SOLIX
Fueling a better world

Colorado State University

Large Scale Production of Microalgae for Biofuels

Dr. Morgan DeFoort

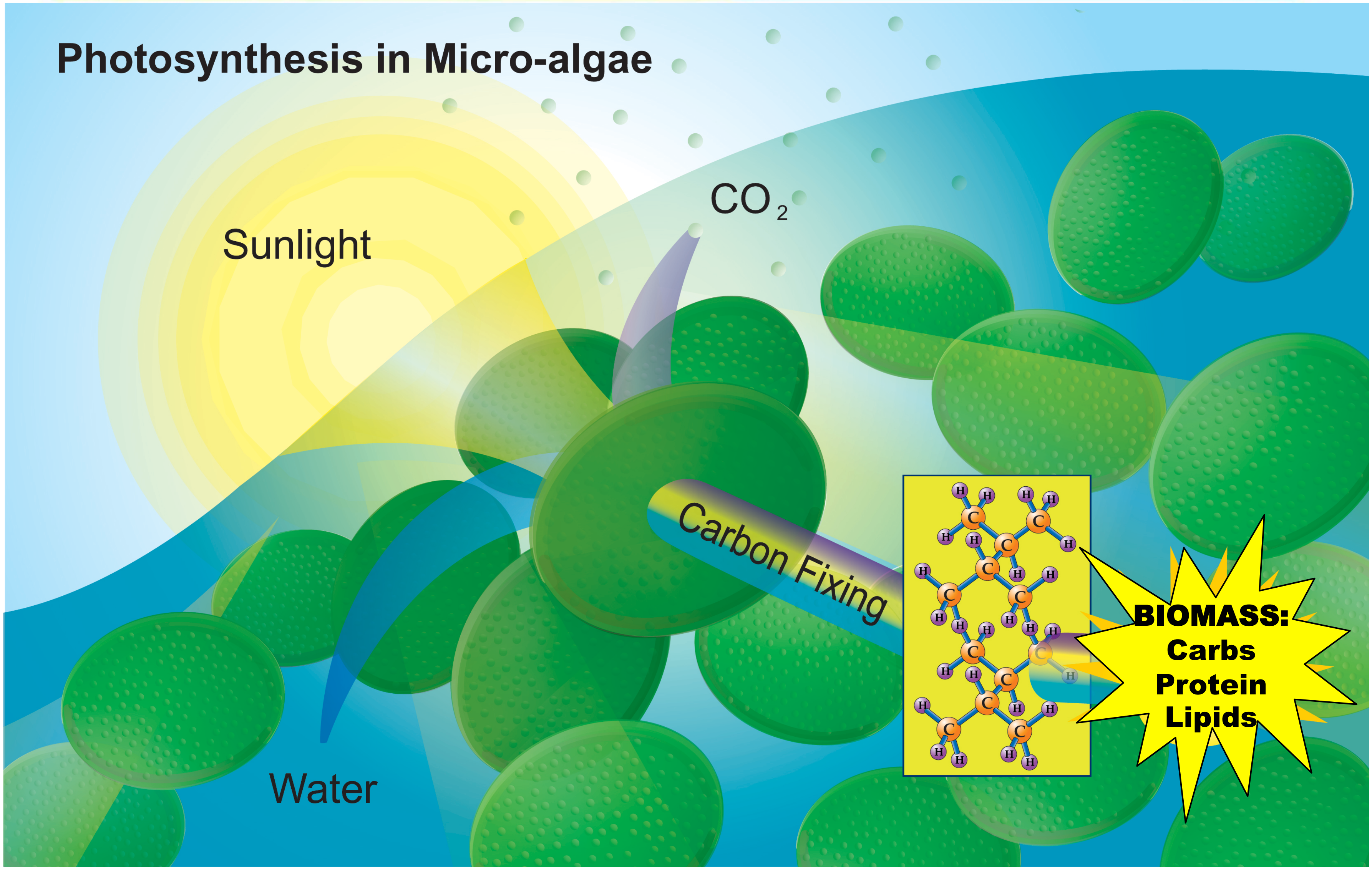
Conference on Alternative Energy Issues
LSU, April 22, 2009

About Solix

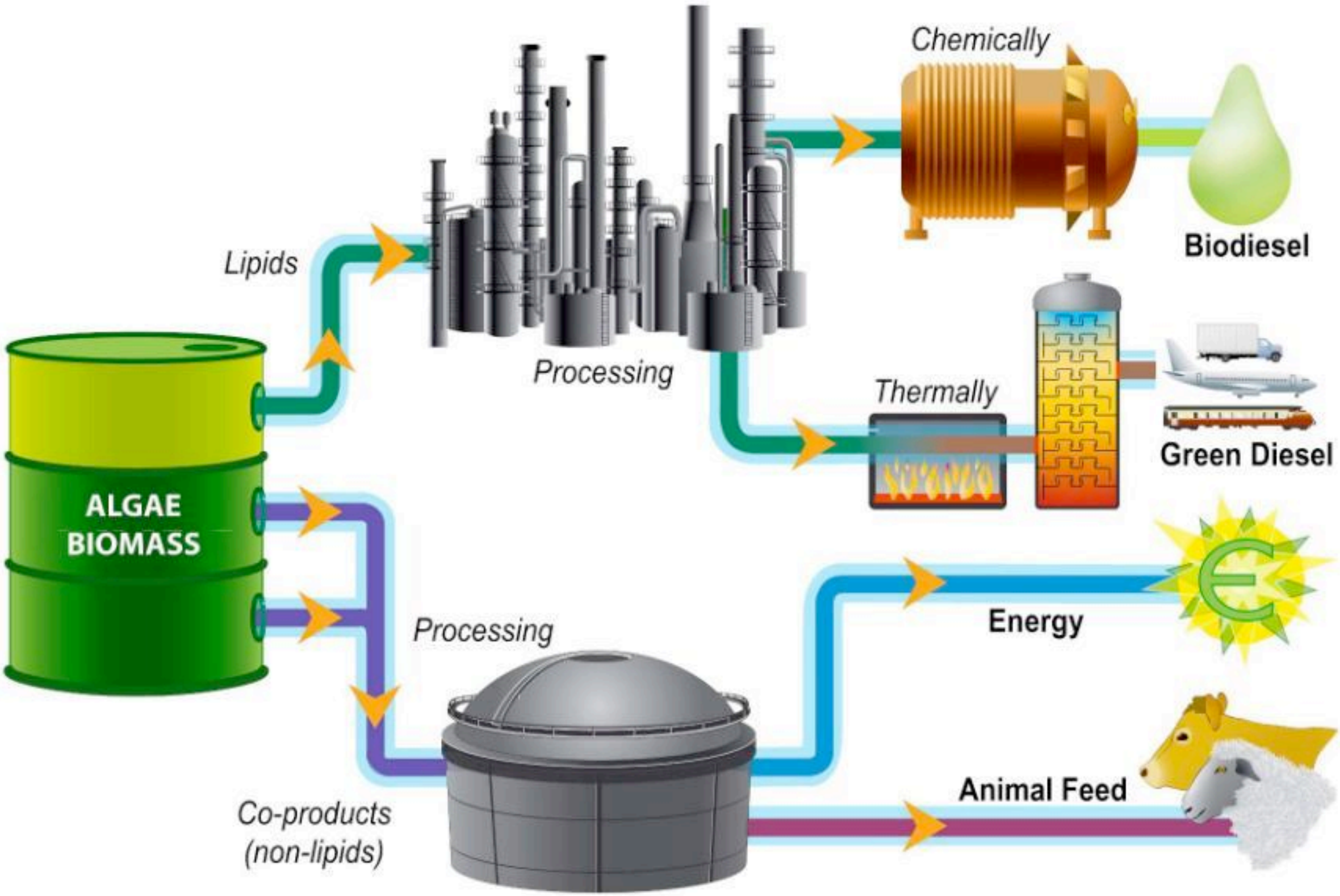
- **Focused on the development and commercialization of large-scale algae-to-biofuels systems**
- **Launched in March, 2006**
- **Located in Fort Collins, Colorado**
- **Privately funded**
- **50+ employees: 40 full-time + 15 FTE from students / faculty**
- **Headquartered at CSU Engines & Energy Conversion Laboratory**

- **Solix facilities**
  - **6,000 ft^2 office space, 18,000 ft^2 lab / fab space**
  - **Outdoor R&D facility in Fort Collins**
  - **Scaleup facility being constructed in SW Colorado**
- **Significant strategic partners in industry, science and engineering**

Basic Photosynthesis



Processing


ALGAE BIOMASS
Lipids
Processing
Chemically
Biodiesel
Thermally
Green Diesel
Processing
Co-products (non-lipids)
Energy
Animal Feed

Land & Water Efficiency

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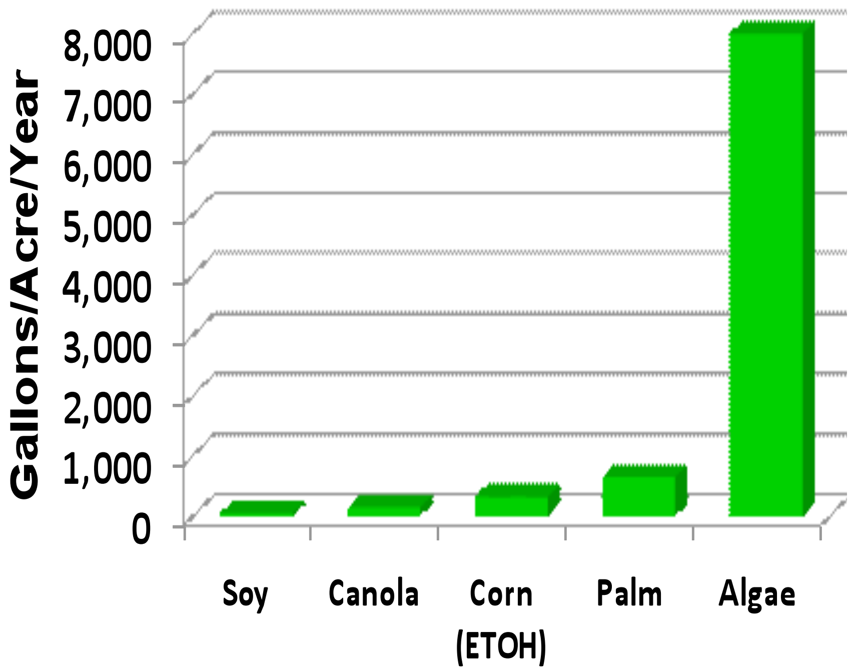
Annual Production

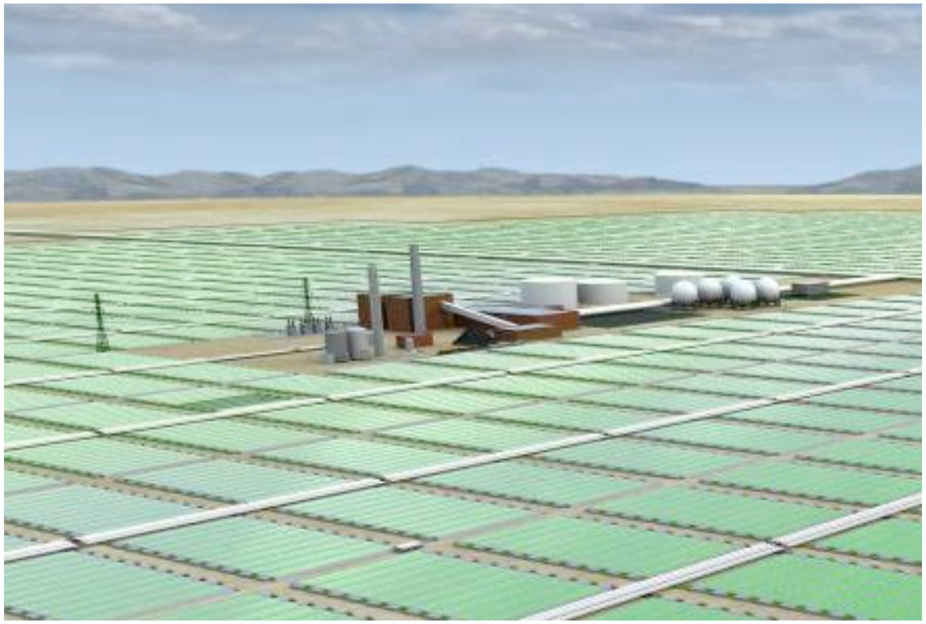
- Soybean: 40 to 50 gal/acre
- Rapeseed: 110-145 gal/acre
- Mustard: 140 gal/acre
- Jatropha: 175 gal/acre
- Palm oil: 650 gal/acre
- Algae est.: 5,000-10,000 gal/acre
  7,000 “nominal”



Realism

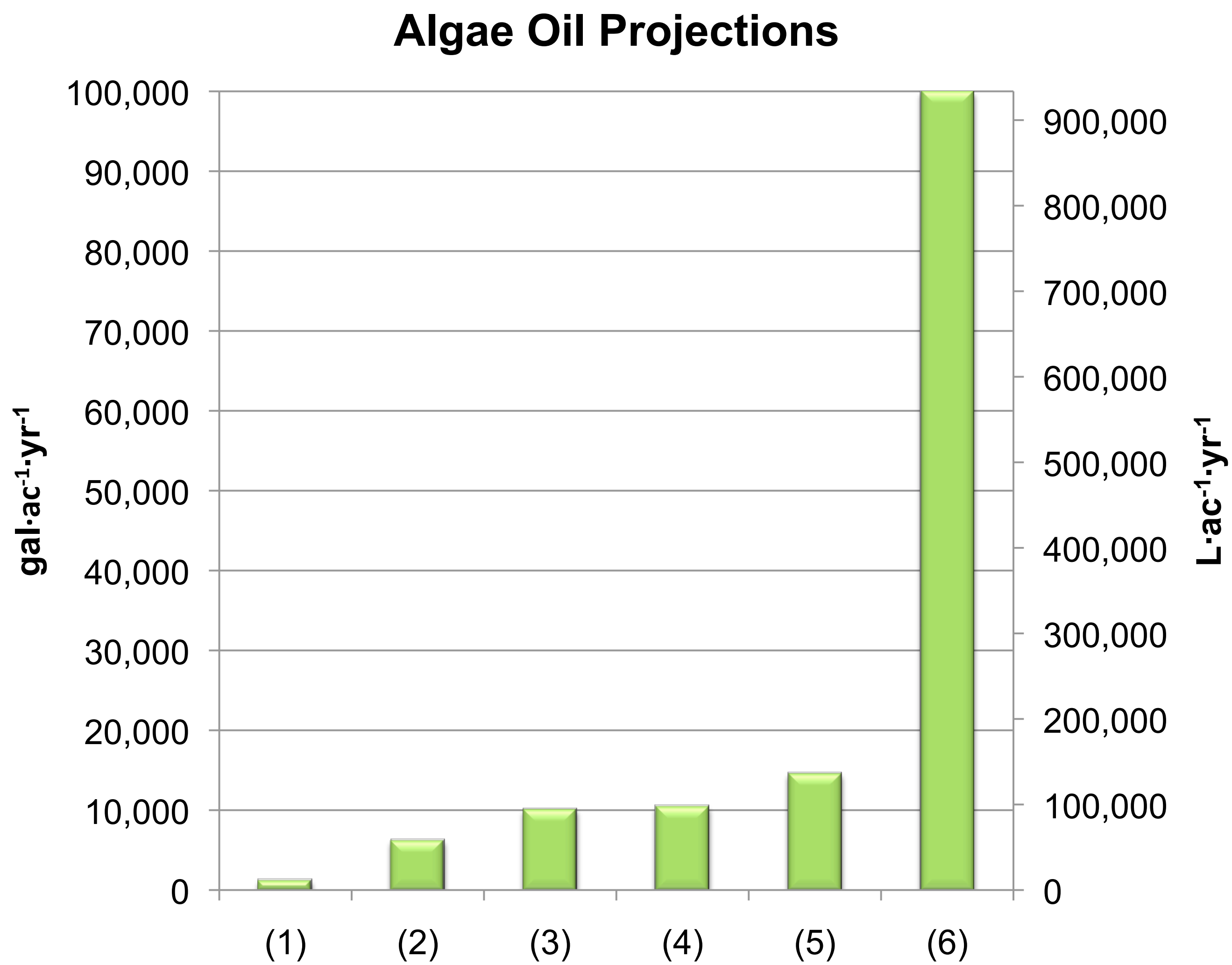
Ya gotta dream. . .

But you also gotta obey the laws of physics. . .



"We expect to produce 100,000 gallons (of vegetable oil) per acre per year," which is a much higher yield than soybeans and other plants being used for biofuel…"

Motivation

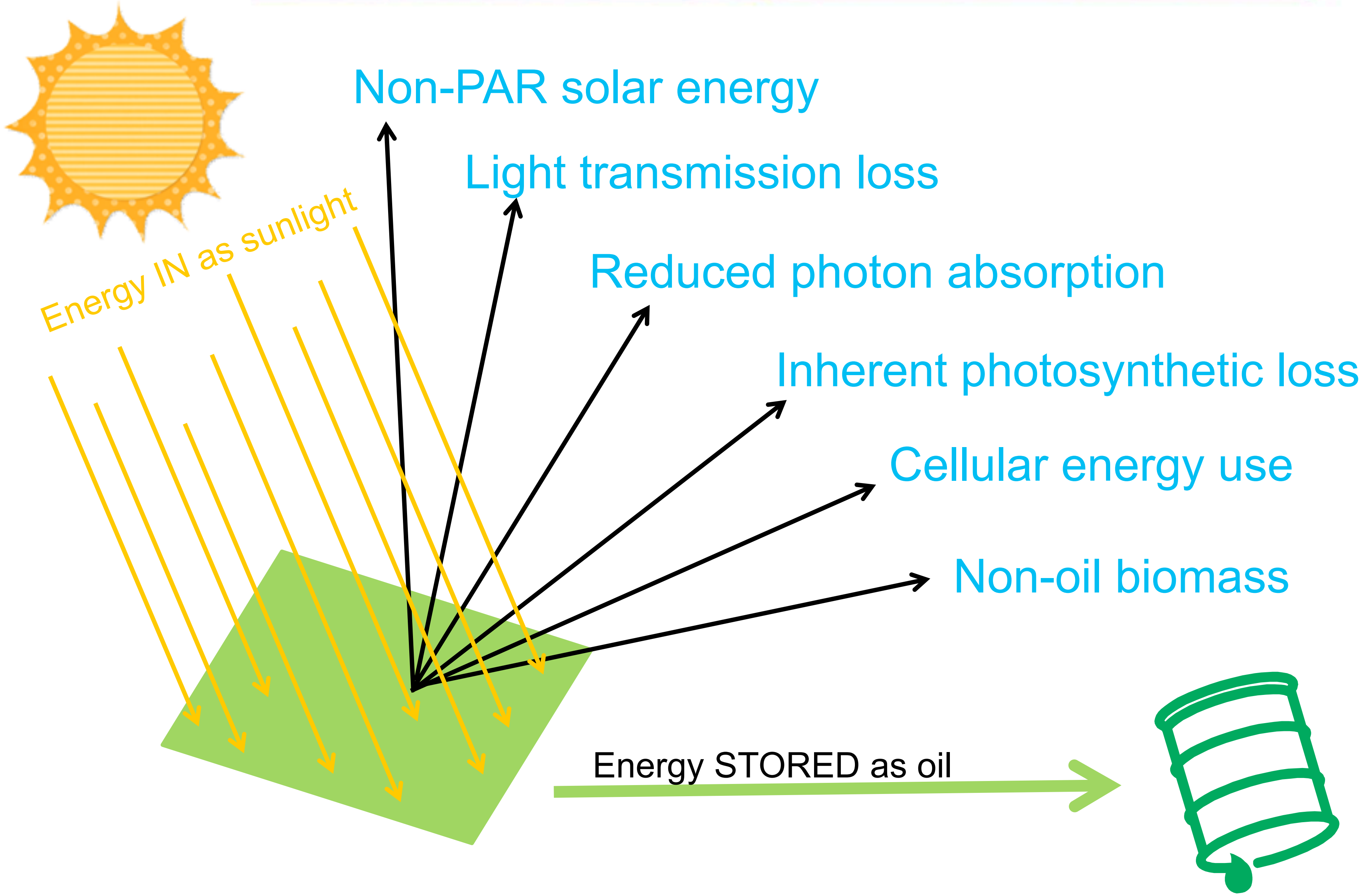


(1) Schenk, 2008
(2) Chisti, 2007
(3) NREL ASP, Sheehan et al., 1998
(4) Schenk, 2008
(5) Chisti, 2007
(6) Report on CNN, Apr 4, 2008

Wide range of projections…

What is the ultimate upper limit?

Method


Non-PAR solar energy
Light transmission loss
Reduced photon absorption
Inherent photosynthetic loss
Cellular energy use
Non-oil biomass
Energy IN as sunlight
Energy STORED as oil

Practical Case: Results

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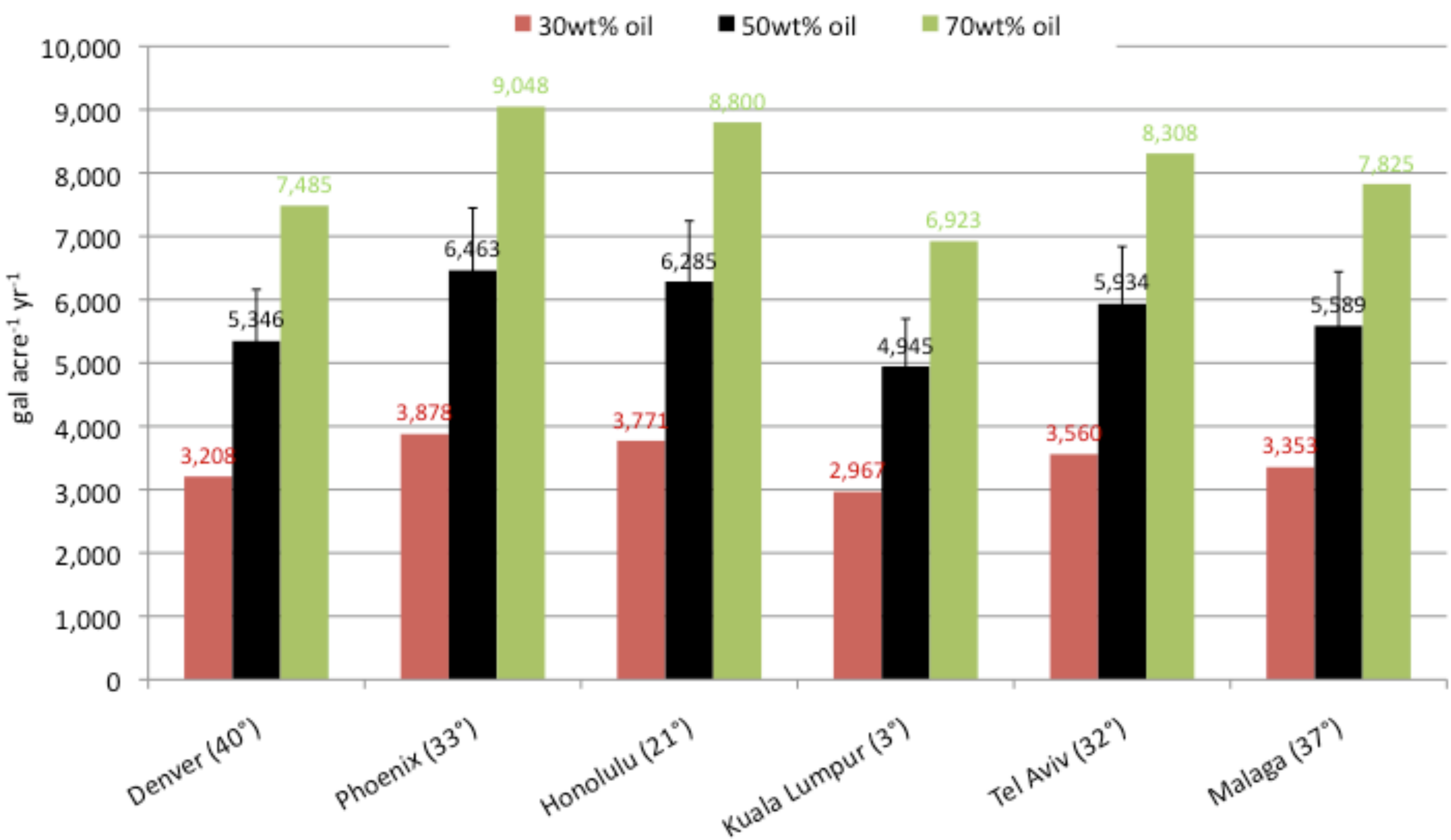
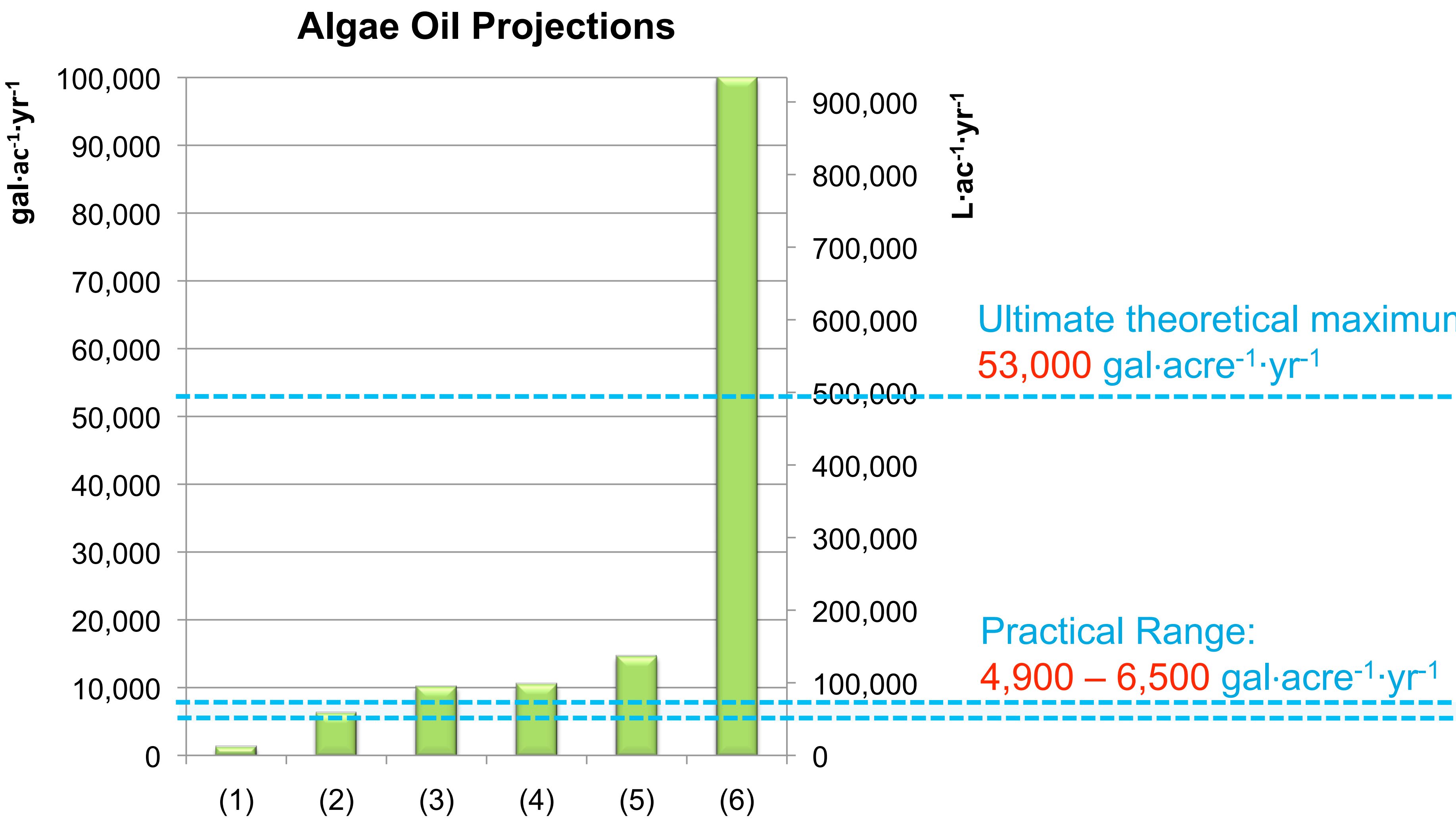
Practical Maximum Range: 4,900 – 6,500 gal·acre^{-1}·yr^{-1}



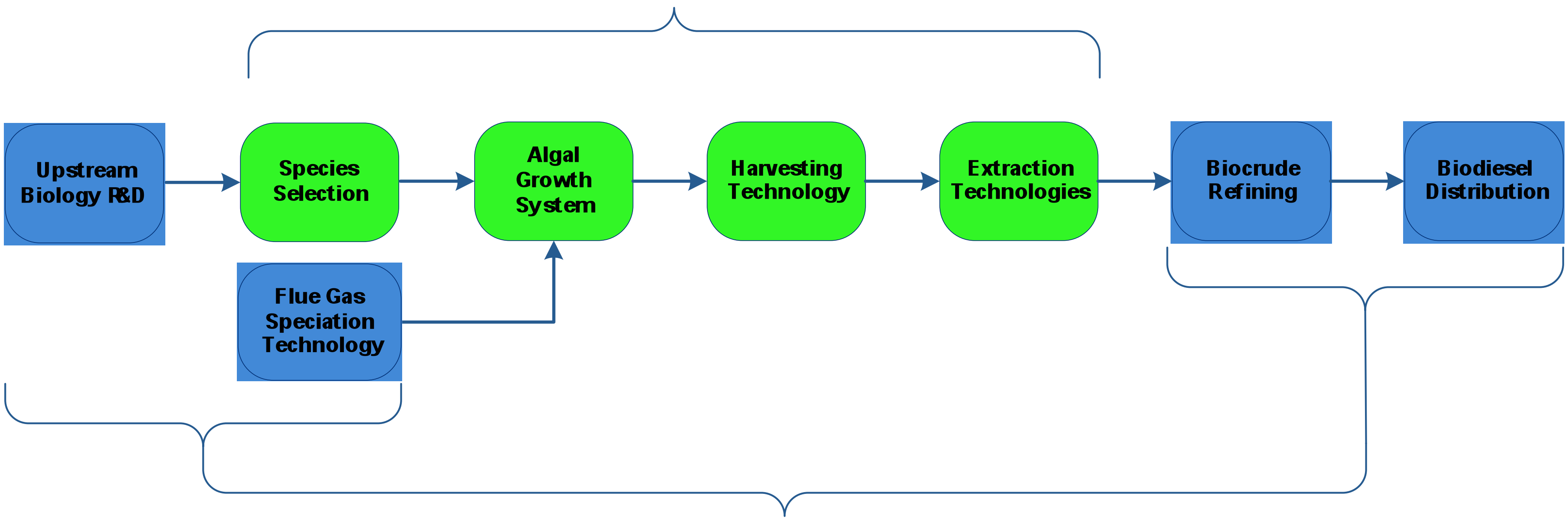
Conclusions



Ultimate theoretical maximum:
53,000 gal·acre^{-1}·yr^{-1}

Practical Range:
4,900 – 6,500 gal·acre^{-1}·yr^{-1}

Solix Focus Area



Outline

- Solix / Algae Intro
- **Open Pond Overview**
- Closed Photobioreactor Overview
- Solix AGS System
- Harvesting & Extraction
- Scaleup
- Production Costs
- Conclusions

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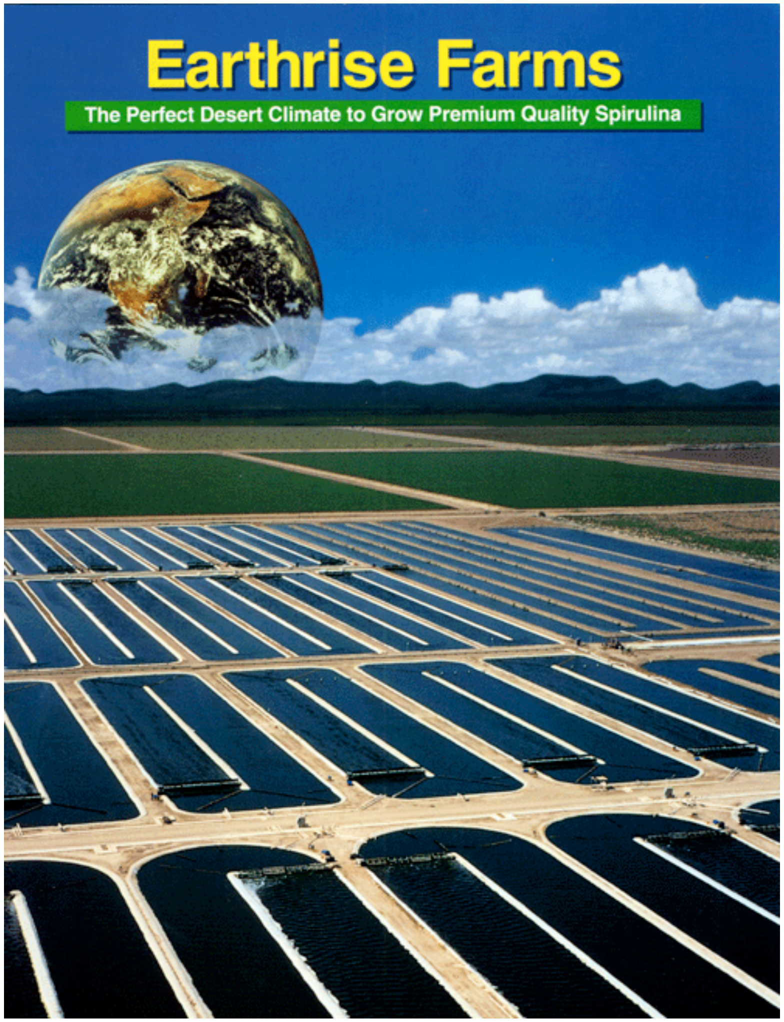
Open Pond Cultivation: Dunaliella, Eilat, Israel

Open Pond Production: Earthrise *Spirulina*. California



Open Pond Production: Seambiotic
Nanno. Ashkelon, Israel

Open Pond Attributes

Advantages

- Lowest capital cost
- Only technology demonstrated at large scale – to date
- Can maintain specific cultures of extremophiles

Disadvantages

- Allows contamination of specific culture with local species / strains
- Potential for loss / migration of GMO
- Susceptible to weather
- Water loss from evaporation / percolation

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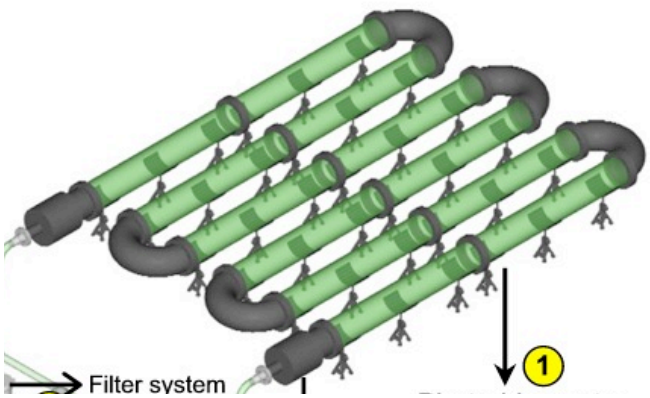
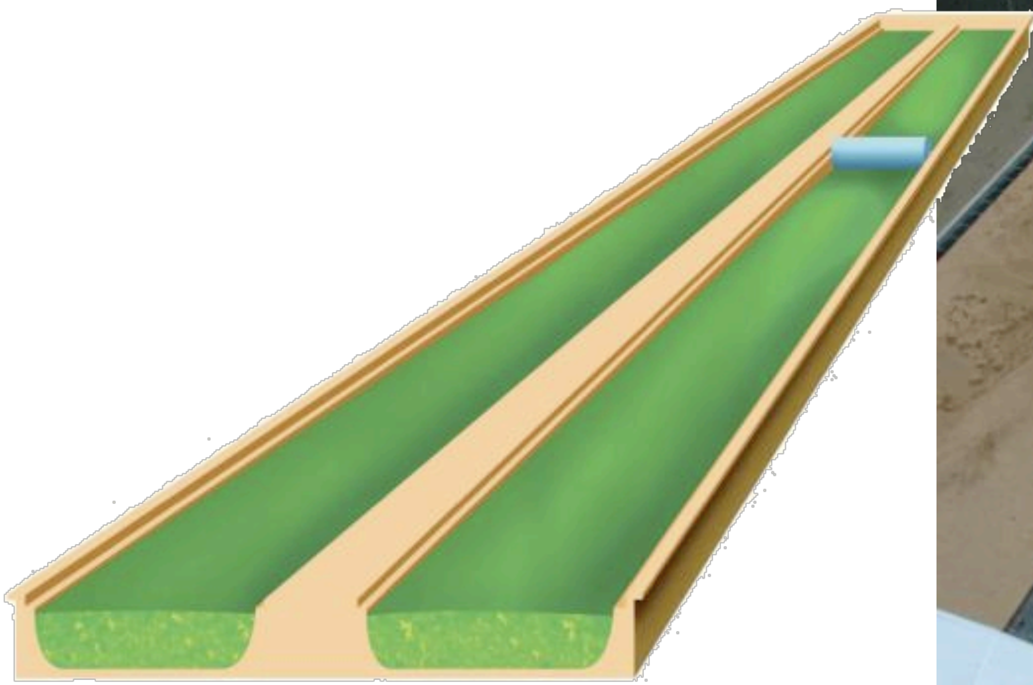
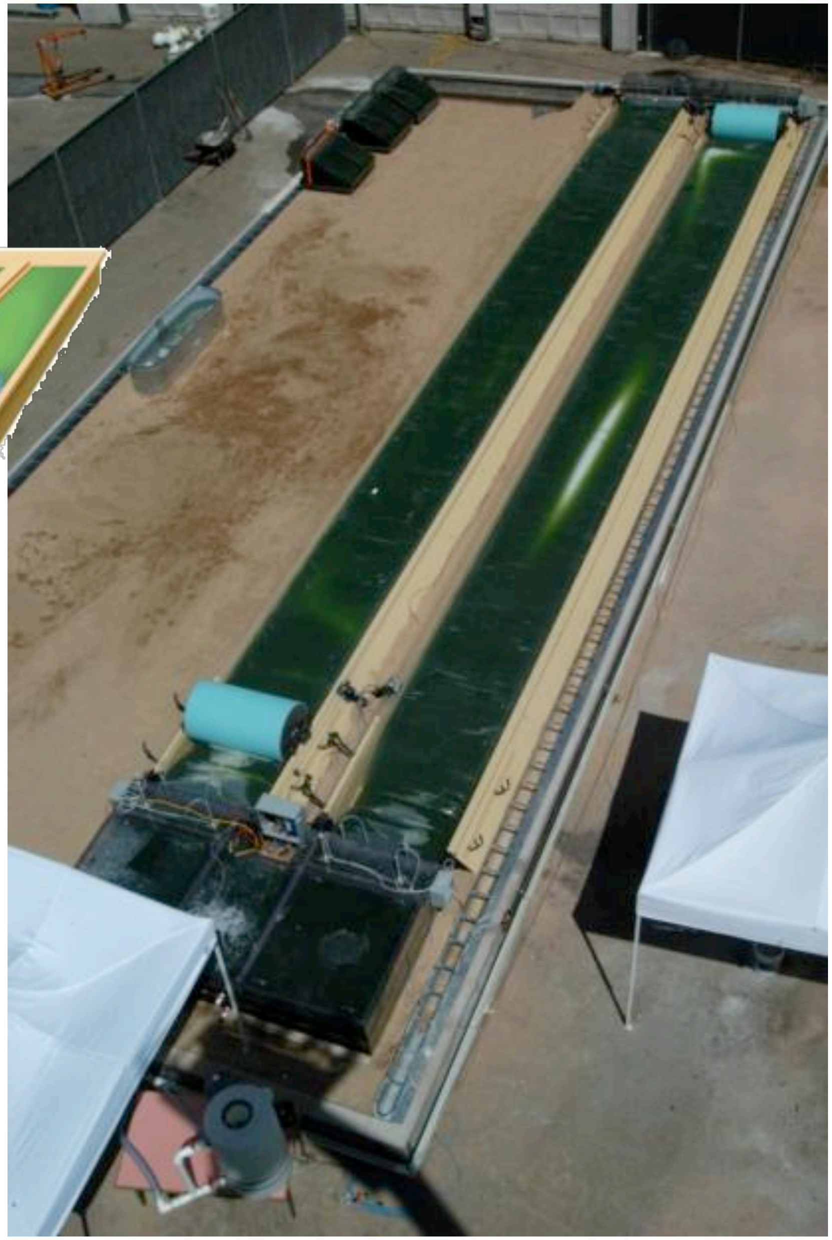
Direct Light PBRs:
GreenFuels, 1st Gen

Direct Light PBRs:
AlgaeLink / Bioking

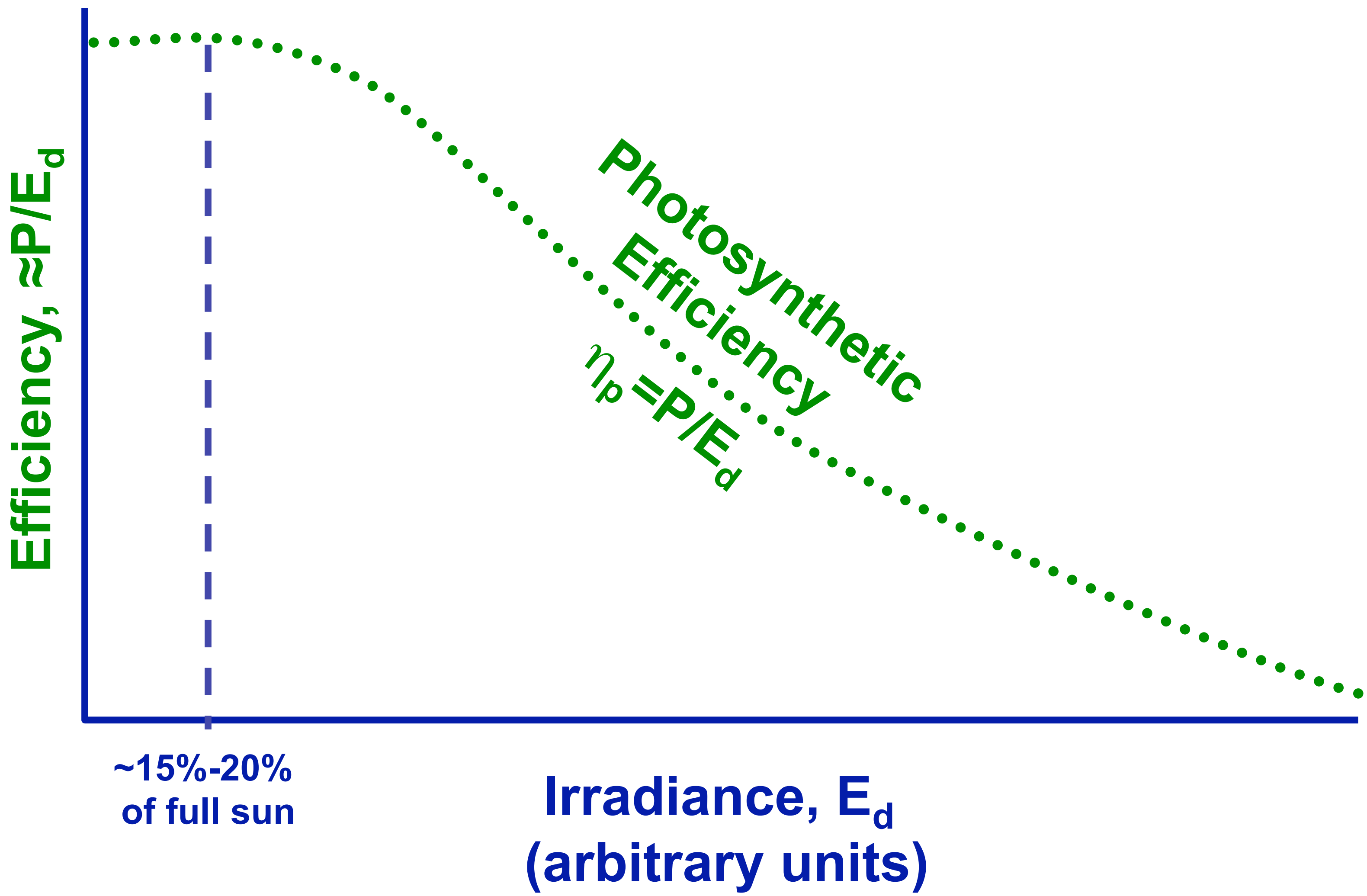


Direct Light PBRs:
Solix, Gen1 (1st Generation)





Photosynthetic Efficiency



Impact of Light Intensity

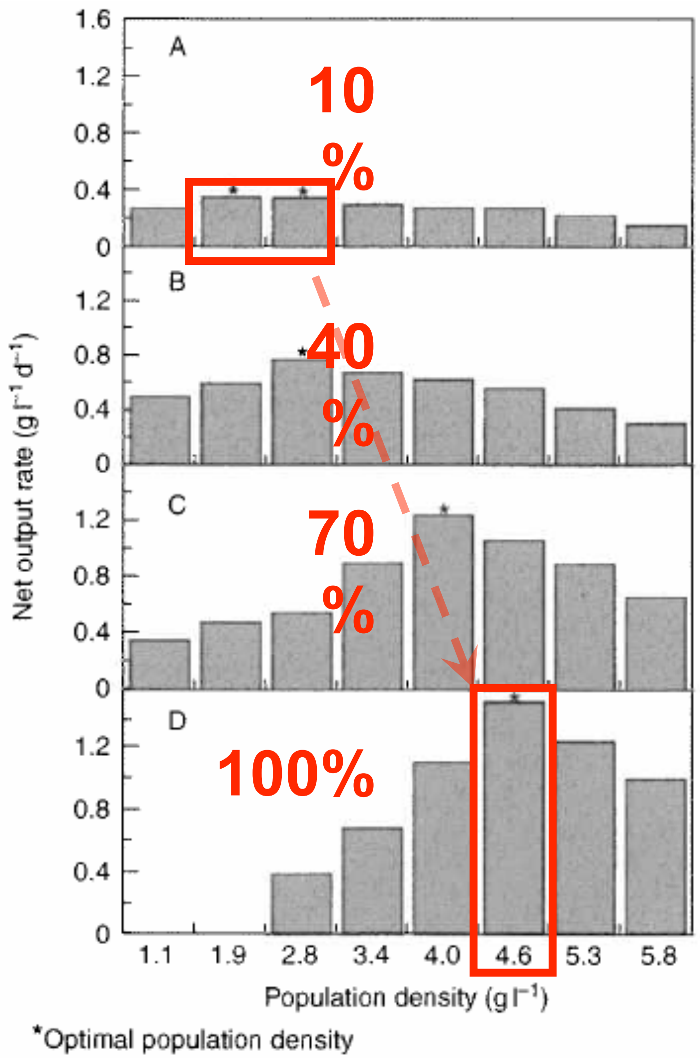


Fig. 8.3. Interrelationships between incident PFD, optimal population density and net output rate. A = 90% shade; B = 60% shade; C = 30% shade; D = no shade, full sunlight (from Hu & Richmond, 1994). Reprinted with permission from Kluwer Academic Publishers (*J. Appl. Phycol.*).

Note: 10X increase in light, but only 3.5X increase in output. Implies a 3X reduction in photosynthetic efficiency.

Conversely, if diffuse light can be used over extended surface area, 3X increase in output possible.

Extended Area PBRs

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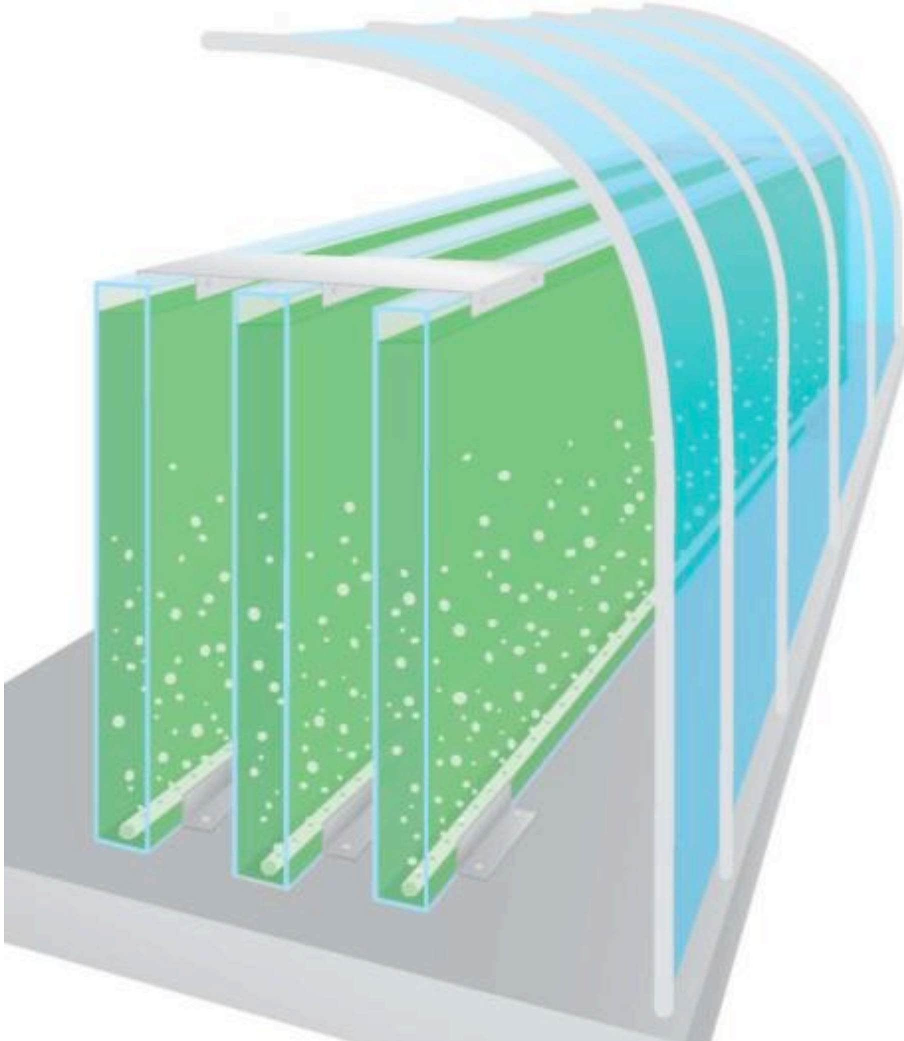
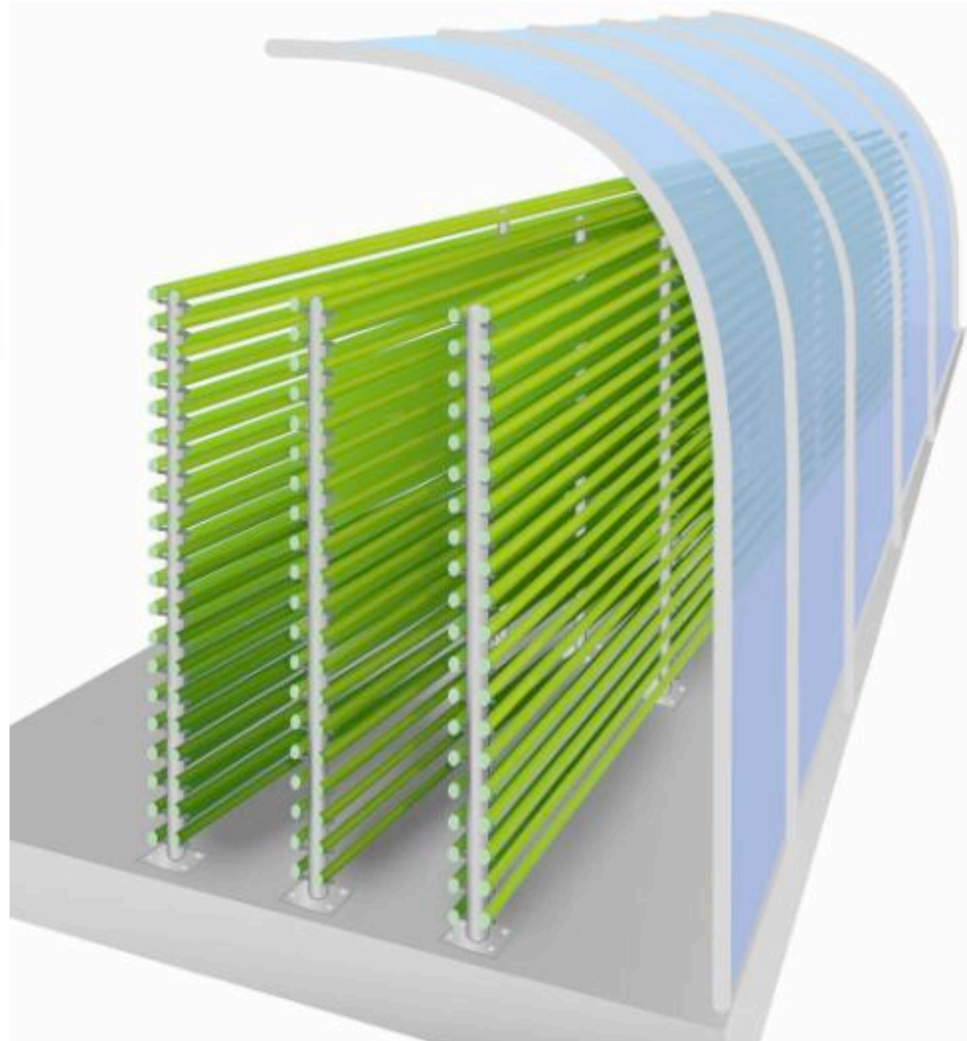
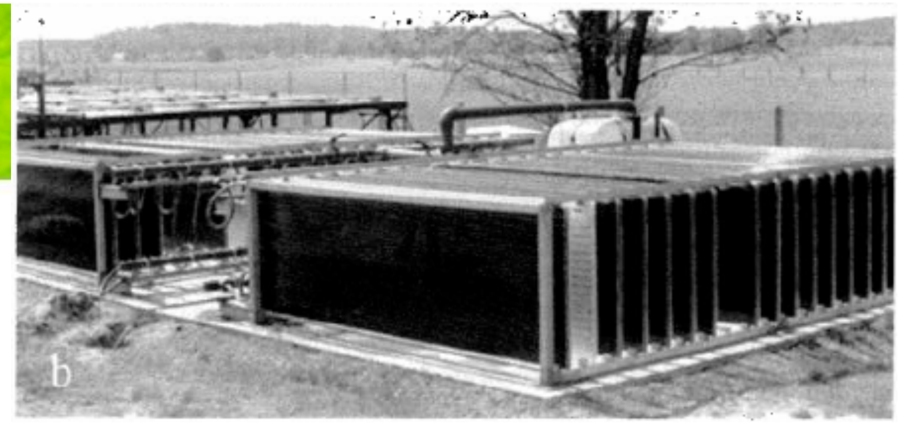


Glass Plate Photobioreactor
(Pulz, Richmond, others)

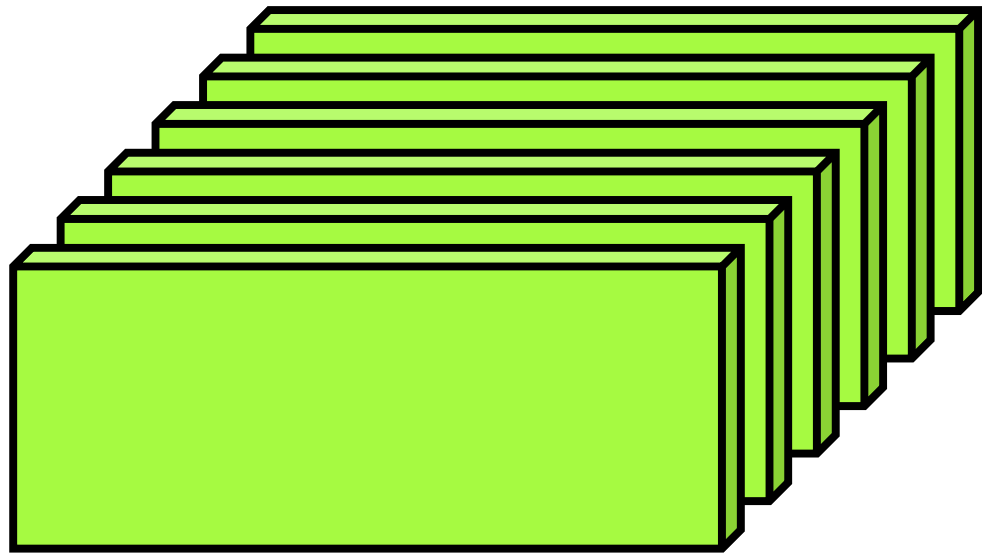


Glass Tube Photobioreactor
(Pulz, IGV, Ketura, Torzillo, others)

IGV Diffuse PBR



≈5 m² illuminated area
for 1 m² of ground area



Utilizes diffuse light, short photic distances (approaches ideal cycle time of 20 ms) for high photosynthetic efficiency

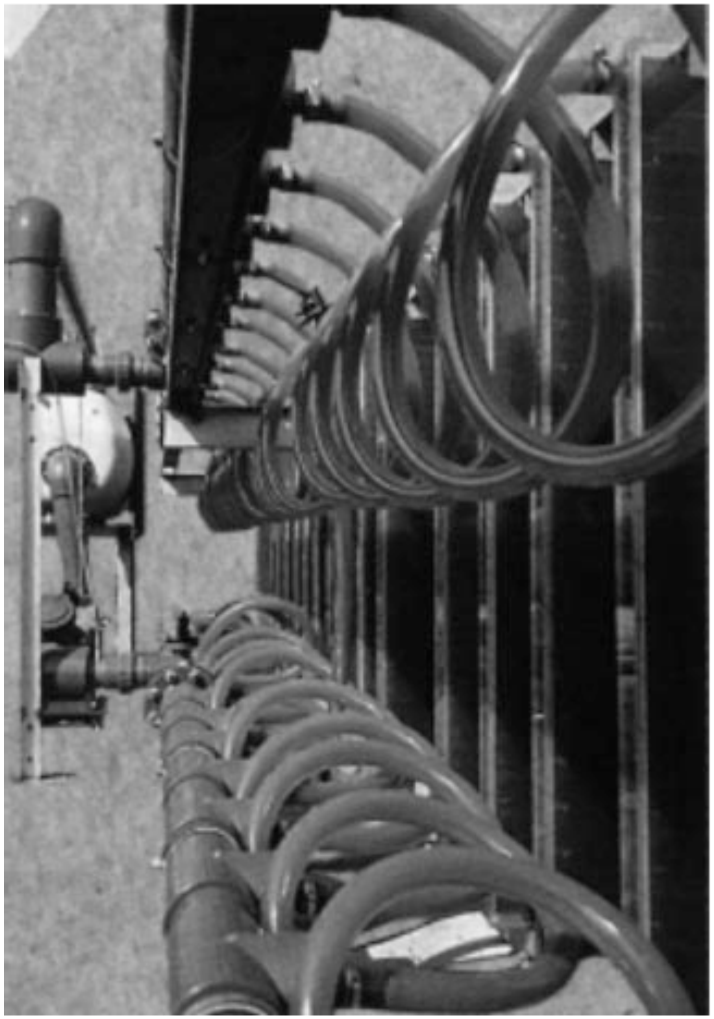


Figure 8. Meandering plate cultivator 100 to 6000 L. IGV Institut für Getreideverarbeitung.

Pumped Tubewall PBR: IGV
Haematococcus Pluvialis

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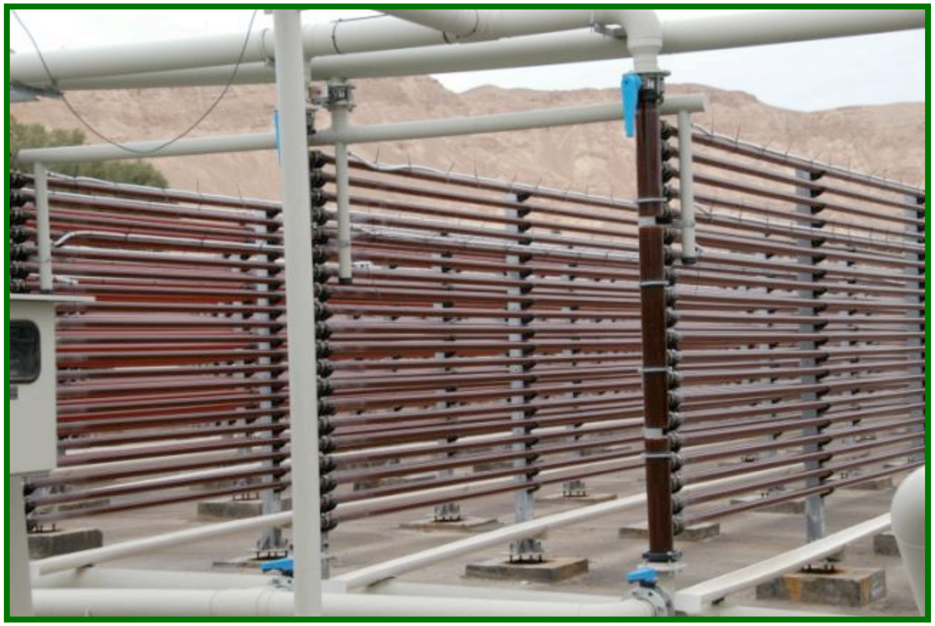
Figure 4: The cultivation in the PBR 4000 from 21.04.2006 to 21.05.2006 with sunlight and no artificial light

Pumped Tubewall PBR: AlgaTech
Haematococcus Pluvialis



High-Growth Phase **Stress Phase**

Closed PBR Attributes

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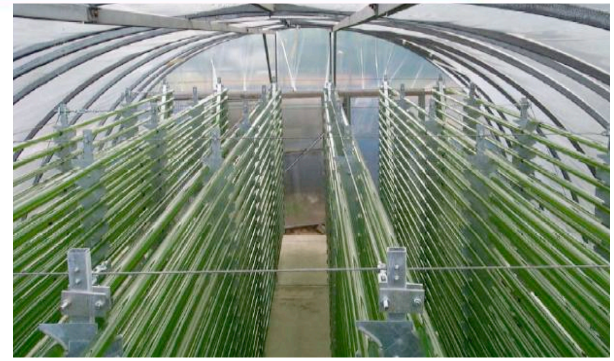

<u>Advantages</u>

- Allow growth of specific cultures
- Allows environmental control
- Potential for much higher growth rates (with extended surface area and/or high turbulence)

<u>Disadvantages</u>

- Potential for high capital cost
- Potential for high energy costs
- Low-cost production has not been demonstrated

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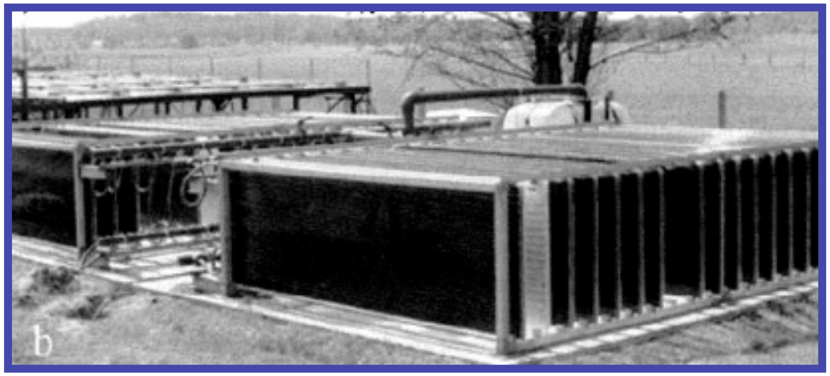
Cost vs. Productivity

Direct Light PBR:
Low Cost & Productivity



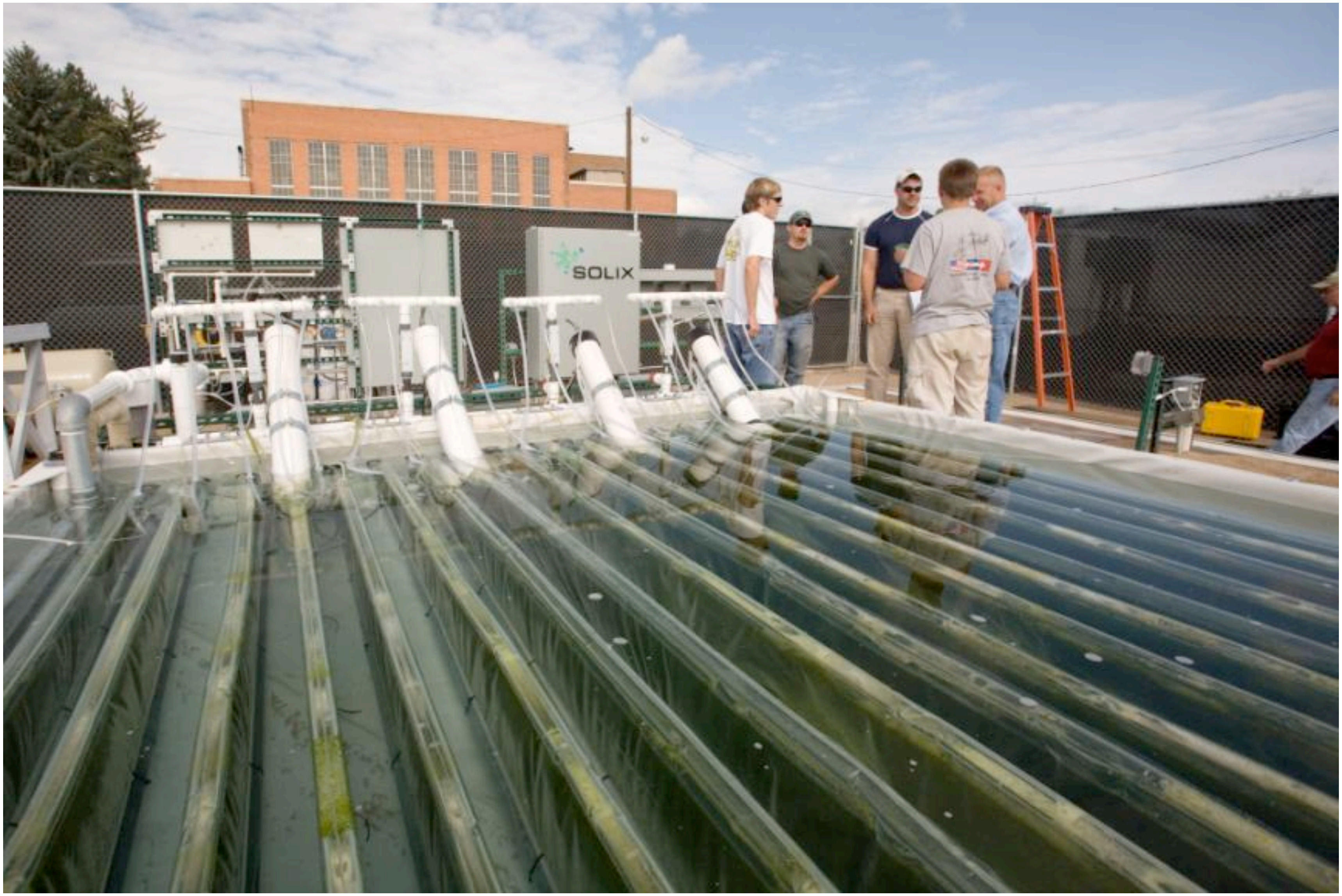
Diffuse PBR:
High Cost & Productivity

Solix G2 – May ‘07

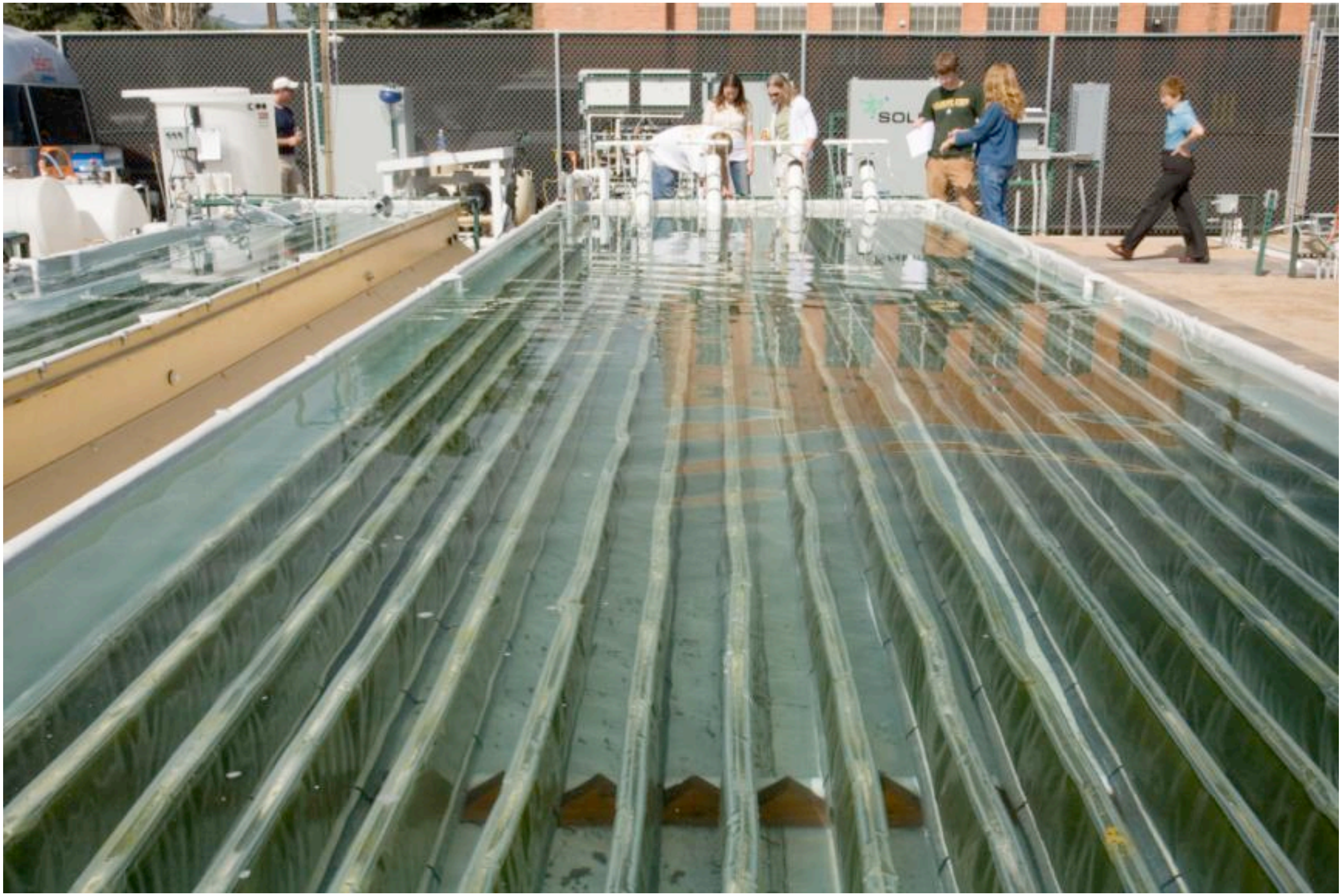
Photo-bioreactor (G3)

Solix G3 Technology:
- Extended surface area
- Water supported
- Integrated CO_2 / air sparging
- G4 – membrane exchange in development

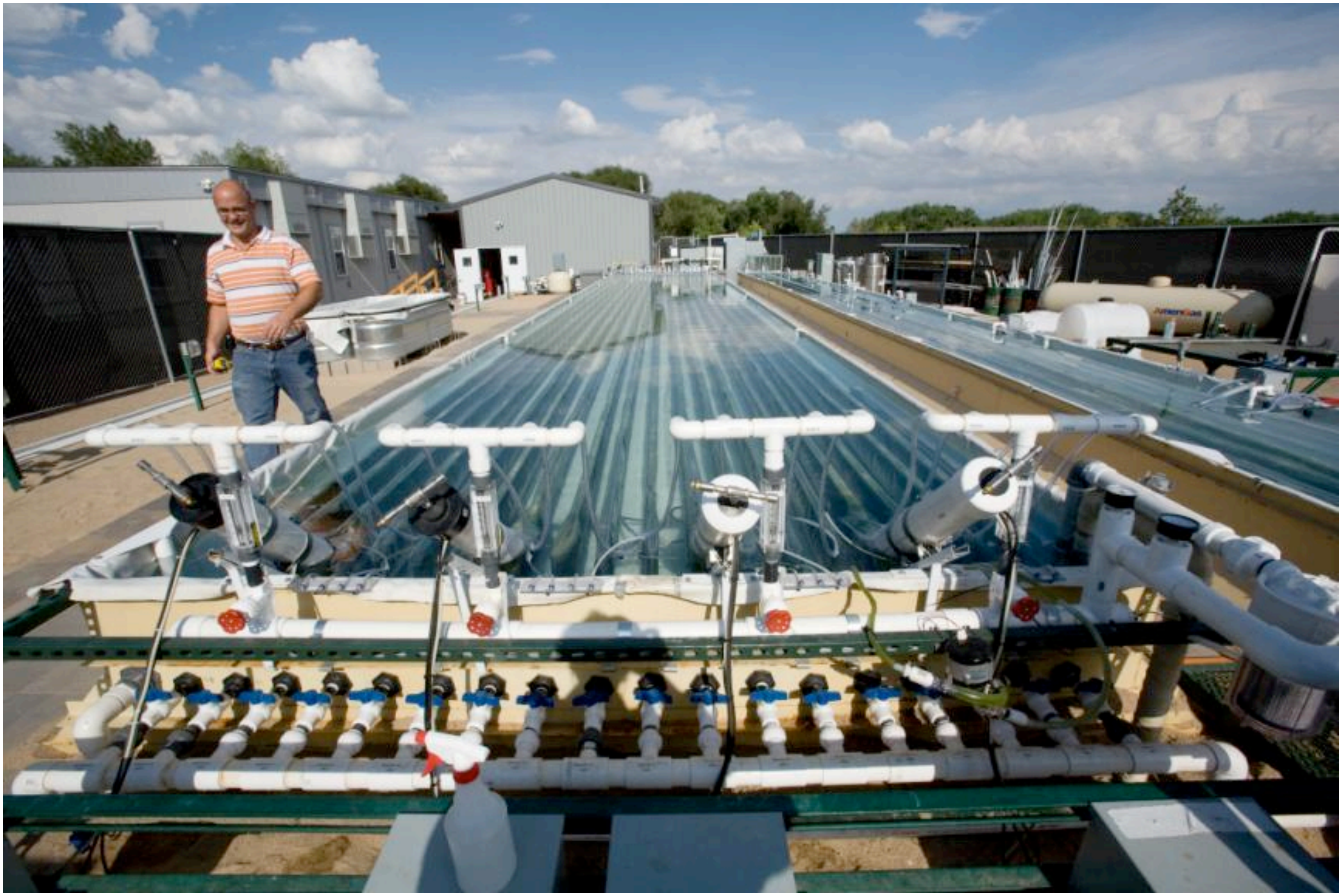
Solix G3 (cont)



Solix G3 (cont)



Solix G3 (cont)



Solix G3 (cont)

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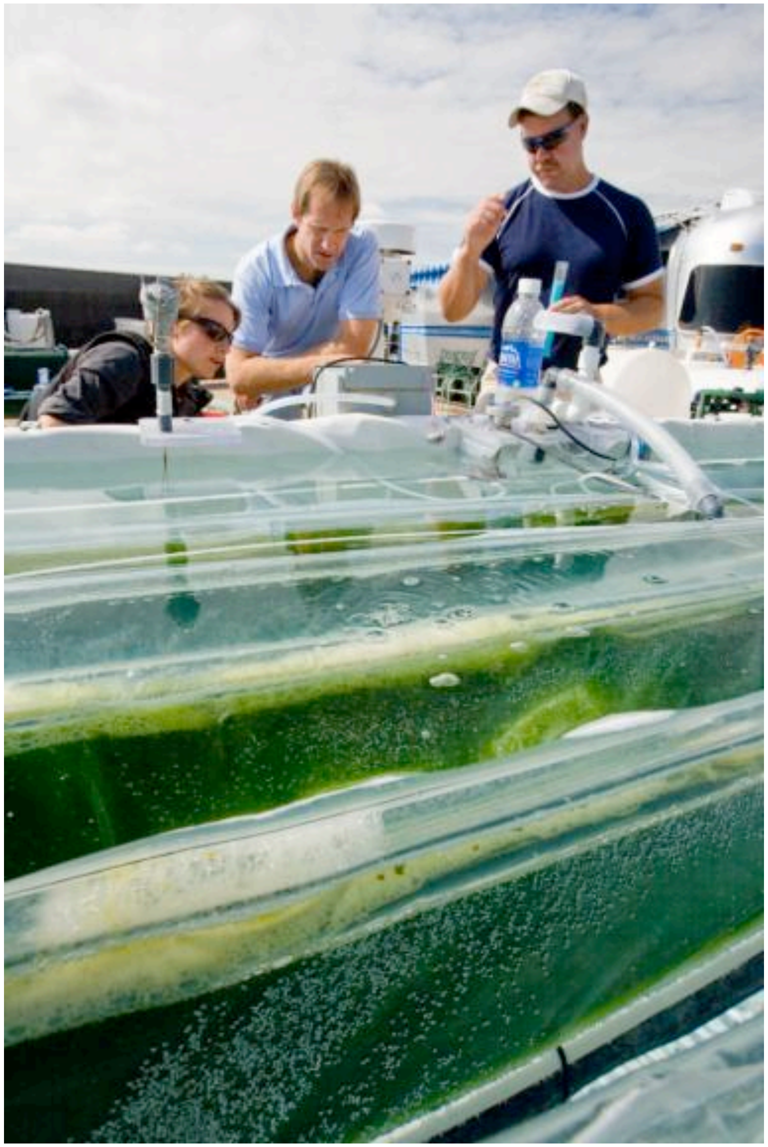
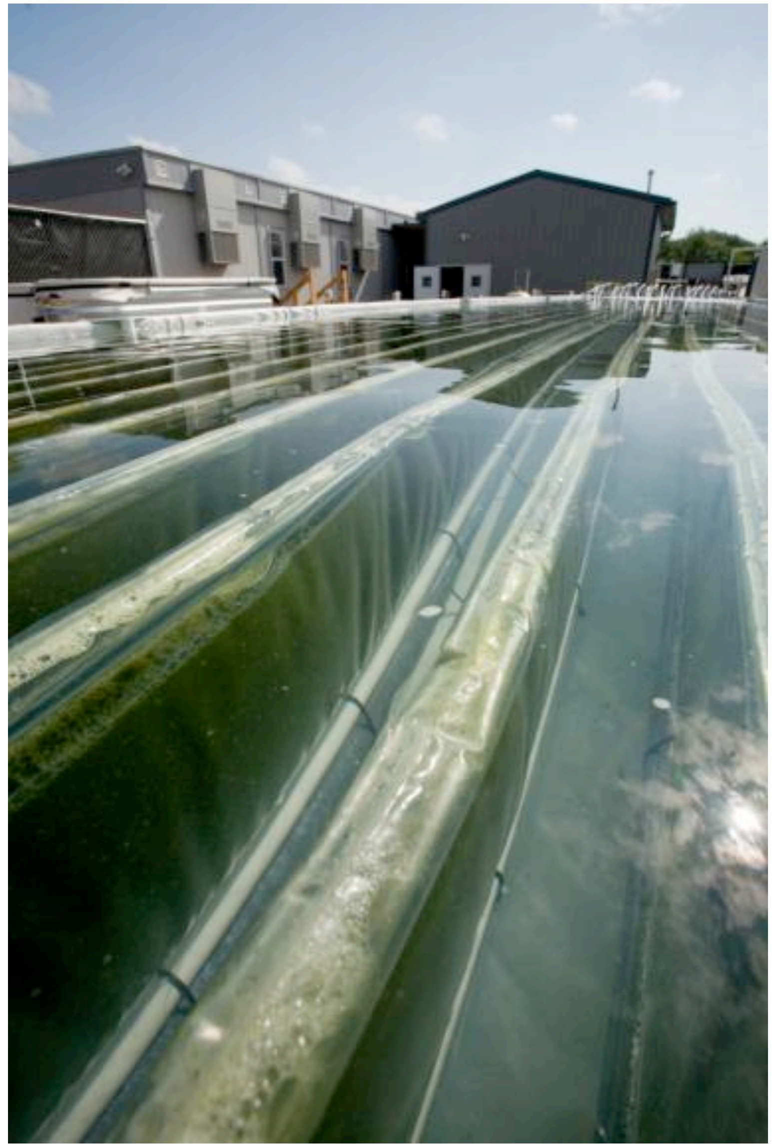
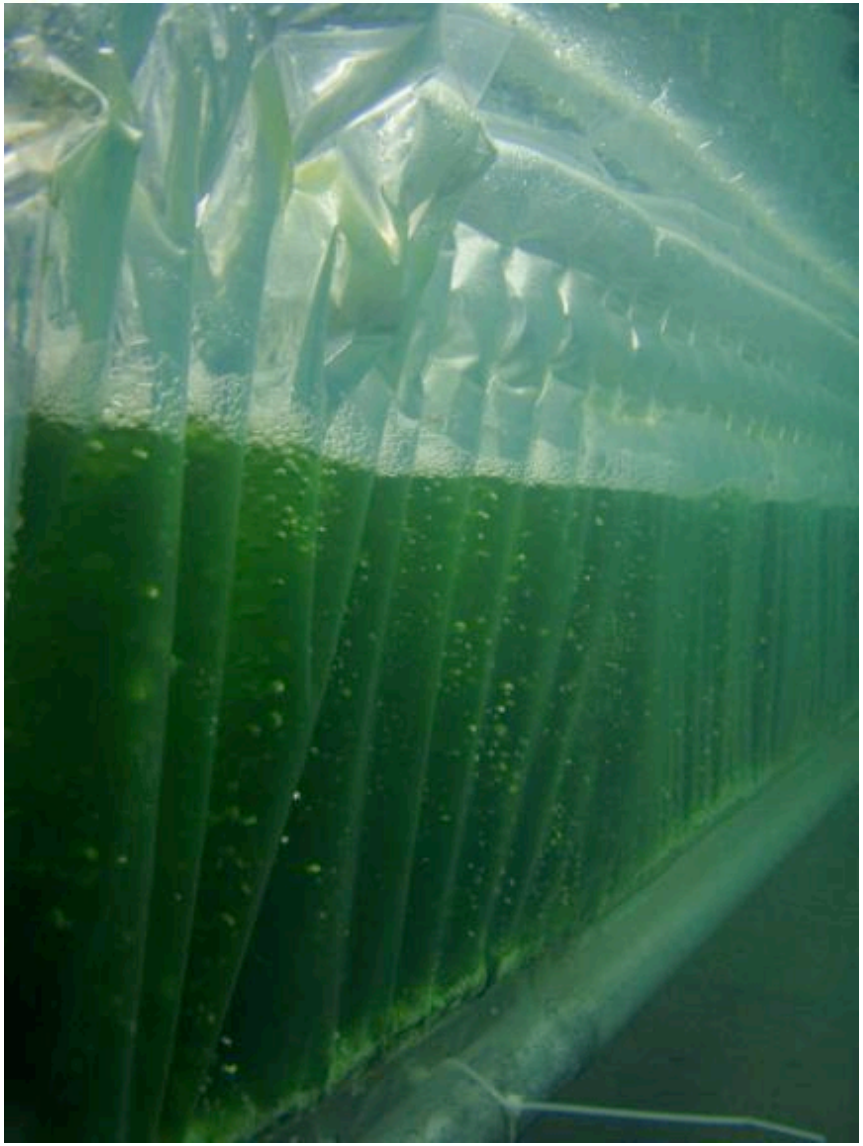




Solix G3 (cont)

Solix G3 (cont)



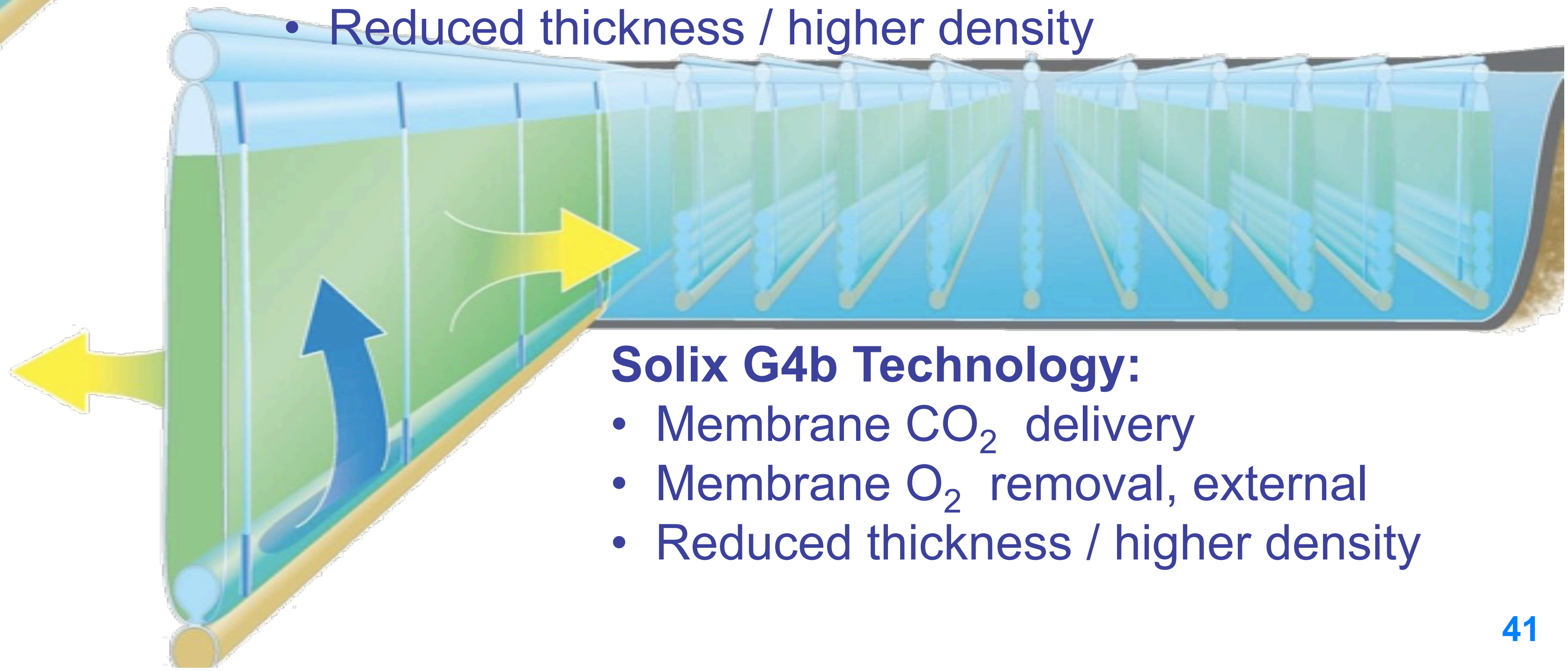
Solix G3 (cont)

Colorado – Algae Paradise?

Solix G4

Solix G4a Technology:

- Membrane CO_2 delivery
- Membrane O_2 removal, internal
- Reduced thickness / higher density

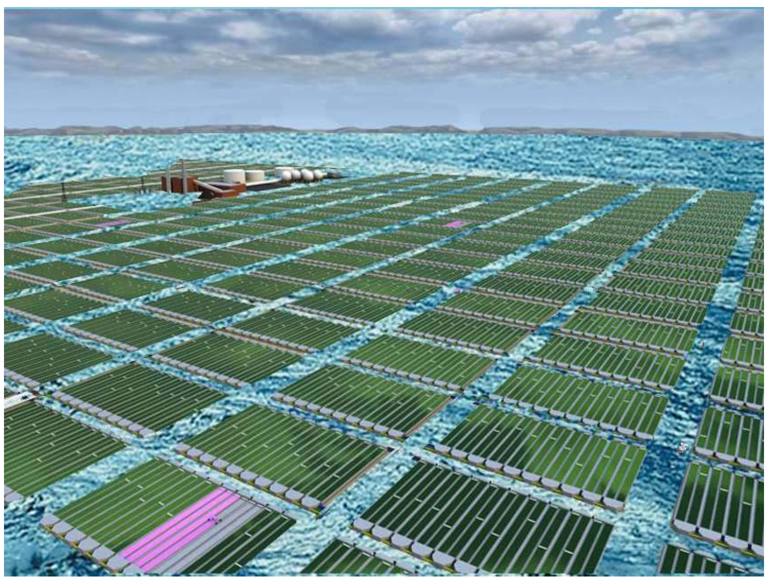


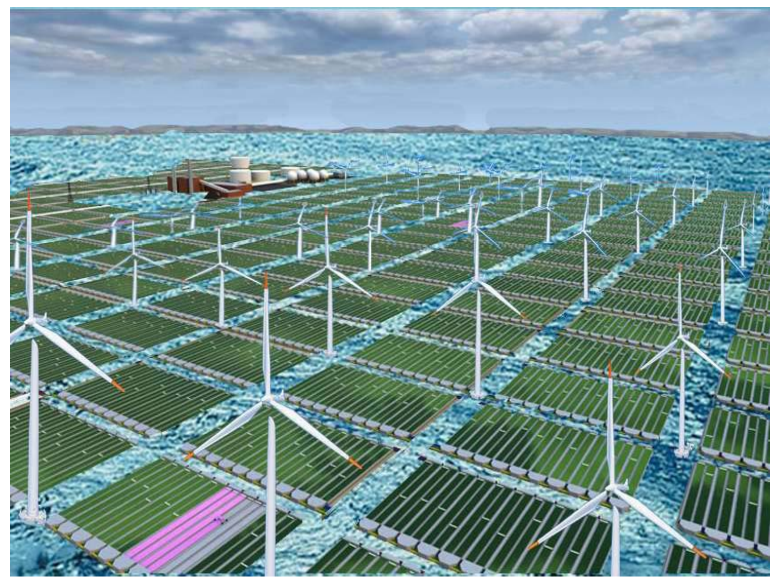
Solix G4b Technology:

- Membrane CO_2 delivery
- Membrane O_2 removal, external
- Reduced thickness / higher density

Potential Open-Water Application

Offshore Production?





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Extraction

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Extraction

Extraction

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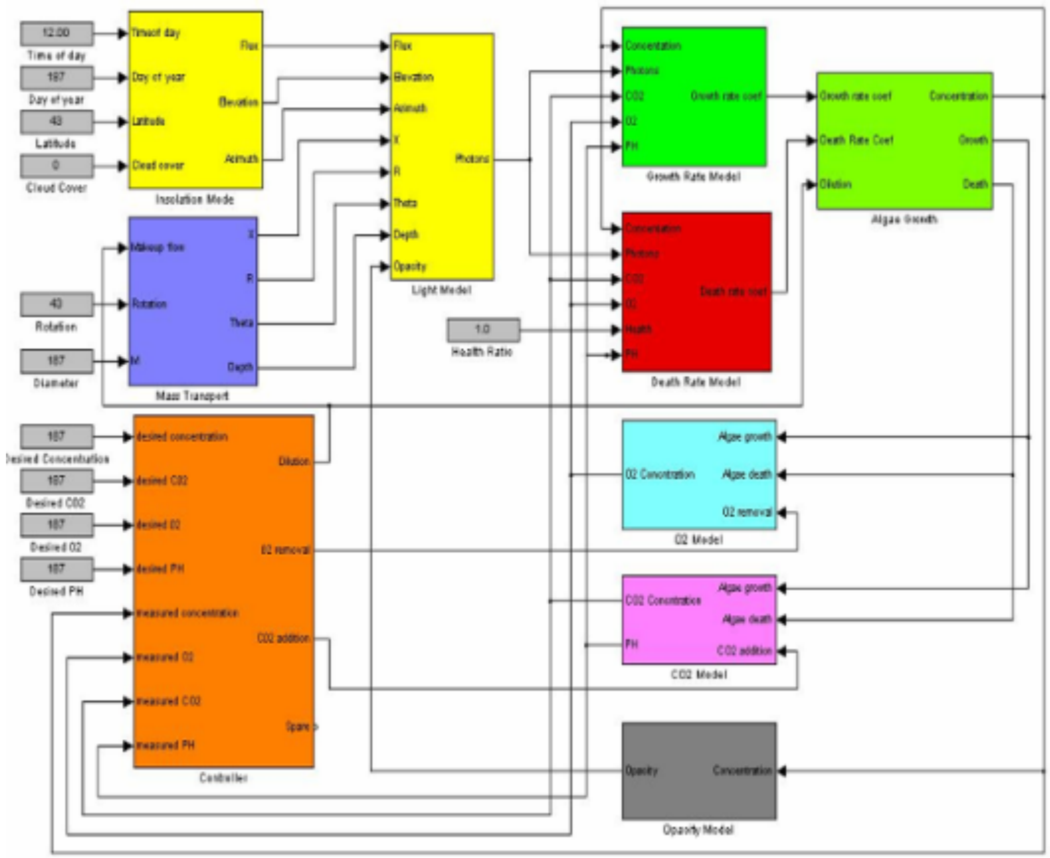
Model-Based Control

- ***Automates conditions for optimal productivity of different organisms in different climates***
- ***Gives predictive and diagnostic capabilities***



Biology

Fuel Properties - General

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CLIMATE ***CHANGE***, Global Risks, Challenges & Decisions
COPENHAGEN 2009, 10-12 March

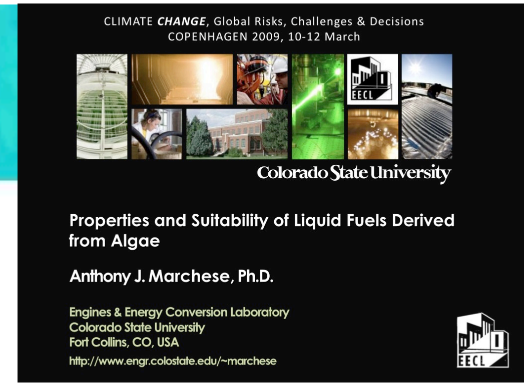
Colorado State University

Properties and Suitability of Liquid Fuels Derived from Algae

Anthony J. Marchese, Ph.D.

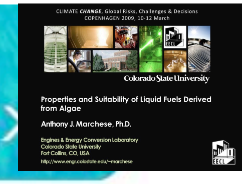
Engines & Energy Conversion Laboratory
Colorado State University
Fort Collins, CO, USA
http://www.engr.colostate.edu/~marchese

Fuel Properties - General



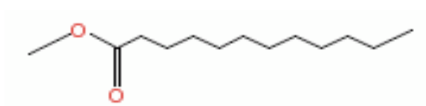
- Algal oil is unique in that it tends to contain a significant quantity (~5-20% by volume) of long highly unsaturated oils, which are rarely observed in more traditional biodiesel feedstocks, such as soy and rapeseed (canola) oil.
- The two most common types of long and highly unsaturated oils found in algae oil tested to date are eicosapentaeonic acid (EPA) and Docosahexaenoic acid (DHA).

Feedstock Composition

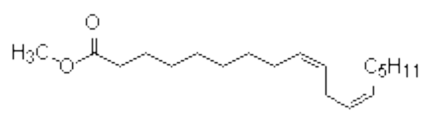


Fatty acid content varies widely depending on the feedstock. The chemical composition has implications in terms of combustion characteristics.

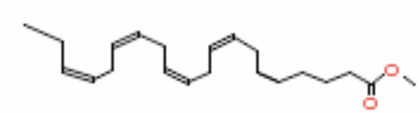
	Saturated Acids						Mono Unsaturated Acids			Total Poly Unsaturated Acids		
	10:0	*12:0*	*14:0*	*16:0*	*18:0*	*>18:0*	*16:1*	*18:1*	*22:1*	*n:2*	*n:3*	*n:4-6*
Coconut	7	**47**	15	8	2			6		2		
Palm			3	40	3			46				
Rapeseed			3	2	1	1		12	**55**	15	8	
Soybean				9	4	8	1	26		**55**	6	
Nannochloropsis Oculata			2	15	2	2	16	10	1	6	4	**31**
Nannochloropsis sp.			3	14	11	3	19	6		7	3	**20**



methyl dodecanoate (coconut)

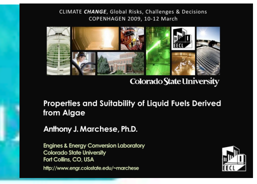


methyl linoleate (soy)

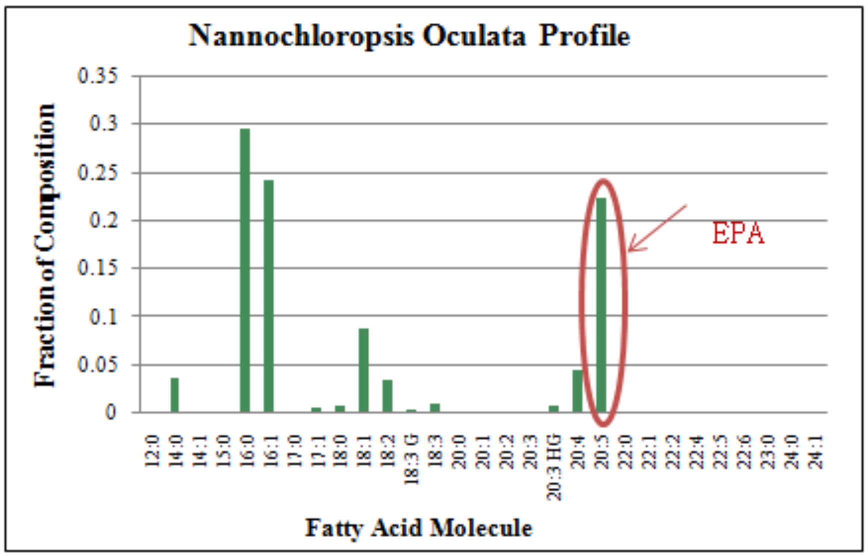


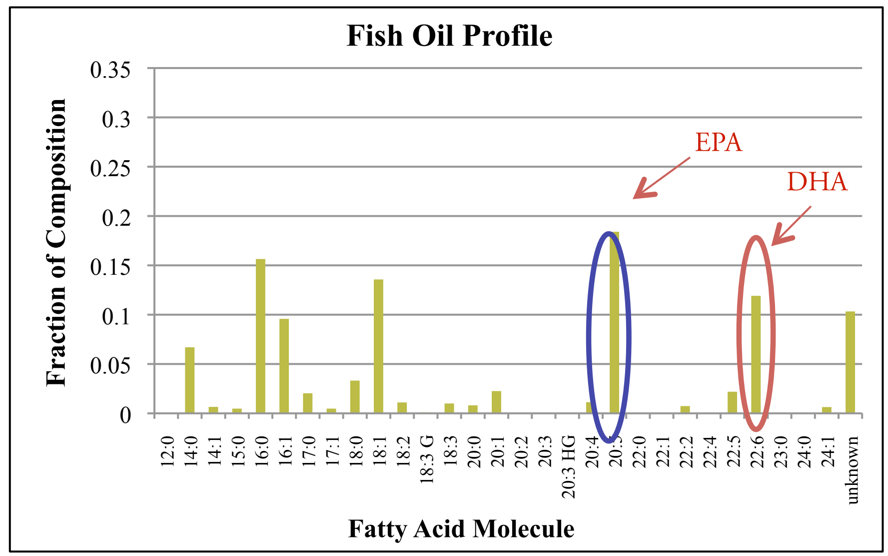
eicosapentaeonic acid methyl ester (algae)

Composite Algal Oil



- **Algal oil differs from soy and rapeseed in that many algae species under consideration produce up 20% of Omega-3 fatty acids.**
- **For engine tests, "synthetic" algae oil is created by mixing a variety of vegetable oils with pharmaceutical grade fish oil.**
- **Pharmaceutical grade fish oil is used as a source of Omega-3 fatty acids found in algal oil (e.g EPA and DHA)**

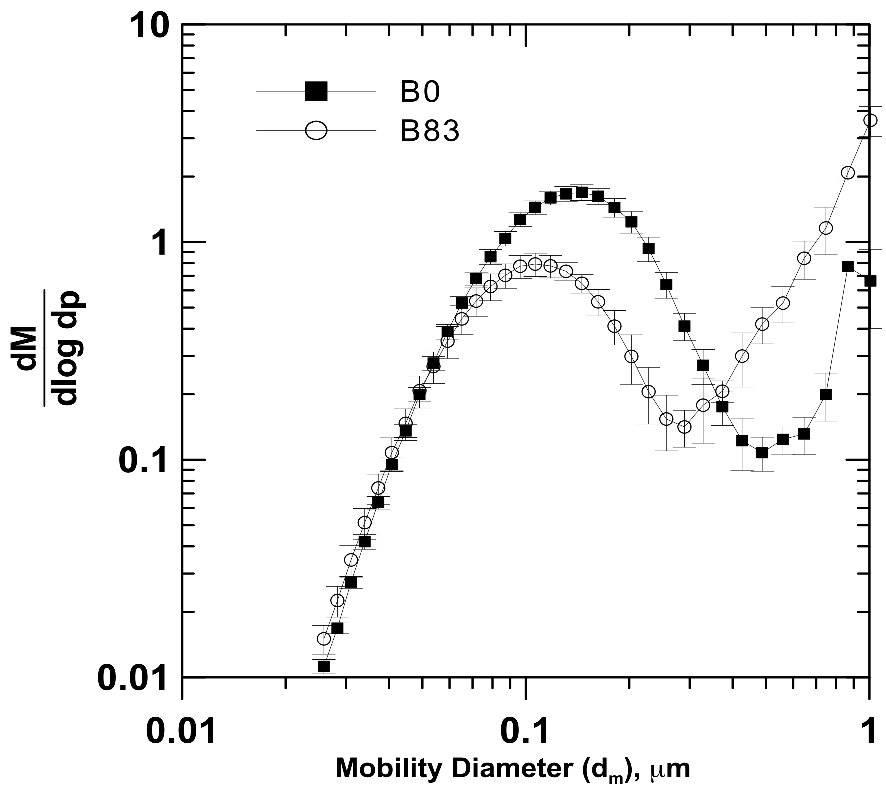




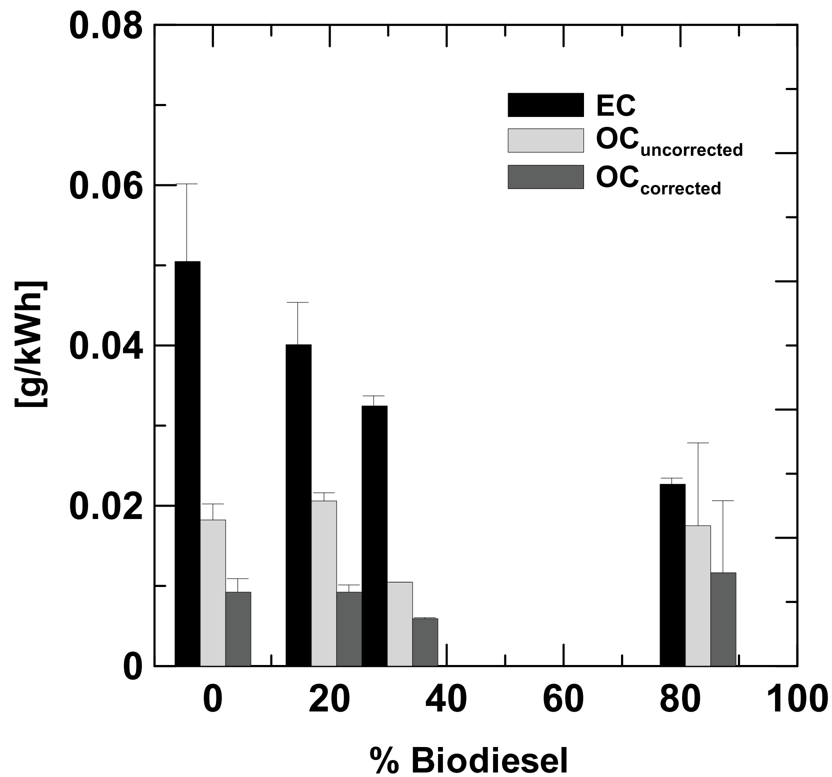
PM Size Distribution and OC/EC Ratio

Previous Work at CSU with Soy Biodiesel

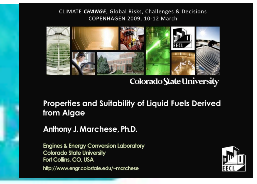
Soy based biodiesel results in decreased mean particle size (Bennett, et al, 2008)



Soy based biodiesel blends result in increase in ratio of organic carbon to elemental carbon in PM (Cheng, 2001 Bennett, 2008)

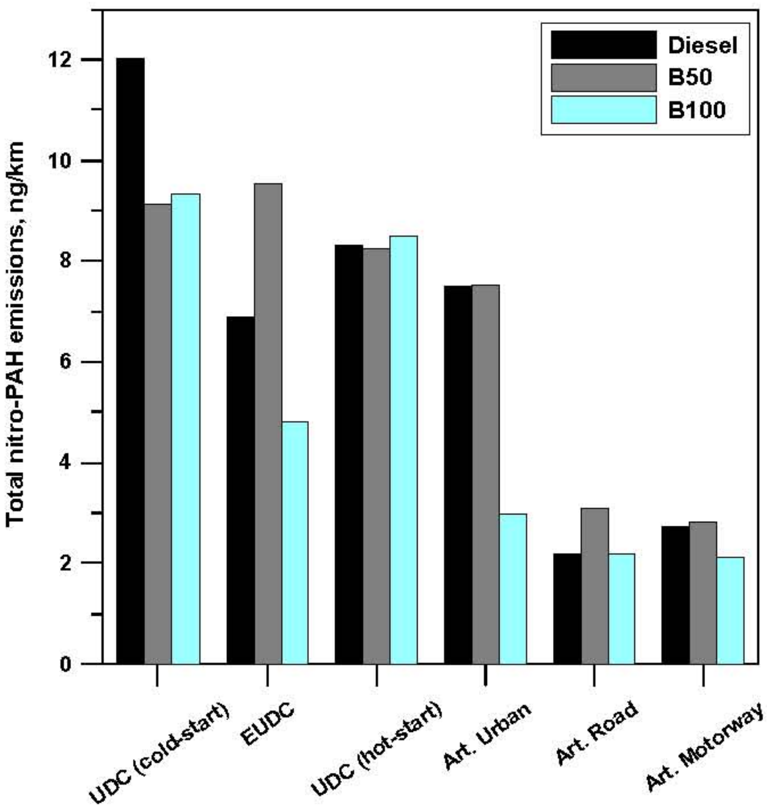


PAH, oxy-PAH and nitro-PAH
Previous Work with Soy Biodiesel

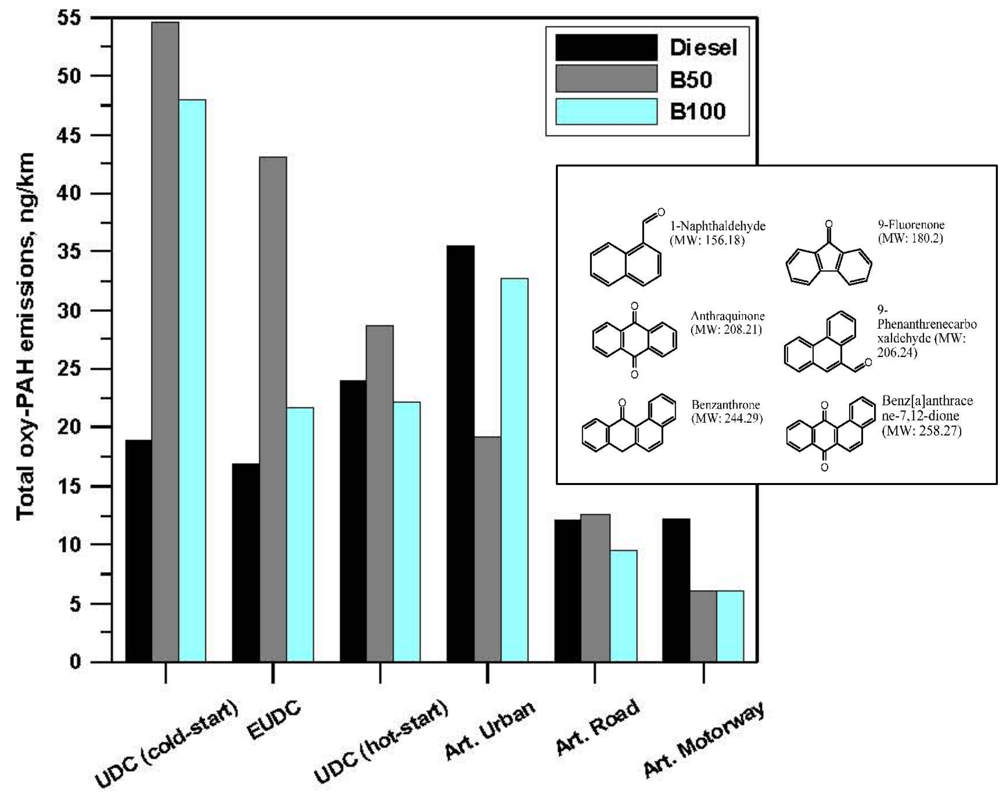


Soy based biodiesel blends can result in increased emissions of oxy-PAH's and nitro-PAH's (Karavalakis, et al, 2009)

nitro-PAH's

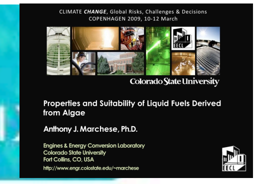


oxy-PAH's



Health Effects Research

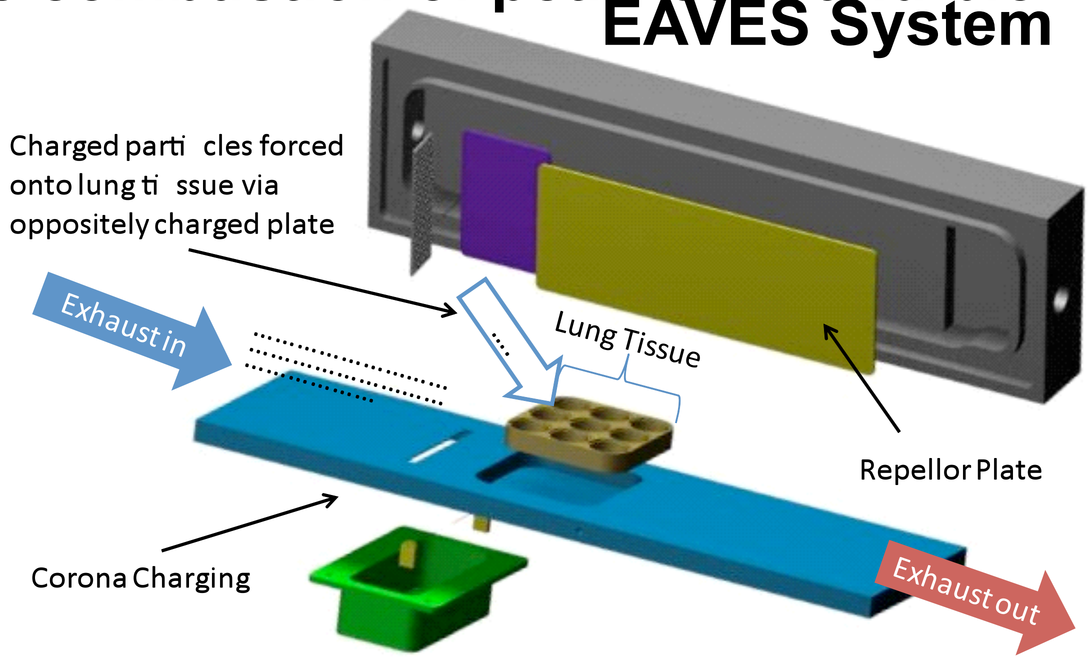
Algae-Derived Diesel Exhaust



In addition to characterizing the particles, research is underway to determine the health effects of these particles by depositing them on living lung tissue.

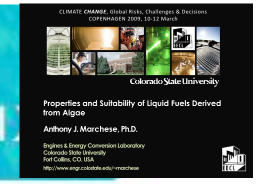
The goal of the project is to characterize the health effects caused by the combustion of petroleum and bio-fuels

EAVES System

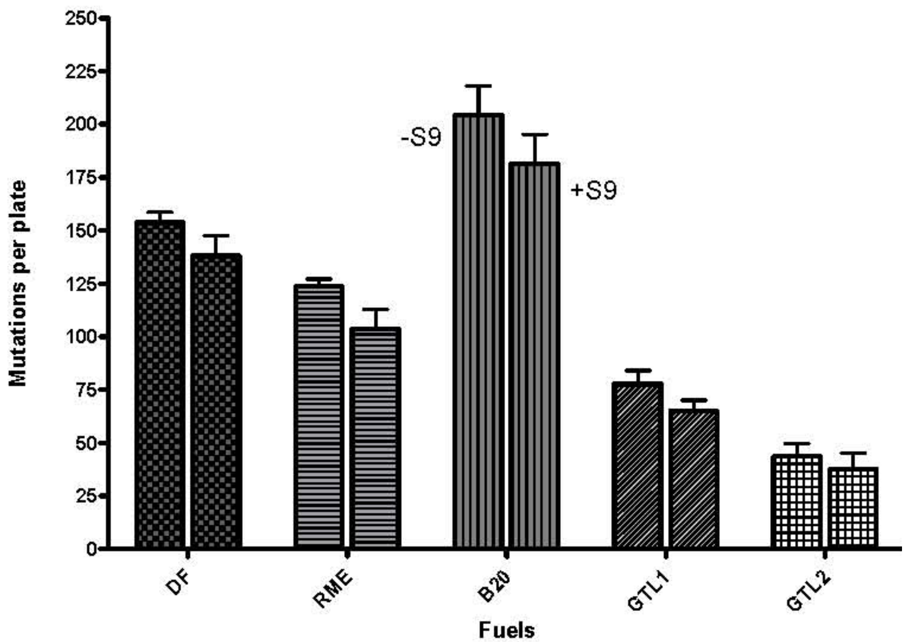


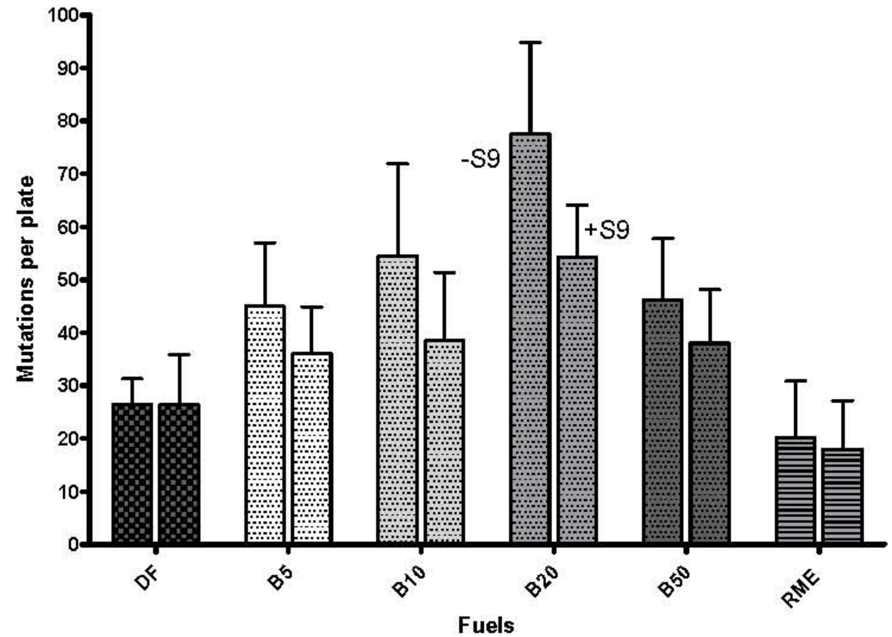
Mutagenicity of Biodiesel Exhaust

Rapeseed Biodiesel Results (Krahl, et al, 2008)



Blends of diesel fuel with rapeseed methyl ester (RME) showed higher mutagenicity* than pure diesel fuel or pure RME. In fact, B20 was the most mutagenic blend tested (Krahl, et al, 2008).





***Tests were performed using modified Ames Test with and without metabolic activation (+S9/-S9) from rat liver enzymes.**

Outline

Solix / Algae Intro

Open Pond Overview

Closed Photobioreactor Overview

Solix AGS System

Harvesting & Extraction

Scaleup

Production Costs

Conclusions

Colorado State University

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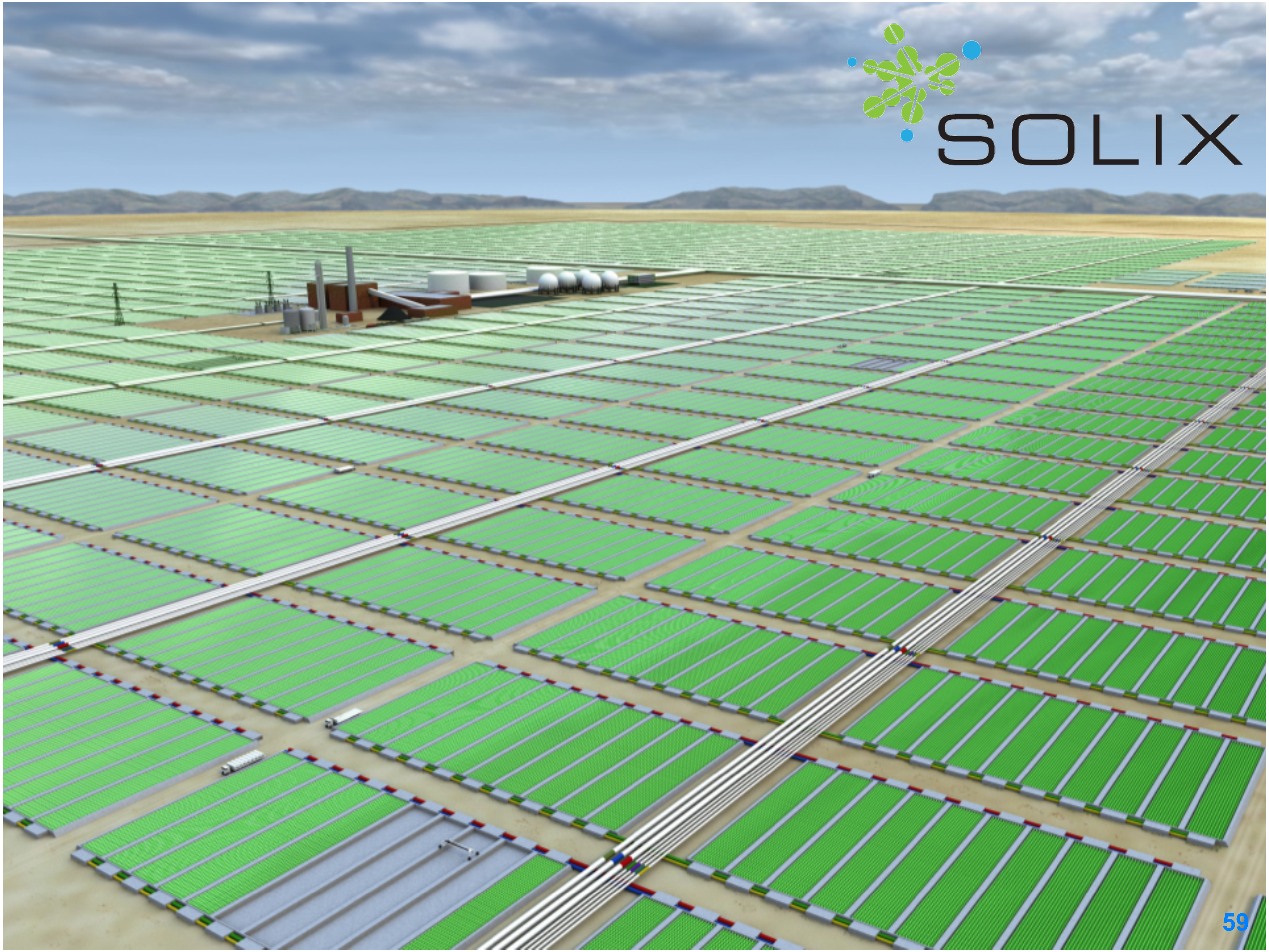
Fueling a better world

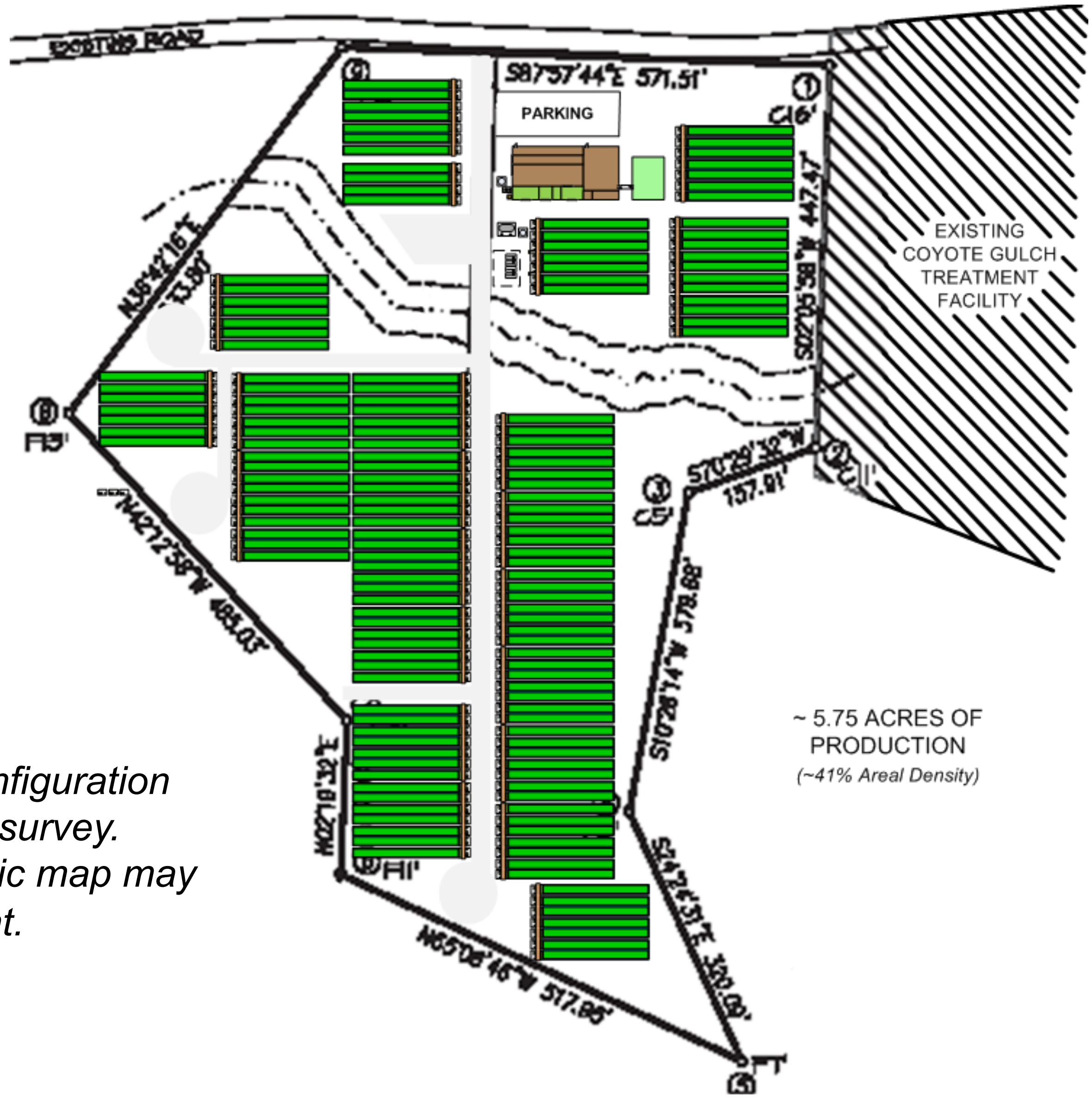

SOLIX

Scaling Up. . .

New Site:
Southwest Colorado, Coyote Gulch

Coyote Gulch

SOLIX



Conceptual Site Configuration

- *Conceptual site configuration based on 11.14.08 survey.*
- *Pending topographic map may impact arrangement.*

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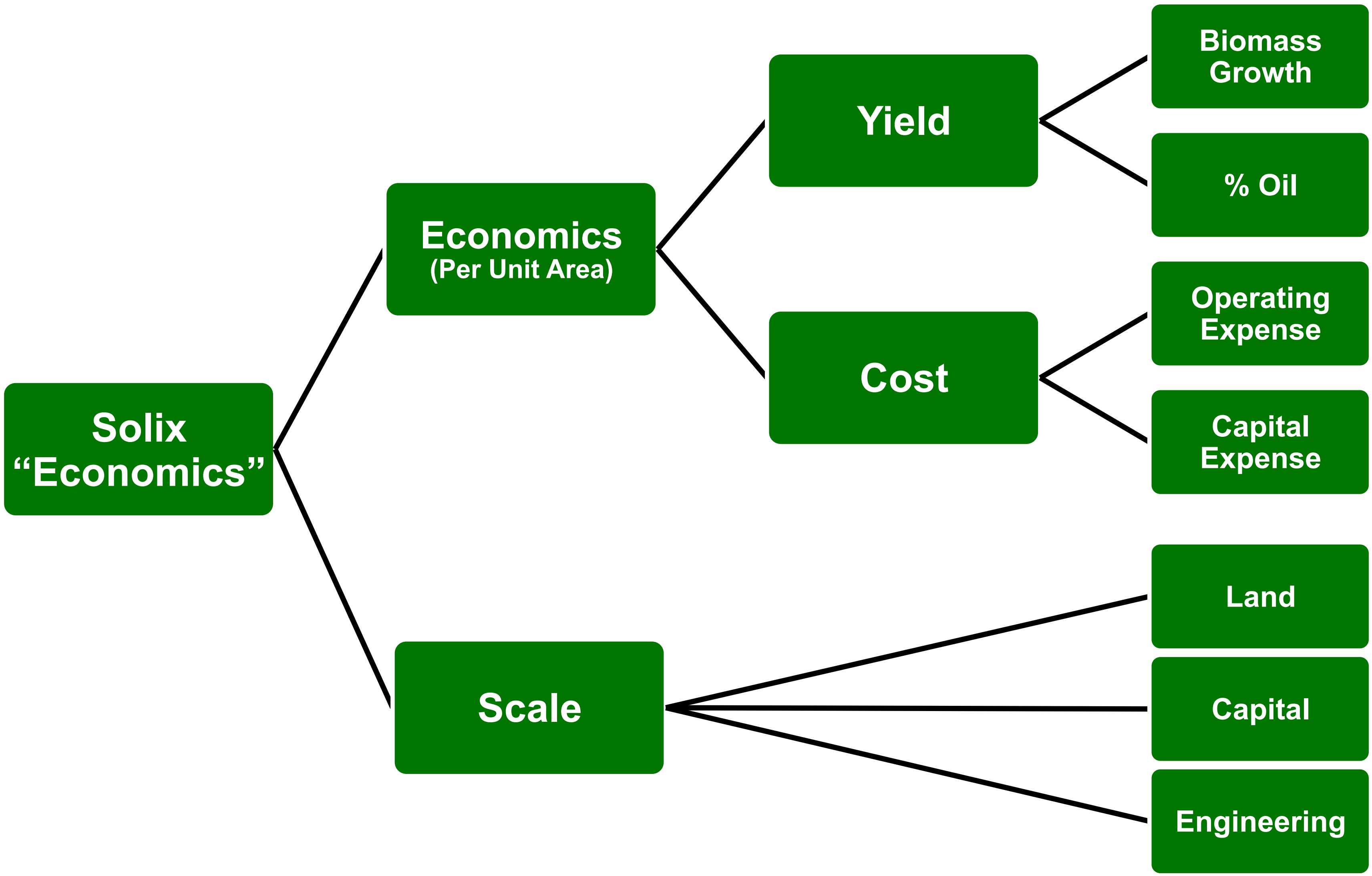
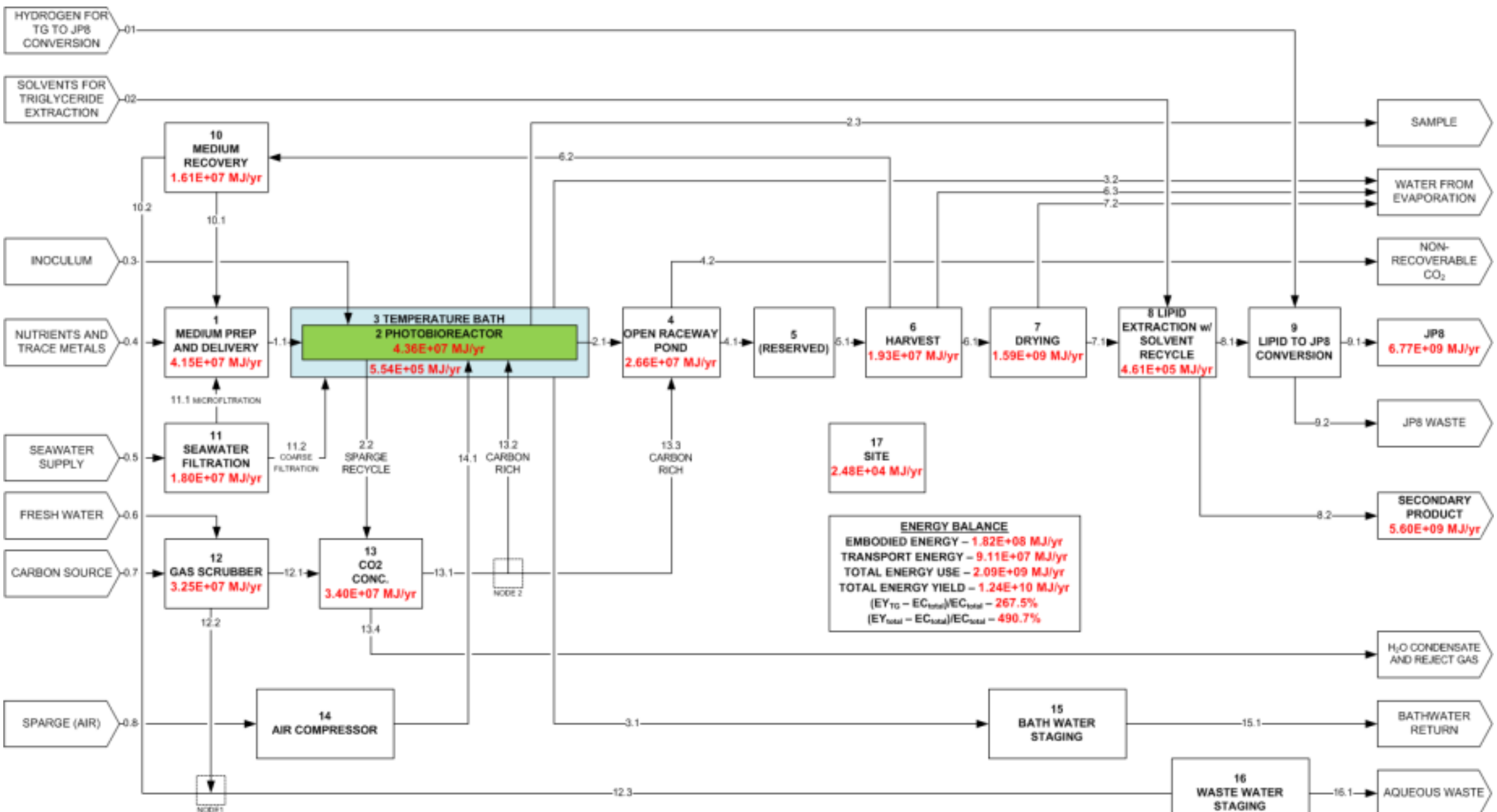
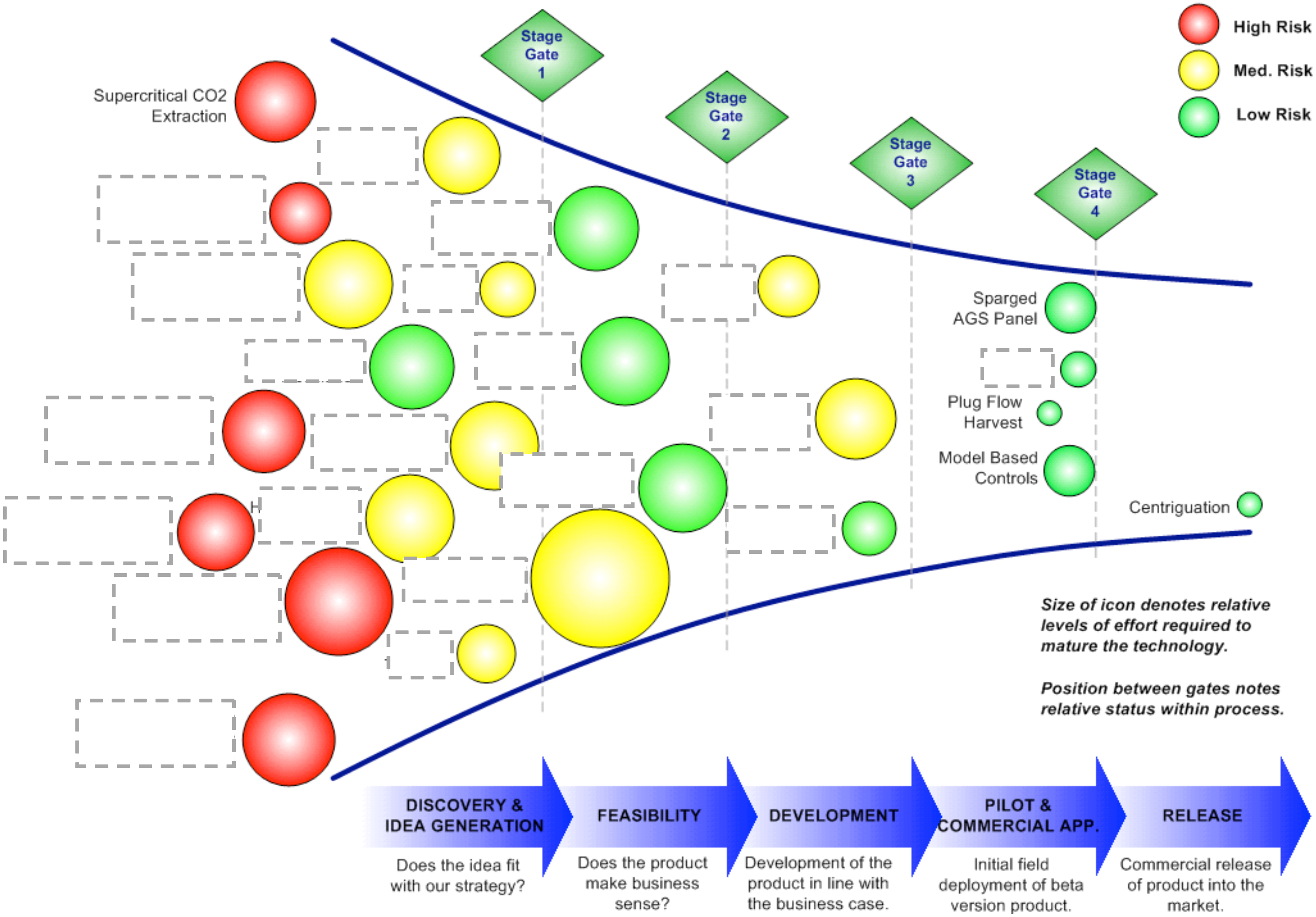
Economic Overview



System Analysis / Modeling

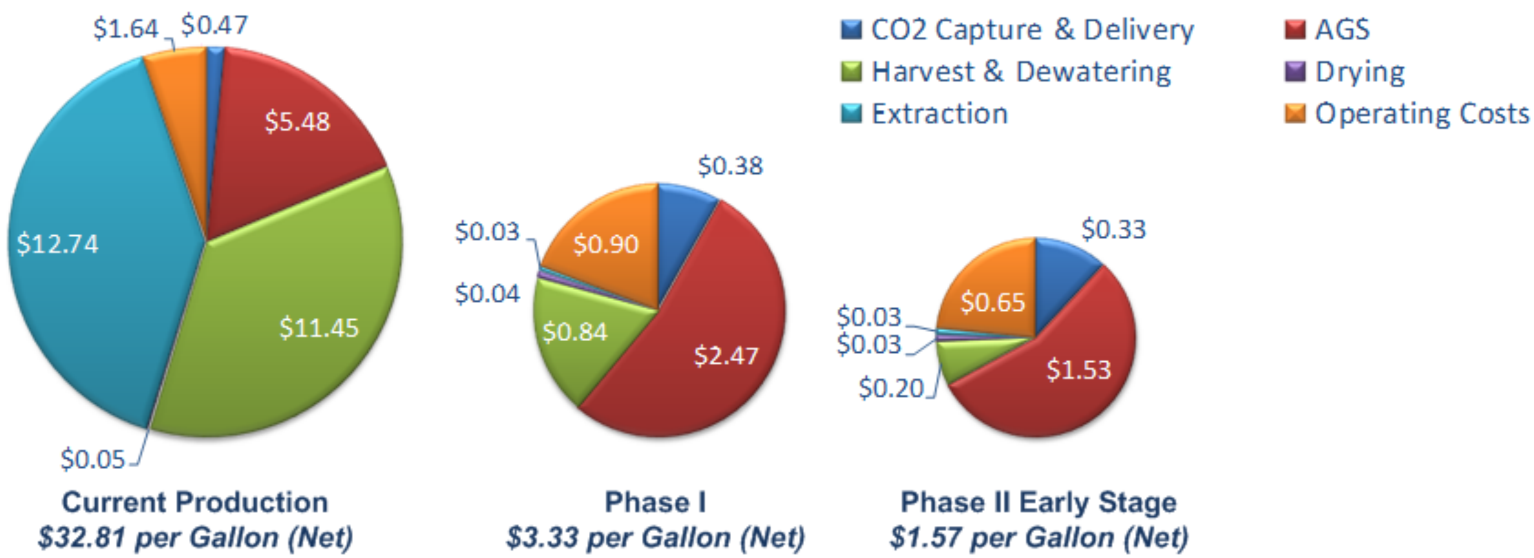


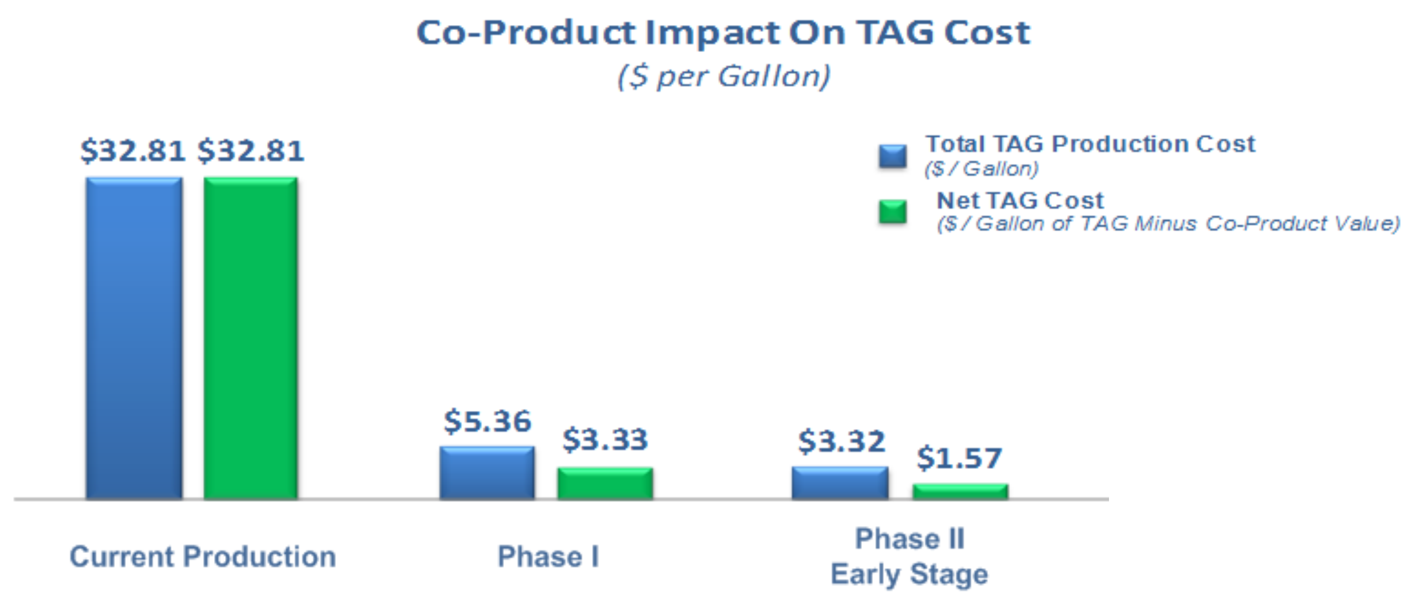
Technology Development Process



COST OF TAG PRODUCTION

(Production @ $0.06/kW-Hr)





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Conclusions

- Economical biofuel production appears feasible, using low-cost high productivity photobioreactors
- Requires tight coupling of biology and engineering
- Value of co-products must be captured; may approach or exceed value of oil
- Systems modeling/integration required to achieve cost targets

Contact Information

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