Future Fuels - Algae

Norman M. Whitton
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Norm Whitton

- BChE, BChem, Univ of Minn 1982
- MBA, Univ of Houston, 1985
- Petroleum and Chemical Industry
  - 12 years at Conoco and DuPont
- Management Consulting
  - 10 years at Arthur D. Little
- Entrepreneur
  - 4 years starting new businesses in oil, refining and biodiesel
- Algae Entrepreneur
  - 3 years in Austin, collaborating with University of Texas
Sunrise Ridge Operations

- University of Texas
  - Algae selection / culture
  - Species engineering
  - Separation
- City of Austin
  - Pilot plant site
  - Potential expansion
- State of Texas
  - ETF investment
Future Fuels - Algae

- Commodity Production of Algae
  - The Promise of Algae
  - Photosynthesis
  - Generic Production Processes
  - Algae Species
  - Commodity Products
- Current State of Technology
- Environmental and Regulatory Issues
- Economic Feasibility Models
- Question and Answers
How Fast? How Bad?

Global warming shock

Studies find people are well aware of greenhouse effect, but don’t really know what to make of it; there’s a kind of ‘psychic numbing’ in the face of possible catastrophe.

Surprise Increase in Atmosphere’s CO₂

Facts and Fiction Of Global Warming

Scientists ask if hotter world is bad for life

Warming alarms scientists

Report says most global warming still avoidable
Peak Oil 3Q2005 – Cantarell Field

PEAK OIL – WHEN? (billions of barrels of oil/year)

© J.R. Benemann, Nov 15, 2007, Algae Biomass Summit
More Problems

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.

*ENERGY and WATER* (Approved for Public Release, Distribution Unlimited)
Renewable Liquid Fuels

**EISA 2007 Renewable Fuels Standard**

36-Billion Gallons of Biofuel by 2022

- **Biomass-based Diesel:**
  - maximum = ?

- **Corn Ethanol:**
  - maximum 15 bgy

- **Biofuel from Cellulose:**
  - 16 bgy, 2022

- **Technology-neutral Advanced Biofuel:**
  - maximum = ?
Vast Areas of the Globe Are Not Suitable for High Levels of Terrestrial Agriculture

But could be used for algal culture.
Why We Like Algae

- Doesn’t compete with food
- Reduces greenhouse gas
- Does not require arable land, rain or irrigation

![Oil Yield Chart]

- Sunrise Ridge Technology Focus
Algae – Drive Train Compatibility

- **Algal Oil – Conventional Diesel Drive Trains**
  - Potentially compatible with existing liquid fuel industry
  - Crude oil pipelines
  - Biodiesel or traditional petroleum refineries
  - Produce diesel fuel, which is in short supply worldwide
  - Wide application in trucks, cars, rail, ships; possibly to aircraft
  - Little or no change required for end-users
Value Chain

Oil Field

Algae Farm

Refinery

Blending and Distribution

Biodiesel Plant

Animal Feed Mill

ByProduct

Oil

Value Chain

Oil Field

Algae Farm

Refinery

Blending and Distribution

Biodiesel Plant

Animal Feed Mill

ByProduct

Oil
Photosynthesis

The Underlying Photosynthetic Mechanism

2 NADPH + 3 ATP + CO₂ → Carbohydrate

Photosynthetic membrane

not less than 10 mol photons are required for the formation of the two moles of NADPH necessary, together with 3 moles of ATP, to reduce one mole of CO₂ to the level of carbohydrate

1-3% efficient
Photosynthesis

- **Biomass**
  - \( \text{H}_2\text{O} + \text{CO}_2 + \sim 8-10 \ h\nu \rightarrow (\text{CH}_2\text{O}) + \text{O}_2 \)

- **Redfield Ratio**
  - 106 Carbon
  - 16 Nitrogen
  - 1 Phosphorus
  - Silicon (diatoms)
## Micronutrients

<table>
<thead>
<tr>
<th>Major nutrients</th>
<th>Concentration in culture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/l</td>
</tr>
<tr>
<td>KNO₃</td>
<td>1.21</td>
</tr>
<tr>
<td>MgSO₄·7H₂O</td>
<td>2.46</td>
</tr>
<tr>
<td>KH₂PO₄</td>
<td>1.23</td>
</tr>
<tr>
<td>Fe₂(3O₄)₃</td>
<td>0.052</td>
</tr>
<tr>
<td>Na citrate</td>
<td>0.195</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Micronutrients (Amon A4)</th>
<th>ppm element</th>
<th>Molarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>B as H₃BO₃</td>
<td>0.5</td>
<td>46X10⁻⁵</td>
</tr>
<tr>
<td>Mn as MnCl₂·4H₂O</td>
<td>0.05</td>
<td>92X10⁻⁸</td>
</tr>
<tr>
<td>Zn as ZnSO₄·H₂O</td>
<td>0.05</td>
<td>77X10⁻⁸</td>
</tr>
<tr>
<td>Cu as CuSO₄·5H₂O</td>
<td>0.02</td>
<td>32X10⁻⁸</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Possible micronutrients (Amon B7)</th>
<th>ppm element</th>
<th>Molarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo as MoO₃</td>
<td>0.01</td>
<td>10X10⁻⁸</td>
</tr>
<tr>
<td>V as NH₄VO₃</td>
<td>0.01</td>
<td>20X10⁻⁸</td>
</tr>
<tr>
<td>Cr as Cr₂K₃(SO₄)₄·24H₂O</td>
<td>0.01</td>
<td>97X10⁻⁹</td>
</tr>
<tr>
<td>Ni as NiSO₄·6H₂O</td>
<td>0.01</td>
<td>11X10⁻⁸</td>
</tr>
<tr>
<td>Co as Co(NO₃)₂·6H₂O</td>
<td>0.01</td>
<td>17X10⁻⁸</td>
</tr>
<tr>
<td>W as Na₂WO₄·2H₂O</td>
<td>0.01</td>
<td>55X10⁻⁹</td>
</tr>
<tr>
<td>Ti as TiO₂ (COO·COOK)·2H₂O</td>
<td>0.01</td>
<td>32X10⁻⁸</td>
</tr>
</tbody>
</table>

*Used in 10 times this concentration by Amon [183].
Cell Division and Growth

- Exponential Growth
  - Typically matched to diurnal cycle
  - One to six divisions per day (doublings)
Solar Algae Production Process

- **CO2**
- **Species + Nutrients**
- **Solar Algae Farm**
- **Separations & Processing**
- **Waste Treatment**
- **Product Logistics**

Water flows into the **Solar Algae Farm** and is separated and processed. The waste is treated and the logistics are managed.
Fermentation Processes

Species + Nutrients

Sugar → Dark Algae Tanks → Separations & Processing → Product Logistics

Water → Waste Treatment
CO2 - Electric Conversion
Algae Species

- Estimated fifty thousand to hundreds of thousands of species
- High genetic diversity, rapid mutation rates
- Ubiquitous
- Range in size from 2 microns (cyanobacteria) to macro (kelp)

The divisions of algae include:

- Bacillariophyta - Diatoms
  - Charophyta - Stoneworts
- Chlorophyta - Green algae
- Chrysophyta - Golden-brown algae
- Cryptomonadinae - Cryptomonads
- Cyanophyta - Blue-green algae (also known as Myxophyceae)
- Dinophyta - Dinoflagellates
- Euglenophyta - Euglenoids
- Phaeophyta - Brown algae
- Rhodophyta - Red algae
- Xanthophyta - Yellow-green algae
Algae Species

Neochloris alveroteras

Ankistrodesmus arcuatus

Botryococcus brauneii
Cell Components

- Cell walls and membranes
  - Fatty acids
  - Sugar / protein binders
  - Silica (diatoms)
  - Not much cellulose

- Nucleus
  - Sugars and nucleic acids
  - Proteins

- Pyrenoid
  - Starches and sugars

- Organelles
  - DNA, proteins, cell membranes
## Algae Products

<table>
<thead>
<tr>
<th>Current</th>
<th>Commodities</th>
<th>Specialties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health supplements</td>
<td>Triglycerides</td>
<td>Vitamins (A, B)</td>
</tr>
<tr>
<td>- <em>Spirulina</em></td>
<td>Mixed Oils</td>
<td>Omega 3 Fatty Acids</td>
</tr>
<tr>
<td>- <em>Chlorella</em></td>
<td>Carbohydrates</td>
<td>Dyes</td>
</tr>
<tr>
<td>Pigment</td>
<td>Proteins / Amino Acids</td>
<td>Drugs</td>
</tr>
<tr>
<td>- Astraxanthin</td>
<td>Ethanol / Lactic Acid</td>
<td></td>
</tr>
<tr>
<td>Aquaculture</td>
<td>Other Chemical Feedstocks</td>
<td></td>
</tr>
<tr>
<td>- Sea bass</td>
<td>Animal Feeds</td>
<td></td>
</tr>
<tr>
<td>- Shrimp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Mussels / Abalone</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hawaii
California (Salton Sea)
New Mexico
Israel
Southeast Asia
Future Fuels - Algae

- Commodity Production of Algae
- Current State of Technology
  - Algae Species Selection and Engineering
  - Greenhouse Systems (Open, Closed, Hybrid)
  - Dewatering
  - Product Separations
- Environmental and Regulatory Issues
- Economic Feasibility Models
- Question and Answers
Algae Selection

- Local collection
- Algae culture collections
  - UT, Maryland, California, Hawaii, Japan, UK
- Rapid screening and sequencing
- Desired properties
  - Oil production
  - Growth rate
  - Size / Harvesting
  - Predator and disease resistance
Oleaginous Green Algae (ASU)

![Graph showing total lipids percentage of species strains](image)
Genetic Engineering Targets

- Solar efficiency
- Oil production
- Harvesting
- Predator and disease resistance

But
- Mutation rates
- Evolutionary success vs environment
Growth Based on Temperature

Results
- Strain 1 grew maximally at 30-33°C and growth ceased past 36°C
- Strain 2 grew fast from 35-42°C and growth ceased past 45°C
- Strain 3 grew well between 29-35°C and growth ceased past 39°C
“Greenhouse” Systems

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

*A* (Approved for Public Release, Distribution Unlimited)
Ponds
Raceways

Schematic of paddle wheel mixed raceway pond for microalgae cultivation. Pond depth typically 20 - 30 cm.
Horizontal Closed Systems
Vertical Closed Systems
Light Conversion

One unit

Four units

Photobioreactor

Glass tube
Fluorescent lamp
Broth
Species Control Failures

Native species + Vorticella (predator)

Bi-Culture of our desired species + blue-green cyanobacteria (filaments)
Species Control Strategies

- Accept whatever falls in
- Make the environment specialized
  - Salinity
  - pH
  - Temperature
- Closed greenhouse, physical barrier
- Periodic sterilization
- Small, stable, symbiotic ecology
# System Productivity

<table>
<thead>
<tr>
<th>Type</th>
<th>g / m² / d</th>
<th>Species Control</th>
<th>Temperature Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural pond</td>
<td>0-2</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>High Rate Pond CO2 addition</td>
<td>0-5</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Open Raceway with mixing and CO2 addition</td>
<td>20</td>
<td>Via salinity or pH</td>
<td>None</td>
</tr>
<tr>
<td>Closed horizontal system</td>
<td>40-60</td>
<td>Physical barrier Salinity pH</td>
<td>Evaporative cooling barrier gives longer growing season</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>External evaporative cooling required in summer</td>
</tr>
<tr>
<td>Closed vertical system</td>
<td>100-150</td>
<td>Physical barrier Sterilization protocols</td>
<td>Shading</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Evaporative cooling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heated / chilled water</td>
</tr>
<tr>
<td>Hybrid</td>
<td>20-40, but higher oil content</td>
<td>Nutrient starvation</td>
<td>Mixed</td>
</tr>
</tbody>
</table>
Dewatering

“It looks like green paint to me!”

Algae Harvesting Options

- Chemical Coagulation + Flotation
- Natural Settling
**PREVIOUSLY DEVELOPED METHODS OF MICROALGAE HARVEST ARE INEFFICIENT AND EXPENSIVE**

<table>
<thead>
<tr>
<th>Algae Harvest Method</th>
<th>Relative Cost</th>
<th>Algal Species</th>
<th>Previous Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam fractionation</td>
<td>Very High</td>
<td>Scenedesmus, Chlorella</td>
<td>Smith 1988</td>
</tr>
<tr>
<td>Ozone flocculation</td>
<td>Very High?</td>
<td></td>
<td>Sukenik et al. 1987</td>
</tr>
<tr>
<td>Centrifugation</td>
<td>Very high</td>
<td>Scenedesmus, Chlorella</td>
<td>Brunner and Hemfort 1990</td>
</tr>
<tr>
<td>Electrofloation</td>
<td>High?</td>
<td></td>
<td>Shelef et al. 1984</td>
</tr>
<tr>
<td>Inorganic Chemical Flocculation</td>
<td>High</td>
<td>Oxidation ponds</td>
<td>Golueke and Oswald 1965</td>
</tr>
<tr>
<td>Polyelectrolyte Flocculation</td>
<td>High</td>
<td>Dunaliella</td>
<td>Barclay et al. 1987</td>
</tr>
<tr>
<td>Filtration</td>
<td>High</td>
<td>Spirulina, Coelastrum</td>
<td>Shelef et al. 1984</td>
</tr>
<tr>
<td>Microstrainers</td>
<td>High</td>
<td>Spirulina</td>
<td>Kormarik and Cravens 1979</td>
</tr>
<tr>
<td>Tube Settling</td>
<td>High?</td>
<td>Micractinium</td>
<td>Nurdogan and Oswald 1996</td>
</tr>
<tr>
<td>Discrete Sedimentation</td>
<td>Medium?</td>
<td>Coelastrum</td>
<td>Mohn 1980</td>
</tr>
<tr>
<td>Phototactic Autoconcentration</td>
<td>Unknown</td>
<td>Euglena, Dunaliella</td>
<td>Nakajima and Takahashi 1991</td>
</tr>
<tr>
<td>Autoflocculation</td>
<td>Low?</td>
<td>Micractinium</td>
<td>Moellmer 1970</td>
</tr>
<tr>
<td>Bioflocculation</td>
<td>Low?</td>
<td>Micractinium</td>
<td>Beneman et al. 1980</td>
</tr>
<tr>
<td>Tilapia-Enhanced Sedimentation</td>
<td>Very Low?</td>
<td>Scenedesmus, Chlorella</td>
<td>Schwartz et al. 2004</td>
</tr>
</tbody>
</table>
New Tech Harvesting – Fish Poo

Algae Removal by Tilapia (O. Mosambicus) in Studies at Kent SeaTech

- POC IN
- Replicate 1 - POC OU
- Replicate 2 - POC OU
- Replicate 3 - POC OU

Experiment Date: Jul 23, Jul 26, Jul 30, Jul 31, Aug 2

Ave = 81%
Ave = 62%
Ave = 86%
Ave = 81%
Ave = 83%
Lysing

Dried algal cell (no grinding)
-- cell wall intact

Dried and ground algal cell
-- cell wall ruptured

*Image: Michael Cooney, University of Hawaii*
“Traditional” Extraction
# Oil Content & Quality

## Lipid Yields GA Samples

<table>
<thead>
<tr>
<th></th>
<th>Nannochloris oculata</th>
<th>Phaeodactylum tricornutum</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of dry mass</td>
<td>33.60%</td>
<td>53.10%</td>
</tr>
<tr>
<td>% of crude extract</td>
<td>53.10%</td>
<td>50.80%</td>
</tr>
<tr>
<td>FAME, HC, TG</td>
<td>33.60%</td>
<td></td>
</tr>
<tr>
<td>TG, HC</td>
<td>24.20%</td>
<td>24.40%</td>
</tr>
<tr>
<td>FFA</td>
<td>9.40%</td>
<td>26.40%</td>
</tr>
<tr>
<td>Cell counts</td>
<td>1.725x10^5 cells/ml</td>
<td>3.14x10^7 cells/ml</td>
</tr>
</tbody>
</table>

TG = Triglycerides  
HC = Hydrocarbons  
FAME = Fatty Acid Methyl Esters
Other Conversion Options

- Acidolysis
- Fermentation
- Gasification
- Drying / Pelleting
- Anaerobic Digestion
Future Fuels - Algae

- Commodity Production of Algae
- Current State of Technology
- Environmental and Regulatory Issues
  - Water
  - Species
  - Genetic Engineering
- Economic Feasibility Models
- Question and Answers
Water Issues

- Saline systems
  - Make up water sources
  - Saline water disposal

- Non-saline systems
  - Make up water
  - Discharge to aquifer / aquifer quality
  - Discharge permits (nutrients N, P)

- Large-scale farm disturbance of surface flow and aquifer recharge
Non-native species

- Invasive “pests”
- Texas “black list” regulations – Parks & Wildlife
- Global transport
- Mutation and adaptation
- Proving “Harm”
- Proposed “white list” regulation
Genetically Engineered Species

- Fitness improving features
  - Growth rates
  - Predator resistance
  - Toxics
- Fitness reducing features
  - Oil content
  - Other “toxic” products
  - Product export outside the cell
- Testing?
- Deployment?
More regulation issues

- Downstream solvent extraction / processing emissions & waste
- Plastic recycling
- Land use and zoning
  - “Look and feel” of the farms
  - Flat land is relatively scarce – how to use contour?
- Radio waves / spectrum for radio-controlled equipment in the farms
Future Fuels - Algae

- Commodity Production of Algae
- Current State of Technology
- Environmental and Regulatory Issues
- Economic Feasibility Models
- Question and Answers
Challenges…

- **Cost:**
  - Commodity products from algae have relatively low value
  - We must be very low in cost (capital and operating)

- **Scale:**
  - Sunlight is a dilute source of energy; and it’s variable
  - We need enormous scale to make a difference
    (1 MMBPD ~ 1-2,000,000 acres)

- **Yields:**
  - Algae convert 3-4% of sunlight to biomass, which might be only 30%-40% oil.
  - Our production systems need to maximize desirable products and revenues.
More challenges…

- Siting:
  - Microclimates and repeatability
  - CO2 source?
  - Water and nutrients source?
  - Land – and lots of it
  - Get everyone to agree without destroying the project
Orders of Magnitude…

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? FBRs?)
- CO₂ 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)

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

Algal Oil Production Scale-Up and Cost Reduction

Today
3 - 5 years?
... 5 - 10 years?
... beyond 10 years?

Future
1 - 3 $/gal Algal Oil

Production Scale
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)
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 kWh = 37.7 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>11,582</td>
</tr>
<tr>
<td>Dryer</td>
<td>264,805</td>
</tr>
<tr>
<td>Solvent Extraction</td>
<td>69,024</td>
</tr>
<tr>
<td>Degumming</td>
<td>7,780</td>
</tr>
</tbody>
</table>

Pump = 0.3
Cooling = 4.3
H2O Inlet

Air
CO2

Water
Residue 1.2

Neutral Lipids
Polar Lipids

Sandia National Laboratories
Techno-Economics - Assumptions

- **Revenue / Prices**
  - Oil prices: $40 – 200 / bbl
  - Carbon credits: $2 – 40 / ton
  - Byproduct values: $30 – 300 / ton

- **Yields**
  - Biomass production rate: 25 – 200 g / m² / day
  - Oil content: 3% to >60%

- **Costs**
  - “Greenhouse”: $0.50 - >$10 psf
  - Separations: 0.02 - $20 / gal (product)
  - Feedstocks / Inputs: Site and process specific
Techno-Economics - Targets

- Based on our models for an “interesting” project at reasonable revenue assumptions

- Targets include:
  - Biomass yields > 75 g / m² / day AND
  - Oil yields > 30%
  - Greenhouse cost < $2.00 psf, all in AND
  - Separation cost < 0.40 / gal oil, all in AND
  - Byproduct is recovered and sold at feed value
Target Markets

<table>
<thead>
<tr>
<th>Product</th>
<th>Size, $Bn/yr</th>
<th>Price, $/Ton</th>
<th>Revenue %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetable Oil</td>
<td>500</td>
<td>1000</td>
<td>50-70%</td>
</tr>
<tr>
<td>Renewable Diesel (2015)</td>
<td>1000</td>
<td>1000</td>
<td>30-50%</td>
</tr>
<tr>
<td>Animal Feed</td>
<td>10</td>
<td>10</td>
<td>65%</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>500</td>
<td>1000</td>
<td>45%</td>
</tr>
</tbody>
</table>

- **Renewable Diesel** (2015): 65% Protein
- **Biodiesel**: 45% Protein
Challenges to Algae Commercialization

- Techno-economics
- Obtaining Inputs
- Effective Operations
- Obtaining Permits
- Penetrating Markets
- Creating Confidence

How do we make it happen?
### Algae Biofuel Companies

<table>
<thead>
<tr>
<th>A2BE Carbon Capture*</th>
<th>IGV</th>
<th>Imperium Renewables*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae Biofuels</td>
<td></td>
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Future Fuels - Algae

- Commodity Production of Algae
- Current State of Technology
- Environmental and Regulatory Issues
- Economic Feasibility Models
- Question and Answers