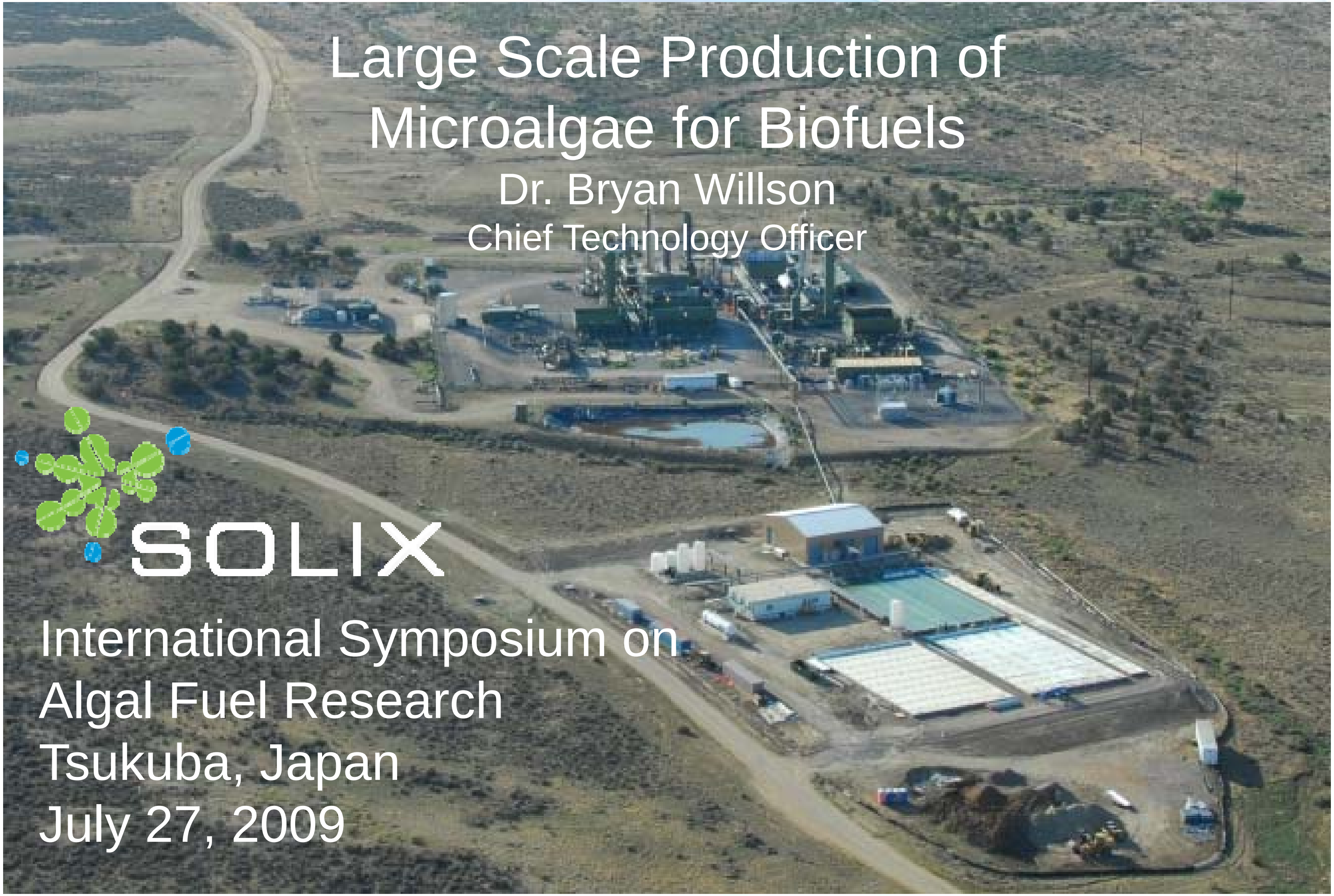


Large Scale Production of Microalgae for Biofuels

Dr. Bryan Willson
Chief Technology Officer

SOLIX

International Symposium on
Algal Fuel Research
Tsukuba, Japan
July 27, 2009

3 Main Points

- Solix is a leading developer of closed photobioreactor-based production systems for algae-based biofuels
- Solix's cost trajectory shows that fuel production from algae can be cost-competitive with petroleum – but requires full value extraction from the production co-products
- Solix has now begun operation of the world's largest closed photobioreactor for biofuel production.

Outline

Solix / Algae Intro

Production in Open Ponds

Production in Closed PBRs

Solix AGS System

Harvesting & Extraction

Scaleup: Coyote Gulch

Production Costs

Solix Business Model

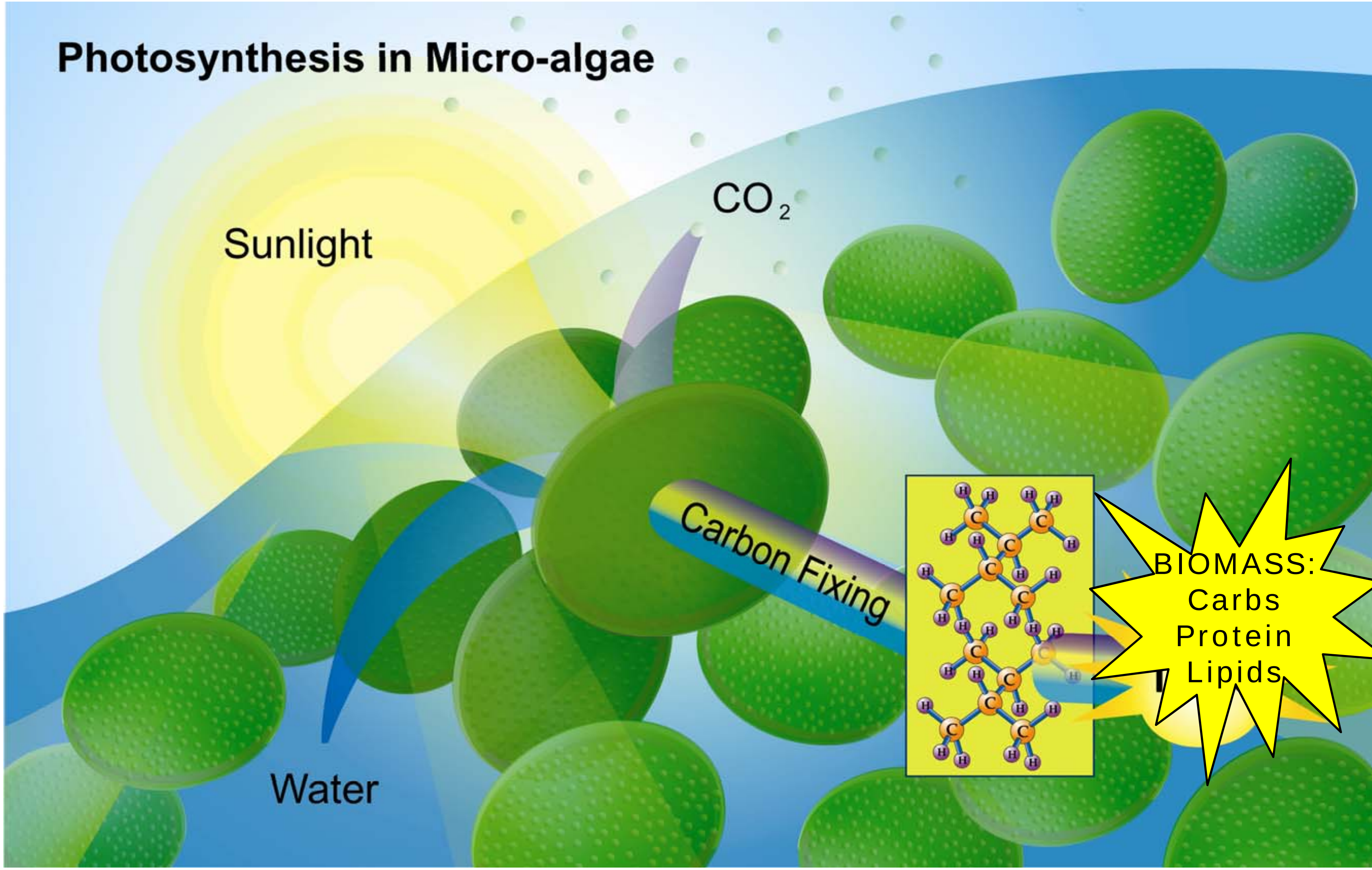
Conclusions

SOLIX
Fueling a better world

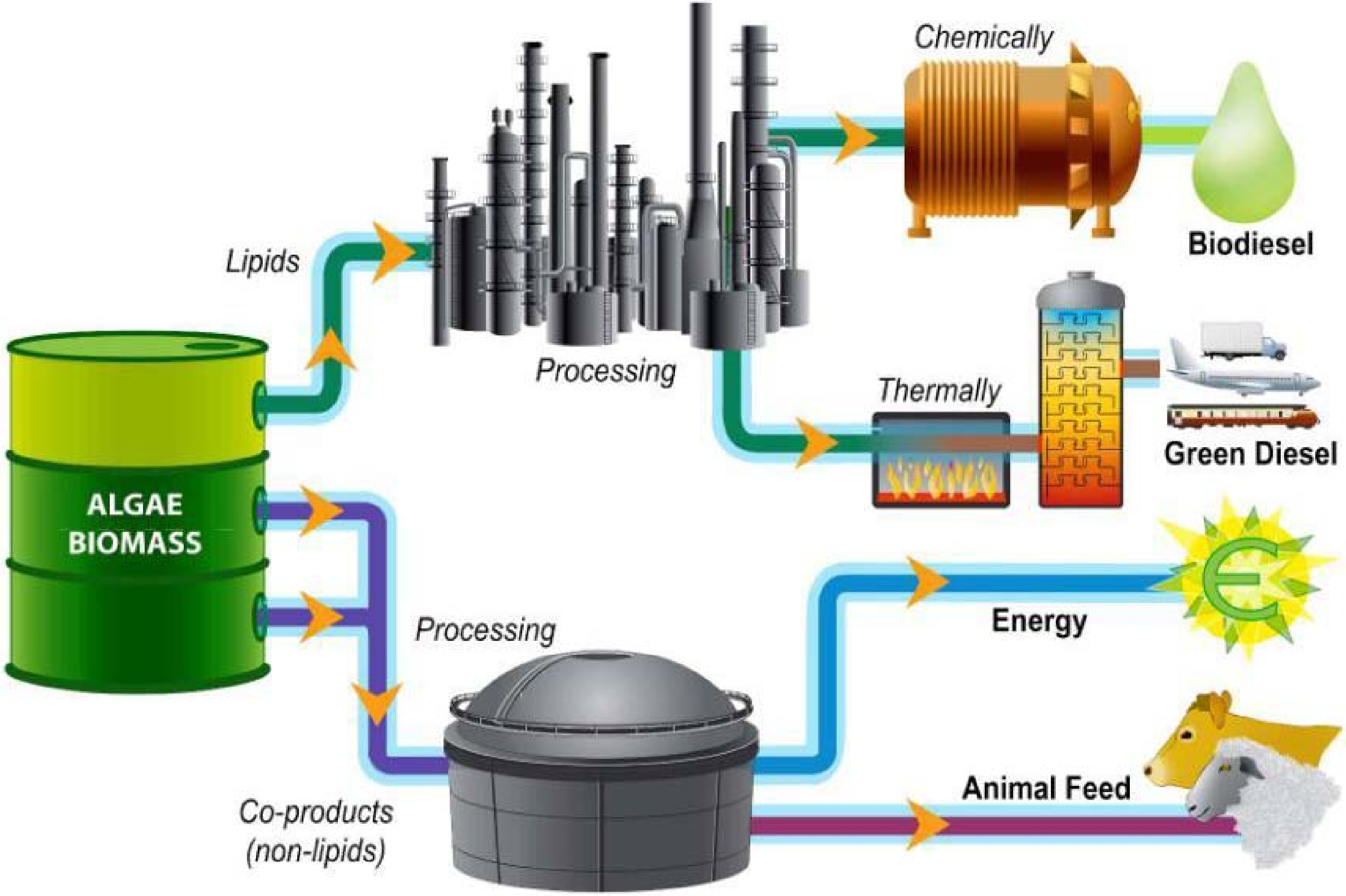
About Solix

- *Focused on the development and commercialization of large-scale algae-to-biofuels systems*
- *Launched in March, 2006*
- *Privately funded*
- *65+ employees*
- *Headquartered in Fort Collins, Colorado, USA*
- *1st scaleup site on the Southern Ute Indian reservation in southwest Colorado*
- *Significant strategic partners in advanced biology, midstream processing, fuel processing, and scaleup engineering*

Photosynthetis / Algae



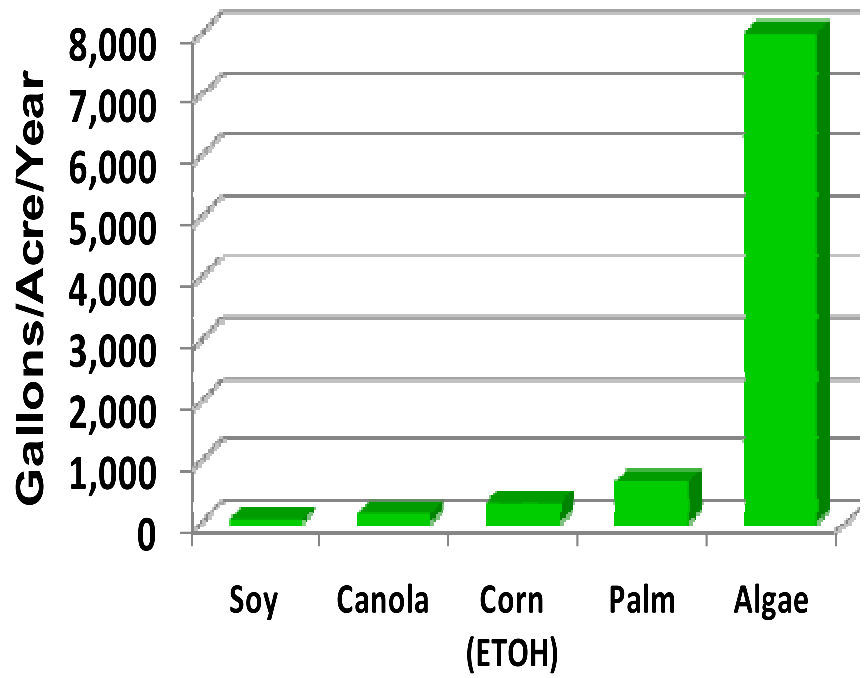
Processing


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

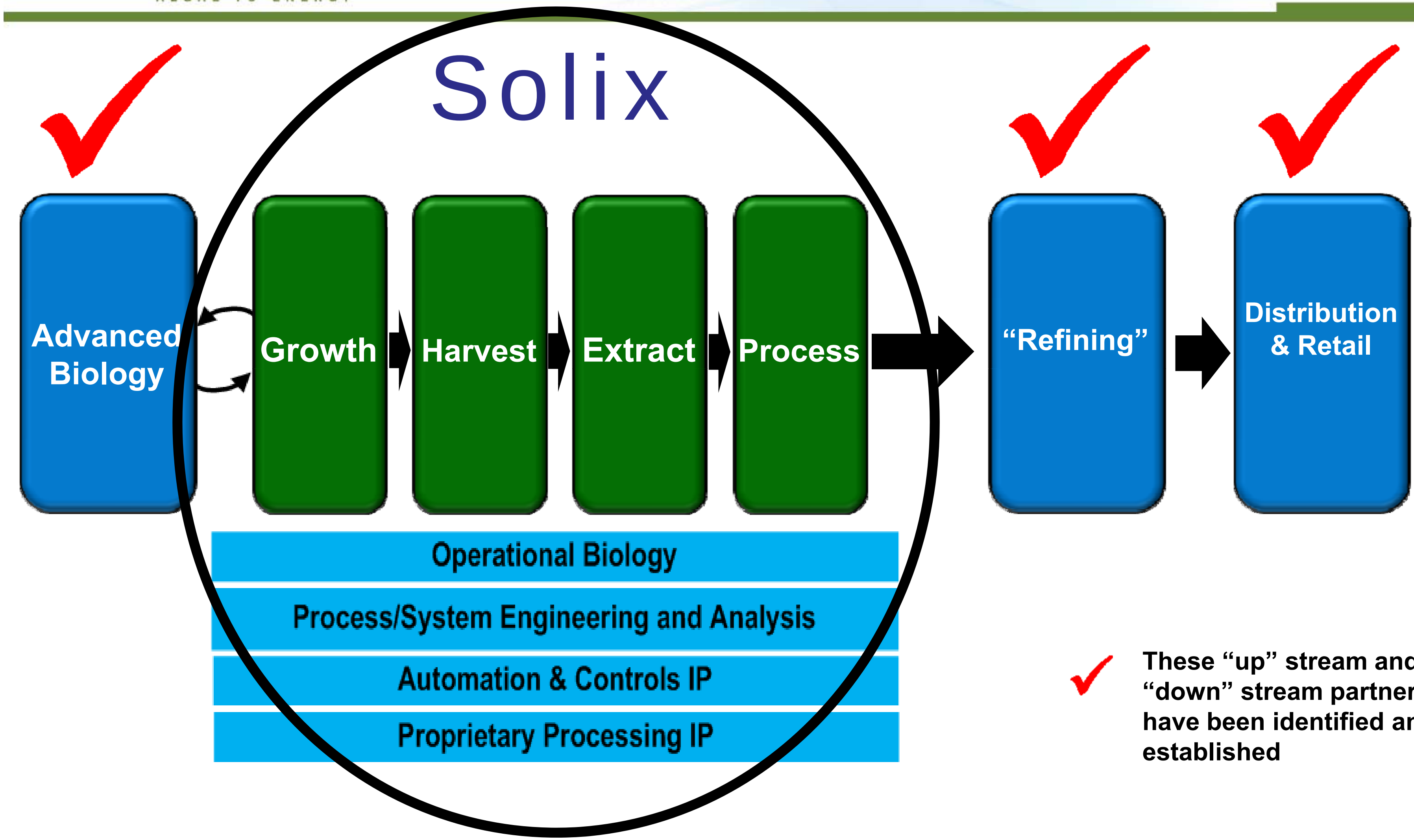
Land & Water Efficiency

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"



Solix Value Chain Positioning



✓ **These "up" stream and "down" stream partnerships have been identified and established**

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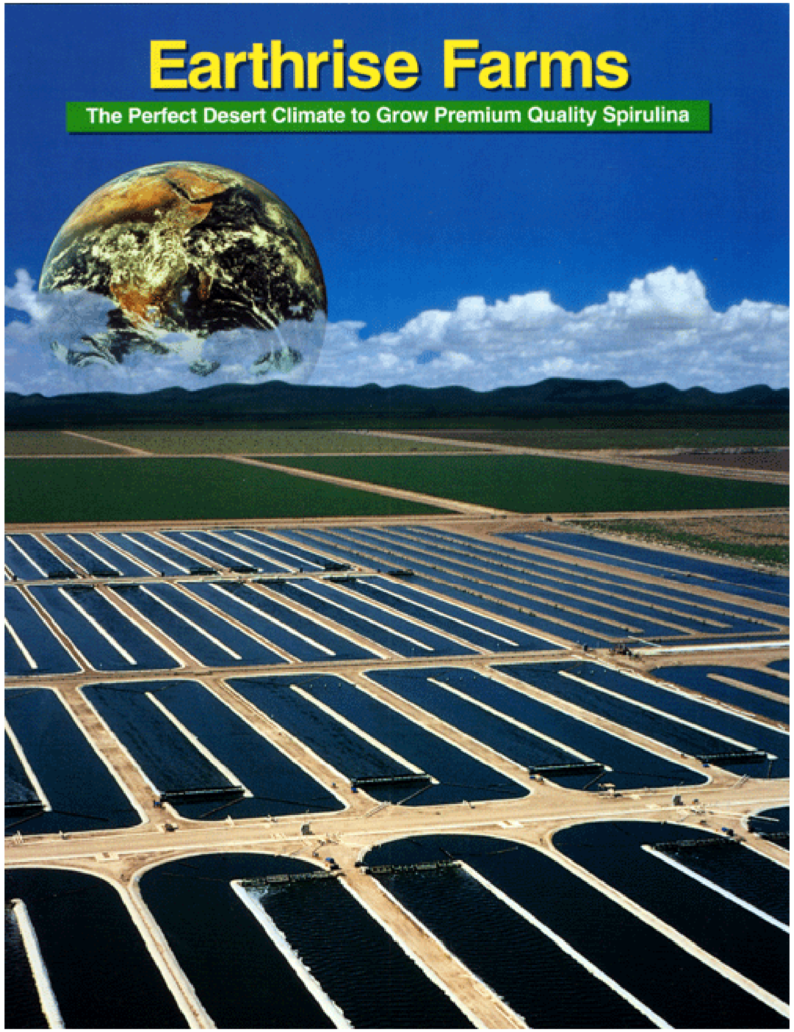
Open Pond Cultivation: Dunaliella - Eilat, Israel

Open Pond Production: Earthrise Spirulina - California



Open Pond Production: Seambiotic - 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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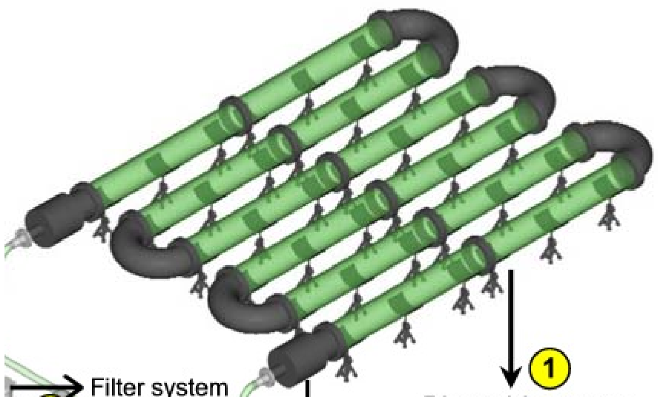
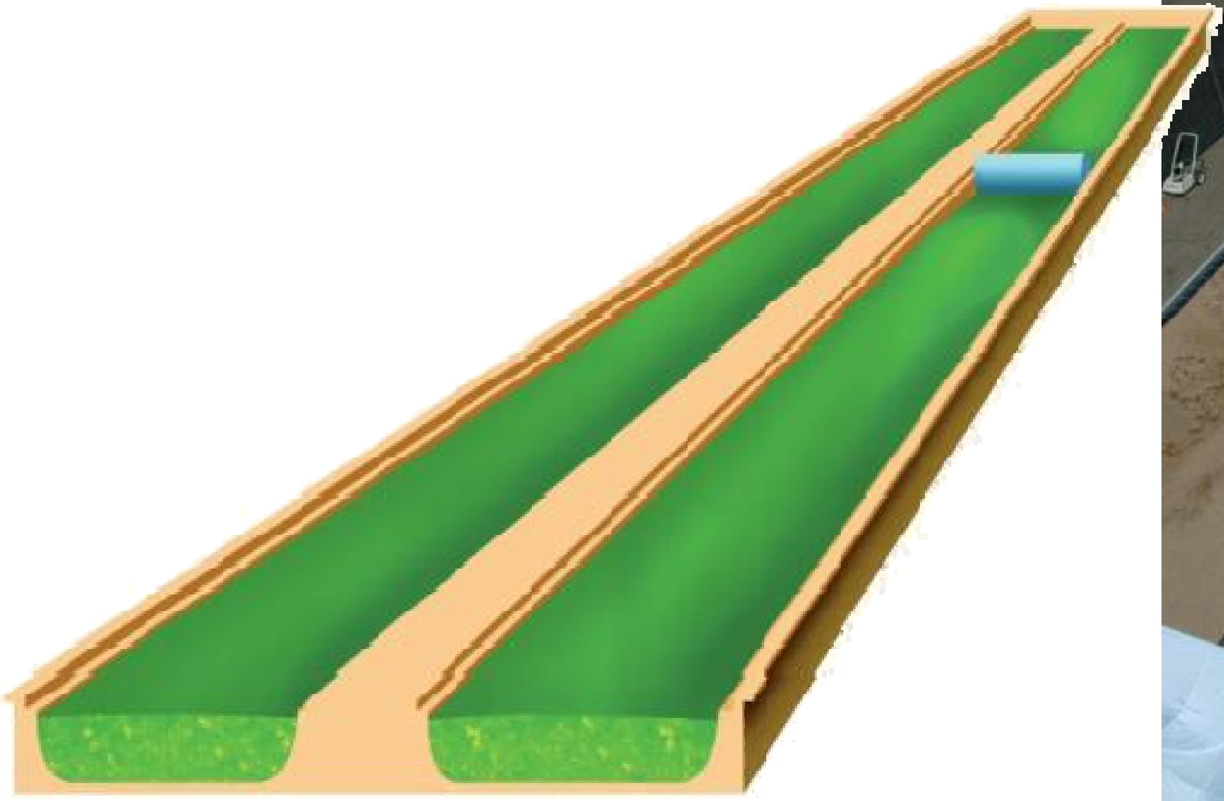
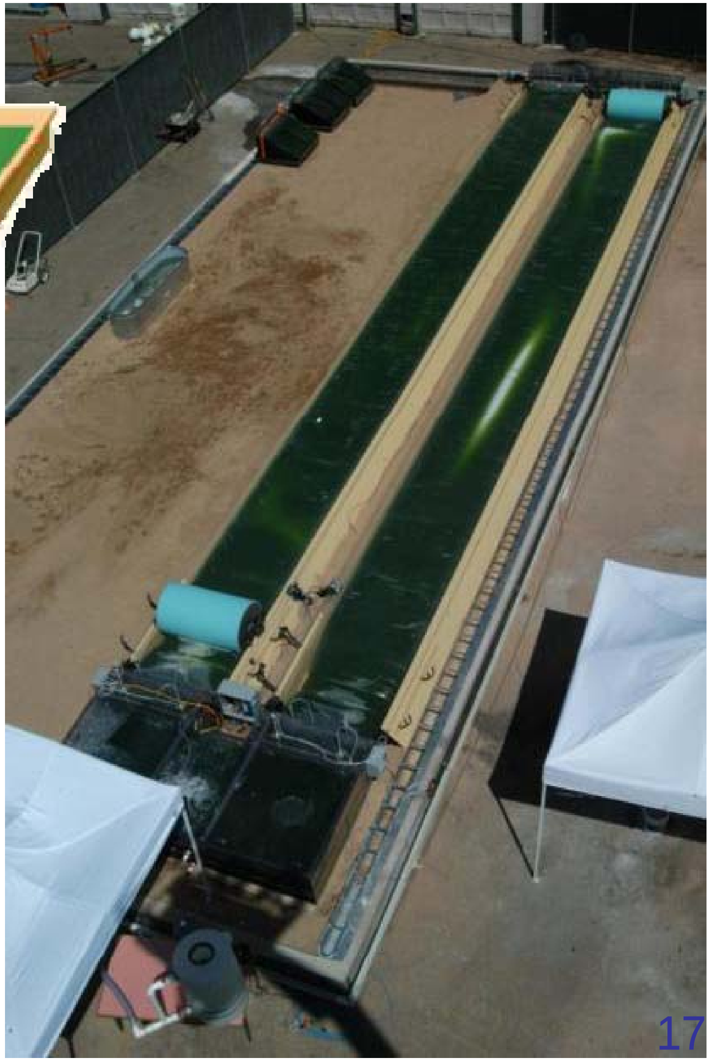
Direct Light PBRs: GreenFuels, 1st Gen

Direct Light PBRs:
AlgaeLink / Bioking

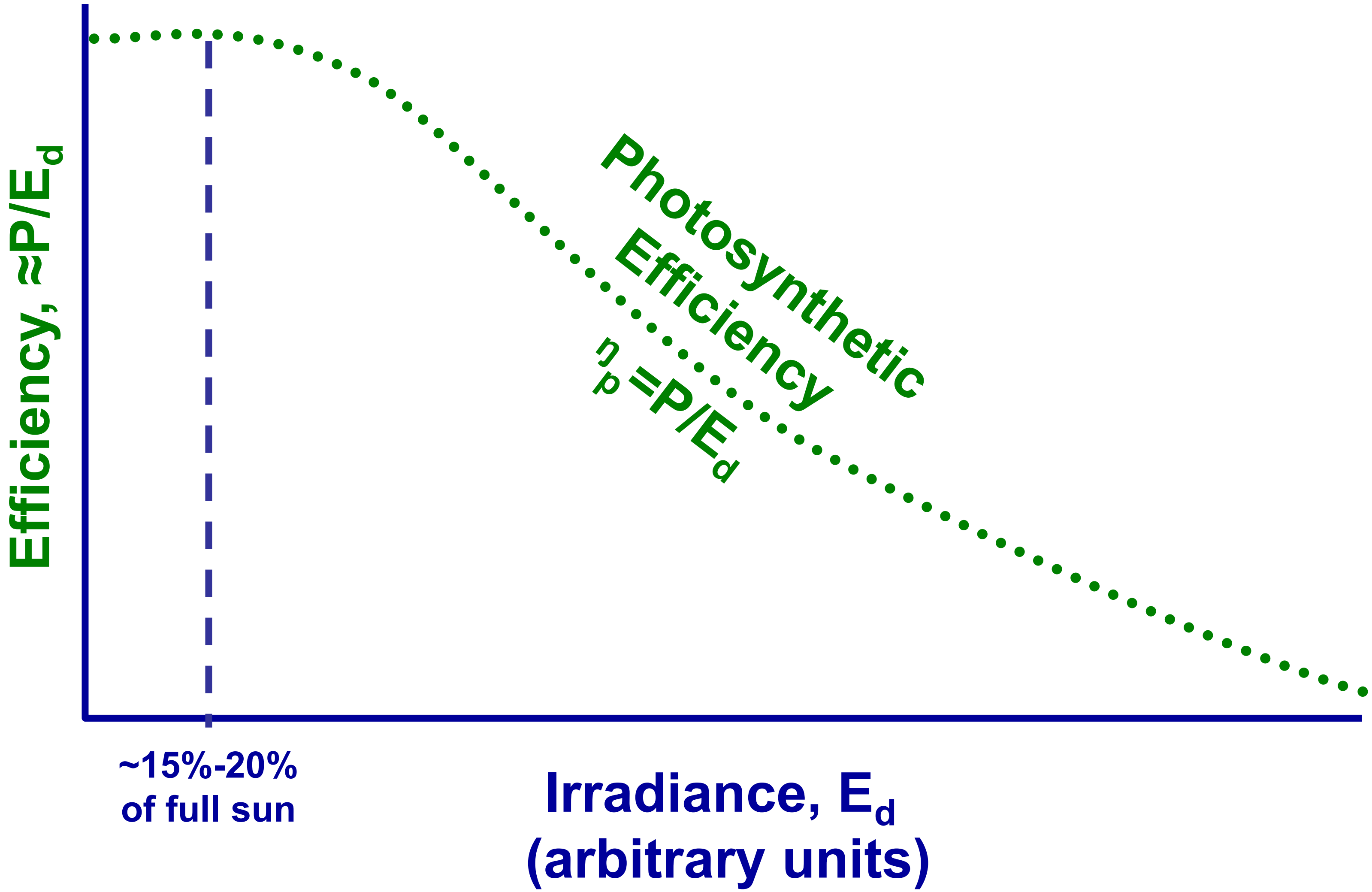


Direct Light PBRs.
Solix 1st Generation





Photosynthetic Efficiency



Impact of Light Intensity

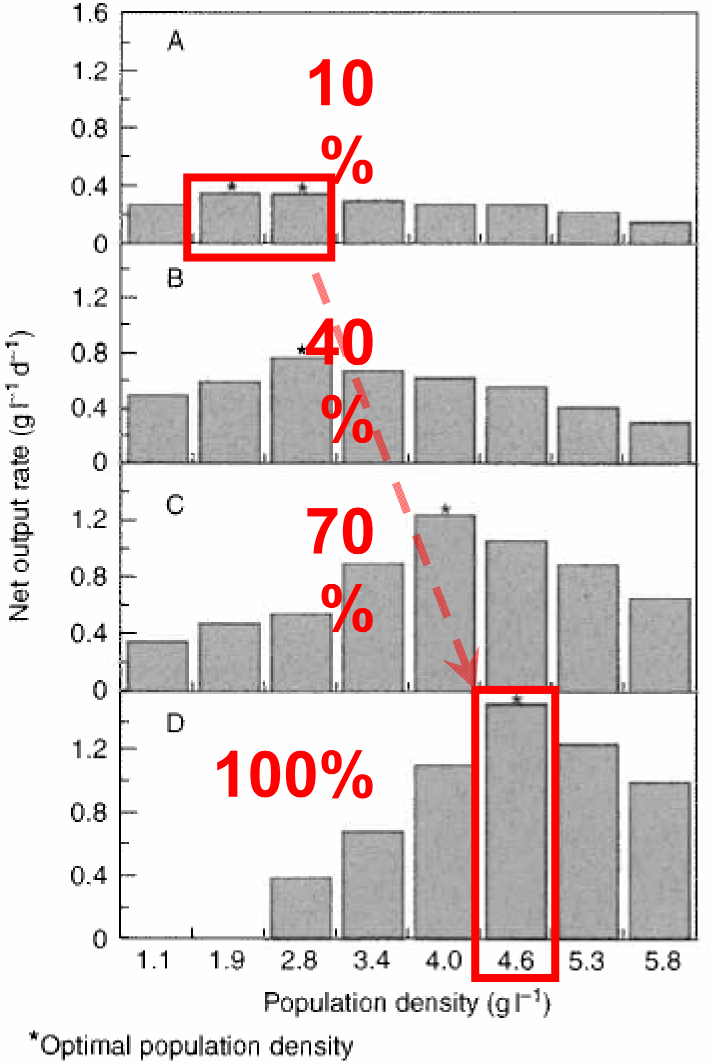
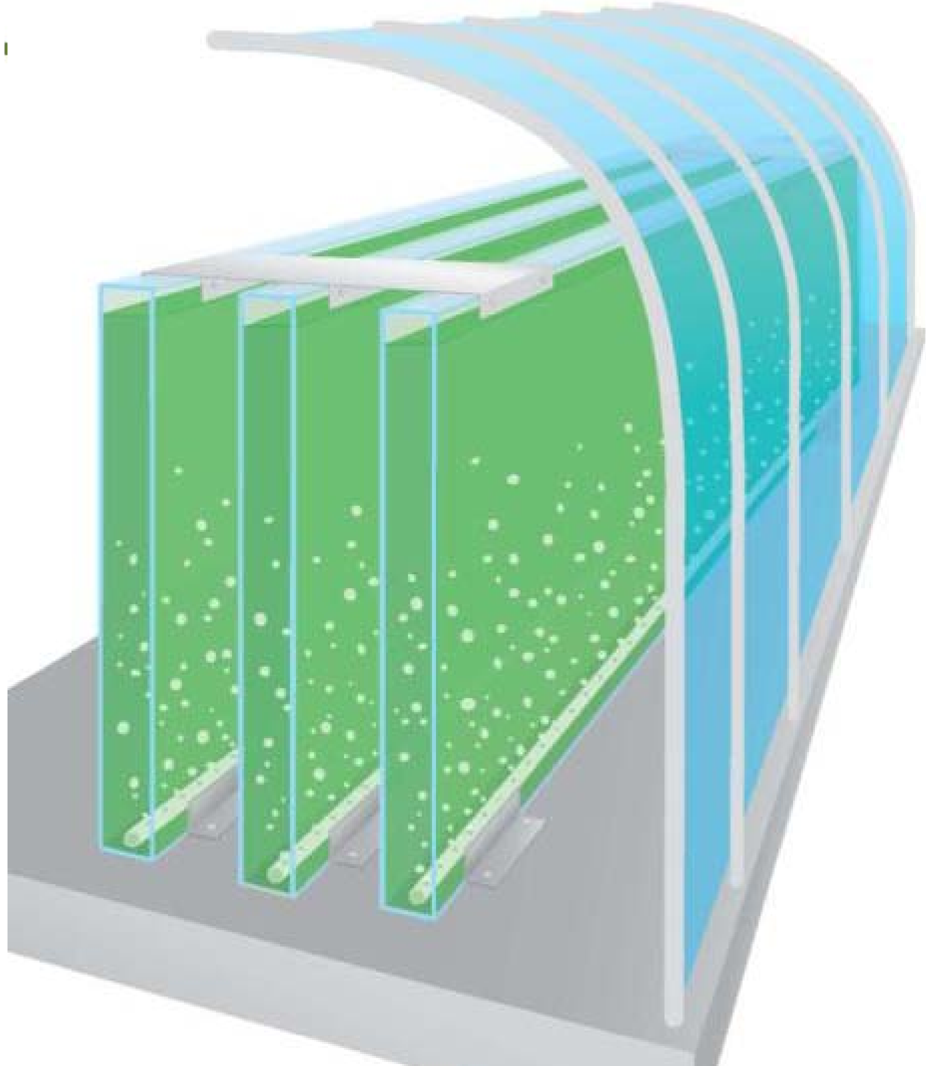


Fig. 8.3. Interrelationships between incident PFD, optimal population density and net output rate. A = 90% shade; B = 60% shade; C = 30% shade; D = no shade, full sunlight (from Hu & Richmond, 1994). Reprinted with permission from Kluwer Academic Publishers (*J. Appl. Phycol.*).

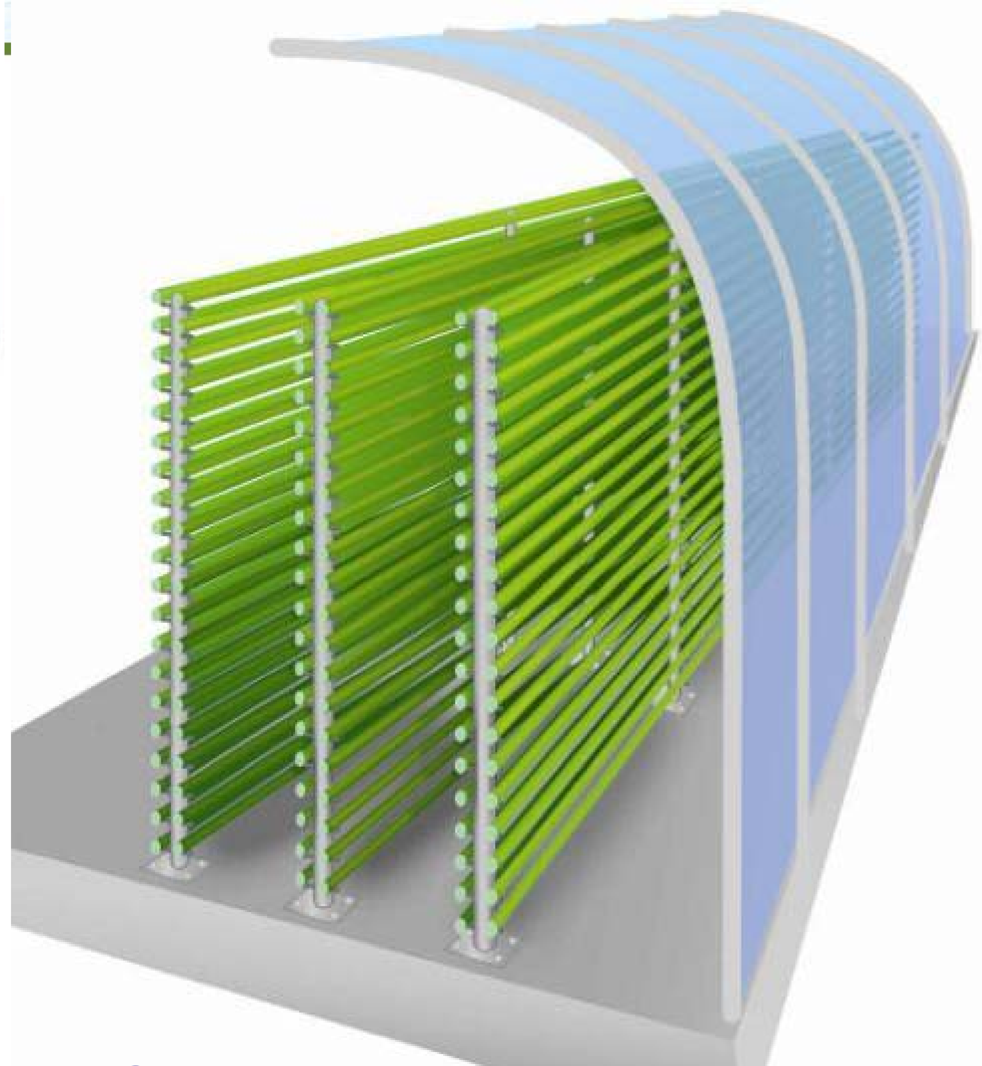
Note: 10X increase in light, but only 3.5X increase in output. Implies a 3X reduction in photosynthetic efficiency.

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

Extended Area PBRs

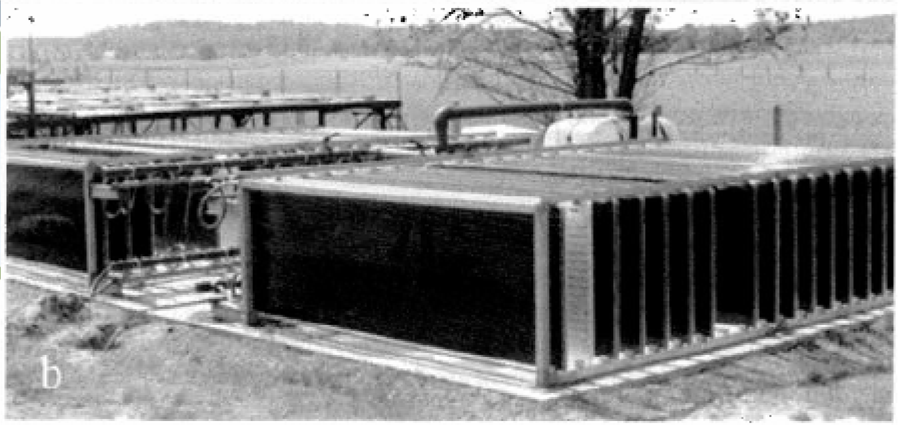


Glass Plate Photobioreactor
(Pulz, Richmond, others)

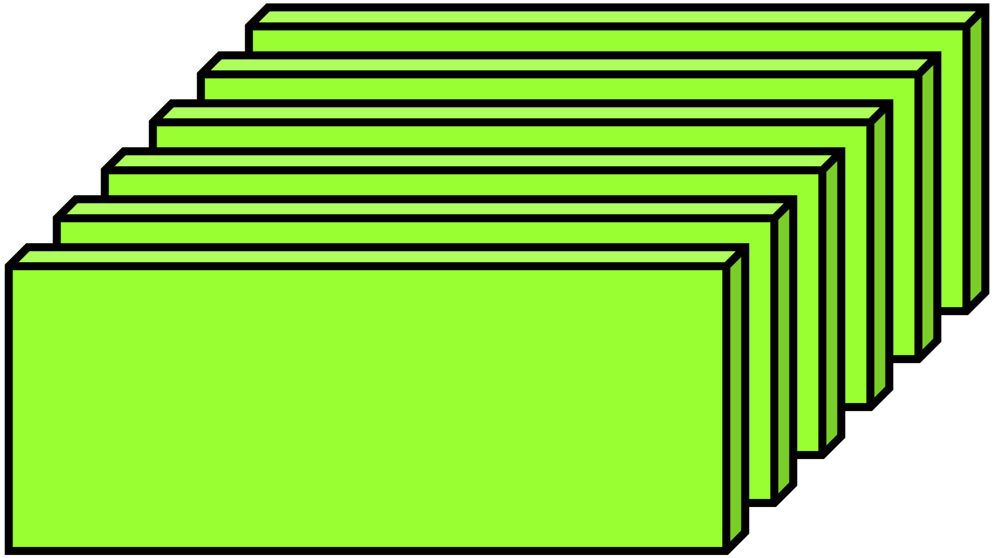


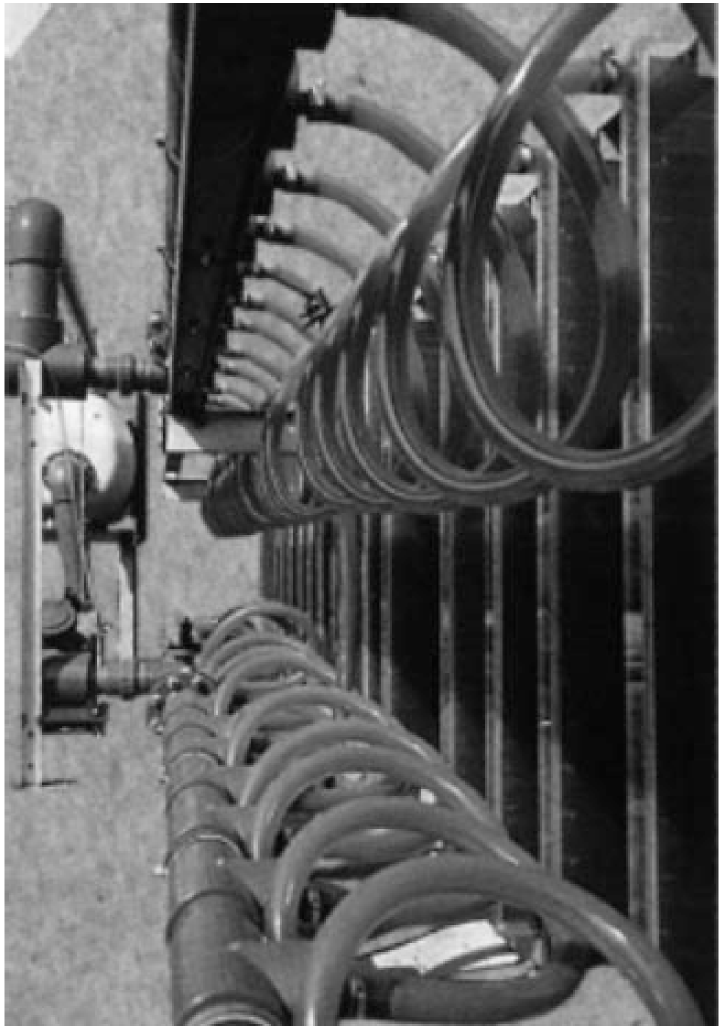
Glass Tube Photobioreactor
(Pulz, IGV, Ketura, Torzillo, others)

IGV Diffuse



≈5 m^2 illuminated area
for 1 m^2 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

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

High-Growth Phase

Stress Phase

Closed PBR Attributes

<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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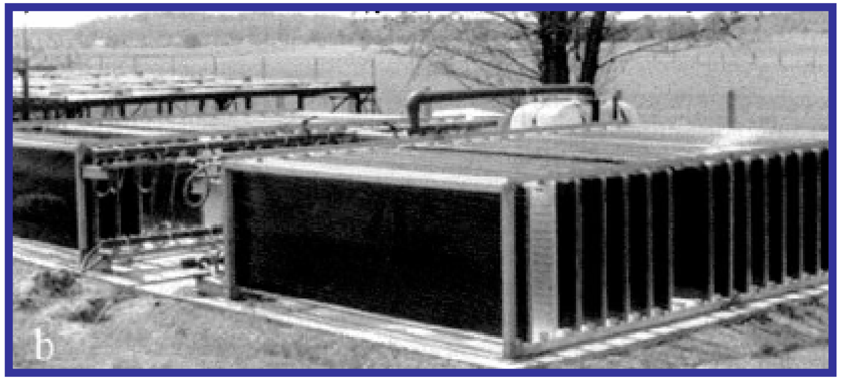
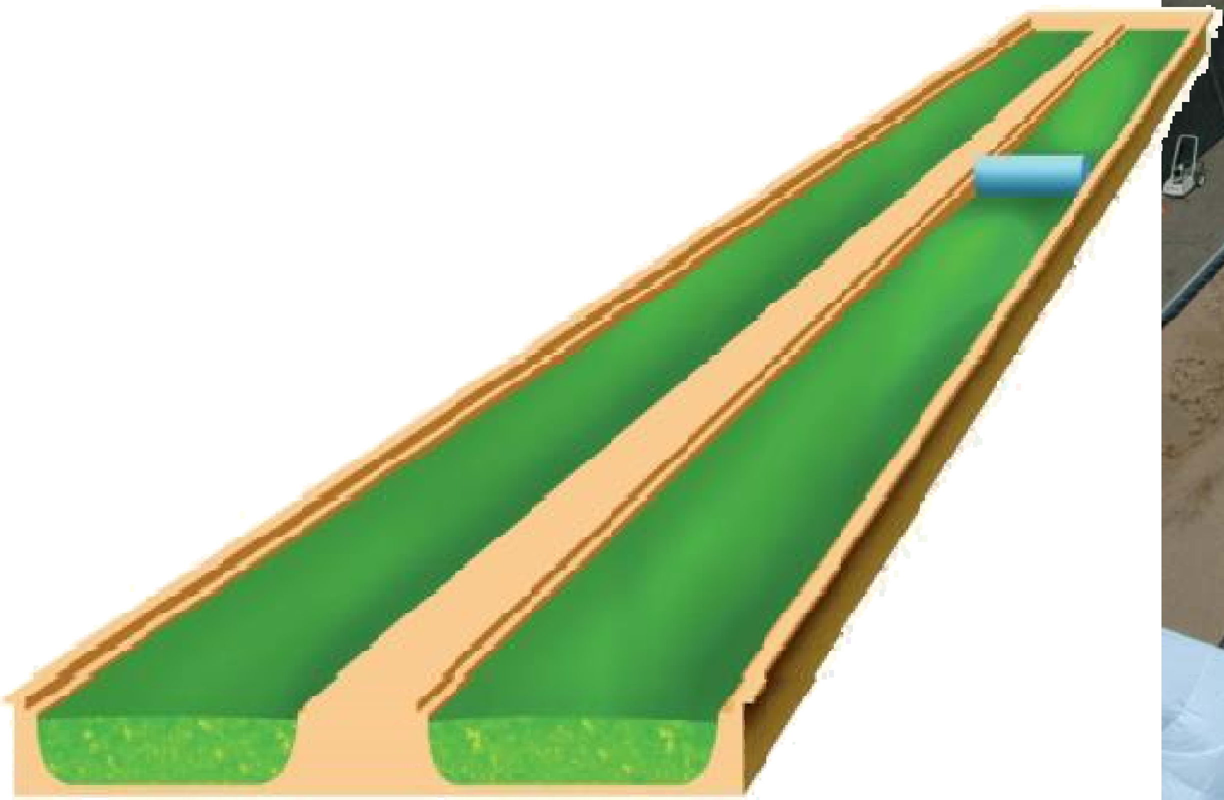
Cost vs. Productivity



Direct Light PBR:
Low Cost & Productivity

Diffuse PBR:
High Cost & Productivity

1st Generation PBR. July '06



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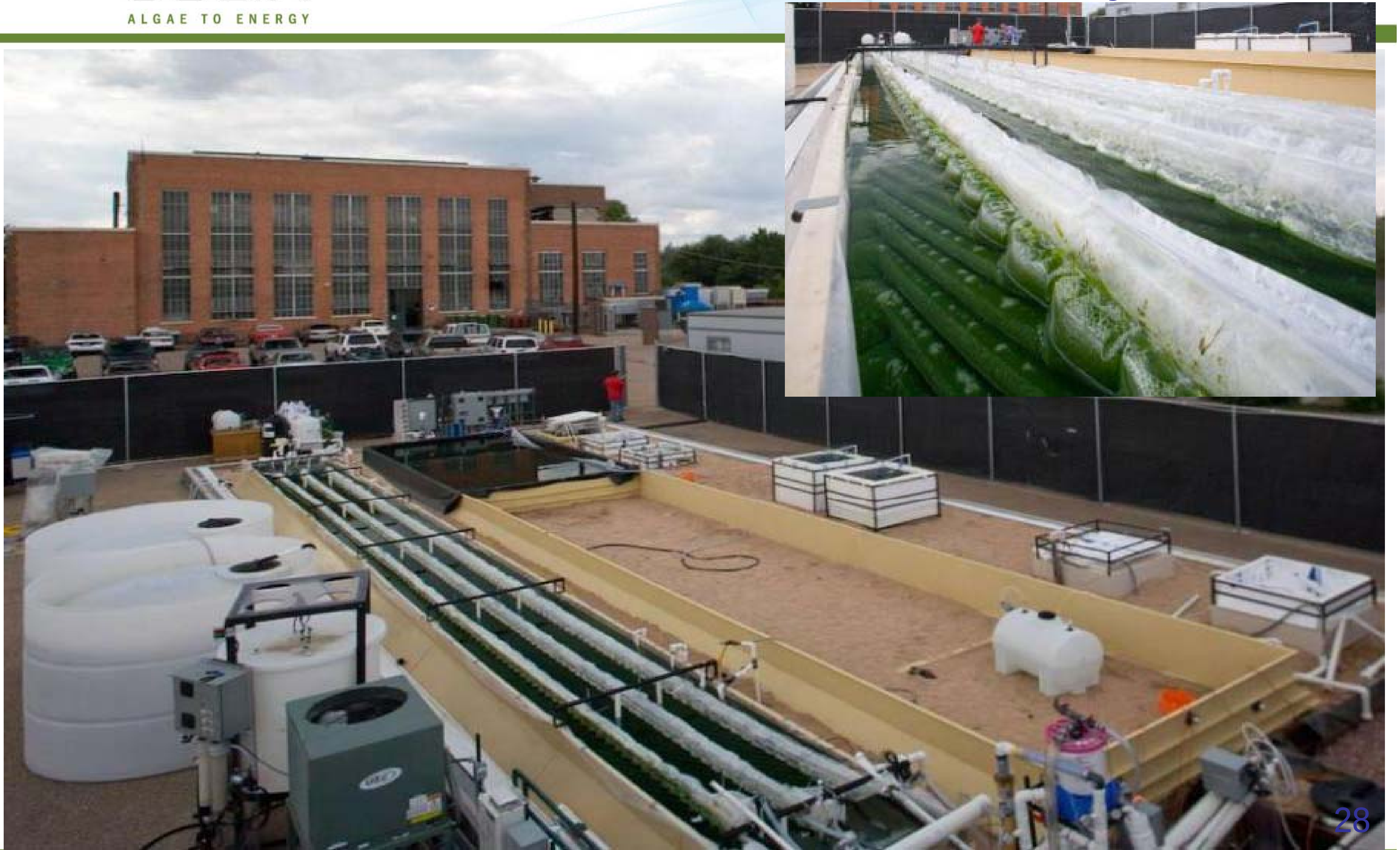
2nd Generation PBR – May '07

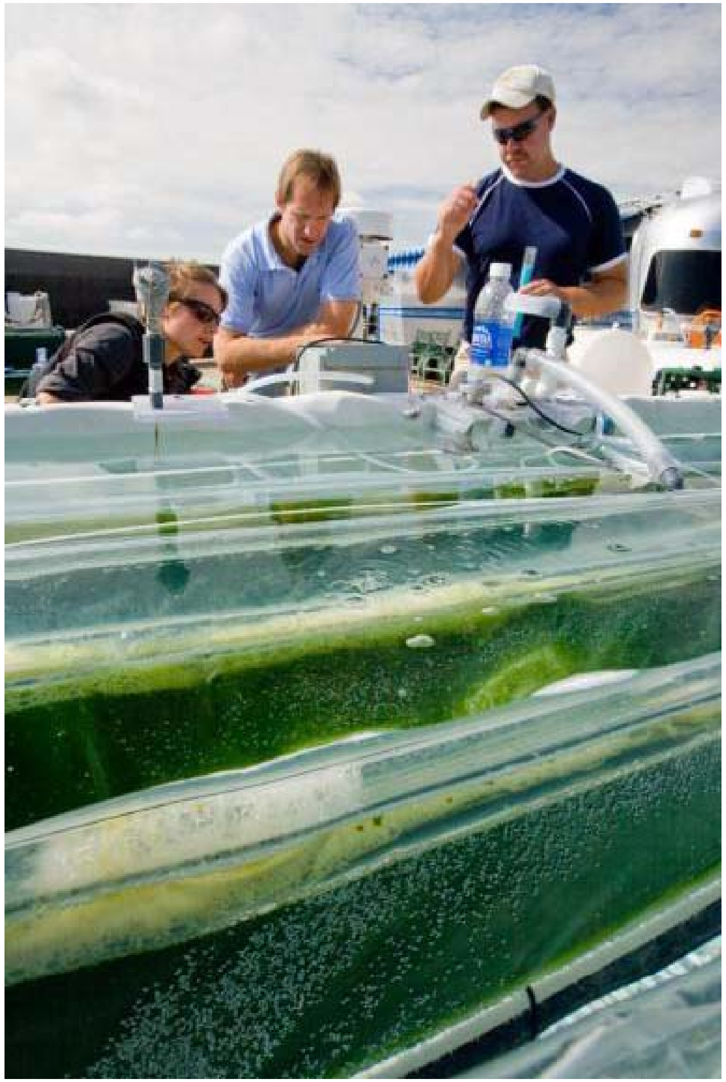


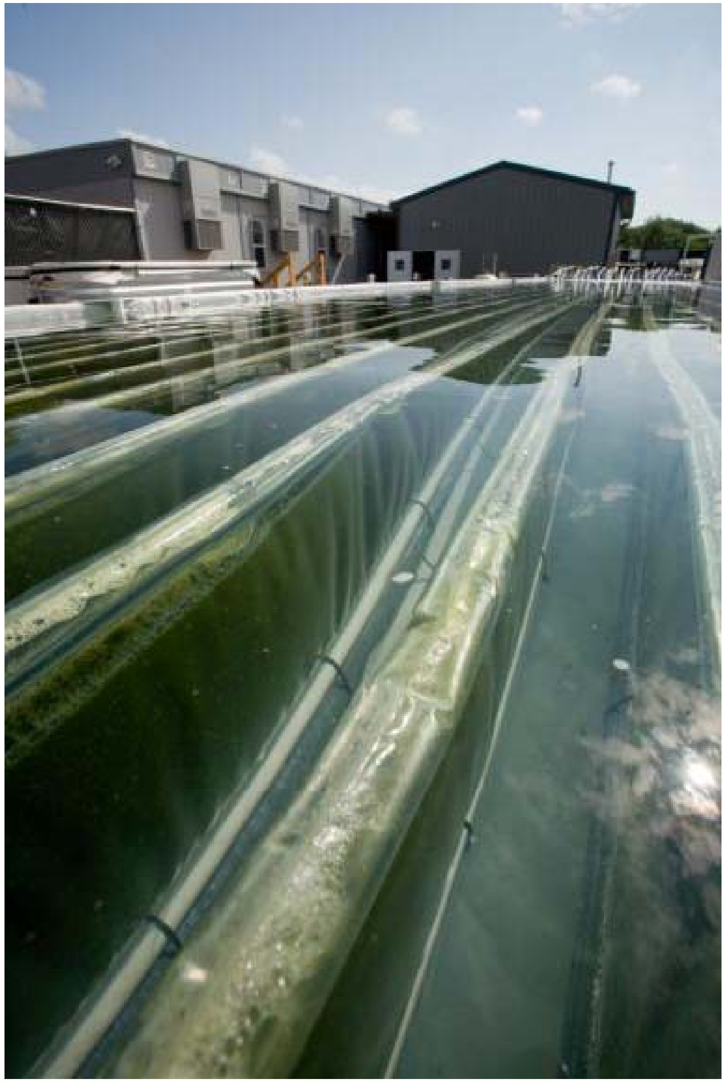
3rd Generation PBR –Nov '07

Solix G3 Technology:

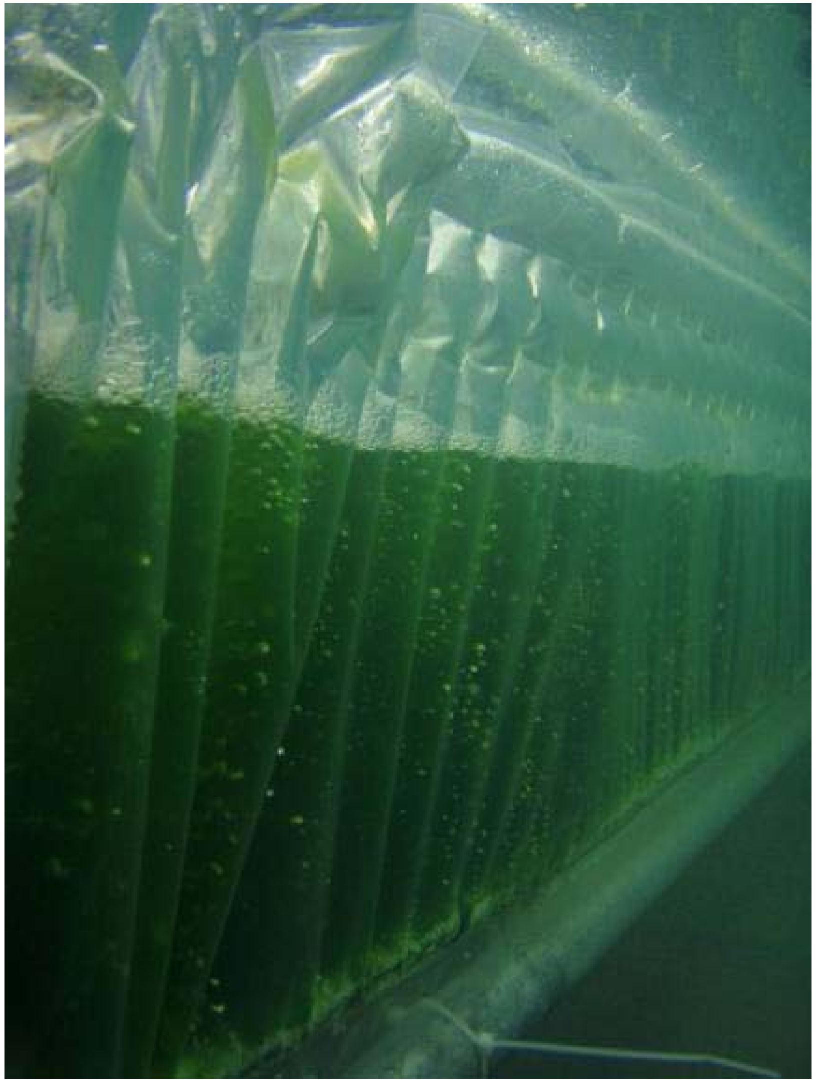
- Extended surface area
- Water supported
- Integrated CO_2 / air sparging
- G4 under development

Solix G3 (cont)





Solix G3 (cont)



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ALGAE TO ENERGY

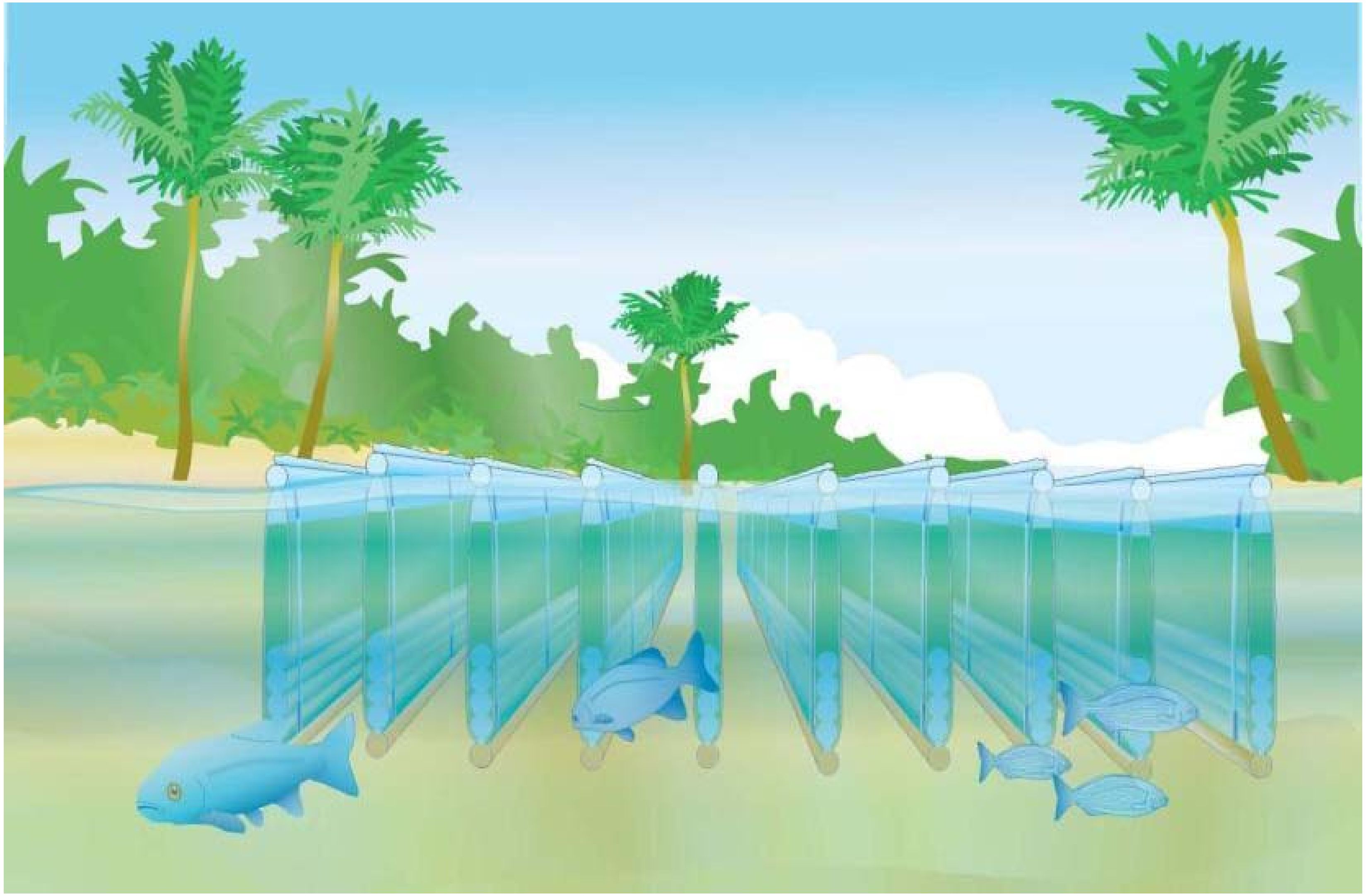
Solix G3 (cont)

Winter Operation: '07 & '08

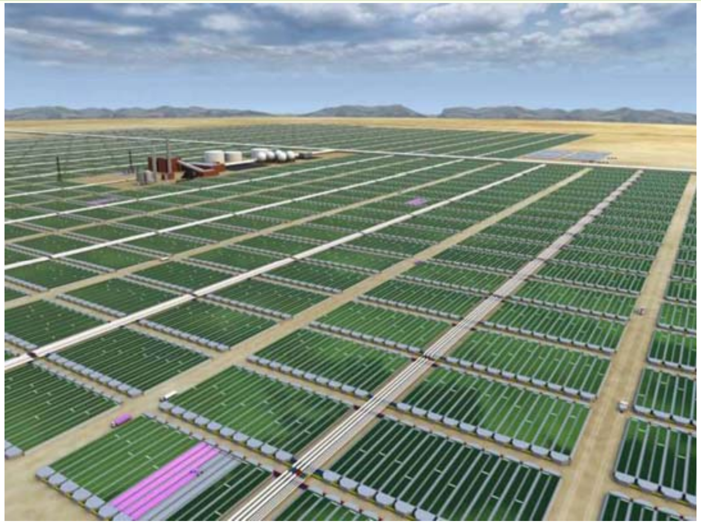
Continuing AGS Improvements

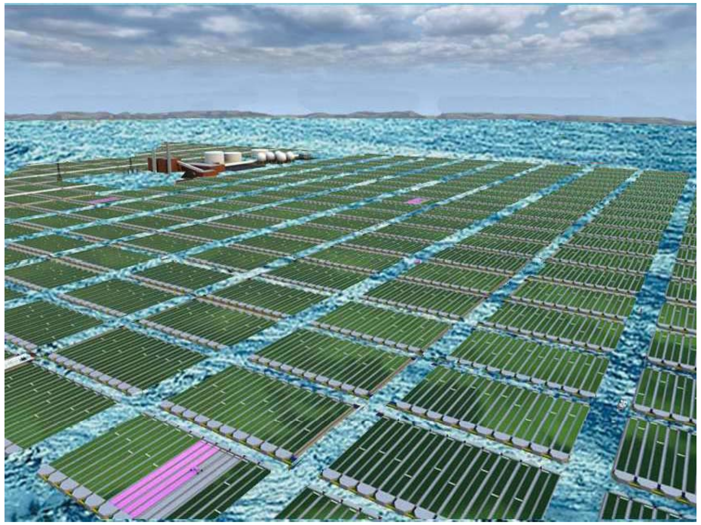
Solix G4a Technology:
- Membrane CO_2 delivery
- Membrane O_2 removal, internal
- Reduced thickness / higher density

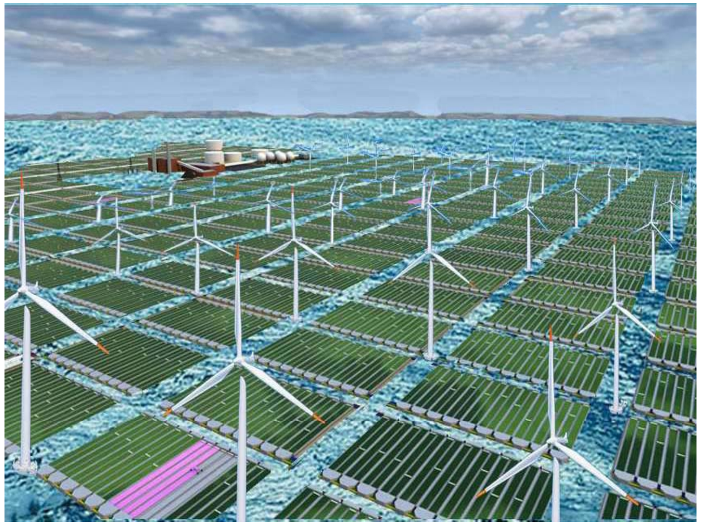
Potential Open-Water Application



Offshore Production?
Denmark Workshop, Apr 20-22







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Biology

Harvesting & Extraction

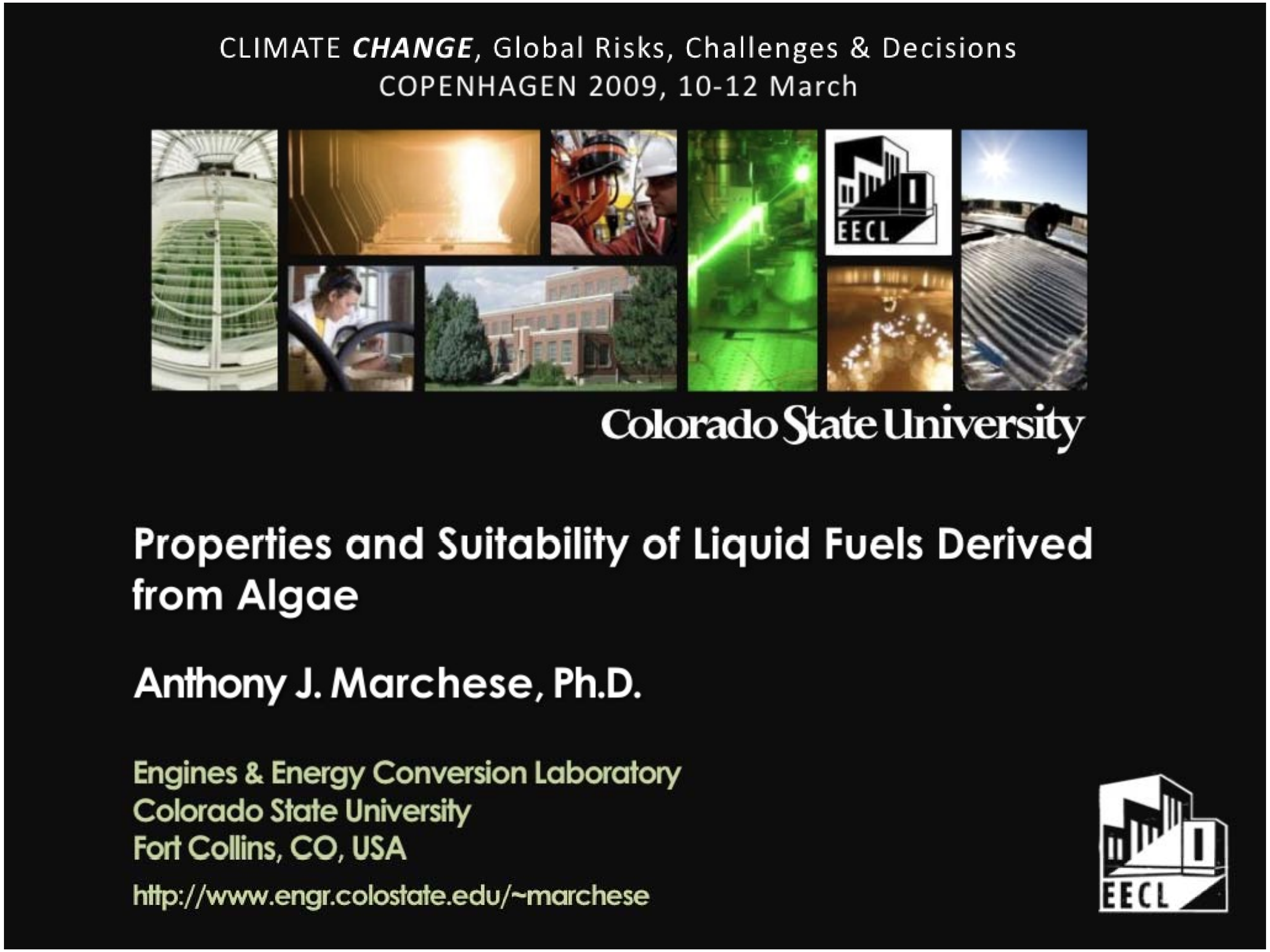
SOLIX
ALGAE TO ENERGY

Extraction

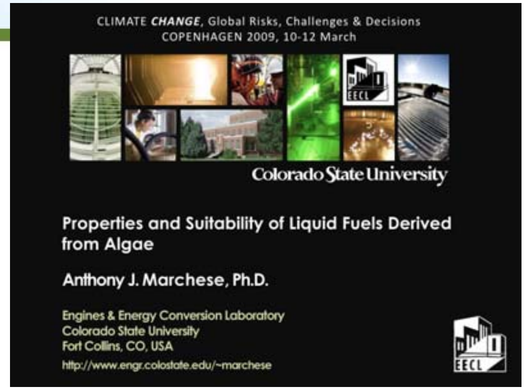
Extraction

SOLIX ALGAE TO ENERGY

Fuel Properties - General



Fuel Properties - General

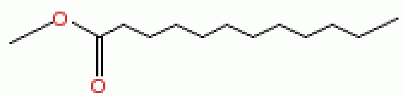


- Algal oil is unique in that it tends to contain a significant quantity (~5-20% by volume) of long highly unsaturated oils, which are rarely observed in more traditional biodiesel feedstocks, such as soy and rapeseed (canola) oil.
- The two most common types of long and highly unsaturated oils found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

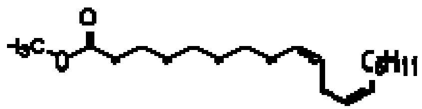
Feedstock Composition

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

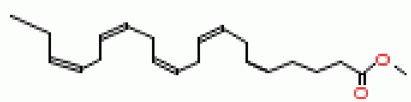
	Saturated Acids						Mono Unsaturated Acids			Total Poly Unsaturated Acids		
	10:0	*12:0*	*14:0*	*16:0*	*18:0*	*>18:0*	*16:1*	*18:1*	*22:1*	*n:2*	*n:3*	*n:4-6*
Coconut	7	**47**	15	8	2			6		2		
Palm			3	40	3			46				
Rapeseed			3	2	1	1		12	**55**	15	8	
Soybean				9	4	8	1	26		**55**	6	
Nannochloropsis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



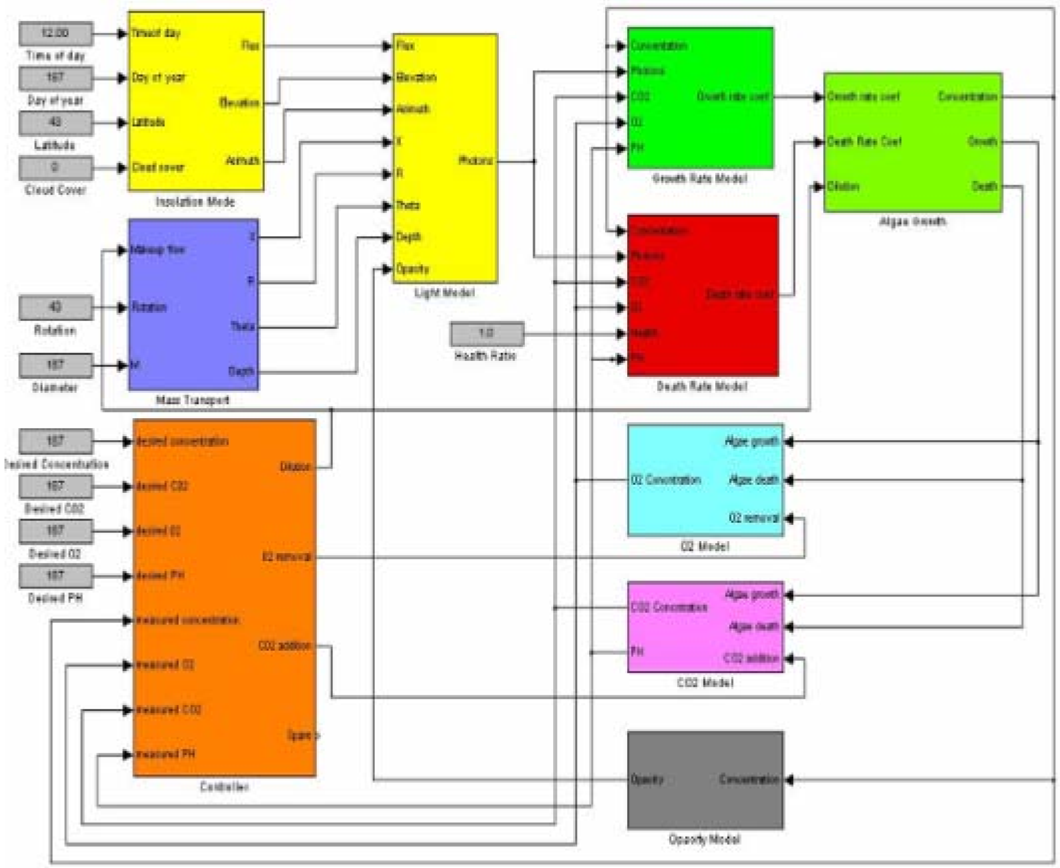
methyl linoleate (soy)



eicosapentaenoic acid methyl ester (algae)

Automation & Controls

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



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- Solix Business Model
- Conclusions

Scaling Up. . .


SOLIX

Coyote Gulch Amine Plant
Indian Route 111
N
Image © 2008 DigitalGlobe
© 2008 Tele Atlas
400 feet

Coyote Gulch Amine Plant


CO2 FEED PIPE
FROM RED CEDAR

Basin A

Basin A

Coyote Gulch

Coyote Gulch Layout

Basin C

Bulk CO_2 Supply

Basin B

Offices & :Lab

Basin D

Produced Water Handling

Basin A

Waste CO_2 & Nat. Gas Supplies

Operations Building

Photo taken 07.19.2009

Basin A

Basin A

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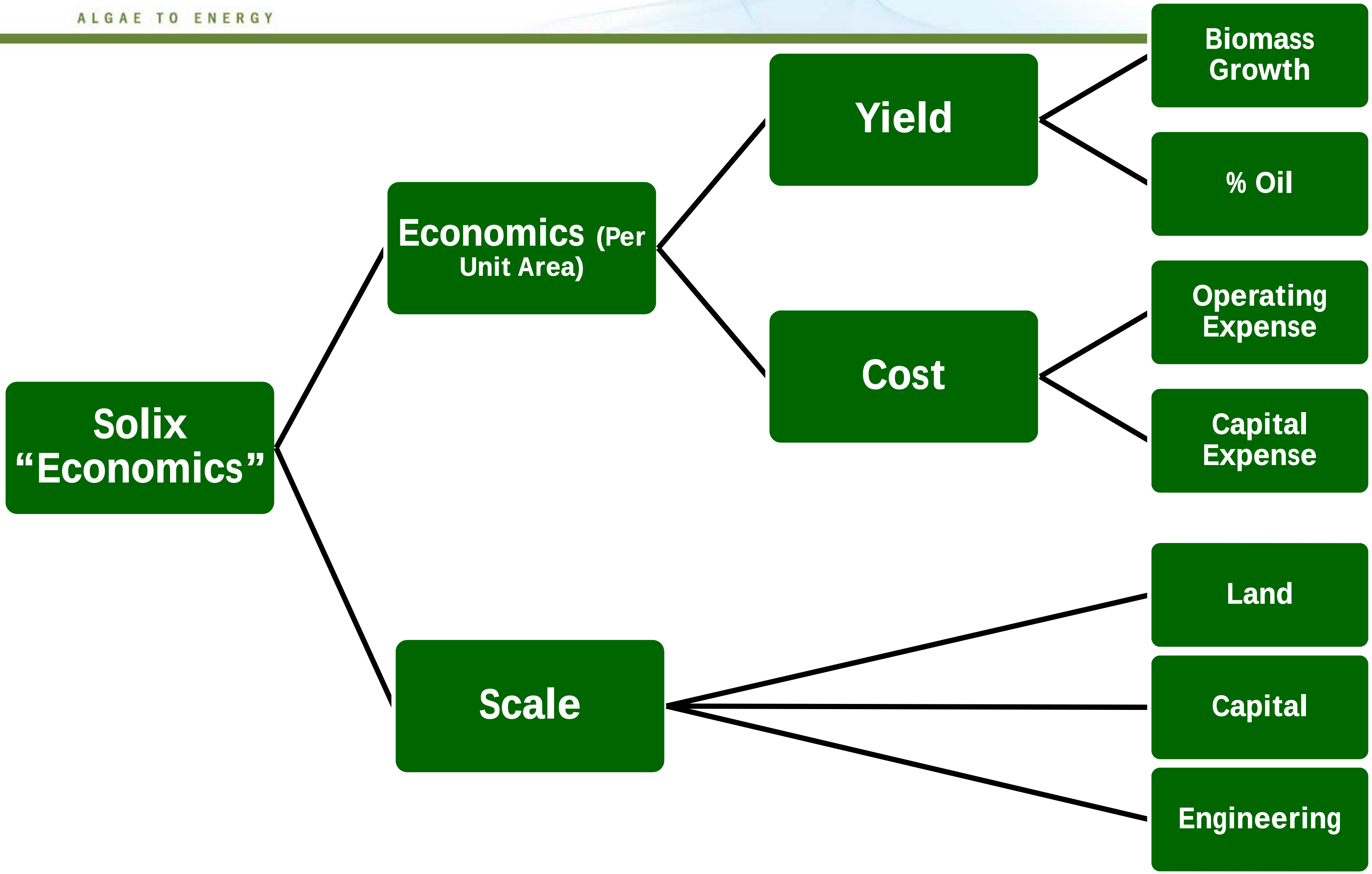
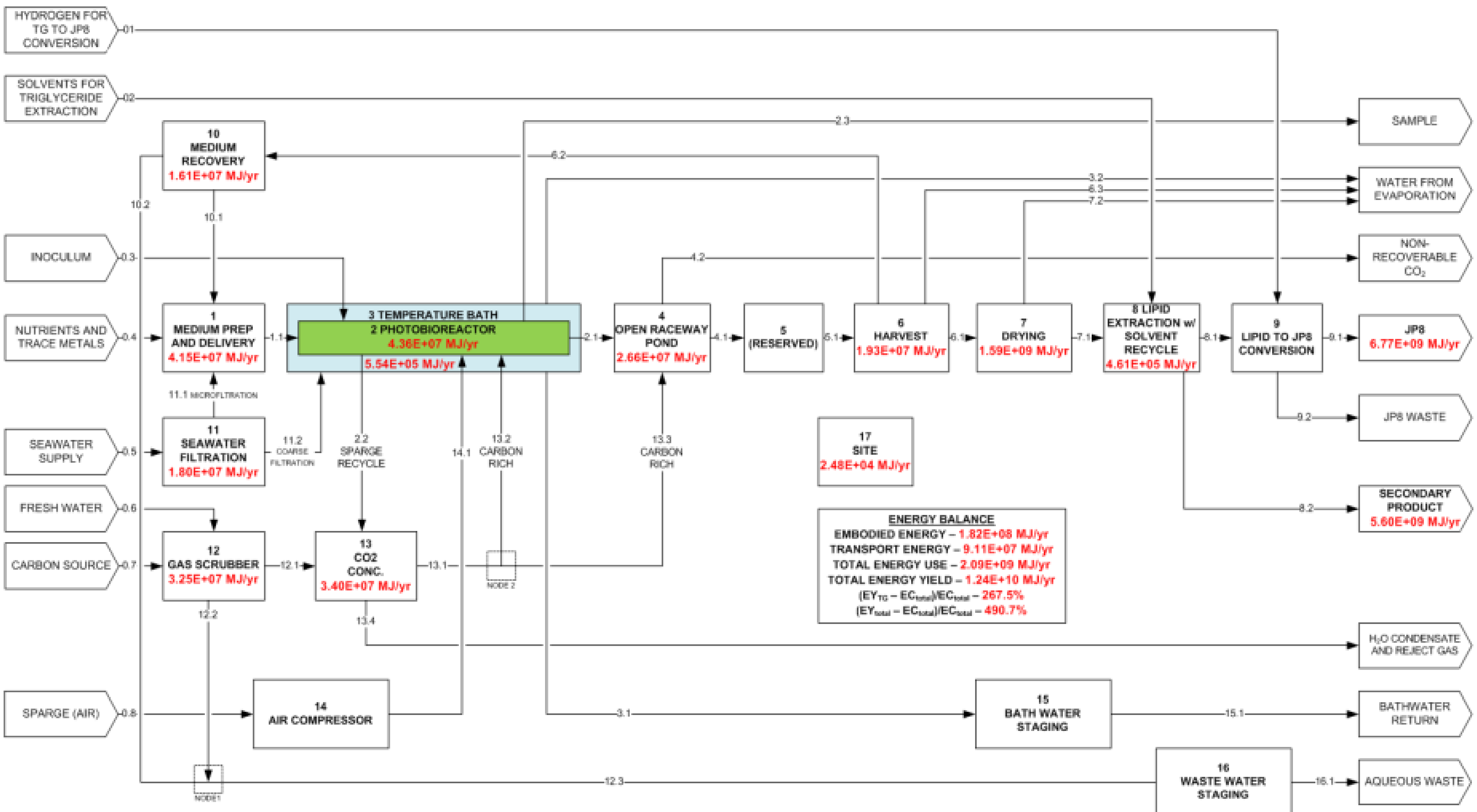
Economic Overview



System Analysis / Modeling



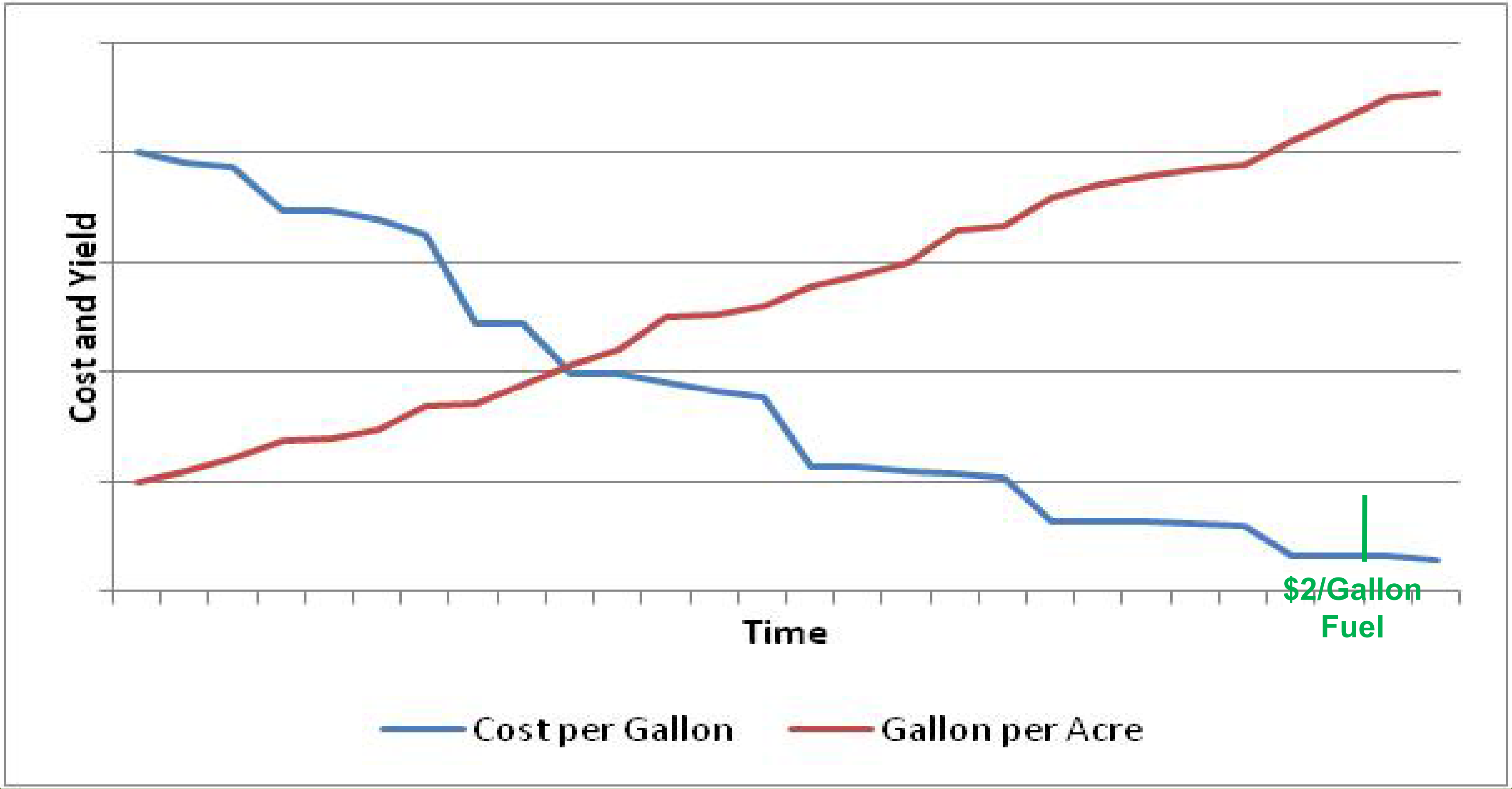
R&D Roadmap

$250/Gal

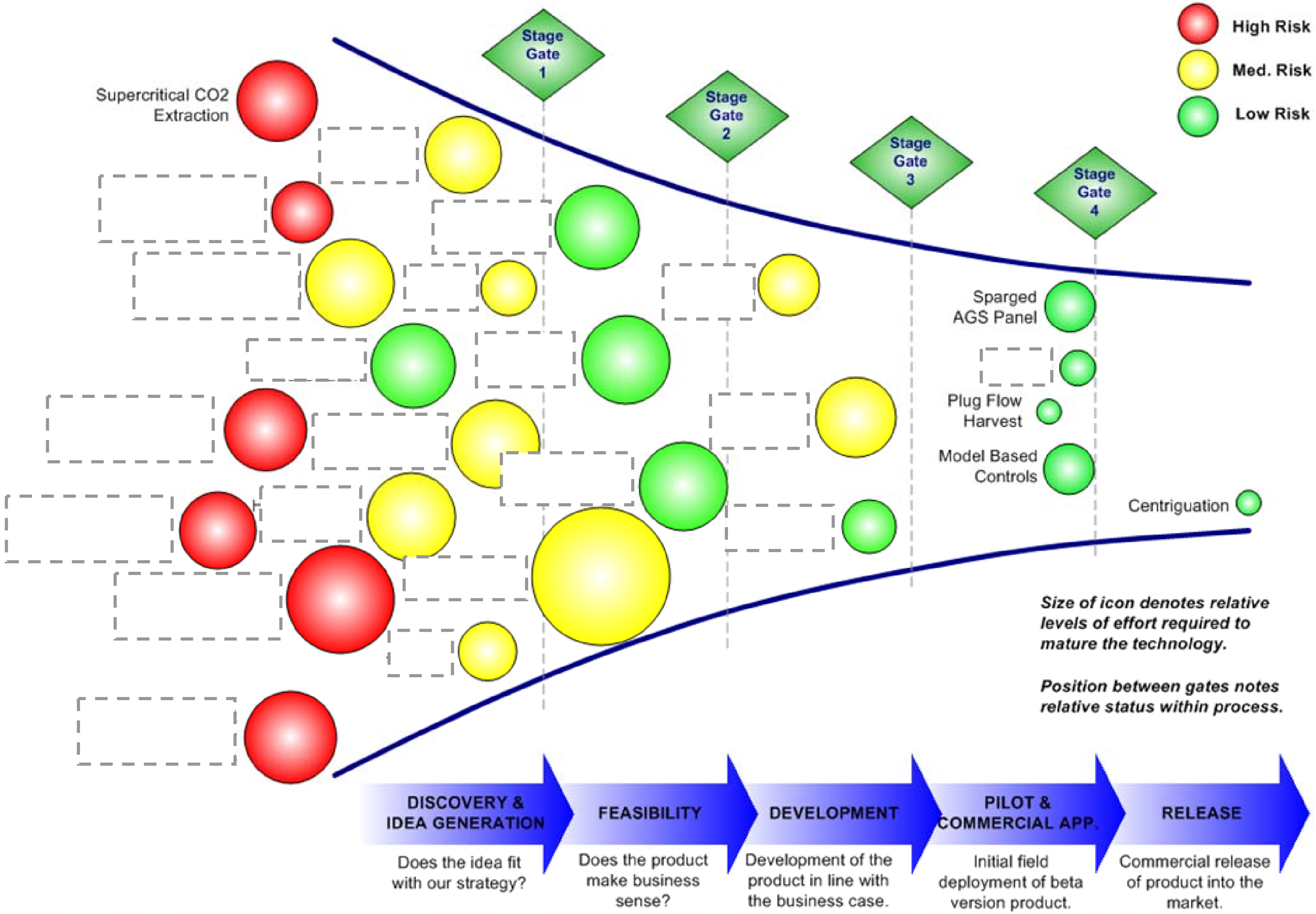
$2/Gal

Path to Fuel Cost Parity

The path to fuel cost parity will require both incremental and step function improvements



Technology Roadmap



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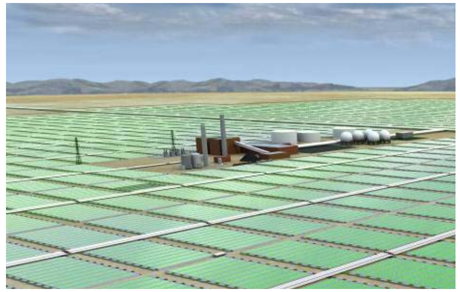
Business Model

- *Solix* **contributes:**
  - **production/processing technology**
  - **project development and operational expertise**
- **Partner contributes:**
  - **CO_2, land and capital**
- **Value from:**
  - **Fuel, co-products and CO_2**

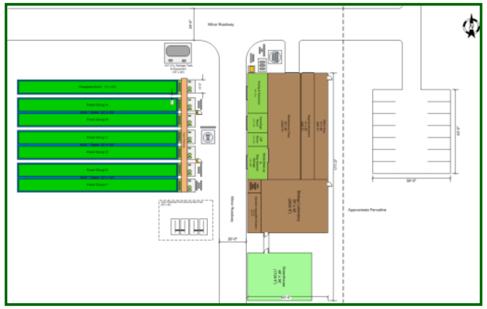
- **Solix is teaming with international partners in order to develop large-scale production**

Path to Commercialization

SOLIX
ALGAE TO ENERGY



Apollo



Gemini 1

Mercury 3 & 4

Mercury
1 & 2

Lab

Mariners

2006

2008

2010

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SOLIX
ALGAE TO ENERGY

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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Colorado State University

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