Algenol – Technology Overview and Systematic Analysis of Direct to Ethanol®

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Algenol Overview

- Algenol is an advanced industrial biotechnology company
  - Headquartered in Bonita Springs, Florida
  - Research labs in Fort Myers, Florida and Berlin, Germany
  - 120 employees and consultants including 60 Ph.D.s
- Algenol is commercializing its patented algae technology platform for ethanol production and green chemistry
  - $25MM DOE grant for Integrated Biorefinery
    - Project passed DOE Gate 1
    - Partnered with Dow Chemical, NREL, Georgia Tech, Membrane Tech & Research, University of Colorado
  - Licensed Direct To Ethanol® technology in Mexico
- New Fort Myers, Florida facility which consolidates Algenol’s existing U.S. lab and outdoor testing facilities
  - Lab operations began in early August 2010
  - 40,000 ft² of biology and engineering lab space
  - 4 acre outdoor Process Development Unit
  - 36 acre outdoor demonstration facility

**Direct To Ethanol® technology**

\[ 2 \text{CO}_2 + 3 \text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_5\text{OH} + 3 \text{O}_2 \]
Uses enhanced algae, CO₂ and energy from the sun to produce ethanol

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CO₂ can be sourced from:
- Power Plant
- Refinery or Chem. Plant
- Cement Plant
- Natural Gas Well
- Ambient Air?
Biological Carbon Platform

Blue-green Algae (Cyanobacteria)
- Fast-growing photosynthetic prokaryotes with high rates of photo-conversion of $\text{CO}_2$ into photosynthate and biomass
- Capacity for stable genetic enhancement and availability of molecular tools
- High rates of $\text{CO}_2/\text{HCO}_3^-$ assimilation in marine and freshwater environments
- Defined inorganic growth medium with no organic C sources required
- Amenable for growth in enclosed photobioreactors
- Wide range of growth forms and ecotypes among different genera
  - Over 1500 curated strains from diverse environments available in-house within the Algenol Biofuels Culture Collection (ABCC)
  - Screening program used to identify candidate species for genetic enhancement
  - Candidate species selected on the basis of numerous physiological, morphological and molecular criteria
Enhanced ethanol production via over-expression of genes for fermentation pathway enzymes

- These enzymes, pyruvate decarboxylase (PDC) and alcohol dehydrogenase (ADH), are found widely in nature.
- PDC catalyzes the non-oxidative decarboxylation of pyruvate to produce acetaldehyde.
- ADH converts acetaldehyde to ethanol.
- Ethanol diffuses from the cell into the culture medium and is collected without the need to destroy the algae.
Laboratory to Photo-bioreactor

- Algenol has the capability to move biology and engineering from the lab scale to the field at one site
- Enhanced algae have been approved for use in Algenol’s Florida facility
Enhanced algae, photobioreactors, and ethanol separation systems are key, proprietary components of the Algenol technology.

- Algenol grows ethanologenic algae in patented photobioreactors (PBRs) which allow for optimum solar transmission and efficient ethanol collection
  - Made of polyethylene with special additives and coatings to optimize performance
  - 4500 liter seawater culture
  - 15m long X 1.5m wide
- Ethanol-freshwater condensate is collected from photobioreactors and concentrated to feedstock-grade or fuel-grade ethanol using a combination of Algenol proprietary and conventional technology.

First step in purification process is accomplished with solar energy and provides a clean, ethanol-freshwater solution.
Engineering Group – Current Initiatives

- **Separations**
  - CO₂ Capture
    - Industrial sources
    - Capture from air
  - CO₂ Delivery
    - Gas and Liquid Phase
    - Coupled to O₂ Management
  - O₂ Management
  - Ethanol Separation
    - Via condensate
    - Via adsorption or membranes

- **System Design and Modeling**
  - Scale Optimization/Economic Analysis/Research Guidance
  - Unit operations
  - Phase equilibria
  - Mixing systems
  - Biomass management/utilization
  - Life Cycle Analysis

Integration of CO₂ capture, delivery to and utilization by algae culture – demonstrated in collaboration with Georgia Tech

Blue-green algae (a) after filter, wash and centrifuge at 4000 rpm (3hrs) and (b) microscope image of india ink tracer experiment
Purification Technology

Vapor liquid equilibrium diagram showing non-ideality of EtOH/H₂O system

- Photo-Bioreactor: 0.5 – 2 wt%
- Vapor Compression: 5 – 20 wt%
- Steam Stripping: 90 – 95 wt%
- Mol Sieve Extract: 99.7% Fuel Grade
Example of Optimizing Scale

- Assuming “commercial module” of a given land area we can look at how scale economies will dictate the design.
- Understanding the optimal # of separation units per commercial module provides an illustrative example of scale optimization in distributed systems.

In this case the optimum is between 1 and 4 units per commercial module.
Simple View of Scaling Approach

- Cost = Separation Unit + Piping Network
- General equipment cost equation:
  Scaling: Cost 2 = Cost 1 x (capacity 2/capacity 1)^m
- Here, capacity = acres/separation unit
  In the current context, m:
  <1 for Separation Unit
  >1 for Piping Network or Distribution System\textsuperscript{a,b}

Approach needs to further incorporate factors to arrive at Total Installed Cost
The slight negative scaling for piping slowly picks up and starts dominating the cost after a point. The minimum ‘cost/acre’ corresponds to the optimum plant size

System Description for Life Cycle Analysis

[Diagram showing a flowchart for EtOH production, including stages such as seawater intake, water pumping, sterilization, mixing, scrubber, EtOH production, VCSS & VCD, molecular sieve, EtOH separation, and final steps like combustion in vehicle.]
LCA for Evaluating Technology Options

- LCA* developed with Georgia Tech is based on publicly available information and engineering calculations.
- LCA intended to be evergreen – continuously updated as Algenol evaluates new technology options.
- Recent example: Membrane technology evaluated based on membrane data available from open literature (work of Vane and MTR) combined with Algenol’s process simulation and integration concepts.
- Membrane has lower carbon footprint (and OPEX) and initial CAPEX estimates indicate lower cost vs. distillation + mol sieve dehydration.
- Next steps include work on waste biomass disposition in collaboration with NREL.


**Carbon Footprint for Gasoline: 91.3 gCO₂/MJ**

**Diagram:**
- VCSS+SS+Membrane
- VCSS+VCD+MS
- VCSS+CD
- VCSS + Conventional Distillation + Mol Sieves
- VCSS + Vapor Compression Distillation + Mol Sieves
- VCSS + Membrane

**Graph:**
- GHG Emission (gCO₂e/MJ-EtOH)
- Initial Ethanol Concentration (wt%)
Advantages of Integration with Membrane

- Produce fuel-grade ethanol directly on site in small modules
- Lower initial capital expense/faster initial operation of entire plant
- Quicker approach to full commercial maturity
- Reduce piping/pumping cost
- Isolated modules reduce cross-contamination risk
Conclusions

• In order to assess economic viability and environmental impact, the entire system must be analyzed

• Analysis must include:
  • Design and scaling key unit operations and their interplay with distributed systems (Unit Ops + Farming)
  • Techno-economic model – CAPEX (with all necessary factors to estimate total installed cost), OPEX and Cash Flows
  • Life Cycle Analysis – not only provides carbon footprint information but helps in evaluation of technology options

• The work shown here is the result of many different approaches – process simulation, mathematical optimization of piping/distribution networks, cost estimating etc.

• The synthesis of the above steps give a holistic view of the process and the “right sizing” of a commercial facility to maximize return on investment
## Engineering Technical Partnerships - Leveraging

<table>
<thead>
<tr>
<th>Key Technical Areas</th>
<th>Level of Effort/Other Contributions</th>
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<tbody>
<tr>
<td>PBRs; water treatment; process engineering; mixing systems</td>
<td>Over 20 scientists involved in DOE project and beyond</td>
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<tr>
<td>Gas management; product separation; process engineering</td>
<td>6 scientists involved in plant design, thermodynamics, techno-economic modeling; know-how in CO₂</td>
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<tr>
<td>Infrastructure and ethanol distribution</td>
<td>Joint development exploring integration of Algenol process with refinery processes</td>
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<tr>
<td>Separations, life cycle analysis, CO₂ delivery, biomass disposal</td>
<td>7 professors, 5 postdocs, 3 students</td>
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<td>Membrane separations, integration of the Bio-Sep system with our VCSS</td>
<td>3 scientists, extensive know-how in membrane applications</td>
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<td>Biomass disposition and LCA support; evaluation of industrial CO₂ sources</td>
<td>4 scientists, extensive connections to algae science area</td>
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