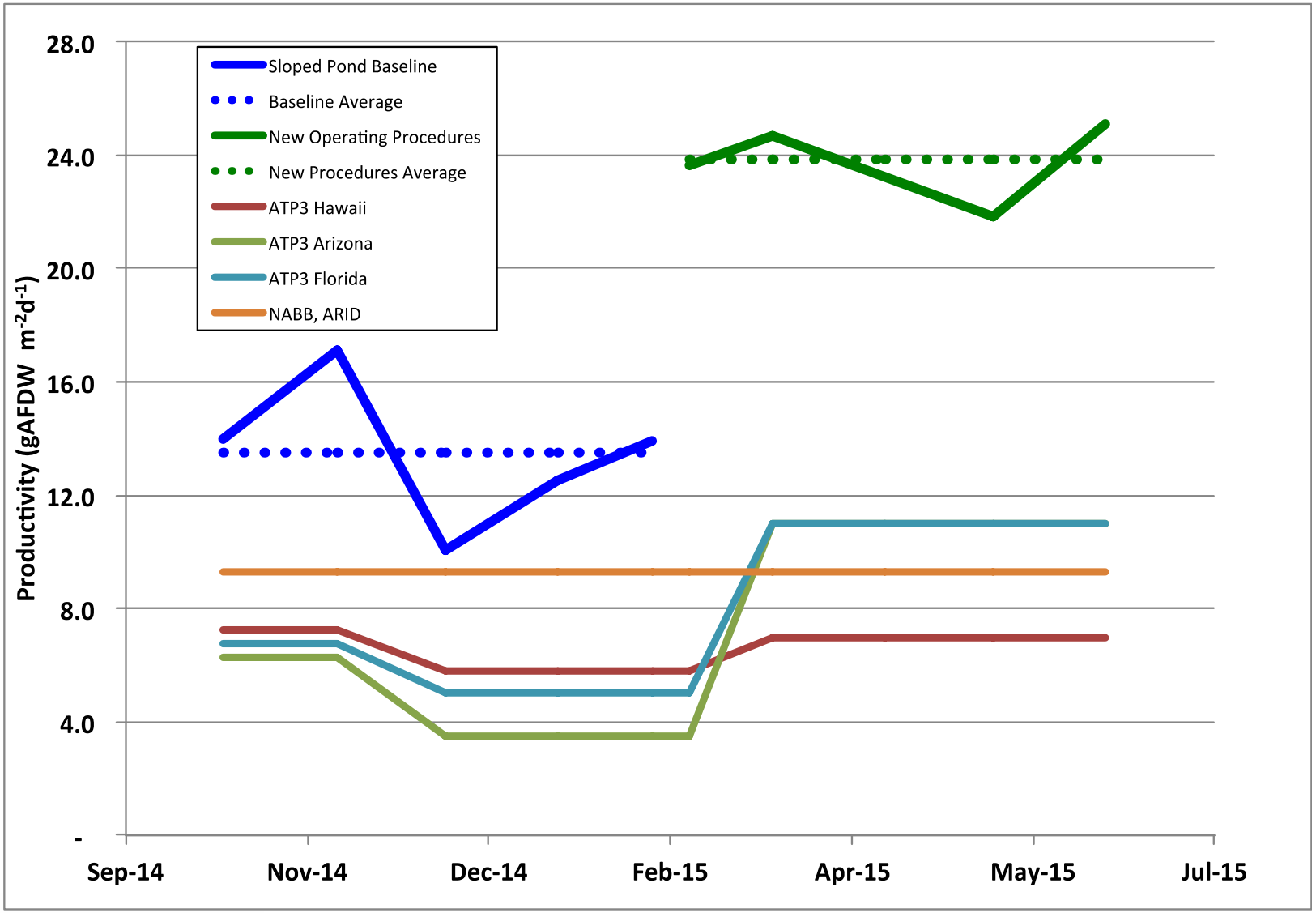


Top Challenges

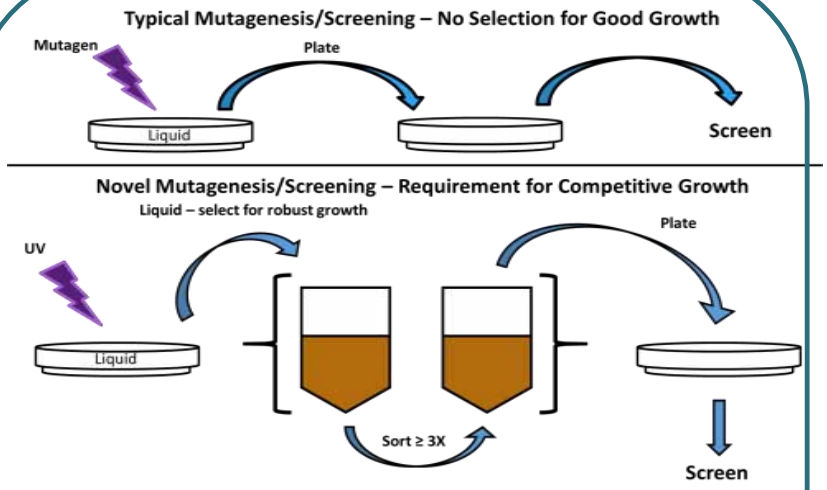
- Complexity of abiotic and biotic variation
- Translating lab to large-scale outdoor cultivation
- Inability to achieve early risk retirement for strain optimization
- Producing sufficient material for downstream processing work

Technical Accomplishments, Progress and Results

Advanced cultivation methods



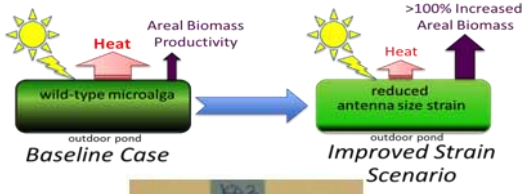
Strain improvement - Hildebrand lab



Novel mutagenesis/high throughput fluorescent activated cell sorting:

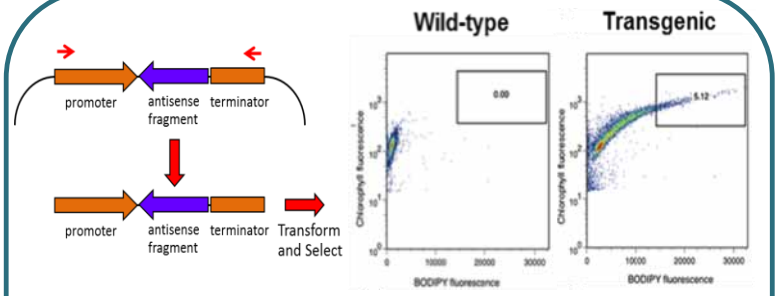
- 3,600x's more efficient in viable mutants[1]
- Applied to GAI-229, *Nitzschia amphibia*
- Nine new strain lines generated with improved lipid accumulation

[1]Manadhar-Shrestha and Hildebrand (2013) J. Appl. Phycology. DOI 10.1007/s10811-013-0021-8



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

Global Algae Innovations

Zobi™ provides a solution to harvesting and dewatering issues

Options Tested by Global Algae Innovations	High efficiency	Low Energy	Low Cost	No Flocculent	Universal	High Conc.	Scalable
Centrifuge	NO	NO	NO	YES	YES	YES	NO
Dissolved air floatation	NO	NO	YES	NO	NO	NO	YES
Clarifier	NO	YES	YES	NO	NO	NO	YES
Wicking belt	NO	YES	NO	NO	NO	YES	NO
Belt press	NO	YES	YES	NO	NO	YES	YES
Cross-flow filtration	YES	NO	NO	YES	YES	NO	NO
VSEP membrane	YES	NO	NO	YES	YES	YES	NO
Other novel membrane	YES	YES	NO	YES	YES	YES	NO
Zobi Harvester™	YES	YES	YES	YES	YES	YES	YES

Zobi Harvester™ - 100% harvest efficiency

5 m^3/hr system

Crystal Clear Permeate

- Less than 0.1 NTU
- No algae, bacteria or predators

Permeate **Feed** **Retentate**

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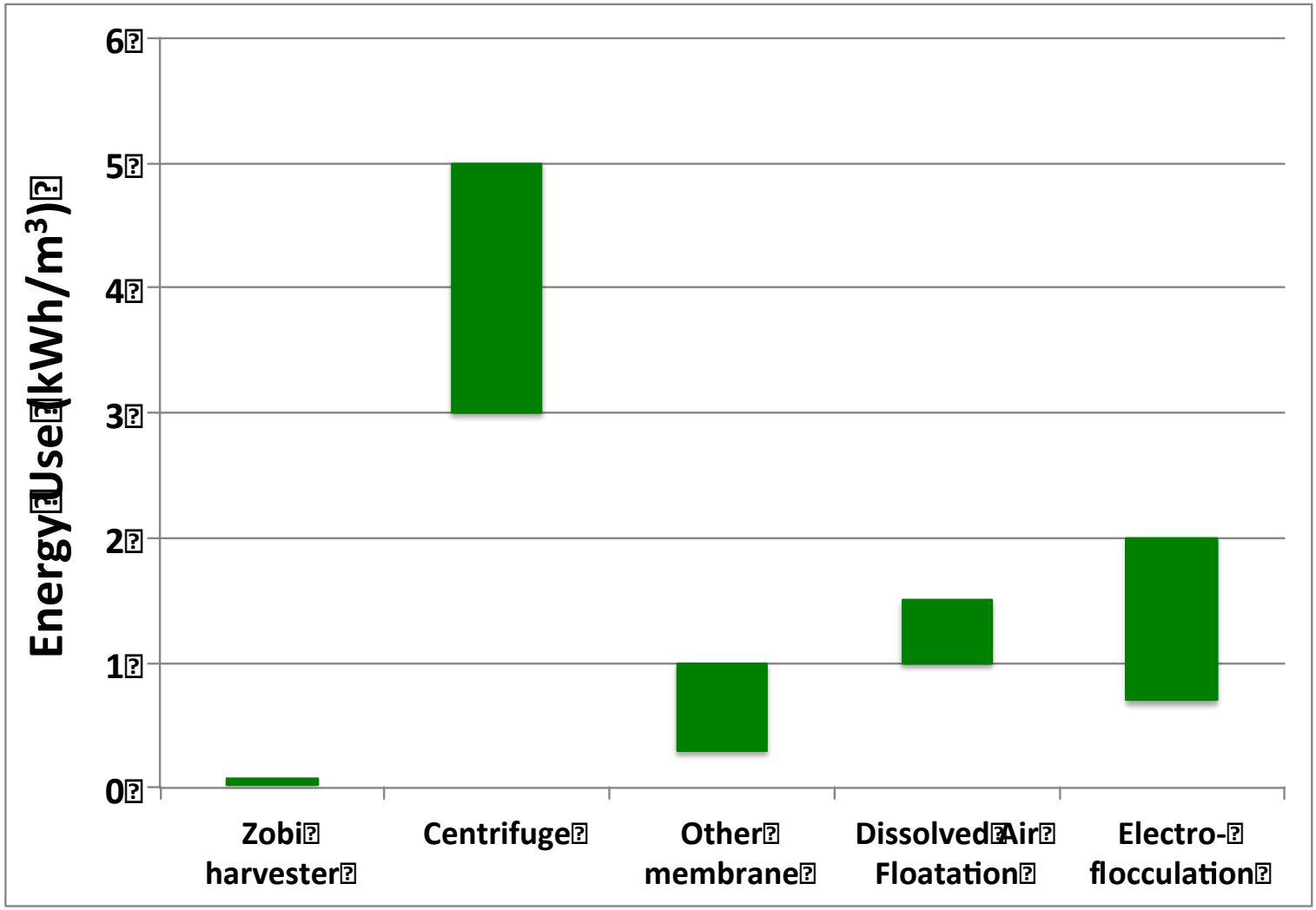
Zobi Harvester™ - 15 to 20% algal slurry

Eliminates need for secondary dewatering

Zobi Harvester™ - very low energy use



Global Algae Innovations

Zobi Harvester™ - universally applicable

- Many green algae
- Many diatoms
- Six cyanobacteria
- One red algae

No flocculent

20 m^3/hr system

Collets enable use of standard Crown Iron Works solvent extractors

Collets

Crown Iron Works
Model IV immersion extractor

Crown utilized our pilot-scale data to develop a quote and utility requirements for commercial scale facilities

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."

By achieving three major Algal R&D targets:

- Achieved BETO MYPP 2020 yield target
- Achieved BETO MYPP 2022 energy use target
- Achieved BETO MYPP 2022 algal biomass and fuel cost targets

State of the art advancements

- Zobi Harvester™: 1/10th to 1/150th energy use, 100% harvest, 15-20% solids
- Advanced cultivation: 80% higher productivity than prior sloped raceways

Tech Transfer/marketability

- Zobi Harvester™ commercially available and in commercial algae operations
- Advanced cultivation
  - included on 8 teams for ABY2 and PEAK FOAs
  - incorporated in a recently awarded integrated biorefinery scale-up project
  - being tested for high value product applications.

5 – Future Work

- **Close out the project**
- **Remaining budget is sufficient**

Summary

1. **Overview:** Addressed key BETO targets - yield, energy use, cost

2. **Approach:** Comprehensive cost model
   Early risk retirement with multiple technology options
   Fully integrated large-scale outdoor operations

3. **Technical Accomplishments/Progress/Results:**

- Harvesting: more than order of magnitude improvement
- Cultivation: advanced methods – nearly doubled productivity
- Strain: cutting edge tools developed for vital improvements
- Exceeded yield, energy use & cost goals as well as MYPP future targets

4. **Relevance**

- Harvesting technology is commercially available product and in use
- Cultivation methods incorporated into a new IBR scale-up project

and made available to multiple R&D teams bidding on BETO FOA's

Additional Slides

Patents & Commercialization

Patent Area	# of Patents	Anticipated Divisional patents	Application dates
Zobi harvester	3 US and 1 PCT	20 US patents	5/9/16 to 9/22/16
Advanced Cultivation	4 US provisional	6 US patents	5/9/16

Zobi Harvester™ in production for commercial sale and in use

In discussions on use of cultivation technology for high value products

Integrated biorefinery project to scale-up to 160 acres for biofuels and poly-ols

Zobi™ harvester incorporates GE's scalable membrane technology

- Over 6 billion gallons per day installed capacity
- Plant sizes up to 228 million gallons per day