1 THESIS ABSTRACT

There has been considerable discussion in recent years about the potential of micro-algae for the production of sustainable and renewable biofuels. Unfortunately the scientific studies are accompanied by a multitude of semi-technical and commercial literature in which the claims made are difficult to substantiate or validate on the basis of theoretical considerations.

To determine whether biofuel from micro-algae is a viable source of renewable energy three questions must be answered:

a. How much energy can be produced by the micro-algae?
b. How much energy is used in the production of micro-algae?
c. Is more energy produced than used?

A simple approach has been developed that allows calculation of maximum theoretical dry algal biomass and oil yields which can be used to counter some of the extreme yield values suggested in the 'grey' literature.

No ready-made platform was found that was capable of producing an energy balance model for micro-algal biofuel. A mechanistic energy balance model was successfully developed for the production of biogas from the anaerobic digestion of micro-algal biomass from raceways. Preliminary calculations had suggested this was the most promising approach. The energy balance model was used to consider the energetic viability of a number of production scenarios, and to identify the most critical parameters affecting net energy production. These were:

a. Favourable climatic conditions. The production of micro-algal 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 CO₂ and nutrients from flue gas and wastewater
d. Mesophilic rather than thermophilic digestion
e. Adequate conversion of the organic carbon to biogas (≥ 60 %)
f. A low dose and low embodied energy organic flocculant that is readily digested, or micro-algal communities that settle readily
g. Additional concentration after flocculation or sedimentation
h. Exploitation of the heat produced from parasitic combustion of micro-algal biogas in CHP units
i. Minimisation of pumping of dilute micro-algal suspension

It was concluded that the production of only biodiesel from micro-algae is not economically or energetically viable using current commercial technology, however, the production of micro-algal biogas is energetically viable, but is dependent on the exploitation of the heat generated by the combustion of biogas in combined heat and power units to show a positive balance.

Two novel concepts are briefly examined and proposed for further research:

a. The co-production of Dunaliella in open pan salt pans.
b. A 'Horizontal biorefinery' where micro-algae species and useful products vary with salt concentration driven by solar evaporation.
2 CONCLUSIONS

There are a wide range of combinations of growth, harvesting and energy extraction unit operations that can form a micro-algal biofuel production system, but as yet there is no successful economically viable system producing biofuel.

Currently the commercial exploitation of micro-algae is for non-fuel products, and there appears to be increasing research interest in the production of non-fuel products rather than fuel from micro-algae. In the short term, and possibly in the medium term, higher value products appear to be needed for economic exploitation of micro-algae. Biorefineries could allow the exploitation of the micro-algal biomass for a range of products, and produce fuel either for ‘export’ or for parasitic use to improve sustainability. The lessons learned from non-fuel products, together with their potential for co-production with fuel, may lead to the more rapid commercial realisation of micro-algal biofuel. Although high value algal products may allow the commercialisation of algae in the short term, the immense scale that is required to replace fossil fuels will result in the creation of such large quantities of algal non-fuel materials that the market price is likely to be dramatically reduced. Methods that allow exploitation of the entire organic biomass for energy production and that can produce energy profitably independent of co-product pricing are therefore needed.

A methodology has been developed that allows calculation of maximum theoretical dry algal biomass and oil yields, and this can be used to counter some of the extreme yield values suggested in the ‘grey literature’. It can also produce realistic, practical or pragmatic yields, and can be adapted for a wide range of locations. There was no ready-made platform to rapidly produce an energy balance model for micro-algal biofuel. An Excel spreadsheet model was successfully developed which allowed the production of energy balances for a number of process options and scenarios.

The majority of the literature indicated that the open systems are the most energetically viable method of producing micro-algae for biofuel. This study has shown that open raceway system can be part of an energetically viable micro-algal biogas production process. It was also estimated that the build-up of oxygen in the raceway should remain below the level predicted to inhibit growth, and night time ‘crashes’, due de-oxygenation by micro-algal respiration, are unlikely to occur in raceways of typical depths.

Effective and energy efficient harvesting are vital for viable micro-algal biofuel.

Disc-stack centrifuges, although suited to the separation of the particle sizes and concentrations found in micro-algal suspensions, have too high an energy consumption to be the sole means of harvesting micro-algae for the production of algal biofuel. Flocculation and/or sedimentation may not produce sufficiently high micro-algal concentrations. The combination of flocculation and/or sedimentation with centrifugation was shown to be energetically viable as part of micro-algal biogas production process, but a low dose and low embodied energy organic flocculant that is readily digested or micro-algal communities that settle readily is required.

The challenge for achieving energy-positive micro-algal biofuel is converting low energy density materials to energy-dense fuels; a process that requires energy input. The production of only biodiesel from micro-algae is not economically or energetically viable using current commercial technology. The energy balance assessment, however, has shown that the production of micro-algal biogas is energetically viable, but will be dependent on the exploitation of the heat generated by CHP.

Although this research has shown the production of micro-algal biogas being energetically viable, the production of biofuel from micro-algae is still in its embryonic stage, and thus considerable future research is required.

The specific contributions of this work are:

a. Development of a calculation method to estimate the maximum, realistic or achievable theoretical dry algal biomass and oil yields, which can be adapted for a wide range of locations by varying the value for solar insolation.

b. Appraisal and evaluation of current process integration software which showed that much of the data and many of the unit operations required for micro-algal biofuel production are not available within the current commercially available software packages.

c. Development of a spreadsheet-based calculation tool to estimate the mixing energy requirement and biomass calorific yields for raceways, and the use of this to show that the required energy inputs relative to the biomass calorific value decrease with the addition of a liner, reduction in fluid velocity and increase in raceway size.
e. Demonstration that night-time crashes are unlikely to occur in raceway ponds due to oxygen depletion by micro-algal respiration.
f. Although CO$_2$ for micro-algal growth is provided by bacteria in facultative wastewater treatment ponds, the work showed additional CO$_2$ is required to utilise all the nitrogen in wastewater for micro-algal biomass production.
g. Demonstration that 1 hectare lined raceways appear to be possible and that raceways should be as wide as practicable. These results support the recommendation from the US Energy Department of a length to width ratio of 11 to 1.
h. Results from the model showing that increasing fluid velocity from 0.15 to 0.45 m s$^{-1}$ at the same depth (0.3 m) reduces relative CO$_2$ outgassing, but increases energy input.
i. Results showing that there appears to no energy balance advantage to raceways being deeper than 0.3 m or flowing faster than 0.3 m s$^{-1}$.
j. A clear demonstration that it is not energetically viable to bubble air into a raceway as a source of CO$_2$.
k. Results from the model showing thermophilic digestion of micro-algal biomass is unlikely to be energetically viable.
l. A clear demonstration that flocculation by alum is not a viable option for the production of micro-algal biogas.
m. Results confirming that production of micro-algal biogas in the UK would be energetically challenging at best.
n. A clear demonstration that the use of a disc-stack centrifuge as the sole means of harvesting micro-algae for biodiesel and biogas production is too energy intensive to be energetically viable.
o. Proposal of the use of disc stack centrifugation for joint cell separation and disruption, and identification of required performance for process viability.
p. Quantitative evidence that the production of micro-algal biogas was energetically viable, but is dependent on the exploitation of the heat generated by the combustion of biogas in combined heat and power units to show a positive balance.
q. Proposal and evaluation of the co-production of Dunaliella and salt, and demonstration that it is potentially economically viable.
r. Proposal of a novel concept for a novel horizontal biorefinery.

Specific further research following on from this work:
a. Further development, refinement and extension of the methods reported in this dissertation to make them more user-friendly and capable of assessing more process combinations and variables.
b. Comparison of the output of the energy model with data from micro-algal pilot and demonstration plants, such as those of the FP7 All-Gas project, as they are developed. This will allow the accuracy of the model to be assessed and adjustments to be made.
c. The further examination of the co-production of micro-algae with salt.
d. The assessment of the feasibility of the novel concept of a horizontal biorefinery.

3 ADDITIONAL INFORMATION

3.1 Publications


3.2 Supervisory team
Dr Sonia Heaven & Professor Charles Banks

3.3 Funding
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