The Algae to Fuels Value Chain
Presentation for National Research Council
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UOP LLC
UOP Interest in Alternative Fuels

• Since 2005, a Honeywell Company – part of Specialty Materials business unit
• Leading supplier and licensor of processing technology, catalysts, adsorbents, process plants, and technical services to the petroleum refining, petrochemical, and gas processing industries.
• UOP Licensed Technology produces: 60% of the world’s gasoline; 85% of the world’s biodegradable detergents; 60% of the world’s para-xylene.
• UOP: 3400 employees worldwide.
• Honeywell: >130,000 employees, $33.6B (2010)
• Strong relationships with leading refining and petrochemical customers worldwide.

Biofuels: Next in a Series of Industry Solutions
Algal Products – Why We Care

• Proteins, meal, valuable health supplements

• Triglycerides
  – Conversion to valuable chemicals and fuels
  – Productivity promise unsurpassed by any other organisms

Honeywell’s UOP – Focused on Products from Algal Oils
# UOP’s View of the Algae to Fuels Value Chain

## RAW INPUTS
- Sunlight, CO2, Sugar, Land, Water, Chemicals (P, N)

## STRAIN SELECTION
- Microalgae, Cyanobacteria, Macroalgae, other bacteria

## CULTIVATION
- Open pond, photobioreactor, fermentation, hybrid

## HARVESTING
- Flocculation, filtration, centrifugation, biological assist

## DRYING
- Solar, fueled drying, vacuum drying

## EXTRACTION
- Physical, chemical, osmotic (lipids, proteins, carbos)

## CONVERSION
- Biodiesel, renewable diesel / jet, gasoline, power

## DISTRIBUTION
- Established
Downstream: Conversion and Distribution

- Conversion and distribution are both well-known areas
- Conversion can be to biodiesel or Renewable Diesel
  - **Biodiesel**
    - Lower capital cost, higher operating cost
    - Blending limits to achieve correct diesel properties
    - No “product lift” of light fuel oil possible
  - **Renewable Diesel**
    - Slightly higher capital cost, lower operating cost
    - No blending limits – chemical indistinguishable
    - Substantial ability to uplift light fuel oil to diesel pool

Renewable Diesel and Renewable Jet Fuel provide significant benefits
Extracting Valuable Chemicals from Algae

<table>
<thead>
<tr>
<th>RAW INPUTS</th>
<th>Several different methods exist today</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>- Mechanical Rupture (milling, osmotic shock, etc.)</td>
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<tr>
<td></td>
<td>- Solvent Extraction</td>
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<tr>
<td></td>
<td>- Accelerated Solvent Extraction (high P, T)</td>
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<td>- Co-Solvent Extraction</td>
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<td>- Selective Extraction</td>
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<td>- Supercritical Fluid Extraction</td>
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<tr>
<td></td>
<td>- Others</td>
</tr>
<tr>
<td>STRAIN SELECTION</td>
<td>Elimination of contaminants (P, N, Cl) is significant area of challenge as well</td>
</tr>
<tr>
<td>CULTIVATION</td>
<td>In general, least understood and most important for the economics.</td>
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<tr>
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<td>- High energy use</td>
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<tr>
<td>HARVESTING</td>
<td>- Expensive solvent recycle or high solvent losses</td>
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<tr>
<td>DRYING</td>
<td>- Increases in yields of lipids drop directly to bottom line cost</td>
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<tr>
<td>EXTRACTION</td>
<td>DISTRIBUTION</td>
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</table>

UOP believes this is most promising area for improvements, novelty
Drying Algae

- **Known technology used for algae drying**
  - Solar drying
  - Ambient air (where humidity allows)
  - Heated drum / oven dryers in use today

- **Significant challenges with drying algal biomass**
  - Lipid energy content ~17 BTU per gram
  - Heat of Vaporization of Water: ~2.1 BTU per gram

- **Have to get lipids out without evaporating off all water**

  ![Flowchart](chart.png)

  - Cultivation: <0.1% solid
  - Harvesting/Dewatering: ~20% solid
  - Drying: ~90% solid

- **Energy consumption in drying is limited by thermodynamics**
- **The problem can best be addressed up / downstream**

**Strong driver for improved harvesting, dewatering or water-tolerant extraction**
Algal Value Chain Summary

• Many challenges and opportunities do exist
  – Lipid Extraction
  – Purification of Extracted Lipids
  – Value Engineering / Capital Reduction in Cultivation Methods
  – Strain Selection
  – Availability of Nutrients (P, N)

• Literally hundreds (thousands globally) of small algae companies operating

• Sustainable advantage to be had in technology, operation scale, operational excellence
  – Opinion: No company has yet developed technology with sustainable advantage

Widely fragmented field with lots of opportunity, risk
Backup Material
Algae-based Fuels: Complex Value Chain
Inputs: Challenges and Opportunities

- Harvesting solar energy: through algae or other?

**RAW INPUTS**

- STRAIN SELECTION
- CULTIVATION
- HARVESTING
- DRYING
- EXTRACTION
- CONVERSION
- DISTRIBUTION

**Ambient Conditions**

- Sunlight + CO₂

**CO₂ Injected**

**Heterotrophic**

- Agriculture and industrial biomass: glycerol, starches, sugars (cane + beets)
- Cellulosics: switch grasses, wood waste

- Algae converts agriculture and industrial biomass into renewable oils

**LED Supplied Light**
### Heterotrophic Algae Growth Challenges

<table>
<thead>
<tr>
<th>Section</th>
<th>Details</th>
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<tbody>
<tr>
<td>RAW INPUTS</td>
<td>1 barrel of oil weighs ~138 kg of which ~85% is carbon; 1 mole carbon = 12 grams; 42 gallons in 1 barrel</td>
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<tr>
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<td>- Total carbon: 0.85*138= 117 Kg carbon</td>
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<tr>
<td></td>
<td>- Total moles carbon: 117 kg * 1 mole/12 g *1000g/kg = 9750 moles carbon in 1 barrel of oil or 9750/42= 232 moles in 1 gallon of oil</td>
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<tr>
<td></td>
<td>- Sucrose = C12H22O11 and weighs 342 g/mole</td>
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<tr>
<td></td>
<td>- Total moles sucrose needed per gallon of oil (based on carbon alone): 232/12= 19.3 moles sucrose</td>
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<tr>
<td></td>
<td>- 19.3 moles sucrose* 342 g/mole*1 kg/1000 g= 6.6 kg sucrose</td>
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<tr>
<td></td>
<td>- Sugar commodity price = ~ 15 cents per pound</td>
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<td></td>
<td>- 6.6 kg <em>$0.15/pound</em>2.2 pounds/kg = $2.18 per gallon</td>
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<tr>
<td></td>
<td>- About 20% of sugar goes into growth, not lipid so cost for sugar alone is $2.73 per gallon</td>
</tr>
</tbody>
</table>

Heterotrophic Algae Good Solution with Cheap Sugar – Food Disruption
Strain Selection / Development is Crowded

- Strain selection consists of three basic types
  - Wild-type selection
  - Synthetic Biology for Evolutionary Selection
  - Synthetic Biology for Genetic Modification (GMO)

- At least hundreds, perhaps thousands of companies involved in strain selection activities

- GMO will almost certainly be restricted to closed photobioreactors for the near future.

- Cyanobacteria appear most favored for GMO – ability to use existing gene / enzyme manipulation technology
  - Used in PBR’s and fermentation systems

Engineering cyanobacteria appears most attractive
Cultivation Methods

- Four basic types: open ponds, photobioreactors, hybrid systems, and fermentation (heterotrophic).

Open Ponds
- Simple construction
- Surprisingly expensive
  - Liners, ground preparation
- Invasive species growth
- Environmental control

PBR
- Perceived to be more expensive
- Higher fluid movement cost
- Reliability and maintenance?
  - Cleaning
  - Recovery from shock
### Cultivation Methods

- **RAW INPUTS**

- **STRAIN SELECTION**

- **CULTIVATION**

- **HARVESTING**

- **DRYING**

- **EXTRACTION**

- **CONVERSION**

- **DISTRIBUTION**

- **Fermentation**

#### RAW INPUTS

- Four basic types: open ponds, photobioreactors, hybrid systems, and fermentation (heterotrophic).

#### STRAIN SELECTION

- Choice depends significantly on strain selection

#### CULTIVATION

- Uses well-known, standard equipment from ethanol, other industry
- Somewhat capital intensive, but infrastructure exists
  - Capital on par with open ponds
- Offers ability to control conditions
- Requires energy from carbon source – indirect energy conversion

#### DISTRIBUTION
# Methods for Harvesting Algae

## RAW INPUTS

## STRAIN SELECTION

## CULTIVATION

### Harvesting the aquaculture species and press the oil

### Has gained prominence in recent years as “sustainable” solution providing food + fuel

### Concern raised among environmentalists, animal rights lobby

## HARVESTING

### Bio-assisted Harvesting

- Utilize shrimp or fish to eat the algae
- Harvest the aquaculture species and press the oil
- Has gained prominence in recent years as “sustainable” solution providing food + fuel
- Concern raised among environmentalists, animal rights lobby

### Basic Calculations / Estimates

- **Fish Mass Balance**: 1 kg fish yields 40 g of oil, 450 g of food
- 40 g of fish oil yields about 55 cc of fuels (theoretical)
- 0.72 kg of fish oil per liter of fuel
- **US Distillate Consumption**: ~280 billion liters per year
- **Need**: 200 MM MT of fish oil, > 2 B MT of fish for food
- **World Consumption**: 88 MM MT of fish

### Contrast

- 88 MM MT of fish = 7.8 MM MT of fish oil = 68.3 MM bbls

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**Bioharvesting, while intriguing, may only be partial solution**
## Methods for Harvesting Algae

### RAW INPUTS

- **Flocculation**
  - Chemical additives – must control amount, type for cost
  - Downstream purity issues – water release, processing
  - Can be used with any physical separation technique – sedimentation, filtration, dissolved-air flotation, centrifugation, etc.

### STRAIN SELECTION

- **Filtration**
  - Single-cell organisms, < 10 microns
  - Recovery efficiency low, process operation problems

### CULTIVATION

- **Sedimentation**
  - Simplest, usually requires largest flocculent levels
  - Cleaning out of sedimentation tanks, culture age issues

### HARVESTING

- **Dissolved-Air Flotation**
  - Used in sewage, waste water treatment
  - Must manage size of flocculated algae carefully

### DRYING

- **Centrifugation**
  - High capital cost, rotating equipment, maintenance issues

### EXTRACTION

### CONVERSION

### DISTRIBUTION
**UOP Renewable Fuels Technologies**

**Feed**
- Natural Oil/Fats
- Hydrogen

**Process**
- Ecofining™ Process
- Renewable Jet Process
- RTP™ (Pyrolysis)

**Product**
- Honeywell Green Diesel™
- Green Jet (if req)
- Honeywell Green Jet Fuel™
- Green Diesel
- Green Power / Fuel Oil (now)
- Green Fuels (2011)

**Envergent Technologies – UOP/Ensyn JV**

**Sustainable Technologies – Feedstock Flexible And 2nd Gen Ready**
UOP/ENI Ecofining™ Green Diesel

Ecofining Process Chemistry and Flow Scheme

- Technology that produces a fully fungible hydrocarbon product
- Uses existing refining infrastructure, can be transported via pipeline, and can be used in existing automotive fleet
- Two units licensed in Europe with first commercial start-up in 2010
- Excellent blending component, allowing refiners to expand diesel pool by mixing in “bottoms”
- Can be used as an approach to increase refinery diesel output

Process Comparison vs. Biodiesel

| Natural Oil/Grease + Methanol | Biodiesel (FAME) + Glycerol |
| Natural Oil/Grease + Hydrogen | Green Diesel + nC3 & Naphtha |

Performance Comparison

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<tr>
<th></th>
<th>Petrodiesel</th>
<th>Biodiesel</th>
<th>Green Diesel</th>
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<tbody>
<tr>
<td>NOx</td>
<td>Baseline</td>
<td>+10</td>
<td>Baseline or better</td>
</tr>
<tr>
<td>Cetane</td>
<td>40-55</td>
<td>50-65</td>
<td>75-90</td>
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<tr>
<td>Cold Flow Properties</td>
<td>Baseline</td>
<td>Needs Additives</td>
<td>Baseline or better</td>
</tr>
<tr>
<td>Oxidative Stability</td>
<td>Baseline</td>
<td>Needs Additives</td>
<td>Baseline or better</td>
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UOP Renewable Jet Process

- Initially a DARPA-funded project to develop process technology to produce military jet fuel (JP-8) from renewable sources
- Targets maximum Green Jet production
- Green Jet Fuel can meet all the key properties of petroleum derived aviation fuel, flash point, cold temperature performance, stability
- Certification of Green Jet as a 50% blending component in progress

**Built on Ecofining Technology**

Natural Oil/Grease → Deoxygenating/Isomerization → Green Diesel

Natural Oil/Grease → Deoxygenating/Selective Cracking/Isomerization → Green Jet

**DARPA Project Partners**

Southwest Research Institute
Sandia National Laboratories
DARPA
Cargill
UOP
Honeywell