Energy Balance Analysis of Biodiesel and Biogas from the Microalgae: *Haematococcus pluvialis* and *Nannochloropsis*

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What is biodiesel?

- A fuel for diesel engines derived from vegetable oils, consisting of the alkyl esters formed from fatty acids and an alcohol.
- Biodiesel offers many advantages:
  - A renewable resource
  - Up to a 20% mixture, requires no change in existing engines
  - Small changes required in the distribution infrastructure
  - Biodegradable
  - Soot is reduced
  - Frequently non-toxic
  - Better lubrication properties
  - Considerable experience in its manufacture
    - The Philippines, Indonesia, Brazil, some US states now require that diesel fuel contain biodiesel

Why is alternative feedstock needed?

- Cost
  - Biodiesel is more expensive than petrodiesel
  - 60-85% of the cost is from the feedstock
- Food versus Fuel
  - Traditional feedstocks like soy, palm, coconut and cottonseed are food.
  - Might result in an increase in edible oil prices
- Increased planting of vegetable oil crops may result in worse greenhouse effect because forest land is converted to agricultural land
- Increased NO_x emission seems to be related to the feedstock
- Global vegetable oil production ≈ 18% global transport diesel demand

Phototrophic Microalgae

- Microscopic photosynthetic plants that can live in salt or fresh water
- Have a higher photon conversion efficiency than terrestrial plants--increased biomass yields per hectare
- Can be harvested batch-wise nearly all-year-round
- Can utilize salt and waste water streams
- Can couple CO_2-neutral fuel production with CO_2 sequestration.

Phototrophic Microalgae (great technical challenges)

- Oil yield, purity and fatty acid profile are affected by: nutrient availability, light intensity, pH, salinity, presence of other microorganisms, etc.
- Consume large amounts of energy during production, harvest and processing
  - Photobioreactor or Raceway pond
  - Fertilizer
  - Water removal

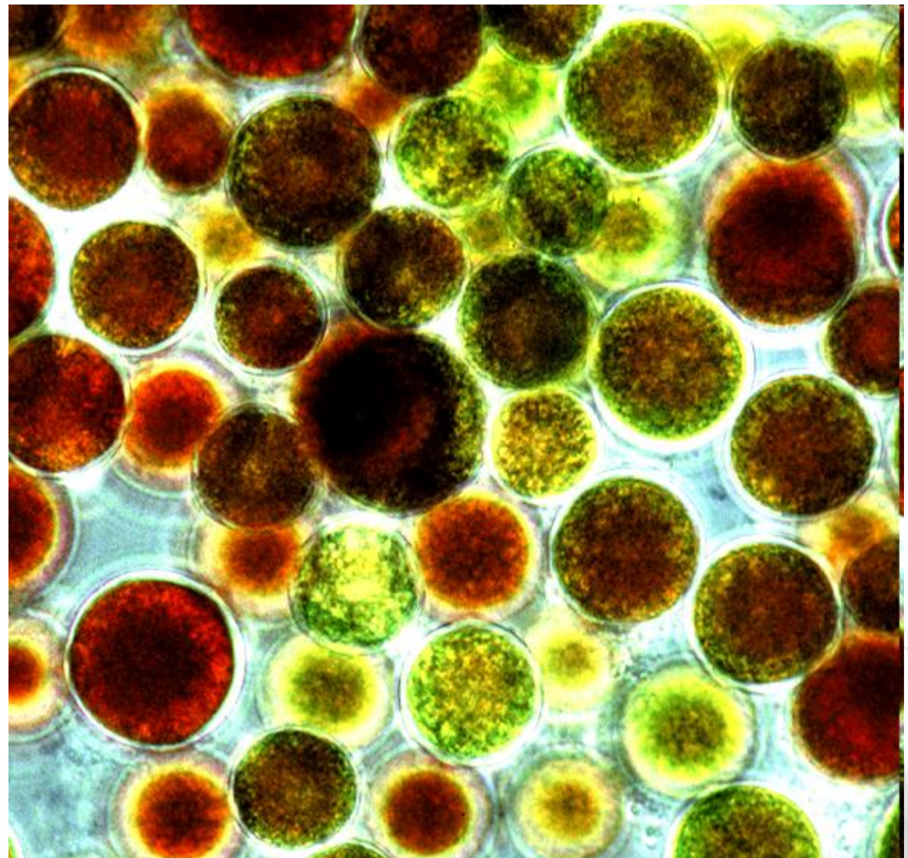
Energy Balance (Life-Cycle Assessment)

- Complete accounting for all of the energy requirements from "pond-to-pump"
  - Direct energy inputs like electricity and heat
  - Indirect energy inputs like energy to produce chemicals
- Life-cycle data from ecoinvent® database
- Functional unit: 1 kg of biodiesel = 37 MJ
  - Non-lipid components converted to biogas (by-product)
- Net Energy Ratio

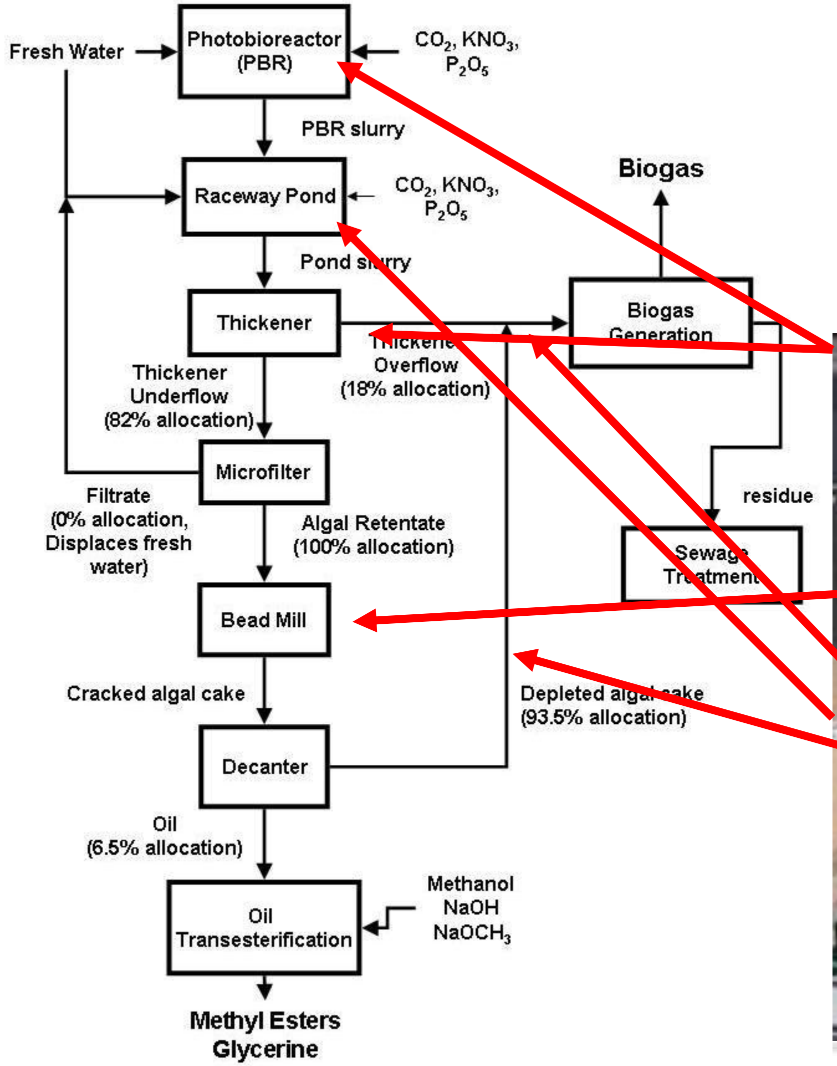
$$NER = \frac{\text{Energy Output}}{\text{Energy Input}} = 1 + \frac{\text{Net Energy}}{\text{Energy Demand}}$$

Haematococcus pluvialis

- Fresh-water, photosynthetic microalga
- Fatty acid profile that can provide a good quality biodiesel
- Commonly cultured for astaxanthin, a very high-value coloring agent
  - high-value product which could indirectly subsidize the lower-value products and vice-versa.
- Accumulation of astaxanthin is accompanied by accumulation of fatty acids and oleic acid in particular.



Haematococcus process



- Photobioreactor feeds axenic culture continuously to control alien species
- No flocculant to thickener
- No dryer
- Bead mill is necessary for release of triglycerides
- Thickener overflow and depleted algal cake is fed to biomass digester to make biogas
- Electricity and Heat is from a natural-gas CHP plant

Energy Balance Results
(1 kg biodiesel and 2.6 m³ biogas)

Process	Amount	Energy Equivalent (MJ)
Photobioreactor		
KNO_3	0.032 kg	2.9
P_2O_5	0.018 kg	0.9
Electricity		56.5
Raceway Pond		
KNO_3	0.34 kg	30
P_2O_5	0.10 kg	4.7
Electricity		26.6
Microfilter		
Allocation from Thickener Underflow		99.7
Electricity		2.2
Credit for "fresh" water		-6.0
Bead Mill		
Electricity		70.1
Transesterification		
Allocation for Oil		5.7
Methanol	0.21 kg	14.9
NaOH	0.002 kg	0.2
$NaOCH_3$	0.01 kg	1.3
Electricity		0.1
Heat		2.8
Credit for Glycerin		-20.9
Total for Methyl Esters		**43**

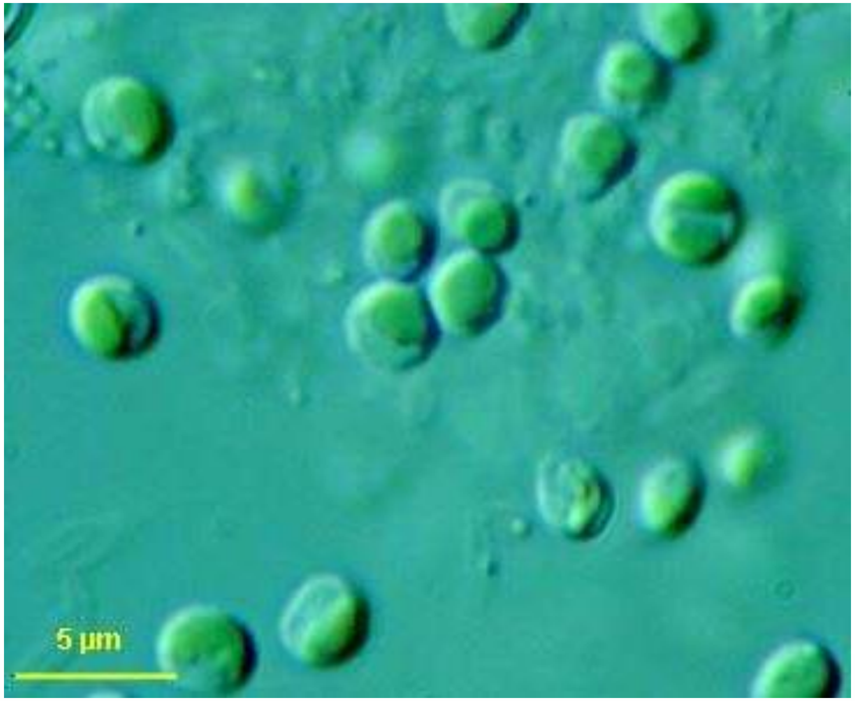
Biogas Generation		
Allocation for Depleted Algal Cake		182.6
Allocation for Thickener Overflow		22.4
Electricity		3.3
Treatment (Sewage)		32.7
Credit for Ammonium Compounds		-1.0
Total for Biogas		**218**

- Net Energy Ratio (NER) > 1 for biodiesel, NER << 1 for biogas
- Total NER = 0.4
- Largest contributors are the electricity for the bead mill and the photobioreactor; fertilizer

Process Alternatives

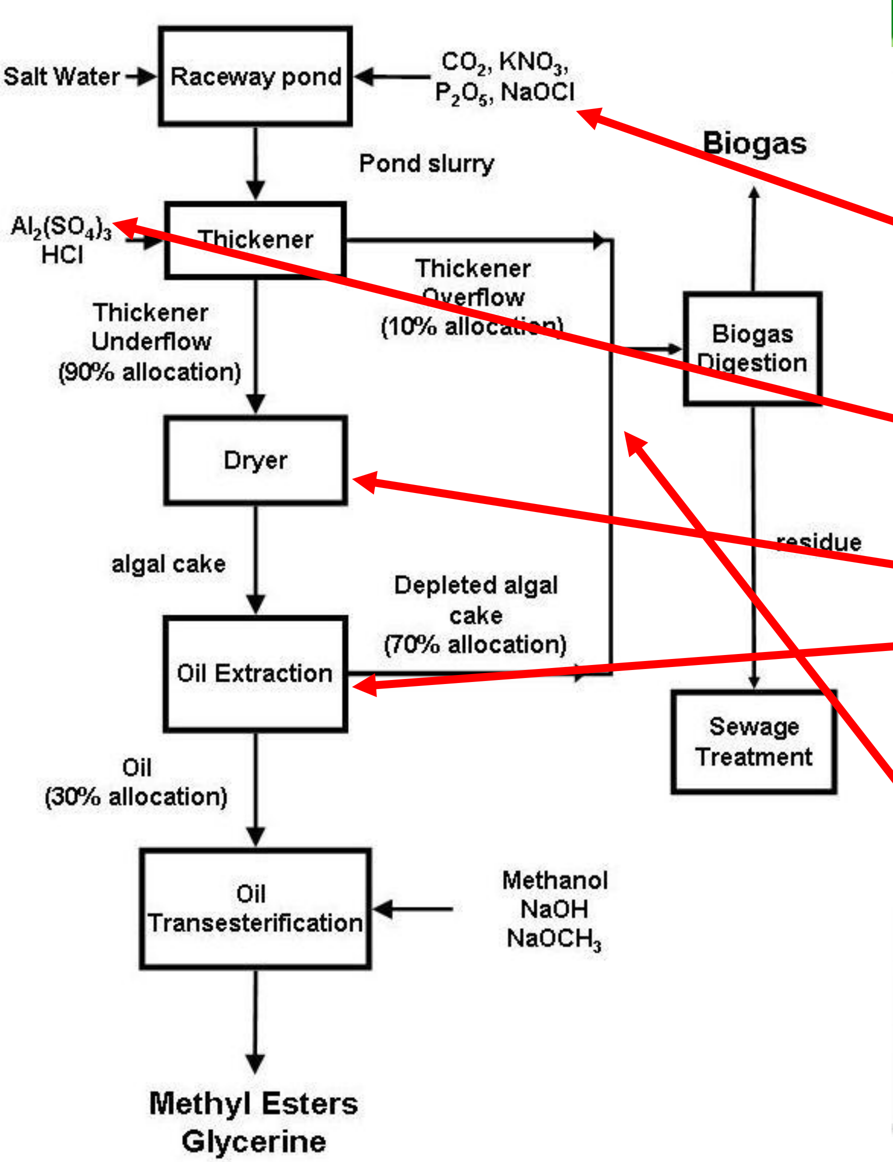
- Use of primary treated wastewater
  - Removes fertilizer use
  - NER = 0.48
- Recycling thickener overflow to pond
  - eliminates the PBR and fertilizer for it
  - NER = 0.47
- Increase biomass yield to 625 g/m^3 and oil content to 35%
  - NER = 0.50

Nannochloropsis



- Grows in salt water
  - No need for fresh water
  - Requires special equipment
- High oil content
- High biomass productivity
- High amounts of unsaturated fatty acids
  - May require further processing to make the biodiesel comply with standards

Nannochloropsis process



- Foreign species are controlled by chlorination
- *Nannochloropsis* is small; needs aluminum sulfate
- Dryer is used followed by traditional oil extraction
- Thickener overflow and depleted algal cake is fed to biomass digester to make biogas

Energy Balance Results
(1 kg biodiesel and 1.5 m³ biogas)

Process	Amount	Energy Equivalent (MJ)
Raceway Pond		
KNO_3	0.17 kg	15.5
P_2O_5	0.10 kg	4.8
NaOCl	0.23 kg	4.1
Electricity		15.1
Thickener		
$Al_2(SO_4)_3$	3.9 kg	35.6
HCl (15%)	0.9 g	(nil)
Algal Biomass Dryer		
Allocation from Thickener Underflow		90.9
Heat from CHP plant		319.0
Oil Extraction		
Hexane	0.003 kg	0.2
Electricity		20.3
Transesterification		
Allocation for Oil		122.8
Methanol	0.21 kg	14.9
NaOH	0.002 kg	0.2
$NaOCH_3$	0.01 kg	1.3
Electricity		0.1
Heat		2.8
Credit for Glycerin		-20.9
Total for Methyl Esters		**142**

Biogas Generation		
Allocation from thickener overflow		10.1
Allocation for depleted algal cake		335.6
Electricity		1.9
Treatment (Sewage)	27.7 m^3	190.3
Credit for Ammonium Compounds		-11.1
Total for Biogas		**527**

- Net Energy Ratio (NER) << 1 for biodiesel, NER << 1 for biogas
- Total NER = 0.09
- Largest contributors are the heat for the dryer; sewage treatment

Process Alternatives

- Use of Nannochloropsis strains with higher productivity and oil content
  - F&M-M26
    - 25 $g/m^2/day$, 29.6% oil
    - NER = 0.13
  - F&M-M28
    - 20.4 $g/m^2/day$, 35.7% oil
    - NER = 0.12
- Recycle the thickener overflow to the pond
  - NER = 0.12

Conclusions and Recommendations

- NER for the 2 systems studied are << 1
  - Not feasible as purely energy systems; palm oil NER = 3.5; jatropha NER = 6-7.5
  - Consistent with other studies (Sander & Murthy; Lardon et al.)
  - Biomass yields assumed for *H. pluvialis* was already 62% of thermodynamic limit
  - Can still be used for other purposes:
    - Astaxanthin is the main product. Biodiesel and biogas are just by-products
    - GHG sequestration
- Harvest and post-harvest processes are large contributors to energy requirements
  - "Wet" extraction must be developed

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