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
You Are Here

Patents approved; prepare to collect royalties.

Sell stake to oil company.

Low cost feedstock becomes available; begin process development.

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 roadmapping 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

## 1. Siting & Inputs
- Geolocation/elevation
- Land characteristics
- Climate/Weather
- Solar Insolation
- Water Sources/issue
  - brackish
  - wastewater
  - produced
  - desal concentrate
  - marine
  - fresh
  - losses, re-use
  - salt build-up
- CO₂ 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
- Photosynthetic organism operation
- Heterotrophic organism operation
- Algae Pathogens, Predators, and Mitigations
- Operations, Monitoring & Maintenance

## 3. Cultivation Systems
- Photoautotrophic
  - Open Ponds
    - lined
    - unlined
    - raceway
    - wastewater treatment
  - Closed PBRs
    - horizontal tube
    - vertical tube
    - vertical planar
    - other

## 4. Harvesting & Dewatering
- Filtering
  - Flocculation/Settling
  - Airlift Flocculation
  - Centrifuge
  - Drying
  - Biological Assist
    - brine shrimp
    - fish
  - 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

## 7. Policy & Regulatory
- Taxes
- Incentives
- Permitting
- Environmental Impact
- Health & Safety
- Algae Control & Regulation
- Other

## 8. Systems Integration & Interdependencies

## 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
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**
- 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

\[
\text{Total Production Cost $/gal}
\]
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: TIAAX
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
## Source Material for TE Models

<table>
<thead>
<tr>
<th>Source</th>
<th>Authors</th>
<th>Year</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NREL</td>
<td>Matt Ringer</td>
<td>2008</td>
<td>Analysis completed for this exercise</td>
</tr>
<tr>
<td></td>
<td>Bob Wallace</td>
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<td></td>
<td>Phil Pienkos</td>
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<tr>
<td>NMSU</td>
<td>Meghan Starbuck</td>
<td>2008</td>
<td>Analysis completed for this exercise</td>
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<td></td>
<td>Pete Lammers</td>
<td></td>
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<tr>
<td>Solix</td>
<td>Bryan Willson</td>
<td>2008</td>
<td>2nd Bundes-Algen-Stammtisch</td>
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<tr>
<td>Seambiotics</td>
<td>Ami Ben-Amotz, Israel</td>
<td>2007-2008</td>
<td>Algae Biomass Summit</td>
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<tr>
<td>Sandia</td>
<td>Ben Wu</td>
<td>2007</td>
<td>Analysis completed for this exercise</td>
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<tr>
<td>Bayer</td>
<td>Ulrich Steiner</td>
<td>2008</td>
<td>European White Biotechnology Summit</td>
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<tr>
<td>General Atomics</td>
<td>David Hazlebeck</td>
<td>2008</td>
<td>Algae Biomass Summit</td>
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<tr>
<td>California Polytechnic Institute</td>
<td>Tryg Lundquist</td>
<td>2008</td>
<td>Algae Biomass Summit</td>
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<tr>
<td></td>
<td>E. Belarbi</td>
<td></td>
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<td></td>
<td>F. Fernandez</td>
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<td></td>
<td>A. Medina</td>
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<td></td>
<td>Y. Chisti</td>
<td></td>
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<tr>
<td>University of California</td>
<td>John Benemann,</td>
<td>1996</td>
<td>PETC Final Report</td>
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<td></td>
<td>William Oswald</td>
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</tbody>
</table>
Standardized Cost Comparison

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

PER GALLON Triglyceride Production Cost

USD/gal

NREL
- current
- aggressive
- max yield

NMSU
- 1 acre, current vs. best
- 2,000 ha current vs. best

Solix:
- current, Phase I
- Phase II

General Atomics:
- low vs. high

Seambiotic/IEC:
- waste-heat coupling

Bayer:
- "WOS" PBR

Cal Poly:
- WWT+ algal oil

Sandia:
- pond vs. PBR

France,
- ground tubes vs. double tubes

Benemann (1996), 30g/m2/d
Benemann (1996), 60g/m2/d
NREL - current
NREL - aggressive
NREL - max
NMSU - 1ac, current
NMSU - 1ac, best
NMSU - 2000ha, current
NMSU - 2000ha, best
Solix - current
Solix - PI
Seambiotic/IEC, Israel
Bayer AG, "WOS"
General Atomics, low
General Atomics, high
Cal Poly, Case 1
Sandia - Raceway
Sandia - PBR
Molina Grima et al. (2003)
Tapie & Bernard (1987)
### Inherent Assumptions Vary Widely

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>Reactor Type</th>
<th>Lipid yield (wt% of dry mass)</th>
<th>Areal Dry Algae Mass Yield (g/m²/day)</th>
<th>Loan Period (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benemann per ha basis</td>
<td>open pond</td>
<td>50%</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>Benemann per ha basis</td>
<td>open pond, max</td>
<td>50%</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>NREL Current Case</td>
<td>open pond</td>
<td>25%</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>NREL Aggressive Case</td>
<td>open pond</td>
<td>50%</td>
<td>40</td>
<td>15</td>
</tr>
<tr>
<td>NREL Maximum Case</td>
<td>open pond</td>
<td>60%</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>NMSU current yield</td>
<td>open pond</td>
<td>35%</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>NMSU highest yield</td>
<td>open pond</td>
<td>60%</td>
<td>58</td>
<td>20</td>
</tr>
<tr>
<td>Solix Current</td>
<td>hybrid</td>
<td>16% - 47%</td>
<td>0 - 24.5</td>
<td>unk</td>
</tr>
<tr>
<td>Solix Q2, 2009</td>
<td>hybrid</td>
<td>16% - 47%</td>
<td>30-40</td>
<td>unk</td>
</tr>
<tr>
<td>NBT, Israel Dunaliella</td>
<td>open</td>
<td>35%*</td>
<td>2</td>
<td>unk</td>
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<tr>
<td>Seambiotic/IEC, Israel</td>
<td>Best Yield</td>
<td>35%*</td>
<td>20</td>
<td>unk</td>
</tr>
<tr>
<td>Sandia Raceway&amp;PBR</td>
<td>both</td>
<td>35%</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Bayer Tech Services</td>
<td>PBR</td>
<td>33%</td>
<td>52</td>
<td>10</td>
</tr>
<tr>
<td>Bayer Tech Services</td>
<td>PBR</td>
<td>33%</td>
<td>110</td>
<td>10</td>
</tr>
<tr>
<td>General Atomics</td>
<td>open/hybrid</td>
<td>unk</td>
<td>unk</td>
<td>unk</td>
</tr>
<tr>
<td>Molina-Grima et al.</td>
<td>26.2 metric ton/annum</td>
<td>75 0.8 m³ outdoor T-PBRs</td>
<td>10%</td>
<td>unk</td>
</tr>
<tr>
<td>Cal Poly, Case1</td>
<td>100 ha</td>
<td>wastewater treatment + digester</td>
<td>25%</td>
<td>20</td>
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<tr>
<td>Tapie &amp; Bernard</td>
<td>10 ha</td>
<td>T-PBR</td>
<td>35%*</td>
<td>20</td>
</tr>
</tbody>
</table>

* Assumed quantity required to convert from weight-basis to oil-basis
• 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 (Solix)

<table>
<thead>
<tr>
<th>Production Metrics (current &amp; near-term)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated PAR</td>
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<tr>
<td>Culture Density</td>
</tr>
<tr>
<td>Volumetric Production</td>
</tr>
<tr>
<td>(≈0.45 “typical” before depletion, ≈0.25 after)</td>
</tr>
<tr>
<td>Lipids (as FAMEs)</td>
</tr>
<tr>
<td>Areal Production</td>
</tr>
<tr>
<td>Production</td>
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<tr>
<td>Expected productivity by ’09 Q2:</td>
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<tr>
<td></td>
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<tr>
<td>Gen 2 Operation</td>
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<tr>
<td>Gen 3 Operation</td>
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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, CO₂, 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.