National Renewable Energy Laboratory
Innovation for Our Energy Future

Historical Overview of Algal Biofuel Technoeconomic Analyses

DOE Algal Biofuels Workshop

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NREL

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National Algal Biofuels Technology Roadmap Workshop

University of Maryland

NREL/PR-510-45622

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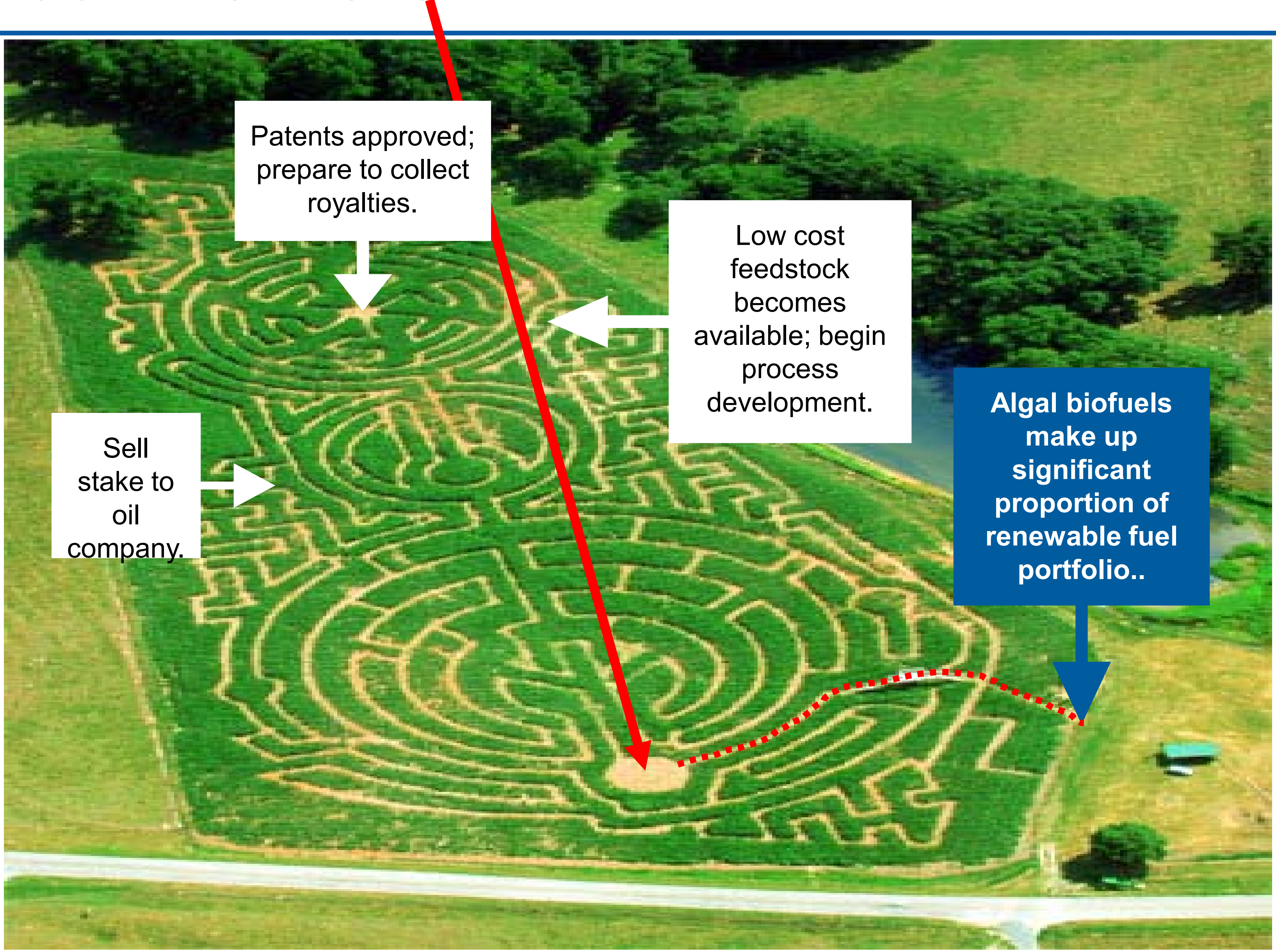


Patents approved; prepare to collect royalties.
Low cost feedstock becomes available; begin process development.
Sell stake to oil company.
Algal biofuels make up significant proportion of renewable fuel portfolio..

Technoeconomic Modeling for Workshop

- Discussions began in August as part of workshop planning process (SNL/NREL/DOE)
- Work began in earnest with meeting at SNL in October (SNL/NREL/NMSU/CSU)
- Establish goal to capture and consolidate all publicly available algal biofuel models
- Use information to help guide roadmappping effort
  - Current state of technology
  - Identify known knowns, known unknowns, and unknown unknowns
  - Provide focus on critical path elements
  - Estimate time and cost to achieve technical milestones

Cast of Characters

- NREL
  - Al Darzins
  - David Humbird
  - Phil Pienkos
- NMSU
  - Pete Lammers
  - Meghan Starbuck
- CSU
  - Bryan Willson
- SNL
  - Katherine Dunphy-Guzman
  - Ray Finley
  - Geoff Klise
  - Len Malczynski
  - Ron Pate
  - Amy Sun
  - Cecelia Williams

Acknowledgements

These people did most of the heavy lifting, consolidating information from a variety of models and providing key slides for this presentation:

– **Amy Sun**
– Katherine Dunphy-Guzman
– Cecelia Williams
– Ron Pate

Algal Biofuels TE Modeling & Analysis

Near Term Purpose, Goals & Plans for Algae Roadmap Workshop

- Updated Presentation on Current Status of Algae Biofuels Techno-Economics
- Formulate key questions for workshop breakouts to inform TE modeling & assessment
- Conduct evening session at workshop on Algae TE Modeling & Analysis
  - present and elicit expert comment on strawman TE modeling / analysis purpose, goals, & approach
  - present and elicit expert feedback comments / suggestions on baseline systems/processes diagram
  - present and elicit expert comment on strawman list of system & process evaluation criteria/metrics
  - elicit initial expert evaluation of systems, processes, and pathways based on evaluation criteria/metrics

Longer Term Purpose, Goals and Desired Outcomes for Algae R&D Program

- Assess algal biofuel production scale-up potential, constraints, consequences, preferred paths
  - technical, economic, environmental, policy
  - comparative tradeoffs of alternative technologies/systems/processes pathways
- Understand and quantify impact(s) of proposed R&D strategies using key selected criteria or "objective function" metrics that can be represented as model parameters… use to inform and guide R&D investments and monitor performance of technology, process and applications development
- Project cost (& other performance metrics) of biofuel feedstock and/or biofuels production
- Project cost (& other performance metrics) of co-product feedstock or co-products production
- Inform policy decisions

Elements and Issues for Techno-Economic Assessment of Algae Biomass Feedstock, Fuels, & Co-Products

8. Systems Integration & Interdependencies

1. Siting & Inputs

Geolocation/elevation
Land characteristics
Climate/Weather
Solar Insolation
Water Sources/Issues
- brackish
- wastewater
- produced
- desal concentrate
- marine
- fresh
- losses, re-use
- salt build-up

CO_2 Sources
- power plants
- cement plants
- fermentation/other

Chemicals/Materials
Energy/Power
Infrastructure

2. Algal Biology S&T

Species Selection & Matching to Growth Conditions

Characterization

Performance

Strain Improvement

Biomass Growth & Oil Content Optimization

Photoautotrophic organism operation

Heterotrophic organism operation

Algae Pathogens, Predators, and Mitigations

3. Cultivation Systems

Photoautotrophic

Open Ponds
- lined
- unlined
- raceway
- wastewater treatment

Closed PBRs
- horizontal tube
- vertical tube
- vertical planar
- other

Hybrid System Combinations
- covered ponds
- pond/PBR mix

Heterotrophic

- Industrial Bioreactors
- Wastewater Facilities

Operations, Monitoring & Maintenance

4. Harvesting & Dewatering

Filtering
Flocculation/Settling
Airlift Flocculation
Centrifuge
Drying
Biological Assist
- brine shrimp
- fish

Other

7. Policy & Regulatory

Taxes
Incentives
Permitting
Environmental Impact
Health & Safety
Algae Control & Regulation
Other

5. Extraction & Fractionation

Extract Processes
- Solvent
- Acoustic
- EM
- Other

Separation/Fractionation
- Membrane
- Distillation
- Centrifuge
- Other

Intermediate Products
- TAG Oil
- Other Lipids
  - Polar
  - Neutral
- Carbohydrates
- Proteins
- Other Compounds
- Water

Direct secretion of EtOH or hydrocarbon fuel precursors into growth medium, avoiding Harvest & Dewatering steps

6. Conversion Processes Biofuels, Co-products, & Services

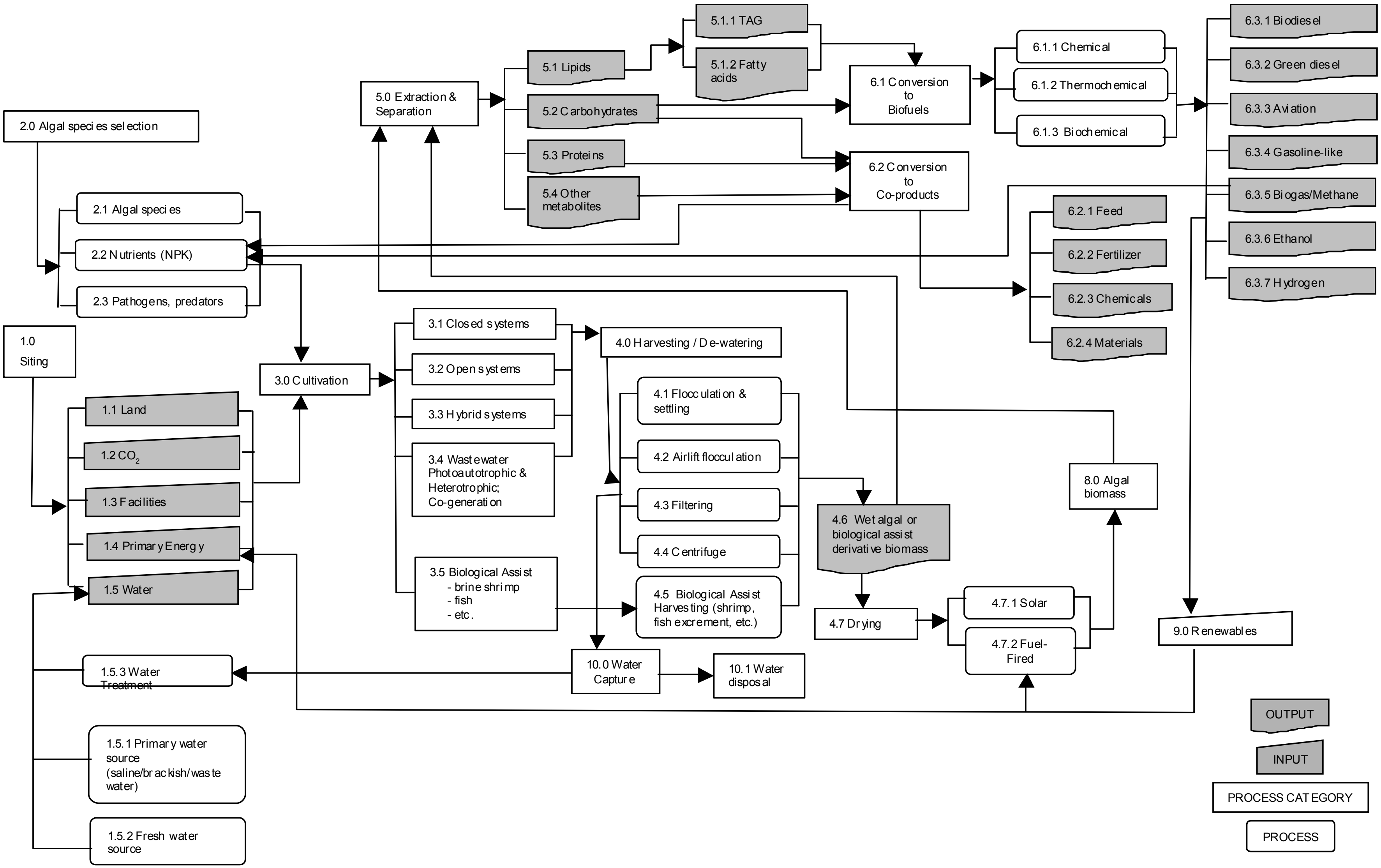
Conversion Processes
- Biochemical
- Thermochemical
- Digestion
- Hydrotreat/Refine

Fuels
- Biodiesel
- Green diesel
- Aviation
- Gasoline-like
- EtOH
- Biogas/methane
- Other

Co-Products
- Feed
- Fertilizer
- Chemicals

Services
- Carbon capture
- Water treatment

Process Flow Diagram



Evaluation Criteria & Objective Functions

Comparative TE analysis results depend on metrics used

- Minimize **Capital Costs** per unit of biofuel
- Minimize **Operating Costs** per unit of biofuel
- Maximize Biofuel **Production Yield**

(Capital Costs, Operating Costs and Production Yield together: Total Production Cost $/gal)

- Minimize net **GHG Footprint** per unit of biofuel produced
- Maximize net **Energy Balance**
- Minimize net **Water Usage**
- Minimize **Land Footprint** per unit of biofuel produced
- Minimize **Time Required** to reach desired production volume
- Minimize **Investment** Needed to reach desired prod. volume

Precedent for DOE: H2A

- President Bush launched the Hydrogen Fuel Initiative in February, 2003 to help ensure U.S. energy security and to reduce greenhouse gas and other harmful emission.
- In response, DOE established the Hydrogen, Fuel Cells and Infrastructure Program
  - Set research priorities and make other important program direction decisions informed by sound analysis
  - Evaluate costs, energy and environmental tradeoffs
  - Consider various pathways toward a hydrogen economy.
- A review of the public information available in this area led to these conclusions:
  - Many excellent analyses had been conducted.
  - Many analyses of the same or similar routes to produce hydrogen appeared to yield different results. Principal discrepancies lie in the basis and assumptions used in the analysis.

H2A Objectives

- Establish a standard format and list of parameters for reporting analysis results for central production, distributed (forecourt) production, and delivery.
- Seek better validation of public analyses through dialog with industry.
- Enhance understanding of the differences among publicly available analyses and make these differences more transparent.
- Establish a mechanism for facile dissemination of public analysis results.
- Work to reach consensus on specific analysis parameters for production and delivery.

H2A Participants

Core Members

Daryl Brown: PNNL

Jerry Gillette: ANL

Brian James: Directed Technologies

Steve Lasher: TIAX

Johanna Levene: NREL

Margaret Mann: NREL

Dan Mears: Technology Insights

Marianne Mintz: ANL

Joan Ogden: UC, Davis

Marylynn Placet: PNNL

Matt Ringer: NREL

Mike Rutkowski: Parsons

Harry Stone: Battelle

Michael Wang: ANL

Key Industry Collaborators

AEP

BOC

BP

Chevron

Eastman Chemical

Entergy

ExxonMobil

Ferco

Framatome

General Electric

Praxair

Stuart Energy

Thermochem

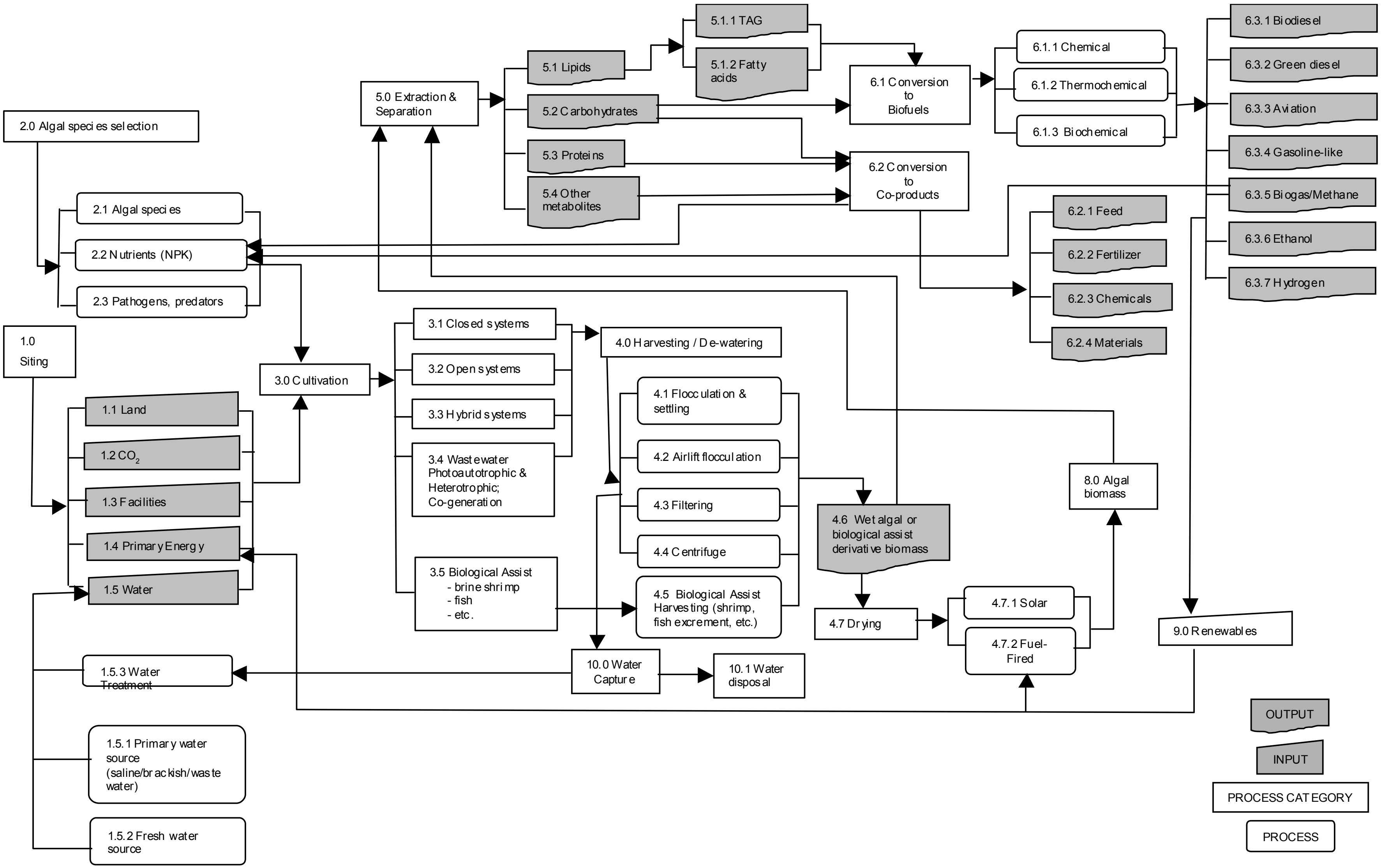
H2A Analyses

- Original source(s) of all the data (i.e., report title, authors, etc.)
- Basic process information (feedstock and energy inputs, size of plant, co-products produced, etc.)
- Process flowsheet and stream summary (flowrate, temperature, pressure, composition of each stream)
- Technology performance assumptions (e.g., process efficiency and hydrogen product conditions)
- Economic assumptions (after tax internal rate of return, depreciation schedule, plant lifetime, income tax rate, capacity factor, etc.)
- Calculation of the discounted cash flow (the calculation procedure is built into the standardized spreadsheet so that all technologies use the same methodology)
- Results (plant-gate hydrogen selling price and cost contributions in $/kg H2, operating efficiency, total fuel and feedstock consumption, and emissions)
- Sensitivity of the results to assumptions (e.g., feedstock cost, co-product selling price, capital cost, operating costs, internal rate of return, conversion efficiencies, etc.)
- Quantification of the level of uncertainty in the analysis

H2A Production Technologies

- Central Production of Hydrogen
  - Coal Gasification: Hydrogen Production
  - Coal Gasification: Hydrogen and Electricity Production
  - Natural Gas Hydrogen Production
  - Biomass Gasification Hydrogen Production
  - Nuclear Energy Hydrogen Production
  - Wind Electrolysis Hydrogen Production
- Forecourt Production of Hydrogen
  - Natural Gas Reforming
  - Electrolysis
  - Reforming of Ethanol sourced from biomass
  - Reforming of Methanol sourced from biomass

Not As Bad As We Thought

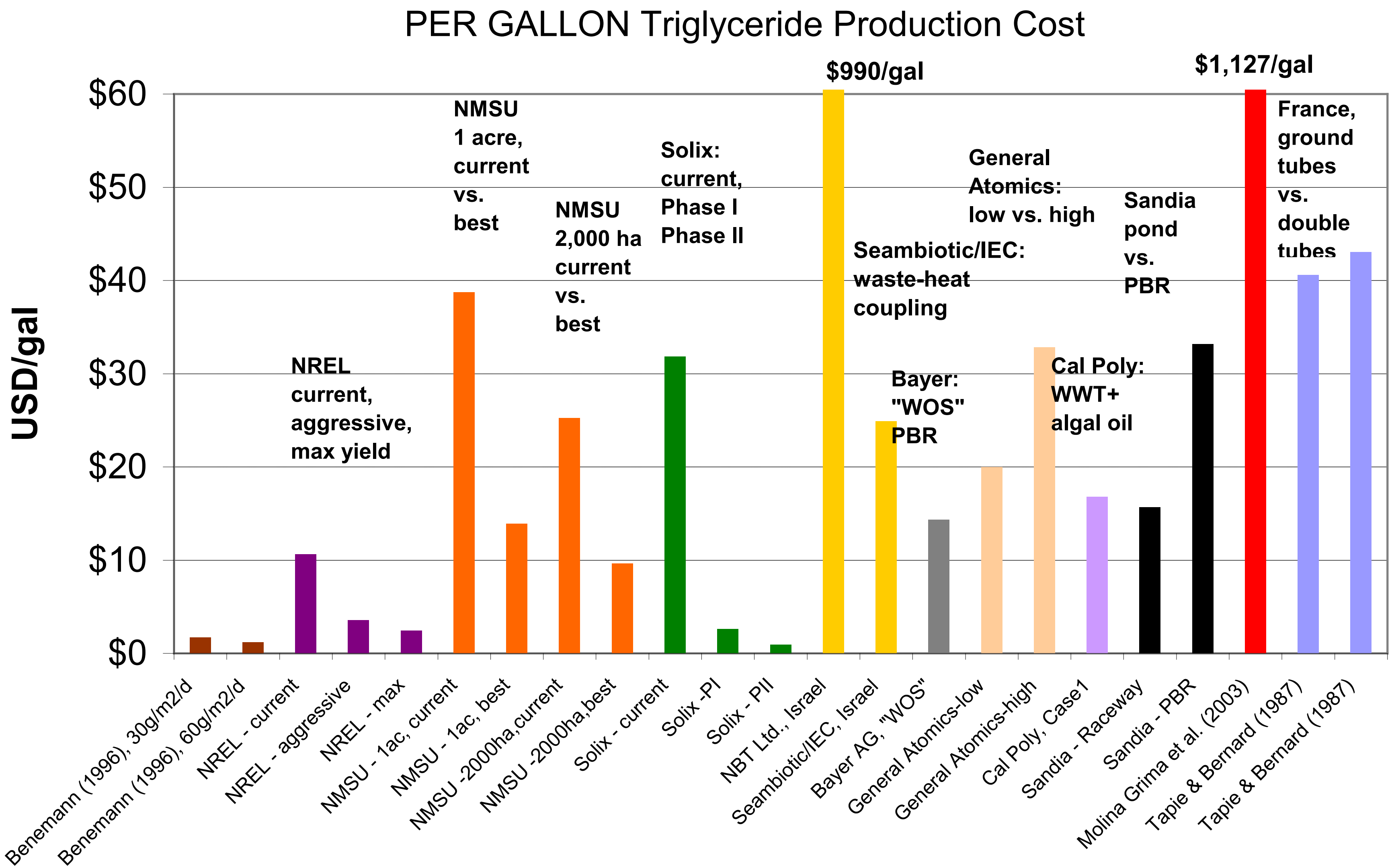


Source Material for TE Models

Source	Authors	Year	Reference
NREL	Matt Ringer Bob Wallace Phil Pienkos	2008	Analysis completed for this exercise
NMSU	Meghan Starbuck Pete Lammers	2008	Analysis completed for this exercise
Solix	Bryan Willson	2008	2nd Bundes-Algen-Stammtisch
Seambiotics	Ami Ben-Amotz, Israel	2007-2008	Algae Biomass Summit
Sandia	Ben Wu	2007	Analysis completed for this exercise
Bayer	Ulrich Steiner	2008	European White Biotechnology Summit
General Atomics	David Hazlebeck	2008	Algae Biomass Summit
California Polytechnic Institute	Tryg Lundquist	2008	Algae Biomass Summit
University of Almeria	E. Molina Grima E. Belarbi F. Fernandez A. Medina Y. Chisti	2003	Biotechnol. Adv. (2003) 20:491-515
Association pour la Recherche en Bioenergie	P. Tapie A. Bernard	1988	Biotech. Bioeng. (1988) 32:873-885
University of California	John Benemann William Oswald	1996	PETC Final Report

Standardized Cost Comparison

- *Average = $109 USD/gal*
- *Variability is wide, Std. Dev. = $301 USD/gal*

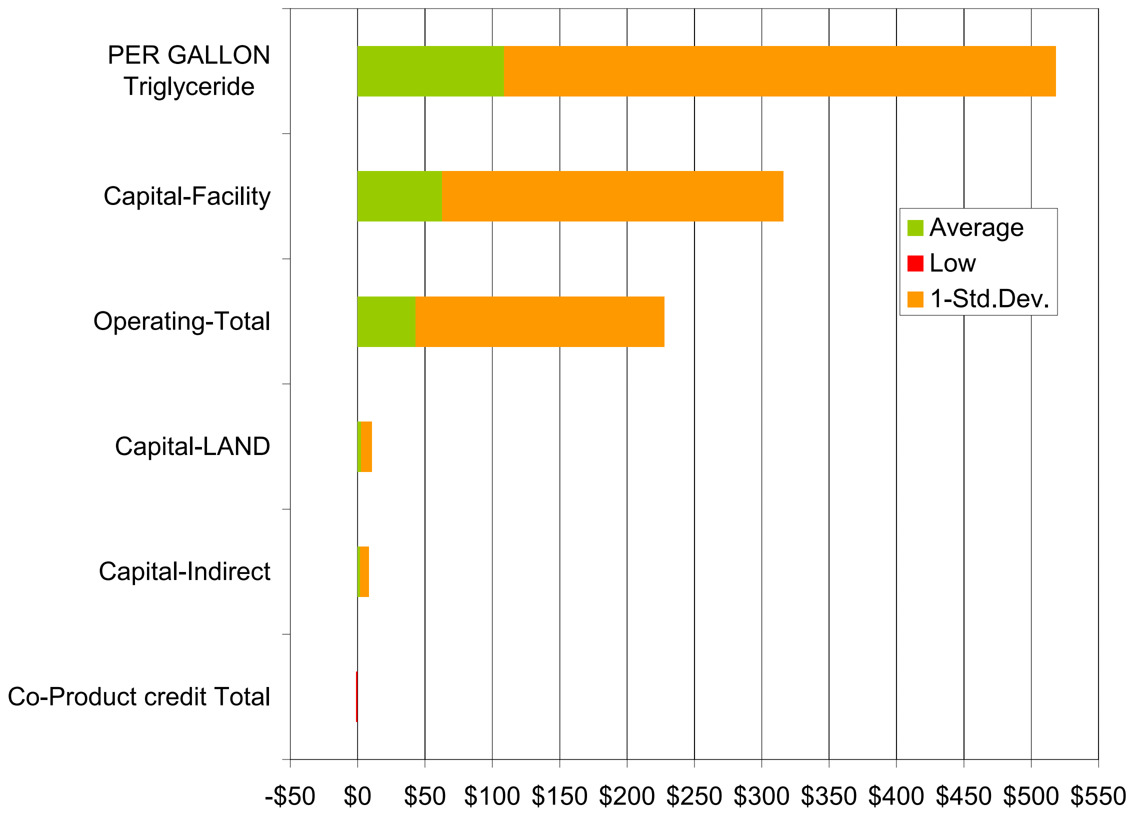


Inherent Assumptions Vary Widely

	SCENARIO	Reactor Type	Lipid yield (wt% of dry mass)	Areal Dry Algae Mass Yield (g/m2/day)	Loan Period (yrs)
Benemann	per ha basis	open pond	50%	30	5
Benemann	per ha basis	open pond, max	50%	60	5
NREL	Current Case	open pond	25%	20	15
NREL	Aggressive Case	open pond	50%	40	15
NREL	Maximum Case	open pond	60%	60	15
NMSU	current yield	open pond	35%	35	20
NMSU	highest yield	open pond	60%	58	20
Solix	Current	hybrid	16% - 47%	0 - 24.5	unk
Solix	Q2, 2009	hybrid	16% - 47%	30-40	unk
NBT, Israel	Dunaliella	open	35%*	2	unk
Seambiotic/IEC, Israel	Best Yield	open	35%*	20	unk
Sandia	Raceway&PBR	both	35%	30	20
Bayer Tech Services	Germany	PBR	33%	52	10
Bayer Tech Services	El Paso, TX	PBR	33%	110	10
General Atomics	100 acres	open/hybrid	unk	unk	unk
Molina-Grima et al.	26.2 metric ton/annum	75 0.8 m^3 outdoor T-PBRs	10%	unk	10
Cal Poly, Case1	100 ha	wastewater treatment + digester	25%	20	8
Tapie & Bernard	10 ha	T-PBR	35%*	20	5

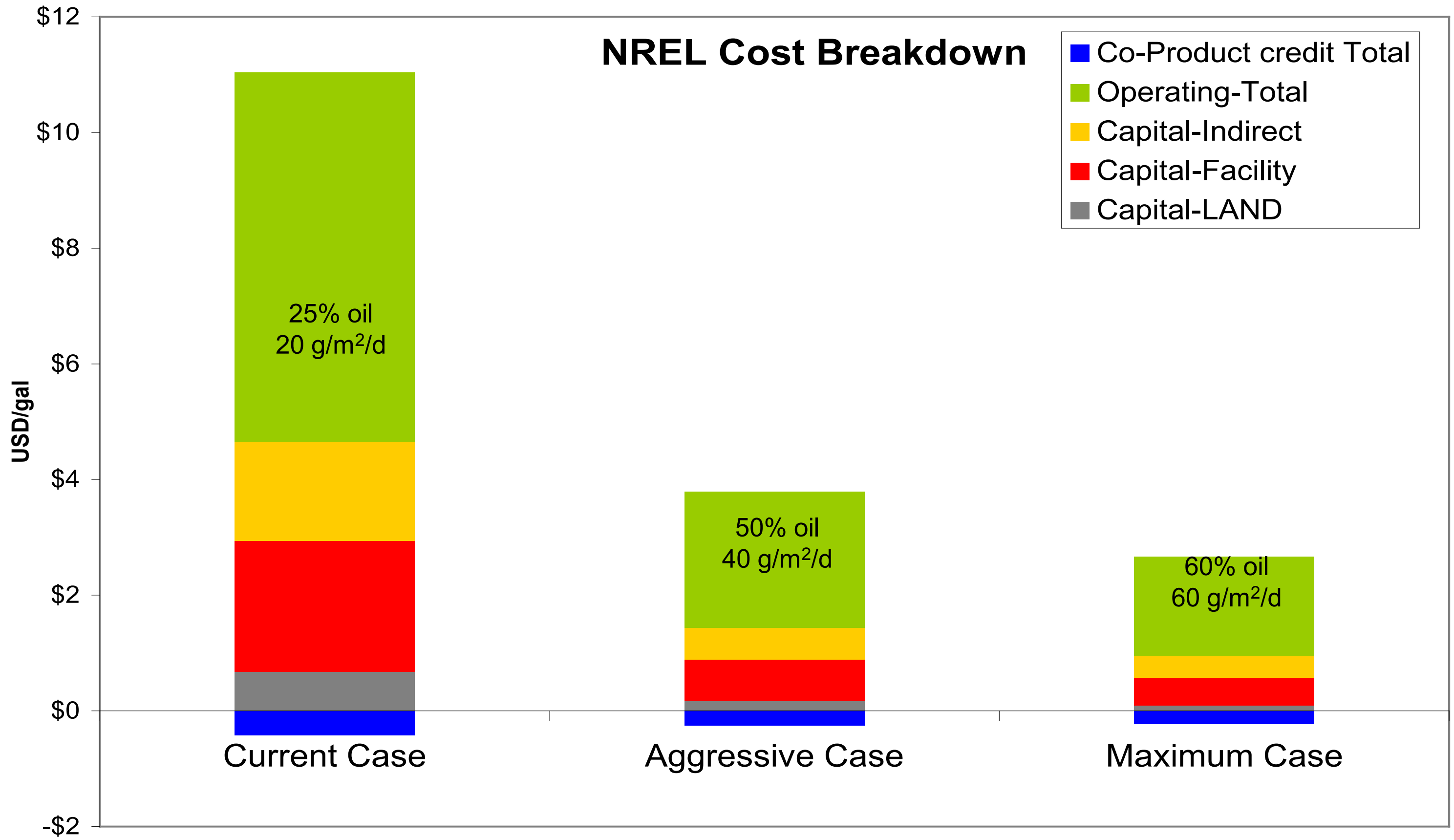
* Assumed quantity required to convert from weight-basis to oil-basis

Uncertainty by Cost Categories



- *Cost Uncertainties dominated by uncertainties in Facility and Operating cost estimation.*
- *Land cost is either not considered or small in most sources relative to Total Capital Cost.*
- *Co-product credit does not reduce the overall uncertainty in cost estimation.*

Cost Reductions (NREL)



Cost Reductions (Solix)

Production Metrics (current & near-term)

SOLIX

Integrated PAR	10-65 mol/m²/d
Culture Density	1-10 g/l
Volumetric Production	≈0-0.7 g/l/d (≈0.45 "typical" before depletion, ≈0.25 after)
Lipids (as FAMEs)	16% - 47%
Areal Production	0 – 24.5 g/m²/d
Production	0 – 1800 gal/ac/yr
Expected productivity by '09 Q2:	30-40 g/m²/d 2500 gal/ac/yr
Gen 2 Operation	May '07 – Oct '07
Gen 3 Operation	Oct '07 - present

Slide used with permission of Dr. Bryan Willson

Conclusions

- Many things have changed since the last major push for algal biofuels
  - The price of oil has fluctuated wildly
  - Energy security is a real issue
  - Climate change is widely recognized as a significant threat
  - Real capital is being raised for algal biofuel commercialization
  - Not many more known knowns but a few more known unknowns
- Technoeconomic modeling is a critical element to determine:
  - Best estimate for current cost of algal biofuel production
  - Fastest road forward to commercialization
- The current state of technoeconomic modeling
  - Is more dependent upon assumptions than on data
  - Results in huge variations in cost estimates and uncertainty

Conclusions, continued

- Modeling for algal biofuel production is extremely complicated
  - Alternative approaches to cultivation, harvest, extraction
  - Different assumptions about input costs and byproduct values
  - Availability of essential resources (sunlight, land, CO_2, and water) vary significantly across the US and models must take these variations into account
- The H2A program for hydrogen production and storage can provide valuable insight and precedent for improved modeling
- The work initiated for this workshop is a step towards the development of a unified model that can be shared with all stakeholders to provide a common metric to measure progress towards the goal of commercialization of algal biofuels.