Life Cycle Analysis of Algae-Based Fuels with the GREET Model

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Argonne National Laboratory

Illinois Sustainable Technology Center
University of Illinois

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This talk summarizes a new Argonne report:

http://greet.es.anl.gov/publications
Motivation, Background & Approach
Algae

- Kinds
  - Macroalgae ("seaweed")
  - Microalgae (typically unicellular, fresh or saltwater)

- Microalgae
  - Metabolism focused on growth (no woody structure)
  - Autotrophic, Heterotrophic, Mixotrophic
  - Few inputs: light, water, nutrients, carbon
  - Grown for nutraceutical market

- Possible biomass crop?
  - Complement other sources
  - Marginal land?

Cyanotech, HI
Algae Process

- Planktonic autotrophic microalgae
  - Dilute suspensions
  - 0.5 to a few grams/liter at harvest
- After dewatering, extract lipids
  - Lipids are a few wt% to 60 wt%
  - Dewatering requires energy
  - Cell disruption
- Convert lipids to a fuel
  - Transesterification to biodiesel
  - Hydrotreating to renewable diesel
- Total energy content approximately 18 kJ/dry-gram-algae
  - 6 kJ in product if 30% lipid

Many steps, limited energy budget
Approaches

1. Photobioreactors
   CalPoly (above)
   RWE, Germany

2. Raceway Ponds
   UNM
   RFE Renewable Fuel & Energy B. V.
Algae - Introduction

- 1996 Economic analysis (Benemann & Oswald)
  - Could not afford plastic sheeting liner in earthen raceway ponds.
  - PBR advocates say increased productivity will pay for their higher cost
  - Our analysis focuses on open ponds

Who is who?

- More like, Who is not?
- List is endless and ranges from “Levi Strauss” to end-to-end
  - Algenol, Phycal, Sapphire, UOP Honeywell, HydroMentia,....
- DOE Consortia
  - National Alliance for Advanced Biofuels and Bioproducts (NAABB)
  - Sustainable Algal Biofuels Consortium (Un AZ): fuel suitability
  - Consortium of Algal Biofuels Commercialization (UCSD): feedstock
  - Cellana, Inc (HI): seawater, aquaculture feed, pilot
- Integrated Biorefineries (IBR)
  - Algenol (FL), Solazyme (PA), Sapphire (NM)
Algae- Sustainable?

- Many questions
  - Land requirements, Land-use change
  - Water consumption
  - Nutrient requirements, reuse, CO₂
  - Emissions

- This talk focuses on Airborne Emissions
  - VOC CO NOx PM10 PM2.5 SOx CH4 N2O CO₂
  - **Greenhouse gases**: CH4, N2O, CO₂

- Do algal fuels lead to more, less, or same level of emissions as what they replace?
  - Renewable Fuel Standard requires less than 50% GHG vs. the fossil fuel displaced to qualify as an advanced biofuel
  - RFS mandates for advanced biofuel production levels year by year
Sources of Emissions

- **Direct Emissions**
  - Fuel combustion for process
  - Boilers, engines, motors, solvents

- **Upstream or indirect emissions**
  - Energy to obtain feedstocks, e.g., crude petroleum
  - Energy to convert feedstocks to fuel, e.g., refining
  - Energy to manufacture all materials, e.g., chemicals, nutrients
  - Energy to transport materials

- **Downstream emissions**
  - Combustion of fuel in an engine
  - Different fuels, different efficiencies, emissions
Can Algae Reduce Transportation GHG Emissions and Energy Consumption?

- Life Cycle Analysis (LCA)
  - Net energy and material, “cradle to grave”
  - System boundary a matter of choice
  - Allocation of burdens to co-products

- LCA integral to DOE evaluation methodology
  - Vehicle technology
  - New fuels

- This project:
  - Identify key issues for algae LCA
  - Compare process options
  - Facilitate community LCAs
Algae LCA Flow Diagram

Materials & Energy

Nutrients:
- CO$_2$ transport & transfer
- N, P fertilizer production & transport
- Water

Algal Lipids:
- Production, transport, and storage
- Energy & nutrient recovery
- Co-product transport & use

Fuel:
- Production, transport, and storage

Vehicle:
- Vehicle use

Emissions to Air, Water, Land

Well-to-Pump (WTP)  Pump-to-Wheels (PTW)

Well-to-Wheels (WTW)
Some Relevant LCA Work

- Kadam 2001- Coal power plant co-fired with algae
  - GHG reduction possible, but MEA CO$_2$ capture would greatly reduce benefits

- Campbell 2009- Open ponds, Australia
  - Seven of nine power plants lacked nearby land
  - Pressurized flue-gas pipelines used 30% of total algal energy

- Lardon 2009- Open ponds, hexane extraction, no treatment of residues
  - Must avoid drying for extraction and increase lipid fraction
  - Much of the algal biomass energy remains in the lipid-extracted algae

- Clarens 2010- Algae biomass vs. corn, switchgrass, and canola
  - Nutrient demand (no recycling) could cause algal biomass to have higher emissions than other energy crops listed.

- Stephenson 2010- Raceway vs. airlift tubular PBR
  - Culture mixing for PBR 8x higher than for open pond at 30 cm/s

- Collet/Ras 2011- Algal biomethane as transportation fuel
  - Detailed assessment of anaerobic digestion (AD) for algae

- Moller 2009- Fugitive emissions & N$_2$O associated with AD
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- GREET LCA model development has been supported by DOE EERE programs since 1995
- GREET and its documents are available at http://greet.es.anl.gov/
- The most recent GREET version was released in October 2011
- At present, there are more than 15,000 registered GREET users
The GREET Model Estimates Energy Use and Emissions of GHGs and Criteria Pollutants for Vehicle/Fuel Systems

- **Energy use**
  - Total energy: fossil energy and renewable energy
    - Fossil energy: petroleum, natural gas, and coal
    - Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy

- **Greenhouse gases (GHGs)**
  - CO₂, CH₄, and N₂O
  - CO₂e of the three (with their global warming potentials)

- **Criteria pollutants**
  - VOC, CO, NOₓ, PM₁₀, PM₂.₅, and SOₓ
  - They are estimated separately for
    - Total (emissions everywhere)
    - Urban (a subset of the total)
GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstocks

The yellow boxes contain the names of the feedstocks and the red boxes contain the names of the fuels that can be produced from each of those feedstocks.
Approach: GREET was Expanded with an Add-On Helper Tool - Algae Process Description (APD)

- Challenges for algae LCAs
  - Commercial pathways not yet defined: many scenarios
  - Lack of validated data, much proprietary
  - Published LCAs differ methodologically: hard to compare

- APD is intended to overcome some of these challenges
  - Allows rapid definition of algae pathway from process inventory
  - Separates GREET from complexity of algae pathway definition
  - New processes easy to add: simple interface for users
  - Assembles model and passes back to GREET for LCA
**Pathway Abstraction in APD**

- Organizes process inventory, accounting, and reporting
- Helps user know where to plug-in and set parameters

![Pathway Diagram]

- **Growth & 1st Dewatering**
- **Culture**
- **Further Dewatering**
- **Paste**
- **Extraction**
- **Metabolite Conversion**
- **Transport**
- **Fuel**
- **<From all>**
- **<To all>**
- **Metabolites**
- **Waste & Co-product**
### APM Example: Process Selection for Dewatering

<table>
<thead>
<tr>
<th>Net-Process Summary</th>
<th>Summary of remaining dewatering</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Dissolved</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Air</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input per unit output</th>
<th>1.23E+00</th>
<th>1.11E+00</th>
<th>1.11E+00</th>
<th>1.00E+00</th>
<th>0.00E+00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoverable CO2, g/g produc</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Mass to recovery, dry-g/g produc</td>
<td>2.34E-01</td>
<td>1.11E-01</td>
<td>1.11E-01</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials consumed, g per unit output except as noted</th>
<th>Air</th>
<th>Flotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chitosan</td>
<td>1.11E-02</td>
<td>1.00E-02</td>
</tr>
<tr>
<td>None</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>None</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
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<td>None</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>None</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy consumed: KWh/g-output except as noted</th>
<th>Air</th>
<th>Flotation</th>
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</thead>
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<tr>
<td>Residual oil</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Coal</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Liquefied petroleum gas</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Site thermal</td>
<td>3.45E-03</td>
<td>1.47E-04</td>
</tr>
<tr>
<td>Site Electricity</td>
<td>3.29E-03</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>
Three Pathways Possible
- Five processes with co-products
- Five co-products from algae
Current LCA includes open pond systems only
System boundary currently excludes infrastructure materials and land-use change
Reference Pathway (LS diesel) System Boundary is Comparable to Algae’s
Overview of Carbon Accounting

- Carbon traced back to power plants is treated as zero (biogenic)
- Carbon from fossil-based process fuels is treated as anthropogenic

Emissions from processes, direct + upstream, are charged:

- Pathway Processes
- Transport
- Biogas and Residue Combustion
- Nutrients

GHG Penalty

Carbon from power plant (flue gas) is treated as atmospheric:

- CO₂ Lost from Pond

Zero

Credits for CO₂ input and displaced fertilizer nutrients:

- CO₂ Credit for Flue-Gas Inputs
- Displaced Fertilizer Production

GHG Credit + Net GHGs
Recovered Materials and Energy
Reduce Internal Energy Demand

Imported Electricity, Natural Gas, and Nutrients

On-site processes

On-Site Demand

Recovered Power & heat

AD

Clean biogas

CHP

Co-methane

Raw biogas

Upgrade

E_{co-power}

E_{co-methane}

E_{oil}

Recovered nutrients

Remnants

Algae Growth & Oil Production

Algal oil
Net LCA Results Are Based on a Hybrid Approach

- Algae processes
  - On-site Energy Demand
    - AD
    - CHP
    - Remnants
  - Biomass
    - Algal Oil

- Conversion processes
  - Biodiesel Energy Demand

- Algae production and lipid-conversion allocation factors
  - $A_{\text{algae}} = \frac{E_{\text{oil}}}{E_{\text{oil}} + E_{\text{co-power}} + E_{\text{co-methane}}}$
  - $A_{\text{BD}} = \frac{E_{\text{BD}}}{E_{\text{BD}} + E_{\text{glycerin}}}$

- Sub-pathways combined with displacement method
  - $GHG_{\text{Total, Allocated}} = A_{\text{BD}} \left( A_{\text{algae}} \left( GHG_{\text{algae}} - GHG_{N, P2O5-displaced} \right) + GHG_{\text{BD}} \right)$
Definition of Pathway Model for Baseline Scenario
Lipid Production Model - Baseline Scenario

- Open pond
  - Bio-Flocculation
  - DAF & Centrifuge
  - Transport
  - Homogenizer, Hexane Extraction

- Recovery of H20
- Recovery of CO2
- N, P in liquid
- N, P in solids

- CHP
- Biogas Clean-up
- Anaerobic Digestion

- Urea
- DAP
- Flue gas

- Electricity
- Soil Amendment
Mixing Maintains Algal Suspension

- Mixing power depends upon cube of mixing speed
  - Typically 15-30 cm/s, depending upon species

<table>
<thead>
<tr>
<th>Source</th>
<th>W/ha</th>
<th>Speed, cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benemann 1996</td>
<td>1226</td>
<td>20</td>
</tr>
<tr>
<td>Stephenson, 2010</td>
<td>3670</td>
<td>30</td>
</tr>
<tr>
<td>Weissman, 1988</td>
<td>—</td>
<td>1 to 30 cm/s</td>
</tr>
<tr>
<td>Kadam, 2001</td>
<td>2344</td>
<td></td>
</tr>
<tr>
<td>Lundquist, 2010</td>
<td>2000</td>
<td>25</td>
</tr>
</tbody>
</table>

- Baseline from Lundquist, then scale by $v^3$
Pumping Power Model

- Per gram of harvested algae
  - 2 L $H_2O$ moves to settling then, 1.9 L moves back
  - 0.23 L additional water to replace evaporation
  - 4.23 L pumping per gram-algae

- "CAPDET"
  - A wastewater treatment simulator based upon Harris 1982
  - Intermediate water moved at ~15 ft total head
  - $KWh/yr = 67,000 Q^{0.9967}$, (Flow, Q, in million gallons/day)
  - Treat as good practice
### Anaerobic Digestion CH₄ Yield is Estimated from Literature

<table>
<thead>
<tr>
<th>Source</th>
<th>Feed</th>
<th>Digestable fraction</th>
<th>gVS/gTS</th>
<th>Theoretical CH₄ yield, L/g-VS</th>
<th>CH₄ Yield, L/g-VS</th>
<th>CH₄ Yield, L/g-TS</th>
<th>Digestion Time (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ras 2010</td>
<td>Chlorella</td>
<td>33% of COD</td>
<td>0.85-0.90</td>
<td>0.15</td>
<td>0.15</td>
<td>16d</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>51% of COD</td>
<td>0.85-0.90</td>
<td>0.15</td>
<td>0.22</td>
<td>28d</td>
<td></td>
</tr>
<tr>
<td>Samson 1982</td>
<td>Spirulina</td>
<td>66% of VS</td>
<td>0.89</td>
<td>0.26</td>
<td>0.23</td>
<td>33d, 70% CH₄</td>
<td></td>
</tr>
<tr>
<td>Sialve 2009</td>
<td>Chlorella vulgaris</td>
<td>46% of VS</td>
<td>0.63-0.79</td>
<td>0.31-0.35</td>
<td>0.30^d</td>
<td>64d</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chlorella scenedesmus sludge</td>
<td>36% of VS</td>
<td>0.59-0.79</td>
<td>0.17-0.32</td>
<td>0.22</td>
<td>3-30d HRT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dunaliella salina</td>
<td>65% of VS</td>
<td>0.68</td>
<td>0.44</td>
<td>0.40</td>
<td>28d</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spirulina maxima</td>
<td>38% of VS</td>
<td>0.63-0.74</td>
<td>0.26</td>
<td>0.23</td>
<td>33d HRT</td>
<td></td>
</tr>
<tr>
<td>Collet 2011</td>
<td>Chlorella</td>
<td>56% of COD</td>
<td>0.90</td>
<td>0.29</td>
<td>0.26</td>
<td>46d</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>46d, extrapolated from Ras.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5-15d</td>
<td></td>
</tr>
<tr>
<td>Ehimen, 2011</td>
<td>Chlorella</td>
<td>25%-65% of VS</td>
<td>0.946</td>
<td>0.0-0.30</td>
<td>0.0-0.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Anaerobic Digestion Model

Based on literature, the model uses:
- 0.9 g-VS/g-TS
- low, baseline, high = 0.2, 0.3, and 0.4 L CH\(_4\)/g-TS,
- 67% CH\(_4\) in biogas

AD process energy (Collet, 2011)
- 0.68 KWh\(_{\text{thermal}}\)/kg-TS
- 0.14 KWh\(_{\text{electrical}}\)/kg-TS (includes solids separation)
- Completely stirred mesophilic tank, 42d HRT, 5% TS
Direct Emissions from Biogas Production

- **Fugitive CH\(_4\) from AD**
  - Flesch (2011): measured 3.1%
    - Loading, maintenance, and flaring
    - Fell to 1.7% when hopper was kept at negative pressure
  - Liebetrau (2010): Studied 10 biogas facilities in Germany
    - Several sources in plant ranged from 0.1% to 1.7% of total CH\(_4\)
    - Noted potential emissions from stored digestate
  - **Baseline scenario uses 2% total CH\(_4\) emissions, AD + clean-up**

- **Direct N\(_2\)O emissions from N in digestate**
  - IPCC method: 0.01 g N\(_2\)O-N/g applied N
  - 40% bioavailability (e.g., Metcalf & Eddy / Bruun 2006)
**CHP - Combined Heat and Power via Turbine**

- 4,000 ha facility produces few x 10 MW\textsubscript{electrical}

<table>
<thead>
<tr>
<th></th>
<th>Gas Turbine</th>
<th>Internal Combustion Engine</th>
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</thead>
<tbody>
<tr>
<td>Electric efficiency</td>
<td>33%</td>
<td>37%</td>
</tr>
<tr>
<td>Heat recovery</td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>NOx, g/mmBTU-in</td>
<td>113</td>
<td>1,200</td>
</tr>
<tr>
<td>CH\textsubscript{4}, g/mmBTU-in</td>
<td>4.3</td>
<td>369</td>
</tr>
</tbody>
</table>

Efficiencies adapted from *Catalog of CHP Technologies*, EPA (2008)

- Model uses gas turbine (appropriate for this scale)
  - Recovered heat is used for hexane extraction and AD
Nutrient Recovery

- Literature
  - Weissman and Goebel (1987)
    - N: 25% in sludge, 75% in liquid (inorganic)
    - P: 50% in sludge, 50% in liquid
    - 30% out-gassing if liquid returned to pond
  - Ras (2011): 68% of N in supernatant at 28d (Chlorella)
  - Collet (2001): Extrapolate Ras to 42d.
    - 90% N in supernatant, 5% volatilization (pH<7)

- This study:
  - 80% N in supernatant, 5% volatilization
    - 76% N to culture, 20% N to soil, of which 40% is bioavailable
  - Phosphorus
    - 50% to culture, 50% to soil
Nutrient Flow in Algae Pathway

- New Nutrients
  - Algae Process, Through Extraction
    - Lipid Extracted Algae
    - Retained in Extracted Oil
  - Volatilization Loss
    - Nutrients Added to Digester
      - Digester Supernatant
        - Returned to Culture
        - Soil Amendment
        - Treatment and Discharge
      - Digester Solids
Algae in Pond

<table>
<thead>
<tr>
<th>N</th>
<th>P</th>
</tr>
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<tbody>
<tr>
<td>0.0422 g/g</td>
<td>0.0063 g/g</td>
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</table>

Net Recovered to Culture

<table>
<thead>
<tr>
<th>N</th>
<th>P</th>
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<tr>
<td>0.0422 g/g</td>
<td>0.0063 g/g</td>
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Digester Supernatant

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<tbody>
<tr>
<td>0.0444 g/g</td>
<td>0.0063 g/g</td>
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Residuals in Digester

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<th>P</th>
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<tr>
<td>0.0555 g/g</td>
<td>0.0125 g/g</td>
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Digester Solids

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<tbody>
<tr>
<td>0.0111 g/g</td>
<td>0.0063 g/g</td>
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Lost in Return

<table>
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</thead>
<tbody>
<tr>
<td>0.0022 g/g</td>
<td>0 g/g</td>
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New Nutrients

<table>
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<th>N</th>
<th>P</th>
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</thead>
<tbody>
<tr>
<td>0.014 g/g</td>
<td>0.0063 g/g</td>
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Loss of New Nutrients

<table>
<thead>
<tr>
<th>N</th>
<th>P</th>
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<tbody>
<tr>
<td>0.0007 g/g</td>
<td>0 g/g</td>
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</table>
Algal Oil Extraction - Wet Hexane Extraction

- Theoretical process
- On-site rather than regional, since wet
- Energy consumption via previous modeling studies
  - Heat is obtained from CHP

<table>
<thead>
<tr>
<th>Source</th>
<th>Process</th>
<th>NG, Wh/gm-oil</th>
<th>Electricity, Wh/gm-oil</th>
<th>Hexane, mg/gm-oil</th>
</tr>
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<tbody>
<tr>
<td>Lardon</td>
<td>dry</td>
<td>2</td>
<td>0.4</td>
<td>11</td>
</tr>
<tr>
<td>Lardon</td>
<td>wet</td>
<td>6</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Lardon</td>
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<td>0.045</td>
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<td>1.72</td>
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<td>dry</td>
<td>0.74</td>
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Details for the Baseline Scenario Model

Growth, Harvest, and Extraction

Raceway (pond) → Flocc. & Settle → DAF → Centrifuge → Homogenizer → Wet Hexane Extraction

- Raceway (pond)
  - 0.5 g/L
- Flocc. & Settle
  - 10 g/L
- DAF
  - 100 g/L
- Centrifuge
  - 200 g/L
- Homogenizer
  - 90% effic.
  - CAPDET 1.5e-4 kWh/dry-g
- Wet Hexane Extraction
  - 95% effic.
  - 1 HP/gpm
  - EPA/Davis/GEA Niro Soavi

- 25 cm/s
- 48 kWh/ha/d
- 2.2 g-CO₂/g-algae (15% CO₂ loss)
- 1.5m sump
- 0.6 cm/day
- 25 g/m²/d
- 25 wt% lipid
- 25 wt% protein
- 50 wt% carbohydrate
- C:N:P = 103 : 9.8 : 1
- 50 wt% carbon

Recovery

- Anaerobic Digestion
  - 0.3 L/g-TS
  - 67% CH₄
- CHP
  - 33% Elect.
  - 76% Total

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<thead>
<tr>
<th>g/g-algae</th>
<th>N</th>
<th>P</th>
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<tr>
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<tr>
<td>Recovered</td>
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Results for Baseline Scenario
## Aggregated Energy and CO2 Balance

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<tr>
<th></th>
<th>CHP Electricity</th>
<th>Btu / Btu-BD</th>
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<tr>
<td>Total on-site generation</td>
<td>0.387</td>
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<td>Total on-site demand</td>
<td>0.514</td>
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<td><strong>Deficit Imported</strong></td>
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<table>
<thead>
<tr>
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<th>CHP Heat</th>
<th>Btu / Btu-BD</th>
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<tr>
<td>Total on-site generation</td>
<td>0.500</td>
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<td>Total on-site demand</td>
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<td><strong>Discarded heat</strong></td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>kg / mmBtu-BD</th>
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<tbody>
<tr>
<td>Total recovered on-site</td>
<td>92</td>
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<tr>
<td>Total on-site demand</td>
<td>323</td>
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<tr>
<td><strong>Deficit imported</strong></td>
<td><strong>231</strong></td>
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</table>
Reminder: WTP, PTW, WTW Definitions

Nutrients:
- CO₂ transport & transfer
- N, P fertilizer production & transport
- Water

Algal Lipids:
- Production, transport, and storage
- Energy & nutrient recovery
- Co-product transport & use

Fuel:
- Production, transport, and storage

Vehicle:
- Vehicle use

Well-to-Pump (WTP)

Pump-to-Wheels

Well-to-Wheels (WTW)
Total energy use includes renewable energy in the biomass as well as fossil energy.
Baseline scenario has significant GHG reduction

Accurate treatment of recovery (AD, CHP) is essential

- 128,000 BTU-electricity imported (fossil) per mmBTU of biofuel
- Would be 514,000 BTU-electricity without AD recovery
- 76% of N and 100% of P recovered
Biogenic credit cancels substantial emissions from growth and processing
- Substantial direct CH₄ from AD + biogas clean-up
  - Technology choice, operations and maintenance are important
  - Beware of shortcuts for CAPEX, OPEX reduction here
- Also, significant amount of N₂O emissions from AD residues in AD sites and farming fields
Breakdown of Fossil Energy Use

Breakdown is before a fertilizer credit of 55,500 BTU/mmBTU-BD for farming land application of AD residues.
Credit from using AD digestate solids (residue) as fertilizer is largely canceled by transport and \( \text{N}_2\text{O} \) emissions in the field.

Understanding \( \text{N}_2\text{O} \) emission factor is important.
Confidence interval not uniform parameter to parameter
- Not fair comparison but does show \((dG/dx \cdot \Delta x)\) for \(\Delta x\) shown
Reduced Emissions Scenarios

- **Low-A**
  - Increase lipid fraction from 25 wt% to 35 wt%
  - Replace AD with catalytic hydrothermal gasification
    - “Thermochemical digester”
    - 95% N recovery and 90% P recovery
  - Total fugitive CH$_4$ emissions reduced from 2% to 0.2%
  - Reduce CHP efficiency from 33% to 29%
  - Reduce DAF performance from 10 wt% solids output to 8 wt%

- **Low-B**
  - Increase lipid fraction from 25 wt% to 35 wt%
  - Productivity increased from 25 g/m$^2$/d to 30 g/m$^2$/d
  - Total fugitive CH$_4$ emissions reduced from 2% to 0.2%
  - Hexane extraction energy demand is reduced by 41% from baseline scenario
  - Reduce C-sequestration to zero
For Reduced Emission Scenarios

Baseline scenario had 55,440 gCO$_2$e/mmBTU-BD
Renewable Diesel and Renewable Gasoline Have Similar GHGs Because of Energy Allocation

![Bar chart comparing GHG emissions for different fuel types and energy allocation perspectives.](chart.png)
Energy and GHG Results: Algae vs. Other Fuels
Conclusions

- GHG emission reductions may vary from less than 50% to more than 60%, relative to that of low-sulfur petroleum diesel
  - Baseline scenario results in 45% reduction
  - Two low-emission scenarios result in 61-64% reductions
- Total fossil energy appears to be high vs. other biofuels
- Cautionary notes to current results
  - Based, in part, upon undemonstrated processes and performances
  - Flue-gas CO₂ was treated as atmospheric

- Key outstanding issues
  - Electricity and nutrient recovery from residuals is essential but could be a substantial source of emissions
    - Fugitive CH₄ from AD and from biogas clean-up
    - N₂O from digestate-solids applied to fields
  - Extraction process
  - Improved estimates for water movement
  - Demonstrated 1st level dewatering, e.g., bioflocculation

- R&D required for economic viability likely will improve GHG further
  - Not necessarily contradictory goals
  - Exception might be costs to control CH₄ or N₂O emissions
Future Work

- Harmonization with technoeconomic and resource assessment models

- Increased community engagement
  - Process data updates
  - Expand process inventory

- Additional pathways
  - Hydrothermal liquefaction
  - Heterotrophic growth

- Finish PBR model

- Add infrastructure materials
Acknowledgment

This project is funded by the Biomass Program of DOE’s Office of Energy Efficiency and Renewable Energy. We thank Joyce Yang and Zia Haq of that Program for their support and inputs.

A technical report from which this presentation is based on will be available at the GREET website in days (http://greet.es.anl.gov/)

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