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1. Introduction

1.1 Algae for biofuels

Algae are a large and diverse group of plant-like aquatic organisms which range from multi-cellular macroalgae – e.g. seaweeds such as giant kelp, which can grow up to 60m – to unicellular microalgae – as small as 3µm. Most algae are photoautotrophic, converting solar energy into chemical forms through photosynthesis. They can also be farmed (algaculture) in diverse environments: some species thrive in freshwater conditions, others in saline conditions or sea water (Carlsson, et al., 2007, Schenk, et al., 2008).

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 or biodiesel transport fuels. They also produce proteins that could be used as a source of animal feed. Another attraction is that algae are fast growing, although productivity estimates need to be treated with caution.

In addition to being of economic interest, algae production could have a wide variety of environmental impacts. These will vary depending on the production technology and location, and may be positive (e.g. contributing to water remediation), or negative (e.g. release of nutrients leading to eutrophication). The nature of the impacts differs for micro- and macro- algae and this largely reflects the way in which they are cultivated. macro-algae may be harvested from the wild or cultivated off-shore on long ropes, on a very small scale it may also be cultivated on-shore in tanks. Micro-algae may be grown in raceway ponds or photobioreactors (PBRs).

This report summarises some of the key factors that will affect whether producing biofuels from algae is sustainable.

1.2 Objectives and structure of this report

This report reviews three aspects of the sustainability of micro and macro algae production: *energy and carbon balance*, *environmental impacts* and *economic viability*. The material presented here is drawn from reports produced within the EU FP7 Project "Aquafuels". The report is structured as follows:

- *Chapter 1:* Describes the objectives and structure of the report and introduces the AquaFUELs project of which this research is part.
- *Chapter 2:* Reviews the sustainability of bio-fuel production from micro-algae. The energetic performance, environmental and economic impacts are discussed here. The chapter concludes with a framework of key factors for sustainability assessment.

- *Chapter 3:* reviews the sustainability of bio-fuel production from macro-algae. The energetic performance and environmental impacts are discussed. The chapter concludes with a framework of key factors for sustainability assessment.
- *Chapter 4:* Conclusions and recommendations.

1.3 The Aquafuels project

The work presented here was undertaken within the context of an EU sponsored project: Aquafuels (AquaFUELs 2010). This project aims to bring together and co-ordinate existing knowledge, and 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 is to put robust and credible information about algae into the public domain, and thereby counter some of the more extravagant claims that have been expressed in the media.

2. The sustainability of the microalgae

2.1 Life cycle assessment: energy and carbon balance

There have been many attempts to estimate the energy and carbon balance of micro-algae biofuels production using life cycle assessment (LCA). LCA is a formalised method that aims to describe and quantify inputs and emissions from the production process and evaluate the results.

If micro-algae are to be a viable feedstock for biofuel production then the overall energy balance must be positive. Although there is a high level of interest, no industrial scale processes designed specifically for micro-algal biofuel production yet exist. Consequently the data that underpins micro-algae LCA must be extrapolated from laboratory scale systems and 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 highlight potential impacts and constraints upon system design.

Only a small[1] number of LCA studies are in the public domain, and, because of the lack of data, the ones that are available are to a large extent hypothetical. Cross comparison between studies is also impeded by the use of inconsistent boundaries and assumptions. The analysis undertaken within Aquafuels project sought to compare the results from existing LCA on a consistent basis. This was done using a simple a meta-model to normalise boundaries and assumptions for the *cultivation*, *harvesting* and *oil extraction* stages. The results of this analysis are shown in Figure 2.1, described in terms of the net energy ratio[2] (NER) of biomass production. It can be seen that in all cases the primary energy input for the normalized process is equal to, or less attractive than, the original case. It is also noticeable that the closed systems, especially tubular PBR, demonstrate poor energetic performances compared to raceway ponds.

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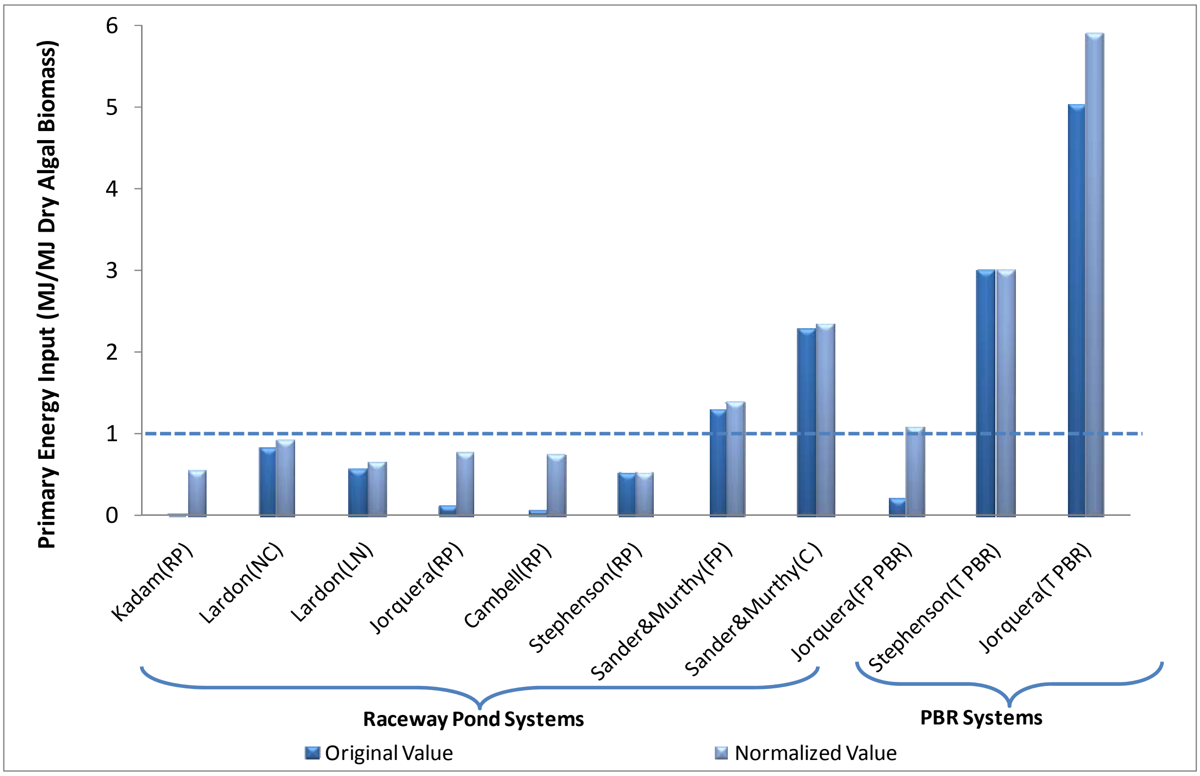
[1] A review of the academic literature in late 2010 identified seven studies – we are aware that ongoing projects are aiming to publish further in this area in the near future.

[2] 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. Provided the NER is less than unity, the process produces more energy than it consumes.

Figure 2.1: Net energy ration for micro-algae biomass production: comparison of published values with normalised values.



NC: Normal Cultivation; LN: Low Nitrogen Cultivation; FP: Filter Press; C: Centrifuge; Flat-plate PBR: Flat-plate Photobioreactor; Tubular PBR: Tubular Photobioreactor. RP: Raceway Pond
****=Normalised system boundary***

The carbon dioxide emissions associated with algal biomass production were estimated by multiplying the primary energy inputs to the process by the default emissions factors described in the EU renewable energy directive (2009/28/EC)[3]. The results obtained are shown in Figures 2.2 and 2.3. These results essentially mirror the results for the energy consumption: the majority of emissions are associated with electricity consumption and heat used 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.

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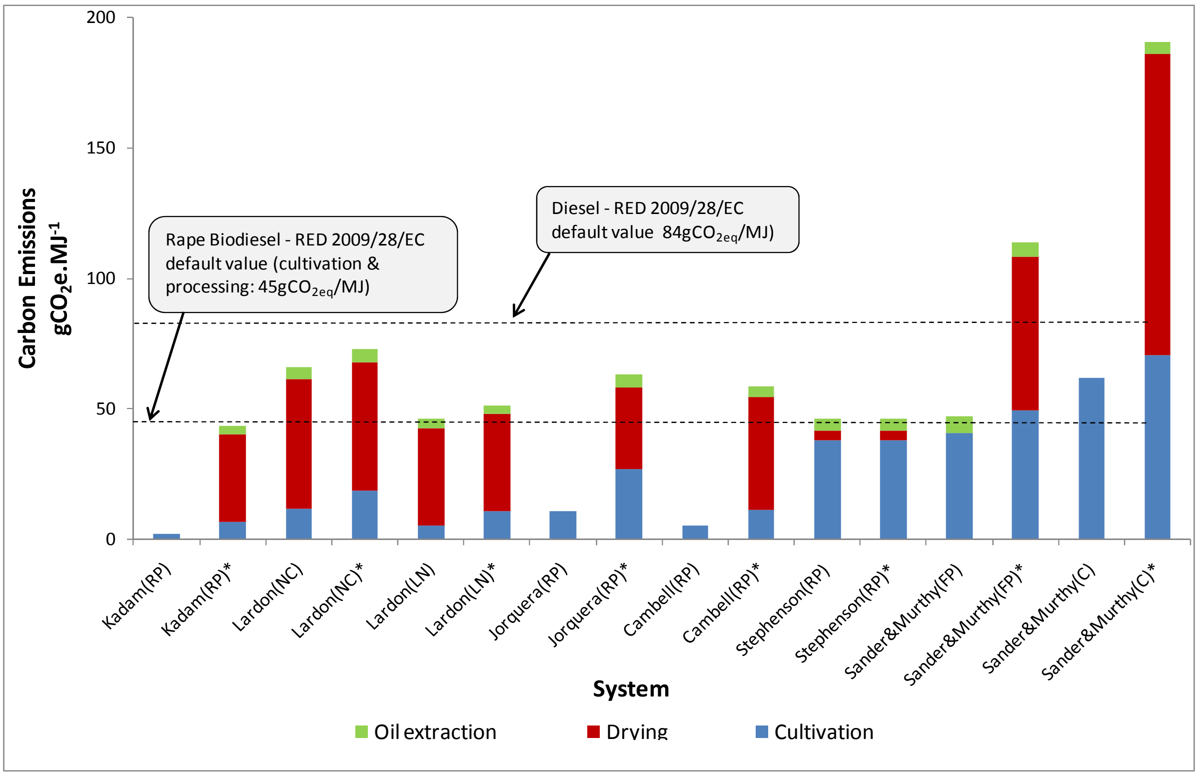
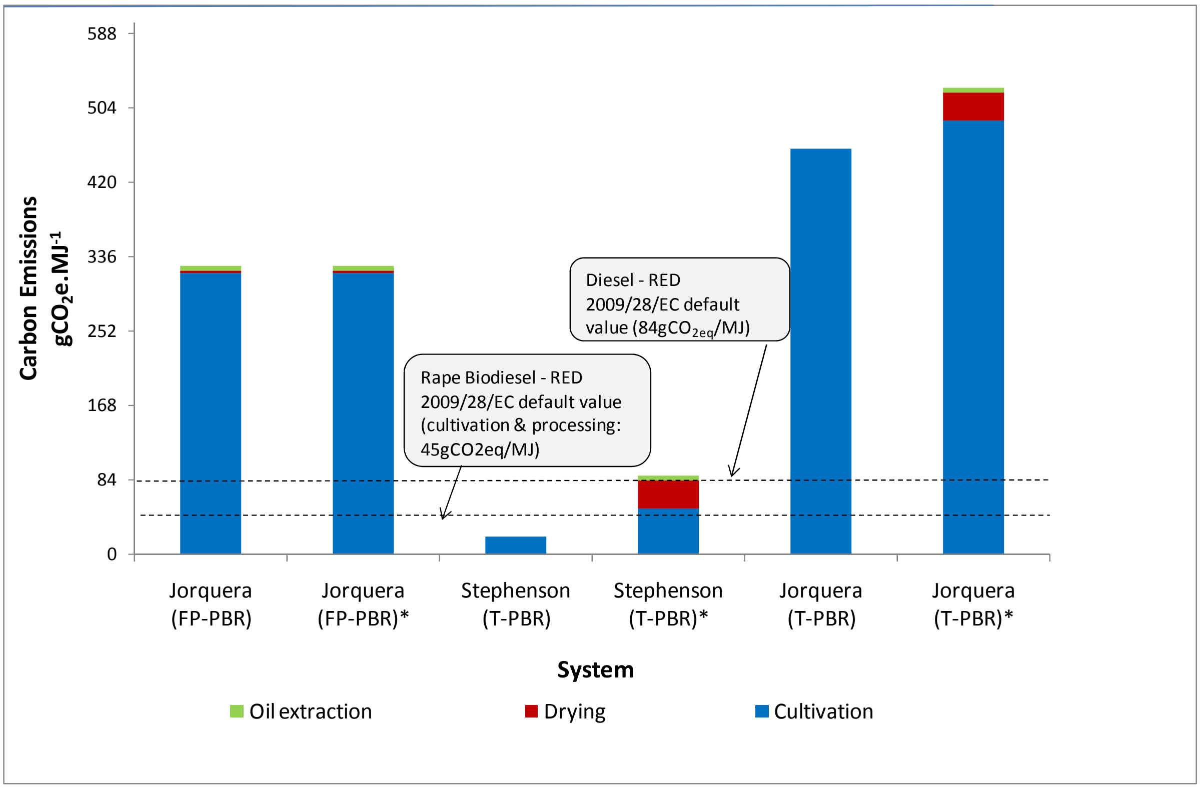
[3] The default emissions factors outlined in the renewable energy directive(2009/28/EC) are – diesel: 83.80gCO_2.MJ^{-1}; electricity: 91 gCO_2.MJ^{-1}; Heat: 77 gCO_2.MJ^{-1}. The emissions factor for the embodied energy in fertiliser and for production of PVC lining (in the case of raceway ponds) and tubes (in the case of PBRs) was assumed to be the same as for heat.

Figure 2.2: Illustrative estimates for carbon dioxide emissions from algal biomass production in raceway ponds



NC: Normal Cultivation; LN: Low Nitrogen Cultivation; FP: Filter Press; C: Centrifuge; RP: Raceway Pond
****=Normalised system boundary***

Figure 2.3: Illustrative estimates for carbon dioxide emissions from algal biomass production in photobioreactors



FP PBR: Flat-plate Photobioreactor; T PBR: Tubular Photobioreactor
****Normalised system boundary***

2.1.1 Conclusions on energy balance of micro-algae production

Re-examining the LCA studies for micro-algae production provides some insight into the assumptions used in each of the studies and the energy balance for micro-algae biomass production. We consider that this analysis supports the following conclusions:

- Raceway Pond Systems demonstrate a lower (more desirable) NER for both biomass and lipid production than PBR Systems.
- The NER for biomass production in the normalized system described is unattractive, or at best, marginal. This indicates that algae production may be most attractive where energy is not the main product.
- The most optimistic NER values for algae production come from the systems that are the least complete. The addition of additional process steps makes the NER less attractive in all cases.
- The carbon emissions from algae biomass produced in raceway ponds is comparable to the emissions from conventional biodiesel.
- The carbon emissions from algae biomass produced in PBRs is greater than the emissions from conventional diesel. The principle reason for this is the electricity used for pumping the algal broth around the system.

- While the meta-model includes some additional process steps, others might also reasonably be included in a complete system. These include: the energy embodied in chemical flocculant, and hexane loss during harvesting and lipid extraction. In hot climates PBRs may also require cooling. The addition of these processes would make the NER less attractive.
- There is a significant variation in the energy consumed in the cultivation and harvesting phase per MJ algae (biomass or lipid) produced. Key assumptions that affect this are the productivity of the algae, its calorific value and lipid content (assuming both a high productivity and high lipid content may be over optimistic.)
- Assumptions in the original studies are often obscure, or open to interpretation. For example, one of the studies (Kadam 2002) 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 possible that the missing nitrogen may be recycled or come from some other source.
- 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: the energy required for pumping, the embodied energy required for construction, the embodied energy in fertilizer, and the energy required for drying and de-watering.

2.2 Environmental impacts

Micro-algae production could have a wide variety of environmental impacts beyond the consumption of energy in the production process. These impacts were reviewed during the course of the Aquafuels project. The main classes of impacts are considered here.

2.2.1 Water Resources

A reliable, low cost water supply is a critical factor in the overall success of biofuel production from micro-algae. Fresh water needs to be added to raceway pond systems to compensate water evaporation; water is also used for cooling Closed Systems (PBRs). One suggestion is that algae cultivation could utilize water with few competing uses, such as seawater and brackish water from aquifers. Brackish water, however, may require pre-treatment if the chemical constituents of the water could inhibit algae growth. This pre-treatment could raise the energy demand of the process (Darzins, Pienkos et al. 2010). Evaporation would still need to be compensated to prevent salinity increasing.

The distance to the water source is also an important factor in locating the cultivation site, as 100 meters elevation could mean that 6% of the energy produced by the algae would be used for pumping (Lundquist, Woertz et al. 2010).

2.2.2 Land Use

One of the suggested benefits of algae production is that it could use marginal land, and thus would entail little additional competition on land required for food production. Land use change may have a variety of consequential impacts> Moreover, physical constrains from topography and soil could limit the land availability

2.2.3 Nutrient and Fertilizer Use

Algae cultivation requires several fertilizers, primarily Nitrogen (N), Phosphorus (P) and Potassium (K). The requirement for fertilization cannot be avoided as the algal biomass itself consists of ~7% Nitrogen and ~1% Phosphorus. Recycling nutrients from waste water could potentially provide some of the nutrients required.

2.2.4 Carbon fertilisation

Algae cultivation requires a source of carbon dioxide as producing 1 kg dry algal biomass requires at least 1.83kg CO_2 (to provide the carbon contained in the algae). In reality, CO_2 usage will several times higher. For example, in open raceways the CO_2 fixation efficiency is less than 10%. For thin layer cultivation the CO_2 efficiency is roughly 35%. In closed tubular photobioreactors (PBRs) the CO_2 efficiency may be up to 50%. Only by using advanced control strategies might the CO_2 efficiency be increased. It is generally not permissible to expulse CO_2 in large amounts at ground level. If CO_2 from flue gas were used, managing these gases could have negative effect on the energy balance of the system, it may also be restricted for health and environmental reasons.

2.2.5 Fossil Fuel Inputs

As discussed in the previous chapter, the majority of the of the fossil fuel inputs to algae cultivation come from electricity consumption during cultivation sector and natural gas consumption from the biomass drying process. Algae are quite sensitive to temperature, and maintaining a high level of productivity could also require temperature control. If required, both heating and cooling could require additional fossil fuel. The environmental performance could, however, be improved by system integration that to utilize the waste heating from power generation for drying the algal biomass.

2.2.6 Eutrophication

Nutrient pollution is termed eutrophication and can lead to highly undesirable changes in ecosystem structure and function. The impact of algal aquaculture on eutrophication 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 eutrophication.

2.2.7 Genetic Modified Algae

In the search for algae that can deliver both a high biomass productivity and a high oil content, genetic modification is one possible option (Lundquist, Woertz et al. 2010).

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 could be desirable include herbicide resistance to prevent contamination of cultures by wild type organisms. GMO cannot be contained in open systems, culture leakage and transfer (e.g. by waterfowl) is unavoidable. Closed bioreactors may appear more secure but Lundquist et al., (2010) comments that PBRs are only cosmetically different from open ponds and some culture leakage is inevitable.

2.2.8 Algal toxicity

Many algae species can produce a variety of toxins ranging from simple ammonia to physiological active polypeptides and polysaccharides. Algal toxicity may be a concern where co-products are used to produce food. Where algae are harvested from the wild for human consumption the principal concern is contamination from undesirable species.

2.2.9 Conclusions on environmental impacts of micro-algae production

Micro-algae culture can have a diverse range of environmental impacts. Many of these impacts are location specific, e.g. water and land use. Impacts such as the use of genetic engineering are uncertain, but may affect what systems are viable in particular legislatures. The impacts presented here are the ones identified as most important in the existing literature, but should not be considered exhaustive. In any algae cultivation scheme it should be anticipated that environmental monitoring will play an important role and will be an ongoing requirement.

2.3 Economic impacts

Economic analysis is a powerful tool that can be used to both evaluate the ultimate cost of algae biofuels and help identify the major factors which contribute most to the production cost – thereby helping to focus future engineering research. The analysis undertaken within the Aquafuels project reviewed recent literature, and provided an illustrative analysis of the current and projected costs for producing algal biomass in raceway ponds and photo-bioreactors. These analyses drew on the experience of experts within the Aquafuels consortia, and a roundtable meeting on the state of the art and future perspectives for algae biofuels held in Brussels in October 2010.

From our review of the literature we conclude that:

- Existing cost assessments are hypothetical in nature. There are limited sources of primary data: some sources and assumptions are over two decades old and may not reflect the current state of micro-algae culture.
- Estimates and assumptions, particularly those for *algal productivity*, *CO_2 capture efficiency* and *system availability* often reflect future aspirations rather than currently achievable results.
- The production of co-products, or provision of co-services, greatly affects estimates of economic viability.

Combining data from the literature with estimates solicited from experts, four scenarios for cultivation and harvest of micro-algae from in raceway ponds and PBR systems were described and compared.

The first two scenarios: *base-case high/low* aimed to illustrate what might be achieved by integrating current technology. The difference between the high and low case was the number of productive days assumed per year (300 cf. 360 days). The second two scenarios *projected-case high/low* assumed that productivity could be increased and that the main inputs[4] were free of charge.

A comparison of the cost of producing algal biomass for each of these scenarios is shown in Figure 2.4. Overall it can be seen that producing biomass in a PBR (4-10€/kg) is roughly 5-10 times more expensive than in raceway ponds (0.4-1.8€/kg). It can also be seen that there is little difference between the low and high availability cases (~5%), whereas moving from the *base case* to the *projected case* results in a ~50% decrease in costs. For comparison, the market price for delivered woody biomass pellets in the UK is ~ 0.2-0.4€/kg (E4tech 2010) (although it should be noted that the composition and potential uses of algal biomass are more interesting).

Both the *base case* scenarios consume a great deal of CO_2 (because the open pond system has poor CO_2 fixation performance), and this dominates the production cost (~1.8€/kg). The *projected case* gives a much reduced cost (~0.25€/kg). 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. Only in this optimistic scenario can the production cost approach the level required to service the biofuels market.

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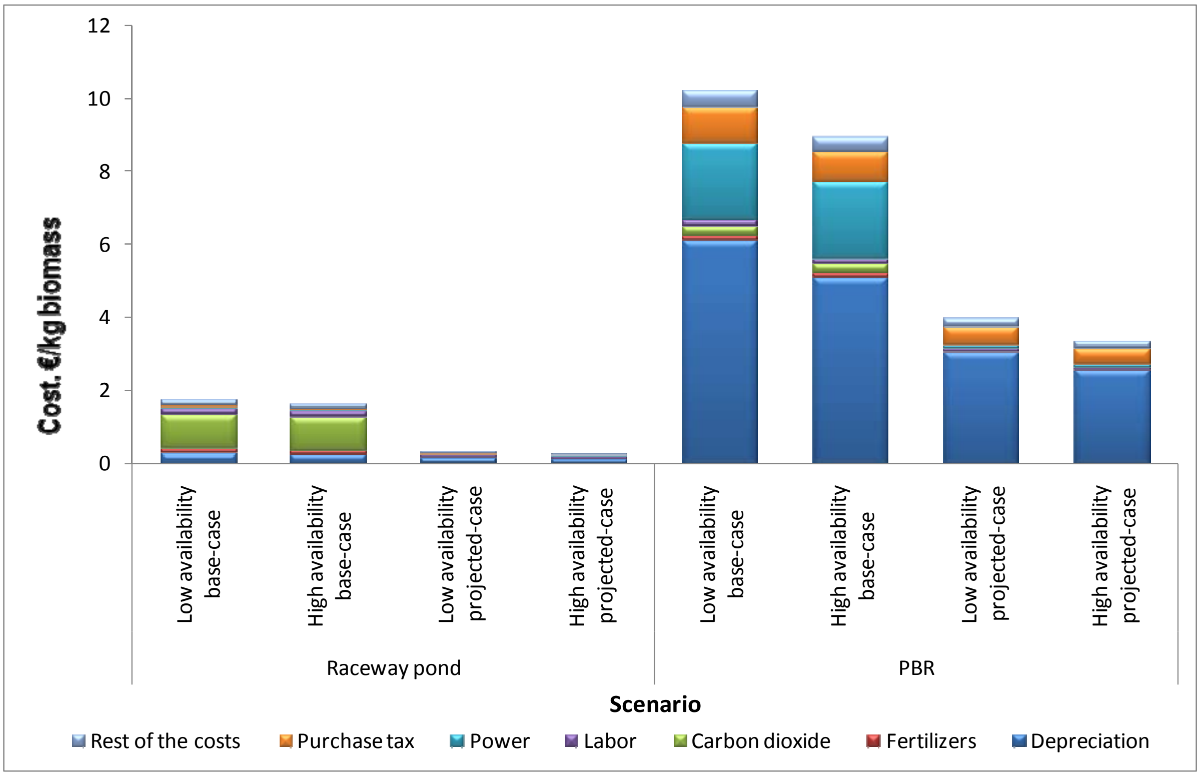
[4] CO_2 was assumed to come from flue gases; nutrients were assumed to come from wastewater

Figure 2.4: Breakdown of cost estimates for both Raceway Pond and PBR



The results shown here are likely underestimate the true cost of algae production. This is because a real project would incur other significant costs such as the cost of finance and the cost of land which have been excluded from this analysis. The two future scenarios also postulate dramatic improvements in technical performance that may, or may not, be achieved.

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 costs in raceway system production are associated with operation (labor, utilities and raw materials). The cost of production in PBRs, in contrast, is dominated by the capital cost of the PBRs[5].
- Dramatic improvements in both productivity and energy efficiency would be required to greatly reduce the cost of biomass production.
- Significant (>50%) cost reductions may be achieved if CO_2, nutrients and water can be obtained at zero cost. This is a very demanding requirement, however, and it could dramatically restrict the number of locations available.

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[5] The cost of harvesting from a PBR may be less than from a raceway pond, differences here will depend on the specific combination of technologies selected, algae species etc.

From the discussion of the economics of algae production, held at the AquaFUELs roundtable in 2010, we concluded that:

- Experts in algae production are cautious about its future prospects for use as a biofuel feedstock. There was a consensus that biofuels could not be the only end market, co-product and co-service valorisation would be essential.
- Many opportunities to reduce costs exist though improved engineering and biotechnology,

2.3.1 Conclusions on economic impacts of micro-algae production

Cost assessments of micro-algae production are at an early stage of development. They are appropriate to guide engineering development, and test the sensitivity of design assumptions, but they are insufficient to guide policy or investment decisions in anything but the broadest of terms.

Improving on the existing cost estimates will require empirical data on the performance of systems designed specifically to produce biofuels. Ideally this date would come from systems operated for an extended period of time at large scale.

2.4 A framework for assessing the sustainability of micro-algae production.

Key issues that will affect the sustainability of micro-algae production are presented in Table 2.1

Table 2.1: A framework for assessing the sustainability of micro-algae production

Sustainability factor	Key issues
Energy balance and CO_2 emissions	
Energy balance must be positive	The following aspects will need to be addressed in a viable commercial system: • energy required for pumping (water and gases) • embodied energy required for construction • embodied energy in fertilizer • energy required for drying and de-watering
Process assumptions must be realistic	Caution is needed that assumptions are not over optimistic. Key parameters include: • algae productivity • calorific value • oil content It should be noted that a high productivity may be incompatible with a high oil content.
Environmental performance	
Water Resources	Water management is a critical issue • Evaporation must be compensated • Pumping costs limit height above sea level in systems using

	seawater - Nutrient leakage may cause eutrophication - Use of waste water may limit use of co-products
Land Use	This is excluded from many analyses. On a large scale impacts may be very important
Nutrient and Fertilizer Use	The requirement for fertilization cannot be avoided. Recycling nutrients from waste water could potentially provide some of the nutrients required.
Carbon fertilisation	CO_2 efficiency has the potential to be a major issue. Producing 1 kg dry algal biomass requires at least 1.83kg CO_2 but in reality will several times higher. Handling large quantities of CO_2 or flue gas at ground level presents an environmental hazard,
Eutrophication	Where fertilizer is used, release of spent growth media into the environment may be a hazard.
Algal toxicity	Production of toxins depends on species and cultivation conditions. Contamination may be a problem if any products enter the food chain
Genetic Modified Algae	Containment presents a challenge in both open ponds and photobioreactors
Economic performance	
Applicability of costing methodology	Current methods are appropriate to guide engineering development and test the sensitivity of design assumptions only. (Improved methods require better data)
Cost of inputs	Inputs (CO2 and water) may only be available at significant cost. (Many models assume that they are free).
Cost of capital	Reductions in capital cost are required
Co-products / Co-services	The production of co-products (or provision of co-services) is likely to be essential. Co-product valorisation will be more difficult if the process uses waste water or flue gas as an input.
Performance data	Empirical data on the performance of systems designed specifically to produce biofuels is required. Ideally this date would come from systems operated for an extended period of time at large scale.

3. The sustainability of macro-algae

3.1 Life cycle assessment: energy and carbon balance

No detailed LCA for the energy and carbon balance of macro-algae are available in the literature. This is attributed to a lack of data with which to populate the models, and, until recently, a relatively low level of interest.

In contrast to micro-algae, there is extensive experience of macro-algae cultivation in South-East Asia. Despite the existence of a large-scale and fully commercial industry, however, it appears that the environmental impacts of macro-algae production remain uncertain (whether positive or negative). The authors are aware, however, of a number of research projects expected to publish on this subject in the near future.

3.2 Environment impacts

Macro-algae production could have a wide variety of environmental impacts. These impacts are related to the four main cultivation methods: cultivation at sea; cultivation in tanks; harvest of the wild resource, and harvest of nuisance bloom species. The impacts of each cultivation scenario may be considered in terms of *land and sea-surface area required, Use of fresh water, fertiliser and nutrients, genetic engineering,* and *ecosystem effects.*

3.2.1 land and sea-surface area

Space in the near-shore coastal environment is likely to be limited, particularly in Europe where there is intense competition for coastal resources. Cultivation further offshore is possible but brings additional challenges and costs.

3.2.2 Use of fresh water

Freshwater requirements for production of marine macroalgae are minimal and are limited to equipment care and maintenance.

3.2.3 Fertiliser and nutrients

Fertilisation at sea, it is unlikely to be an acceptable option. Conversely, the high capacity of kelps to remove inorganic N and P from the environment makes them potential nutrient ‘scrubbers’ and their ability to mitigate the impact of nutrients from fish farms (and other sources) is being assessed.

3.2.4 Macro-algal Domestication and Genetic Engineering

Macro-algae cultivation is in its infancy by comparison with terrestrial crops. Domestication of kelp began in earnest in China during the mid 1950’s, and strain selection began to be developed in the early 1960’s (Zhang, Liu et al. 2011). Strain selection has led to dramatic increases in yields in recent years and is considered vital to development of an economically viable industry.

3.2.5 Ecosystem Effects

Cultivation at sea: again there is little published data. Effects on the benthos have been demonstrated. Physical and biological changes have also been observed, for example: decreased sediment organic matter, decreased macroalgae and seagrass diversity, decreased abundance and biomass of macrofauna, and a shift in seagrass community structure – these changes, via speculated mechanisms of shading, emergence stress and mechanical abrasion, are typically associated with a decrease in ecological quality

Wild Harvest: Kelp forest ecosystems have a high intrinsic ecological stability and are relatively resilient. They can withstand considerable physical disturbance, including that of harvesting. However, kelp individuals and ecosystems support a very diverse and abundant flora and fauna e.g. Christie et al. (2003), Norderhaug et al. (2003) and studies have shown that the resilience of the associated communities tends to be less than that of kelp forest itself and the recovery times post-harvest slower than for the kelps (Christie, Fredriksen et al. 1998). Further to this, multi-trophic interactions are largely unknown. Kelp ecosystems tend to provide trophic subsidies to other inter-related ecosystems so de-stabilisation of kelp ecosystems has the potential to have far-reaching consequences. The effect will be very much dependent on scale of the harvest.

Harvest of blooms: Removal of bloom biomass is important to prevent anoxic conditions developing as the biomass begins to rot. Bloom events resulting from eutrophic water bodies are not uncommon and can result in substantial quantities of biomass however, they may be unpredictable in terms of time and space which results in logistical difficulties for harvesting and processing, particularly in terms of transport of a wet, bulky material, which will impact the GHG emissions budget for the process.

3.3 A framework for assessing the sustainability of macro-algae production.

Key issues that will affect the sustainability of micro-algae production are presented in Table 3.1

Table 3.1: A framework for assessing the sustainability of micro-algae production

Sustainability factor	Key issues
Energy balance and CO$_2$ emissions	
Energy balance must be positive	Despite the existence of a large-scale commercial industry the energy balance is not known.
Environmental performance	
Water Resources	Water management is not thought to be a major issue.
Use of nearshore sea area	Competition may be anticipated.
Nutrient and Fertilizer Use	Fertilization is likely to be impractical.
Carbon fertilisation	Fertilization is likely to be impractical.
Eutrophication	Macro-algae present an opportunity to remove nutrients from eutrophic water bodies.
Algal toxicity	Production of toxins depends on species and cultivation conditions. Contamination may be a problem if any products enter the food chain
Genetic Modified Algae	Strain selection presents opportunities to increase yield. Containment is not possible.
Economic performance	
Financial viability	Production for food and chemicals is already viable and practiced on large scale in SE Asia.

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