Economic Feasibility and Life Cycle Impact of a Turf-Scrubber Based Biorefinery

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2Sandia National Laboratories, Albuquerque, NM
3Sandia National Laboratories, Livermore, CA
4HydroMentia, Inc., Ocala, FL
Large Variability in Economics

- Large variability in reported costs
- Inconsistencies in system boundaries
- Minimal resolution
- Sub-process design evaluation
- Excluded systems
- Simplifying assumptions

![Biofuel Cost (\$ gal$^{-1}$)](chart)

- Benemann & Oswald (1996)-SE
- Peinkos & Darzins (2009)-SE
- Thilakaratne et al. (2014)-HTL
- Chisti (2007)
- Benemann et al. (1992)-SE
- Davis et al. (2014)-HTL
- Sun et al. (2011)-SE
- ANL, NREL, PNNL (2012)-SE
- Amer et al. (2017)-in situ
- Davis et al. (2011)-SE
- Richardson et al. (2012)-SE
• Understand current costs for large-scale production

• Direct comparison of growth architectures
  • Similar appropriate system boundaries
  • Productivity

• Integration into biorefinery
  • Report results on consistent metrics
• Biomass production costs represent a significant hurdle to commercialization

• Downstream processing requires feedstock

• Current design reports assume fixed costs
  • $430 ton$^{-1}$
Scope of this Work

Direct comparison of 2 open technologies

Open Raceway Pond
- Homogeneous cultures
- Harvest density 1 g L\(^{-1}\)
- Temperature sensitivity
- High lipid
- Requires co-location with CO\(_2\) source

Algal Turf Scrubber
- Native cultures
- Harvest density 200 g L\(^{-1}\)
- Temperature insensitive
- Low lipid
- High ash


Defined 2 System boundaries
1. Production of biomass
   Economic Metric: $ \text{ton}^{-1}
2. Production of fuel
   Economic Metric: $ \text{gal}^{-1}

Defined 3 production scenarios
1. Baseline-consistent assumptions
2. Optimistic
3. Conservative

System Boundary

General Architecture for Assessments

Production → Harvest → Conversion

ORP or ATS → Growth Platform → Specific Tractor

Algal Turf Platform → Open Raceway → Floc/Daf/Centrifuge

Thermochemical Conversion to Renewable Diesel (Jones et al.)

HTL/CHG → Hydro-processing

Defined 2 production scenarios
1. Baseline-consistent assumptions
2. Path to $3 \text{ GGE}$

Recycle stream included in analysis
Modeling Architecture

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1. Production of biomass
   Economic Metric: $\text{ton}^{-1}$
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General Architecture for Assessments

- Production
- Harvest
- Conversion

ORP or ATS
Growth Platform
Thermochemical Conversion to Renewable Diesel (Jones et al.)

Algal Turf Platform -> Specific Tractor -> HTL/CHG
Open Raceway -> Floc/Daf/Centrifuge -> Hydro-processing

Defined 2 production scenarios
1. Baseline-consistent assumptions
2. Path to $3 \text{ GGE}$
ATS Foundational Assumptions

**ATS Growth**

- Growth Rate (AFDW): $20 \text{ g m}^{-2} \text{d}^{-1}$
- Lipid yield: 10%
- Pumping Duty Cycle: 14 hr d$^{-1}$
- Hydraulic Loading Rate: 10 gal min$^{-1}$ ft$^{-1}$
- Pumping $\eta$: 67%
- Pumping Head: 4 m
- ATS Length: 152 m
- ATS Tilt Slope: 0.50%
- Biomass (AFDW) Flow: 1340 ton d$^{-1}$
- Capital Cost: $10 \text{ m}^{-2}$

**Harvest**

- Harvest Density: 20% solids
- Harvesting Units
- Earthworks, Roads, Piping, Surge: 50%
- Liner and Attachment Screen: 7 days
- Pump System: $0.23 \text{ m}^{-2}\text{yr}^{-1}$
- Engineering: $0.35 \text{ m}^{-2}$
- Technology Fee (2.75%)

**Growth System**

- Earthworks, Roads, Piping, Surge: 4%
- Liner and Attachment Screen: 52%
- Pump System: 9%

Optimistic- Decrease Capital, No Liners, Increased Growth Rate
Conservative- $$$ Liners, Decreased Growth Rate
ORP Foundational Assumptions

### ORP Growth

- **Growth Rate (AFDW)**
- **Lipid yield**
- **Paddle Wheel Duty Cycle**
- **H2O Recycled**
- **ORP Module Size**
- **Pond Depth**
- **Volumetric Growth**
- **Evaporation Rate**
- **Biomass (AFDW) Flow**
- **Capital Cost** $13 \text{ m}^2$

### Harvest

<table>
<thead>
<tr>
<th>Harvest Density</th>
<th>20% Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest system</td>
<td></td>
</tr>
<tr>
<td>Ponds + paddle wheels</td>
<td>38%</td>
</tr>
<tr>
<td>Pond liners</td>
<td>9%</td>
</tr>
<tr>
<td>CO2 delivery+sumps</td>
<td>6%</td>
</tr>
<tr>
<td>Primary harvesting (settling)</td>
<td>19%</td>
</tr>
<tr>
<td>Water/Nutrient/Waste/Electrical Supply</td>
<td>11%</td>
</tr>
<tr>
<td>Inoculum production system</td>
<td>14%</td>
</tr>
<tr>
<td>General machinery</td>
<td></td>
</tr>
</tbody>
</table>

### Optimistic-Decrease Capital, No Liners, Increased Growth Rate

### Conservative- $$$ Liners, Decreased Growth Rate
Biorefinery Assumptions

Consistent assumptions across production platforms

HTL/CHG Processing
- NG Energy: 3.7 M-MJ d⁻¹
- Electrical Energy: 120 MWh d⁻¹
- Capital Cost: $183 M

Hydrotreating
- Fuel Yield: 78%
- Capital Costs: $69 M
- Processing Capacity: 153 kgal d⁻¹
- Diesel Yield: 83%
- Naphtha Yield: 17%

Growth platform Specific

<table>
<thead>
<tr>
<th>Input</th>
<th>ATS</th>
<th>ORP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Yield</td>
<td>30%</td>
<td>55%</td>
</tr>
<tr>
<td>Ash</td>
<td>50%</td>
<td>8%</td>
</tr>
</tbody>
</table>
## Economic Scenario

### Design Case Scenario

#### Yearly Cash Flow

- Loan Payment
- Loan Interest Payment
- Loan Principal
- Total Annual Sales
- Annual Manufacturing Cost
- Depreciation Charge
- Net Revenue
- Taxable Income
- Income Tax

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td><strong>Value</strong></td>
<td></td>
</tr>
<tr>
<td>Equity</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Loan Interest Rate</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>Loan Term</td>
<td>10 yrs</td>
<td></td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Income Tax Rate</td>
<td>35%</td>
<td></td>
</tr>
<tr>
<td>Plant Life</td>
<td>30 yrs</td>
<td></td>
</tr>
<tr>
<td>Build Time</td>
<td>3 yrs</td>
<td></td>
</tr>
<tr>
<td>Annual Fuel Production</td>
<td>46 Mgal</td>
<td></td>
</tr>
</tbody>
</table>
Defined 3 production scenarios
1. Baseline-consistent assumptions
2. Optimistic
3. Conservative

Defined 2 production scenarios
1. Baseline-consistent assumptions
2. Path to $3 GGE

Modeling Architecture

<table>
<thead>
<tr>
<th>Input</th>
<th>ATS</th>
<th>ORP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth Rate</td>
<td>20 g m$^{-2}$ d$^{-1}$</td>
<td>20 g m$^{-2}$ d$^{-1}$</td>
</tr>
<tr>
<td>Liner Cost</td>
<td>$$$</td>
<td>$$$</td>
</tr>
<tr>
<td>Duty Cycles</td>
<td>14 hr d$^{-1}$</td>
<td>14 hr d$^{-1}$</td>
</tr>
</tbody>
</table>
ATS-Baseline Biomass

Capital Cost Breakdown - $307/ton
- Earthworks, Roads, Piping, Surge
- Liner and Attachment Screen
- Pump System
- Engineering/Tech
- Harvest
- Site Development
- Piping
- Land
- Building Costs
- Other

Operation Cost Breakdown - $106/ton
- Power
- Fuel
- Labor
- Maintenance

ATS Growth Cost Breakdown - $463/ton
- Capital Costs
- Operation Costs
- Tax

$307.34
$48.87
$106.95
$307.34
ORP-Baseline Biomass

Capital Cost Breakdown
- $287/ton

Capital Costs
- Ponds + paddle wheels
- Pond liners
- CO2 delivery+sumps
- Water/Nutrient/Waste/Electrical Supply
- Land Costs
- Inoculum production system
- Building Costs
- Other Costs
- Harvest Systems
- Site Development

Operation Cost Breakdown
- $241/ton

Operation Costs
- Power
- Nutrients (N,P) + wastewater nutrients
- CO2
- Flocculant
- Waste Disposal
- Labor and Overhead
- Maint/Insur

ORP Growth Costs Breakdown
- $574/ton

Capital Costs
- $287.47

Operation Costs
- $240.60

Tax
- $46.14
Understanding *Productivity, Capital costs, Operational costs* are important parameters.
Modeling Architecture

Defined 3 production scenarios
1. Baseline-consistent assumptions
2. Optimistic
3. Conservative

System Boundary

Defined 2 production scenarios
1. Baseline-consistent assumptions
2. Path to $3 GGE

<table>
<thead>
<tr>
<th>Optimality</th>
<th>Input</th>
<th>ATS (opt)</th>
<th>ATS (con)</th>
<th>ORP (opt)</th>
<th>ORP (con)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimistic</td>
<td>Growth</td>
<td>25g m⁻² d⁻¹</td>
<td>15g m⁻² d⁻¹</td>
<td>30g m⁻² d⁻¹</td>
<td>15g m⁻² d⁻¹</td>
</tr>
<tr>
<td>Baseline</td>
<td>Liner cost</td>
<td>None</td>
<td>$$$</td>
<td>None</td>
<td>$$$</td>
</tr>
<tr>
<td>Conservative</td>
<td>Op cost decrease</td>
<td>10%</td>
<td>0%</td>
<td>10%</td>
<td>0%</td>
</tr>
</tbody>
</table>
ATS-Sensitivities Biomass

$/ton

Capital  Operation  Tax  Total

Best  Worst  Base
Direct Comparison

• Baseline are direct comparisons
• ORP requires CO$_2$ integration
• ATS system includes high ash content
Defined 3 production scenarios
1. Baseline-consistent assumptions
2. Optimistic
3. Conservative

Defined 2 production scenarios
1. Baseline-consistent assumptions
2. Path to $3 GGE

Modeling Architecture

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<tbody>
<tr>
<td>Growth Rate</td>
<td>20 g m$^{-2}$ d$^{-1}$</td>
<td>20 g m$^{-2}$ d$^{-1}$</td>
</tr>
<tr>
<td>Lipid Content</td>
<td>55%</td>
<td>10%</td>
</tr>
<tr>
<td>Ash Content</td>
<td>8%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Put in inputs
ATS-Biorefinery

Total Cost: $10.57/gal

Capital Costs: $6.89
- ATS-Biorefinery: $4.61
- ATS Growth System: $0.78
- Harvest: $1.35
- HTL: $0.15
- Hydrotreating: $0.15

Operation Costs: $2.58
- Power Requirements: $0.88
- HTL Cost of Supplies: $0.83
- Fuel For Harvesting: $0.28
- Pumping Costs: $0.20
- Labor for ATS/Harvesting: $0.14

Tax: $1.09
ORP-Biorefinery

Capital Cost Breakdown - $3.54/gal
- Ponds + paddle wheels
- Pond liners
- CO2 delivery + sumps
- Water/Nutrient/Waste/Electrical Supply
- Land Costs
- Inoculum production system
- HTL
- Building Costs
- Other Costs
- Harvest Systems
- Site Development

ORP Costs Breakdown - $6.72/gal
- Capital Costs $2.13
- Operation Costs $1.81
- Tax $0.33

Operation Cost Breakdown - $2.61/gal
- Power
- Nutrients (N,P) + wastewater nutrients
- CO2
- Flocculant
- Waste Disposal
- Labor and Overhead
- Maint/Insur
- HTL
ATS-$3 GGE

- Reduce ash content to 13%
- Growth rate 30 g/m^2/day
- 10% Decrease in Capital Costs
- Subsidies at 2x Fertilizer Costs
- Results in a cost of $3.07/gal

ATS Cost Breakdown - 3.07 $/gal

- Capital Costs
- Operation Costs
- Tax

$1.88
$0.88
$0.30

$- $2.00 $4.00 $6.00 $8.00 $10.00 $12.00

$/gge

- Baseline (50% Ash)
- Reduce Ash to 13%
- 10% Decrease in Capital Costs
- Subsidies at 2x Fertilizer Costs
- Growth Rate 30 g/(m^2*d)
- Combined
ORP-$3 GGE

- Growth rate 35 g/m^2/day
- 15% Decrease in Capital Costs
- 15% Decrease in Operation Costs
- Byproduct sales of Naptha
- No pond liners

ORP Costs Breakdown - $3.84/GGE

- Capital Costs: $3.19
- Operation Costs: $2.13
- Tax: $0.50
ATS lifecycle Results

Engineering process models integrated with Life cycle inventory data

Baseline

- GHG emissions (g-CO2-eq GGE-1)
  - Growth credit
  - Production
  - Biorefinery
  - PTW
  - Total

Optimistic

- GHG emissions (g-CO2-eq GGE-1)
  - Growth credit
  - Production
  - Biorefinery
  - PTW
  - Total

Baseline: 2.07
Optimistic: -14.4
Summary

• Both Platforms have paths to $3 GGE
• Productivity (culture stability) dominates impact of costs

• ATS system
  • Biomass production ranging between $212 to $672 per ton
  • Improved productivity and stability support feasibility of the growth systems
  • Ash content needs to be minimized for downstream processing

• ORP system
  • Biomass production ranging between $437 to $752 per ton
  • High lipid yield algae is required for economic feasibility
  • Culture robustness is a requirement for the system
  • CO$_2$ co-location is a requirement
Thank You for Your Attention

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