# Energy balance of algal biogas production

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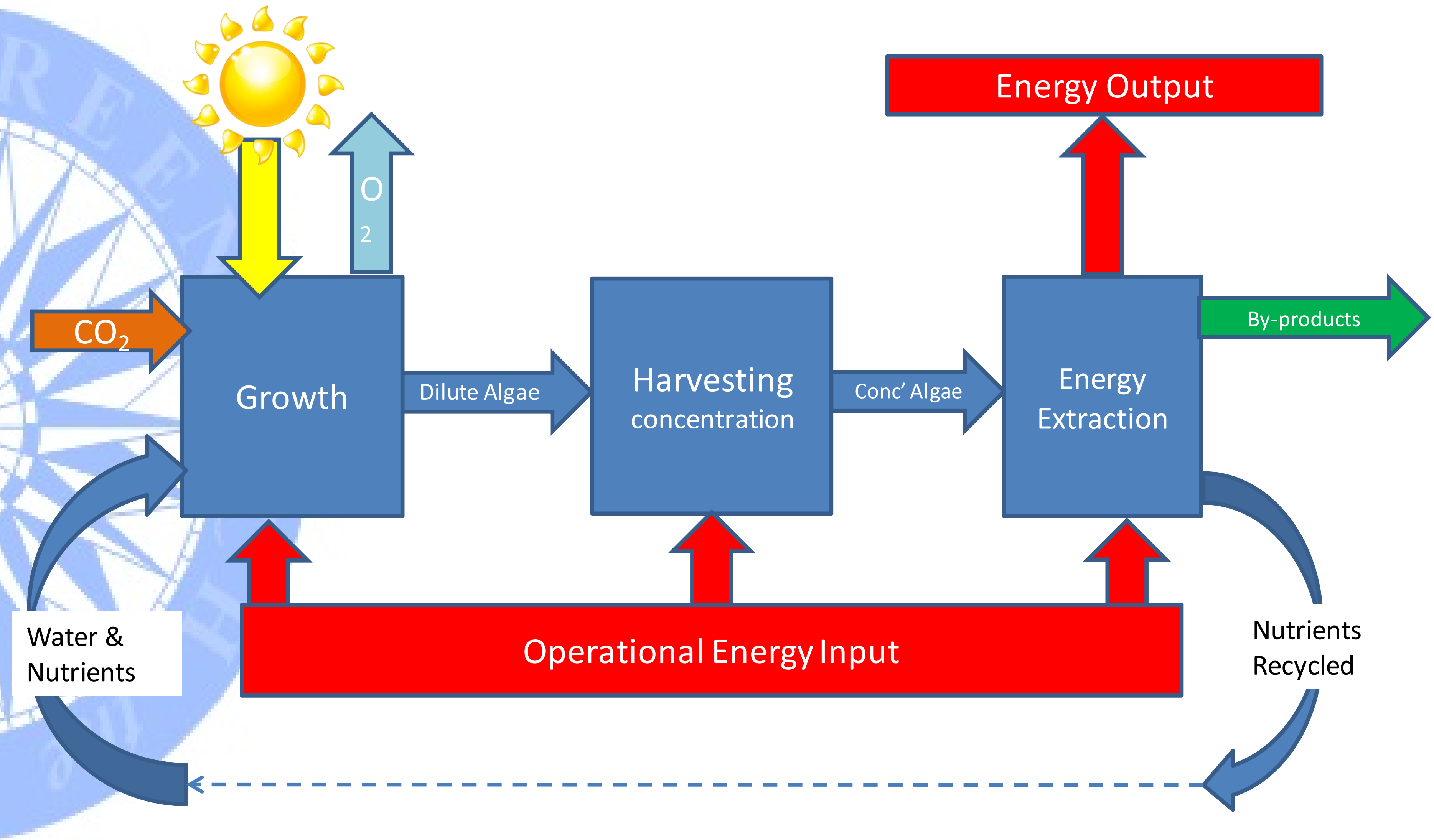
# Algal Biofuel Process



# Algal Biodiesel

- The high lipid content of some microalgae has led much of the published research work to be focused on the production of biodiesel from microalgal lipids via trans-esterification

•From 1978 to 1996, the US Department of Energy's Office of Fuels Development funded a program to develop renewable transportation fuels from algae.

•The total cost of the Program was $25.05 million

•The overall conclusion of these studies was that in principle and practice large-scale microalgae production is not limited by design, engineering, or net energy considerations and could be economically competitive with other renewable energy sources

NREL, 1998. A Look Back at the U.S. Department of Energy's Aquatic Species Program—Biodiesel from Algae.
http://www.nrel.gov/docs/legosti/fy98/24190.pdf

# Algal biofuel is not currently viable

- Nearly 70 years of sometimes intensive research on microalgae fuels and over two billion dollars of private investment since 2000 (Service, 2011) have not produced economically viable commercial-scale quantities of algal fuel, and this suggests there are major technical and engineering difficulties to be resolved before economic algal biofuel production can be achieved

SERVICE, R. F. 2011. Algae's Second Try. Science, 333, 1238-39.

# Energy return on energy investment (EROEI or EROI)

- The ratio of the energy produced compared to the amount of energy invested in its production
- A ratio of less than one indicates that more energy is used than produced
- EROI can be a useful indicator of biofuel economics
- Energy balances can be used as a starting point for GHG emission analysis

# ~50% of the published LCAs have a net energy ratio less than 1

Positive economic/energy studies required

- High value co-products
- Biogas production by anaerobic digestion
- Use of technology unproven at commercial scale such wet biomass trans-esterification

An EROI of 3 has been suggested as the minimum that is viable to 'support continued economic activity'[1,2]

1. CLARENS, A. F., NASSAU, H., RESURRECCION, E. P., WHITE, M. A. & COLOSI, L. M. 2011. Environmental Impacts of Algae-Derived Biodiesel and Bioelectricity for Transportation. Environmental Science & Technology, 45 (17), 7554–7560 .
2. HALL, C., BALOGH, S. & MURPHY, D. 2009. What is the Minimum EROI that a Sustainable Society Must Have? Energies, 2, 25-47.

## Growth

- Open
- Closed

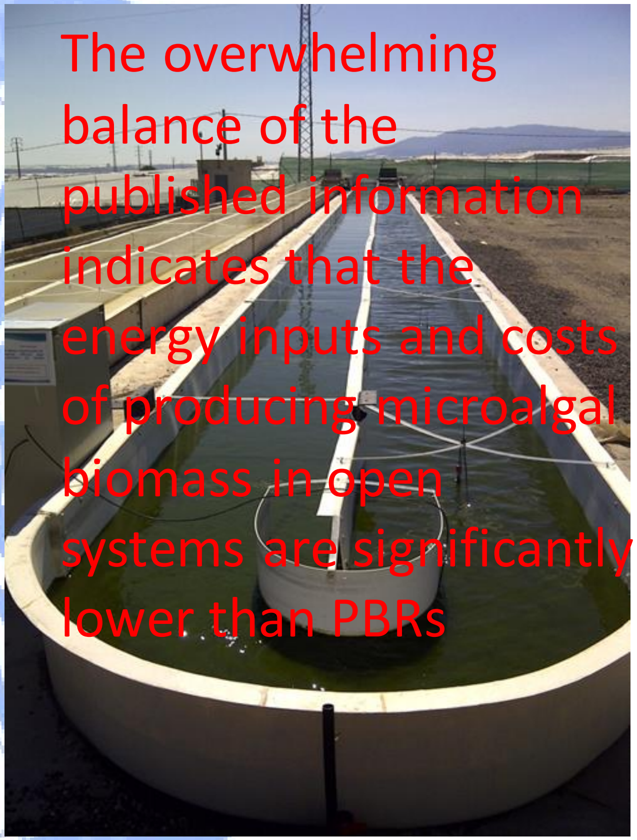
## Harvesting

- Centrifugation
- Sedimentation
- Flocculation
- **Flotation**
- **Filtration**
- **Other**

## Energy

- Anaerobic Digestion
- Trans-esterification
- Direct Combustion
- Fermentation
- Pyrolysis & Thermal Conversions
- Bio-hydrogen
- Fuel Cells

# Could microalgal biogas produce net energy ?



The overwhelming balance of the published information indicates that the energy inputs and costs of producing microalgal biomass in open systems are significantly lower than PBRs

Completely Stirred Tank Reactor (CSTR) digesters are widely used to for treating liquid wastes with up to 10 % solids

There are many shapes of digester, but a vertical cylindrical tank design is the most common in the UK and USA

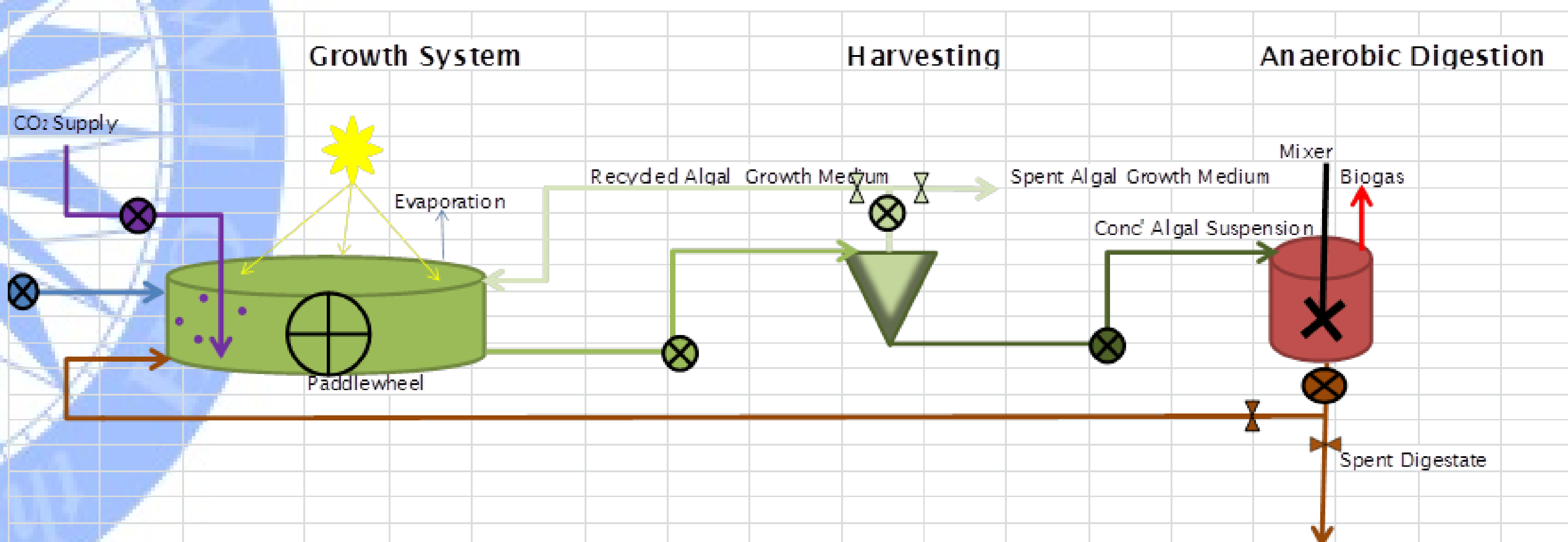
# Flow-sheet simulation software

| Software | Dynamic |
|---|---|
| Superpro | No |
| UNISIM | Yes |
| Aspen Plus | Yes |

1. Many unit operations and components are not among the defaults available and needed to be modelled
2. A considerable database of potential process stream materials exists, but many key components are not available

Initial evaluation trials found that both UniSim and Aspen Plus may be capable of producing dynamic mass and energy balances of an entire algal biofuel production process , but a very considerable amount of effort and time was needed to produce them

A mechanistic operational energy and mass balance process integration model for microalgal biogas production was developed, and implemented in a Microsoft Excel spreadsheet.



# The model was divided into 3 main operational areas: growth, harvesting and energy extraction

- The three areas were considered to be linked by a requirement for pumping power which has not been fully accounted for in many studies

- The model was comprised of nine worksheets, and was built up from fundamental equations such as those for fluid flow in pipes and literature data such as that for fresh and salt water densities and viscosities

- The calorific yield of algal biomass was calculated using the annualised solar insolation and overall photosynthetic efficiency

# The algal biomass was assumed to consist of lipids, carbohydrate, proteins and inorganic material

- The value of each could be set from 0 to 100 %, with the total of all these components always being equal to 100 %. Default values were assumed of 20 % lipids, 30 % carbohydrate, 50 % proteins and 0 % inorganic material, equivalent to an overall empirical formula of $C_1H_{1.8}O_{0.5}N_{0.1}$ typical of microalgae

- The higher heating value of the algal biomass was calculated from the typical empirical formulae for microalgal lipid, carbohydrate and protein using a version of the Du Long equation

- The potential methane and biogas yields were estimated from the typical empirical formulae for microalgal lipid, carbohydrate and protein using the Buswell equation

# The anaerobic digester section of the model was validated against an existing AD model


The AD4RD model (http://www.ad4rd.soton.ac.uk) produces energy inputs and biogas outputs for a range of terrestrial agriculture products and wastes, but not microalgae.

One feedstock in AD4RD is whey and the feedstock for comparison was assumed to be whey in both models. The microalgal biogas energy balance was simplified to consist only of the anaerobic digester.

# Conclusion from a number of model scenarios

a. Favourable climatic conditions. The production of microalgal biofuel in UK would be energetically challenging at best

b. Achievement of 'reasonable yields' equivalent to ~3 % photosynthetic efficiency (25 g $m^{-2}$ $day^{-1}$)

c. Low or no cost and embodied energy sources of $CO_2$ and nutrients from flue gas and wastewater

d. Mesophilic rather than thermophilic digestion

e. Adequate conversion of the organic carbon to biogas (≥ 60 %)

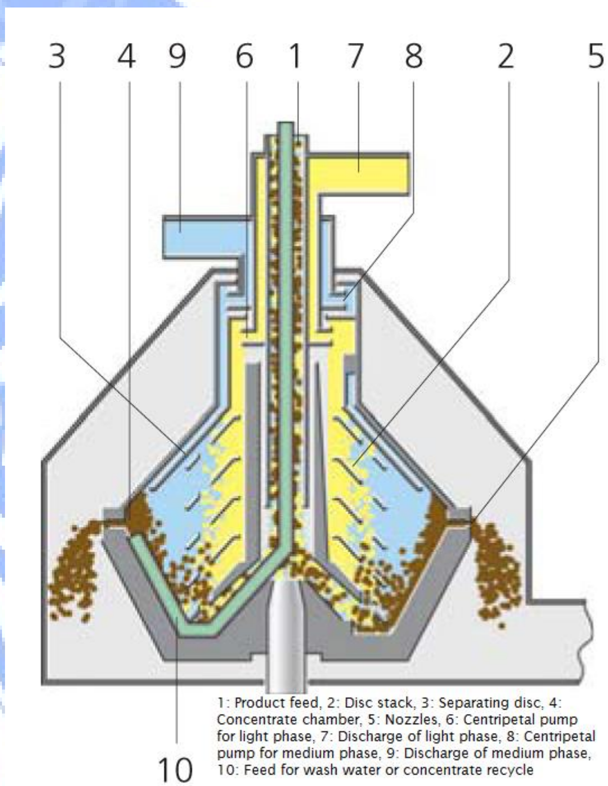
f. Minimisation of pumping of dilute microalgal suspension

# Pragmatic case assumptions

| | | |
|---|---|---|
| **Environmental** | | |
| Solar Insolation | kWh $m^{-2}$ $year^{1}$ | 2000 |
| Photosynthetic Efficiency | % | 3 |
| Yield of 20% lipid algae | g $m^{-2}$ $day^{-1}$ | 25 |
| Ambient Temperature | ° C | 20 |
| **Pond** | | |
| Pond Area | $m^2$ | 10017 |
| Pond depth | m | 0.3 |
| Pond Fluid Velocity | m $s^{-1}$ | 0.3 |
| **Gaseous Exchange** | | |
| CO2 Concentration in Supply | % | 12 |
| **Anaerobic Digestion** | | |
| % of "Buswell" estimated CH4 | % | 60 |
| Hydraulic Retention time | days | 20 |
| Reactor Temperature | Mesophilic | 35 |
| **Efficiencies** | | |
| Paddlewheel Efficiency | % | 50 |
| Gas Transfer Efficiency | % | 80 |
| Blower Efficiency | % | 80 |
| Pump Efficiency | % | 80 |
| Percentage Heat Recovery | % | 50 |
| Heater Efficiency | % | 80 |
| Mixer Efficiency | % | 80 |

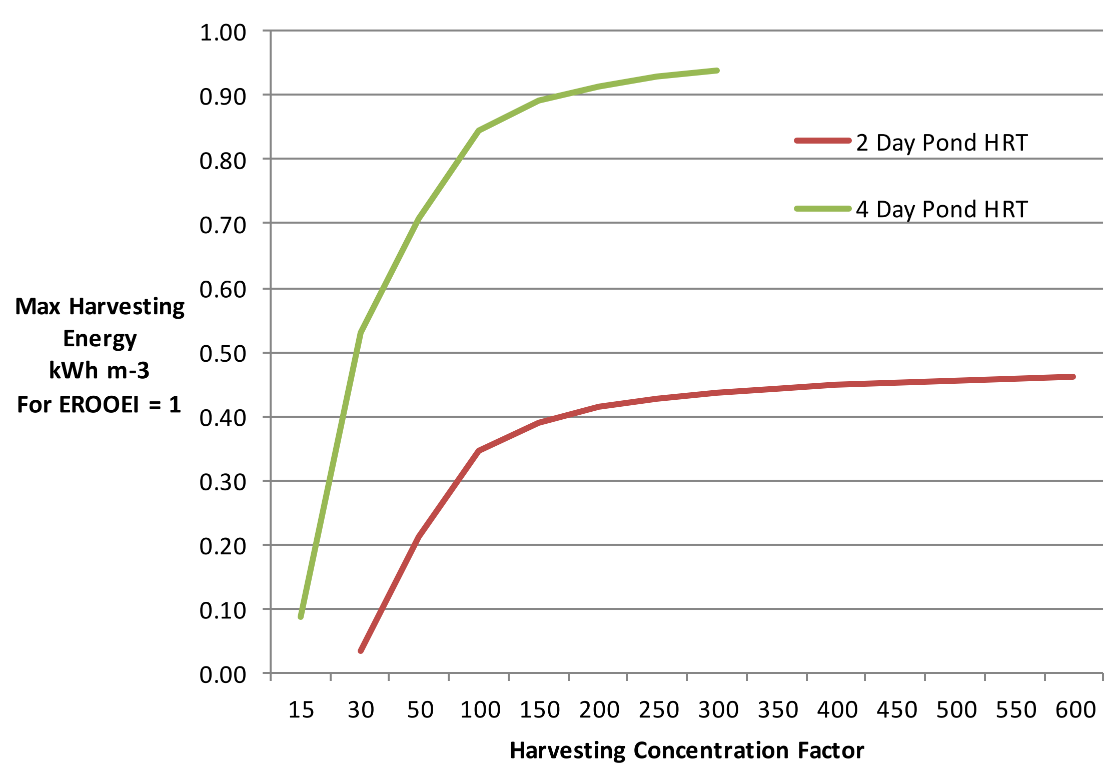
# Harvesting microalgae

**A critical issue in the development of a commercially viable process for production of microalgal biofuel**




Disc Stack Centrifuge for Liquid/Liquid/Solid Separation (Courtesy GEA Westfalia

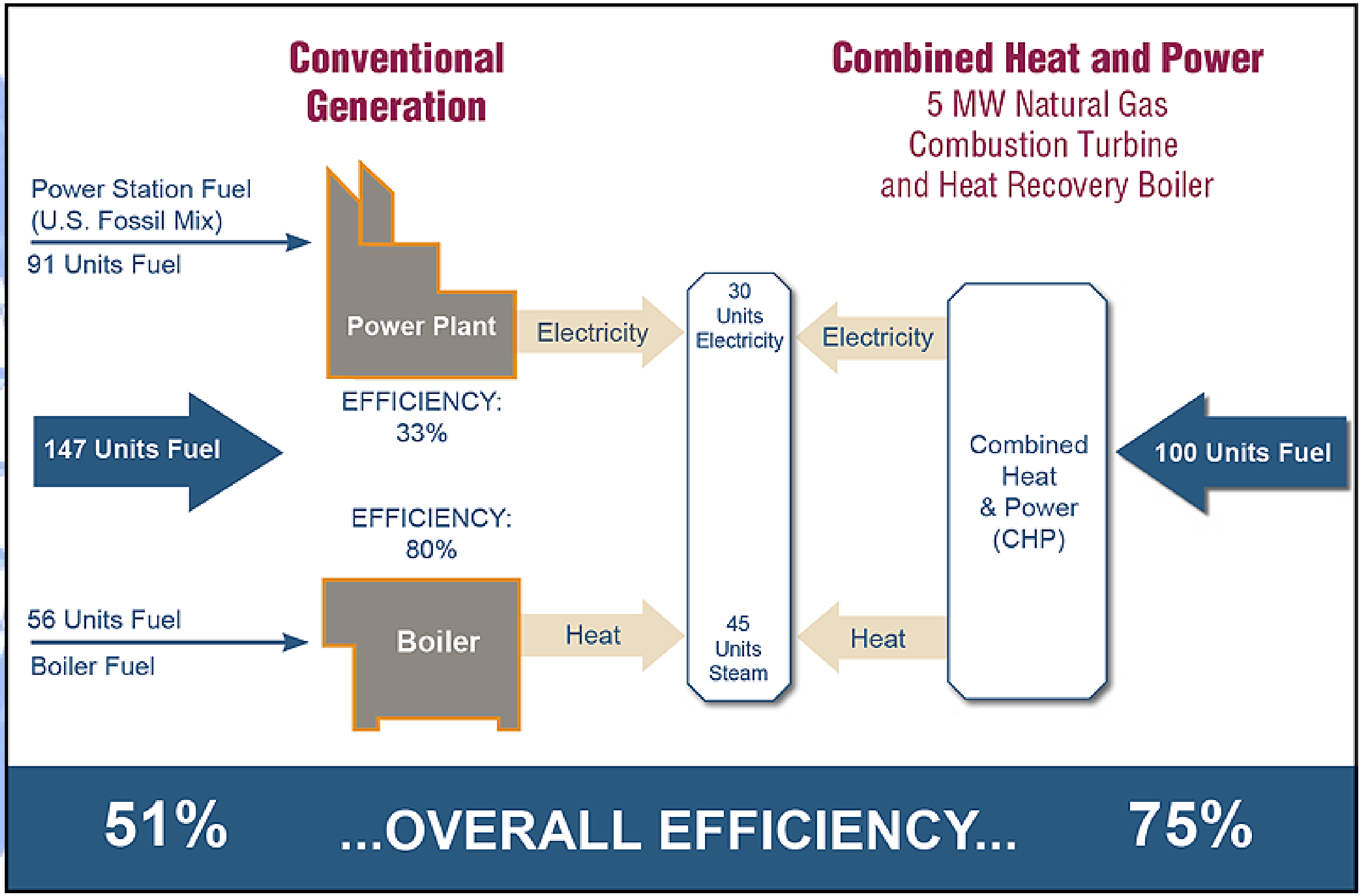
**Disc Stack Centrifuges alone used too much energy**



# Anaerobic digestion of algae could produce net energy

| | | Settlement Centrifugation | | | Flocculation Centrifugation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Harvesting | | | | | Organic 1 mg $l^{-1}$ | | Organic 10 mg $l^{-1}$ | | Alum 120 mg $l^{-1}$ | |
| Algal Harvesting Settlement | % | 60 | 60 | 60 | 70 | 90 | 70 | 90 | 70 | 90 |
| Concentration Factor Settlement | | 20 | 20 | 20 | 30 | 30 | 30 | 30 | 30 | 30 |
| Algal Harvesting Centrifugation | % | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 |
| Concentration Factor Centrifugation | | 30 | 30 | 30 | 20 | 20 | 20 | 20 | 20 | 20 |
| Harvesting Equipment Settlement | kWh $d^{-1}$ | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| Harvesting Equipment Centrifugation | kWh $d^{-1}$ | 1.4 | 1 | 0.35 | 1 | 1 | 1 | 1 | 1 | 1 |
| <u>Energy Output</u> | | | | | | | | | | |
| Calorific Value of CH4 production | kWh $d^{-1}$ | 505.20 | 505.20 | 505.20 | 589.40 | 757.80 | 589.40 | 757.80 | 589.40 | 757.80 |
| <u>Energy Input</u> | | | | | | | | | | |
| Mixing | kWh $d^{-1}$ | 43.67 | 43.67 | 43.67 | 43.67 | 43.67 | 43.67 | 43.67 | 43.67 | 43.67 |
| Total Pumping Energy | kWh $d^{-1}$ | 29.50 | 29.50 | 29.50 | 29.43 | 29.51 | 29.43 | 29.51 | 29.43 | 29.51 |
| Blower Energy for Pond | kWh $d^{-1}$ | 28.48 | 28.48 | 28.48 | 28.48 | 28.48 | 28.48 | 28.48 | 28.48 | 28.48 |
| Harvesting Energy | kWh $d^{-1}$ | 72.22 | 53.78 | 23.82 | 52.35 | 62.59 | 129.17 | 139.42 | 788.70 | 798.95 |
| AD Energy | | | | | | | | | | |
| Heating | kWh $d^{-1}$ | 20.13 | 20.13 | 20.13 | 23.19 | 29.23 | 23.19 | 29.23 | 23.19 | 29.23 |
| Mixing | kWh $d^{-1}$ | 4.15 | 4.15 | 4.15 | 4.84 | 6.22 | 4.84 | 6.22 | 4.84 | 6.22 |
| Total AD Input Energy | kWh $d^{-1}$ | 24.28 | 24.28 | 24.28 | 28.03 | 35.45 | 28.03 | 35.45 | 28.03 | 35.45 |
| Total Operational Energy Input | | 198.14 | 179.70 | 149.74 | 181.95 | 199.70 | 258.78 | 276.52 | 918.31 | 936.05 |
| Net Energy | kWh $d^{-1}$ | 307.06 | 325.50 | 355.46 | 407.45 | 558.11 | 330.63 | 481.28 | -328.91 | -178.25 |
| Energy Return on Operational Energy Invested | | 2.5 | 2.8 | 3.4 | 3.2 | 3.8 | 2.3 | 2.7 | 0.6 | 0.8 |

# CHP can be efficient, but ratio electrical to heat energy 0.67




USA Environmental Protection Agency 2013

# Algal biogas production has higher demand for electrical energy

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Settlement Centrifugation | | | Flocculation Centrifugation | | |
| Electrical Energy | kWh$^{-1}$ d$^{-1}$ | 178.0 | 159.6 | 129.6 | 150.2 | 161.9 | 150.2 | 161.9 |
| Heating | kWh$^{-1}$ d$^{-1}$ | 20.1 | 20.1 | 20.1 | 23.2 | 29.2 | 23.2 | 29.2 |
| Ratio | | 8.8 | 7.9 | 6.4 | 6.5 | 5.5 | 6.5 | 5.5 |

## What do we do with the excess heat energy?

# Related Publications


- HEAVEN, S., MILLEDGE, J. & ZHANG, Y. 2011. Comments on 'Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable'. Biotechnology Advances, 29, 164-7.
- MILLEDGE, J. J. 2010. The potential yield of microalgal oil. Biofuels International 4, 44 45.
- MILLEDGE, J. J. 2012. Micro-algal process flow-sheet energy balance optimisation: initial software evaluation. Algal Biotechnology: Biofuels and Beyond. UCL.
- MILLEDGE, J. J. 2013. Micro-algal biorefineries. Towards Establishing Value Chains for Bioenergy. Swakopmund, Namibia: The African, Caribbean and Pacific Group of States (ACP) Science and Technology Programme.
- MILLEDGE, J. J. & HEAVEN, S. 2011. Disc Stack Centrifugation Separation and Cell Disruption of Microalgae: A Technical Note. Environment and Natural Resources Research, 1, 17-24.
- MILLEDGE, J. J. & HEAVEN, S. 2013. A review of the harvesting of microalgae for biofuel production. Reviews in Environmental Science and Biotechnology, 12, 165-178.
- MILLEDGE, J. J. & HEAVEN, S. 2014. Methods of energy extraction from microalgal biomass: a review. Reviews in Environmental Science and Bio/Technology, Online

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