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

Production of Biocrude in an Advanced Photobioreactor-Based Biorefinery

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Algae Session

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Goal Statement: Production of Biocrude in an Advanced Photobioreactor-Based Biorefinery

This project will demonstrate the following technology advancements:

- **Biofuel Intermediate (BFI, Biocrude) productivity of >4,000 gal-BFI/acre-yr in a PBR-based production system**
- **Biomass harvesting, dewatering, and HTL integration that has an energy expenditure <10% of the energy content in BFI and an overall >60% carbon footprint reduction**
- **Comprehensive economic analysis that includes comparison of PBR to open pond systems and considers co-product generation as an enabling approach to market entry**

Closely aligned with three ABY2 Priority Areas:

1. Strain/productivity improvement
2. Improvements in pre-processing technologies (harvesting, dewatering, and extraction and/or equivalent processes)
3. Integration of cultivation with pre-processing technologies

Quad Chart Overview

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Timeline

- Project Start: 4Q/2016
- Project Completion: 1Q/2020
- Percent Complete: 5%

Barriers

- BFI Productivity and Quality
- Overall economics, including co-product scenario
- Overall energy efficiency of bio-refinery

Budget

	Total Costs FY 16–FY 20	FY 16 Costs	FY 17 Costs	Total Planned Funding (FY 16-Project End Date)
DOE Funded	$5.0M	$0.243M	$1.626M	$3.131M
Project Cost Share (Comp.)*	$1.25M	$0.058M	$0.411M	$0.781M

Partners

- **DOE funded:**
- Algenol 71%
- NREL 15% (P. Pienkos, J. Yu)
- GaTech 10% (M. Realff, V. Thomas)
- ASU 4% (J. McGowen)

- **Cost share:**
- Algenol 50%
- RIL 50% (M. Phadke, R. Bhujade)

1 – Project Overview: Headquarters and Commercial Development Campus, Fort Myers, FL

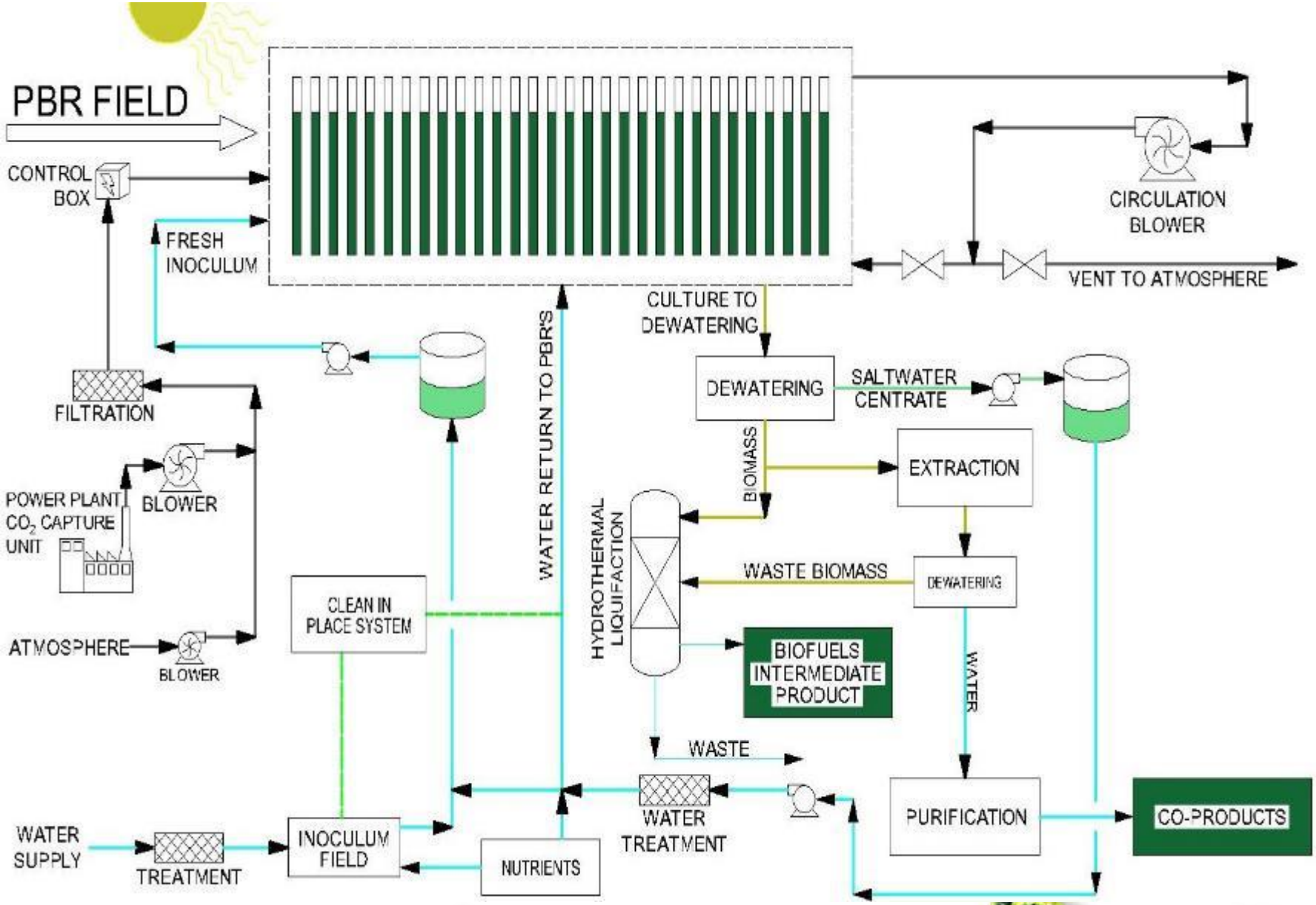
Additional Facilities

- Biological Research – Berlin, Germany
- Photobioreactor Manufacturing – Lehigh Acres, Florida

1 – Project Overview: Background

- *Algenol has built and operated a 2 acre biorefinery for production of ethanol from cyanobacteria cultured in proprietary photobioreactors designed and manufactured by Algenol. (2011-2016, DOE-funded IBR)*
- *Background Technology relevant to current project*
  - *Large, diverse, proprietary strain collection (Algenol)*
  - *Expertise in the genetic modification of cyanobacteria for biomass production and co-product production (Algenol and NREL)*
  - *Extensive experience with outdoor cyanobacteria cultivation and translating laboratory results to outdoor environment (Algenol and RIL)*
  - *Validated, multi-variable productivity models for PBR arrays or ponds at any location where light and temperature data are available (Algenol)*
  - *Advanced, diverse separation technologies (Algenol, RIL, GaTech)*
  - *CO_2 Management and IBR integration systems (Algenol/Gatech)*
  - *Biomass conversion via HTL (RIL, NREL, PNNL, Algenol)*
  - *Scale-up experience to reduce uncertainty in both larger scale performance expectations and cost projections for techno-economic analysis (TEA) and life cycle analysis (LCA), including peer reviewed publications (Algenol, RIL, GaTech)*
  - *PBR manufacturing facility and design expertise for PBR optimization for biomass production (Algenol)*

1 – Project Overview: Flow Diagram for BFI Production with Co-product Option



2 – Approach (Management)

- *The Project Management Plan (PMP) will be modeled after the PMP successfully used to build and operate the Integrated Bio-Refinery*
- *The Project Management Team*
  - *Led by co-PIs (Drs. Chance and Roessler)*
  - *One senior member from each organization (Algenol, RIL, NREL, GaTech)*
  - *Monthly teleconferences and semi-annual face-to-face meetings to review progress*
- *Management process*
  - *Project teams built around all major tasks as listed in Technical Volume*
  - *Stage gate process for go/no-go decisions for each budget period*
  - *Gatekeepers will be senior representatives from each organization (led by Ed Legere, CEO of Algenol and business contact for this project)*
  - *Proactive risk management is a key part of the PMP with a risk management plan (RMP) developed for all major deliverables and following the guidance provided in DOE Order 413.3.*

2 – Approach (Technical)

Task	Expected Outcomes	Responsible Parties
1.0 – DOE Project validation	A go/no go decision for Project commencement	DOE/All Team Members
Objective 1 – Improve biofuel intermediate (BFI) productivity		
2.0 – Strain development to improve productivity and processing	Strains improved for productivity, downstream processing and higher HTL-based BFI yield and quality	Algenol/NREL
3.0 – Improved productivity through operational and engineering approaches	Stable outdoor operation with improved yield and product quality and without major system upsets	Algenol
4.0 – Intermediate scale process validation	30% greater biomass yield compared to base strain and current PBR system	Algenol/GaTech/ASU
Objective 2 – Pilot and improve efficiency of unit operations		
5.0 – Iterative strain and process optimization	Advance strains based on field trial feedback, combine best traits into high performance strain	Algenol/NREL
6.0 – Operation and biomass harvest at scale	Production yield potential in PBR systems and open ponds; harvest biomass for downstream processing studies	Algenol/GaTech/RIL
7.0 – Downstream processing optimization	Unit operation specifications, unit heat and material balances, and BFI quantity and quality	Algenol/RIL/GaTech
Objective 3 – Integrated algal biofuels operation / comprehensive TEA/LCA		
8.0 – Integrated operation and commercial assessment	Integrated system demonstrated at scale. Targeted values attained for TEA and LCA for algal BFI and co-products.	All Team Members

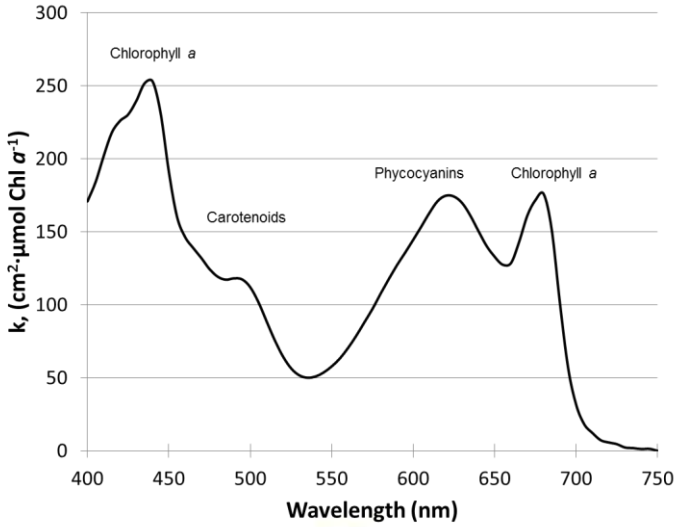
2 – Approach (Technical – Productivity)

Improved BFI productivity

- Improved biomass productivity
  - Strain development *via* targeted and non-targeted approaches to improve photosynthetic efficiency (Algenol)
  - PBR optimization to enhance mixing and light utilization (Algenol)
  - Engineering systems - semi-continuous operation (Algenol)
  - Cultivation optimization (Algenol)
- Improved HTL yield and quality
  - Strain development to optimize biochemical composition (Algenol, NREL)
  - Engineering systems (RIL, NREL, Algenol)

Co-Product

- Productivity and content important
- Efficiency of extraction process
- Disposition of residue



2-LvPBR Indoor Turbidostat AB1 Cultivation

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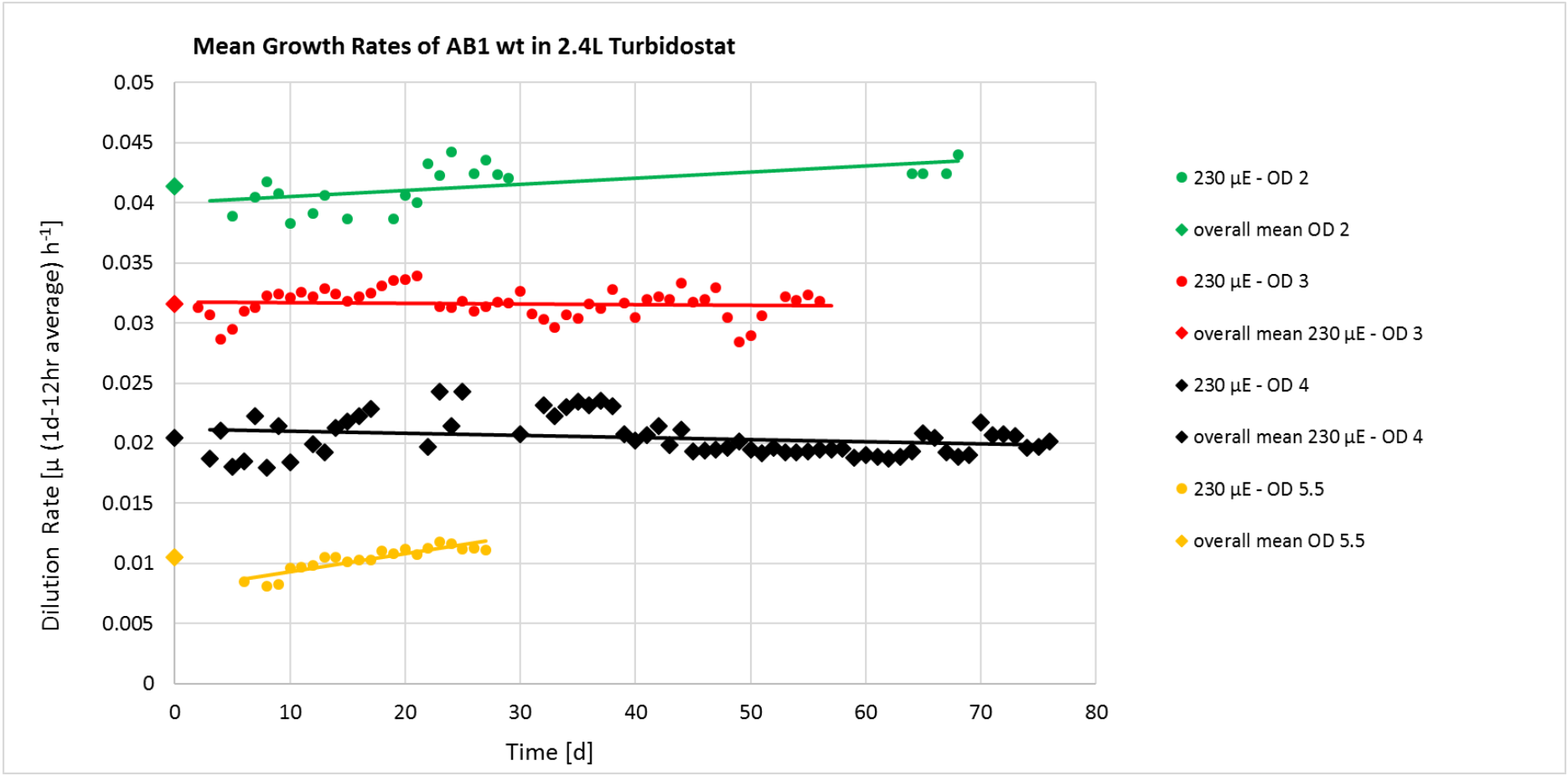
- sOD = 2, growth rate 1 sOD per day (@ 230µE/m^2-s)
- sOD = 3, growth rate 1.15 sOD per day (@ 230µE/m^2-s)
- sOD = 4, growth rate 1 sOD per day (@ 230µE/m^2-s)
- sOD =5.5, growth rate 0.7 sOD per day (@230 µE/m^2-s)



Annualized Productivities Derived from Laboratory Turbidostat Experiments on AB1

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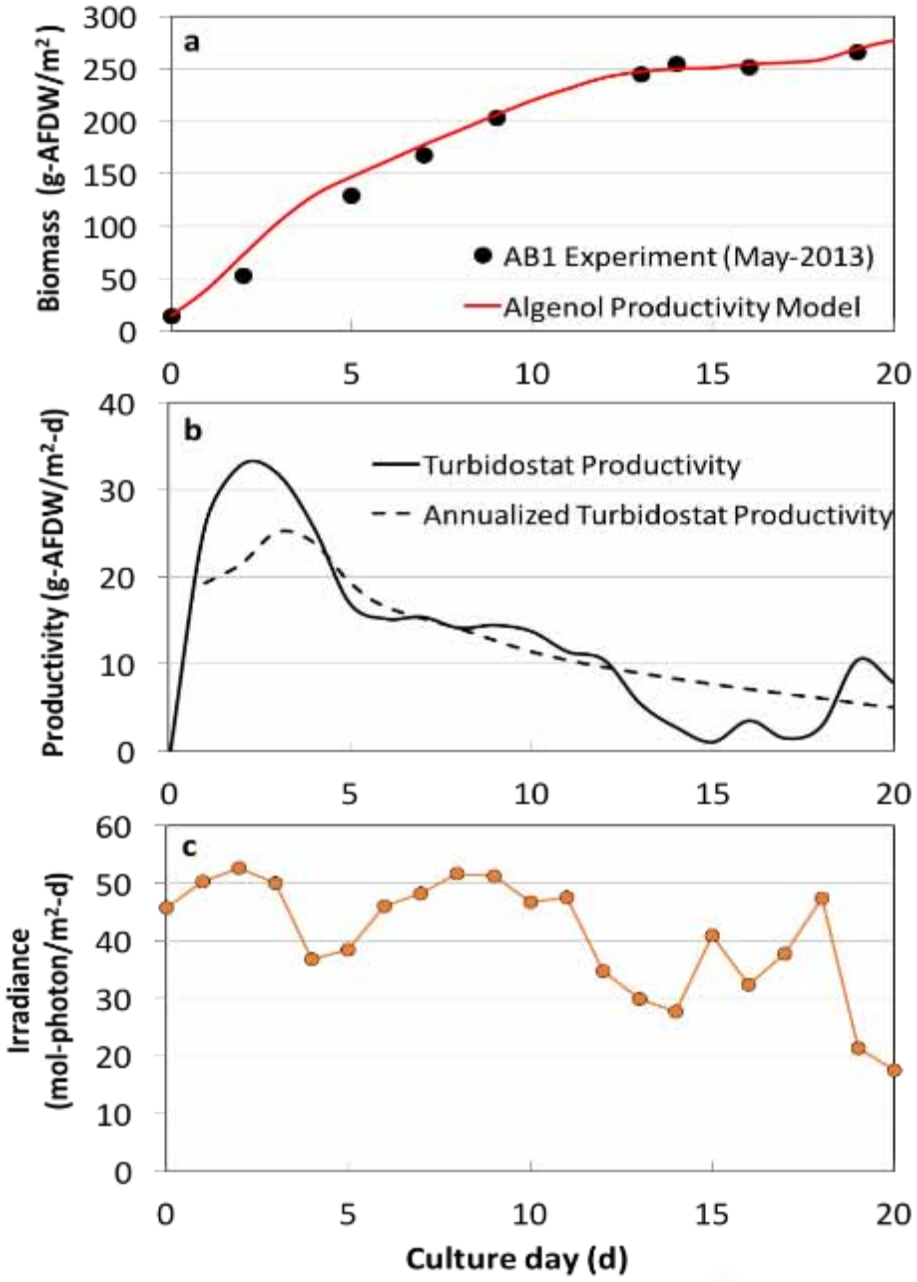
Indoor Experiment sOD@indoor_light[1]	Average Indoor Dilution rate (12-hr average)	Indoor growth rate[2]	Predicted Outdoor HS=4:1 (95 L/m^2) [3]	Predicted Outdoor HS =2.4:1 (0.85% of HS=4 productivity)
μE/m^2-s	%/hr	gAFDW/L-d	gAFDW/L-d	gAFDW/L-d
2.0 @ 230 μE/m^2-s	0.040 (70 days)	0.24	22.8	19.4
3.0 @ 230 μE/m^2-s	0.032 (55 days)	0.29	27.4	23.3
4.0 @ 230 μE/m^2-s	0.020 (75 days)	0.24	22.8	19.4
5.5 @ 230 μE/m^2-s	0.011 (30 days)	0.18	17.1	14.5

[1] 230 μE/m^2-s is the average annual irradiance over the PBR surface for a height to spacing ratio (HS) of 4.0 for Florida climate conditions (NASA data base); for HS = 2.4 the average irradiance is 350 μE/m^2-s. Stated reduction for HS=2.4:1 is an estimate for biomass production.

[2] Growth rate (gAFDW/L-d) = 12 hr × Dilution rate × sOD@Turbidostat × 0.25 gAFDW/L; (Algenol History WT AB1 dataset, 1 sOD = 0.25 g AFDW/L, 0.26 gDW/L per sOD, ~ 5% ash content).

[3] Outdoor Areal Productivity (gAFDW/m^2-d) = Growth rate (gAFDW/L-d) × PBR volume (L/m^2); about 15% uncertainty in outdoor productivity projection from indoor experiment, because of light acclimation time scale, DOC release, etc.

2 – Approach Technical: Semi-Continuous Operation



AB1 outdoor experiment at 15 L scale in May 2013, Fort Myers, Florida:

a Cumulative ash-free biomass (average of two 15 L PBRs) with model fit using Algenol Productivity Model

b Predicted productivity (observed and annualized results) for operation in turbidostat mode with turbidostat setting chosen for indicated culture day

c Average daily irradiance for the experiment

Note: Peak annualized productivity in middle panel would correspond to 3000 gal-BFI/acre-yr assuming 35% HTL yield and 90% up-time for the biorefinery.

2 – Approach (Technical – Energy Efficiency)

Energy efficient operations and carbon footprint reduction

- Improved biomass harvesting
  - Identification or development of low viscosity strains (Algenol)
  - Process optimization (Algenol, GaTech)
- Improved dewatering technology
  - Identification or development of low viscosity strains (Algenol)
  - Membrane systems and combinations with centrifuge (Algenol)
- Reduced energy consumption in plant operations
  - Piping network optimization for gas and liquid transport (Algenol, RIL)
  - HTL optimization (RIL, Algenol)
- CO_2 utilization
  - Optimize sourcing and energy generation systems (Algenol, RIL, GaTech)
  - Optimize utilization efficiency (Algenol)

2 – Approach (Technical – Economics)

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Limitations and opportunities for economic development

- Develop TEA model
  - Modify existing TEA model for ethanol production to biocrude production (Algenol, RIL, GaTech)
  - Extend model to include co-product scenario (Algenol, GaTech)
  - Examine and incorporate carbon footprint reduction incentives (Algenol)
- Compare economics for PBR-based system with open-pond system
  - Conduct open-pond experiments with Algenol strains at ATP^3 test bed at ASU and potentially at RIL facilities in India (Algenol, ASU, RIL)
  - Continue working with DOE to establish cost comparisons for PBR vs open pond systems (Algenol)
- Develop economic model for co-product strategy
  - Develop production system for co-product production combined with conversion of residual biomass to biocrude (Algenol, RIL)
  - Adapt TEA and LCA models to assess co-product system and scaling limitations (Algenol, GaTech)

3 – Technical Accomplishments/Progress/Results

- This is a new project (started in 4Q2016) and does not have technical accomplishments/progress/results update criteria.

4 – Relevance

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Project Goals

- Biofuel Intermediate (BFI, Biocrude) productivity of >4,000 gal-BFI/acre-yr in a PBR-based process
- Biomass harvesting, dewatering, and HTL integration that has an energy expenditure <10% of the energy content in BFI and an overall >60% carbon footprint reduction
- Comprehensive economic analysis that includes comparison of PBR to open pond systems and considers co-product generation as market entry strategy

Importance to bioenergy industry

- Establishment of biocrude production potential in PBR based biorefinery with all aspects of the value proposition: production levels, economics, carbon footprint, and application scope
- Provide a market entry strategy based on a high-value co-product, that can yield short term profits while demonstrating long term operability at reasonable scale, thus reducing the investment risk/economic uncertainty for biofuel facilities
- Provide a detailed, experimentally-based comparison of PBR and open-pond systems for biocrude production

4 – Relevance

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Relevance to BETO goals

- Provides a comprehensive assessment of a pathway to a product that is a drop-in to existing refinery infrastructure
- Provides a fossil fuel replacement with greatly reduced carbon footprint
- Provides a market entry strategy that can reduce the risk and uncertainty associated with biofuel development
- Provides a promising opportunity for a high-value bioproduct, with co-production of a biofuel, thus enhancing biorefinery economics

Relevance to ABY2 Goals

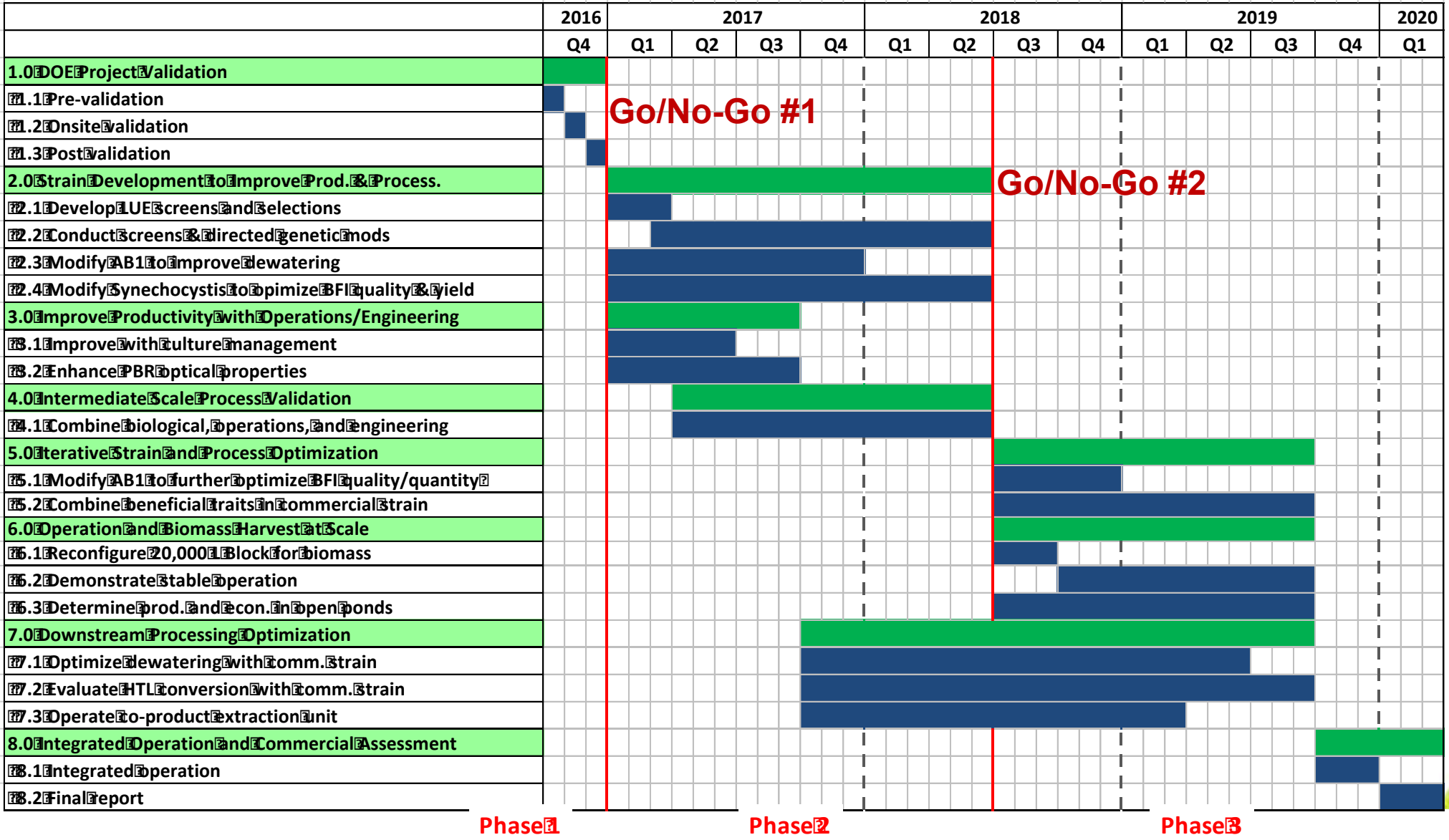
- Addresses, in detail, all three priority areas for ABY2: productivity, process technologies, and cultivation
- High potential for meeting ABY2 2020 productivity goal (3700 gal-BFI/acre-yr) and some significant potential for meeting ABY3 2022 productivity goal (5000 gal-BFI/acre-yr)

5 – Future Work: Key Milestones and Deliverables

Year 1	• >10% biomass increase with strain development • >20% biomass increase with operation/engineering
Year 2	• 20,000 L PBR operation and harvest • Dewatering and HTL unit operation and optimization
Year 3	• Integrated 20,000 L PBR operation • >40% increase biocrude production • Dewatering and HTL heat/material balance completed • TEA and LCA targets achieved

5 – Future Work

Program Schedule of Tasks and Subtasks



5 – Future Work: Go/No-Go Decision Points

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	Gate Criteria	Verification Process
Go/No-Go #1	DOE validation review complete and Project approved to continue	DOE Validation Team determines if process metrics support technical readiness and submits a report to DOE. Technology Manager and Project Team release remaining scope and funding.
Go/No-Go #2	Improvements in strain, cultivation operations, PBR system design, and HTL efficiency combine to yield >30% increase in biocrude productivity; no LCA or TEA related showstoppers	Project Team delivers to Gatekeepers documentation for higher yielding strain, optimized cultivation/harvest system, operational enhancements, optimized PBR system, and upgraded TEA/LCA analysis consistent with established gate criteria.

Summary

1. Overview: *The project provides a plan for meeting all goals associated with FOA-0001471 (ABY2) employing a PBR-based system*
2. Approach: *The work plan addresses all three Priority Areas for ABY2 and builds on experience gained in the deployment of Algenol's DOE-funded biorefinery focused on ethanol production, as well as established working relationships amongst the partners*
3. Technical Accomplishments/Progress/Results: *New Project*
4. Relevance: *Well-aligned with ABY2 and BETO goals*
5. Future work: *Work plan has sound scientific footing and can take advantage of existing infrastructure, cultivation experience, and engineering expertise to advance DOE goals for biocrude production*

Additional Slides

Responses to Previous Reviewers' Comments

- This is a new project (started in 4Q2016) that has not been reviewed in previous BETO meetings.
- Phase I Validation review (Go/No-Go #1) passed in December 2016.

Publications, Patents, Presentations, Awards, and Commercialization

- This is a new project (started in 4Q2016) and no publications, patents, presentations, awards or commercialization efforts, deriving specifically from this work, are available yet.