DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

Production of Biocrude in an Advanced Photobioreactor-Based Biorefinery

March 4-8, 2019

Advanced Algal Systems R&D

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Algenol Biotech

Goal Statement

Project Goal: Develop highly productive algal strains, a cost-effective photobioreactor (PBR)-based production system, enhanced cultivation practices, energy-efficient downstream processes, and a co-product strategy that will advance the technology needed for economical, large-scale algal biofuel production.

Expected Outcome: A system able to produce >4,000 gal BFI/acre-yr, energy-efficient harvesting and HTL conversion processes that use <10% of the energy content of the BFI with an overall 60% carbon footprint reduction, and data that support an economic analysis that compares open pond *vs* PBR-based production systems.

These project goals and outcomes will facilitate achievement of the overall strategic and performance goals of BETO's Advanced Algal Systems R&D Program (summarized below):

- *Develop algae production systems & logistics capable of sustainable, reliable, and affordable production of 5 B gallons of algae-based biofuel per year by 2030*
- *Demonstrate technologies to produce sustainable algal BFI feedstocks and convert to renewable fuels at $3/gasoline gallon equivalent by 2022*

Quad Chart Overview

Production of Biocrude in an Advanced Photobioreactor-Based Biorefinery

Timeline

- Project Start Date: 10/01/2016
- Project End Date: 03/31/2020
- Percent complete: 73%

	Total Costs Pre FY17	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$0M	$2.4M	$1.3M	$1.3M
Project Cost Share Algenol	$0M	$0.3M	$0.2M	$0.1M
Project Cost Share RIL	$0M	$0.3M	$0.1M	$0.3M

Partners: FY 17-18 Project Funding: NREL (9%); GA Tech (4%); RIL (Reliance Industries, Ltd) (8%, cost-share); Algenol (78%, including cost-share)

Barriers addressed

- Aft-A. Biomass Availability and Cost
- Aft-B. Sustainable Algae Production
- Aft-C. Biomass Genetics & Development
- Aft-H. Overall Integration and Scale-Up

Objective

- Integrated development of algal strains, PBR-based production systems, cultivation practices, and energy-efficient downstream processes for BFI and selected co-product production

End of Project Goals

- Productivity of 4000 gal BFI/acre-yr
- Harvesting, dewatering, and HTL processes that utilize <10% of the energy content of the BFI
- Comprehensive TEA to compare open pond and PBR production systems
- Co-product strategy identified

1 - Project Overview

- ***Background:*** Algenol has developed low-cost photobioreactor (PBR) systems and robust production strains for biofuel production. This project is intended to further advance these technologies and provide a data base that allows open pond *vs* PBR comparisons for techno-economic and life cycle analyses.
- ***Specific objectives:***
  - 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
- ***Expectations:*** Algenol is well-positioned to achieve these objectives based on a solid track record of R&D in strain development, cultivation practices, engineering, and manufacturing. We have established numerous partnerships with universities, national labs, and other companies to further develop algal biofuel technologies.

2 – Approach (Management)

- ***Management Approach*:** Team partners meet on a regular basis to discuss results and make plans based on research progress and new developments.
- ***Project Team Institutions and Key Contributors*:**

Algenol Biotech – Chance, Roessler, Porubsky, Miller, Yuan

- strain development (higher productivity and reduced viscosity), cultivation research, harvesting and downstream processing, modeling, PBR research and manufacturing, pilot scale operations, co-product development, TEA and LCA analyses

National Renewable Energy Lab (NREL) – Yu, Dong, Pienkos

- strain development (improved BFI yield and quality), lab-scale HTL

Georgia Institute of Technology – Realff, Thomas

- Techno-Economic and Life Cycle Analyses

Reliance Industries (cost-share partner) – Phadke, Ghadge

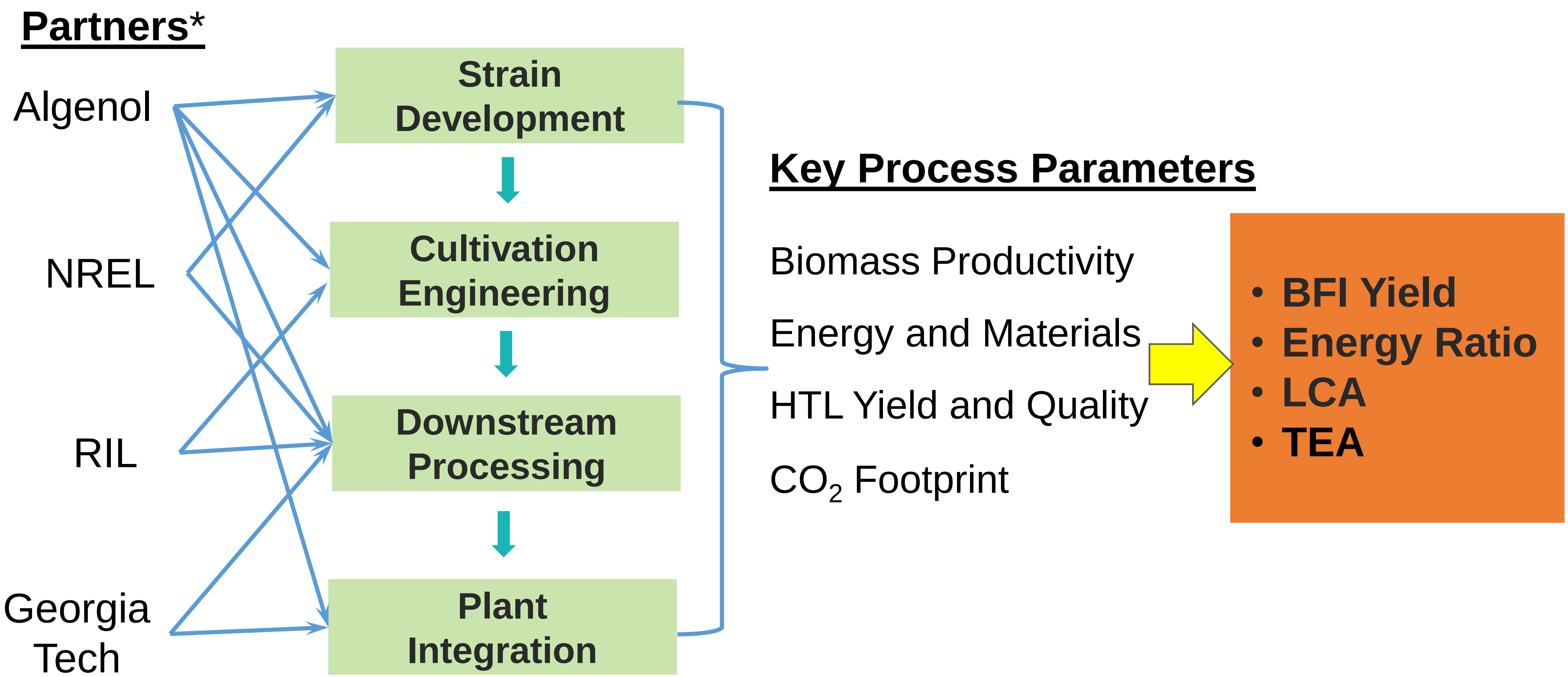
- HTL R&D, open pond tests

Subcontractor: Arizona State (AzCATI) – McGowen, Dempster

- Open pond studies

Algenol-DOE ABY2 Program Workflow

- **Goals: >4000 gal BFI/acre-yr; processing energy expenditure <10% of BFI energy content; >60% CO_2 footprint reduction; Techno-Economic Analysis**



*Subcontractor: ASU, pond experiments on AB1 and *Arthrospira*

2 – Approach (Technical)

- **Multi-pronged approach to increase biomass and BFI productivity:**
  - Higher algal biomass and BFI productivity *via* strain development, improved cultivation practices (*e.g*. semi-continuous operations), improved PBR design, higher HTL yields
- **Research to reduce biomass and BFI production costs:**
  - Lower operational costs *via* improved dewatering (lower energy cost and higher throughput), enhanced CO_2 use efficiency, water and nutrient recycle, reduction in overall energy requirements
  - Lower capital costs based on more robust PBR films, lower cost PBR components, efficient PBR deployment methods, improved support systems
  - Approaches and targets guided by Techno-Economic and Life Cycle Analyses
- **Co-product development to facilitate market entry:**
  - Process developed for producing phycocyanin from *Arthrospira* (spirulina) to provide a higher value product to support early biorefinery economics

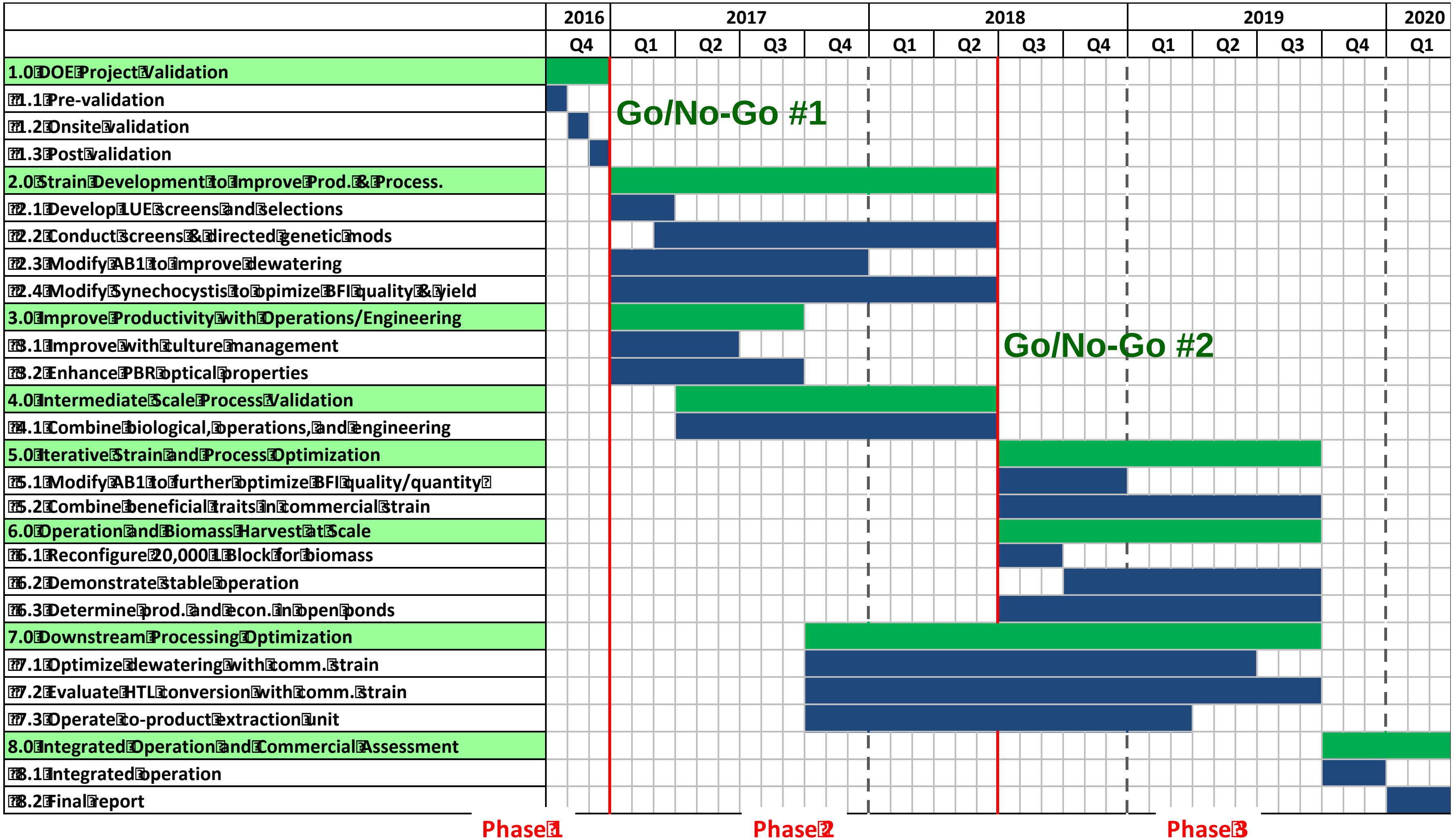
Key Decision Point for entering Phase 3:

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

➢ **Meeting held in July 2018 – "Go" decision made**

2 – Approach (Technical)

- Gantt Chart: Program Schedule of Tasks and Subtasks -

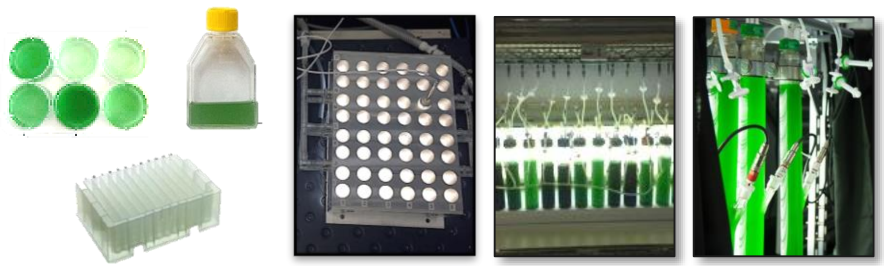


ALGENOL

3 – Technical Accomplishments / Progress / Results

- Process Scaling from 2 mL to 24,000 L -

Scale



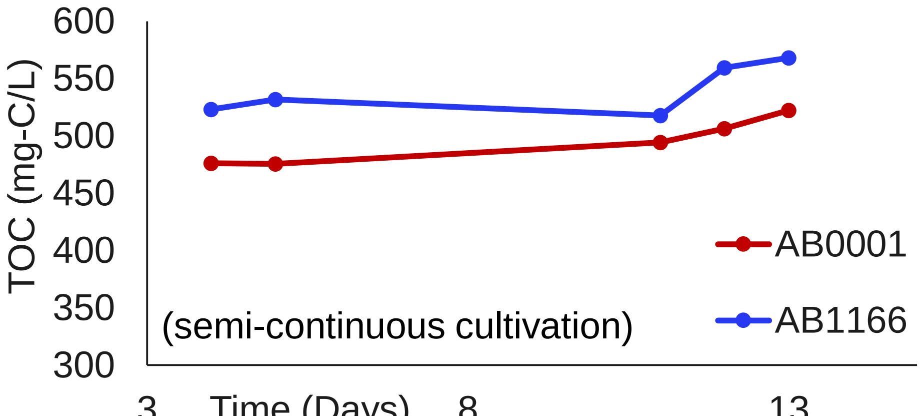
Lab-scale:
- <1 mL to 5 L
- Multiple screening/selection options
- Directed & non-directed genetic mods
- Control algorithm development

PDU-scale:
- 50 to 300L
- High replication possible
- Advanced control algorithms
- Predictable productivity

Pilot-scale:
- 24,000L
- Single culture volume
- Advanced control algorithms
- Predictable productivity

- Strain Development -

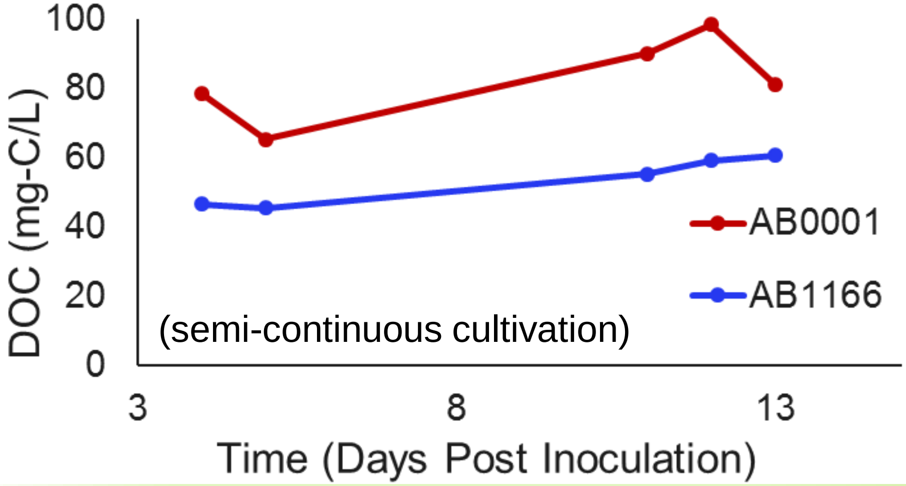
- **Higher biomass productivity**
  - Multiple approaches taken in attempts to improve the light utilization efficiency of our primary commercial organism (*Cyanobacterium* sp. AB1):
    - Addition, knockout, and knockdown of various genes (~20 strains)
    - Non-recombinant screening and selection (multiple strategies)
    - Productivity up to 20% higher in batch cultures, but generally only 5-10% higher in outdoor, semi-continuous cultivations
  - New *Cyanobacterium* strain AB1166 identified that naturally has >10% higher productivity than AB1 under semi-continuous cultivation
    - Many genetic tools now in place for AB1166
  - ➢ **Milestone for 10% higher productivity achieved**

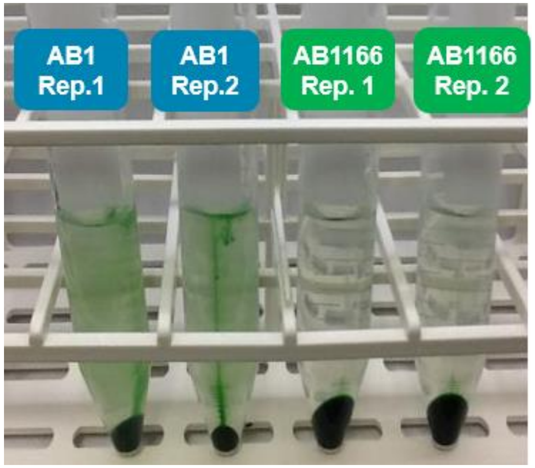


3 – Technical Accomplishments / Progress / Results

- Strain Development -

- **Improved harvestability (reduced viscosity)**
  - Knockout of putative EPS biosynthesis gene led to a large reduction in culture viscosity, thereby enabling more effective centrifugal harvesting
    - Cells tended to clump and settle out during cultivation, however, so not commercially viable
  - Native AB1166 cultures were much less viscous (less released EPS, *i.e.* lowered dissolved organic carbon, DOC) than native AB1 cultures and equivalent to the AB1 EPS knockout strain
  - Centrifugation using industrially-relevant conditions removed more biomass from AB1166 cultures compared to AB1
  - **Milestone for 50% reduction in low shear rate viscosity achieved**

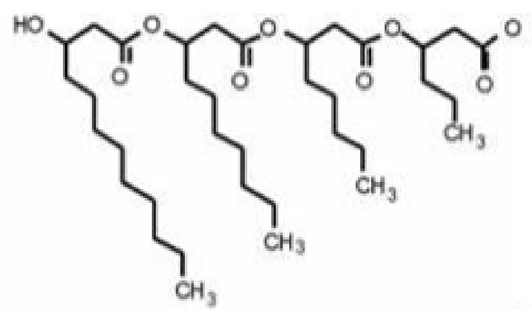




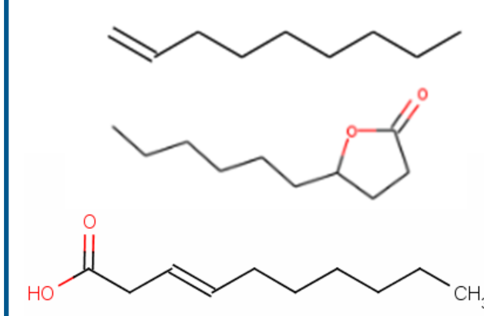
- Strain Development -

- **Higher BFI yield and quality *via* HTL of algal biomass (NREL)**
  - Reduced glycogen strain met milestone for yield increase, but cells unhealthy
  - Identified medium chain length polyhydroxyalkanoates (PHAmcl) as a useful compound to enhance biomass composition

C6-C12 PHA



	BFI wt%	
S6803 control	33.6	± 1.1
PHA 15wt%	39.5	± 3.0
PHA 30wt%	43.7	
PHA control	63.7	



HTL Products from PHAmcl including α-olefin. Manuscript submitted to *Applied Energy*.

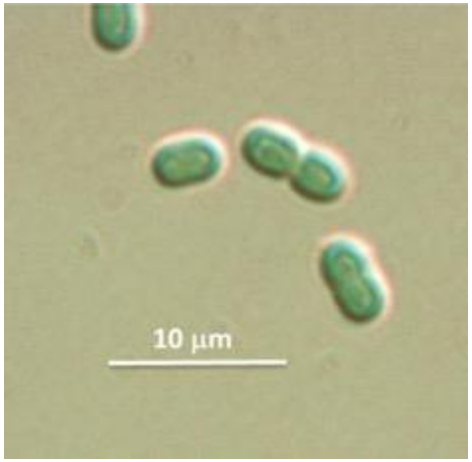
Pseudomonas genes introduced into *Synechocystis:*

1) 3-hydroxyacyl-ACP thioesterase
2) MCL fatty acid CoA ligase
3) PHA synthase

- No expression observed to date in *Synechocystis*, but expression does occur in *E. coli.*
- Algenol scientists introducing *Pseudomonas* genes into *Cyanobacterium* sp.

- Strain Selection for Advancement to Outdoor Evaluations -

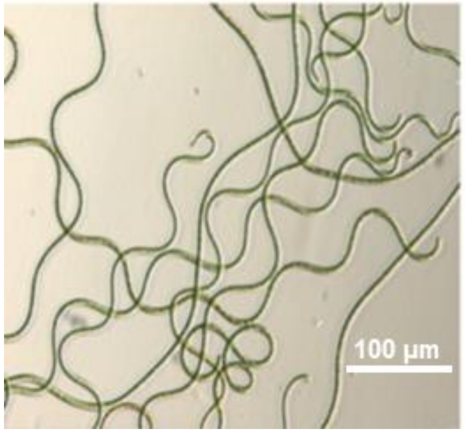
***Cyanobacterium* sp.**



- Robust, productive cyanobacteria (AB1 and AB1166)
- Grows very well at high temperatures, saline water, and high oxygen levels
- High photosynthetic capacity
- Efficient nutrient utilization
- Extensive, proprietary toolbox for further genetic enhancement

➢ **Biocrude – Large Scale Production Candidate**

***Arthrospira platensis* (Spirulina)**

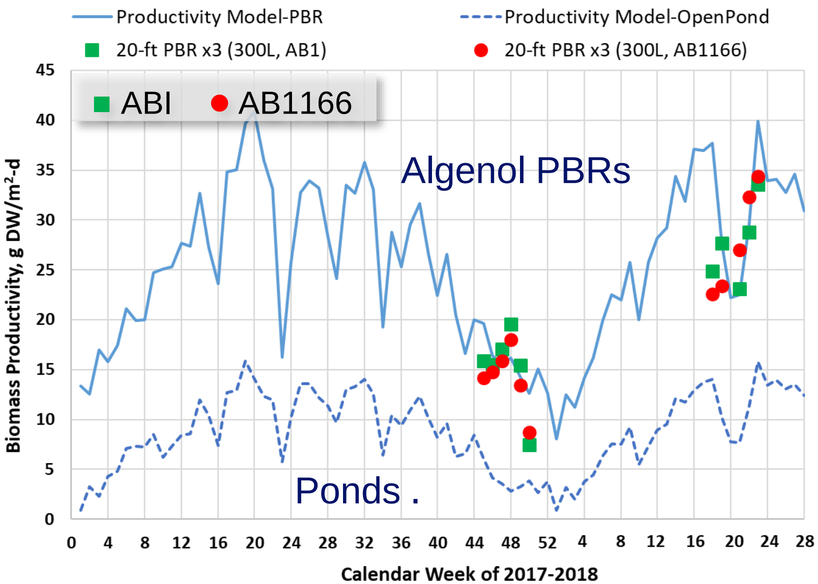


- Filamentous, moderately productive cyanobacteria
- Common organism for open pond systems
- An extremophile (high alkalinity & pH)
- Commonly used as dietary supplement
- Parent organism for extraction of phycocyanin (PC, blue food colorant)

➢ **Co-Product (PC) – Smaller Scale Production Candidate**
➢ **Potential Biocrude Candidate**

- Go/No-Go Milestone Experiment (2017-2018, Fort Myers) -

Data and model weekly averages



- Algenol Productivity Model parameters from indoor experiments, including light and temperature dependence (same parameters for PBRs and Ponds)
- Geometry taken into account, *e.g*. reactor spacing and thickness, pond depth (20 cm)
- For AB1, PBRs are predicted to be 2.9x more productive than ponds with the same "wet" footprint (includes spaces between PBRs)

Go/No-Go Productivity Hurdle: 30% increase over baseline

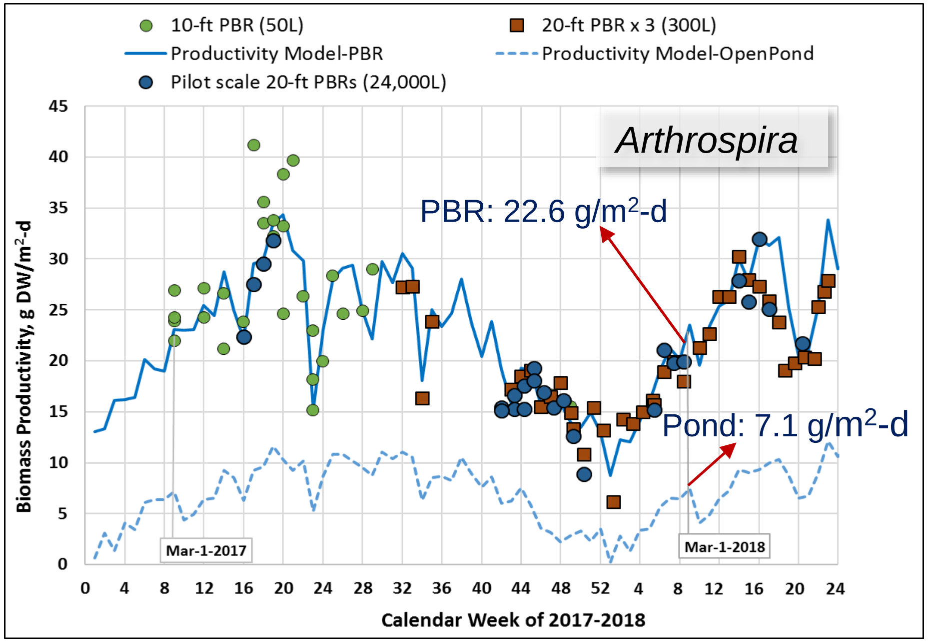
	Harvest *Annualized* Productivity (g/m^2-d)	% increase compared to 15 g/m^2-d baseline
AB1 Batch Mode (confirmation)	15.5	–
AB1 Semi-Continuous Operation	24.2	61%
AB1166 Semi-Continuous Operation	26.8	79%

Go/No-Go Meeting July 2018 Decision: Pass

- Productivity Modeling: PBR vs Open Pond for *Arthrospira* -

- Algenol Productivity Model parameters from indoor experiments, including light and temperature dependence (same parameters for PBRs and Ponds)
- Geometry taken into account: PBR spacing, thickness, orientation; pond depth (20 cm)
- **PBRs vs Ponds:**
  - Algenol Productivity Model predicts PBRs to be 3.2x more productive than ponds for *Arthrospira* with the same "wet" footprint (includes spaces between PBRs)
  - Excellent agreement with reported results for commercial operations (average 7.5 g/m^2-d during operating period, typically 6-8 months per year)
- **Operability**
  - Excellent agreement over scale range for reactors from 2 mL to 24,000 L
  - Stable operation demonstrated for ABY2 proposed scale (>20,000 L)

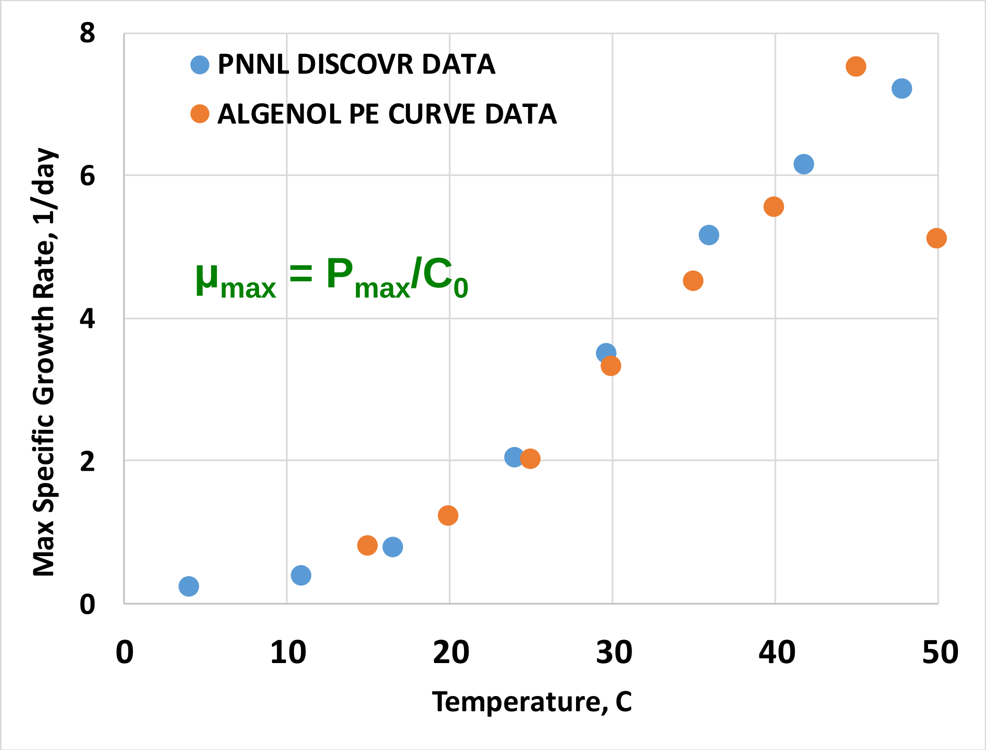
Fort Myers experimental data and model (weekly averages)



Assumed open pond culture temp as ambient; PBR temp includes impact of light absorption

- Cooperation with PNNL DISCOVR Program -

- Algenol supplied PNNL with AB1 for inclusion in their DISCOVR program
- PNNL reported back that it showed the highest temperature tolerance of any of their candidates. Also a high specific growth rate.
- Good agreement between PNNL and Algenol determinations of specific growth rates.
- Maximum growth rate at about 48C corresponds to a doubling time of 2-3 hours with saturating irradiance
- Degradation in performance above 50C



Comparison of PNNL and Algenol determinations of specific growth rates for AB1

- Annualized BFI Productivities -

- **HTL BFI Yield = kg BFI/kg AFDW algae HTL feed**
- **Overall BFI Productivity = Annualized Biomass Productivity × HTL BFI Yield**

Annualized Biomass Productivity (1)	HTL BFI Yield (AFDW basis)			
	34% (2)	40%	50% (3)	60% (3)
gAFDW/m²-d	BFI/acre-yr	BFI/acre-yr	BFI/acre-yr	BFI/acre-yr
15*	2,030	2,390	2,990	3,580
20	2,700	3,185	3,980	4,780
25	3,385	3,980	4,980	5,970
30	4,060	4,780	5,970	7,170
35	4,740	5,575	6,970	8,360
40	5,415	6,370	7,960	**9,560**

TEA for AB1 ~$100/bbl

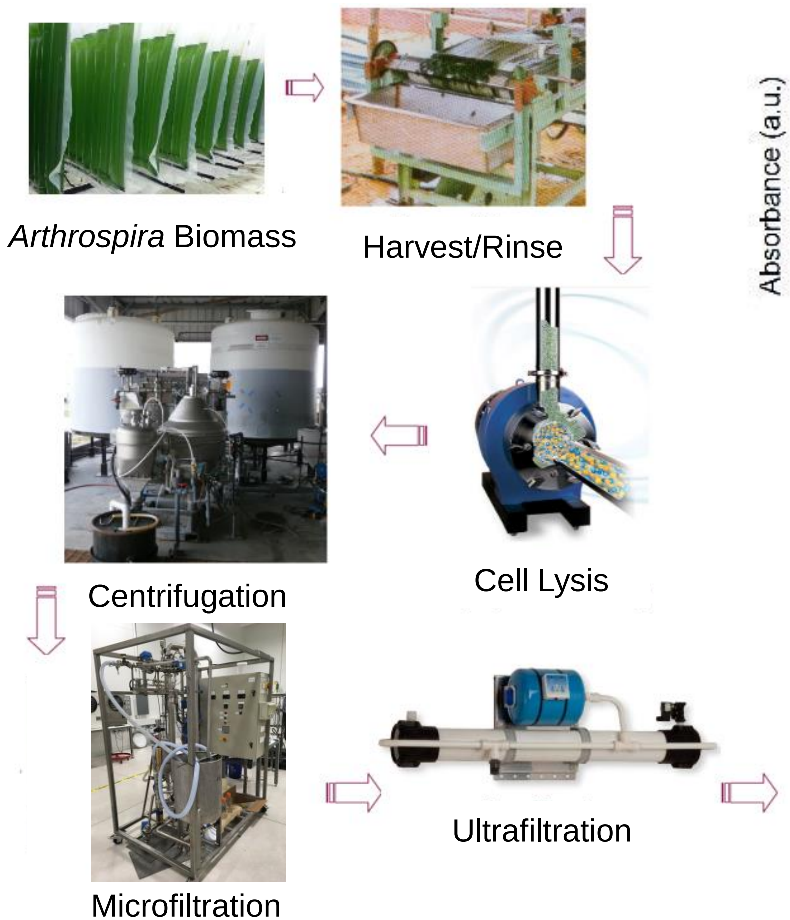
Notes: 1) Algenol productivity range (22 ~ 27 gAFDW/m^2-d) derived from indoor turbidostat experiments, modeling of growth curves at PDU (outdoor) scale, and 2018 outdoor semi-continuous experiments at PDU (AB1, AB1166, and *Arthrospira*); *reference batch productivity value

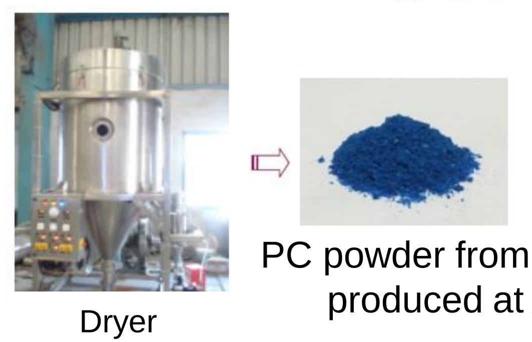
2) From PNNL and NREL Labs, HTL BFI Yield (30% to 38%) with AB1

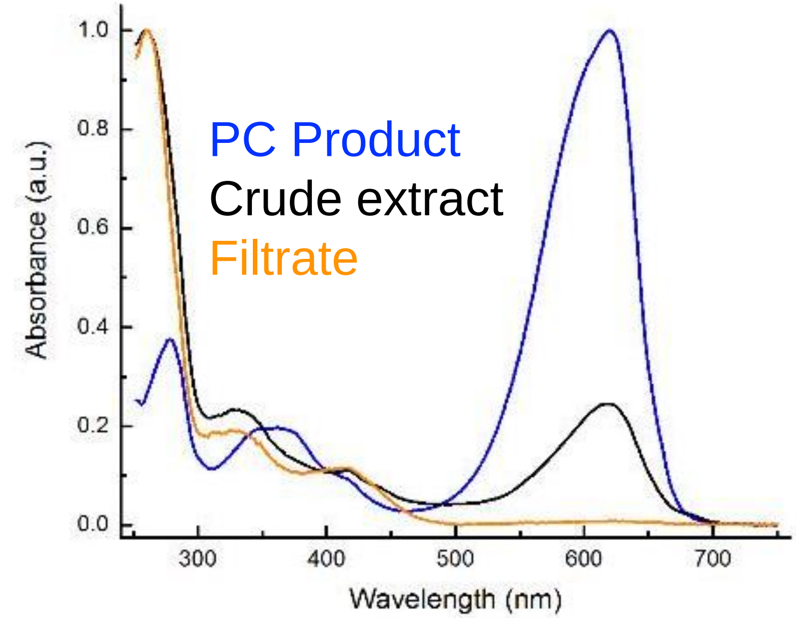
3) From RIL Lab, HTL BFI Yield: 28 - 43% (variable process conditions) with AB1; up to 65% for *Arthrospira* (with catalyst)

DOE ABY2 Program Target: 3700 gal-BFI/acre-yr, Project Target 4000

- Phycocyanin (PC) Coproduct: *Arthrospira* Harvest and PC Extraction -



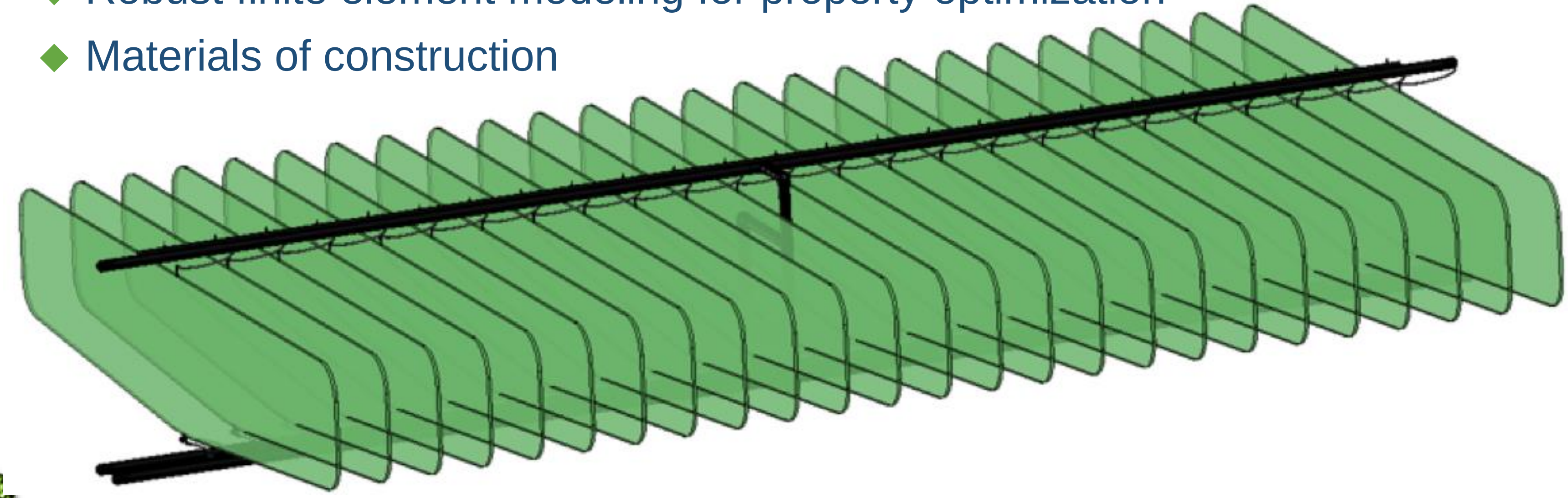




- ***Milestone for downstream processing for PC production achieved***
  - Favorable comparison to existing commercial PC derived from pond systems
  - Favorable feedback from potential customers

- Photobioreactor System Cost Reduction -

- Thin gauge plastic film – long field life from experience and accelerated testing
- Simplified PBR support structure
- Optimized tubing and header piping
- Optimizing connected PBRs - minimizing valves
- Eliminating tanks and other supporting infrastructure
- Single point CO_2 and nutrient injection points
- System control without the use of pH probes
- Robust finite element modeling for property optimization
- Materials of construction



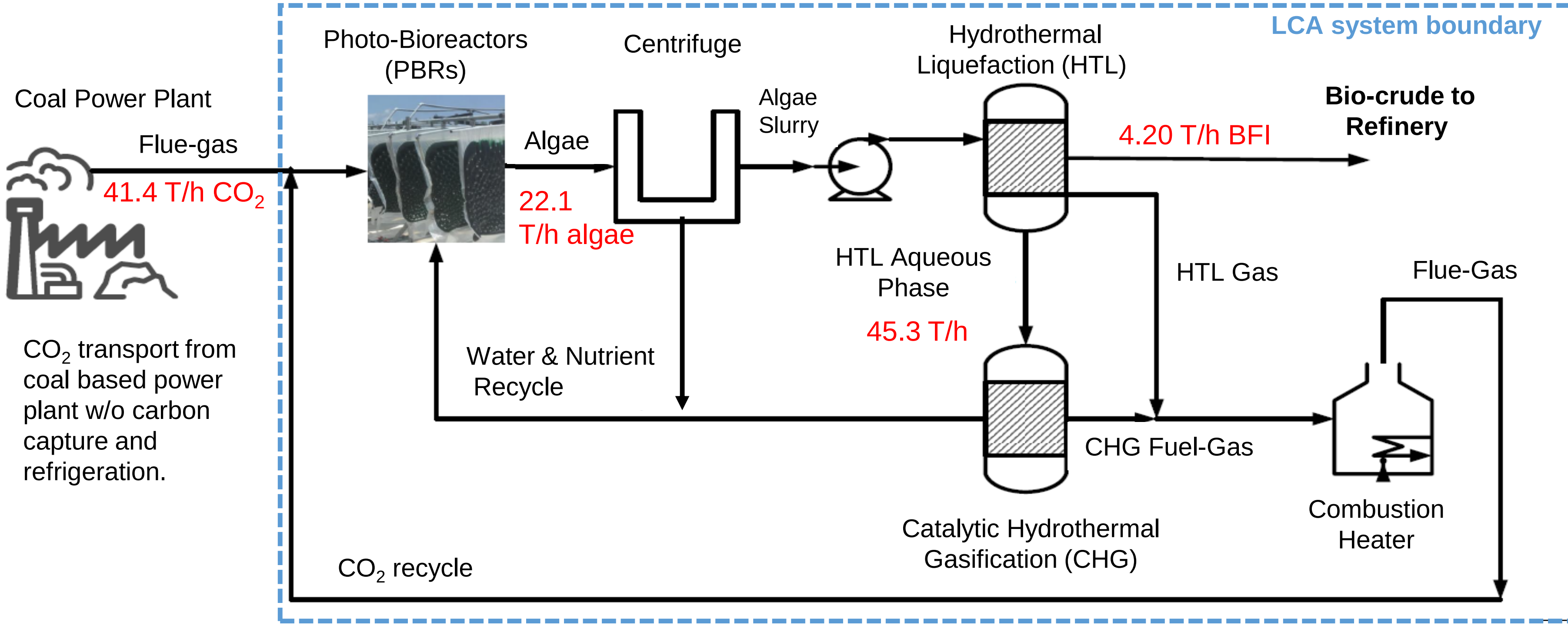
Algenol Photobioreactor Manufacturing

High speed plastic film welding enables large-scale deployments

- Algenol has both prototyping and commercial manufacturing lines
- Manufacturing system allows plastic and weld design changes to support culture and product requirements
- Construct large complex PBRs with most any geometric shape
- High speed manufacture for large installations (~250 20-foot reactors per day currently for single manufacturing line)
- Quality manufacturing
  - Constant digital heat and pressure monitoring for quality control
  - Accelerated testing for PBR life
  - Complete in-house raw material, plastics and finished goods quality testing

- Heat and mass balance from ASPEN for an Algenol Biocrude Facility -

(CO_2 transport from coal-based power plant)



Energy Input rate	MW	Energy Output rate	MW
Electricity			
CO_2 transport (Coal flue gas)	3.93		
Aeration, centrifuge and filtration	5.50		
Algae and aqueous phase pumps	0.79		
Heat		**Heat**	
Hydrothermal liquefaction	6.23	**Bio-crude (BFI)**	**41.70**
Catalytic hydrothermal gasification	7.03	Fuel-gas combustion	20.78

- **Energy Return ratio (EROI) ~ 4**
- **Electricity is the major energy input**
- **Internal heat integration with fuel gas from CHG**
- **EROI = 10 is ABY2 target**

2000 Acre Algenol Facility

4 – Relevance

Main Project Goals:

- 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

Importance: Broadly addresses key factors associated with deployment of algae-based biofuels, the role of co-products, and the potential for PBR-based systems

Contribution to BETO goals: Closely aligned with three DOE ABY2 Priority Areas: Strain/productivity improvement, Improvements in pre-processing, and Integration of cultivation with pre-processing technologies. Several AAS R&D Milestones met.

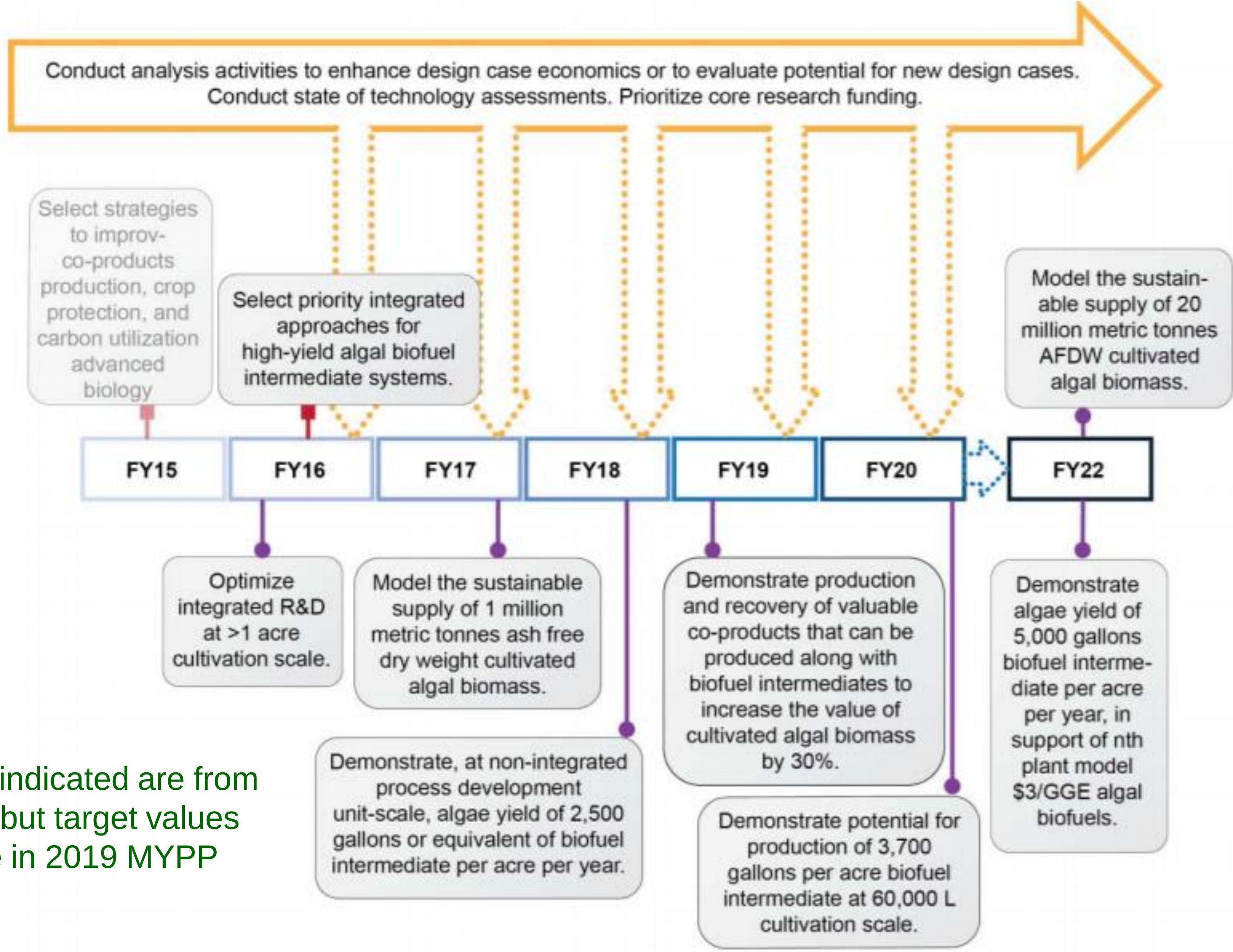
Tech Transfer/Marketability: For co-product, demonstrated integrated operation at significant scale; demonstrated customer acceptance of on-spec product (phycocyanin).

4 – Relevance

Relevance to Bioenergy Industry: Successful development of highly productive strains coupled with a cost-effective PBR-based growth system and energy-efficient downstream processes will help achieve BETO goals and accelerate commercial investment in the biofuel industry.

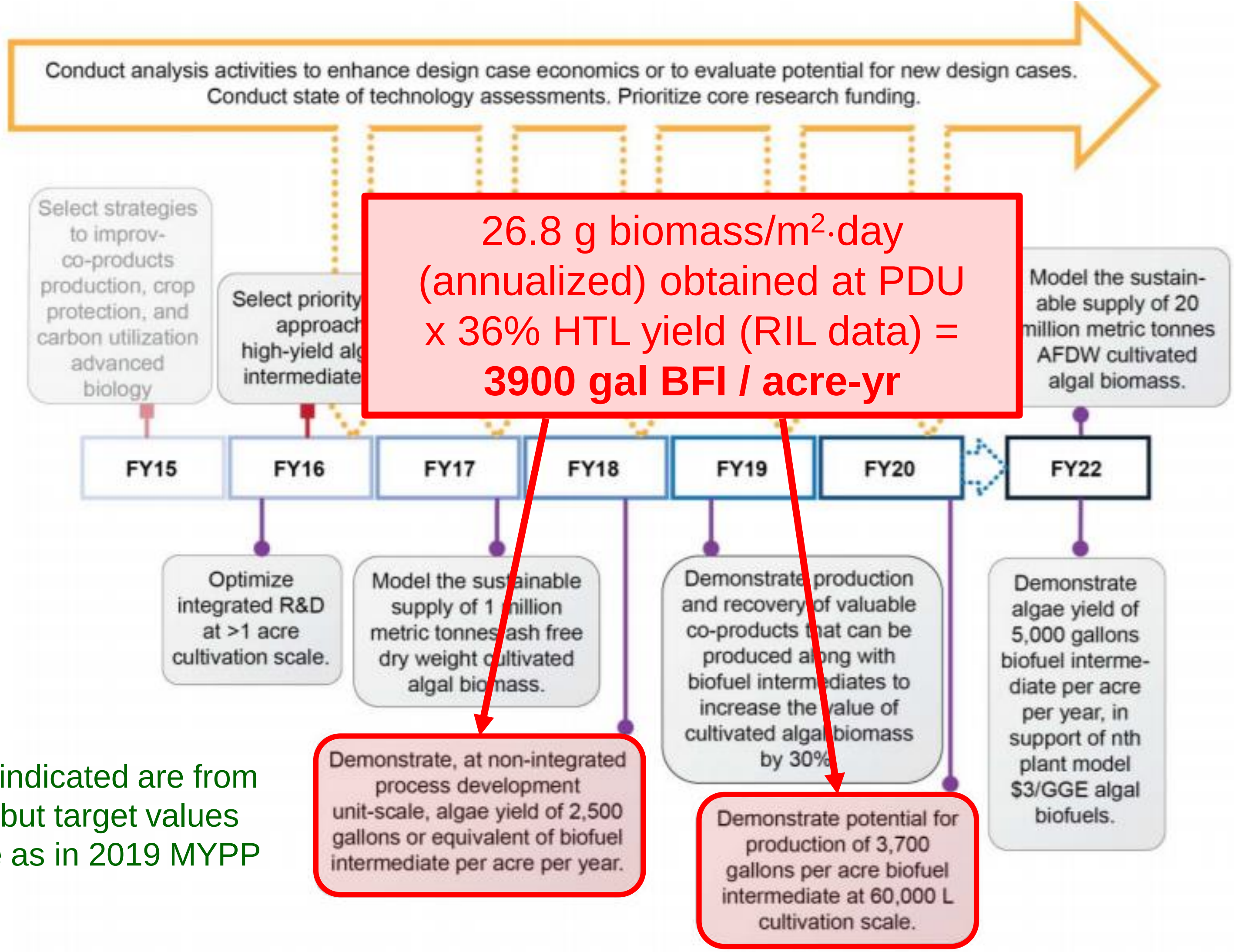
- Lower cost of biomass and biocrude (BFI) production
- Production system capable of widespread, sustainable, large-scale deployment
- Higher quality biocrude to facilitate market acceptance
- High value co-product coupled to biofuel production to improve pioneer biorefinery plant profitability and facilitate project financing by reducing risk
- Detailed Techno-Economic and Life Cycle Analyses that can be used to make more informed decisions for commercial implementation and provide research guidance for technology improvements

➢ **Project results directly address Advanced Algal Systems R&D Milestones:**



* Milestones indicated are from 2016 MYPP, but target values are the same in 2019 MYPP

- **Project results directly address Advanced Algal Systems R&D Milestones*:**



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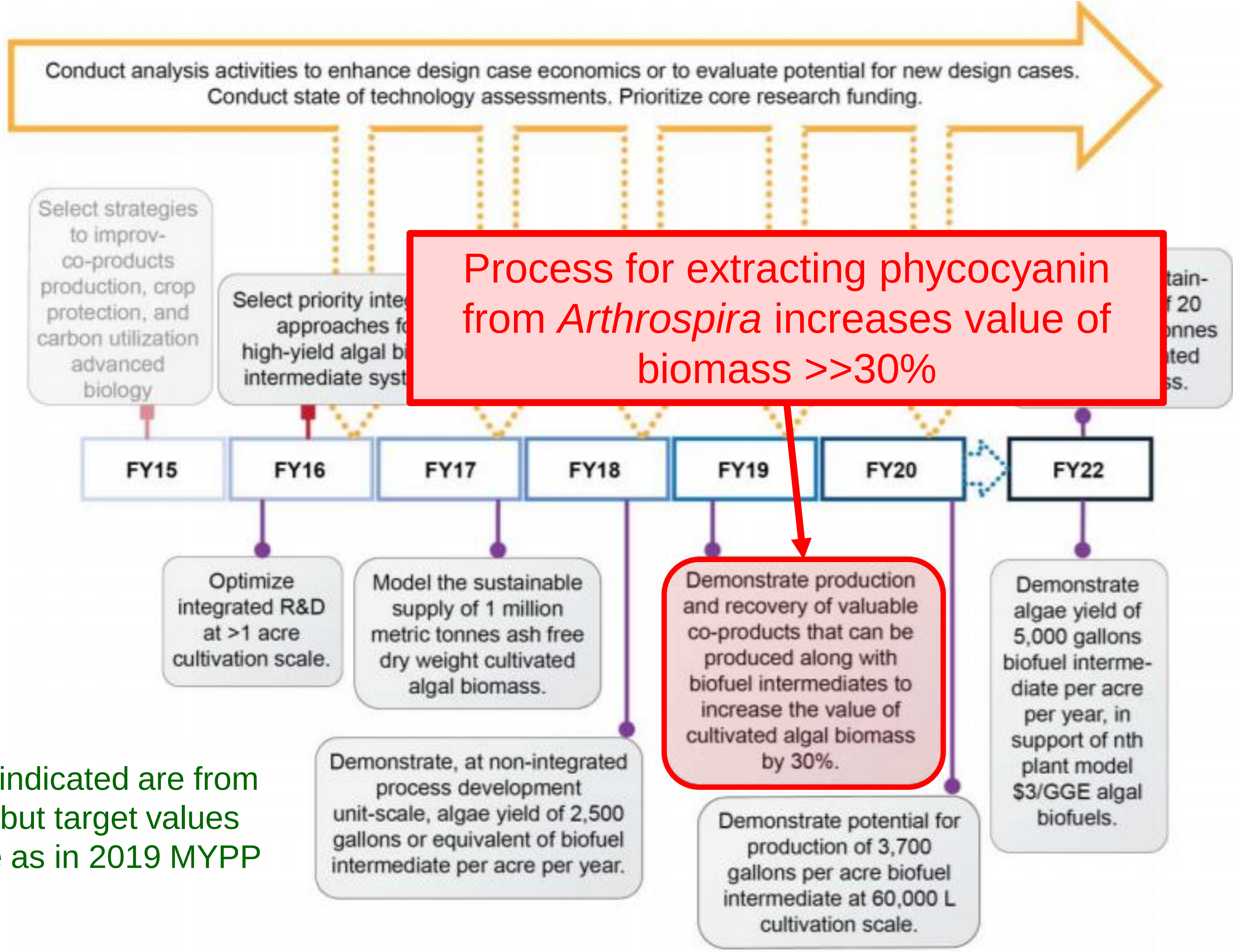


* Milestones indicated are from 2016 MYPP, but target values are the same as in 2019 MYPP

5 – Future Work

- **Key Elements of Work Plan (through 1Q 2020)**
  - Downstream biofuel process optimization
    - Continue strain development (NREL and Algenol)
    - Process improvements (Algenol, RIL and NREL)
    - Improve scale-up modeling for HTL and CHG for energy balance and product quality (GaTech, Algenol)
    - Biofuel TEA and LCA models at 2000 acre deployment scale (GaTech, Algenol)
  - Ponds *vs* PBR Comparisons
    - Pond experiments (RIL and ASU)
    - Firm up modeling for productivity comparisons (Algenol)
    - Techno-Economic Analysis (Algenol, GaTech)
    - Sustainability Comparisons (GaTech, Algenol)
  - Outdoor deployment of AB1/AB1166 system at 4000 – 6000 L scale (Algenol)
  - Expand role of *Arthrospira* in biorefinery-related assessments (Algenol, GaTech)
  - Explore medium cost range co-product for step-wise biofuel development, *e.g*. a 100-200 acre facility (Algenol, GaTech)

5 – Future Work

- **Key Upcoming Milestones**
  - Improved HTL yield via strain development
  - Stable biomass operation at 4000-6000 L with AB1/AB1166
  - Open pond raceway experiments completed for AB1 and *Arthrospira*
  - Modeling of system integration for final BFI yield, TEA, LCA, and energy ratio assessments at 2000 acre scale

- **There are no additional Go/No-Go decisions: Final Report due 1Q 2020**

Summary

- **Significant progress made toward achieving project objectives:**
  - More productive strain identified; also better for dewatering steps
  - Cultivation engineering successful at developing higher productivity and more efficient and sustainable use of water, nutrients, and CO_2
  - 24,000 L integrated PBR system used to grow *Arthrospira;* downstream operations developed for phycocyanin co-product; real commercial prospect
  - Excellent translation of laboratory results to outdoor performance
  - TEA and LCA well underway based on data obtained in project; PBR *vs* open pond system comparisons have begun to be made and look favorable for PBRs
  - Almost all milestones achieved; final Go/No-Go decision = “Go”
- **Project objectives have successfully addressed:**
  - ABY2 program priorities and many of the identified AAS R&D barriers
  - 2017-2019 AAS R&D MYPP milestones (several already achieved or significant progress made toward them)
- **Work in 2019 through Q1-2020**:
  - Additional strain modifications for higher BFI yields and quality
  - Completion of open pond *vs* PBR system comparisons
  - Process integration: growth, harvesting, HTL (modeled from lab/pilot results)
  - Completion of TEA, LCA, and final report

Additional Slides

Responses to Previous Reviewers' Comments

References: 2017 Peer Review Report and March 2017 Algenol Presentation

- Reviewer Comment: "A systematic TEA comparison with open ponds will be of particular value"
  - Response: A detailed TEA comparison of PBRs and open ponds has been completed and shared with DOE during Go/No-Go Meeting and with NREL (Ryan Davis group). Still being refined (awaiting more Pond data), but shows PBRs can be fully competitive, consistent with NREL and PNNL recent work. Details have not been released for publication yet.
- Reviewer Comment: "Phycocyanin (PC) market analysis should be done…"
  - Response: Extensive market analysis has been completed, mostly outside scope of this ABY2 effort. Numerous, very positive interactions with potential customers. Plant design and costing completed. Commercialization of PC is a serious possibility at 10-20 acre plant scale on Fort Myers site.

- Go/No-Go Meeting held July 2018 in Fort Myers, almost exactly as anticipated in Gantt Chart. Productivity target met (see earlier slide). No showstoppers in TEA or LCA analysis. Decision: Pass

Presentations (Algenol):

Ron Chance: “Biofuels and Bioproducts Produced in Photobioreactors.” School of Chemical and Biological Engineering, Georgia Tech, Atlanta, GA on April 11, 2017.

Laura Belicka: “Algae-based Biofuel Production in the Algenol Direct-to-Ethanol Process.” Renewable Energy Systems and Sustainability Conference, sponsored by the Florida Energy Systems Consortium, in Lakeland, FL on July 31, 2017.

Ron Chance: “Carbon Capture and Utilization in a Photobioreactor-based Biorefinery.” Invited lecture at ExxonMobil’s Corporate Strategic Research Laboratories in Annandale, NJ on September 7, 2017.

Ron Chance: “Impacts of CO_2 Supply Systems for Algae-Based Biorefineries on Biofuel Life Cycle Assessments.” AIChE Meeting in Minneapolis, MN on October 29, 2017.

Paul Roessler: “Application of Synthetic Biology at Algenol Biotech.” Algal Biomass Summit in Salt Lake City, UT on October 30, 2017.

Ron Chance: “High Value Products from a Photobioreactor-Based Biorefinery.” AIChE Meeting in Minneapolis, MN on October 31, 2017.

Jacques Beaudry-Losique: “CO_2 Supply Systems for Algal Biorefineries.” Algal Biomass Summit in Salt Lake City, UT on October 31, 2017.

Ed Legere: “Between the Pond and the Tube”. Algal Biomass Summit in Salt Lake City, UT on October 31, 2017.

Ron Chance: “CO_2 Capture and Utilization in a Photobioreactor-Based Biorefinery.” 10th CO_2 Utilization Summit in Tampa, FL on February 28, 2018.

Paul Roessler: “Integrated Development of Novel Strains, Production Systems, and Downstream Processes for New Commercial Products at Algenol Biotech.” 8th International Conference on Algal Biomass, Biofuels and Bioproducts held in Seattle, WA, June 10-14, 2018. He also served as a panel member at the “DOE Listening Day” held immediately after the ABBB Conference.

Ed Legere: “The Algenol Photobioreactor: Evolution of Design and Performance.” Algal Biomass Summit held in Houston, TX, October 14-17, 2018.

Ron Chance: “The Algenol Photobioreactor System: Comparison to Pond Based Systems.” Algal Biomass Summit held in Houston, TX, October 14-17, 2018.

Josee Bouchard: “Biomass Production in an Advanced Photobioreactor-Based Biorefinery.” Algal Biomass Summit held in Houston, TX, October 14-17, 2018.

Publications, Patents, Presentations, Awards, and Commercialization

Presentations (NREL):

Philip T. Pienkos: “Outside the Box Thinking at NREL—New Feedstocks, New Targets, New Processes.” ABLC Next meeting held in San Francisco, CA, October 18, 2017.

Tao Dong: “An integrated biorefinery to co-produce linear α-olefins and bio-oil through hydrothermal liquefaction.” AOCS Meeting in Minneapolis, MN on May 6-9, 2018.

Tao Dong: “Improving biofuel intermediate yield and quality by tuning algal composition.” Algae Biomass Summit in Houston, TX on October 14-17, 2018

Publications (NREL):

Tao Dong, Wei Xiong, Jianping Yu and Philip T. Pienkos (2018) Co-production of fully renewable medium chain α-olefins and bio-oil via hydrothermal liquefaction of biomass containing polyhydroxyalkanoic acid. RSC Adv. 8, 34380-34387.

Patents (Algenol):

Chares Budinoff, Lauren Hehman, and Kevin Sweeney: “Methods for Extracting Phycocyanin.” U.S. application No. 62,489,912, filed April 25, 2017.

Awards, Prizes, and Recognition:

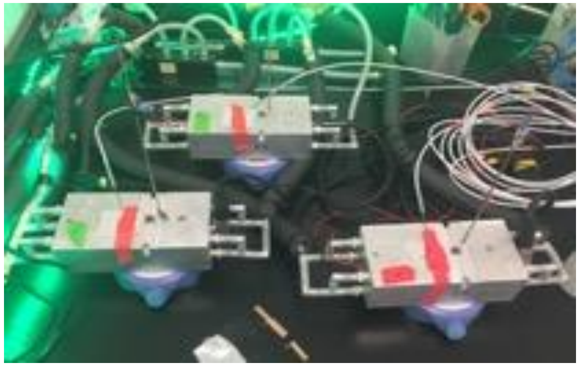
Dr. Ron Chance is the recipient of the Lawrence B. Evans Award from the American Institute of Chemical Engineers. This is an institute level award recognizing lifetime achievement. The award carries with it a travel allowance and a $3000 prize. The award was presented on October 28, 2018 at the annual AIChE meeting in Pittsburgh, PA.

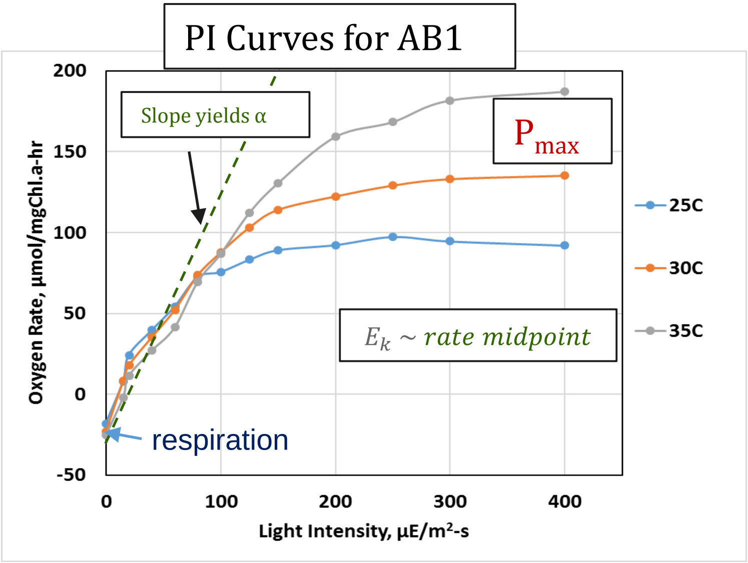
Backup

Productivity Model Development Including Temperature Effects

Productivity Modeling:

- Photosynthetic capacity parameterization derived from O_2 evolution vs Irradiance – PI (or PE) Curve
- Algenol developed a proprietary system for PI Curve generation and analysis
- PI Curves can be generated for cultures under multiple conditions to discern the photosynthetic response to parameters such as average light and temperature of cultures
- Key parameters: α (C fixed per photon in low light limit), E_k (photosaturation, μE/m^2-s), and respiration rate. Responses are unique for each organism and are used as inputs into the Productivity Model
- Use Monod fit model to be consistent with math of Algenol Productivity Model





Literature *Arthrospira* Productivity in Open Ponds

- Large variation from 5-10 g/m^2-d during operating days (system up-time)
- Commonly operated ~ 6 month/yr in Northern China and Earthrise (CA)
- Average productivity for <u>operating</u> days: 7.5 ±1.5 g/m^2-d (n=12)
- *Results consistent with productivity modeling and ~3x PBR productivity advantage*

Yun-Ming Lu *et al*

J Appl Phycol (2011) 23:265–269 267

Northern China

Table 1 Main *Spirulina* plants in Ordos and their production profile in 2008

Company	Ponds area (ha)	Annual production (Ton, dw)	Productivity (gm^{-2} d^{-1})[a]	Products sold
Shuangfengbao Greenalgae Co., Ltd.	9.30	132	8.61	Alga powder as food and animal feeds
Luyuan microalgae Co., Ltd.	6.20	57	5.57	Alga powder, oral liquid, phycocyanin, polysaccharides
Erdos Jiali Srirulina Co., Ltd.	6.50	83	7.74	Alga powder, tablets, polypeptide
Luweibao *Spirulina* Bioeng. Co., Ltd.	4.75	58	7.41	Alga powder, tablets, capsule
Mengjian *Spirulina* Industry Co., Ltd.	3.00	39	7.88	Alga powder as food and animal feeds
Bulonghu Bioeng. Develop. Co., Ltd.	4.09	38	5.64	Alga powder, capsule
Derong algal Industry Co., Ltd.	3.80	57	9.09	Alga powder, tablets,
Lufeng Bioeng. Co., Ltd.	2.84	28	5.97	Alga powder, tablets,
Weida *Spirulina* Industry Co., Ltd.	4.52	65	8.72	Alga powder, tablets
Huayitai *Spirulina* Co., Ltd	5.50	48	5.29	Alga powder, tablets

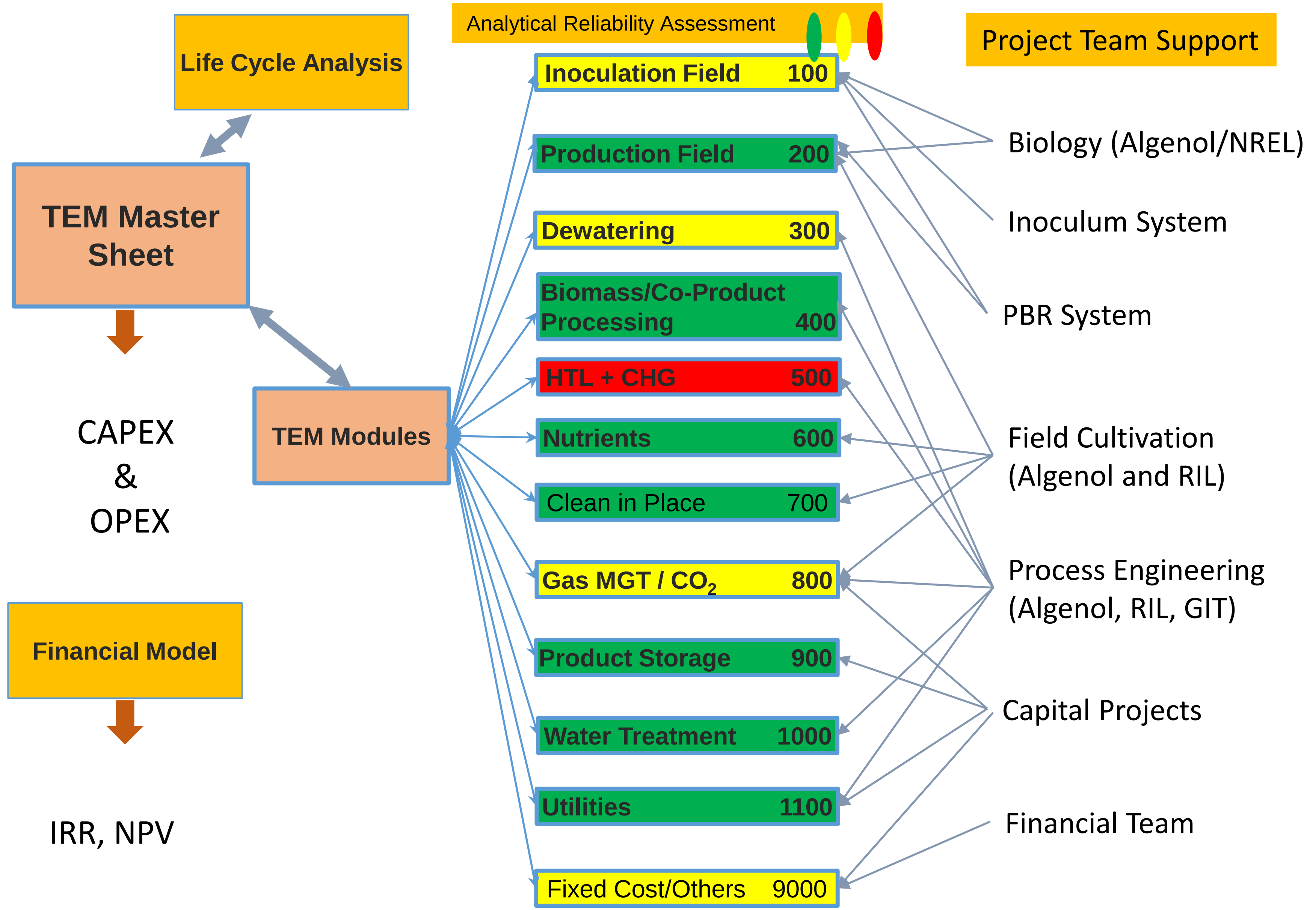
[a] The productivity was calculated on the basis of average annual production period, 165 days

Notes:
Northern China summer average irradiance very similar to Fort Myers annual average

DIC-China ~300 tonne from ~ 25 acre in Hainan, South China, year round, average 8.2 g/m^2-d (climate similar to Ft. Myers)

Earthrise, CA ~500 tonne from ~ 100 acre, 8-10 g/m^2-d during 6-8 month system uptime

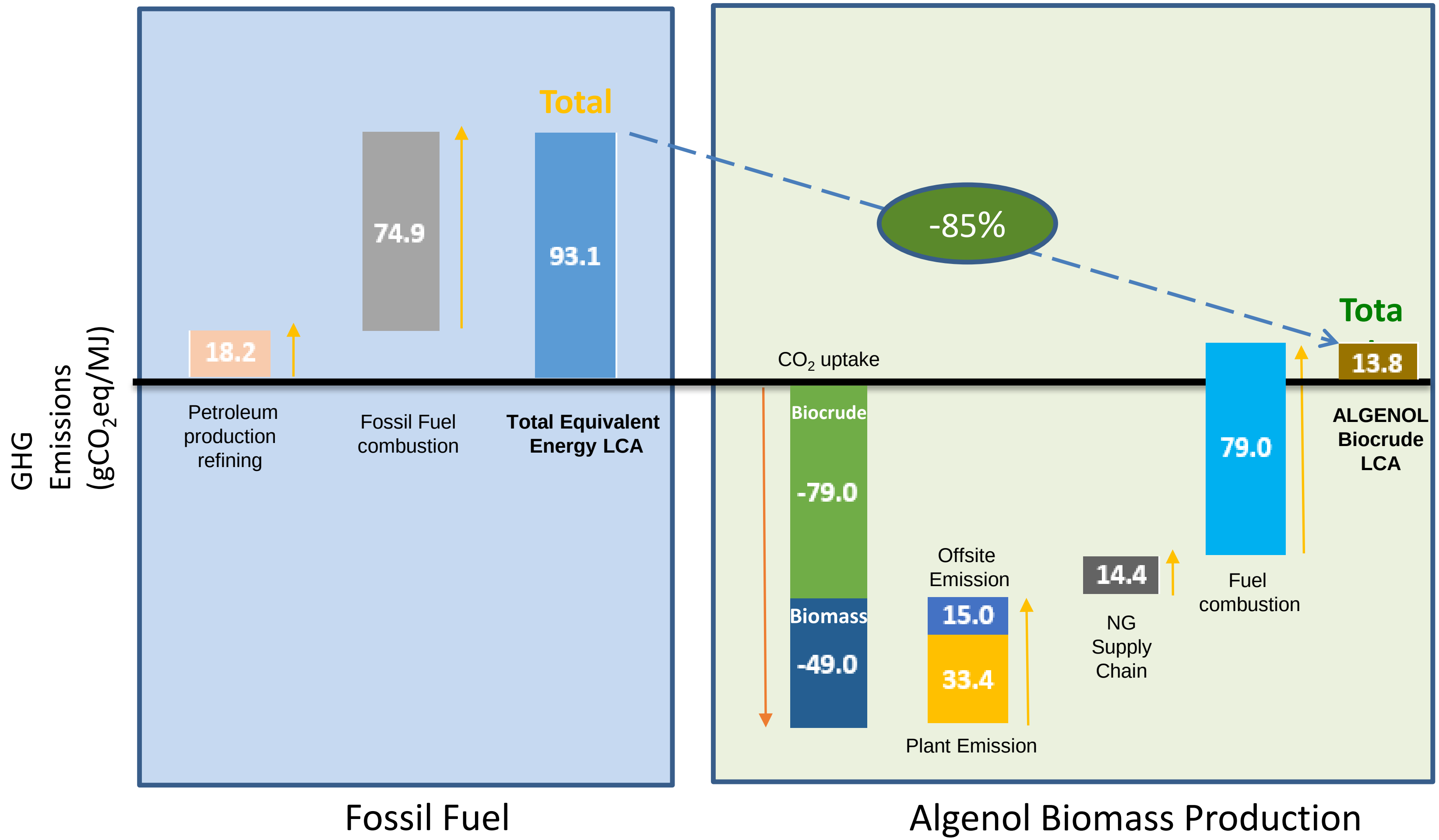
Techno-Economic Model Structure for Biomass



Preliminary LCA: 2000 Acre, 4000 gal/acre-yr Biocrude

Coal Flue Gas Transport with Power Generation (CHP Unit)

The Algenol biocrude pathway reduces GHG emissions by 85% compared to power and fossil fuel (gasoline) equivalent 1 MJ energy



Plastic Film Photobioreactors

Advancements in plastic film technology open new possibilities for PBR materials

Plastic film

- Highly engineered
- Thin gauge multi-layer blown film
- Proprietary additive formulations
- Long lasting field performance (12 year target)
- Approved food contact materials

Design challenges

- Long-term exposure to UV and heat
- Structural stability under culture weight for the life of the PBR
- Interaction of CIP chemicals with inner plastic layer

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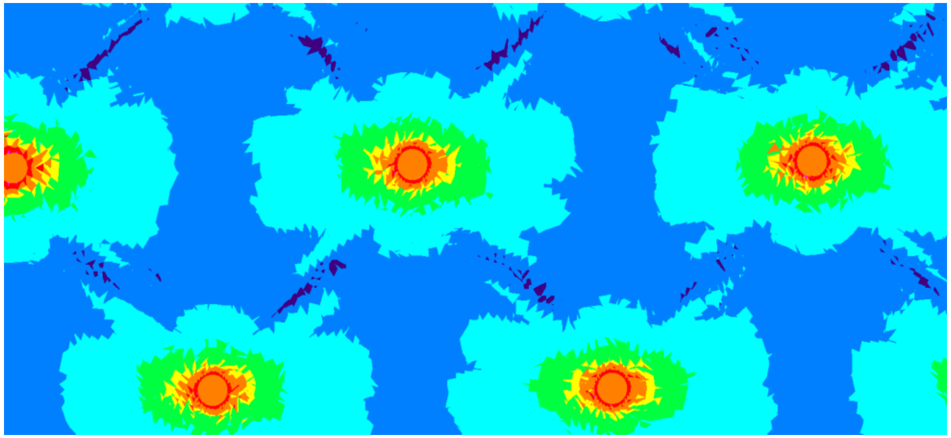
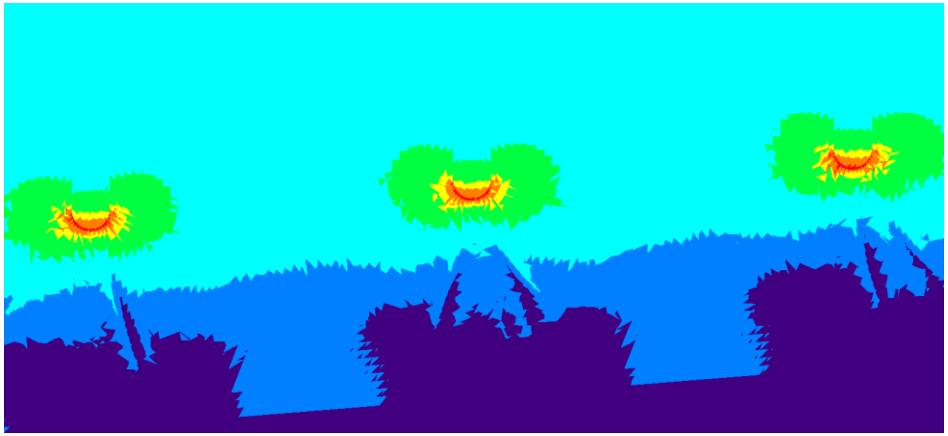
Adina Modeling for New Design Innovations

Examples of stress analysis informing design

- Calculate stress along welds; highest effective stresses fail first
  - Modify weld properties to lower, redistribute stress
- Able to design PBR failure point if over pressurization occurs
  - Control of pressure point can avoid culture loss



Middle spot welds



Bottom of vertical welds