Micro-algae cultivation for biofuels: cost, energy balance, environmental impacts and future prospects

Corresponding Author:
Raphael Slade (1)
Email. raphael.slade@imperial.ac.uk
Tel. +44 (0)20 7594 7306
Fax. +44 (0)207 594 9334
Address: Imperial Centre for Energy Policy and Technology, Centre for Environmental Policy, Imperial College London, South Kensington Campus, London, SW7 2AZ, UK

Other Authors:
Ausilio Bauen (2)
Address: Imperial Centre for Energy Policy and Technology, Centre for Environmental Policy, Imperial College London, South Kensington Campus, London, SW7 2AZ, UK

Abstract:

Micro-algae have received considerable interest as a potential feedstock for producing sustainable transport fuels (biofuels). The perceived benefits provide the underpinning rationale for much of the public support directed towards micro-algae research. Here we examine three aspects of micro-algae production that will ultimately determine the future economic viability and environmental sustainability: the *energy and carbon balance*, *environmental impacts* and *production cost*. This analysis combines systematic review and meta-analysis with insights gained from expert workshops.

We find that achieving a positive energy balance will require technological advances and highly optimised production systems. Aspects that will need to be addressed in a viable commercial system include: energy required for pumping, the embodied energy required for construction, the embodied energy in fertilizer, and the energy required for drying and de-watering. The conceptual and often incomplete nature of algae production systems investigated within the existing literature, together with limited sources of primary data for process and scale-up assumptions, highlights future uncertainties around micro-algae biofuel production. Environmental impacts from water management, carbon dioxide handling, and nutrient supply could constrain system design and implementation options. Cost estimates need to be improved and this will require empirical data on the performance of systems designed specifically to produce biofuels. Significant (>50%) cost reductions may be achieved if CO_2, nutrients and water can be obtained at low cost. This is a very demanding requirement, however, and it could dramatically restrict the number of production locations available.

Keywords:

Algae, Biofuel, Energy balance , Cost, Sustainability, LCA

1. Algae for biofuels

Micro-algae are a large and diverse group of aquatic organisms that lack the complex cell structures found in higher plants. They can be found in diverse environments, some species thriving in freshwater, others in saline conditions and sea water [1, 2]. Most species are photoautotrophic, converting solar energy into chemical forms through photosynthesis.

Micro-algae have received considerable interest as a potential feedstock for biofuel production because, depending on the species and cultivation conditions, they can produce useful quantities of polysaccharides (sugars) and triacylglycerides (fats). These are the raw materials for producing bioethanol and biodiesel transport fuels. Micro-algae also produce proteins that could be used as a source of animal feed, and some species can produce commercially valuable compounds such as pigments and pharmaceuticals [1].

There are two main alternatives for cultivating photoautotrophic algae: raceway pond systems and photo-bioreactors (PBRs). A typical raceway pond comprises a closed loop oval channel, ~0.25-0.4m deep, open to the air, and mixed with a paddle wheel to circulate the water and prevent sedimentation. (Ponds are kept shallow as optical absorption and self-shading by the algal cells limits light penetration through the algal broth). In PBRs the culture medium is enclosed in a transparent array of tubes or plates and the micro-algal broth is circulated from a central reservoir. PBR systems allow for better control of the algae culture environment but tend to be more expensive than raceway ponds. Auxiliary energy demand may also be higher [2-5].

The perceived potential of micro-algae as a source of environmentally sustainable transport fuel is a strong driver behind their development and provides the underpinning rationale for much of the public support directed towards micro-algae R&D. It is important, therefore, that algae biofuel systems are able to clearly demonstrate their environmental and longer term economic credentials. Here we examine three aspects of micro algae production that will ultimately determine the future economic viability and environmental sustainability: the *energy and carbon balance*, *environmental impacts* and *production cost*. Examining each of these aspects in turn provides the structure for this paper. The analytical approach we adopt combines systematic review and meta-analysis with insights gained from expert workshops convened in 2010 and 2011 as part of a European FP7 research project: AquaFUELs [6].

2. The energy and carbon balance of micro-algae production

If micro-algae are to be a viable feedstock for biofuel production the overall energy (and carbon balance) must be favourable. There have been many attempts to estimate this for large scale micro-algae biofuels production using life cycle assessment (LCA) methods to describe and quantify inputs and emissions from the production process. Attempts have been hampered, however, by the fact that no industrial scale process designed specifically for biofuel production yet exists. Consequently, the data that underpins micro-algae LCA must be extrapolated from laboratory scale systems or from commercial schemes that have been designed to produce high value products such as pigments and heath food supplements. Despite this limitation, it is anticipated that LCA can still serve as a tool to assist with system design.

Here we review seven recent LCA studies (summarised in Table 1). These studies describe eleven production concepts, but comparison is impeded by the use of inconsistent boundaries, functional units and assumptions. To compare the results on a consistent basis a simple meta-model was developed. This model was used to standardise units and normalise the process description to a consistent system boundary comprising the *cultivation*, *harvesting* and *oil extraction* stages (a complete description of the modelling approach is provided in the electronic supplementary information).

Table 1: Life cycle assessment studies on micro-algae derived fuels

Ref.	Lead author	Description
[7]	Kadam	Compares a conventional coal-fired power station with one in which coal is co-fired with algae cultivated using recycled flue gas as a source of CO_2. The system is located in the southern USA, where there is a high incidence of solar radiation.
[8]	Jorquera	Compares the energetic balance of oil rich microalgae production. Three systems are described: raceway ponds, tubular horizontal PBR, and flat-plate PBRs. No specific location was assumed. The study only considers the cultivation stage and the system energy balance.
[9]	Campbell	Examines the environmental impacts of growing algae in raceway ponds using seawater. Lipids are extracted using hexane, and then transesterified. The study is located in Australia, which has a high solar incidence, but limited fresh water supply.
[10]	Sander	A well-to-pump study that aimed to determine the overall sustainability of algae biodiesel and identify energy and emission bottlenecks. The primary water source was treated wastewater, and was assumed to contain all the necessary nutrients except for carbon dioxide. Filtration and centrifugation were compared for harvesting. Lipids were extracted using hexane, and then transesterified.
[11]	Stephenson	A well-to-pump analysis, including a sensitivity analysis on various operating parameters. Two systems were considered, a raceway pond and an air-lift tubular PBR. The location of the study is in the UK, which has lower solar radiation than the other studies.
[12]	Lardon	Considers a hypothetical system consisting of an open pond raceway covering 100ha, and cultivating *Chlorella vulgaris*. Two operating regimes are considered: i) normal levels of nitrogen fertilisation; ii) low nitrogen fertilisation. The stated objective was to identify obstacles and limitations requiring further research.
[13]	Clarens	Compares algae cultivation with corn, switch grass and canola (rape seed). The study was located in Virginia, Iowa and California, each of which has different levels of solar radiation and water availability. Five impact categories considered: energy consumption (MJ), water use (m^3), greenhouse gas emissions (kg CO_2 equivalent), land use (ha), and eutrophication (kg PO_4).

Production systems were compared in terms of the net energy ratio (NER) of biomass production. NER is defined here as the sum of the energy used for cultivation, harvesting and drying, divided by the energy content of the dry biomass. Provided the NER is less than unity, the process produces more energy than it consumes. The results of this comparison are shown in Figure 1. Of the eight raceway pond concepts it can be seen that six have an NER less than 1. This suggests that a positive energy balance may be achievable for these systems, although this benefit is marginal in the normalized case. The NER of the PBR systems are all greater than 1. The best performing PBR is the flat-plate system which outperforms the tubular PBRs as it benefits from a large illumination surface area and low oxygen build-up.

It can be seen that in all cases the primary energy input for the normalized process boundary is equal to, or less attractive than, the original case. The three studies where normalisation has the greatest impact are the systems described by Kadam [7], Jorquera [8] and Campbell [9]. Originally these studies only considered the cultivation stage; the addition of drying and dewatering processes and lipid extraction changes the NER from ~0.05-0.1 to 0.5-0.75. For these studies, even if drying and lipid extraction were excluded, the normalised value for cultivation is less favourable. This is because the original studies did not include system construction. (In addition to the energy required for system construction, the normalised system boundary also includes the energy needed to transport fertiliser and the embodied energy in the fertiliser, although these last two factors are comparatively insignificant.)

The Sander [10] study uses high values for the energy required for cultivation, drying and harvesting, and the systems this study describes will deliver less energy output than they require input. The original assumptions about the algal species and its productivity are unclear but the data appears to come from studies completed in the 1980's, and so may not be representative of more recent designs.

The Stephenson [11] study is the only LCA that gives a complete description of the cultivation, and harvesting process, and so normalisation makes no difference in this case. The energy demands of the cultivation stage are higher than other studies because the authors assume more electricity is required at this stage to overcome frictional losses (which they estimate from first principles). Less energy is required for drying than other studies because, for the subsequent downstream processing steps, the authors assume the use of an oil extraction process that can accept wet biomass (homogenisation with heat recovery), hence less drying is required overall.

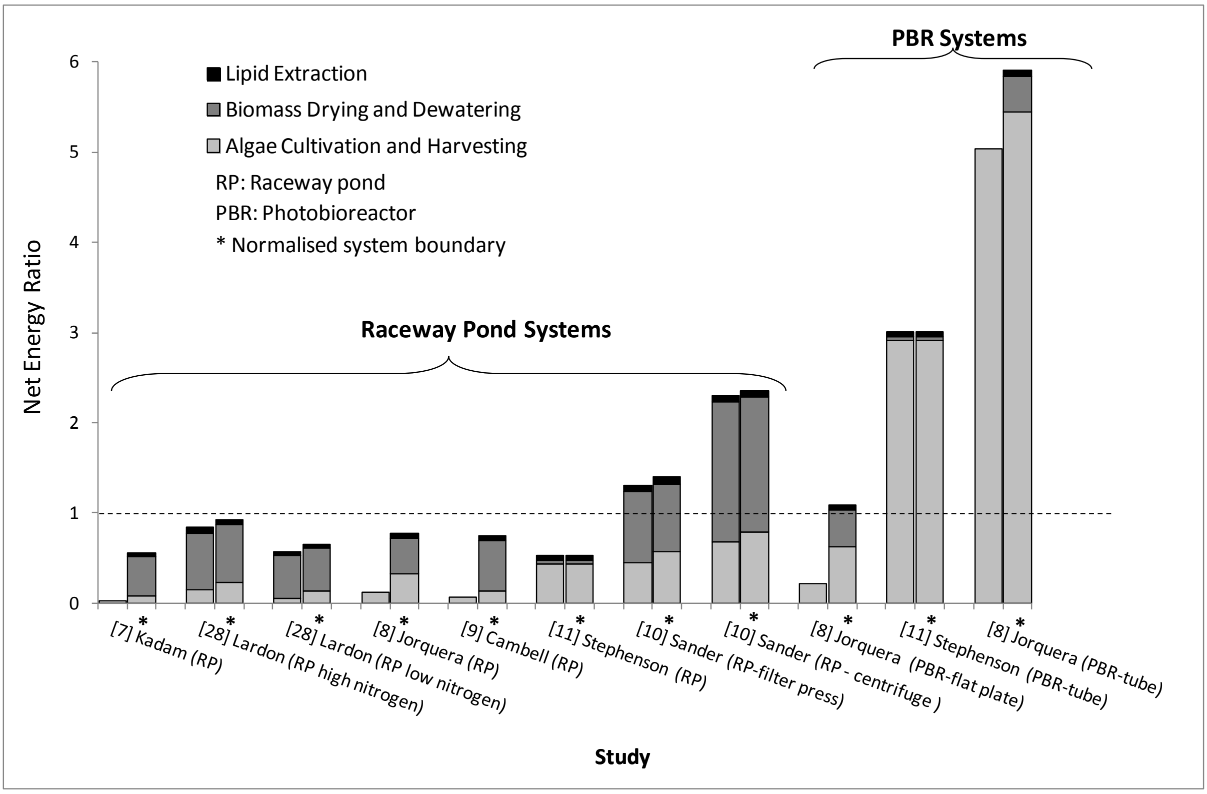
For the cultivation phase in raceway ponds, the most important contributions to the energy demand come from the electricity required to circulate the culture (energy fraction 22 % - 79 %) and the embodied energy in pond construction (energy fraction 8 % - 70 %). The energy embodied in the nitrogen fertiliser may also make a substantial contribution to the energy demand (energy fraction for the cultivation phase 6 % - 40 %),(Note – this range excludes the

Kadam [7] study which includes a nitrogen input mass fraction of 0.05, a value that appears unfeasibly low given that this study assumes the biomass contains a protein mass fraction >30 %).

All the normalised PBR systems consume more energy than they produce. Biomass drying and de-watering are proportionately less important than the energy consumed in cultivation and harvesting. This is partly because greater algal biomass concentrations can be achieved in PBR systems, and partly because PBRs consume more energy at the cultivation stage. The energy used to pump the culture medium around the PBR and overcome frictional losses accounts for the majority of energy consumption during the cultivation stage (energy fraction for tubular PBRs is 86 % - 92 %, the energy fraction for flat plat PBRs is 22 %. System construction accounts for the majority of the remainder (the energy fraction for system construction is 6 % - 12 %).

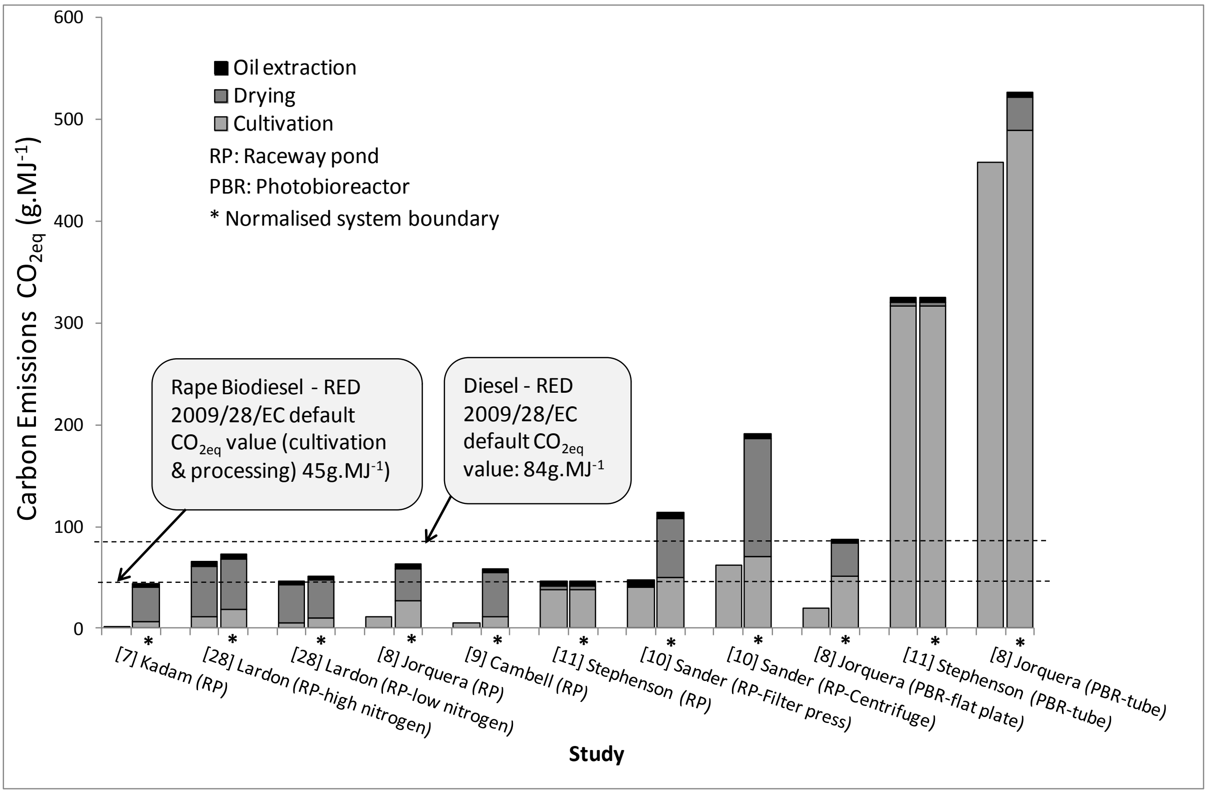
Another source of variation is that each study selects a different composition for the algae produced and a different productivity for the growth phase; this affects the energy required per functional unit produced. All else being equal, if the productivity of the algae is assumed to be low, then it follows that the energy required to produce 1MJ dry biomass will be greater (as the mixing requirement per unit time will not be reduced). One complicating factor is that growing the algae under lower productivity conditions, such as nitrogen starvation, may allow the algae to accumulate more lipid and so may result in a higher calorific value for the biomass overall. It is clearly important that productivity and composition values correspond with one another and reflect how the system is operated.

Figure 1: Net energy ratio for micro-algae biomass production: comparison of published values with normalised values. (The NER is defined as the sum of the energy used for cultivation, harvesting and drying, divided by the energy content of the dry biomass)



The carbon dioxide emissions associated with algal biomass production were estimated by multiplying the external energy inputs to the process by the default emissions factors described in the EU renewable energy directive [14]. The results obtained are shown in Figure 2. It can be seen that the majority of emissions are associated with electricity consumption for pumping and mixing and the provision of heat to dry the algae. Notably, emissions associated with algal biomass production in raceway ponds are comparable with the emissions from the cultivation and production stages of rape methyl ester biodiesel. Production in PBRs, however, demonstrates emissions greater than conventional fossil diesel. An important caveat to this analysis is that the carbon emissions are highly dependent on the emissions factors used for the different energy inputs into the system (and in particular electricity) and *generic* factors may not be appropriate in all situations.

Figure 2: Illustrative estimates for carbon dioxide emissions from algal biomass production in raceway ponds. (The default emissions factors used to estimate carbon dioxide emissions were – diesel 83.80g.MJ^{-1}; electricity: 91 g.MJ^{-1}; Heat: 77 g.MJ^{-1} [14]. The emissions factor for the embodied energy in fertiliser and for production of PVC lining (in the case of raceway ponds) and PBR was assumed to be the same as for heat.)



The validity of current LCA studies and the inferences that can be drawn from them were discussed at the AquaFUELs roundtable [14] and independently with experts during the course of the AquaFUELs project. The views expressed below reflect the tone of the discussion and the comments received. One of the major criticisms of the current LCA studies was the lack of transparency around data sources, and the lack of critical thinking around how reliable these sources and assumptions actually are. It was also noted that assumptions in the studies analysed here are often obscure, or open to interpretation. As noted above, the system described in the study by Kadam [7] includes less nitrogen as an input than is contained in the algae output. This may be an oversight, or the authors may have made some additional assumption that is not explicit: it is also possible that the missing nitrogen may be recycled or come from some other source.

Another identified concern is the extent to which genuine expertise in algae cultivation is available to LCA modellers. One UK academic expert summed this up as follows: *"[LCA studies] tend to be conducted by either LCA specialists who are not specialists in the technology, or do not have enough aspects of the process covered"*. There is also concern that LCA studies could be misleading and detrimental to the development of a young industry, as argued by the representative of a micro-algae producing company: "*From an industry point of view, what is happening is the worst possible thing: a pollution of publications on micro-algae production*

LCA which refer to each other and in many cases are careless and get strange conclusions (which are interesting to publish)".

Some experts also believe that scope for technical advance is significant and consequently, the literature used to inform LCA models may be outdated and the assumptions unduly conservative, or incorrectly chosen. As asserted by one of the AquaFUEL project's industrial partners: "*available options for optimization in each step of the technology are many, but just few have been analysed [in LCA studies]. The negative values some LCA demonstrate for algae biotechnology do not mirror reality because the initial conditions and technological options were not correctly chosen*".

There was a general consensus among the experts questioned, however, that algae growth rate estimates (both in terms of biomass productivity and lipid yield) err towards optimistic values and do not take into account the losses that would occur with scaling up the process. Stakeholders at the Aquafuels round table also noted that biomass productivity estimates should be based on the yearly average values, stressing the point that this is not equivalent to the mean productivity on a summer's day [15].

2.1 Insights from LCA studies

Life Cycle Assessment studies of micro-algal biofuel production share a common aspiration to identify production bottlenecks and help steer the future development of algae biofuel technology. Yet, the extent to which the studies meet this aspiration appears to be somewhat limited. Issues of concern include:

- The conceptual, and often incomplete, nature of the systems under investigation, and the absence of coherent and well designed processes. The use of inconsistent boundaries, functional units and allocation methodologies impedes comparison between studies.
- The limited sources of primary data upon which process assumptions are based, and the extrapolation of laboratory data to production scale. The transparency of assumptions is also poor.
- The validity of specific assumptions, particularly those relating to the biomass productivity and lipid yield, has been called into question. It is important to distinguish between what can be achieved currently and future projections contingent on technological progress.

Despite these shortcomings, and bearing in mind the concerns voiced by stakeholders about the extent to which the existing LCA can be considered representative, this examination of LCA studies suggest that:

- The energy balance for algal biomass production (in a simplistic system considering only the production, harvesting and oil extraction stages) shows that energy inputs to algae production systems could be high. This may limit their value as a source of energy and indicates that algae production may be most attractive where energy is not the main product.

- Raceway Pond systems demonstrate a more attractive energy balance than PBR systems (it should also be borne in mind that a commercial system may combine elements of both).
- Algae production requires a number of energy demanding processes. However, within the LCA studies considered here there is no consistent hierarchy of energy consumption. Aspects that will need to be addressed in a viable commercial system include: energy required for pumping, the embodied energy required for construction, the embodied energy in fertilizer, and the energy required for drying and de-watering.
- If inputs of energy and nutrients are carbon intensive the carbon emissions from algae biomass produced in raceway ponds could be comparable to the emissions from conventional biodiesel; the corresponding emissions from algae biomass produced in PBRs may exceed the emissions from conventional fossil diesel. The principle reason for this is the electricity used to pump the algal broth around the system. Using co-products to generate electricity is one strategy that might improve the overall carbon balance.

3. Environmental impacts and constraints

Large scale micro-algae production could have a wide variety of environmental impacts beyond the consumption of energy in the production process. Many of these impacts could constrain system design and operation. The impacts presented here are the ones most prominent in the existing literature, and identified as important in discussion with stakeholders.

3.1 Water Resources

A reliable, low cost water supply is critical to the success of biofuel production from micro-algae. Fresh water needs to be added to raceway pond systems to compensate evaporation; water may also be used to cool some PBR designs. One suggestion is that algae cultivation could use water with few competing uses, such as seawater and brackish water from aquifers. Brackish water, however, may require pre-treatment to remove growth inhibiting components and this could raise the energy demand of the process [16]. Re-circulating water has the potential to reduce consumption (and reduce nutrient loss) but comes with a greater risk of infection and inhibition: bacteria, fungi, viruses are found in greater concentrations in recycled waters, along with non-living inhibitors such as organic and inorganic chemicals and remaining metabolites from destroyed algae cells. In the majority of designs a proportion of the overall water must be removed to purge contaminants. The distance to the water source is also an important factor in locating the cultivation site. Lundquist [17] illustrates this with an example showing how a 100 meters elevation could mean that a significant proportion (~6%) of the energy produced by the algae would be used for pumping. In some locations the need for pumping can be reduced by using natural tidal flows to feed cultivation ponds.

3.2 Land use and location

One of the suggested benefits of algae production is that it could use marginal land, thereby minimising competition with food production. Topographic and soil constraints limit the land availability for raceway pond systems as the installation of large shallow ponds requires relatively flat terrain. Soil porosity/ permeability will also affect the need for pond lining and sealing [17].

Solar radiation is one of the most important factors influencing algal growth and to achieve high levels of production throughout the year it is desirable that there is little seasonal variation. For practical purposes, therefore, the most suitable locations are warm countries close to the equator where insolation is not less than 3000 hours.yr^{-1} (average of 250 hours.$month^{-1}$) [18, 19]. To date most commercial micro-algae production to-date has occurred in low-latitude regions. Israel, Hawaii and southern California are home to several commercial micro-algae farms.

3.3 Nutrient and fertilizer use

Algae cultivation requires the addition of nutrients, primarily nitrogen, phosphorus and potassium (some species, e.g. diatoms, also require silicon). Fertilization cannot be avoided as the dry algal mass fraction consists of ~7% nitrogen and ~1% phosphorus. Substituting fossil fuels with algal biomass would require a lot of fertilizer. As an illustration, if the EU substituted all existing transport fuels with algae biofuels this would require ~25 million tonnes of nitrogen and 4 million tonnes of phosphorus per annum [20]. Supplying this would double the current EU capacity for fertilizer production [21]. At a small scale, recycling nutrients from waste water could potentially provide some of the nutrients required, and there may be some scope to combine fuel production and waste water remediation. Some conceptual process designs also incorporate nutrient cycling as a fundamental aspect of system design and operation [17].

3.4 Carbon fertilisation

Algae cultivation requires a source of carbon dioxide. Assuming algae have a carbon mass fraction of 50 % it follows that producing 1 kg dry algal biomass requires at least 1.83 kg CO_2. In reality, however, CO_2 usage will be several times this. For raceway ponds the rate of outgassing is a function of the pond depth, friction coefficient of the lining, mixing velocity, pH and alkalinity. Depending on operational conditions the theoretical efficiency of CO_2 use can range from 20 % - 90 % [22]. In practice the efficiency of CO_2 fixation in open raceways may be less than 10 %; for thin layer cultivation the efficiency of CO_2 fixation is roughly 35% [23]. In closed tubular photobioreactors (PBRs) CO_2 fixation efficiencies of around ~75% have been reported [24].

The need for CO2 fertilisation impacts both where production can be sited and the energy balance of the system. If CO_2 from flue gas were used, the production site would need to be in reasonably close proximity to a power station or other large point source of $CO_{2.}$ These sources tend to be concentrated close to major industrial and urban areas and relatively few are close to oceans [16]. Because separating CO_2 from flue gas is an energy consuming process the direct use of flue gas would be preferable energetically, as long as the algae can tolerate contaminants in the gas. A further consideration is that it may not be permissible to emit CO_2 in large amounts at ground level.

3.5 Fossil Fuel Inputs

The majority of the fossil fuel inputs to algae cultivation come from electricity consumption during cultivation, and, where included, from natural gas used to dry the algae. Algae are temperature sensitive and maintaining high productivity (particularly in PBRs) may require temperature control. Both heating and cooling demand could increase fossil fuel use. The environmental performance could, however, be improved by integration options such as using waste heat from power generation to dry the algal biomass. System optimisation to minimise energy demand will be essential [24].

3.6 Eutrophication

Nutrient pollution (eutrophication) can lead to undesirable changes in ecosystem structure and function. The impact of algal aquaculture could be positive or negative. Negative impacts could occur if residual nutrients in spent culture medium are allowed to leach into local aquatic systems. On the other hand, positive impacts could occur if algae production were to be integrated into the treatment of water bodies already suffering from excess nutrient supply. For example, Agricultural Research Service scientists found that 60 % ~ 90 % of nitrogen runoff and 70 % ~ 100 % of phosphorus runoff can be captured from manure effluents using an algal turf scrubber [25]. Remediation of polluted water bodies suffering from algal blooms may also provide locally significant amounts of free waste biomass, and this could be used for biofuel production on a small scale.

3.7 Genetic Modified Algae

In the search for algae that can deliver high biomass productivity and lipid content simultaneously, genetic modification is one possible option [17]. Applications of molecular genetics range from speeding up the screening and selection of desirable strains, to cultivating modified algae on a large scale. Traits that might be desirable include herbicide resistance to prevent contamination of cultures by wild type organisms and increased tolerance to high light levels. Containment of genetically modified algae poses a major challenge. In open pond systems, culture leakage and transfer (e.g. by waterfowl) is unavoidable. Closed bioreactors appear more secure but Lundquist et al., comments that as far as containment is concerned, PBRs are only cosmetically different from open ponds and some culture leakage is inevitable [17].

3.8 Algal toxicity

At certain stages of their lifecycle many algae species can produce toxins ranging from simple ammonia to physiologically active polypeptides and polysaccharides. Toxic effects can range from the acute (e.g. the algae responsible for paralytic shellfish poison may cause death) to the chronic (e.g. carrageenan toxins produced in red tides can induce carcinogenic and ulcerative tissue changes over long periods of time). Toxin production is species and strain specific and may also depend on environmental conditions. The presence or absence of toxins is thus difficult to predict [26, 27].

From the perspective of producing biofuels, the most important issue is that where co-products are used in the human food chain producers will have to show that the products are safe. Where algae are harvested from the wild for human consumption the principal concern is contamination from undesirable species. From an economic perspective algal toxins may be important and valuable products in their own right with applications in biomedical, toxicological and chemical research.

3.9 Insights on environmental impacts.

Micro-algae culture can have a diverse range of environmental impacts, many of which are location specific. Depending on how the system is configured the balance of impacts may be positive or negative. Impacts such as the use of genetic engineering are uncertain, but may affect what systems are viable in particular legislatures. Possibly the most important environmental aspect of micro-algae culture that needs to be considered is water management: both the water consumed by the process, and the emissions to water courses from the process. In any algae cultivation scheme it should be anticipated that environmental monitoring will play an important role and will be an ongoing requirement.

4. Cost performance

Cost analysis is a powerful tool that can be used to both estimate the ultimate costs of algae biofuels and identify the process elements which contribute most to the production cost – thereby helping focus future research and design. The limitations of algae production cost assessments are similar to those facing life cycle assessments and include data constraints and reliance on parameters extrapolated from lab-scale analyses. The current state of the art for micro-algae culture may also not be captured. For instance, one of the most frequently cited sources of cost modelling parameters is a paper published in 1996 [28] which in turn contains assumptions going back to the mid 1970's. Estimates for algal productivity, CO_2 capture efficiency and system availability may also reflect future aspirations rather than currently achievable results. As with LCA studies the production of co-products, or provision of co-services, greatly affects the economic viability.

Here we compare idealised scenarios for the production of micro-algal biomass in PBRs and raceway ponds, combining data from the literature with discussion with experts. The cost modelling approach includes only the cultivation and harvesting process steps. No credit is assumed for co-products or waste water treatment services. An overview of the scenarios compared is provided in Table 2, a full description of the modelling parameters is provided in the supplementary information.

Table 2: Algae production scenarios

Scenario		**Operating days (day) (availability)**	**Biomass productivity ($g.m^{-2}.day^{-1}$)**	**Power consumption ($W.m^{-2}$)**	**Area (ha)**	**Water evaporation ($L.m^{-2}.day^{-1}$)**	**Cost of water, CO_2, and nutrients**
Raceway Pond	*Base case - Low availability*	300	10 [a]	1	400	10	included
	Base case - high availability	360					
	Projected case - Low availability	300	20 [a]				excluded
	Projected case - high availability	360					
PBR	*Base case - Low availability*	300	20[b]	500	10	0.5	included
	Base case - high availability	360					
	Projected case - Low availability	300	40[b]	50			excluded
	Projected case - high availability	360					

[a] Productivity assumptions based on the judgment and experience of the AquaFUELs project partners [29].

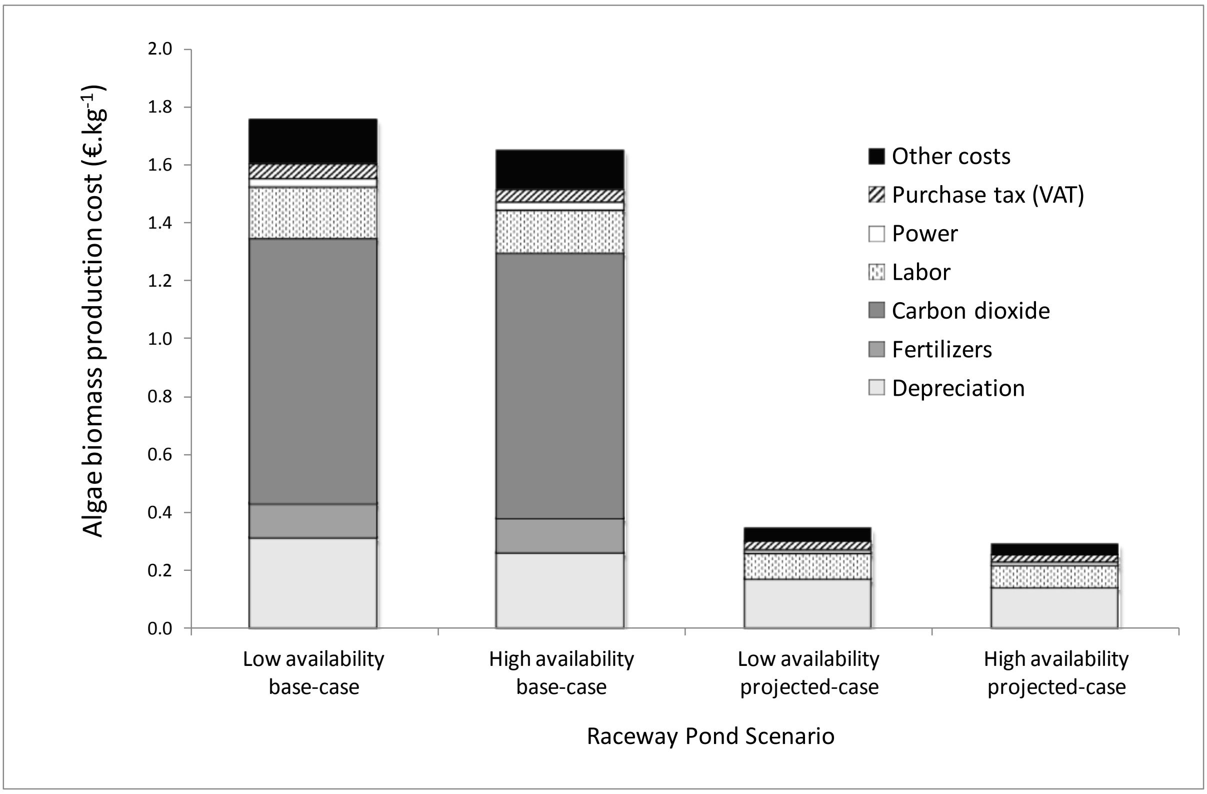
[b] Productivity assumptions extrapolated from experimental data incorporating future technical advances.

4.1 Results:

The production cost of algal biomass in an idealised raceway pond system is shown in Figure 3. The *base case* production cost is ~1.6€.kg-^{1} to 1.8€.kg-^{1} and the *projected case* cost is ~0.3€.kg^{-1} to 0.4€.kg^{-1}. It can also be seen that there is little difference between the low and high availability cases (fractional difference ~5 %). In contrast, moving from the *base case* to the *projected case* results in a fractional decrease in costs of ~50 %. For comparison, the market price for delivered woody biomass pellets in the UK is ~0.2€.kg^{-1} to 0.4€.kg^{-1} [30]. Although, it should be noted that the composition of algal may be more interesting for some applications.

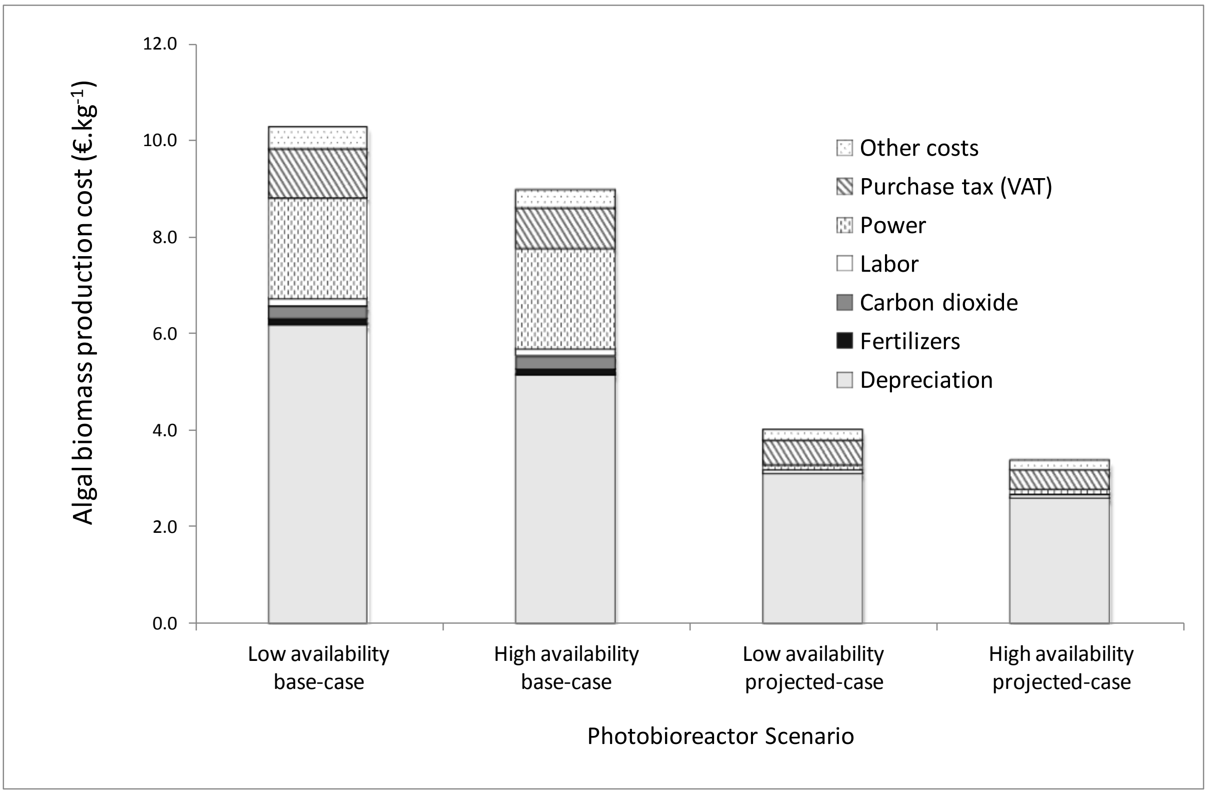
The cost of CO_2 in the *base case* has a significant impact on production cost. This is because the open pond system has poor CO_2 fixation performance. The *projected case* gives a much reduced cost (~0.25€.kg^{-1}). This is due to both the higher productivity assumption and the assumption that the CO_2 comes from an adjacent power plant and is free of charge. Another source of variation between the scenarios is the fertilizer costs: in the projected scenario we assume the cultivation system is coupled with a wastewater treatment facility, and that nutrients are also effectively free of charge. This scenario illustrates that major gains in productivity and efficiency are required to produce algae that could compete with conventional fuels.

Figure 3: Illustrative costs of algal biomass production in an idealised raceway pond system



The production cost of algal biomass produced in the idealised tubular PBR systems is shown in Figure 4. The *base case* cost is ~9€.kg^{-1} to 10€.kg^{-1} and the *projected case* cost is ~3.8€.kg^{-1} . All PBR scenarios are dominated by the system capital cost. The CO_2 cost in the PBR system is proportionately less important than in the raceway pond, this is partly because the PBR system has better CO_2 fixation performance, and partly because other costs – e.g. the cost of electricity consumed – are greater. In the *projected case*, where raw materials are effectively free and the power consumption has been reduced relative to the base case by 90%, the cost of biomass production is reduced (from ~9€.kg^{-1} to ~3.8€.kg^{-1}) but is still greater than the cost of production in raceway ponds. This scenario illustrates that dramatic reductions in the capital cost would be required for the costs of this system to approach the level required to service the biofuels market.

Figure 4: Illustrative costs of algal biomass production in an idealised tubular photobioreactor system



4.2 Insights from cost modelling

The results shown here are for a partially complete system estimated using a simple costing model. This model is appropriate to identifying the cost elements of the process that pose the greatest challenge to engineering development. It is likely, however, to underestimate the true cost of micro-algae production. This is because a real project would incur costs excluded from this analysis such as the cost of finance and the cost of land. The two future scenarios also postulate dramatic improvements in technical performance. With these important caveats in mind, we consider that this analysis supports the following conclusions.

- Raceway pond systems demonstrate a lower cost of algal biomass production than photo-bioreactor systems.
- Most of the production costs in raceway system are associated with operation (labour, utilities and raw materials). The cost of production in PBRs, in contrast, is dominated by the capital cost of the PBRs.
- Dramatic improvements in both productivity and energy efficiency would be required to greatly reduce the cost of biomass production.
- Significant cost reductions (>50%) may be achieved if CO_2, nutrients and water can be obtained at low cost. This is a very demanding requirement, however, and it could dramatically restrict the number of locations available.

- Compared with other sources of biomass used for energy, algal biomass appears expensive – although it has a more interesting composition.

5. Conclusions

This paper examines three aspects of micro-algae production that will strongly influence the future sustainability of algal biofuel production: the *energy and carbon balance*, *environmental impacts* and *production costs*. Against each of these aspects micro-algae production presents a mixed picture. A positive energy balance will require technological advances and highly optimised production systems. The mitigation of environmental impacts, and in particular water management, presents both challenges and opportunities, many of which can only be resolved at the local level. Existing cost estimates need to be improved and this will require empirical data on the performance of systems designed specifically to produce biofuels. At the current time it appears that the sustainable production of biofuels from micro-algae requires a leap of faith, but there are nonetheless grounds for optimism. The diversity of algae species is such that it is highly likely that new applications and products will be found. As experience with algal cultivation increases it may also be found that biofuels have a role to play.

An important caveat to all these conclusions is that they reflect the state of the existing academic literature, and this is inevitably an imperfect reflection of the status of the sector. It is quite possible that many of the challenges identified are being addressed, but that the information about how this is being achieved is yet to make it into the public domain.

6. Acknowledgements

The work presented here was undertaken within the aegis of the project Aquafuels: Algae and aquatic biomass for a sustainable production of 2nd generation biofuels (FP7-Energy-2009-1) [6]. This project aimed to establish the state of the art for research, technological development and demonstration activities regarding the exploitation of algal biomass for 2nd generation biofuels production. A secondary objective of the project was to put robust and credible information about algae into the public domain.

7. References

[1] Carlsson AS, van Beilen JB, Möller R, Clayton D. Micro- and macro-algae: utility for industrial applications, outputs from the EPOBIO project. Bowles D, Editor. Newbury (UK): University of York, CPL Press; 2007 September. 86 p.

[2] Schenk MP, Thomas-Hall SR, Stephens E, Marx UC, Mussgnug JH, Posten C, et al. Second generation biofuels: high-efficiency microalgae for biodiesel production. Bioenerg Res 2008; 1: 20-43.

[3] Pulz O. Photobioreactors: production systems for phototrophic microorganisms. Appl Microbiol Biotech 2001; 57(287-293): 287-93.

[4] Brennan L, Owende P. Biofuels from microalgae: a review of technologies for production, processing, and extractions of biofuels and co-products. Renew Sust Energ Rev 2010; 14(2): 557-77.

[5] Chisti Y. Biodiesel from microalgae. Biotechnol Adv 2007; 25: 294-306.

[6] AquaFUELs (2010) Aquafuels: algae towards biofuels [Internet], available from: <http://www.aquafuels.eu/project-info.html> [Accessed: 1/6/2012].

[7] Kadam KL. Environmental implications of power generation via coal-microalgae cofiring. Energy 2002; 27(10): 905-22.

[8] Jorquera O, Kiperstok A, Sales EA, Embiruçu M, Ghirardi ML. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. Bioresource Technol 2010; 101(4): 1406-13.

[9] Campbell PK, Beer T, Batten D. Life cycle assessment of biodiesel production from microalgae in ponds. Bioresource Technology 2010.

[10] Sander K, Murthy GS. Life cycle analysis of algae biodiesel. Int J Life Cycle Assess 2010; 15: 704–14.

[11] Stephenson AL, Kazamia E, Dennis JS, Howe CJ, Scott SA, Smith AG. Life-cycle assessment of potential algal biodiesel production in the United Kingdom: A comparison of raceways and air-lift tubular bioreactors. Energ Fuel 2010; 24(7): 4062-77.

[12] Lardon L, Helias A, Sialve B, Steyer JP, Bernard O. Life-cycle assessment of biodiesel production from microalgae. Environ Sci Technol 2009; 43(17): 6475-81.

[13] Clarens A, Resurreccion E, White M, Colosi L. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environ Sci Technol 2010; 44(5): 1813-19.

[14] Directive 2009/28/EC. On the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.2009.04.23. Off J EU 2009.L 140: 16-62.

[15] Vernon P-A, Garofalo R (2010) Algae and aquatic biomass for a sustainable production of 2nd generation biofuels: Deliverable 2.2 - Proceedings of the AquaFUELs Roundtable [Internet], available from: <http://www.aquafuels.eu/attachments/075_AquaFUELs%20Roundtable%20Proceedings.pdf> [Accessed: 1/6/2011].

[16] Darzins A, Pienkos P, Edye L. Current status and potential for algae biofuels production: a report to IEA Bioenergy Task39. International Energy Agency (IEA), 2010 August. [Available from: <www.task39.org>]

[17] Lundquist TJ, Woertz IC, Quinn NWT, Benemann JR. A realistic technology and engineering assessment of algae biofuel production. Energy Biosciences Institute, University of California, 2010 October. [Available from: <http://works.bepress.com/tlundqui/5>]

[18] Necton S.A. Estudo de localização de unidade industrial para produção de microalgas em portugal 71 p. Necton, Companhia Portuguesa de Culturas Marinhas, S.A, Olhão, Portugal; 1990 [Portuguese].

[19] Verween A, Queguineur B, Casteleyn G, Fernandez GA, Leu S, Biondi N, et al. (2011) Algae and aquatic biomass for a sustainable production of 2nd generation biofuels: Deliverable 1.6 - mapping of natural resources in artificial, marine and freshwater bodies [Internet], available from: <http://www.aquafuels.eu/deliverables.html> [Accessed: 1/9/2011].

[20] Wijffels RH, Barbosa MJ. An outlook on microalgal biofuels. Science 2010; 329(5993): 796-99.

[21] van Egmond K, Bresser T, Bouwman L. The European nitrogen case. AMBIO: J Hum Environ 2002; 31(2): 72-78.

[22] Weissman JC, Goebel RP, Benemann JR. Photobioreactor design: mixing, carbon utilization, and oxygen accumulation. Biotechnol Bioeng 1988; 31(4): 336-44.

[23] Acien Fernández G. Personal communication from Prof. Francisco Gabriel Acién Fernández, University of Almeria, Spain. 2011.

[24] Acién FG, Fernández JM, Magán JJ, Molina E. Production cost of a real microalgae production plant and strategies to reduce it. Biotechnol Adv 2012.

[25] AquaFUELs. Report on biology and biotechnology of algae with indication of criteria for strain selection. 2011. [Available from: <http://www.aquafuels.eu/deliverables.html>]

[26] Collins M. Algal toxins. Microbiol Rev 1978; 42(4): 726-46.

[27] Rellán S, Osswald J, Saker M, Gago-Martinez A, Vasconcelos V. First detection of anatoxin-a in human and animal dietary supplements containing cyanobacteria. Food Chem Toxicol 2009; 47: 2189-95.

[28] Benemann JR, Oswald WJ. Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass, report number DOE/PC/93204/T5. Department of Civil Engineering, University of California Berkley, CA., 1996 215 p.

[29] Aquafuels: algae towards biofuels [Internet], available from: <http://www.aquafuels.eu/project-info.html> [Accessed: 1/6/2012].

[30] E4tech. Biomass prices in the heat and electricity sectors in the UK. A report for the department of energy and climate change UK (URN 10D/546). E4tech (UK) Ltd, London, 2010. [Available from: <http://www.decc.gov.uk/assets/decc/consultations/rhi/132-biomass-price-heat-elec-e4tech.pdf>]

Micro-algae cultivation for biofuels: cost, energy balance, environmental impacts and future prospects – Supplementary Information

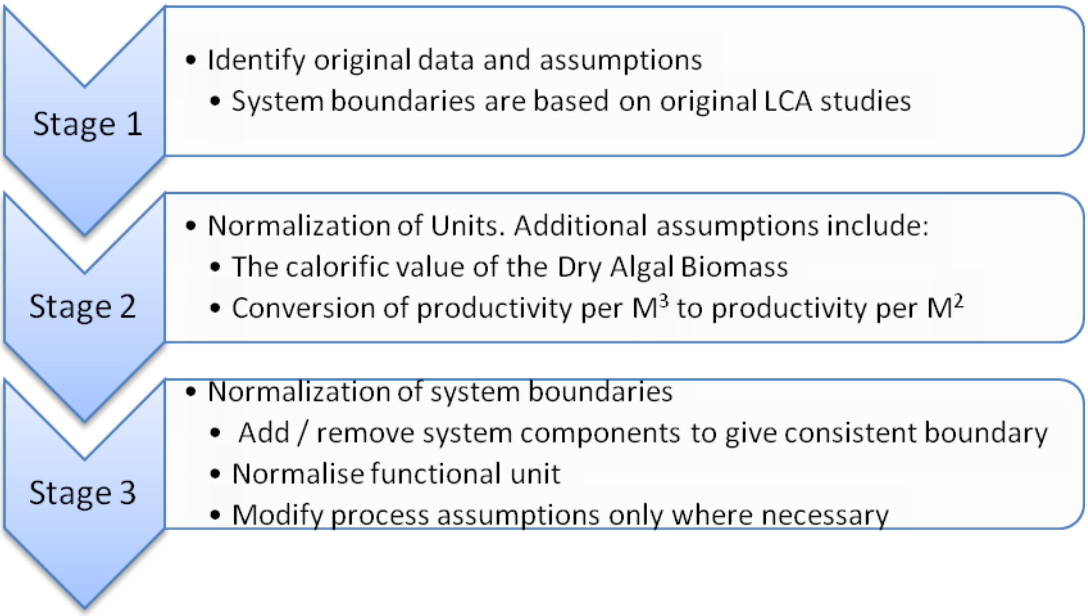
Raphael Slade, Ausilio Bauen
Imperial Centre for Energy Policy and Technology, Centre for Environmental Policy, Imperial College London, South Kensington Campus, London, SW7 2AZ, UK

8. Life Cycle assessment meta-model approach and assumptions

The objectives of the meta-model were two-fold; firstly, to enable a more detailed examination of the assumptions used in the existing LCA, and secondly, to compare studies in terms of the energy produced and consumed. The model was built in Excel using simplified descriptions of the processes involved in micro-algae cultivation, harvesting of algal biomass, and extraction of algal oil

The modelling approach (shown in **Figure SI-1**) was undertaken in three stages. Firstly, the data and assumptions contained in the original studies were identified and transcribed. Secondly, the units were standardised. Lastly, the process descriptions were normalized to fit a consistent system boundary, and to allow comparison using a single functional unit. An overview of the assumptions used to normalize the studies are described below

Figure SI-1: Algae LCA meta-modelling approach



8.1 Meta-model system description and boundaries

The meta-model process system is shown in **Figure SI-2.** In Stage 1, the algae are cultivated and harvested. For each study the efficiency with which nutrients and CO_2 are captured is based on the original study. The residence time of the algae strain in the cultivation system – where algae cell accumulates lipid to the desired level – also follows the original studies. The boundaries include the manufacture of the principal equipment (e.g. the PVC lining for the raceway pond systems and system maintenance and operations).

In Stage 2, the slurry of mature algae cells is de-watered and dried. The amount of drying required is determined by the oil extraction process (Stage 3). Most of the LCA studies adopt hexane extraction as they assume algal oil extraction will be very similar to soybean oil extraction[1]. This process requires that the paste has to be dried up to a solid content of ~90% before being processed in an oil mill[2]. In order to achieve this a belt dryer was chosen as the preferred technology for biomass drying based on data presented by Lardon et al [1].,

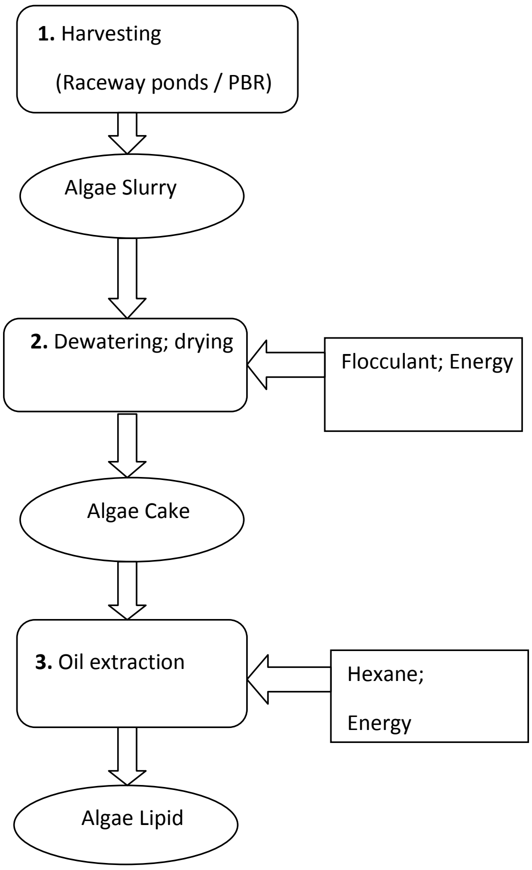
Stage 3 is oil extraction. The extraction efficiencies are based on the data from original studies.

---

[1] It should be noted that some experts contest this assumption

[2] A belt dryer, usually is used for wastewater treatment plant sludge, is assumed as it is one of the less energy demanding drying process. Heating supplied in the system comes from natural gas combustion.

Figure SI-2: Description of meta-model process



8.2

8.3 Functional Unit and basis for comparison

The functional unit selected for comparing energetic performance were 1MJ dry algal biomass. Alternative processes were compared in terms of the Net Energy Ratio (NER) of *biomass* production, defined as:

$$\text{NER Biomass} = \frac{\sum \text{Primary energy inputs (cultivation, drying, oil extraction)}}{\text{Energy content of dry biomass}}$$

If the NER is greater than unity, the process consumes more energy than it produces.

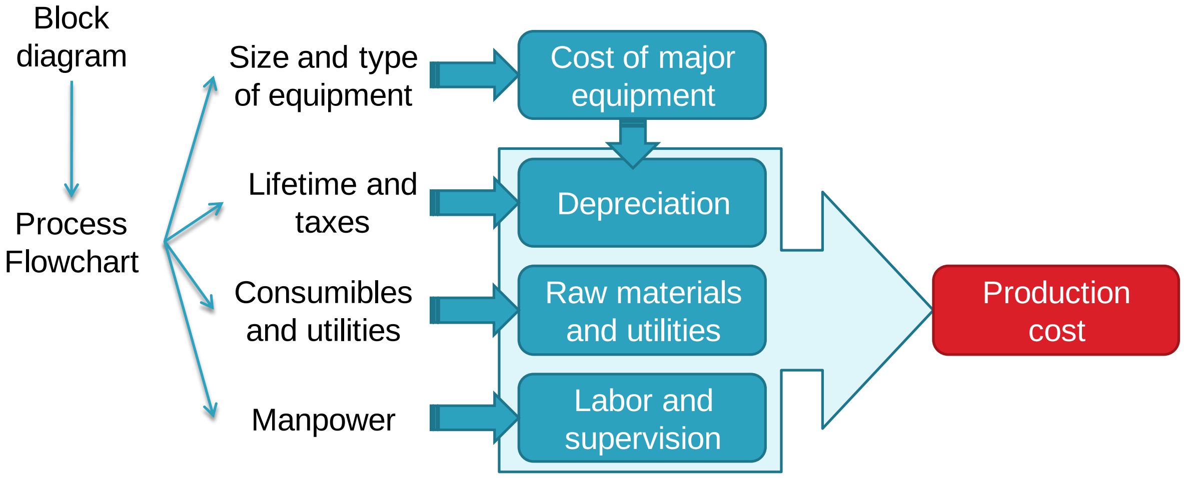
To calculate the $\text{NER}_{\text{Biomass}}$ three processes stages are considered: algal biomass cultivation, drying and dewatering and oil extraction. No co-product allocation was applied and we assume that the energy content of the dry biomass is equal to the lower heating value of the dry algal biomass specified in the original LCA studies. For those studies that didn’t specify heating values, estimates were made by summing the heating values of the biomass compositions given.

Primary Energy Inputs were assumed to include the energy content of the fossil fuel inputs only; i.e. the embedded energy from the production of the fossil fuel itself is excluded from the boundary. The energy associated with building the plant was also included (assuming a 20yr lifetime for concrete and 5yrs for PVC [2]).

9. Cost Model description and parameters

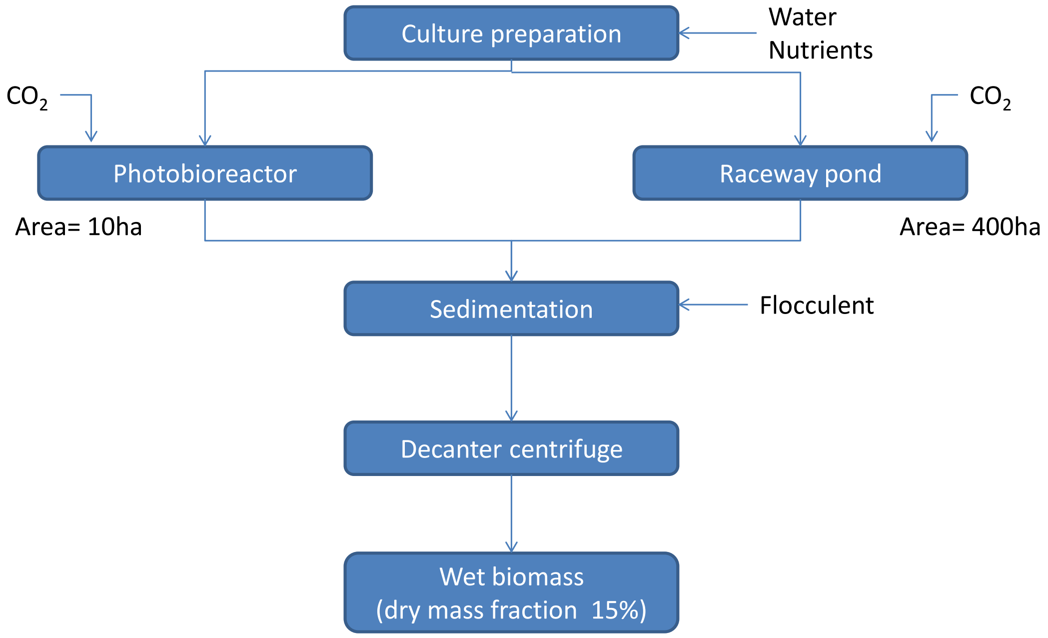
The cost modelling scheme is shown in Figure SI-3 below. Direct production costs include raw materials and utilities, in addition to labour and other costs. The life of the depreciated assets for the facility was assumed to be 10 years. The rate of raw materials consumption was calculated from estimated mass balances for the system. Utilities were quantified from the power and water use. Labour costs includes manpower for system operation and costs of supervision and management, in addition to maintenance, taxes, and contingency.

Figure SI-3. Cost modelling methodology



In the analysis presented here, raceway ponds and photobioreactors (PBR) are compared. The process steps are limited to cultivation and harvesting in both cases. For the PBR system, the process included automatic culture preparation (adding nutrients to water followed by filter sterilisation). The culture medium is then pumped around tubular PBRs. When the algae cells have accumulated sufficient lipid, the algae is settled using flocculants yielding a sludge that is centrifuged in continuous mode decanter to obtain a 15% dry matter paste. In the raceway pond the culture medium is prepared by adding fertilizers to the water directly and filtration is not required. The flow sheet for each process is shown in Figure SI-4.

Figure SI-4: Flowsheet for algae cultivation in photobioreactors and Racewayponds



All the scenarios assumed 400ha land area for open raceway system, and 10ha for closed photobioreactors (PBR). For all the cases, after dewatering process, the liquid medium is recycled, at least in part, back to the micro-algae growth units. In the base case it is assumed that CO_2 is purchased from the market. In the projected case, municipal wastewater is assumed to be the source of all water and nutrient input and that the source of CO_2 is a nearby power plant and assumed to be free. (It is worth noting, however, that in reality additional costs may be incurred for pumping and clean-up). The use of high value co-products to underpin the profitability of large plants is discussed in the literature. However, there is likelihood that production of high value products at a single large facility would saturate a relative small market so no particular product is assumed in this model. Several studies have also emphasized that a credit for wastewater treatment may help reduce the production cost of algae. We only assume we could get free water and nutrients from wastewater facility in the future. A complete breakdown of the other assumptions is described in Table SI-1 and SI-2 below.

Table SI-1: Variable cost modelling parameters

		Raceway pond				PBR			
		Base case		Projected case		Base case		Projected case	
Variable parameters	Units	Availability							
		low	High	low	High	low	High	low	High
Biomass productivity	g.m^{-2}.day^{-1}	10	10	20	20	20	20	40	40
CO2 usage (mass CO$_2$ per mass algae)		9.15	9.15	9.15	9.15	2.61	2.61	2.61	2.61
Water evaporation	L.m^{-2}.day^{-1}	10	10	10	10	0.5	0.5	0.5	0.5
Mixing power consumption	W.m^{-3}	1	1	1	1	500	500	50	50
Labour	People.ha^{-1}	0.18	0.18	0.18	0.18	0.36	0.36	0.36	0.36
Production days	Days	300	360	300	360	300	360	300	360
Land area	ha	400	400	400	400	10	10	10	10
Ratio Volume to surface area (V/S)	m	0.25	0.25	0.25	0.25	0.07	0.07	0.07	0.07
Dilution rate	Day^{-1}	0.02	0.02	0.02	0.02	0.4	0.4	0.4	0.4
Total culture volume	m^{3}	1000,000	1000,000	1000,000	1000,000	7000	7000	7000	7000
Total biomass production	Mg.ha^{-1}.year^{-1}	30	36	60	72	60	72	120	144
Total CO$_2$ consumption	Mg.ha^{-1}.year^{-1}	275	329	549	659	157	188	313	376
Total water evaporation	Mg.ha^{-1}.year^{-1}	30000	36000	30000	36000	1500	1800	1500	1800
Water cost	€.kg^{-1}	0.05	0.05	0	0	0.05	0.05	0	0
CO2 cost	€.kg^{-1}	0.1	0.1	0	0	0.1	0.1	0	0
Nutrients cost	€.kg^{-1}	0.4	0.4	0	0	0.4	0.4	0	0
Fertilizers use (mass fertilizer per mass algae)		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Power cost	€.kWh^{-1}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Power for harvesting and other operations	kWh.m^{-3} harvest	1	1	1	1	1	1	1	1
Photobioreactor cost	€.m-^{3}	10	10	10	10	2000	2000	2000	2000

Table SI-1: Fixed cost modelling parameters

Equipment Capacity	**Units**	**Raceway pond**	**PBR**
Medium preparation unit	$m^3.h^{-1}$	2,000	280
Sterilization process	$m^3.h^{-1}$	0	280
Air blower	$m^3.h^{-1}$	0	42,000
Photobioreactors	m-	1,000,000	7,000
Sedimenter	$m^3.h^{-1}$	2,000	280
Harvest storage tank	m^3	200	28
Decanter	$m^3.h^{-1}$	200	28
Harvest pump	$m^3.h^{-1}$	200	28
$m^3.h^{-1}$	$kg.h^{-1}$	73,200	522

Equipment Costs			
Medium preparation unit	€	855,775	120,172
Sterilization process	€	0	400,574
Air blower	€	0	374,274
Photobioreactors	€	7,081,580	10,111,762
Sedimenter	€	1,152,903	172,990
Harvest storage tank	€	17,569	2,595
Decanter	€	1,455,148	209,119
Harvest pump	€	15,047	2,399
CO2 supply unit	€	1,557,186	12,222

Fixed Capital Costs			
Major purchased equipment	€	12,135,208	11,406,106
Installation costs	€	2,427,042	2,281,221
Instrumentation and control	€	2,427,042	2,281,221
Piping	€	3,640,562	3,421,832
Electrical	€	1,213,521	1,140,611
Buildings	€	1,213,521	1,140,611
Yard improvements	€	606,760	570,305
Service facilities	€	2,427,042	2,281,221
Land	€	0	0
Engineering and supervision	€	2,427,042	2,281,221
Construction expenses	€	7,827,209	7,356,939
Contractor's fee	€	782,721	735,694
Contingency	€	2,598,937	2,442,789
Total fix capital	€	39,726,605	37,339,771

Fix Capital Costs per annum			
Lifetime	€	10	10
Depreciation	€	3,911,984	3,676,947
Property tax (@ 0.01 depreciation)	€	39,120	36,769
Insurance (@ 0.006 depreciation)	€	23,472	22,062
Purchase tax (@ 0.16 of items 1-12/10)	€	635,626	597,436

Direct Production Costs			
Raw materials			
Fertilizers (kg)	€	0	72,000
Water (m3)	€	0	350
Carbon dioxide (kg)	€	0	156,600
Utilities			
Water (m3)	€	0	750
Power mixing (kWh)	€	432,000	1,260,000
Power harvesting and others (Kwh)	€	36,000	4,200
Labor and others			
Labor	€	2,160,000	108,000
Supervision (@ 0.2 labor)	€	86,400	4,320
Payroll charges (@ 0.25 (labor + supervision))	€	140,400	7,020
Maintenance (@ 0.04 MEC)	€	19,416	18,250
Operating supplies (@ 0.004 items 1-5)	€	349	328
General plant overheads (@ 0.55 (labor + supervision + maintenance))	€	685,409	39,497
Tax (@ 0.16 items 1-7, 11 and 12)	€	506	476
Contingency (@ 0.05 items 1-7)	€	54,608	51,327
Marketing (@ 0.05 items 1-13)	€	99,317	93,349
Total raw materials	€	0	228,950
Total utilities	€	468,000	1,264,950
Total labor and others	€	3,246,406	322,568
Total fix capital per annun	€	4,610,202	4,333,214
Total direct production costs	€	3,714,406	1,816,468
Total production costs	€	8,324,608	6,149,682
Unit cost of producing biomass	€.kg^{-1}	0	10

10. Supplementary information references

[1] Lardon L, Helias A, Sialve B, Steyer JP, Bernard O. Life-cycle assessment of biodiesel production from microalgae. Environmental Science & Technology 2009; 43: 6475-6481.

[2] Stephenson AL, Kazamia E, Dennis JS, Howe CJ, Scott SA, Smith AG. Life-cycle assessment of potential algal biodiesel production in the United Kingdom: A comparison of raceways and air-lift tubular bioreactors. Energy Fuels 2010; 24: 4062-4077.