Biofuels and the Energy-Water Nexus

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AAAS/SWARM
April 11, 2008
Albuquerque, NM
Contents of Presentation

- Biofuels Interest and Motivation for Sandia
- Energy-Water Nexus Context for Biofuels
- Water Issues for Alternative Transportation Fuels
- The Promise & Challenge of Algal Biofuels
- Conclusions
Biofuel Interest & Motivation

- **Energy Security ... Heavy U.S. dependence on petroleum imports**
  - Oil imports of ~10-M bbl/day (150+ B-gal/yr)
    - two thirds for transportation fuels
  - Subject to supply disruption from volatile regions
  - Represents $300+ B/yr burden on U.S. economy
    - supports interests hostile to US
  - Increasing competition (China, India, etc.)
    - & price volatility for limited global supplies
  - “Peak Oil” concerns
    - decades away?
    - In 10-years?
    - happening now?

- **Assessing paths for build-up & integration with existing production, energy/fuels, and transportation infrastructure**
  - Sustainable Approaches and Associated Costs/Benefits/Impacts Tradeoffs
  - Technology, Processes, and Systems R&D Needs and Priorities
  - Insight for Technical and Non-Technical (e.g. Policy) Decision-Support

- **Energy-Water Nexus and Climate Change Concerns**
  - Mitigate adverse impacts on land use, water, GHG footprint, etc.

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Biofuel Interest & Motivation

- **Energy-Water Nexus Investigations for DOE**
  - Report to Congress released in early-2006
    
    - Three Needs Assessment Workshops: Western, Central, Eastern U.S.
    - Gaps Analysis Workshop
    - Technology Innovations Workshop
    - Energy-Water Roadmap Report expected to be released by DOE in 2008

- **Among the major findings:**
  - Water for Biofuels is an Emerging Issue
  - Water Impacts of National Biofuels Scale-up Needs Attention
  - Corroborated by recent National Academy Report
    
Energy-Water Nexus
Context for Biofuels

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Future energy development will put new demands on water

- Many newer technologies will be more water intensive
- Transition to biofuels and a possible longer-term future hydrogen economy will require significantly more water than current fossil transportation fuels
- Constraints will grow for power plant siting because of water for cooling needs, advanced scrubbing, and CO₂ removal
- Constraints will grow in some areas for siting of biorefineries and other alternative fuel processing plants (oil shale, coal-to-liquids) due to water supply limitations or impacts

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Projected Trends in Non-Agricultural Water Consumption and Available Water Supplies From Fresh and Treated Sources

Take-Away Message: New Water will be Non-Fresh!!
Water Issues for Alternative Transportation Fuels
## Water Demand/Impact of Transportation Fuels

<table>
<thead>
<tr>
<th>Fuel Type and Process</th>
<th>Relationship to Water Quantity</th>
<th>Relationship to Water Quality</th>
<th>Water Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Oil &amp; Gas</td>
<td>Water needed to extract and refine; Water produced from extraction</td>
<td>Produced water generated from extraction; Wastewater generated from processing;</td>
<td>Water consumed per-unit-energy [gal/MMBTU]†</td>
</tr>
<tr>
<td>- Oil Refining</td>
<td></td>
<td></td>
<td>7 – 20</td>
</tr>
<tr>
<td>- NG extraction/Processing</td>
<td></td>
<td></td>
<td>2 – 3</td>
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<tr>
<td>Biofuels</td>
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<tr>
<td>- Grain Ethanol Processing</td>
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<tr>
<td>- Corn Irrigation for EtOH</td>
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<tr>
<td>- Biodiesel Processing</td>
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<tr>
<td>- Soy Irrigation for Biodiesel</td>
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<tr>
<td>- Lignocellulosic Ethanol and other synthesized Biomass to Liquid (BTL) fuels</td>
<td>Water for processing; Energy crop impacts on hydrologic flows</td>
<td>Wastewater generated; Water quality benefits of perennial energy crops</td>
<td>12 – 160</td>
</tr>
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<td>-</td>
<td></td>
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<td>2500 – 31600</td>
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<td>-</td>
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<td>4 – 5</td>
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<td>13800 – 60000</td>
</tr>
<tr>
<td>Oil Shale</td>
<td>Water needed to Extract / Refine</td>
<td>Wastewater generated; In-situ impact uncertain; Surface leachate runoff</td>
<td>1 – 9 †</td>
</tr>
<tr>
<td>- In situ retort</td>
<td></td>
<td></td>
<td>15 – 40 †</td>
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<tr>
<td>- Ex situ retort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Sands</td>
<td>Water needed to Extract / Refine</td>
<td>Wastewater generated; Leachate runoff</td>
<td>20 – 50</td>
</tr>
<tr>
<td>Synthetic Fuels</td>
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<td></td>
<td></td>
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<tr>
<td>- Coal to Liquid (CTL)</td>
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<tr>
<td>- Hydrogen RE Electrolysis</td>
<td></td>
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<tr>
<td>- Hydrogen (NG Reforming)</td>
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<td>35 – 70</td>
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<td>20 – 24 †</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>40 – 50 †</td>
</tr>
</tbody>
</table>

† Ranges of water use per unit energy largely based on data taken from the Energy-Water Report to Congress (DOE, 2007)
* Conservative estimates of water use intensity for irrigated feedstock production based on per-acre crop water demand and fuel yield
† Estimates based on unvalidated projections for commercial processing; † Assuming rain-fed biomass feedstock production

“A” (Approved for Public Release, Distribution Unlimited)
### Water Demand for Biofuels Production

**Feedstock Production and Fuel Processing**

<table>
<thead>
<tr>
<th>Fuel Type and Conversion Process</th>
<th>Biomass Feedstock</th>
<th>Processing Water Use Intensity (gal H₂O/gal fuel)</th>
<th>Feedstock Water Use Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol, Starch or sugar-based Wet mill or Dry mill</td>
<td>Corn, Sorghum, Sugar Cane, Sugar Beets</td>
<td>~ 2 - 6, ~ 4</td>
<td>~ 1.2, ~ 1.0, ~ 2.0, ~ 2.3</td>
</tr>
<tr>
<td>Ethanol, Cellulose-based Biochem or Thermochem</td>
<td>Switchgrass, Woody biomass</td>
<td>~ 3 – 12 estimate, ~ 2 - 6 estimate</td>
<td>~ 2.3, 500 - 800 (700 estimated)(^b)</td>
</tr>
<tr>
<td>Biodiesel from Oil Extraction and Trans-Esterification</td>
<td>Soybeans, Sunflower, Oil Palm, Algae</td>
<td>~ 0.3 - 3, ~ 1, ~ 1</td>
<td>~ 0.8, ~ 1.5, ~ 2.5, Not determined(^f)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Feedstock Water Demand Ac-ft / Acre</th>
<th>Biofuel Yield gal fuel / Acre</th>
<th>Feedstock Water Consumption gal H₂O/gal fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol, Starch or sugar-based Wet mill or Dry mill</td>
<td>~ 1.2</td>
<td>400</td>
<td>980</td>
</tr>
<tr>
<td>Ethanol, Cellulose-based Biochem or Thermochem</td>
<td>~ 2.3</td>
<td>500 - 800 (700 estimated)(^b)</td>
<td>Rain-fed</td>
</tr>
<tr>
<td>Biodiesel from Oil Extraction and Trans-Esterification</td>
<td>~ 0.8</td>
<td>40</td>
<td>6500</td>
</tr>
<tr>
<td></td>
<td>~ 2.5</td>
<td>510</td>
<td>Rain-fed</td>
</tr>
</tbody>
</table>

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<tr>
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</thead>
<tbody>
<tr>
<td>(^a) Cellulose-based ethanol yields of 100 gal/dry ton based on laboratory data, processes are still experimental</td>
<td></td>
<td></td>
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<tr>
<td>(^b) Switchgrass yields have exceeded 10 dry tons/acre experimentally, but more routinely range from 3 to 7 dry tons/acre</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^c) Algal-based biodiesel production estimates based on laboratory and small scale test data; viable high-yield scale-up still uncertain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^d) Water consumption with irrigated feedstock production at per-acre water demand and per-acre biofuel yield levels shown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^e) Estimates based on unvalidated projections for commercial processing;</td>
<td></td>
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</tr>
<tr>
<td>(^f) Non-fresh water used; losses mainly from evaporation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Biofuels Challenge: Sustainable Scale-Up

Commodity Crops
Sugar, Starch, Oil

Algae

Woody Crops; Ag & Forest Wastes

Cellulosic Biomass

Non-Food Energy Crops e.g., Switchgrass

“Farm Fuel”

Source: Science News

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Replacing Petroleum-based Fuels … is a Huge Challenge!

Significance of the “Billion Ton” Scenario

- End-Use Fuel Efficiency Improvements Also Needed

Based on ORNL & USDA Resource Assessment Study by Periach et al. (April 2005)

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EISA 2007 Renewable Fuels Standard
36-Billion Gallons of Biofuel by 2022

- Corn Ethanol: maximum 15 bgy
- Biomass-based Diesel: maximum = ?
- Biofuel from Cellulose: 16 bgy, 2022
- Technology-neutral Advanced Biofuel: maximum = ?

billion gallons per year

Water Impacts Seen with Increase in Biofuels and Bioenergy Production

Emerging as an energy-water nexus issue
Need better understanding and management
Need innovative approaches & technologies
Need options that exploit non-fresh water
The Biofuel-Water Connection… Subject of Increasing “Discussion”

Water Use by Ethanol Plants: Potential Challenges

Corn and Water: Facts in Perspective
EtOH Production & Groundwater

Source: NAS Report, 2007
The Promise and Challenge of Algal Biofuels
Opportunity from E-W Perspective:
Biofuel from Algae using Non-Fresh Water Sources

Algae-Based Production of Biofuels, Coproducts, & Services w/ Impaired Waters

Impaired Water
- brackish groundwater
- produced water
- desalination concentrate
- Ag wastewater
- Industrial wastewater
- Municipal wastewater
- Geothermal water & heat

Waste CO₂ & Heat
- Electric power generation
- Ag processing
- Industrial processing
- Wastewater treatment
- Desalination

Algae Production Systems
Ponds, PBRs*, Hybrid Systems†

Co-Products
- feeds
- fertilizers
- biopolymers
- glycerine
- other

* PBRs = PhotoBioReactors
† Hybrid Systems = Ponds + PBRs

Biomass Harvesting

Processing

Biofuels
- biodiesel
- biogas
- ethanol
- JP-8

Reclaimed Water
- nutrient removal

Sunlight (photoautotrophic)

Organic Carbon (heterotrophic)

O₂

Biofixation of CO₂

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Saline aquifers in the continental U.S. The brown shading refers to the depth of the aquifer. With appropriate treatment, inland brackish water resources could be an important source of water for thermoelectric power plant cooling and biofuel production. (Data from Feth, 1965)
Produced Water from Oil & Gas Wells …
Potential Resource for Algae Production

Green=oil, Red=gas, Yellow=mixed
Pairing Microalgae to Non-Fresh Water to Maximize Algal Oil Production

Optimal Matches Among Water Properties and Microalgae Growth and Survivability

Maximize Triacylglycerol Production

Maximize Microalgal Based Biodiesel and other BioFuels

Source: EPA

US Saline Aquifers

Source: U.S. Geological Survey
GIS-based Site Analysis for Algal Biomass Production Facilities
Algal Biomass Production Scale-up
Photobioreactor (PBR) vs Pond Systems

... Increased control & performance vs higher infrastructure costs?
... Viability of scale-up for sustainable algal-based biofuel production?

Conceptual Illustration of Commercial Scale Algal Biomass Production Facility using Photobioreactor systems - Solix

Commercial Microalgae Production Facility using Raceway Pond Systems
- Cyanotech Corporation, Kona, Hawaii
Got Algal Oil?
… not enough and too expensive!

Reducing Algal Oil Production Costs
Systems and Processes Scale-up Issues/Challenges

- Algal strain selection / improvement
- Production systems (Ponds? PBRs?)
- CO$_2$ source/infrastructure/cost
- Biomass/oil productivity & reliability
- Harvesting & dewatering processes
- Oil extraction & separation processes
- Oil feedstock yield, properties
- Installed system capital costs
- Production system O&M costs
- Energy & water balances, etc.

Commercially-Viable Scale (e.g., ≥ 50 Mg/yr)

Past / Current
~ 10 - 100 $/gal
Algal Oil

Cost/gal

Algal Oil Production Scale-Up and Cost Reduction

Future
1 - 3 $/gal?
Algal Oil

Production Scale

Time

Today

3 - 5 years?
... 5 - 10 years?
... beyond 10 years?
DOD/DARPA is Stepping UP!

BioFuels Program, BAA 08-07

**Technical area 1: Cellulosic materials to JP-8**
- Cellulosic materials offer the potential as a low-cost feedstock to high-cost oil crops (soy, canola, etc)
- Usage is limited by low processing efficiency
- Leverage and integrate multiple technologies
  - Gasification and liquefaction
  - Biological and catalytic processing
- Key technical challenge is to develop a highly efficient process to JP-8 from cellulosic materials

| Phase 1: 30% energy conversion efficiency |
| Phase 2: 50% energy conversion efficiency |

**Technical area 2: Algal to JP-8**
- Algae offers the potential for high-oil yields/acre
- Usage is limited by high-cost processing factors for large-scale production
- Leverage advances already achieved in current BioFuels program through teaming and/or licensing
- Key technical challenge is to develop an integrated algal production system for low-cost oil production

| Phase 1: production cost at < $2/gal |
| Phase 2: production cost at < $1/gal |

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Bio-Oil-to-JP8 Systems Analysis Framework

Overall bio-oil to JP-8 system & process value chain

**Collateral Issues:**
- CO2 sourcing & integration
- Geo-Location, Climate, Siting
- Water
- Energy
- Materials
- Market dynamics
- Policy

Multiple Processes
- Algal biomass growth
- Oil content optimization
- Harvesting & Dewatering
- Drying
- Oil Extraction & Degumming
- Co-Product Separation
- Recycling

Multiple Systems & Protocols
- Open ponds
- Closed PBR
- Hybrid Combination

Multiple Algal Strains & Characteristics

Integration into existing U.S. infrastructure used for Military Fuel Distribution

End Use

Storage Transportation Distribution

JP-8 (Equivalent) Fuel

Co-Products and Recycling
- water
- energy
- materials
- chemicals

Multiple Pathway Supply / Value-Chain for Algal Oil Feedstock, JP-8 Fuel, and Co-Product Production
Algal Oil Production
Notional “Baseline”
Scale-Up Assessment

PBR & Open Pond
Systems Approaches

Based on limited available information from open sources applied to two generic algal production system configurations:
1) PBR with cooling to prevent overheating;
2) open raceway pond
Baseline Cost/Performance Analysis
Algal Oil Production Systems/Processes

Approach to microalgae oil production cost estimation

- Use Benemann and Oswald’s economic analysis in 1996 PETC report (open pond) and more recent pond and PBR technical/economic analyses (e.g., Chisti (2007), Richmond (2004), Molina Grima, et.al. (2003), etc.) for background and comparison
- Develop mod/sim/analysis/LCA of overall system/process chain (diagram shown above)
- Apply unit operations and designs validated by data from outdoor development systems
- Apply scale-up and infrastructure build-up cost/benefit assessments
- Update economic analysis to reflect
  - Inflation
  - New unit operations
- Identify improvement opportunities with systems and processes through sensitivity analysis of multiple pathway options
Algal PBR Mass Balance at 50M gal/year

- Capture 75% carbon from 1 GW power plant in daylight
- 68 km² (16,796-Ac) to produce 50 million gallons/year of triglyceride
- Productivity ~2977 gal/Ac of Neutral Lipid TAG
- Significant evaporative water loss for cooling PBR ~ 1000:1 (H₂O:oil)

<table>
<thead>
<tr>
<th>Description</th>
<th>Water Inlet</th>
<th>Air Inlet</th>
<th>Fertilizer</th>
<th>Air Outlet</th>
<th>PBR out</th>
<th>Mem Water</th>
<th>Slurry</th>
<th>Cent Water</th>
<th>Paste</th>
<th>Exhaust</th>
<th>Dried Algae</th>
<th>Bioreidue</th>
<th>Crude Oil</th>
<th>Polar Lipids</th>
<th>Pure Oils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass (lbs/hr)</td>
<td>45,917,314</td>
<td></td>
<td></td>
<td></td>
<td>45,871,494</td>
<td>27,236,863</td>
<td>18,634,631</td>
<td>17,702,899</td>
<td>931,732</td>
<td>931,732</td>
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<td>Neutral Lipids (lbs/hr)</td>
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<td>341,635</td>
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<td>Polar Lipids (lbs/hr)</td>
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<td></td>
<td>18,635</td>
<td>18,635</td>
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<tr>
<td>Water (lbs/hr)</td>
<td>45,917,314</td>
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<td>341,635</td>
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<td>CO₂ (lbs/hr)</td>
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<tr>
<td>Air (lbs/hr)</td>
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<td>106,017,391</td>
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<tr>
<td>Fertilizer (lbs/hr)</td>
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</tbody>
</table>
Algal PBR Energy Balance at 50M gal/year

- Direct cooling with chilled water is too energy intensive
- Indirect cooling requires less energy but requires more water
- Drying of biomass is too energy intensive and must be significantly reduced or eliminated

Energy consumption factors normalized to $1 = 222,000 \text{ kWh} = 37.7 \text{ MJ per kg TAG}$

<table>
<thead>
<tr>
<th>Unit Operation</th>
<th>Energy (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBR - Aeration</td>
<td>68,512</td>
</tr>
<tr>
<td>Cooling Requirement</td>
<td>954,693</td>
</tr>
<tr>
<td>Membrane Filtration</td>
<td>12,360</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>11,562</td>
</tr>
<tr>
<td>Dryer</td>
<td>264,805</td>
</tr>
<tr>
<td>Solvent Extraction</td>
<td>69,924</td>
</tr>
<tr>
<td>Degumming</td>
<td>7,790</td>
</tr>
</tbody>
</table>
Algal Oil Production Order-of-Magnitude (OOM) Cost Estimate

Basis

- Costs taken from Benemann and Oswald report (1996) and adjusted to 2008 dollars
- Balance of plant costs\(^1\) estimated from Peters et al. (2002)\(^2\) based on historical data from petrochemical industry
- No credit for co-products

Caveat

- Estimates based on limited data so should only be used with great caution

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Oil Cost ($/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Pond</td>
<td>9 - 17</td>
</tr>
<tr>
<td>PBR ($10/m(^2))(^3)</td>
<td>20 - 38</td>
</tr>
</tbody>
</table>

\(^1\) Costs are (1) equipment costs - purchased off-the-shelf from vendors, and (2) balance of plant, or everything else - installation, infrastructure, utilities, controls, et al.


\(^3\) Aggressive cost estimate based on thin plastic material PBR approaches that may be scaleable.
OOM Cost Breakdown for Open Pond System

More than 50% of operating costs derived from initial capital investment

Total $13.20/gal
OOM Cost Breakdown for Closed PBR System

More than 60% of operating costs derived from initial capital investment

Total $29.22/gal
Algal Oil Production Cost Reduction Opportunities and Areas Needing R&D

- Improved species and growth/lipid production protocols
- Reduce capital costs of systems and equipment with systems innovation (materials, etc.) and by simplifying processes, e.g. - eliminate centrifuge (also big energy user)
- Develop and find market for non-oil co-products
- Alternate oil extraction methods that avoid need for drying
- Utilize waste streams and infrastructure & recycle nutrients/water
  - Ag wastes
  - Wastewater treatment facilities
- Systems integration with CO₂ waste stream sources
Oil Price Reduction from Co-Product Credit

*Oil Price < $2/gal or $0.25/lb*

As reference,
- Fuel Value $0.04/lb
- Soybean Oil $0.50/lb
- Animal Feed $0.04 to $0.08/lb

**Take-Away Message:**
Value of Co-products will be a Critical Element for Commercial Viability of Feedstock Oil Production
Conclusions

• Algal Biofuels of Significant Interest from E-W Perspective

• Potential for Very High Oil Feedstock Productivity with Non-Fresh Waters, Reduced Land Footprint, and CO₂ recycling

• Could Lead to Biofuel Scale-Up w/ Reduced Impacts on:
  – Fresh Water Supplies
  – Higher Productivity Agricultural Lands
  – Food/Feed/Fiber Markets

• Challenges with Algal Biology, Systems, Processes
  – Cost-effective, commercially-viable production scale-up
  – Sustainable resource utilization (Energy-balance, water-balance, net GHG emissions, productive use of waste streams)
  – Thermal management & salt management are issues/concerns

Thank you !