Algenol's Direct to Ethanol® Technology: A Cyanobacteria-Based Photosynthetic Process for the Production of Ethanol

ALGENOL

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FESC Summit

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Background — Algae Cultivation

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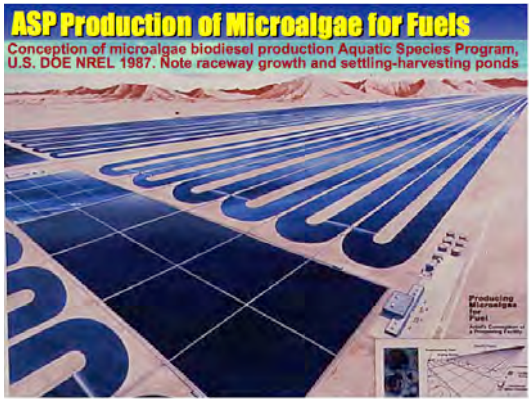
- **Microalgae/Cyanobacteria**
  - Photoautotrophs—carry out photosynthesis (sunlight, CO_2, and water to organic molecules)
  - Much higher productivity than larger plants (~30x)
  - 10's of thousands of known species including blue green algae (cyanobacteria)
  - Commercial production of high value products

Open Ponds (Raceway Design)
Microalgae to High Value Products
Cyanotech, Big Island, Hawaii

- **Aquatic Species Program (NREL 1980-95)**
  - Focus on bio-diesel production from harvested algae
  - Favored Open Pond vs. Closed Systems
  - Pilot plant in New Mexico
  - Major issues with economics and contamination



Raceway Pond Design from
Aquatic Species Program

- **Current Status – Biofuel Production**
  - Numerous algae-to-fuels companies
  - Almost all based on production from harvested algae
  - Mixture of open pond and closed systems
  - None with demonstrated commercial viability for biofuels

Algenol Overview

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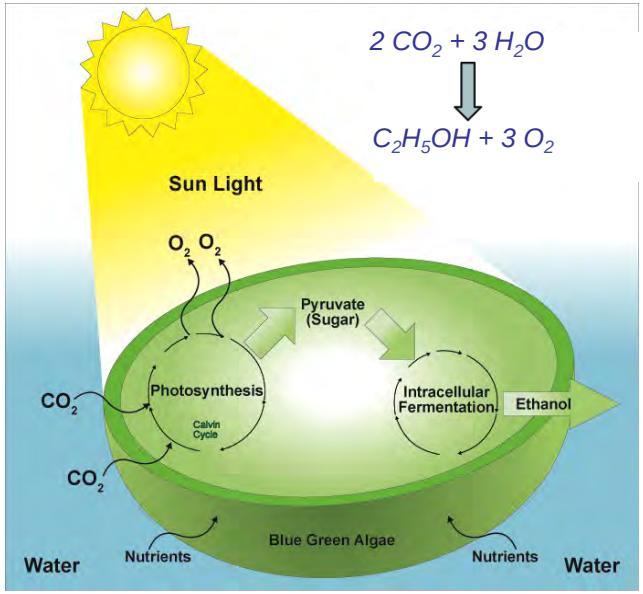
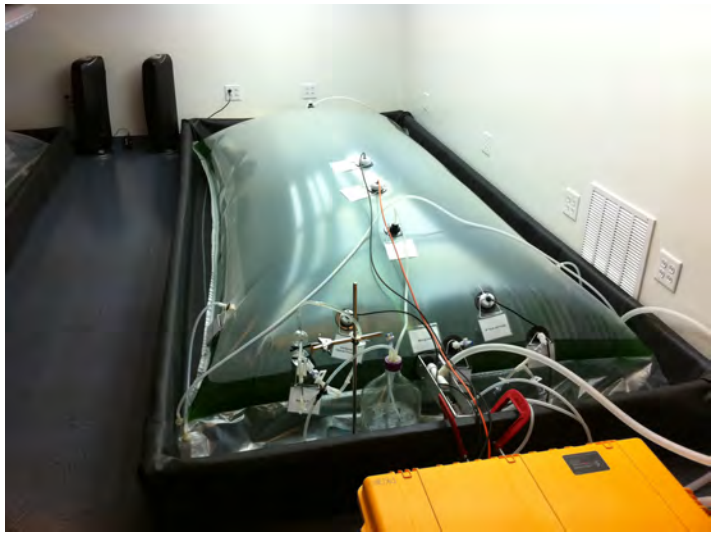
- Algenol is an advanced industrial biotechnology company founded in 2006
  - Headquartered in Bonita Springs, Florida
  - Research labs in Fort Myers, Florida and Berlin, Germany
  - 120 employees and consultants including 60 PhDs
- Algenol is developing its patented cyanobacteria-based technology platform for ethanol production
  - Unique no harvest, Direct to Ethanol© technology with low biomass waste
  - $25MM DOE grant for Integrated Biorefinery
    - Project passed DOE Gate 1
    - Partnered with Dow Chemical, NREL, Georgia Tech, Membrane Tech & Research, University of Colorado
  - Other key partners: Linde, Valero, Biofields, Honeywell



Direct To Ethanol® technology



1000 L scale indoor experiments (Florida)

Algenol Research and Development Facilities

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- New Fort Myers, Florida facility which consolidates Algenol's existing U.S. lab and outdoor testing facilities
  - 40,000 ft^2 lab space (biology, physiology, engineering)
  - 4 acre outdoor Process Development Unit (aquaculture)
  - 36 acres for pilot testing (17 acre DOE-funded pilot)
- Berlin labs (Cyano Biofuels, wholly-owned Algenol subsidiary)
  - Screening of wild-type organisms
  - Metabolic Engineering
  - Lab to medium scale characterization of ethanol production

Fort Myers Laboratory (Completed August 2010)

Berlin Laboratory Group

Process Development Unit
Commercial Scale Photobioreactors

DIRECT TO ETHANOL® *Commercial Vision*

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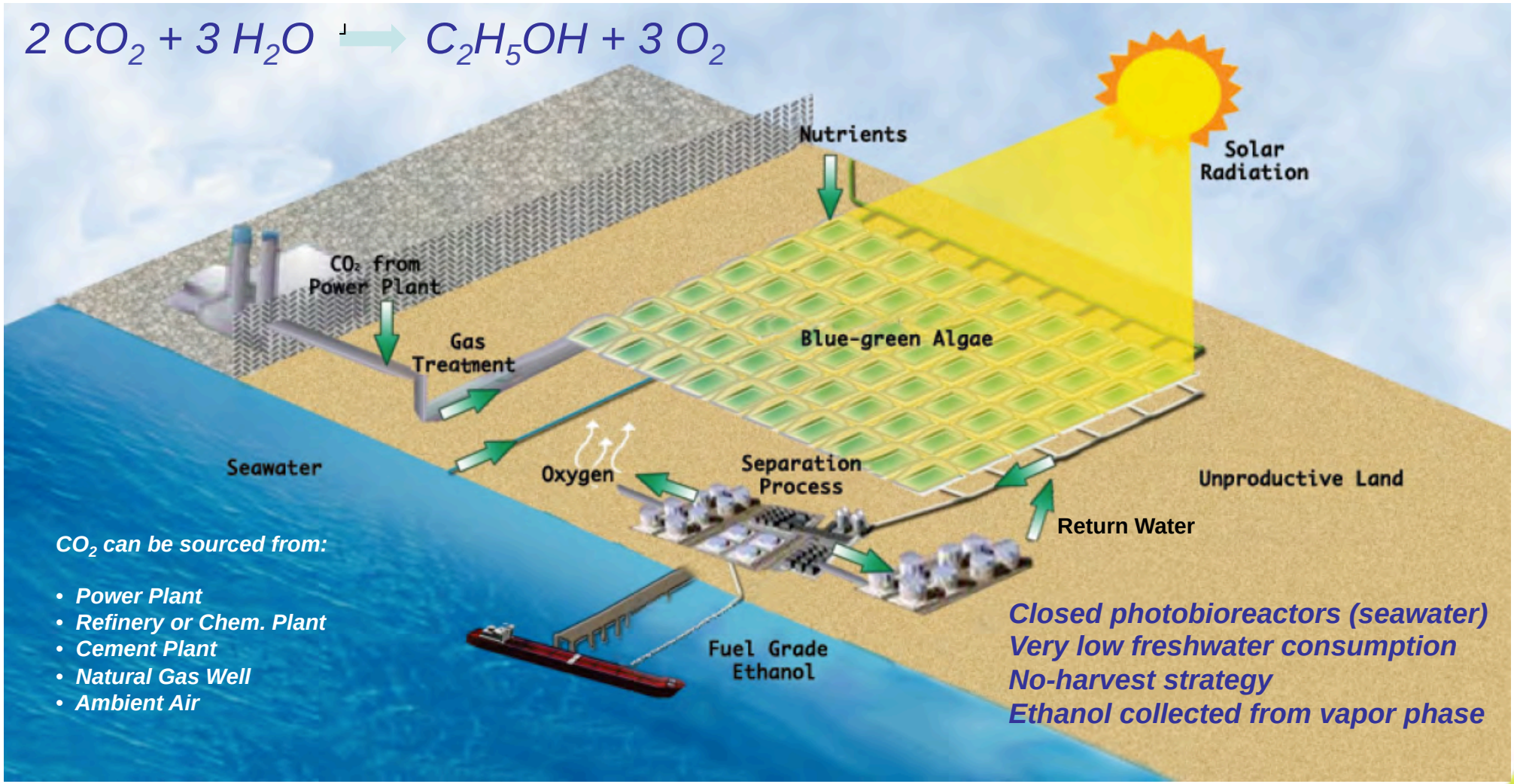
Enhanced cyanobacteria, CO_2 and solar energy to produce ethanol

$$2\ CO_2 + 3\ H_2O \rightarrow C_2H_5OH + 3\ O_2$$



CO_2 can be sourced from:

- ***Power Plant***
- ***Refinery or Chem. Plant***
- ***Cement Plant***
- ***Natural Gas Well***
- ***Ambient Air***

Closed photobioreactors (seawater)
Very low freshwater consumption
No-harvest strategy
Ethanol collected from vapor phase

Biological Carbon Platform

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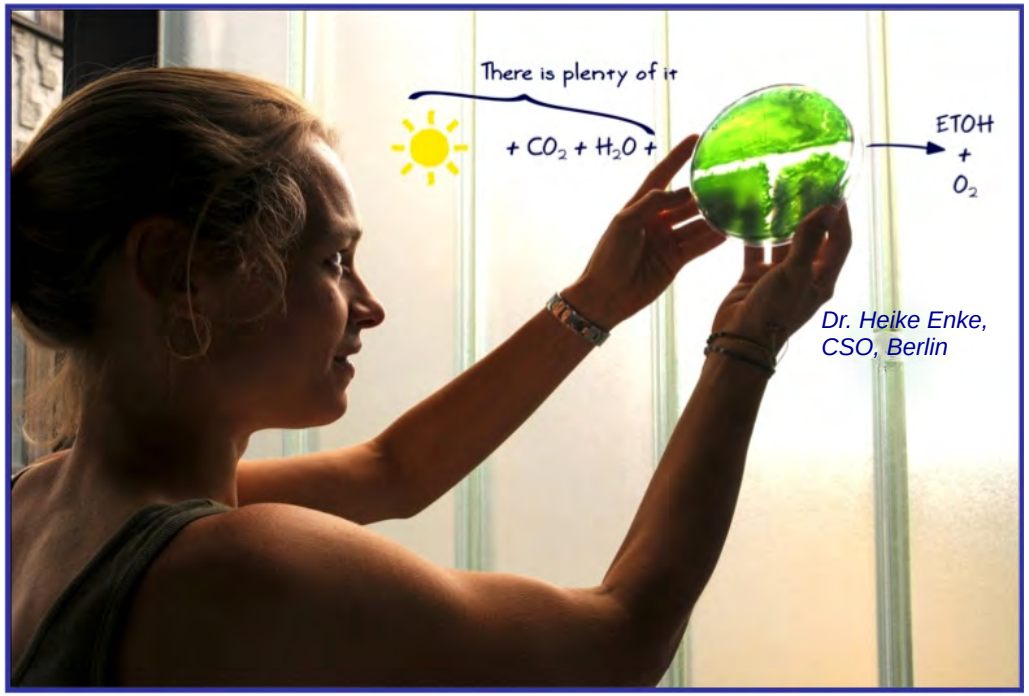
Cyanobacteria (blue-green algae)

- Fast-growing photosynthetic prokaryotes with high rates of photo-conversion of CO_2 into photosynthate and biomass
- Capacity for stable genetic enhancement with available molecular tools
- High rates of CO_2/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

Metabolic Pathway for Ethanol Production

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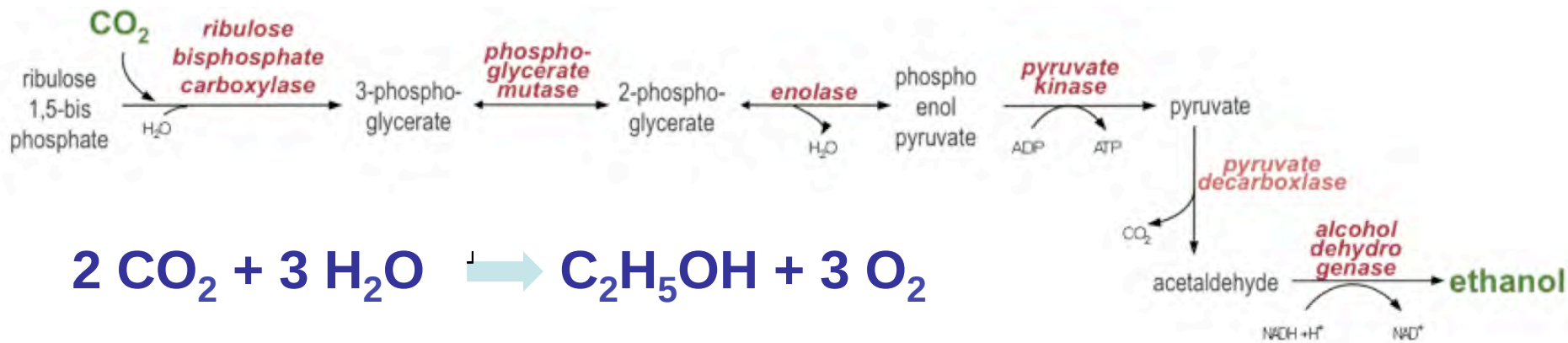
Enhanced cyanobacteria, photobioreactors, and ethanol separation systems are key, proprietary components of the Algenol technology.



$$2\ CO_2 + 3\ H_2O \rightarrow C_2H_5OH + 3\ O_2$$

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 organism.

Photosynthetic Efficiency and Productivity Targets

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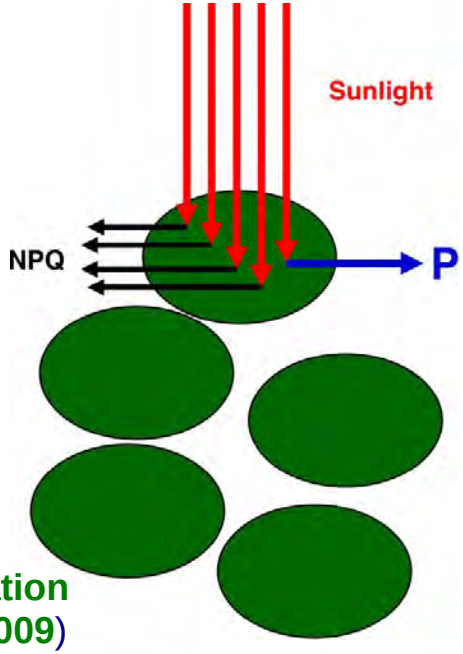
Ethanol Production Target

- Algenol target is 6000 gal/acre-yr
- Corn is about 400 gal/acre-yr; sugarcane about 1000
- Target corresponds to roughly 2% solar energy conversion efficiency (referenced to average US solar radiation)
- Efficiency similar to commercial biomass conversion for Chlorella (food supplements) as well as conventional crops
- Equivalent to about 20 g/m^2-day biomass production, with about 70 having been reported in the literature
- Absolute theoretical limit (8 photons per C fixed, or 24 for ethanol) is about 40,000 gal/acre-yr of ethanol or about 130 g/m^2-day of biomass

Fort Myers Physiology Lab

Potential Yield Limitations

- Light (photosaturation, photoinhibition)
- Diversion of fixed carbon to non-ethanologenic pathways
- Contaminants
- Availability of CO_2
- Nutrient supply



Photosaturation Illustration (Melis, *Plant Science*, 2009)

Photobioreactor Technology

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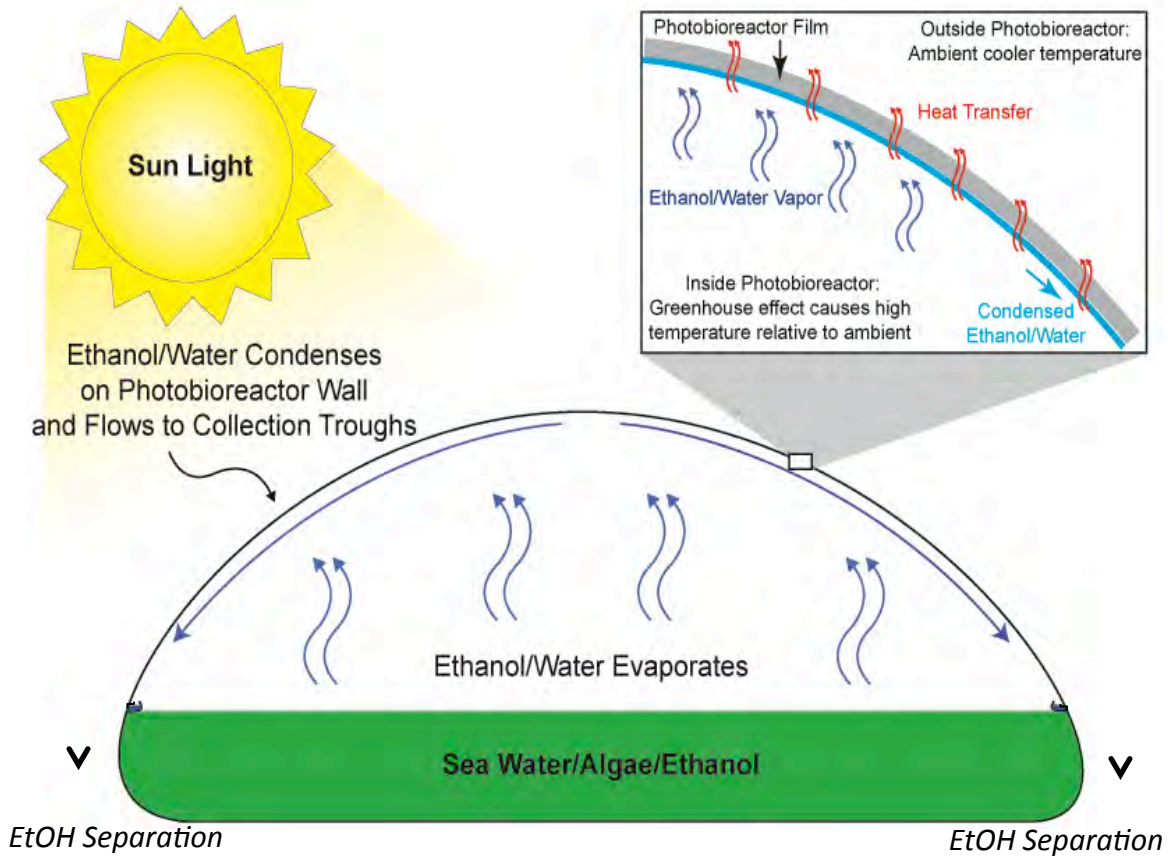
Enhanced cyanobacteria, photobioreactors, and ethanol separation systems are key, proprietary components of the Algenol technology.

- 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.

Low Energy Mixing Technology

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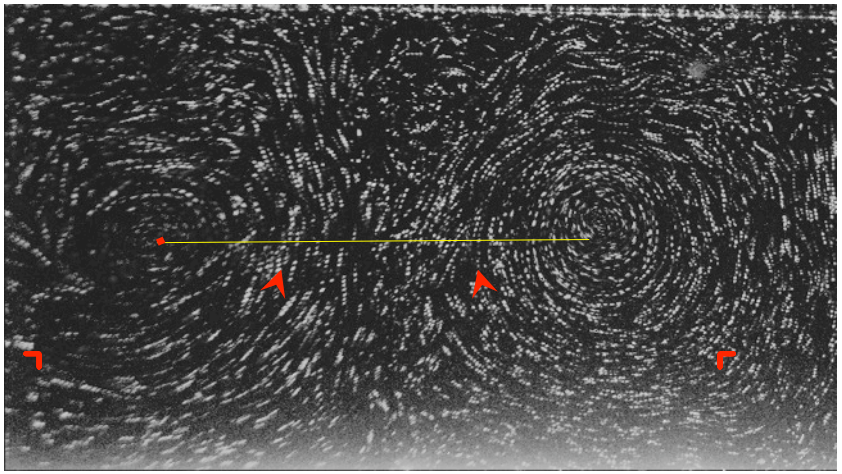
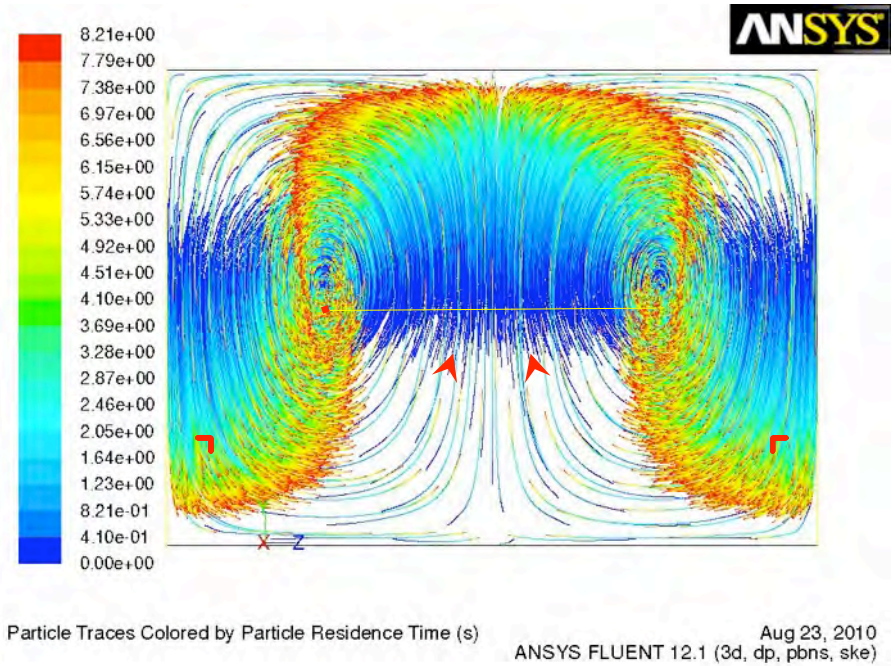
- Keep organisms suspended
- Facilitate gas exchange
- Ensure nutrient availability



Experimental Techniques for Flow Visualization - Laser Sheet Visualization



Computational Methods for Mixing System Modeling and Next Generation Design – CFD

Ethanol Purification Technology

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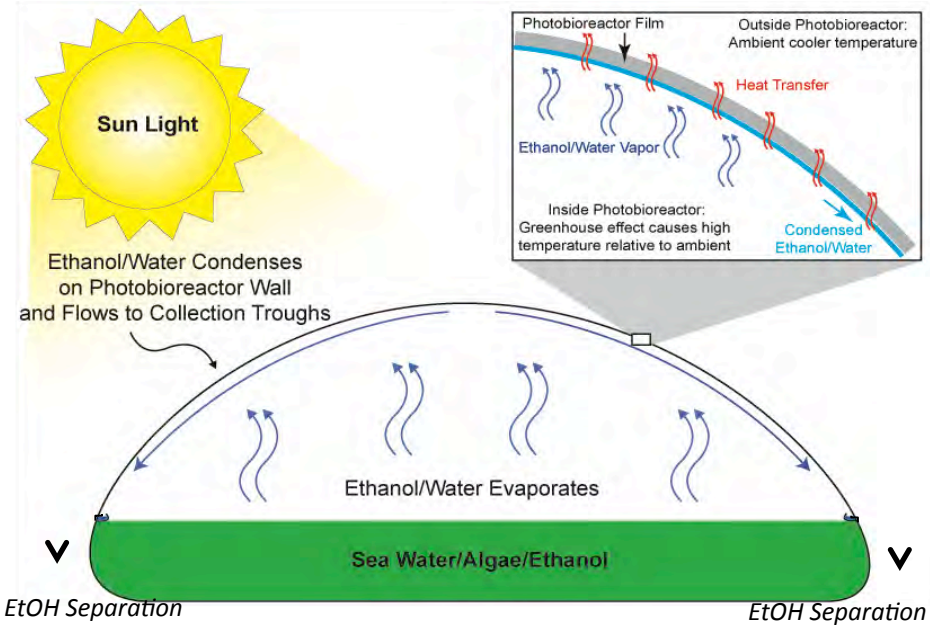

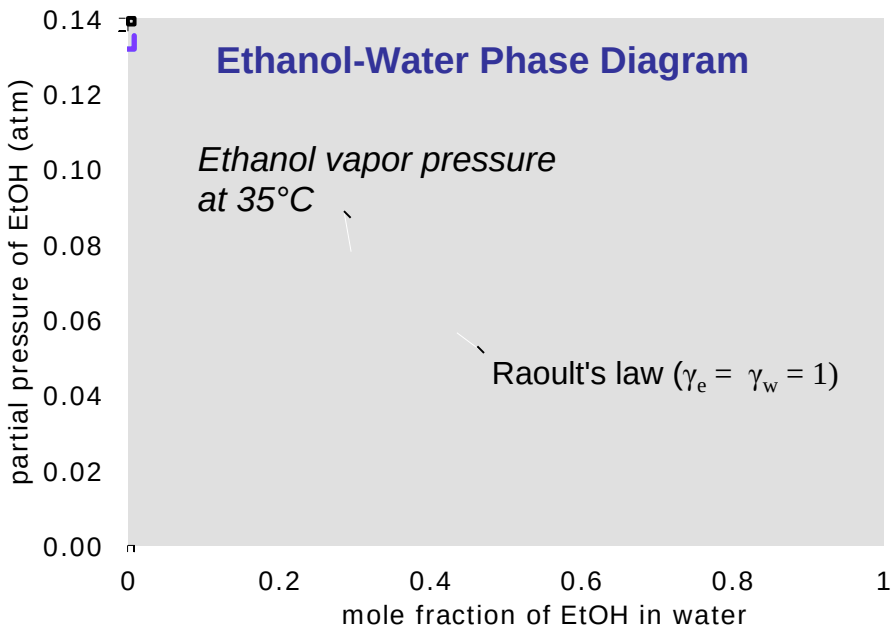

Photo-Bioreactor

0.5 – 2 wt%

Vapor Compression
Steam Stripping

5 – 20 wt%

Conventional Dist.
Vapor Compression Dist.
Membrane Separation

90 - 95 wt%

Mol Sieve
Extract. Dist.
Membrane

99.7% Fuel Grade

Energy Demand for Direct to Ethanol® Process

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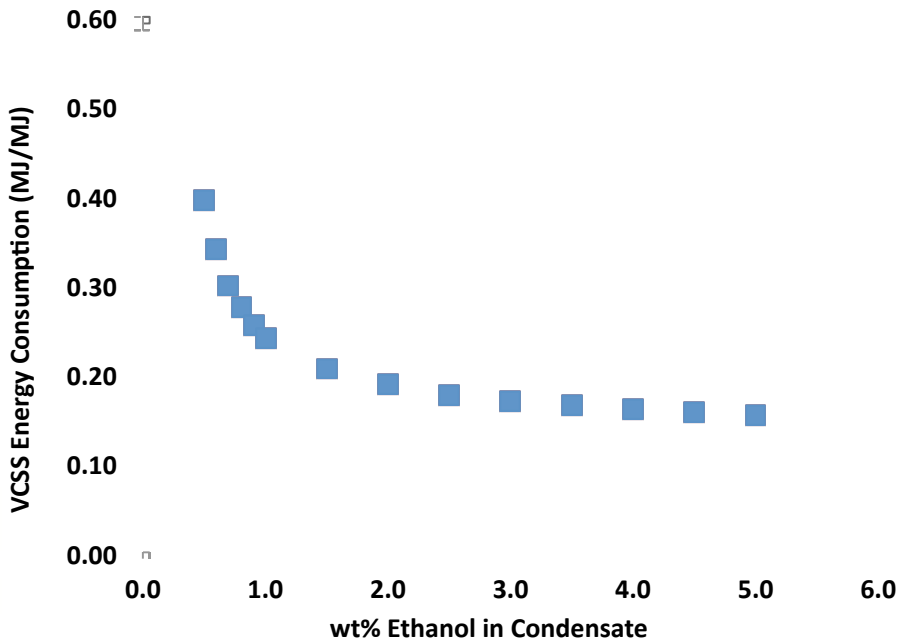
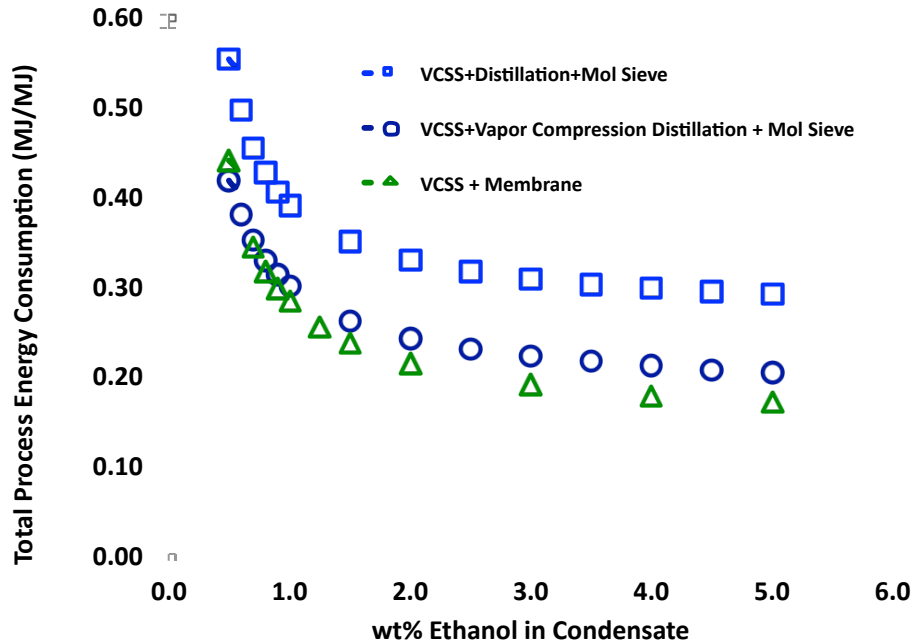
- VCSS is a largest energy consumer
- Energy demand depends strongly on ethanol concentration in condensate*
- At 1% condensate, VCSS represents about 20% parasitic load
- Energy demand for mixing, gas delivery, pumping, etc. added in*
- Total system energy demand plotted vs. condensate concentration for different dehydration options**

Energy Consumption Determined by Process Simulations (GaTech*,)**
(Input to Life Cycle Analysis)





D. Luo, Z. Hu, D. Choi, V. Thomas, M. Realff, and R. Chance, Env. Sci. & Tech., 2010, **44 pp 8670–8677*
***D. Luo, Z. Hu, D. Choi, V. Thomas, M. Realff, B. McCool and R. Chance, unpublished results*

System Description for Life Cycle Analysis

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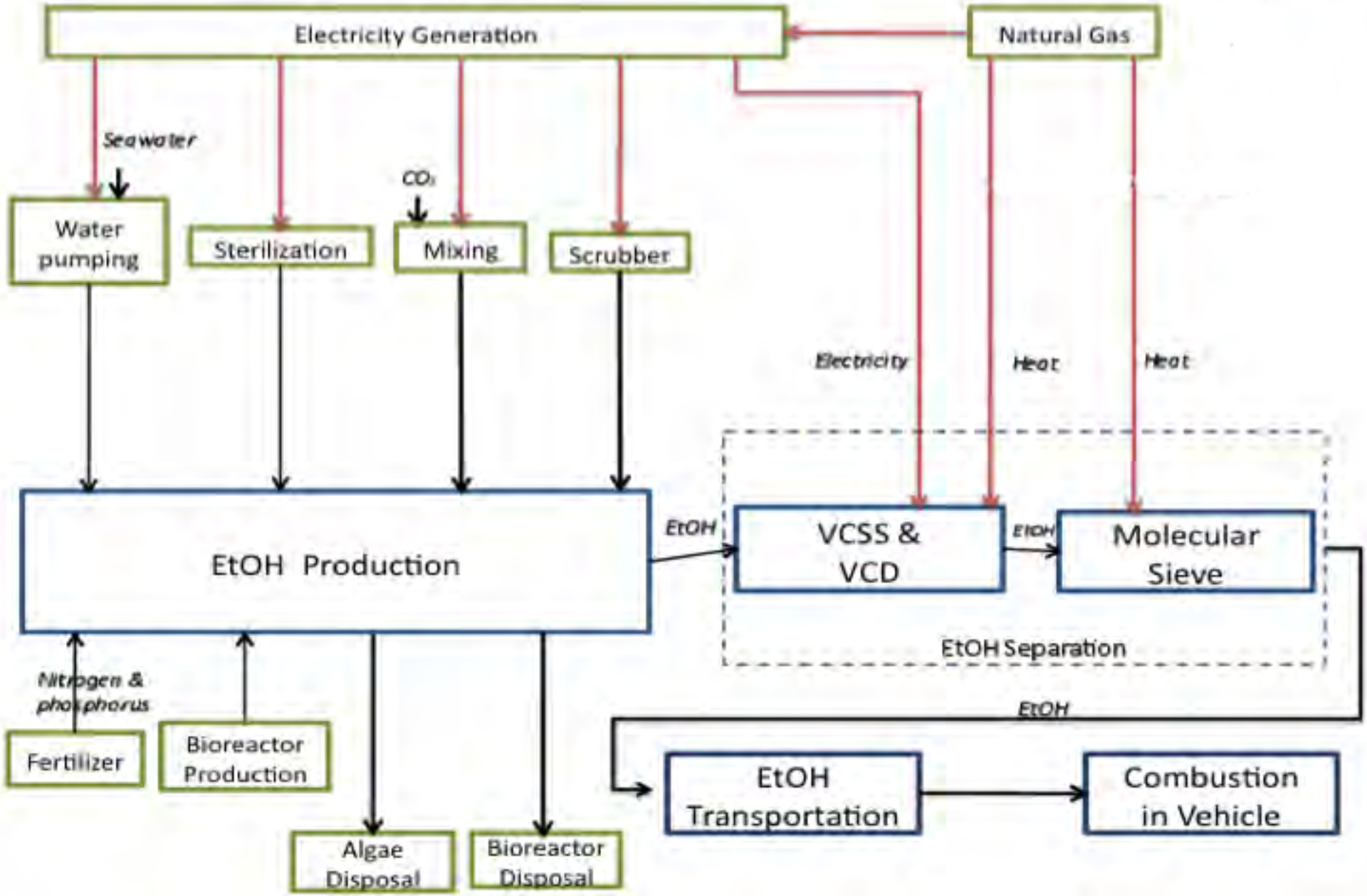

LCA for Evaluating Carbon Footprint and Technology Options

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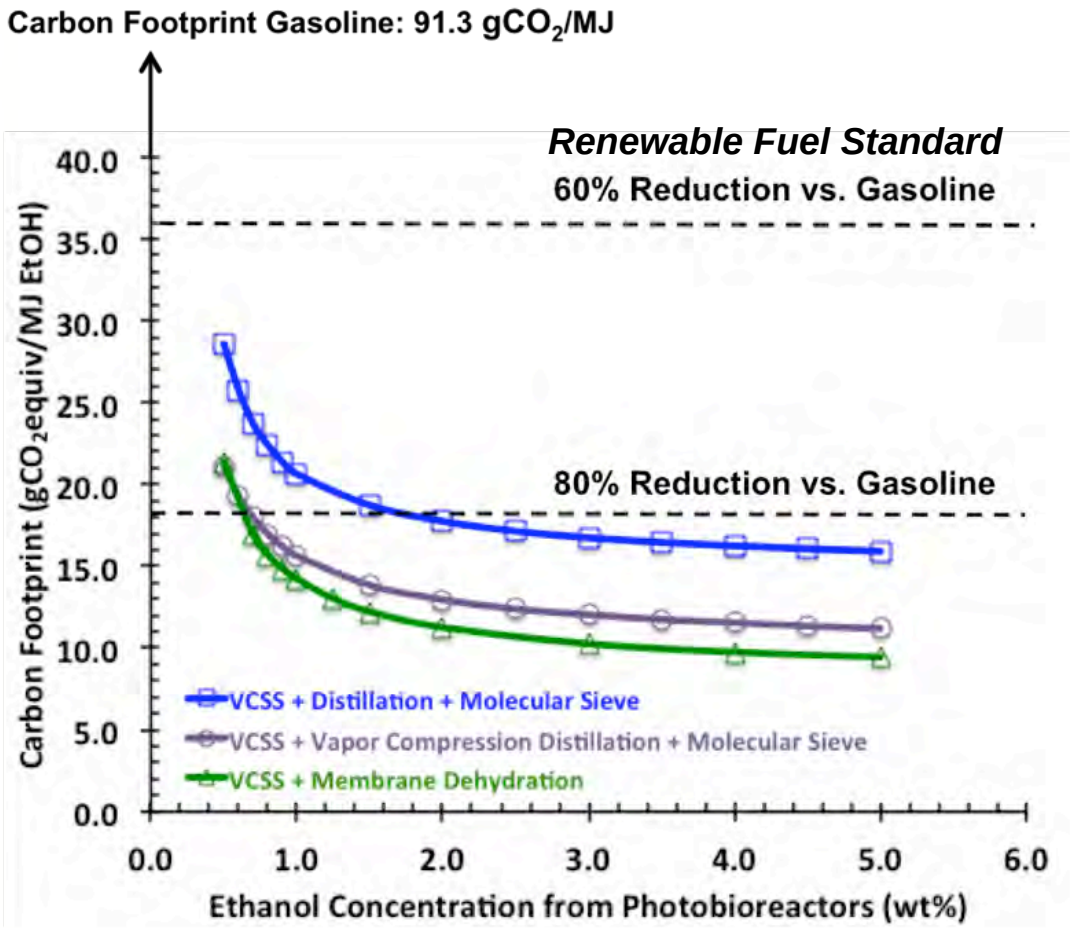

- LCA study is designed to be evergreen – continuously updated as part of our DOE project.
- *Renewable Fuel Standard is met in all scenarios studied.*
- LCA is important part of the evaluation of new technology options.
  - Example: Polymer membrane technology (MTR), in combination with Algenol's process simulations and integration concepts, yields lower carbon footprint, as well as lower CAPEX and OPEX.
  - Work on waste biomass disposition, to be performed at NREL, will be incorporated into LCA and techno-economic model.

Life Cycle Analysis Appears in: D. Luo, Z. Hu, D. Choi, V. Thomas, M. Realff, and R. Chance, *Env. Sci. & Tech*., 2010, **44** pp 8670–8677.

Energy Cost and Carbon Footprint Comparison

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Transportation Fuel	Fuel energy (MJ/gal)	Production cost ($/gal)	Fuel to vehicle efficiency (MJ/MJ)	Energy to vehicle (MJ/gal)	Cents/MJ (vehicle)	GHGs Emissions (g-CO2/MJ (vehicle))
Gasoline	122.5	2.42 [a]	26%[d]	31.9	7.6	351 [h]
Diesel	134.8	2.58 [a]	35%[d]	47.2	5.5	266 [h]
Corn Ethanol	80.5	2.61 [b]	26%[d]	20.9	12.5	275 [h]
Algenol Ethanol	80.5	1.37 [c]	26%[d]	20.9	6.6	55[i]
		$/grid-MJ	Grid to vehicle efficiency (MJ/MJ)	Energy to vehicle (MJ/grid-MJ)	Cents/MJ (vehicle)	GHGs Emissions (g-CO2/MJ (vehicle))
Grid Electricity (Residential Sector)	US Average	0.032 [e]	65% [f,g]	0.65	4.9	308 [h]

a *U.S. Energy Information Administration, "Gasoline and Diesel Fuel Update". http://www.eia.gov/oog/info/gdu/gasdiesel.asp (accessed Feb 2011)*

b *U.S. Energy Information Administration, "Annual Energy Outlook 2007 with Projections to 203"0. http://www.eia.gov/oiaf/archive/aeo07/issues.html (accessed Feb 2011, Ethanol production prices adjusted for Corn and Natural Gas Market Prices as of Feb 2011)*

c *Algenol's Economic Model – Average production cost estimate with 6000 gal/acre-yr target (includes capital cost discounted over 15 years, and operating cost)*

d *Crabtree, G., Argonne National Laboratory, "Where is Transportation Going?" http://ceet.mccormick.northwestern.edu/events/domain_dinner07/crabtree_domain_12-3-07.pdf (accessed Feb 2011)*

e *U.S. Energy Information Administration, "Monthly Electric Sales and Revenue Report with State Distributions Report, Form EIA-826". http://www.eia.gov/cneaf/electricity/page/eia826.html (accessed Feb 2011)*

f *Elgowainy et. al., Argonne National Laboratory, "Well-to-Wheels Analysis of Energy Use and GHG Emissions of Plug-In-Hybrid Electric Vehicles". www.transportation.anl.gov/pdfs/TA/559.pdf (accessed Feb 2011)*

g *U.S. Department of Energy," Fuel Economy". www.fueleconomy.gov (accessed Feb 2011)*

h *Argonne National Laboratory, "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model". http://greet.es.anl.gov/ (accessed Feb 2011) [U.S. Mix Fuel assumed: Residual Oil (1.04%), Natural Gas (19.11%), Coal (47.24%), Nuclear Power (20.92%), Biomass (0.44%), Others (11.25%)]*

i *D. Luo, Z. Hu, D. Choi, V. Thomas, M. Realff, and R. Chance, "Life Cycle Energy and Greenhouse Gas Emissions for an Ethanol Production Process Based on Blue-Green Algae", Env. Sci. & Tech., 2010, **44** pp 8670–8677*

Technical Partnerships/Leveraging

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	Key Technical Areas	Level of Effort/Other Contributions
Dow	PBRs; water treatment; process engineering; mixing systems	Over 20 scientists involved in DOE project and beyond
Linde	Gas management; product separation; process engineering; CO_2 management; vapor liquid equilibria; gasification	6 scientists directly involved; facilitation of contacts with university scientists in gasification and VLE
VALERO	Infrastructure and ethanol distribution	Joint development exploring integration of Algenol process with refinery processes
Georgia Tech	Separations, life cycle analysis, CO_2 delivery, biomass disposition	7 professors, 5 postdocs, 3 students
MTR Membrane Technology & Research	Membrane separations, integration of the Bio-Sep system with our VCSS	3 scientists, extensive know-how in membrane applications
NREL	Biomass disposition and LCA support; evaluation of industrial CO_2 sources	4 scientists, extensive connections to algae science area
	Ethanol separations via inorganic membranes	2 professors, 1 postdoc
Honeywell	Control systems for DOE pilot facility and subsequent commercial projects	3 scientists, extensive science base in sensors and control instrumentation

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