Techno-economic and Fluid Dynamics Analysis for Growing Microalgae with the Intent of Producing Biofuel Using a System Model

PRESENTED TO THE PACIFIC RIM SUMMIT ON INDUSTRIAL BIOTECHNOLOGY AND BIOENERGY

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AUTHOR: LEAH RAFFAELI PHD
UNIVERSITY OF DENVER

MOTIVATION

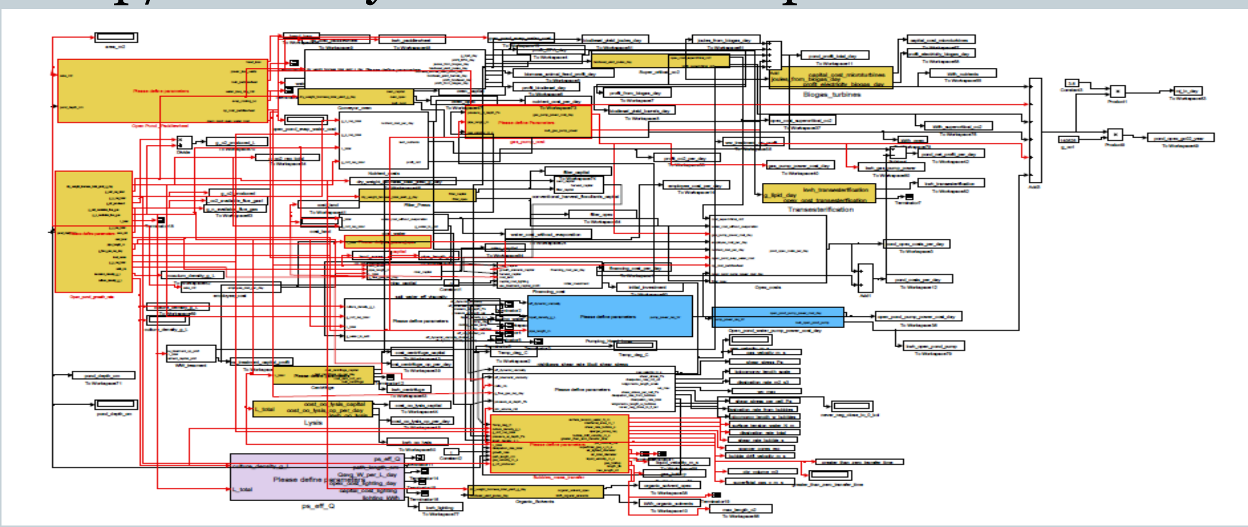
- Biofuel from microalgal growth is not a commercial reality.
- Lacking interdisciplinary research and standard methods for measuring productivity and growth parameter data.

newairplane.com

WE ARE MISSING: Proof of economic feasibility, high yields, low-energy input, reliable, chemical-free, and integrated scale-up for commercial production.

GOAL AND APPROACH

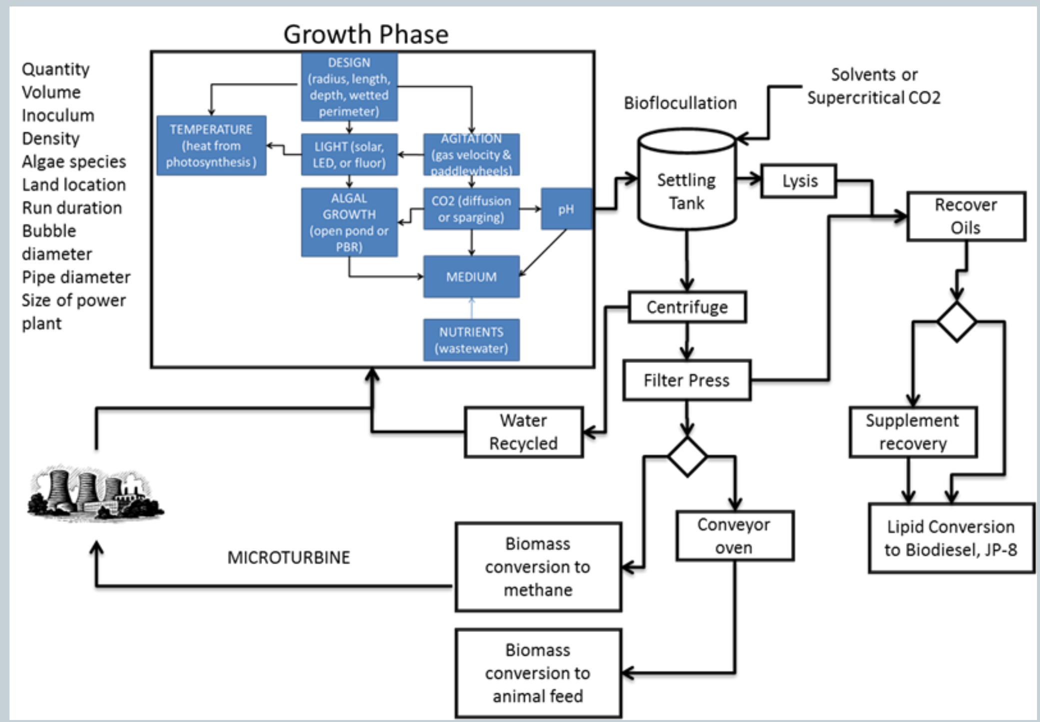
- Goal:
  - Close the business case for producing biofuel from microalgae.
- Approach:
  - Use 50+ years of data.
  - Develop/build a system model and perform iterative analysis.



Variables, analysis and interfaces not included in previous studies are important and impact results.

METHODOLOGY

- Use large amounts of data available in the literature to develop a system model incorporating biology, chemistry, physics, commercial best practices and financial analysis.
  - Define the system.
  - Identify system components.
  - Define components with equations.
  - Build model & simulate.
  - Results.
  - Optimize.
  - Discuss and summarize.



METHODOLOGY (CONT.)

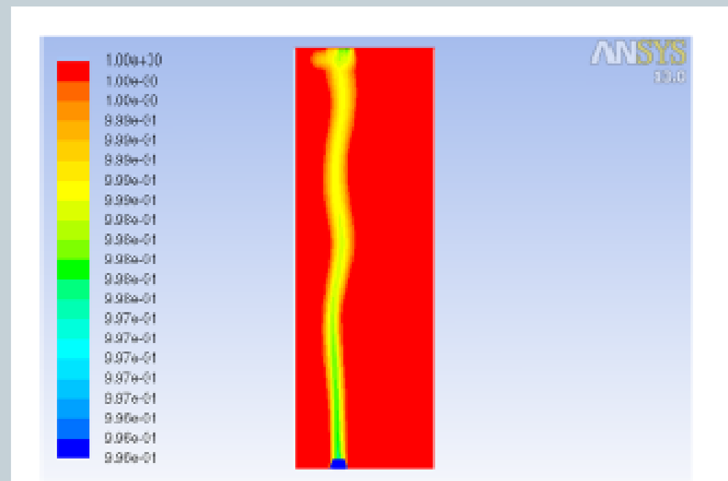
- Meet requirements for Study or feasibility estimate, Class 4, as defined by DOE (2011), cost accuracy goal is -30% - +50%.
- Three growth scenarios analyzed:
  - Solar illuminated PBR's (Photobioreactors)
  - Artificially illuminated ALR's (Air Lift Reactors)
  - Open pond
- Algal species and biological growth rate are key for determining profit from end products.
- Fluids profile and systems analysis tied to culture density are key to calculate cost of production.

The most suitable algal growth system is situation, species and final purpose dependent.

METHODOLOGY
ASSUMPTIONS ON DESIGN

- Open pond design is large surface pond with one paddlewheel and 20 gas spargers/pond.
- Solar illuminated PBR is a single tube design with a single gas sparger.

Open Pond Design.

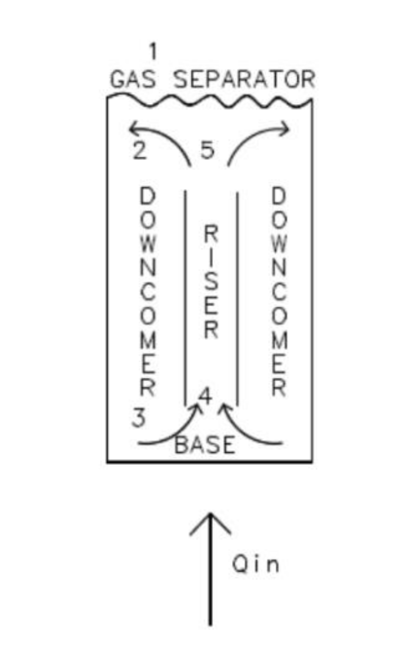


Solar PBR Design.

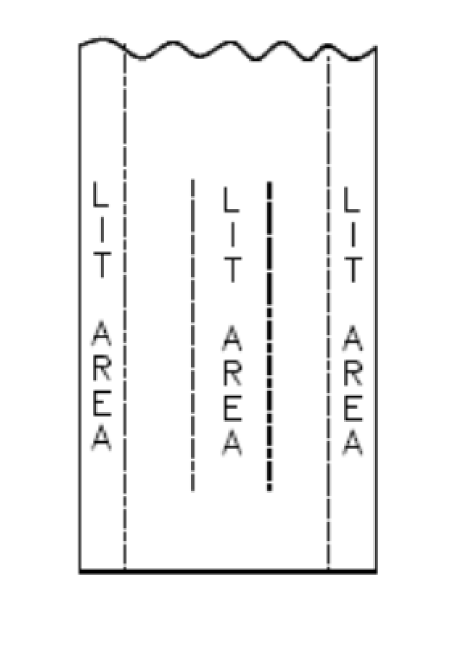
Efficient growing methods would be characterized by high volumetric as well as areal productivity.

METHODOLOGY
ALR DESIGN

- An organized mixing pattern is attained through using an artificially illuminated ALR resulting in nearly constant light/dark cycle frequency approaching a ratio of 1:10.



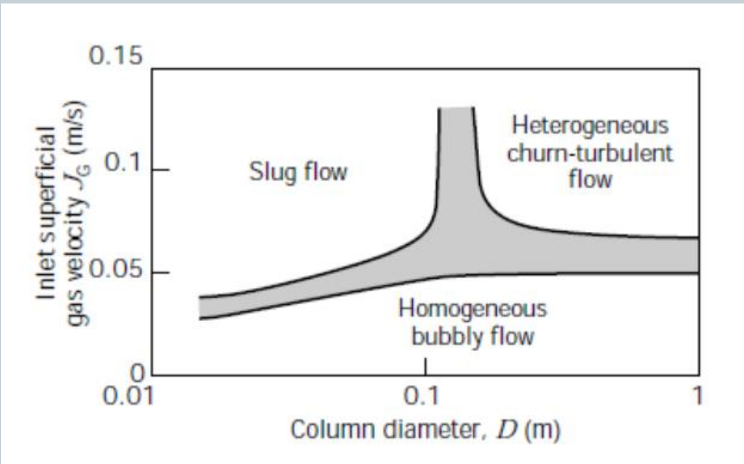
ALR design showing pressure regions.

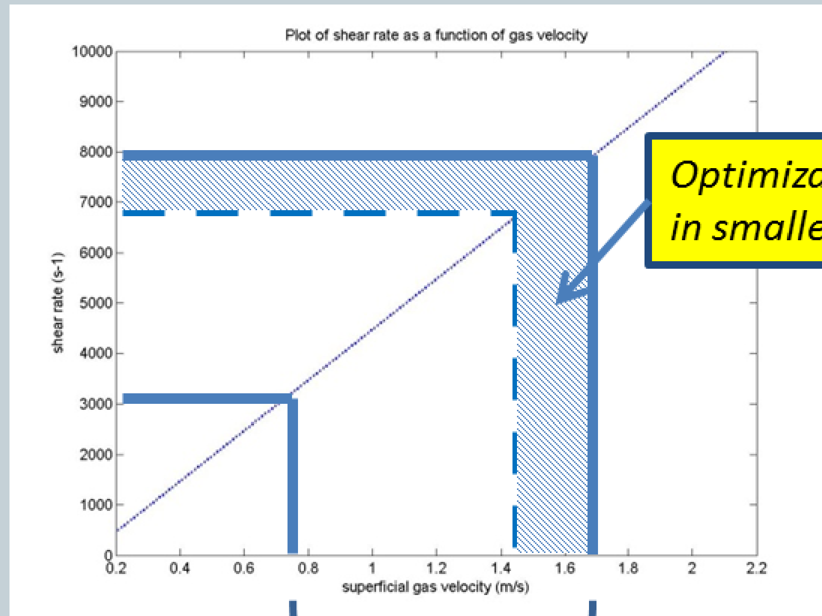


ALR design showing illumination zones.

Tube diameter is limited by illumination zone and length is limited by rate of photosynthesis and oxygen removal.

ANALYSIS OF VARIABLE RANGE OPTIMAL FLUID DYNAMICS-SUMMARY





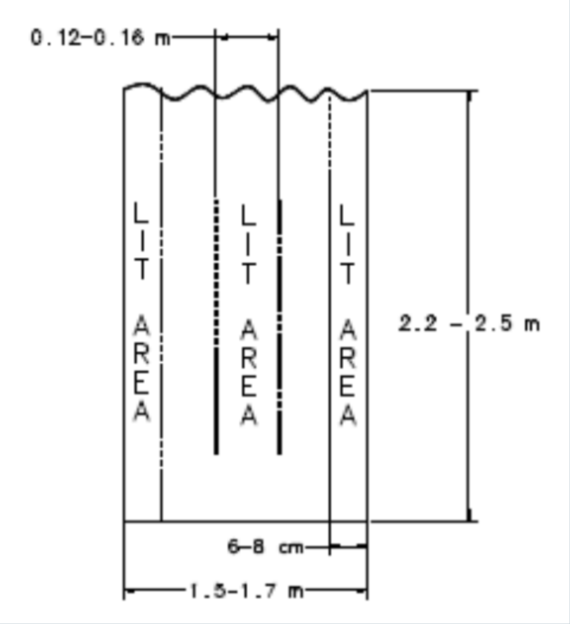
Optimization zone in smaller volume.

Optimization zone in larger volume.

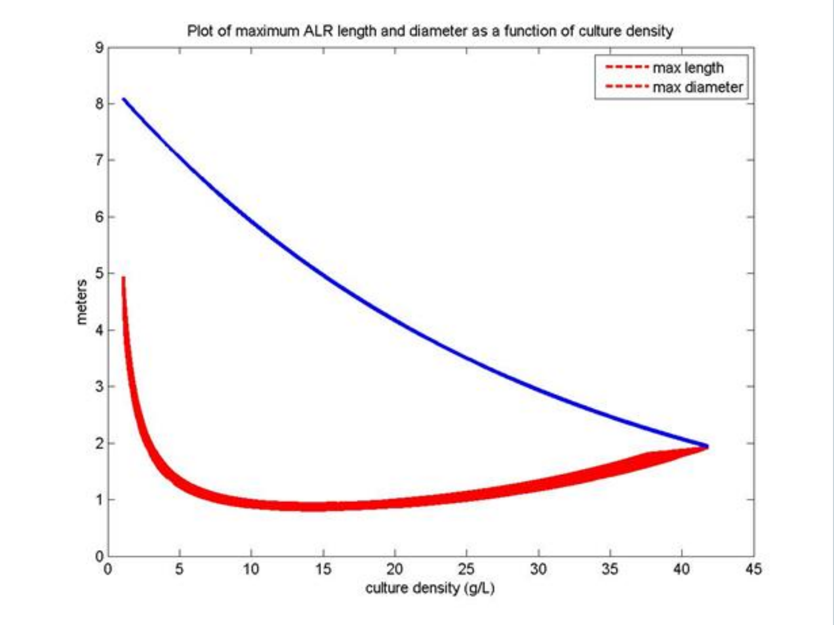
Optimal conditions are located where flow is heterogenous, circulation time is independent of gas velocity, interfacial area reaches a near constant, and level of shear stress is acceptable.

ANALYSIS OF VARIABLE RANGE ALR GEOMETRY

- The ALR diameter is determined from the light path length and the length of the ALR is dependent on the amount of O_2 produced; both factors are dependent on the culture density.



ALR design geometry results (40-50 g/L)

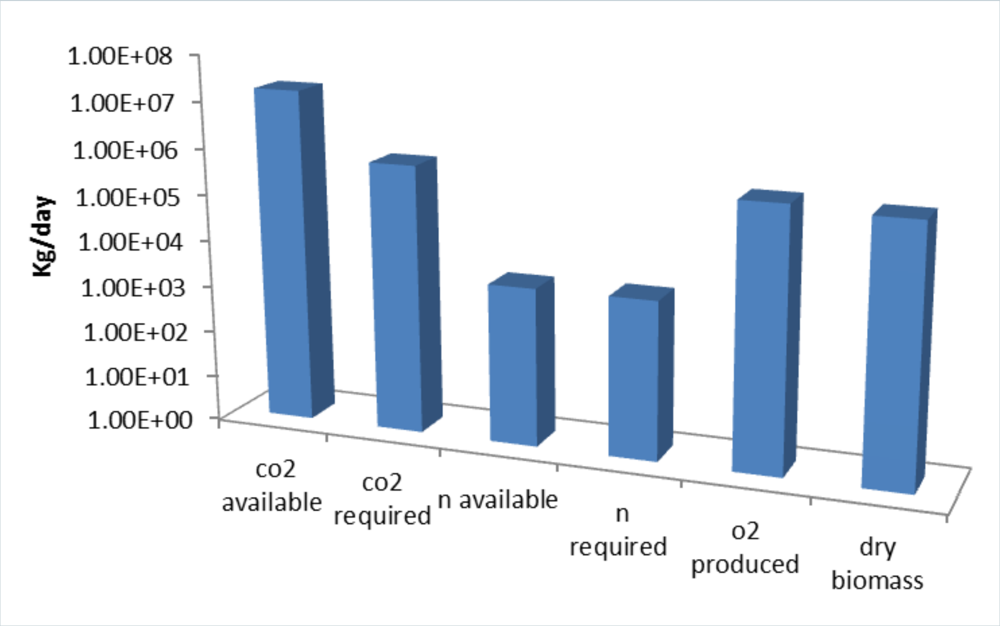


ALR length and total diameter as a function of culture density (0-42 g/L)

Interesting to note that at close to what will be found as optimized algal density (~40 g/L) the length and diameter converge.

RESULTS
FLUE GAS ANALYSIS

- The PBR growth scenario to consume all the nitrogen from the flue gas of a 1,000 MW power plant will cover 17 acres and produce 1,900 barrels of biodiesel per day.

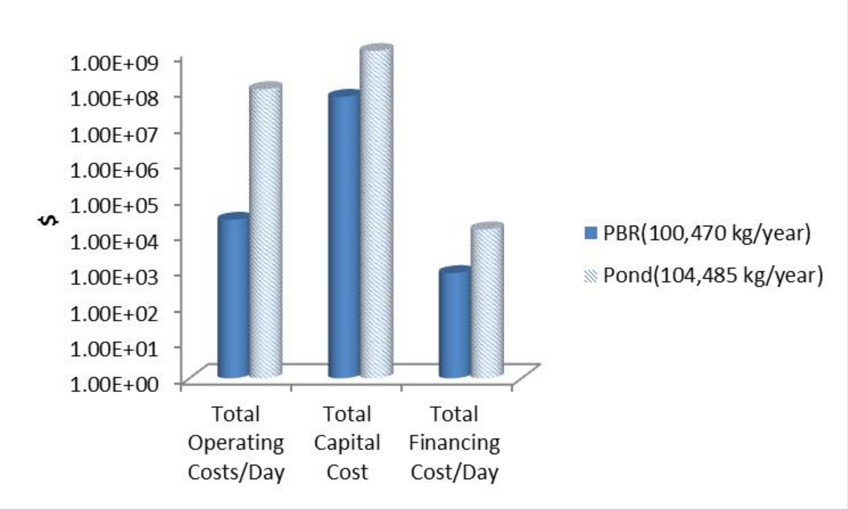


Biomass growth supported and biodiesel produced by flue gas components.

Nitrogen will be the limiting factor when no wastewater is available as an additional nitrogen source.

RESULTS
COST COMPARISON

- Each of the individual costs for open pond scenario surpasses daily profits without even considering their summation, except for replacing water not including what is lost to evaporation and using supercritical CO_2 as a solvent.
- The only PBR operating cost which surpasses daily profits on its own is the use of organic solvents.
- Capital costs for open pond growth scenario are 19.23X that of a PBR growth scenario.



Despite higher costs per acre, the PBR growth scenarios are more cost effective than open pond growth scenario.

RESULTS
END PRODUCTS

Variable	Artificially lit PBR	Solar lit PBR	Raceway ponds
Profit per day	$8,613.37	$8,698.77	$8,406.42
Costs per day	$10313 (FLUOR)$11092(LED)	$18,376.50	$7,184,000.00
% of cost from financing capital	39%(FLUOR)43%(LED)	21%	8%
Acres	0.02	0.23	6,601.30
kg biomass/year per acre	5,882,352.94	434,782.61	15.15
Cost per hectare	$39,686.00	$197,766.90	$2,693.74
Cost per Liter of oil	$91.04(FLUOR)$96.89(LED)	$160.53	$64,783.05
Cost per kg of biomass	$37.64(FLUOR)$40.49(LED)	$67.07	$26,221.60
Nutrient cost per day	$1,057.00	$4,562.25	$25,618.00
Nutrient cost per kg biomass	$3.86	$16.65	$93.51
Harvesting cost per day	$65.70	$658.28	$1,872.57
Harvesting % of total costs/day	1%	3.58%	0.03%
Biodiesel barrels per day	0.95	0.96	0.93
Biodiesel barrels/acre per year	20,397.06	1,523.48	0.05
Biodiesel profit per day	$130.51	$131.23	$127.08
Animal feed profit per day	$40.31	$41.15	$39.70
CO2 credit profit per day	$11.94	$11.94	$11.94
EPA profit per day	$8,442.55	$8,514.45	$8,227.70
Net profit per day	-$1687.6(FLUOR)-$2466(LED)	-$9,677.73	-$7,175,593.58
Net profit per day w/WWTP	$7618(FLUOR)$6840(LED)	$42,460.23	-$5,977,974.08

Cost and profit comparisons for 3 different growth scenarios (all three included Evodos centrifuge, filter press, supercritical co2 and rural location).

Profits are the same for all three scenarios while costs increase from artificially illuminated PBR to solar lit PBR to open ponds.

RESULTS
CARBON EMISSIONS & ENERGY BALANCE

g of CO2 produced per year at a ~100,000 kg biomass/year facility		
VARIABLE	PBR	POND
MJ in/Mj out	1.09E+01	5.49E+01
g of co2 opex cost	6.78E+09	1.22E+13
g of co2 consumed/year	2.40E+08	2.09E+08
tons of co2 consumed/year	2.64E+02	2.30E+02
cost/ton of co2 "captured"	$14,258.50	$154,222,422.79
Total CO2 Emissions in grams	6.54E+09	1.22E+13
Barrels Biodiesel produced/year	343.1	339.9
MJ biodiesel produced/year	1.55E+06	1.51E+06
g of CO2/MJ biodiesel	4.22E+03	8.08E+06
MJ methane produced per year	4.25E+06	4.25E+06
g of CO2/MJ methane	1.54E+03	2.87E+06
g of CO2/MJ biodiesel + methane	1.13E+03	2.12E+06
g of CO2/MJ petro-diesel	8.60E+01	

Overall carbon emission results compared to petro-diesel.

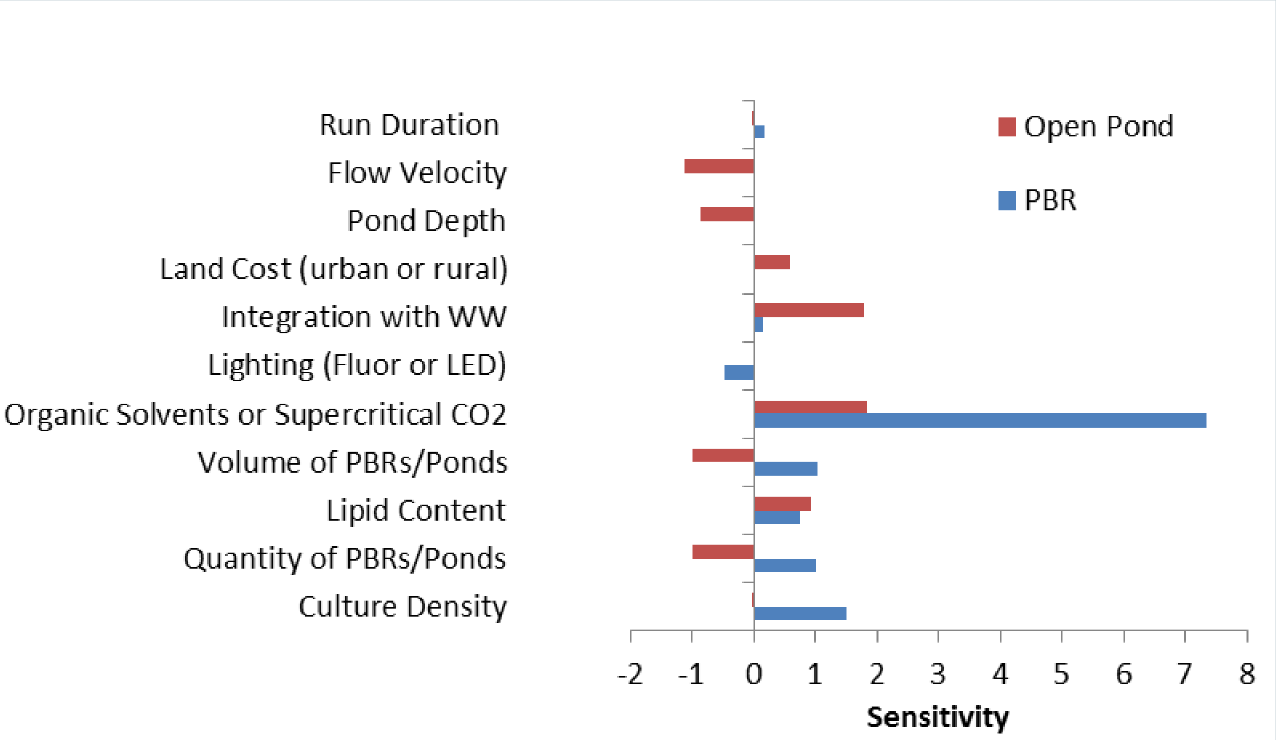
g of CO2 produced per year at a ~100,000 kg biomass/year		
VARIABLE	PBR	POND
Organic solvents	2.85E+08	2.77E+08
Supercritical CO2	6.00E+07	5.83E+07
Lysis power	1.92E+07	2.68E+09
Nutrients	2.30E+08	1.24E+09
Transesterification	3.37E+06	5.82E+07
Lighting power (FLUOR)	6.46E+04	N/A
Gas pump power	6.43E+09	1.68E+11
Water/Media pump power	2.80E+03	3.80E+09
Oven power	1.10E+08	1.10E+08
Centrifuge power	4.00E+05	3.89E+07
Paddlewheel power	N/A	1.20E+13

Comparison of operating carbon emissions.

Algal growth facilities produce at least ***13X*** more carbon emissions than petro-diesel per MJ (operating costs excluding organic solvents & nutrients).

RESULTS
SENSITIVITY ANALYSIS

- Factors which have sensitive ≥ 0.10 in one or both growth scenarios are included.



Sensitivity Analysis.

Parameters to optimize include culture density and size of facility for financial analysis.

OPTIMIZATION

SUMMARY OF RESULTS WITH FINANCIAL ANALYSIS

- Open ponds never show a net profit unless many costs are eliminated and culture density is increased to 226 g/L.
- Solar illuminated PBR's show a net profit starting at a culture density of 2.5 g/L.
- Artificially illuminated ALR's show a local optimum net profit at culture density of 48 g/L.

Growth Scenario	Max NPV ($)	Size (L)	Culture Density(g/L)	Annual IRR (%)
Solar lit PBR w/ WW	5.19E+06	3.50E+06	96-107	5.20%
Solar lit PBR w/ WW	-1.82E+07	3.50E+06	74-83	0.35%
Solar lit PBR	-2.12E+07	3.50E+06	74-83	-0.33%
Fluorescent lit ALR w/ WW	-2.43E+08	5.50E+05	45-50	-22.36%
Fluorescent lit ALR	-2.44E+08	5.50E+05	45-50	-22.88%
Fluorescent lit ALR	-1.44E+10	5.00E+07	21-25	-24.96%
LED lit ALR ($0.48/W/year) w/ WW	-2.95E+08	5.50E+05	45-50	-23.40%
LED lit ALR ($0.48/W/year)	-2.95E+08	5.50E+05	45-50	-23.40%
LED lit ALR($0.10/W/year) w/ WW	-6.34E+07	5.50E+05	45-50	-16.12%
LED lit ALR($0.10/W/year)	-6.39E+07	5.50E+05	45-50	-17.16%
Open Pond w/ WW	-1.25E+08	2.00E+04	.32-.36	-8.14%
Open Pond	-1.25E+08	2.00E+04	.32-.36	NaN
Open Pond	-3.87E+10	2.00E+04	148-165	NaN

Although no algal growth scenario is a worthwhile financial investment at this time, both solar lit and artificially lit PBR's show much more potential than open pond.

SUMMARY/FUTURE RESEARCH

- Despite increasing demand, and many potential customers, the technology is lacking.
  - Inefficient use of water, sub-optimal fluid dynamics resulting in low culture density which in turn results in very large surface area are key for open ponds.

  - Thermal control, low culture density and lighting distribution are key for solar illuminated PBR's.

  - Lighting capital cost is key for artificially illuminated ALR's.

  - Energy input to energy out ratio is deficient for all growth scenarios.

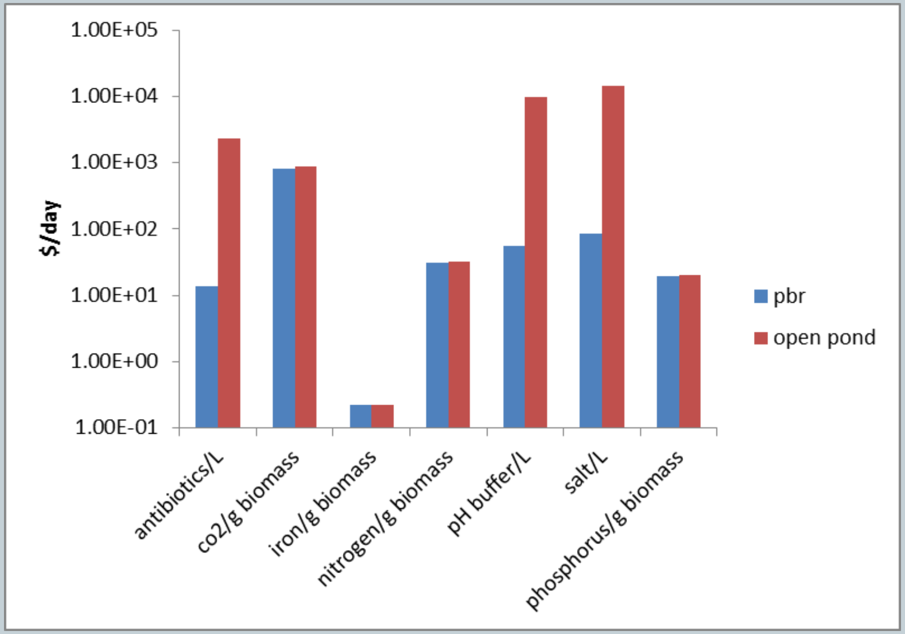
BACKUP SLIDES

NOVELTY

- *EXISTING: Analyses are field centric and limited in scope.*
- MY CONTRIBUTION: Biology, chemistry, engineering, physics and financial into one system model with interfaces.
- *EXISTING: Costs in techno-economic studies are determined by ratios related to an assumed areal productivity.*
- MY CONTRIBUTION: Algal growth rate, algal cell size, culture density, and light path length determine required surface area, pumping, harvesting, and growth parameter costs and carbon emissions.
- *EXISTING: Photosynthetic efficiencies are constants assumed for all growth scenarios with no fluid mechanics, light path length or oxygen production analysis.*
- MY CONTRIBUTION: Photosynthetic efficiency, tube diameters, and length are based on culture density, fluid analysis, light path length and oxygen generation.
- *EXISTING: End products quantities and nutrients required are determined as percentages of assumed biomass yield.*
- MY CONTRIBUTION: Products and required nutrients are based on algal stoichiometry, growth rate and algal species.
- *EXISTING: No sensitivity analyses including algal productivity nor lipid content and no optimization based on net profit nor including financial analysis.*
- MY CONTRIBUTION: Sensitivity analysis on all input parameters (x20), and optimization to improve economic sustainability.

RESULTS
NUTRIENT COSTS

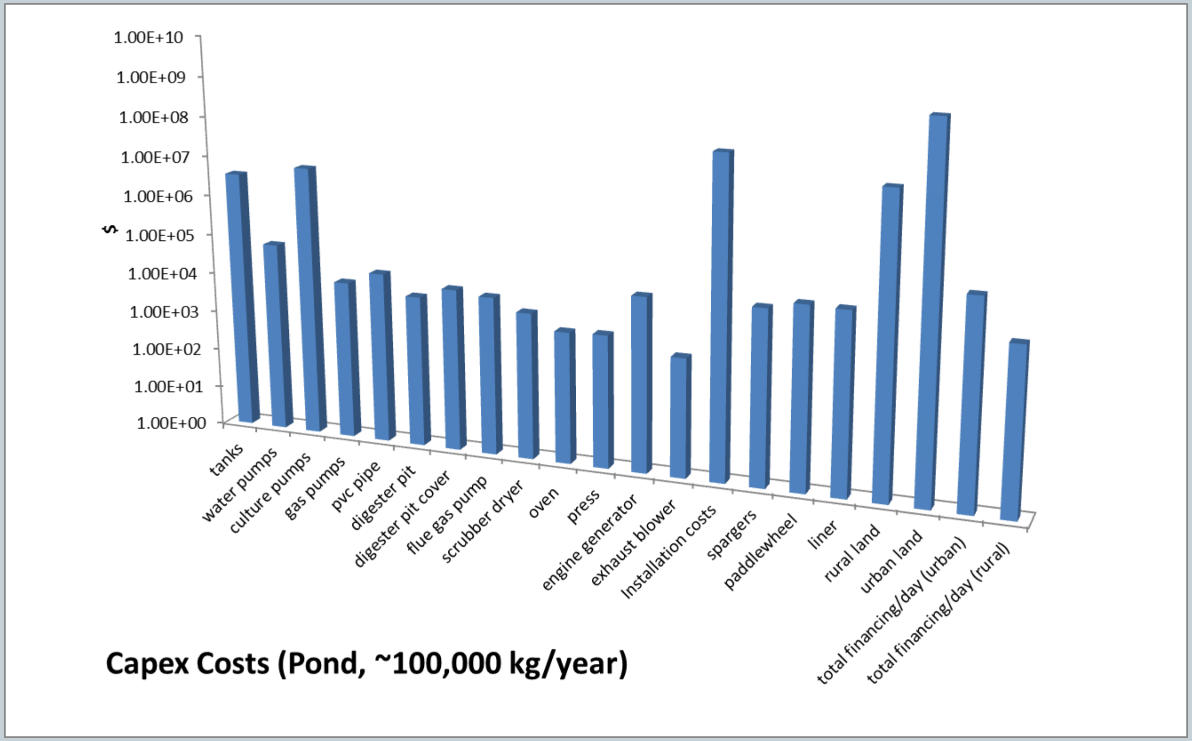
- Salt, pH buffer, & antibiotics are administered by L.
- Highest for open ponds because of low culture density.
- Assuming 80% of salt is recycled and low cost ($.005-.008/L), cost for open pond is $14,203/day.



Nutrient costs per day for PBR and open pond growth scenarios sized to produce ~100,000 kg dry biomass per year.

<u>The three most expensive nutrients for an open pond growth scenario will not be supplied by wastewater or flue gas integration.</u>

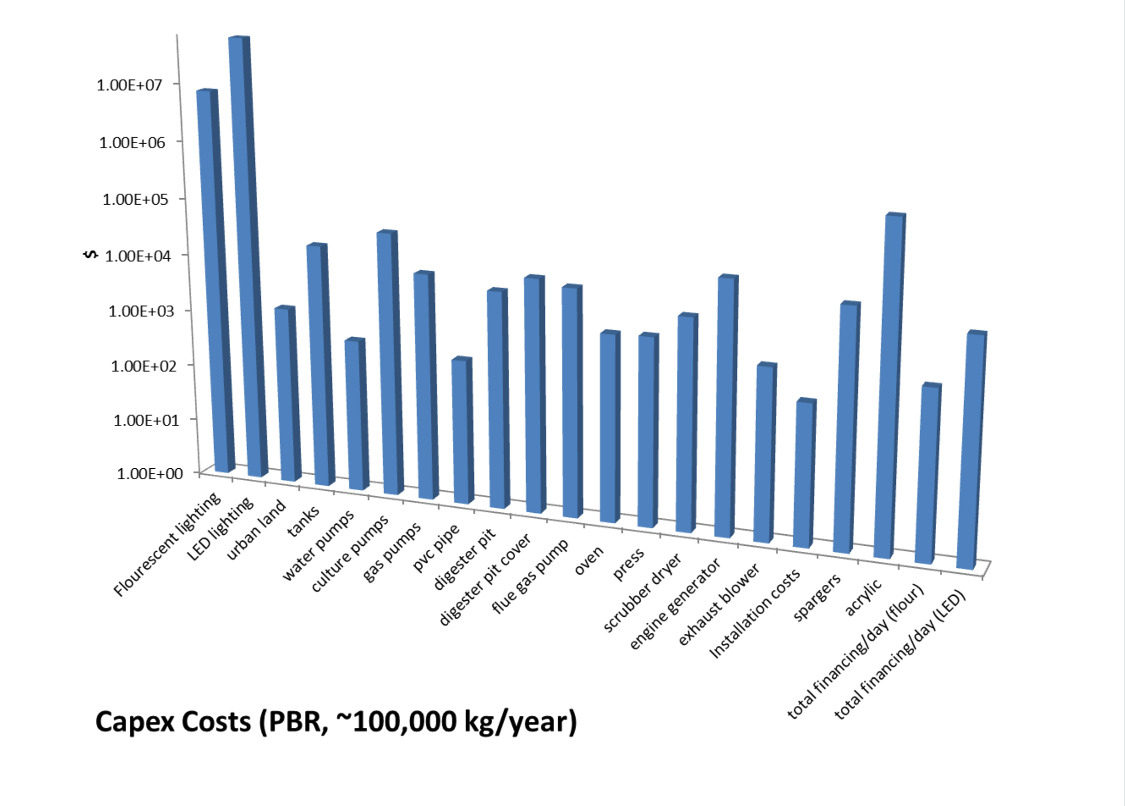
RESULTS
OPEN POND CAPITAL COSTS



Capital costs for open pond (~100,000 kg dry biomass per year).

Highest capital cost is urban land at $1.27e9, followed by installation costs at $9.40e7 and rural land at $2.84e7, financing is $150,000/day for urban scenario and $14,500/day for rural scenario.

RESULTS
PBR CAPITAL COSTS

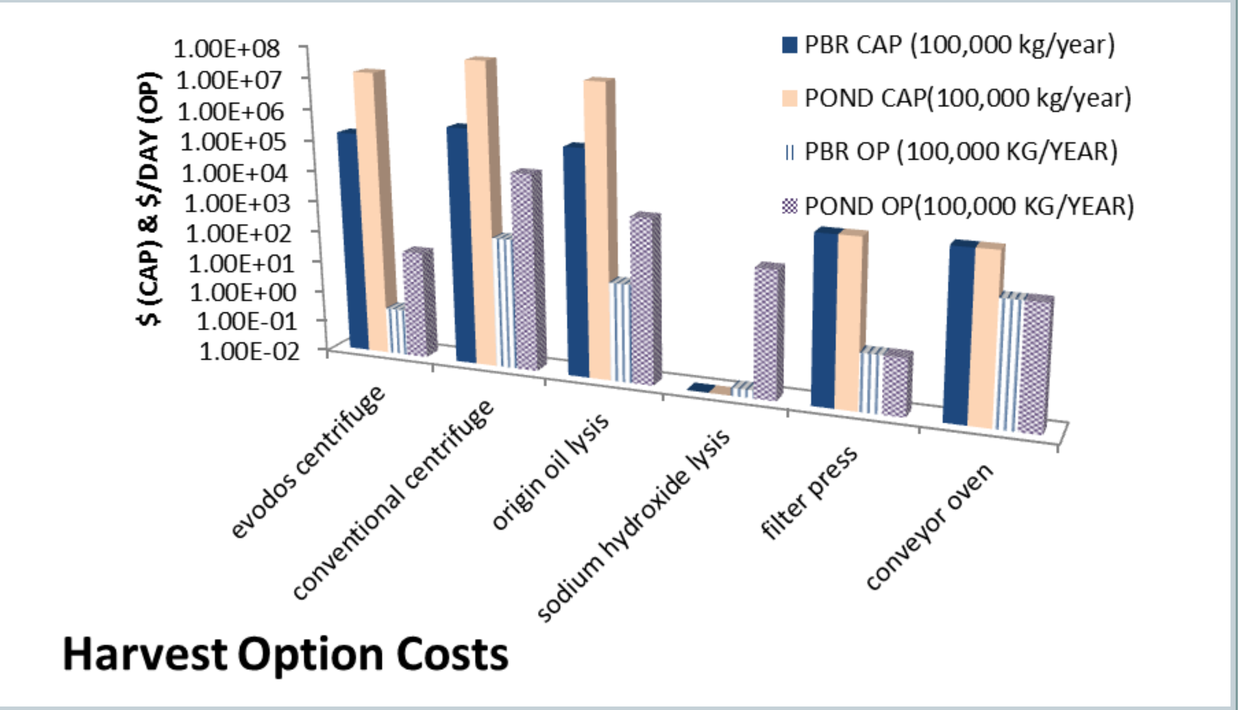


Capital costs for PBR (~100,000 kg dry biomass per year).

Highest capital cost is LED lighting at $6.51e7, followed by fluorescent lighting at $7.49e6, financing is $7150/day for LED lighting and $870/day for fluorescent lighting.

RESULTS
HARVESTING OPTIONS

- Harvest capital and operating costs contribute 1-5% toward the total cost (not including distribution pumping)

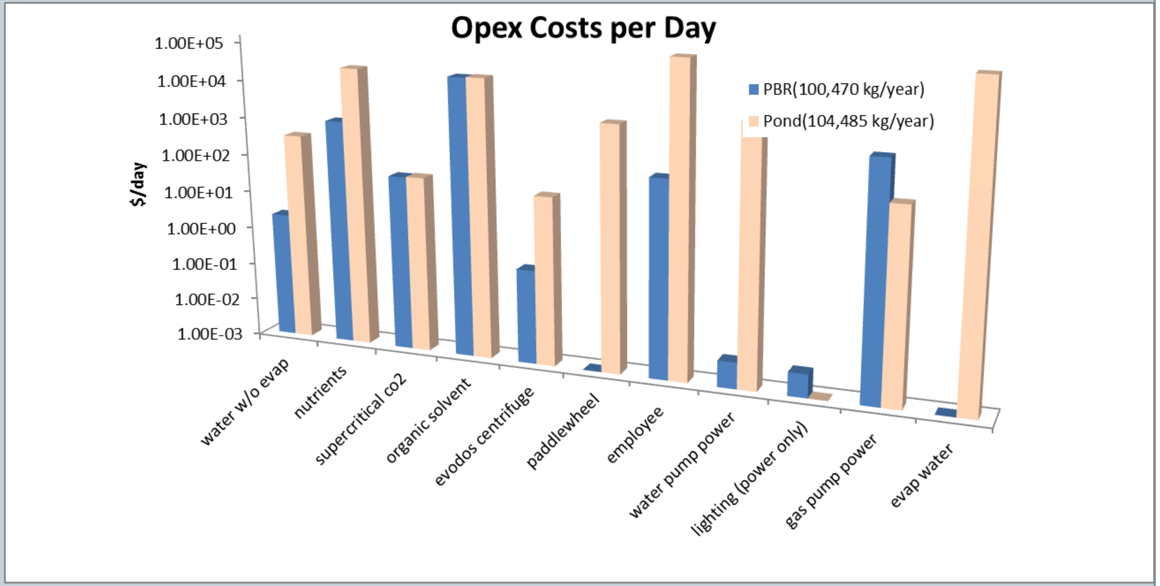


Harvesting option costs (~100,000 kg dry biomass per year).

The capital expenditure and operating expenses of PBR's can be designed to compete with and be less than open ponds from economical and energy perspectives.

RESULTS
OPERATING COSTS

- Replacing evaporated water highest cost for open ponds ($4.36e7/day).
- Cost savings using supercritical CO_2 as solvent are significant (saves ~$25,000/day).



Operating costs (~100,000 kg dry biomass per year).

Operating costs for PBR's per day are $3,400/day compared to $4.37e7/day for open ponds (not including organic solvent cost).

SUMMARY

- Results show biodiesel production from microalgal growth remain economically and environmentally unsustainable even when incorporating co-products.
- My study contains >2x more variables than any other study and interfaces not including in any other studies.
- Biodiesel produced from algae is not "green", and has carbon footprint at least 13X that of petro-diesel, even when consuming power plant flue gas.

- Fluid dynamics analysis made possible by modeling shows geometry can be optimized for higher productivity and scale-up from laboratory size.

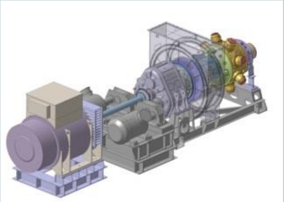
END PRODUCTS
WASTEWATER TREATMENT & METHANE

- Integration with wastewater treatment facilities shows the most potential of any of the available co-products.
- BNR incomplete - Phosphorus would be remaining in an open pond scenario.

Municipal Wastewater Nutrients/Algal Biomass Supported					
N mg/L	mg bm	P mg/L	mg bm	C mg/L	mg bm
26.4	377.1	5.3	530	159.3	312.4

Algal biomass supported by municipal wastewater nutrients.

- Methane profits are only $15/day for direct consumption or ~$100/day for electricity produced from 100,000 kg/year facility, which doesn't cover cost of financing the microturbines (~$30,000/day).



<u>Wastewater treatment shows the most potential of any of the co-products, while methane profits are on par with carbon credits.</u>

END PRODUCTS BIODIESEL

- Profit from biodiesel is only $0.40-0.50/kg dry weight biomass yield at current rate of $120-150/barrel of oil.
- The cost of transesterification is approximately $25/barrel of oil.

CROP	OIL YIELD (GALLONS/ACRE/YR)
Soybean	48
Camelina	62
Sunflower	102
Jatropha	202
Oil palm	635
Algae	1,000-6,500[b]

[a] Adapted from Chisti (2007)
[b] Estimated yields, this report

Gallons of fuel/acre/year for various crops.

Production gallons of fuel/acre/year					
Model (ALR)	*Model (Solar PBR)*	*Model (Pond)*	*Richardson, et al (2010)*	*Lux Research (2012)*	*Putt (2007)*
1080765	421.45	0.0365	834390-1663305	17549	1.78

Gallons of fuel/acre/year from model and various algal studies.

The algal facility, even at maximum productivity, cannot compete with the price for petro-diesel. The most optimistic cost of biodiesel produced from microalgae is *$10,313/barrel* ($245.55 gallon^{-1}).

END PRODUCTS

HUMAN SUPPLEMENTS, CARBON CREDITS, ANIMAL FEED

- Human supplement market will be saturated at a maximum biodiesel yield of 10,000 barrels/day.
- Carbon credits for ~100,000 kg biomass/year facility would be about $20/day.
- Animal feed profit for a ~100,000 kg biomass/year facility would be about $40/day.

Supplement	Worldwide Market/year	% of total market*	Biodiesel yield **	Acres(pond)***	Acres(PBR)***
EPA/DHA omega 3	$34,700,000,000.00	0.01	10000	3.033 billion	135.80
Beta-carotene	$285,000,000.00	.016-6.5	15.38-6250	4.6 - 188 million	.2-84.87
Astaxanthin	$255,000,000.00	3	33.3	10 million	0.45

*~100,000 kg/year algal facility

**barrels/day at supplement market saturation, 18.96 million barrels consumed in US per day

***US total land area is 2.3 billion acres

Worldwide market for human supplements vs. algae biodiesel yield and acres required.

While human supplements are the second most lucrative product after wastewater, the market is quickly saturated with minimal biodiesel production (at best 0.05% of barrels consumed in the U.S. every day).

OPTIMIZATION METHODOLOGY

- Three different constrained optimization methods were used to verify results.
  - A large-scale algorithm was used first (interior point method) - calculates the Hessian by a dense quasi-Newton approximation and by a limited-memory, large-scale quasi-Newton approximation.
  - A medium-scale algorithm (sequential quadratic programming) - uses Kuhn-Tucker equations.
  - A direct search - searches for a set of points around the current point, looking for a value lower than the value at the current point, creates mesh by adding current point to set of vectors called a pattern.
- Matlab blocks can be adaptive while data is changing and model is running but cannot dynamically add/remove nodes.

OPTIMIZATION VALIDATION

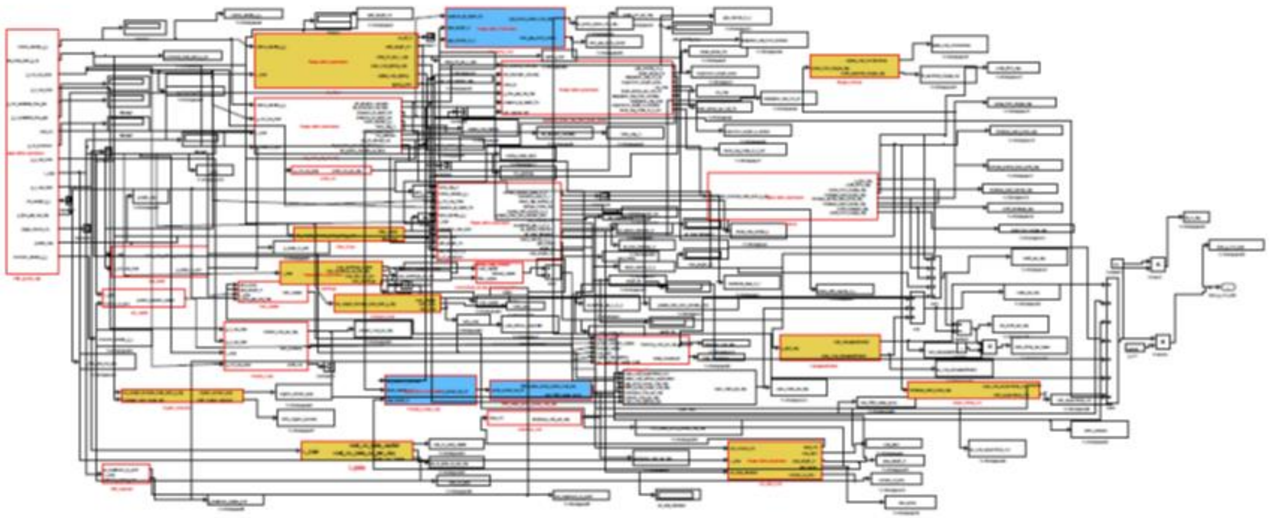
- The known results are where net profit is obtainable the optimization should run to maximum net profit, while a net loss will run the optimization to minimum net loss.

Growth Scen.	Global/Local	Run No.	Variable	X0 initial	X0 final	InitialCost	FinalCost	Minimum	Maximum
Fluorescent ALR - w/o wastewater	constraint max	1	L_total	7500	7500	203.9	-679.14	7500	7500
			inoculum_density	20000	6.50E+08			2000	6.50E+08
			lipid_content	0.75	0.75			0.75	0.75
	local	2	L_total	7500	7500	203.9	-469.64	7500	7500
			inoculum_density	20000	4.29E+08			2000	4.30E+08
			lipid_content	0.75	0.75			0.75	0.75
	constraint max	3	L_total	7500	1.00E+06	203.9	-88467	1	1.00E+06
			inoculum_density	5.00E+08	5.00E+08			2000	5.00E+08
			lipid_content	0.75	0.75			0.75	0.75
	constraint max	4	L_total	7500	7.50E+03	883.36	-488.58	7500	7.50E+03
			inoculum_density	5.00E+08	5.00E+08			5.00E+08	5.00E+08
			lipid_content	0.1	0.75			0.1	0.75
Open Pond- w/o wastewater	global	1	inoculum_density	1	5307	1.38E+11	1.36E+11	1500	Inf
			lipid_content	0.46	0.75			0.46	0.75
	global	2	inoculum_density	5000	5074.4	1.36E+11	1.36E+11	1500	Inf
			lipid_content	0.1	0.75			0.1	0.75
	global	3	inoculum_density	10000	5103.5	1.36E+11	1.36E+11	1500	Inf
			lipid_content	0.1	0.75			0.1	0.75

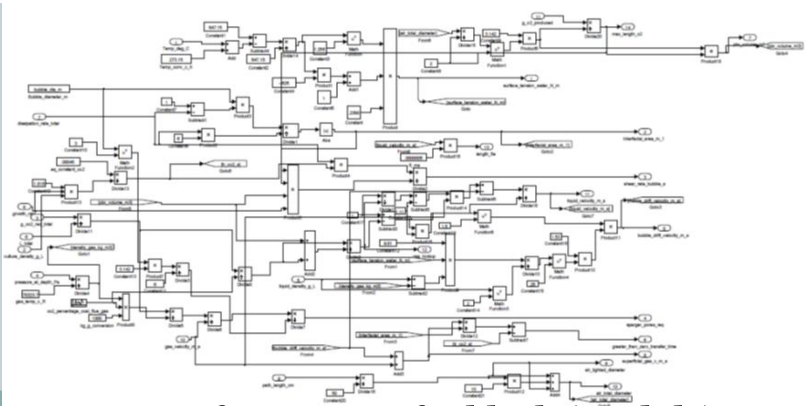
CARBON FOOTPRINT OF PETRODIESEL

- For petro-diesel 86.54% of total carbon emissions occurs at the tailpipe.
- 85.27 g of CO_2 per bhp-h = 2.4 g of CO_2 per MJ (NREL, 1998)
- Major operations within the boundary of the petroleum diesel system include:
  - Extract crude oil from the ground – equivalent included in algal fuel estimate
  - Transport crude oil to an oil refinery – not included in algal fuel estimate
  - Refine crude oil to diesel fuel – not included in algal fuel estimate
  - Transport diesel fuel to its point of use – not included in algal fuel estimate
- 10,180 g of CO_2 per gallon (epa.gov), which is 9.35 g of CO_2 per MJ excluding tailpipe emissions.
- University of Cambridge study reported 86 grams but no justification, I suspect they didn't convert bhp-h to MJ.

MODEL COMPARISON



PBR model



Contents of mass transfer block (module).

MODEL COMPARISON

Lux Analysis Flow Chart (28 variables).

FUNDING/INVESTMENT ANALYSIS

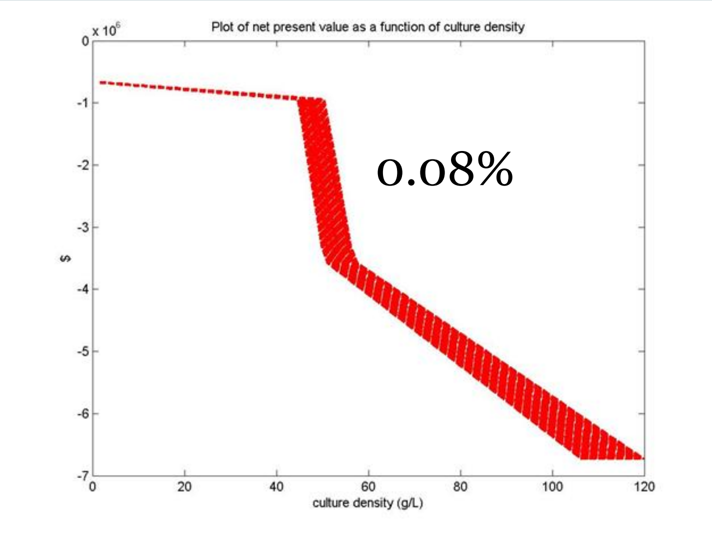
- $NPV = \sum \left[\frac{FV_t}{(1+k)^t}\right] - \Pi$
  - where FV is the future value of the cash inflows ($FV_i = PV\,(1 + k)^n$, where FV_i is the initial value of the investment.),
  - k is the discount rate equal to the firm's capital (8% APR used in model),
  - t is the time in number of years,
  - and Π represents the initial investment.
- NPV rule states if the NPV is >= 0 accept the project, if it is negative reject the project.
- IRR should be benchmark or above for an attractive investment.
- $IRR = \sum \left[\frac{FV_t}{(1+IRR)^t}\right] - \Pi$
  - where IRR is the discount rate when NPV = 0

CULTURE DENSITY

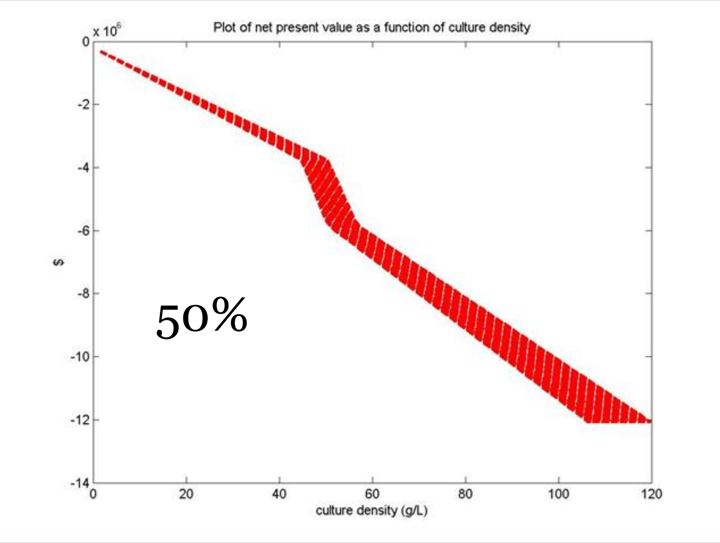
- Productivity of algae grown in photobioreactors range from a volumetric productivity of 0.64 g L^{-1} d^{-1} to 173 g L^{-1} d^{-1} .
- Higher densities of 50 – 60 dry cell mass g L^{-1} have been obtainable only with 2000-3000 µmol photons m^{-2} s^{-1}, vigorous stirring, medium replacement every 2 days at high density, and a 20-30 day growing period, which in the majority of scenarios will not be cost-effective or sustainable.

OPTIMIZATION FINANCIAL ANALYSIS

- Incorporating financial analysis causes size of facility and duration of operation to be factors (duration of 15 years unless otherwise noted).
- Changing rate of return only benefits worst case scenario for NPV, (higher interest rate represents a higher risk.)



NPV for fluorescent illuminated ALR at interest rate of 0.08% (7,500 L).



NPV for fluorescent illuminated ALR at interest rate of 50% (7,500 L).

Decreasing the market rate does decrease the gap between minimum and maximum NPV, but it remains negative and improves only for the worst case scenario.

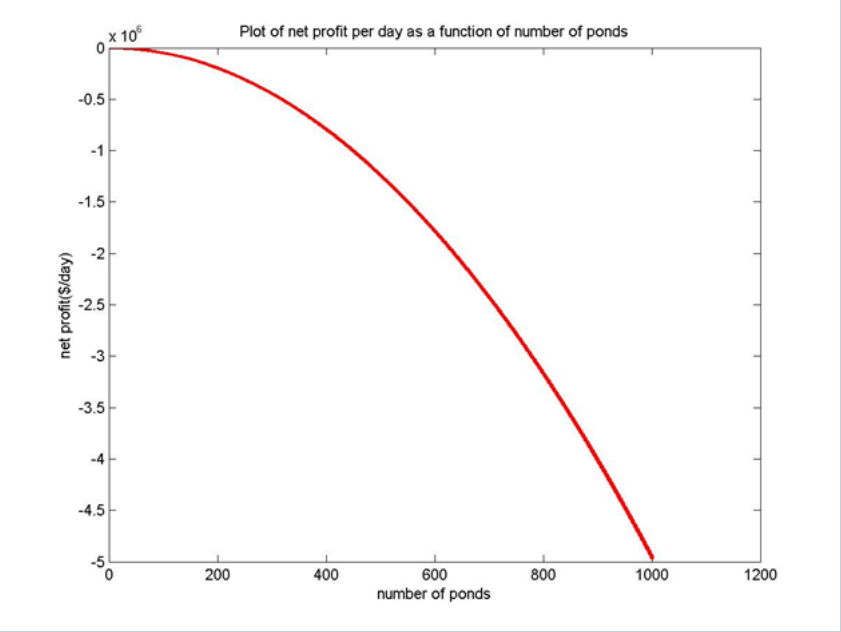
METHODOLOGY ASSUMPTIONS ON DESIGN

- Expected culture densities are assumed at:
  - 40-50 g/L for artificially illuminated ALR's (lit: .64 g L^{-1} d^{-1} to 173 g L^{-1} d^{-1})
  - 1 g/L for solar illuminated PBR's (lit: 1.08 g L^{-1} d^{-1})
  - 0.33 g/L for open ponds (lit: 0.08 g L^{-1} d^{-1} or 20 g m^{-2} d^{-1}).
- ***Algal growth rate is the same for all growth scenarios: $c = e$^$(\mu * t + \ln(c_o))$, μ is 1.12-1.15.***

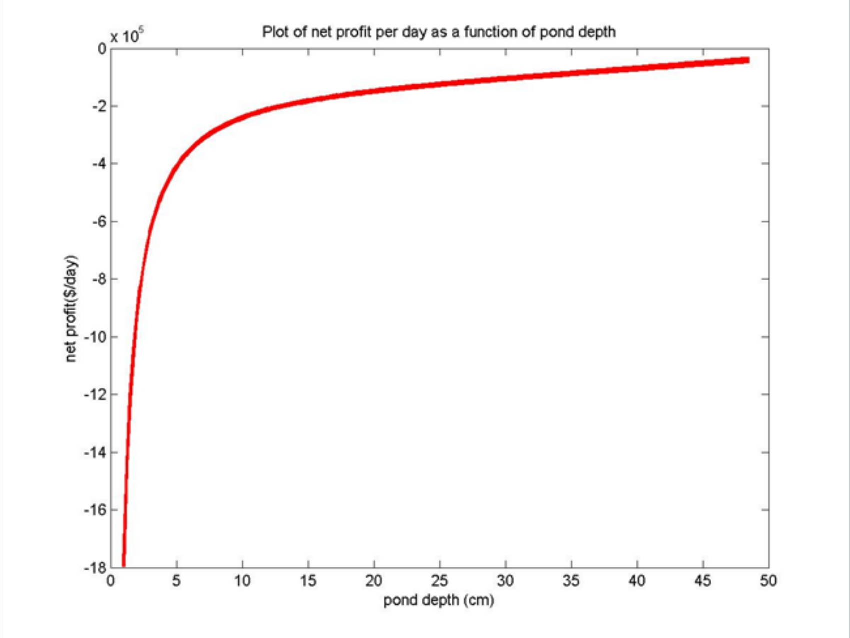
The growth rate is vital for determining productivity and resulting costs, of other studies only Lux Research uses a growth rate which is 20 g m^{-2} d^{-1}.

OPTIMIZATION
OPEN POND

- Net profit is defined as the total sale price of all the end products minus the cost of production.



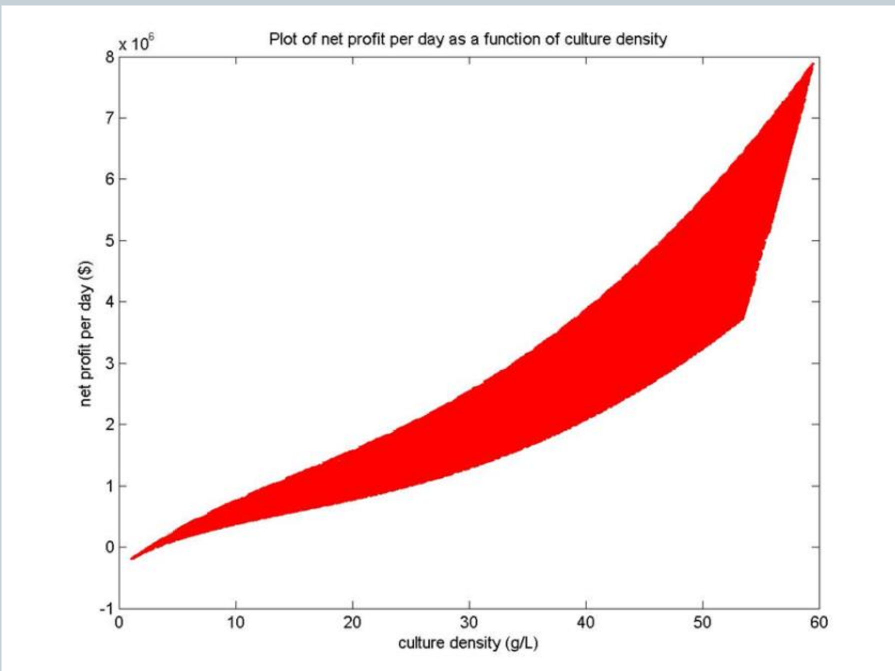
Open pond net profit as a function of number of ponds.



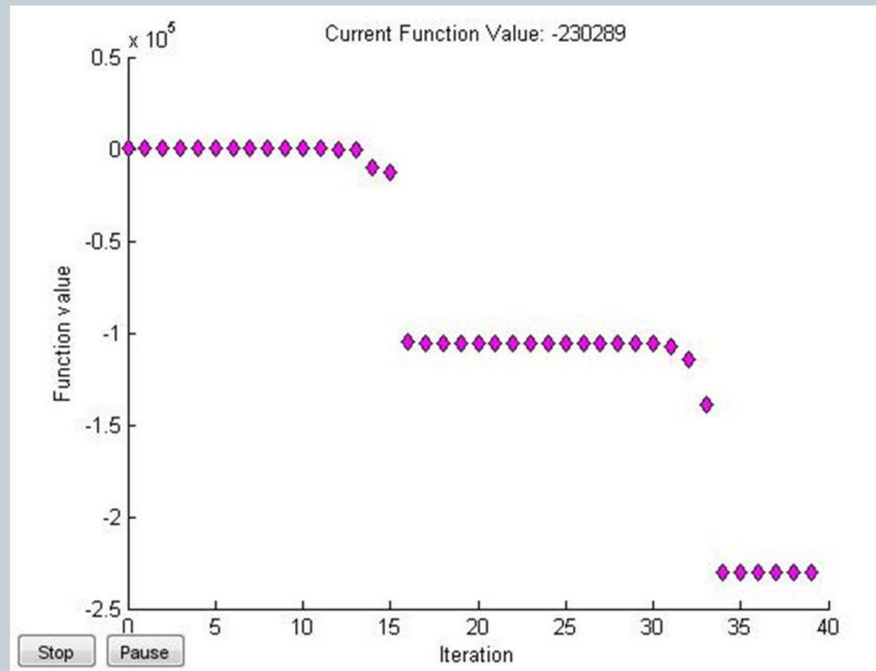
Open pond net profit as a function of pond depth.

Despite lower growth rate and productivity with increasing depth, the solution goes to the greatest depth (lowest density) possible in order to minimize surface area.

OPTIMIZATION
SOLAR ILLUMINATED PBR



Solar illuminated PBR net profit as a function of culture density w/o wastewater treatment and lipid content of 75%.

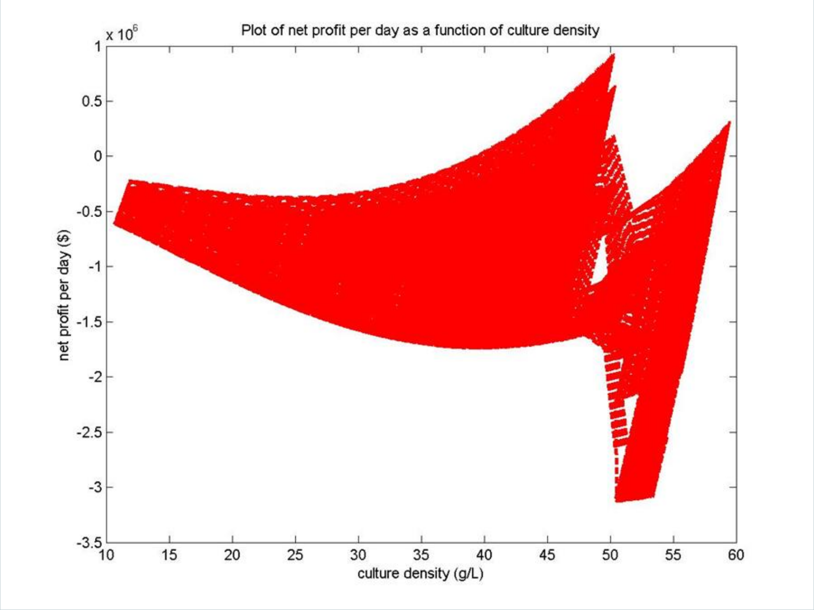


Final Cost as a function of run iterations for solar illuminated PBR optimization.

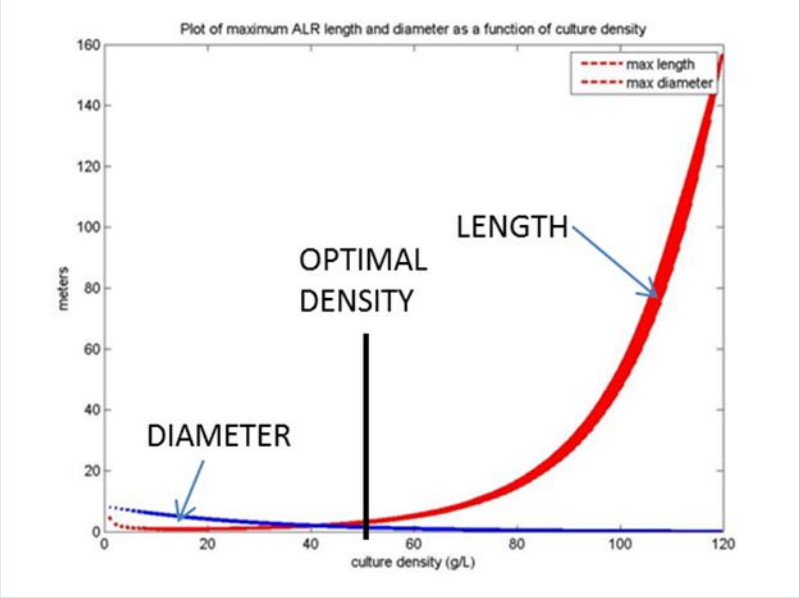
Solar illuminated PBR's show potential for net profit at unproven densities.

OPTIMIZATION
FLURORESCENT ILLUMINATED ALR

- Local optimal density is 47.91 g/L, average net profit is $249.60/day.
- Geometry is total diameter of 1.57 m and length of 2.7 m.



Fluorescent illuminated ALR net profit as a function of culture density w/o wastewater and lipid content of 75%.

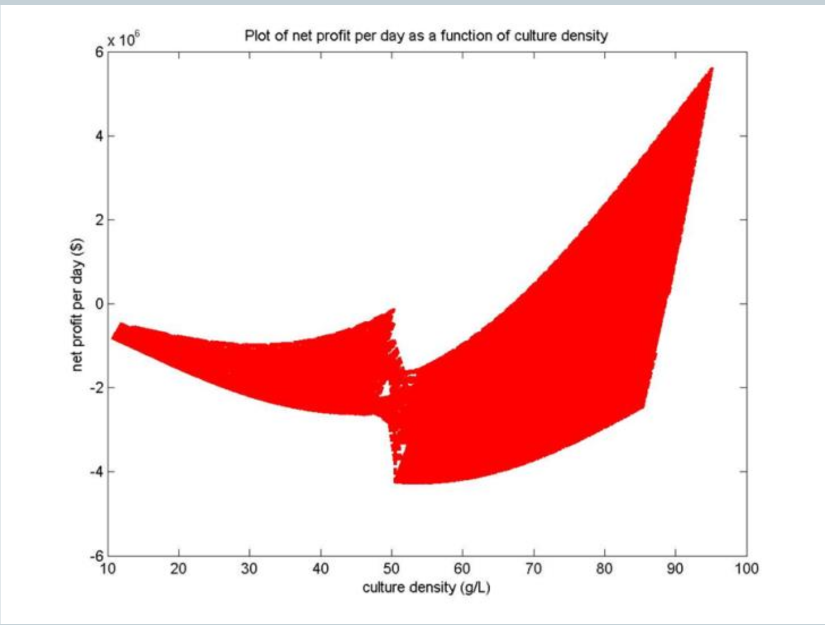


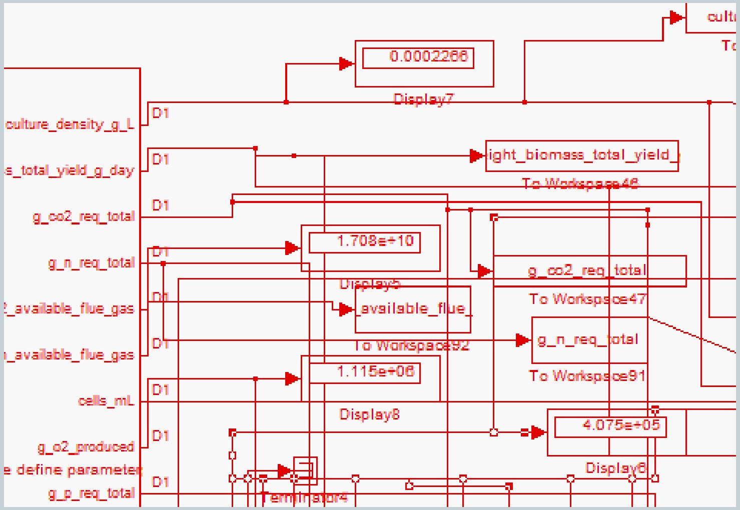
ALR length and diameter as a function of culture density.

Fluorescent illuminated ALR's show a net profit, although not as much as solar PBR's.

OPTIMIZATION
LED ILLUMINATED ALR

- LED illuminated ALR's do not show an average net profit unless capital cost per Watt of lighting is lowered from \$0.48/year to match fluorescent lighting at \$0.35/year.





LED illuminated ALR net profit as a function of culture density w/o wastewater and lipid content of 75%.

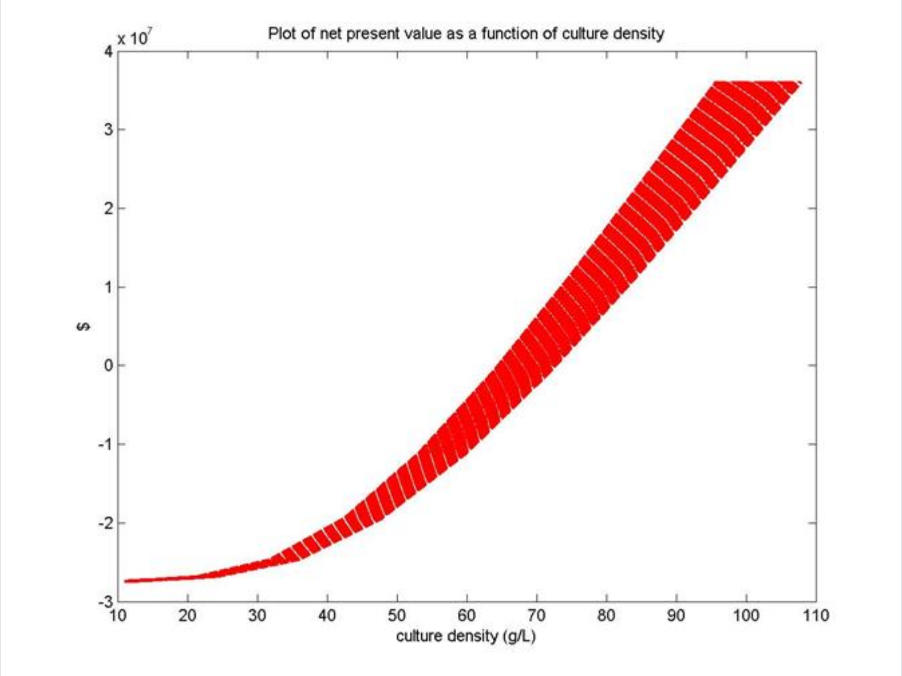
LED illuminated ALR's do not show net profit at realistic densities unless lighting capital cost matches fluorescent lighting.

OPTIMIZATION
OPEN POND WITH FINANCIAL ANALYSIS

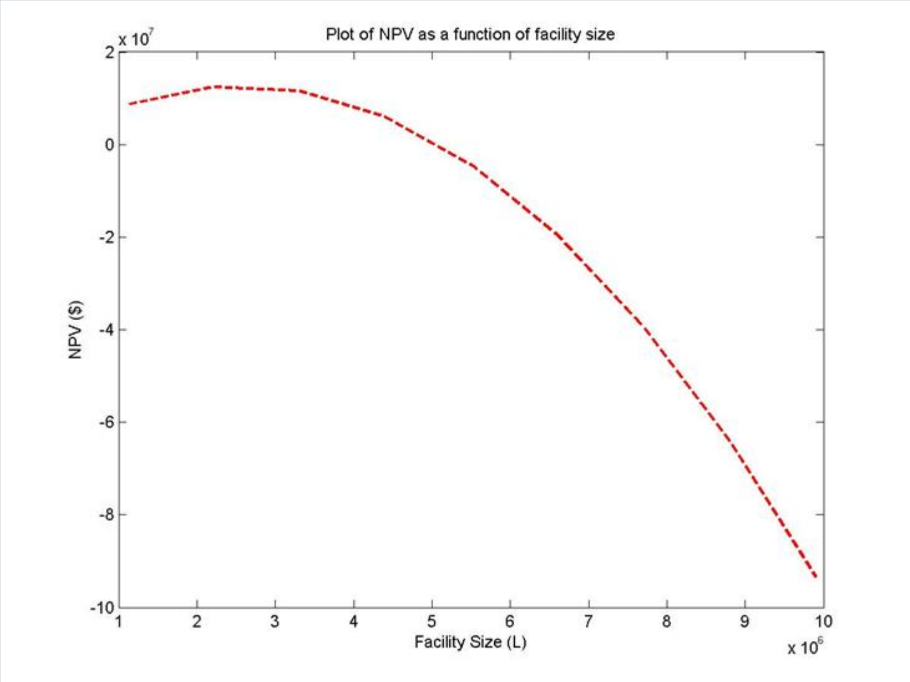
- Even when the gas and water pump energy, paddlewheel energy, employee cost, and land cost are set at 0, there still remains a net loss of some $43,000,000.00/day for a 100,000 kg biomass/year facility.
- NPV is -$1.64e8 and IRR is undefined when algal facility is one pond of 20,000 liters.
- Wastewater treatment improves results by ~$500,000 for a 100,000 kg biomass/year facility, which is significant on its own, but only makes a small dent in the immense loss.

Open pond NPV continues to worsen as pond size or culture density increase and the IRR remains undefined.

OPTIMIZATION
SOLAR ILLUMINATED PBR WITH FINANCIAL ANALYSIS



Solar illuminated NPV as a function of culture density (3,500,000 L).

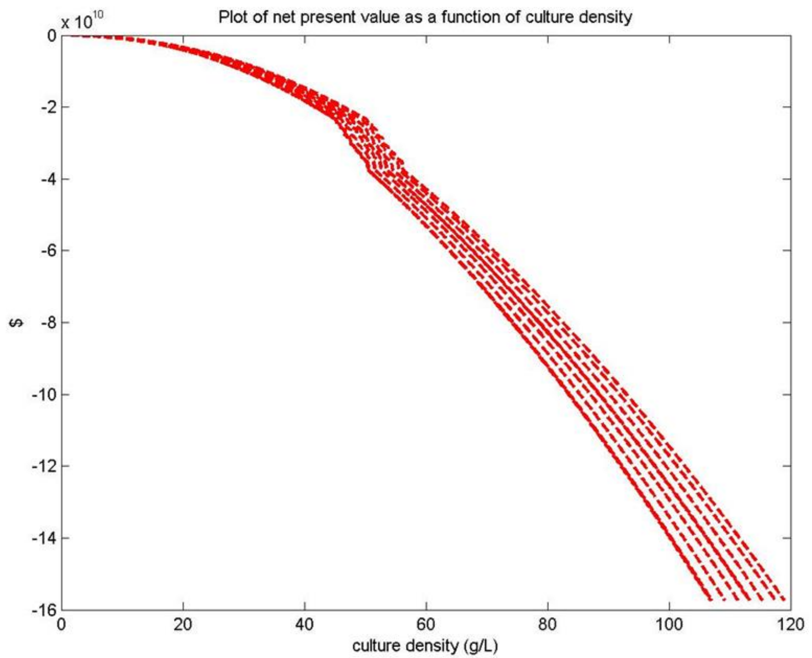


Solar illuminated PBR NPV as a function of facility size (~95 g/L)

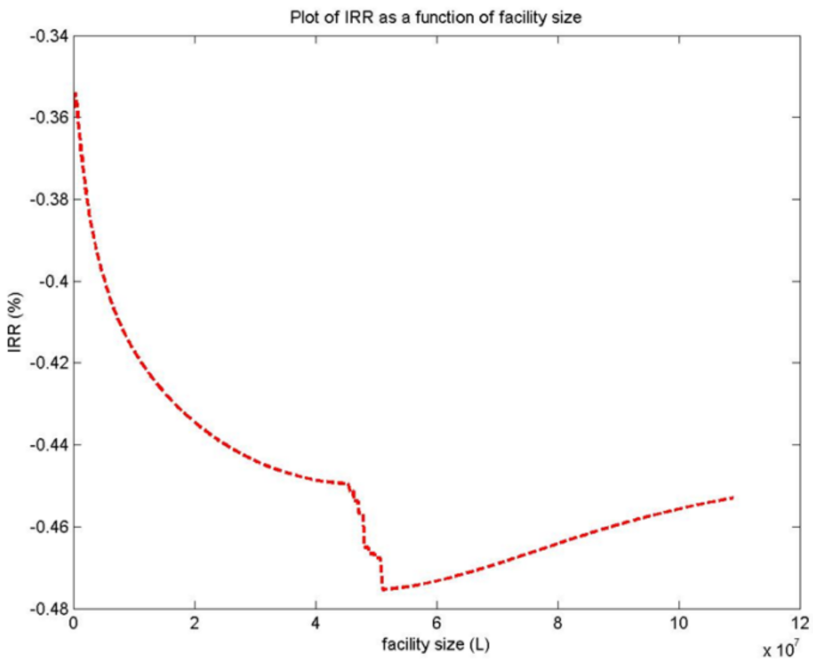
Solar illuminated PBR's show financial attractiveness only at unproven culture density of 95 g/L.

OPTIMIZATION

ARTIFICIALLY ILLUMINATED ALR WITH FINANCIAL ANALYSIS



NPV of fluorescent illuminated ALR as a function of culture density with wastewater and 75% lipid content.



Weekly IRR of fluorescent illuminated ALR as a function of facility size with wastewater & lipid content of 75%

NPV and IRR are never positive for artificially illuminated ALR due to capital cost of lighting.