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Feasibility Study of Algae Biodiesel Production in the Cambois Peninsular (UK)

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ABSTRCT: *The main aim of this project was to undertake a feasibility study of microalgae biodiesel production from the Cambois peninsular, Northumberland England. This particular project site was chosen for its potential to support microalgae growth i.e. close proximity to both water and CO_2 source. Microalgae chlorella specie was chosen for this analysis because of its good productivity (22g m^{-2} day^{-1}) as well as high lipid content (50% dry weight). The analysis considers 150 days farm production (March to August) due to low temperature in the winter. A comparative analysis of foam column microalgae harvesting process followed by oil extraction through in-situ transesterification was undertaking against the conventional centrifugation-harvesting route followed by conventional tranesterification. Lastly a hybrid of the 2 processes of centrifugation followed by in-situ transesterification was also analysed side by side. The 3 different biodiesel processing routes were examined based on final biodiesel yield, cost and energy consumption. The centrifugation route provides high biodiesel yield of 115 L ha^{-1} day^{-1} but with associated high energy and centrifuge installation cost. Foam column separation yield 110 L ha^{-1} day^{-1} with optimum power consumption and installation cost. The hybrid system yield 100 L ha^{-1} day^{-1} with minimum power consumption but may suffer set back due to high cost of centrifuge cost and maintenance. The best-case scenario of foam column separation process was further evaluated to validate its economic potential for large-scale biodiesel production as against the current price of fossil diesel. The outcome confirms the potential of microalgae biodiesel to be cost competitive with diesel if the harvesting process is substituted with the foam column separation technique, while the traditional oil transesterification be substituted with the in-situ transesterification technique.*

KEYWORDS: Microalgae, Biodiesel, Insitu-transesterification, Foam-column separation.

INTRODUCTION

It seems probable that, climate change, greenhouse gas effects, depleting freshwater resources in some regions, growth in human population and shortages of agricultural land will favour the use of third generation biofuel production system such as microalgae. The ability of microalgae to be cultivated on land not suitable for agricultural food production as well as on waste water resources give algal biofuel production systems advantage over first and second generation biofuels production system. This has generated lots of interest in governments, NGOs, the private sector and the research community. Current initiatives such a the carbon trust algal biofuels challenge in the UK and the Aquatic Species Program (ASP) of the 90s in the USA and investment by Shell Petroleum in algae research clearly shows the levels of interest by government and the private sector in the development of algal derived biofuels technologies and enterprises.

As worldwide petroleum reserves diminish due to consumption exceeding discoveries, many countries are becoming increasingly dependent upon imported sources of oil (Darzins et al., 2010). The UK, for example, imports 12% of the 74.4 million tonnes of oil used in 2009. This figure is expected to reach 44% by 2020 (SECURITY, 2010). The demand for energy is growing worldwide especially in many of the fast developing nations such as in China and India. Furthermore, the continued combustion of fossil fuels has created huge environmental issues over global warming as a result of increased release of Green House Gases (GHG).

Biofuels are one of the potential options to reduce the world‘s dependence on fossil fuels but biofuels have their limitations. One of the recent concerns with respect to increased biofuels production is land availability. It is recognized that the GHG benefits of biofuels can be offset if land with existing high carbon intensity is cleared for the production of biofuel feedstocks. Biofuels that could be produced without encroaching arable land, or reductions in tropical rainforests could be very attractive in the future. Algae may offer that opportunity. The basic concept of using algae as a renewable feedstock for biofuels production has been known for many years. However, historical efforts in this field have been inadequate to facilitate the development of a robust algal biofuels industry. Realizing the strategic potential of algal feedstocks will require breakthroughs, not only in algal mass culture and downstream processing technologies, but also in the fundamental biology related to algal physiology and the regulation of algal biochemical pathways (Darzins et al., 2010).

Aim of the Project

The main aim of writing this project was to assess the feasibility of microalgae biodiesel production in Cambois Peninsular as a business option for the local authorities and or business organisation by utilising the available resources located at site to reduce cost and improve production.

Project Site

The proposed site for this feasibility study lies within the Cambois Peninsular, a 140 hectares of land almost surrounded by the tributaries of river Blyth and the A189 Road (Fig 1). The land houses some few settlement and electric pylons from the former power station pass through the area. To the east of the proposed area is the Blyth estuary, the beach and the North Sea. To the west there is the A189 trunk road locally known as the Spine Road and the local habitation. To the north is the demolished site of the old Blyth power station. To the south are the tidal mudflats of the River Blyth and the lower reaches of Sleek Burn,which are designated as a Site of SpecialScientific Interest (SSSI). To the south side of the estuary is Blyth Town Centre and Blyth Harbour.

The site is proposed for residential area from the Cambois Vision Plan (northumberland, 2007) but due to lack of access and susceptibility to flood is making the plan more difficult. The high tension cables that runs through the area from the old power station are also making the situation no better. On the contrary the selection of the area for the proposed project was determined by

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various favourable conditions (economic and environmental) the site offer for microalgae cultivation. These conditions are; the unfavourable nature of the site for both residential and agricultural use, the proximity of the site to the proposed nPower Power Plant which was schedule to be built soon (npower, 2007) . Part of the flue gas coming from the power plant, which contains CO2, will be used to feed the microalgae. This will serve as the CO_2 sink of the power plant as against the Sea. The waste heat from the power plant will also be used to warm the algae ponds during the winter months. The algae residue that will be produce after the oil extraction can also be utilised as a feedstock for the power plant or as valuable by-product. The close proximity of the site to the North Sea (500m) also offers a great opportunity as a source of water for the algal cultivation. The location of 4 Rivers biofuel at the West Sleekburn, who are leading biofuel producers in the peninsula also has a great advantage to the proposed project as it may provide biofuel processing and bulk storage facility. All these advantages add up together will certainly bring down the production cost of the business thus making it much more viable. Finally the proposed project will certainly create job for the teaming local populace as well as improving the local economy.

Figure 1: Propose project site in relation to other important sites (Google Maps)

OPEN POND ALGAE CULTIVATION

The vast majority of microalgae produced today are grown in open ponds. Due to their economic nature in terms of construction operation and maintenance open ponds offer lots of advantages as long as the species for cultivation can be maintained (Weissman et al., 1989). Open ponds are built in different form of sizes and shapes but the most common design is the raceway pond. An area is divided into a rectangular grid, with each rectangle containing a channel in the shape of an oval; a paddle wheel is used to drive water flow continuously around the circuit. They usually operate at water depths of 20–30 cm, as at these depths biomass concentrations of 1 g dry weight per litre and productivities of 60–100 mg L^{-1} day^{-1} (i.e. 10–25 g m^{-2} day^{-1}) are possible (Pulz and Gross, 2004). However, such productivities are not the rule and cannot be maintained on an annual average especially in the North East of UK where the proposed project site is located. Open ponds are relatively easy to maintain since they have large open access to clean off the biofilm that builds up on surfaces.

The main drawback of open systems is that, they lose water by evaporation at a rate similar to land crops and are prone to contamination by unwanted species as a result of exposure to the atmosphere. A new open pond is typically inoculated with the desired algal strain to initiate growth and dominate the pond. But, with time other species may inevitably grow in the pond thus competing with the desired strain. This can reduce yield or even cause the extinction of the desired strain from the pond. Once an unwanted strain has taken over a pond it is extremely difficult to remove. Practically open ponds are usually reported to be dominated by at least six species with varying evolutionary advantages: fast growth, predator resistance, high oxygen tolerance, etc. Sustained and reliable cultivation of a single algae strain in open pond systems can however be encouraged by cultivating strains that dominate, tolerate and outcompete other strain in a particular environment (e.g. high/low pH or salinity).

Algal Strain Selection

The algal strain that will be utilised for this project is the Chlorella sp (Fig 2). ***Chlorella*** is a genus of single-celled green algae, belonging to the phylum Chlorophyta. It has an oval shape of about 2 to 10 μm in diameter, and is without flagella. Chlorella contains the green photosynthetic pigments chlorophyll-a and -b in its chloroplast. Chlorella is a very fast growing and robust algae with adequate nutrients, it can double in concentration in 8 hours (Sheehan et al., 1998). Through photosynthesis it multiplies rapidly requiring only CO_2, water and sunlight, and a small amount of nutrients to reproduce. Chlorella can grow photoautotrophically or heterotrophically under different culture conditions (Xu et al., 2006). Heterotrophic growth of chlorella supplied with organic compounds such as carbon source, results in high biomass and high content of lipid in cells of 20% dw (Xu et al., 2006). With the addition of the organic carbon source (glucose) to the medium and the decrease of the inorganic nitrogen source in the medium, the heterotrophic chlorella can produce crude lipid content up to 55.2%, which was about four times that in photoautotrophic chlorella (Miao and Wu, 2004). Therefore, chlorella has not only become an important source of many products, such as aquaculture feeds, human food supplements, and pharmaceuticals (Running et al., 1994), but also been suggested as a very good candidate for biofuel production (Wen et al., 2002). The only setback for using chlorella as biodiesel feedstock is the high requirement of inoculums needed to start the culture, invasion of the culture medium by unwanted species as well as harvesting difficulty due to their small nature. Some other characteristics that make chlorella our best candidate for this project include;

- All its fatty acids are saturated which gives good cetane number and oxidative stability to biodiesel.
- Palmitic acid content, which are known as the most common fatty acids contain in biodiesel, are present in chlorella.
- The hydrocarbon chain length of fatty acid is between C10 and C18.
- Chlorella has good biomass productivity in both open pond and photobioreactor approx. of 100-150 mg/l (Chisti, 2007).
- Production during the winter months of November - February may be reduced but still possible (Putt, 2007).

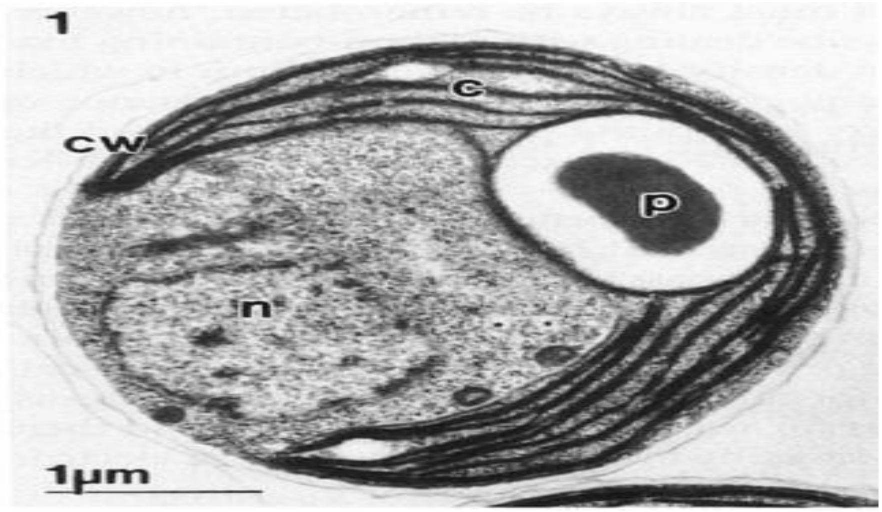


Figure 2: Chlorella Cell (Stead et al., 1995)

Site Conditions

Climate conditions, availability of CO_2, other nutrients (nitrogen and phosphorous), and water resources greatly affect algae productivity. In addition, land considerations, such as topography, use, and stewardship help define the land available for algae production. The perceived availability of water (of low quality with few competing uses), CO_2 and non-arable land resources in suitable climates is a significant driver for the development of algal biofuels. This section reviews these resources in terms of requirements for large scale algal biofuels production.

Climate (Temperature and insolation)

While algae's diverse nature has made them ubiquitous on the earth, the growth of any individual species (like all plants) is constrained by climate. **Fig 3** illustrates the climate parameters affecting open pond algal production systems.

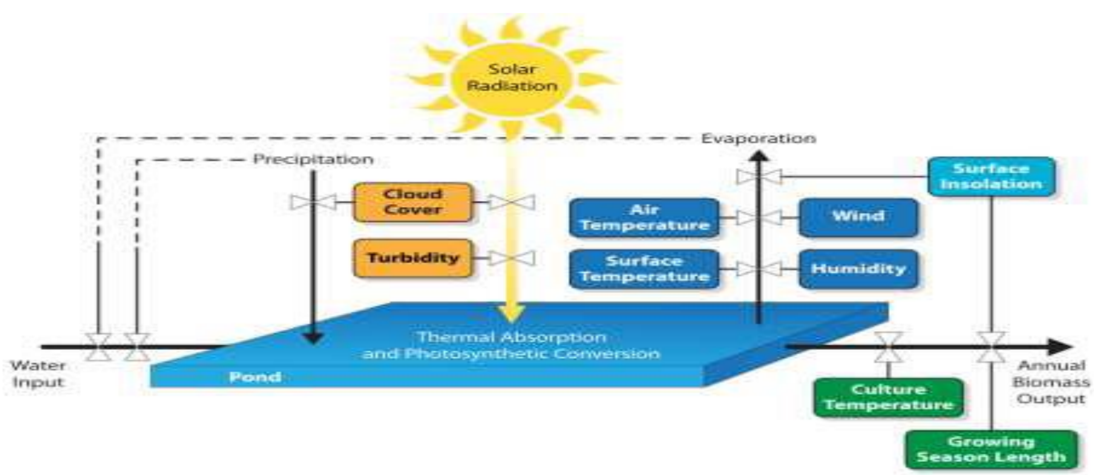


Figure 3: Climate Parameters Affecting Open Pond Algae Production Systems (Darzins et al., 2010).

Autotrophic algae, like terrestrial plants, depend upon sunlight for growth. However, algae evolved to thrive in a low light environment and have maximized their photosynthetic apparatus accordingly. While crop plants grow optimally in full sunlight, high solar radiation can inhibit algal growth and even cause cell death. Fig 4 illustrates the yearly sum of global solar irradiance averages over the period of 1981 to 2000 (Darzins et al., 2010). Solar radiation of ca. 1,300 $kWh \cdot m^{-2} \cdot yr^{-1}$ is considered adequate for algae production, which means the majority of the earth‘s land surface would appear to be potentially suitable for algae production.

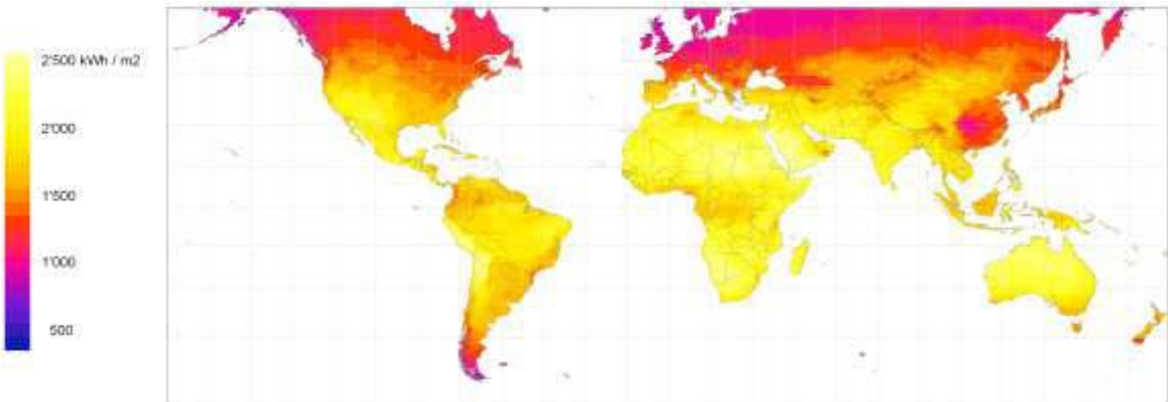


Figure 4: Yearly sum of global solar irradiance averages over the period of 1981 to 2000 (Darzins et al., 2010)

Terrestrial plants that grow in air are responsive to fluctuation in air temperature and sometimes with disastrous consequences for agriculture. Algae suspended in water are less responsive to fluctuation in air temperature since the water temperature will be a function of solar heating, evaporative cooling, and other process factors in open ponds. However, once climatic conditions drive the temperature of the water in open ponds outside of the physiological range for the algal strain production will cease or be challenged by invasive algal species. Consequently, while temperature has a direct affect on growth rate, ambient temperature range or climate defines the effective growing season for an algal production system.

Ambient temperature is strongly linked to economic feasibility. It is generally considered that year round production of algae in open ponds may be achievable where average monthly temperatures of the coldest month exceed 15 °C. There will likely be seasonal production in more temperate climates, with a consequent requirement to shut down and re-establish production on an annual basis. The UK average monthly climatic condition may not make it possible to grow algae in this kind of condition year round but the introduction of waste heat from power plant could significantly aid in overcoming the low temperature problem in the winter. While solar irradiance averages would indicate that the majority of the earth‘s land surface appears to be suitable for algae production, significantly less of this land would be suitable for year round cultivation. In the North East of England were the proposed site for this project lies, the average solar insolation is around $950kWh/m^2/yr$ on the average (Fig 5) (PVGIS © European Communities, 2001-2007). The optimum solar irradiation needed for algal growth is around $1300kWh/m^2/yr$, thus the total algal output in the proposed project site will decrease by about 30%.

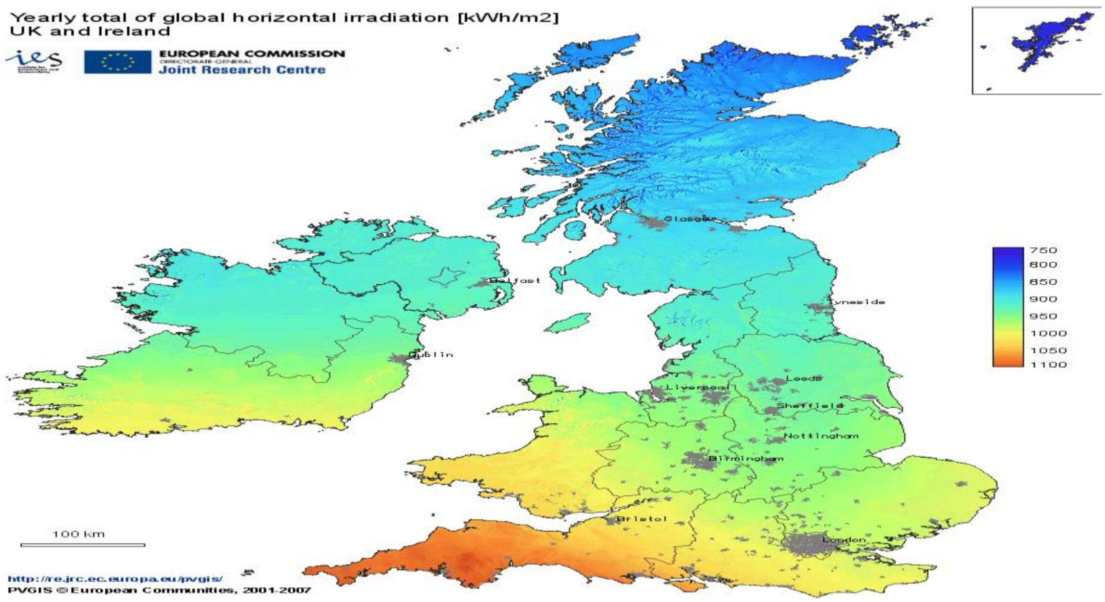


Figure 5: UK/Ireland Average Solar Irradiance.
[PVGIS © European Communities, 2001-2007
(http://re.jrc.ec.europa.eu/pvgis/countries/europe/g13y_uk_ie.png)]

Other climatic elements that impact on the suitability of land for large scale algal pond are precipitation, evaporation, and severe weather. Since sustainable open pond algal production systems are likely to be based on seawater resources, precipitation (as in the case of this project) constitutes significant challenge to the production system. Such precipitation into a 20-30 cm deep pond reduces salinity, causes osmotic shock and death in the algal culture. While evaporation increases water requirements for an algae growth system, it is relatively consistent and the impact on salinity is manageable by dilution (especially in the case of hypersaline systems fed by seawater). Hypersaline systems fed by seawater produce less effluent than systems operating close to seawater salt concentrations. This reduced water demand also reduces pumping energy requirements.

Water Resources

One of the major benefits of growing algae is that unlike terrestrial agriculture, algal culture can utilize water with few competing uses, such as sea water and brackish water from aquifers, oil and natural gas wells, and coal seas. Coastal land is obviously most suitable for sustainable large-scale algal production systems. Waste water, especially municipal sewage, is another possible water resource. In many large cities, the size of this resource and the suitability of the existing treatment infrastructure to modification for algal biomass production will constitute a niche opportunity. However, the algal biomass produced at these modified waste water treatment facilities may not be sufficient to justify investment in oil extraction and liquid fuel production infrastructure. This proposed project is situated less than 500m from the North Sea, this will eventually reduce the cost that may have been incur to source for underground water. The North

Sea will provide the much needed condition for algae growth with a salinity of 7.5-8.4 (Anderson, 2003) and average yearly temperature of 17^0 C (63^0 F) in summer and 6^0 C (43^0 F) in the winter (Anderson, 2003).

Carbon Dioxide Resources

Optimal algae growth occurs in a CO_2 enriched environment. Since CO_2 capture and geo-sequestration (or carbon capture & storage, CCS) is likely to become a necessary activity for stationary energy providers and other large volume industrial CO_2 emitters, it would seem that algae production plants could provide an alternative CCS. Flue gas could be captured from large stationary emission sources, such as power plants and industrial facilities, with CO_2 concentration of up to 15%. Applications separating CO_2 in large industrial plants, including natural gas treatment plants and ammonia production facilities, are already in operation today (Rubin et al., 2005). Power plants with CCS and access to geological or ocean storage require 10 to 40% more energy than plants without CCS to provide the same power to the electricity network. Therefore, there is an economic driver for power generators to consider other lower energy alternatives to CCS. Fig 6 depicts the location of large stationary sources of CO_2. The most obvious characteristic of this distribution is that very few of these large CO_2 emitters are in close proximity to coastal areas not to talk of utilising them in large scale algae production. Large point sources of CO_2 are concentrated in proximity to major industrial and urban areas which makes it difficult to find a suitable site for algae production. Preliminary research on CCS conducted by the Intergovernmental Panel on Climate Chang (IPCC) suggests that, globally, a small proportion of large point sources are close to oceans (potential storage locations for CO_2 in the case of CCS analysis and the water resource in the case of algal biofuel production).

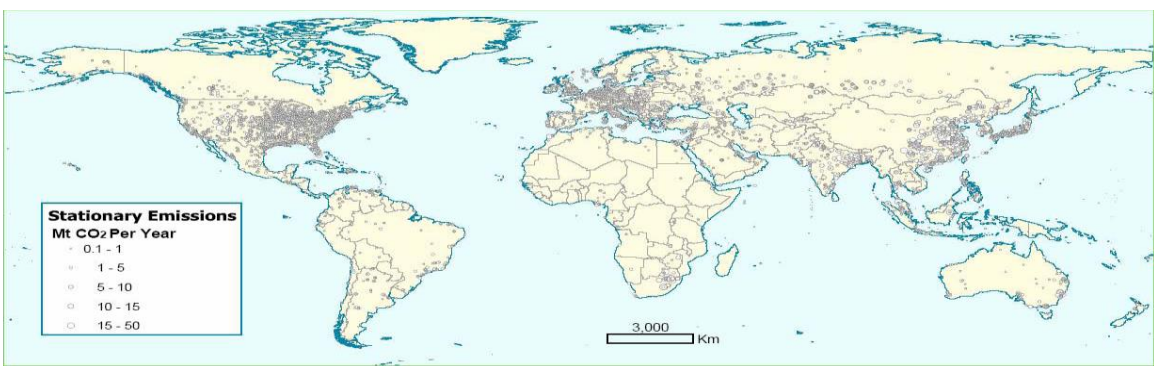


Figure 6: Point Source CO2 Emissions.
(http://www.climatescience.gov/workshop2005/presentations/breakout_2ARubin.pdf)

In circumstances where algae production plants appear to be an attractive alternative to CCS, the capacity to match scale of emissions to scale of algal production will be an important consideration. Solar energy conversion efficiencies in algae production are in the order of 1 % to 2% (300 $GJ \cdot ha^{-1} \cdot yr^{-1}$ to 600 $GJ \cdot ha^{-1} \cdot yr^{-1}$ or 1 $W \cdot m^{-2}$ to 2 $W \cdot m^{-2}$ and the solar energy collection required for micro-algae to capture a power plant‘s CO_2 output is about one hundred times larger than the power plant‘s electricity output. (Larson, 1993). At a pond depth of 30 cm, an algae concentration of 0.6 $g \cdot L^{-1}$, a productivity of 20 $g \cdot m^{-2} d^{-1}$ and an algal oil content of 30% mass a 50 km^2 facility would produce ca. 100 ML of algal biofuel. Since the power plant will produce

CO_2 24 hours per day but the algae will only consume it during daylight, there will be a need for investment in gas storage. In the case where a power company is compelled by carbon tax or legislation to reduce CO_2 emissions, the algal production system will need to match the emission reduction requirement. If it is significantly smaller (e.g. due to the availability of other resources) then the investment decisions will be based on the relative costs of the algal production system and the incremental increase in CCS capacity (and economies of scale may favour the latter).

Table 1 is adapted from the IPCC Special Report on CO_2 Capture and Storage (2005), which shows a breakdown of costs associated with CCS (the alternative to the provision of CO_2 for algal production for a large emitter). There are many underlying assumptions in this table but the message is clear, the major cost of CCS is the physical capture and separation of gases at the point source. In the absence of any regulation or forcing mechanism the cost of algal biofuel production will include cost of CO_2 capture and transport. If the particular industry's flue gas is suitable for the algal production then gas separation will not be necessary (and capture costs will be lower than those shown in Table 3). In the presence of any regulation that compels industry to capture CO_2, rather than purchase emissions credits, the extent to which algal biofuel production might be attractive to industries that produce large amounts of CO_2 will be influenced by many factors (viz. the cost of emissions credits, the avoided costs of available sequestration options, the profitability of algal biofuels production in itself and the industry's understanding of and access to liquid fuel markets). As a business separate to the CO_2 producing industry and in the presence of an emission trading scheme, algal biofuel production will avoid costs for CO_2 only if capture and transport costs are less than the cost of emissions credits for sources without CCS and only if the additional transport costs are less than the storage option for sources with CCS (and not considering expansions that increase emissions).

Table 1: Carbon Capture and Storage Costs (IPCC Special Report on CO2 and Storage 2005)

CCS System Component	Cost Range $.tCO$_2^{-1}$	Remarks
Capture from Coal or gas fired power plan	15-75 (net captured)	Net costs of captured CO_2, compared to the same plant without capture
Capture from hydrogen and ammonia production or gas processing	5-55 (net captured)	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25-115 (net captured)	Range reflects use of a number of different technologies and fuels.
Transportation (pipelines)	1-8 (transported)	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) $MtCO_2\ yr^{-1}$
Transport (liquefaction and shipping	Uncertain	
Geological storagea	0.5-8 (net injected)	Excluding potential revenues from EOR or ECBM
Geological storage: Monitoringand verification	0.1-0.3 (injected)	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements
Ocean storage	5-30 (net injected)	Including offshore transportation of 100-500 km,excluding monitoring and verification

IPCC Special Report on CO_2 Capture and Storage (2005) concludes that for emitters that are not close to oceans or suitable geo-sequestration sites pipelines are preferred for transporting large amounts of CO_2 for distances up to 1,000 km. For amounts smaller than a few million tonnes of CO_2 per year and for larger distances overseas, liquefaction and shipping might be economically feasible for CCS, but the costs are uncertain. Such a transport system would also incur additional energy costs for liquefaction and shipping which would have implications for algal biofuel remote to CO_2 emitters. The requirement of nearness to large point source CO_2 emitters places another constraint on the capacity of algal biofuel production.

One of the motivating factors for this particular project has been the possibility of power plant coming in to existence beside the proposed project site. RWE npower is proposing to develop a coal-fired power station adjacent the project site(npower, 2007). Proposals are currently at a very early stage. The proposed plant will consist of three 800 megawatts (MW) high efficiency supercritical coal-fired units, giving a total station capacity of 2400MW. The station will have an efficiency of up to 46%, which equates to a reduction in CO_2 of about 23% per unit of electricity generated, compared to conventional subcritical coal fired plants (npower, 2007).The station will also be configured to allow for the installation of Carbon Capture and Storage technology when this becomes technically and commercially viable. Fig 7 shows the site of the proposed power station in relation to the project site, the power plant will help in creating the much-needed environment favourable for the growth of microalgae.

Figure 7: Propose power plant site (Google Maps)

Land

Large areas of relatively flat land are required for large scale algal biofuel production . Land availability is influenced by many physical, social, economic, legal, and political factors (Darzins et al., 2010). Land use could constrain the installation of algal biomass production systems due to high cost, value of agricultural activity, or intrinsic environmental or cultural value (e.g. parks, wildlife areas, archaeological sites, and historical monuments). Land use change has often life cycle impacts and sustainability issues. Physical characteristics, such as topography and soil, could also limit the land available for open pond algae farming. Topography would be a limiting factor for these systems because the installation of large shallow ponds requires relatively flat terrain. Areas with more than five percent slope can be effectively eliminated from consideration for site development not only due to the intrinsic needs of the technology, but also due to the increased costs of site development. These considerations can significantly reduce the land area available for algae development. Soils, and particularly their porosity/permeability characteristics, affect the construction costs and design of open systems by virtue of the need for pond lining or sealing.

Nutrients

The nutritional requirements for algae growth are similar to those for terrestrial plants. The main requirements are nitrogen and phosphorous. Algal strains differ in their ability to utilize different nitrogen sources though most can use nitrate, ammonia, or urea. The main nutrients can be supplied in the form of agricultural fertilizer, although there is a growing recognition that fertilizer production is dependent on fossil fuel, and this must be included in life cycle assessments. In addition, use of fertilizer calls to question the issue of food vs. fuel as fertilizer (especially phosphorous) is becoming increasingly in demand and wide scale use for algal cultivation could be seen as exacerbating world food production. One way to avoid this competition (and input cost) is to use Sea water, as discussed earlier, both as a source of nutrient and for cultivation. In addition to the main inorganic nutrients, algae need a number of micronutrients used as part of the catalytic machinery needed for cell replication. These micronutrients include sulphur, iron, magnesium, manganese, calcium, potassium, and molybdenum. Sulphur in the form of sulphur dioxide may be supplied by the flue gas of a coal-fired power plant. Many processes proposed for production of algal biofuels envision energy-related co-products derived from the remaining biomass after lipid extractions. Anaerobic digestion or thermochemical conversion to syngas or pyrolysis fluid may allow for recapture of the inorganic nutrients for recycle to the cultivation medium.

Conclusions on Siting

Undoubtedly land and water in suitable climates for large scale algal biofuels production exist, but the economics of production, and the embodied energy and GHG mitigation of the biofuel will be influenced by the proximity of these resources. It is less obvious that the CO_2 is available in regions most suited to year round algal growth. Optimal siting of large scale algal biofuels production facilities will require that the resources exist in close proximity,(as proposed in this project) or that there are drivers to ensure the provision of the missing resource (most likely CO_2). The impact of resource proximity on the economics of algal biofuels production is addressed later in the project as we consider the economic feasibility of the project.

ECONOMICS OF ALGAL BIODIESEL PRODUCTION SYSTEMS

Overview of Algae Cultivation for Biofuel Production in Cambois Peninsular

The cultivation process begins by growing algal (Chlorella) inoculums in a small high rate PBR that will be used to grow the algae in the main production ponds. The ponds are initiated with the inoculums and maintained by the addition of nutrients in form of fertilizer. CO_2 from the power plant is also injected to feed the algae. In the harvesting stage the algae will be allowed to bioflocculate before being transferred to a large settling tank where autoflocculation will take place. This will concentrate the algal slurry to 1-4%. The water removed from the biomass is recycled back to the ponds. The algae slurry will undergo further dewatering to make the biomass thick suitable for biodiesel processing. Biodiesel can be produce from this stage through transesterification process**.** Fig 8 depicts the whole process in its simplest form. Open pond algae cultivation system will be discuss in details in the succeeding paragraphs.

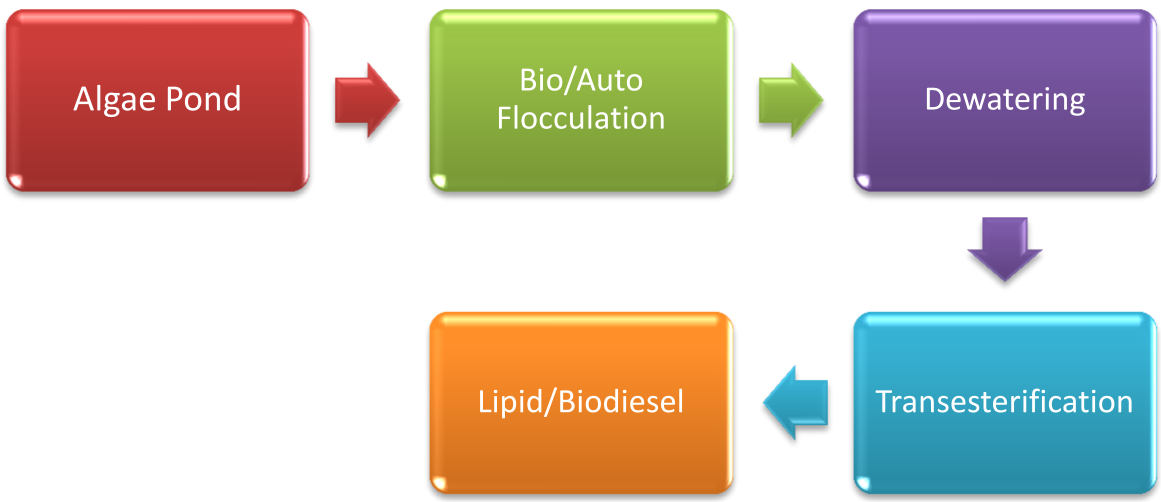


Figure 8: Basic Biodiesel production system employed in this project

Algae Farm Design

A 100 ha of shallow raceway ponds are constructed on approximately 140 ha of flat coastal land, 500m from a coal-fired power station with the following specifications;

- Construction of the 0.7-1 metre deep growth ponds (containing water to a depth of about 25 cm) including site clearing, grading, levelling, and the construction of channel dividers (berms). Ponds are designed in modules, with the basic design element being two trenches running in parallel, separated by a berm (a mound of earth with a level top that acts as a divider) except for the ends which are connected in a semi-circle to allow water to flow continuously. The ponds are unlined, as plastic liners can double the infrastructure cost. However, the pond bottom is compacted. Benemann and Oswald 1996 suggest that this should be all that is required for most of the pond area due to self-sealing.

- One paddle wheel per raceway is used to ensure a flow rate of 10-25 cm s^{-1}; this ensures a suitable amount of mixing of nutrients and CO_2 in the water, as well as avoiding silt suspension and sedimentation of organic solids. Each raceway also has a sump with a baffle through which CO_2 is pumped. This CO_2 is supplied by pipe from a nearby power station (filtered flue gas).

Another pipe runs parallel to the CO_2 pipe that will convey waste heat from the power station to the ponds. This waste heat will be used to warm the pond during low winter temperatures.

- A suitable amount of sea water is pumped from the North Sea to the ponds as well as to offset losses due to transpiration and evaporation. After harvesting the waste water flows via gravity back to sea after treatment.

- Bioflocculation followed by Autoflocculation are used to concentrate algae, which is then fed into a container for further dewatering by centrifugation or foam column separation. This concentrates the algae, removes the majority of the remaining water, then follows by in-situ transesterification to extracts the lipids (oil/fat). It is in this part of the algae farm design as well as removal of centrifugation step that the highest potential for cost reductions occurs.

- Substantial amounts of nitrogen and phosphorus (fertilizer) need to be added regularly to the algae ponds, in addition to the recycle water and CO_2. But the whole production will be done under Nitrogen deficient condition which will increase the algae lipid content. This will also aid in the harvesting process, because high lipid content increase settleability of the algae biomass (Benemann and Oswald 1996).

- The algae farm also requires the construction of roads, drainage and buildings, electrical supply and distribution, instrumentation, machinery (including vehicles). Also people are required to run the facility (including the administrative staff not directly operating the plant, but necessary for the function of the facility).

METHODOLOGY

To many they consider algae cultivation in the UK uneconomic due to the prevailing weather conditions and suitable site. Thus all effort to find data on algal cultivation proved difficult. In light of the above all economic data and assumptions in this project are based on algae production system conducted elsewhere but taking in to account the prevailing UK economic conditions with the exception of those data's that can be sourced independent of the algae production system such as Land, Labour and Energy prices. The downstream biodiesel process from harvesting to lipid esterification will be discussed in 3 different routes to find the most economical route to produce biodiesel. The first route involves the traditional process of algae harvesting through settling in tanks, centrifugation and drying of the biomass after which lipid extraction and subsequent transesterification to biodiesel will follow. The second route substitutes the centrifugation process with foam column separation. While the third route is a hybrid of the 2 process earlier mentioned. The algae cultivation and biodiesel production parameters are summarised in the following table;

Table 2: Algae Biodiesel Production Parameters Table

Parameter	Type/Value
Algae Specie	**Chlorella Sp**
Water	**77,000 t/ha/yr**
Sea Salt Concentration	**35g/L**
North Sea pH	**7.5-8.4**
Production System	**Open Raceway Pond (4ha/pond)**
Total Pond Area	**100ha**
Total Facility Area	**140ha**
Algae Productivity	**22g/m^2/day**
Algae Lipid Content	**50% by mass**
Harvesting Method	**Autofloccultion/Foam Column separation**
FAME production method	**In-situ transesterification**
CO_2 Source	**Flue Gas from Power Station**
Days of Operation	**150**

Algae Harvesting Techniques and Oil Extraction

Open raceway ponds and closed PBR are the only known practical methods of large scale production of microalgae. A raceway is an open system made of a closed loop recirculation channel that is typically about 0.2 - 0.3 m deep (Chisti, 2007). Raceway ponds for mass culture of microalgae have existed since the 1950s. Production of microalgae for making biodiesel has been studied extensively (Sheehan *et al.*, 1998). Raceway ponds are less expensive than photobioreactors, but typically produce less biomass per litre of water (Chisti, 2007). The major challenges facing biofuel production from algae is the harvesting and dewatering stages which consumes significant amount of energy, in this section various methods of algae harvesting and dewatering will be discuss.

Overview of Foam Column Separation of Algae

As mentioned earlier, one of the major problems in the mass cultivation of unicellular algae for biofuels is the lack of an economic method for harvesting the relatively dilute suspension. Harvesting of algal cultures refers to the removal of extra-cellular water to produce an algal paste. It normally contributes 30-40% of the cost of the micro-algal biofuel (Mata et al., 2010)and (Verma et al., 2010). Harvesting is not straightforward due to the low biomass concentration in algal cultures and the small size of the microalgae. One such method that could bring the harvesting cost to a more economically viable production is "Foam Column Separation". The basic idea involves passing air through the algal culture suspension to create algal rich foam on top of the culture suspension. The foam is then collected through a column. Sometimes it may be necessary to add flocculants in to the culture to aid in bringing the algal cells together which makes it easier to be harvested. Sea water pH adjustment (by adding NaOH 300g/m^3) was discovered to aid this process significantly by removing the algae from the suspension to about 90% (Yahi et al., 1994) and (Lardon et al., 2009). As such no flocculent will be added to the culture in this case to allow the extracted water to be recycle back to the pond.

Flotation is a process that utilizes gas bubbles (typically air) to separate particles from a liquid. Flotation was first used in the mineralogical industry to separate mineral ore from water (Liu et al., 1999). During flotation, air bubbles rising through a liquid collect particles that then rise to the surface of the water with the bubbles. The bubbles create a foam at the surface of the water which is skimmed off. There are two main types of flotation processes;

- **Disperse/Induced Air Flotation (DiAF)**: Disperse air flotation, also know as froth flotation, utilizes air bubbles injected into the vessel containing the algae culture. Air can be injected through the bottom of the vessel with a gas sparger or entrained via cavitation. Algae cells contacted by rising bubbles are adsorbed to the bubble surface and travel to the culture surface with the bubbles. The bubbles form a algae rich foam on the surface of the culture. The foam is then skimmed off to separate the algae cells from the culture. Bubble diameters in induced air flotation cells are typically between 1 and 2 mm (Tuin, 2008). These units are typically employed to remove larger particles. DiAF is discussed further in this project.

Dissolved Air Flotation (DAF): DAF is similar to DiAF in that rising bubbles contact algae cells that rise to the surface and form a foam. The primary difference between dissolved and disperse air flotation is the method air bubbles are generated. In DAF, the culture medium is pressurized. Air is sparged into the pressurized stream until the culture is saturated with air at the elevated pressure. The saturated culture is then depressurized in the flotation cell. The pressure drop causes the saturated air to come out of culture as tiny air bubbles. These bubbles are smaller than those produced in DiAF. Typical bubble diameters range from 0.05-0.7 mm (Tuin, 2008). Algae cells adsorb to the bubbles in the same manner as in DiAF and form foam on top of the water. The foam is then skimmed to separate the algae cell from the culture. DAF is more expensive to operate than DiAF because of the pressurization step. It is used to remove smaller particles. Yao-de and Jameson [2003] have studied algae flotation from wastewater maturation ponds utilizing Jameson flotation cell technologies (Tuin, 2008). Bench scale and pilot scale experiments were used to validate the technology. They have demonstrated that algal removal can approach 99% in a full-scale implementation facility in Wagga Wagga, Australia (Tuin, 2008).

Disperse Air Floatation /Foam Column Separation

DiAF will be used in this project due to its simplistic nature as well as low cost. A highly efficient DiAF procedure has been developed for harvesting algae from dilute suspensions such as water treatment facility (Liu et al., 1999). Harvesting is done in a long column containing the algae solution by sparging air from below the system. Near the top of the column a side arm is constructed to recover the algae rich foam from the system. The cell concentration of the harvest usually depends on pH, aeration rate (9g/m^3), aerator porosity, feed concentration, and height of foam in the harvesting column. The economic aspects of this process seem favorable for mass harvesting of algae for biofuels.

Algae dewatering from the culture media is an important Step towards algae biofuel production. As centrifugation, a common procedure for this purpose requires hug amount of energy. Foam separation is already a known method of separating solution components by utilizing the differences in their surface activities. Foam separation is particularly suited for algal cell separation because foams have large interfacial area per unit volume of the liquid. Recently, (Desmaison and Schiiger) separated ***Hansenula polymorpha*** from the media in a batch foam column using the natural surface activity of the microorganism.

In this case sea water pH of 7.5-8.4 will be adjusted to 11-12 by the addition of NaOH,this will significantly aid the harvesting process without any additional flocculent. This serves dual purpose of reducing cost by not purchasing additional flocculent as well as reuse of the culture water after the harvest. It was investigated by Yahi et al., 1994, that by changing pH to slightly alkalinic medium 95% of algae can be remove from aqueous solution (Yahi et al., 1994). Fig 9 shows flocculation efficiency of chlorella by using sea water and addition of NaOH (0.5 g L^{-1}) to increase the pH. Alternatively the sea water pH could be increase by stopping CO_2 supply to the suspension which will raise the pH to about 9-11 as demonstrated by Beneman and Oswald (Benemann and Oswald, 1996). High settling velocity with excellent mechanical resistance of algal cells can be achieved through this process which can be continues without the help of any other mechanical energy transfer device that may consume energy (Yahi et al., 1994).

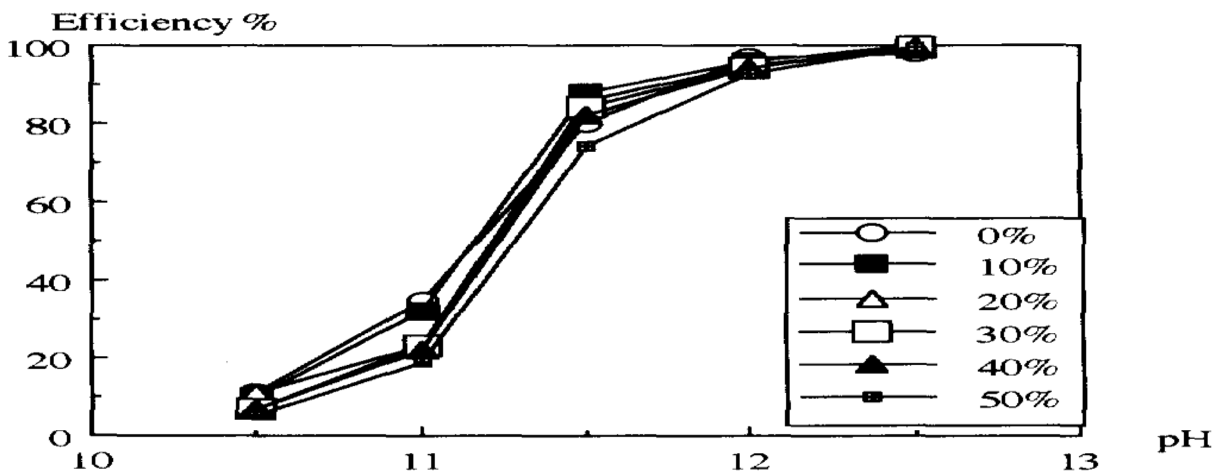


Figure 9: flocculation of algae cell using sea water and NaOH (Yahi et al., 1994)

Foam column separation process concentrates the algae biomass from 0.5 g L^{-1} (0.05% solid) to 23.3 g L^{-1} (23.3% solid). A little mechanical drying process is employed here to further dewater the algae for subsequent wet oil extraction. Fig 10 shows a potential mechanical algae dewatering device that could be employed for this purpose. Caution: the diagram shows dry algae flakes been collected at the end of the process, this may not entirely be true as the machine was not tested for commercial algae dewatering process, but at least may dewater the algae to certain level.

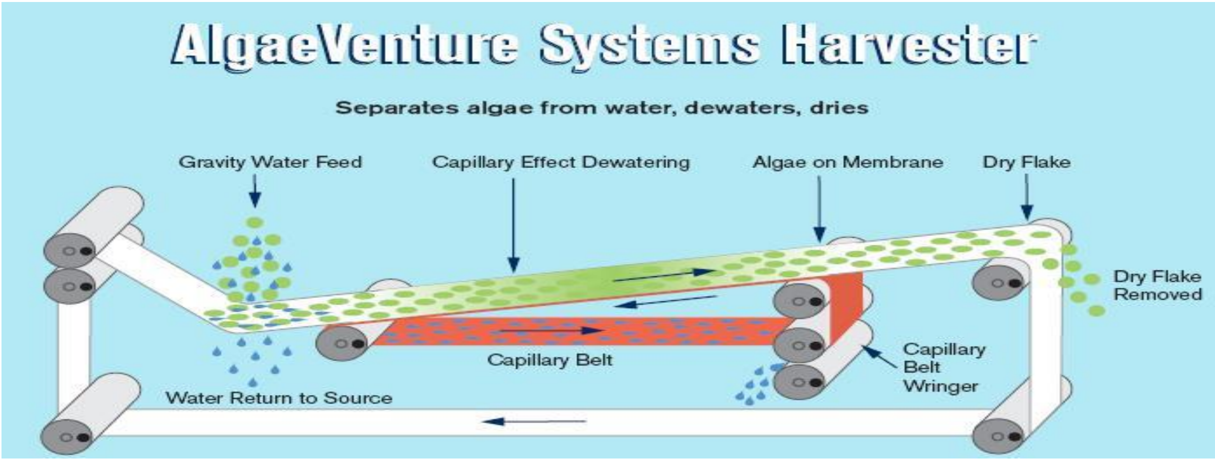


Figure 10: Algae Mechanical Dryer
Image Source Brian Wang at (http://1.bp.blogspot.com/_VyTCyizqrHs/ScvOJcpmkBI/AAAAAAAADQU/sQR7EQlJ6R8/s1600-h/algaeharvest1.JPG)

In-situ Trans esterification

The current algae-based biodiesel is mainly produced by conventional route: extraction of the lipids / Triacylglycerol (TAG) from the microalgae biomass followed by its conversion to Fatty Acid Methyl Esters (FAMEs) and glycerol (Xu et al., 2006). However because of the strong algae cell walls, such method is time consuming, costly, and difficult to be implemented (Johnson and Wen, 2009). Recently *in situ* transesterification method, in which the algae biomass contacts with alcohol directly instead of reacting with pre-extracted oil, has been proposed for algae-based biodiesel production. As a method for biodiesel production, not only FAME content but also conversion efficiency from algal oil to biodiesel is imperative as quality and quantity standards in the process of transesterification (Griffiths et al., 2010). In-situ transesterification is a method of converting lipid (TAGs) in situ directly to FAME by using organic solvent such as methanol as catalyst, this eliminate the extraction step and result in a rapid, one step procedure to form biodiesel. Classical lipid extraction techniques are costly, lengthy and involve multiple steps.

As FAME is the component of biodiesel and transesterification is the major method of biodiesel production, in-situ transesterification has potential large scale application in the rapid, low cost production of biodiesel directly from algal cells without the need for oil extraction. A one step method of in-situ transesterification resulted in a higher FAME yield from schizochytrium limacinum and could produce biodiesel almost meeting the fossil diesel standards (Griffiths et al., 2010). Eliminating the step of oil extraction could make the process cheaper, but does not eliminate the need for harvesting and initial dewatering to remove inter- cellular water.

Sensitivity Analysis

This paragraph explores the economic benefits derived from the use of algae biofuel chosen technology in this project as against the more conventional systems. Savings derived from reduced energy cost as well as system and process efficiency will be highlighted. The traditional centrifugation harvesting processing route will be compared to foam column separation technique and finally a hybrid of the 2 processes will be analysed.

Foam Column Separation versus Centrifuge

There are several algae harvesting technology used worldwide depending on the algae species and the end product. Here the widely applied centrifugation method will be compared with foam separation. Centrifugation has been widely explored as a method for liquid – solid separation technique (Kumar et al., 1987). But due to its high installation cost couple with high power consumption it is not economically suitable for separating alga from its culture. Within the Aquatic Species Program in the US the costs for centrifugation were estimated at 40 % of production cost and 50 % of investment cost (US Aquatic Species Program Report 2010). Rapid operation, low space requirement and moderate cost are the major characteristics of foam column separation process (Liu et al., 1999). The problem with centrifugation was primarily one of cost. Power for the industrial centrifuge used (similar to the one needed for algae harvesting) was estimated at 3,000 kWh/ton of dry algae (Benemann and Oswald, 1996) far more than what is required for foam column per dry ton of product. A striking comparison between the centrifugal method and the foam column process may be made in that the industrial centrifuge, operating on a continuous flow basis, produced a maximum of 0.7 % solids in the first harvesting stage. It was stated that second and possibly third stages would be required to concentrate the harvest to 15 to 20 % solids content required for algae concentration, with significant amount of energy consumption (Molina Grima et al., 2003). Column foam method, in its present form, produces algal biomass of 2.3% solid in the harvest containing 23.4 g/L dry solids (Lee, 2011)

Cell harvesting efficiency of centrifuge was also investigated by Haesman et al., 2000, where 95% efficiency was obtained at 13,000 X ***g.*** The efficiency declined to 60% at 6000 X ***g*** and 40% at 1300 X ***g*** (Heasman et al., 2000) and (Molina Grima et al., 2003). Barclay et al., (1987) estimated the cost of centrifugation to be 40% of algae biomass price while Golueke and Oswald 1965 estimated flocculation to be 40% lower than centrifugation harvesting (Golueke and Oswald, 1965). Although, at present, the total costs of installing large column foam separation device for algae may not be possible to estimate, the process was widely used economically for separating large solid from liquids. The principal cost is in the initial installation. Operating cost largely depends on the cost of air which at the moment is not all that significant.

In-situ Trans esterification Versus Trans esterification

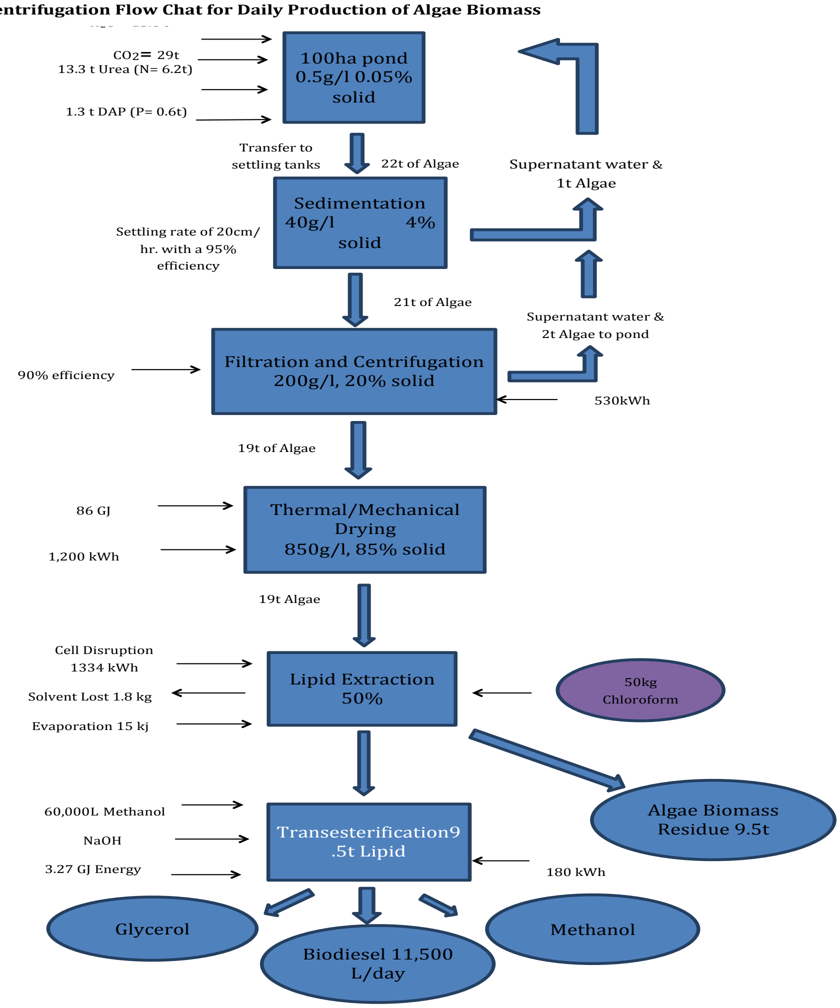
It has been pointed out in literature that the dewatering of microalgae is one of the main bottlenecks in algal culturing. In the model of Lardon the energy required for the dewatering process (to dry algae) accounted for 84.9% of the total energy consumption (Lardon et al., 2009). To improve the overall energy balance, the energy consumption of the dewatering has to be reduced or completely eliminated by applying oil extraction in the water (aqueous) phase. The traditional method of biodiesel production is trans esterification, which is a chemical reaction between fat or oil (triglyceride) and alcohol in the presence of catalyst or without catalyst to produce biodiesel and a by-product glycerol. Usually this process is done on oil from the dried solid algae biomass. In-situ trans esterification obviates the biomass drying and organic solvent use for the oil extraction which could lead to significant energy and cost savings. The total energy consumption for oil production via trans esterification usually drops by 70% (table 5) when compared to oil production via in-situ trans esterification because the thermal drying process is left out (Lardon et al., 2009).

Some major advantage of in-situ trans esterification are;

- Nutrients (Nitrogen and Phosphorous) and glycerol from processed biomass can be captured and reused. This will certainly improves the economics of the process by reduced the quantity of nutrient (fertilizer) needed in the subsequent algae growth.
- Further dewatering of algae cells can be achieve by amassing the cells in to filterable solids prior to transesterification, this may as well save cost (Levine et al., 2010).
- Fatty acid retention in solid lipids removes the difficulty with lipid recovery from the system which ideally consumes energy, expensive and sometimes hazardous (Levine et al., 2010).
- Consumes less amount of solvent compared to traditional transesterification.
- One of the drawbacks of this process is that, final oil extraction via this process consumes 2 times more energy than the oil extraction process via the trans esterification (Xu et al., 2011).

The following flow chat described the 3 different routes of microalgae biodiesel production from cultivation to the final product including energy consumptions etc

Figure11: Centrifugation Flow Chat for Daily Production of Algae Biomass



1.

Figure12: Foam Column Separation Flow Chat for Daily Production of Algae Biomass

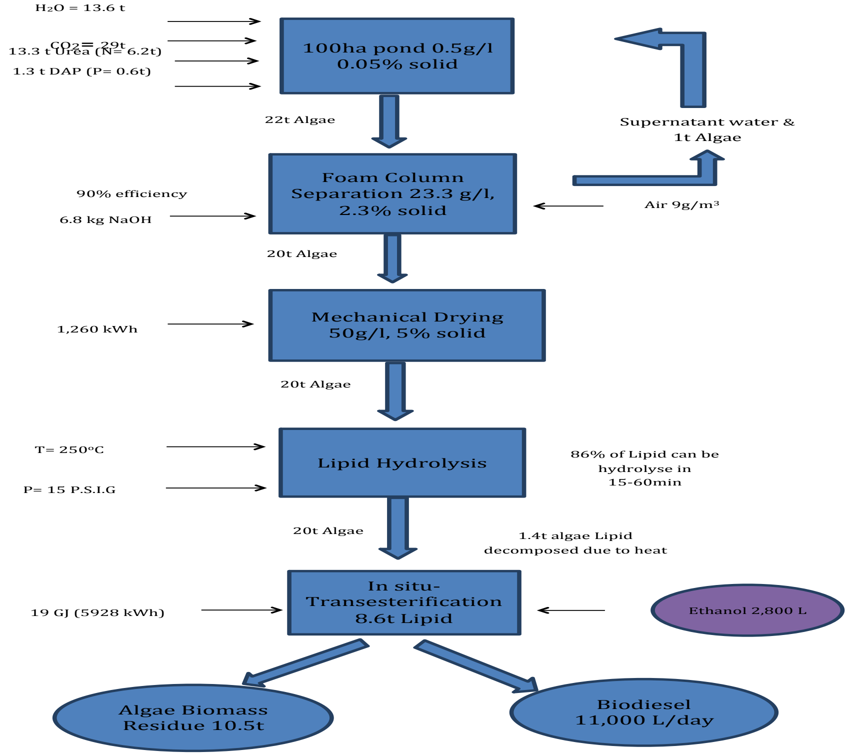
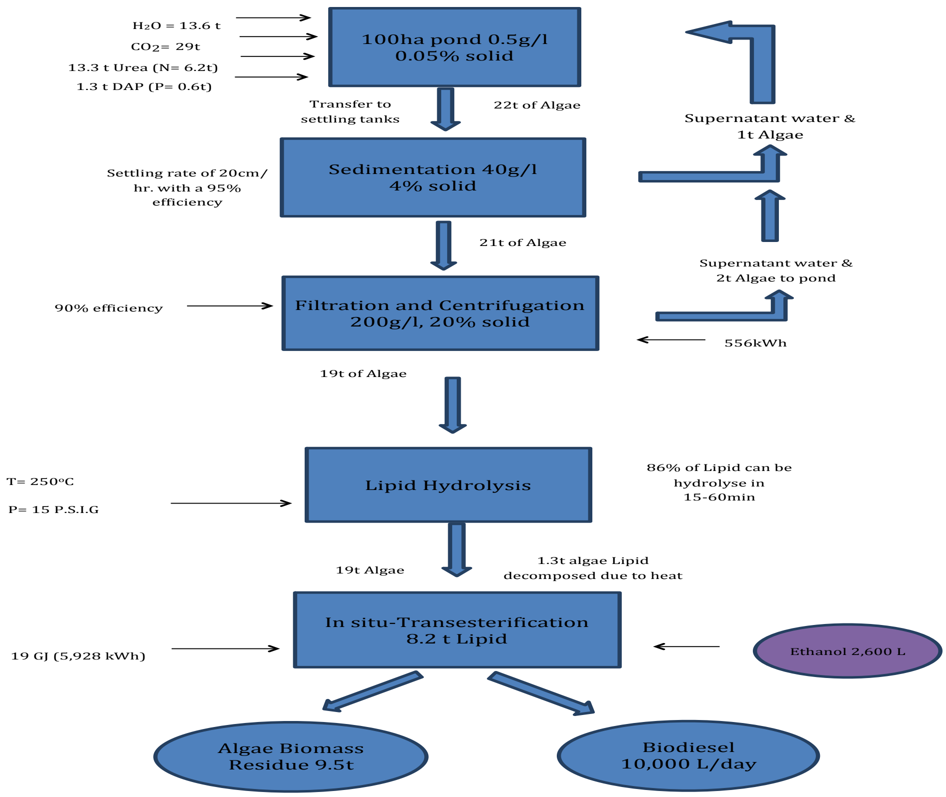


Figure13: Centrifugation and Hydrolysis Flow Chat for Daily Production of Algae Biomass



The Centrifugation Harvesting flow chat

Here the algae biomass (22t) is sent to a settling tank to concentrate it to about 40g/l (4% solid) from initial concentration of 0.5g/l (0.05% solid). The settling process has 95% efficiency thus the total algae biomass going for centrifugation is 21t. The algae biomass undergoes filtration and centrifugation to concentrate the slurry to about 200g/l (20% solid) (Mohn 1980). The centrifugal process consumes 26.5 kWh per ton of algae equivalent to 530 kWh per 21 tonnes algae (Xu et al). The final algae output after the centrifugation (90% efficiency) is 19t.

To further remove water from the biomass the centrifuged algae is subjected to both mechanical and thermal drying process, this process consumes 1,140kWh of power and 86.3GJ of heat respectively (Xu et al 2011). It also brings the algae biomass concentration to 850g/l (85% solid). 50kg chloroform (solvent) needs to be added to the dry algae biomass at a temperature of 90^{o}C to extract the lipid from the algae cells. Similarly 1,267kWh is required to break the algae cell wall to release the algae lipid; 15 GJ of energy is applied to evaporate the solvent (Table 5).

The extracted lipid (9.5t) is transesterified with 60,000L of methanol and energy of 19 GJ to convert the lipid to 11,500 L (taking biodiesel density as 0.85 kg/l) biodiesel leaving a residue of 9.5t algae biomass that can be utilised as fuel for power generation.

Foam Column Separation flow chat

Foam Column Separation is a process that involves sparging of air from the bottom of a tank containing algae slurry. As the air bubbles raises to the top they carry with them the algae cells that can be harvested from the side arm of the tank. This action concentrates the algae slurry from 0.5g/l (0.05% solid) to about 23.3g/l (2.3% solid). The two most important requirement for a successful Foam separation/flocculation are the pH adjustment (from 7-12) and air. pH adjustment can easily be achieved when the algae culture is remove from the production pond (Benemann and Oswald, 1996, Yahi et al 1994 and Grima et al 2003), or by simple addition of NaOH to the media. While the rate of air needed for the process is 9 g/m^3 (Beddow 2009). The efficiency of this process is about 90%, which decrease the algae biomass from 22t to 20t. For insitu transesterification to take place the algae slurry need to be concentrated further to some degree this can be achieved by mechanical drying. Mechanical drying will concentrate the slurry further to 50g/l (5% solid) through the consumption of 1,260 kWh energy for 20t of algae (60kWh/t), (Xu et al 2011).

The wet algae biomass (20t) undergoes lipid hydrolysis at 250^{o}C and a pressure of 15 P.S.I.G for 15 to 60 min. This process hydrolyses the intracellular lipids that will allow it to easily be converted to biodiesel through wet oil extraction process. This process has 86% efficiency, some of the lipid are being destroyed due to high temperature, thus with 50% lipid content in 20t algae biomass the final salvageable lipid is 8.6t. With a ratio of 1:4 (w/w) (Levine et al., 2010) for methanol to algae, 2,800 L of ethanol with energy of 19GJ is required to convert 8.6t lipid to biodiesel of 11,000L/day, (Levine et al., 2010) taking biodiesel density to be 0.85 kg/L. The total energy consumption of this process (7,128 kWh) (Table 5) is less than the centrifuge (33,912 kWh) process, but releases less amount of biodiesel due to loss as a result of lipid hydrolysis. The residual biomass of 10t can be used for power generation through combustion though it is beyond the scope of this project.

Centrifugation and Insitu-transesterification flow chat

This process is a hybrid of the two processes earlier mentioned, after sedimentation the algae biomass undergoes centrifugation twice followed by lipid hydrolysis then insitu-transesterification similar to that conducted in foam column. The total energy consumption (7,014 kWh) (Table 3) is almost the same with foam column separation processes but lower than the centrifugation route (32,653 kWh). Also the final biodiesel produce (10,000l/day) is slightly lower than the 2 processes.

Table 3: Process Energy Consumption Table

Process	Centrifugation Route	FoamColumn Route	Centrifugation/ in-situ TE Route
Centrifugation	530 kWh	-	1086kWh (2 stage)
Thermal Drying	82 GJ (22,773kWh)	-	-
Mechanical Drying	1,140 kWh	1,200 kWh	-
Cell Disruption	1,334 kWh	-	-
Evaporation	15 GJ (4,166kWh)	-	-
Transesterification	2,710 kWh	19 GJ (5,928 kWh)	19 GJ (5,928 kWh)
Total Power	**32,653 kWh**	**7,128 kWh**	**7,014 kWh**

From the above table, it can be seen that while the energy for dewatering the algae biomass is obviated by the foam column process the energy consumption for the oil extraction double that via centrifugation but overall the net energy consumption favours the foam column separation process.

Pond Design and Economic Assumptions

The objective of this project is to determine the economic feasibility of algae biodiesel production on the Cambois Peninsular using available engineering design and practices, harvesting and processing technologies. The fundamental basis here is that algae biodiesel production requires low-cost cultivation and processing systems for it to be cost competitive with the fossil fuel. Thus open pond, rather than PBR were selected as the main cultivation system for the purpose of design and cost estimation. Also the centrifugation option route will not be considered further from this stage due to high installation and maintenance cost as well as huge power consumption associated with it. In the next coming paragraphs design, construction, operation and estimated cost of algae biodiesel facilities will be described. Harvesting and processing of the biomass to FAME is done by Foam Column separation and in-situ trans esterification respectively.

The following are some of the assumptions used in writing this project:

- 25 large size of individual growth ponds (race way) of 4 ha each (25X4=100ha) sited on the overall facility of 140ha;
- Use of alternative source of CO_2 (i.e. Flue gas) from the nearby power station of 2,400MW;
- Use of waste heat from the nearby power station to warm the algal pond at low winter temperature;
- The use of local clay to line the ponds as against the use of more expensive plastic liner.
- Assumption of high biomass productivity and lipid content on the algae strain ‘chlorella’, $22g/m^2$/day of harvested biomass and 50% oil content. This is not impossible to achieve at the proposed site considering what Benemann (1996) reported of $30g/m^2$/day provided that the pond did not freeze for several months in a year.
- Due to dart of data must prices are calculated based on the US Dollars as at 1996 then converted to Sterling Pound taking in to consideration time value of money and inflation.
- PBRs will play a vital role in this production where it is needed to provide the initial starter inoculums for the ponds, but will be insignificant in terms of size i.e. 0.1% of the total production area. The PBRs will provide large amount of starter inoculums at a minimal overall increase in capital and operating cost.

Algae Cultivation and fuel yield Assumption

The algae productivity assumption used here are not base on long term experimental data but on extrapolations of prior work by many authors. Here we assume an annual average productivity of $22g/m^2$/day (80 mt/ha/yr) and 50% extractable oil in the biomass during the summer months from March through to July. Biomass production during the winter months will be reduced to less than $5g/m^2$/day thus insignificant for economic production. For the sake of this feasibility analysis we assume 150 days production scenario. With provision of sufficient CO^2 and other nutrients (N, P, etc), light and temperature are the two main factors limiting algae biomass production. The combine effects of these parameters is poorly understood at the moment, but it is believed that the above productivity assumptions is a good case for near - to mid – term algae production at the Cambois Peninsular. At Cambois Peninsular, the greatest factor determining the algae productivity is temperature, particularly around the winter. Cold weather prevent the ponds from reaching the warm temperatures needed for high productivity but as mentioned earlier waste heat will be used to supplement the low temperatures.

CAPITAL COST

Land and Infrastructural Cost

Despite the Global financial crisis that hit the world in 2007/2008 land prices in the UK still remains high. It was reported that the average price for a hectare of land in Northumberland cost £8,000 as at 2008 (Find a Property.com). The same price is being use here since there was no significant change to that price till now. Thus to purchase the 140ha of land at Canbois Peninsular we require around £1,120,000. Road construction and drainages in and around the farm including any other administrative building is estimated to cost £ 1,763 /ha (Benemann and Oswald, 1996) which translates to £ 246,863 for 140ha facility.

Pond Construction and Cost

The pond is a basic design adopted by Benemann, a single loop raceway design with a paddle wheel for mixing the pond. Pond costs are usually sensitive to lining materials used to prevent ground water seepage and contamination. There are other ways to reduce this cost by using local clay content of the soil which has good water retention characteristics. Using the clay lining will reduce the cost by ¬50% as against using the lining material. Benemann and Oswald proposed 1996 give the cost of lining the pond with clay at £430/ha equivalent to £43,000 for a 100ha. The only set back of the clay lining is that if the pond is allowed to dry up after cleaning it will crack the clay which will allow water to seep under when next the pond is flooded but this is unlikely to happen in this case with abundant sea water at our disposal. Both lined and unlined ponds were considered side by side, (Weissman et al., 1989) and observe only minor differences in productivity. Prior to the pond construction the general area need to be prepared and level to receive the pond. The cost estimate for the site preparation and levelling is estimated to be £ 1,716/ha, thus for a 100ha site the cost is £ 171,600. Pond wall construction and berns (erosion control, earthen levees and geotextile) are estimated to around £3,000/ha equivalent to £300,000. The cost for paddle wheel responsible for mixing the pond content is estimated at £4,300/ha which equals to £430,000 for a 100ha facility.

Water Supply and Cost

The pond main water supply will come from the North Sea less than 500m from the algal farm. The water will be piped and pump from the sea with mechanical pumps using 60 kW of power with efficiency of 90%, detail cost associated with the water pumping power consumption will be discuss under farm power consumption heading. Here it is estimated that £ 3,400/ha equivalent to £ 340,000 will be required as capital cost to pipe the sea water to the farm and to the various ponds. The water will be drain by gravity in to the tributaries of River Blyth bordering the site biweekly.

CO_2 Supply and Cost

Carbon dioxide is a critical nutrient for all photosynthetic plants species, but all conventional higher plant production systems can obtain it from air, algae production is the exception in that it requires an enriched source, as atmospheric CO_2 is not sufficient. The reasons for this is the limited gas exchange at the pond surface interface, limiting productivity to well below the productivity achieved by higher plants, and the excessive energy that would be required to provide CO_2 by sparging air through a culture system. With almost 45% algal biomass being carbon (Chisti, 2007) and all supplied by the CO_2. At the production rate of $22g/m^2/day$ a 100ha algae farm will require 29 tonnes of CO_2 per day (Appendix 1). A coal power plant can produce 18 tonnes of CO_2 per MW of electricity produce (Li et al., 2006). With nPower generating 2,400 MW of electricity near the algal farm at 23% reduced CO_2 emission we have 14 tonnes of CO_2 per MW, equivalent to 33,600 tonnes CO_2 per 2,400 MW. This value is more than enough CO_2 to feed 100 ha algal pond which will translate to about 15% reduction in the overall algae biomass production cost (Jiri et al., 2005). Also £ 1,270/ha (£ 127,000)/100ha is estimated to be used in piping the flue gas from the power plant to the farm (1000m) then to the individual algae pond. A similar amount is estimated for the waste heat piping system.

Harvesting cost

For bioflocculation and autoflocculation to take place prior to foam column separation the algae need to be remove from the culture medium to a settling tank for some time, the cost for such tank is estimated to be £ 6,000. Mechanical dryer is estimated to cost £ 200,000 per unit; we require at least 2 set as one can complement the other this equals to £400,000. Power consumption for the foam column separation is treated under the operating cost.

Table 4: Capital Cost

Item	Cost/ha (£)	Cost/100ha (£)
Land	8,000	1,120,000 (140ha)
Road Construction/Drainage	1,763	246,863 (140ha)
Site Preparation/Levelling	1,716	171,600
Pond Lining	430	43,000
Erosion Control	3,000	300,000
Paddle Wheel/Berns	4,300	430,000
Water Pipe Work	3,400	340,000
CO_2 Pipe Work	1,270	127,000
Waste Heat Pipe Work	1,270	127,000
Harvesting (Settling Tanks)	6,000	600,000
Mechanical Dryer	-	400,000 (2 pieces)
Total	**29,879**	**3,778463**

OPERATING COST

The following paragraphs will highlight the annual operating cost for the algae farm including salaries and wages for the staff responsible for running the facility.

Power Consumption

One immediate issue concerning algae farm is the unit cost for electricity. It is difficult to get the exact cost per kilowatt hour of electricity in the UK due to differences in various suppliers price. Here we use the average from the "British Gas Company" selling at 9.5p/kWh (personal calculation from electricity bills 2011). Still using Benemann and Oswald 1996 Report, the power consume for paddle wheel mixing is estimated to 10,750 kWhr/ha/yr. For 150 days operation this translates to 4,500kWh/ha, equivalent to £ 42750 for 100 ha. Harvesting power consumption (Bio/Auto flocculation and transfer in to settling tanks) is rated at 1,770 kWhr/ha/yr, this translating to £7,000/yr for 100ha in 150 days. 2,300 kWhr/ha/yr is estimated for the column foam separation which equals to £9,100 for the 100 ha farm. This is 40% of the centrifuge power consumption reported by Benemann. Water supply is 5,730kWhr/ha-yr, (mainly for pumping) equivalent to £22,681/yr for a 100ha farm. Power required to pump flue gas is 3,850kWhr/ha/yr, equivalent to £15,240/yr this value is 1/5 of the value used in 1982

Benemann et al., report where they us a 5km long pipe to supply the flue gas from the power station (Benemann et al., 1982). Miscellaneous power consumption for buildings and nutrient supply is estimated to be 1,000kWhr/ha-yr = £9,500/yr for the farm. In summary total power consumption is 25,400 kWhr/ha-yr = £ 241,300/yr for the farm.

Nutrients Price

After CO_2 the most important nutrients for algae cultivation is Nitrogen followed by Phosphorous. It is estimated that 991.3 moles per ha per day of Nitrogen and 61.954 moles per ha per day of phosphorous are required to produce 62 moles per ha per day of algae at the rate of 22g/m2/day (Appendix 1). The main source of these nutrients comes from inorganic fertilizer. Thus the total amount of Nitrogen require for a 100 ha facility is 6.2 tonnes per day (Appendix 1) while 0.6 tonnes per day of phosphorous will be consume for the same purpose. 46% Nitrogen rich Urea will be use equivalent to 13 t/day of Urea; this is equivalent to £ 4,390 @ £330/t. While 1.6 t/day of phosphorous rich Diammonium Phosphate (DAP) will be needed for the algae farm equivalent to £ 614 @ £470/t.
Note: DAP contains 18% N, thus 234kg N required for the farm will come from DAP as against Urea. See Appendix 2.

Price of Chemicals

Chemical compounds such as NaOH, Methanol and Ethanol will be required for both harvesting and transestrification process on daily basis. Their prices gotten from the internet are presented below based on daily consumption;

- NaOH, 6.8 kg = £ 18. (£ 2,700 for 150 days)
- Methanol, 60,000 L = £23,340. (£ 3,501,000)
- Ethanol, 2,800 L = £ 3,100. (£ 465,000)

Labour

Looking at small business in and around the Northeast it is not unusual to find a business with the following personnel managing it;

- Plant Manager
- 2 shift supervisors
- 5 Pond Operators
- 2 Harvesters/DiAF Operators
- Store Keeper
- Sales/Accountant
- Electrician

The total cost for labour is around £202,800/yr (13 staff) assuming full time job for each of the employees for 1,200 hrs /yr (150 days) with average minimum wage (Blyth) of £13/hr (Office of National Statistics).

Maintenance, Tax and insurance

In this study we estimated maintenance costs as a percentage of investment, using an appropriate factor for each item, example 1% of electrical and earthworks, and 3% for other items.

Maintenance labour as assumed to be included in general labour. Here we use an average of 3% for all items, including any special maintenance labour that would not be included in the general labour category. To these 3% annual maintenance are added another 2% for insurance and property taxes. The total of 5% applied to all capital investments, except land costs and working capital.

The table below shows annual operating cost (£) for running algae farm based on Benemann and Oswald 1996 report extrapolated with data from the Campbell et al., report. Power price = £0.095/kWhr

Table 5: Annual Operating Cost

Operation Item	Power (kWh/yr)	Cost (£)
Paddle Wheel Power	450,000	42,750
Harvesting Power	73,750	7,000
Foam Column	95,833	9,100
Water pumping	238,750	22,681
Flue Gas Pumping	160,417	15,240
Miscellaneous	1,000	9,500
Nutrients	-	750,600
Chemicals	-	5,800
Labour	-	202,800
Maintenance	5% Capital Cost	120,000
Total		**1,185,471**

From the above tables:

Capital cost for this project is = £3,778,463

Operating Cost is = £1,185,471 p.a

If we assumes biodiesel to sell at the current fossil diesel price = 140 ppl, then 11,000 L pre day of biodiesel produced by the foam column route = £ 15,400 = £2,310,000 for 150 days production.

Subtracting the annual operating cost; £ 2,310,000 – £ 1,185,471 = £ 1,124,529 as profit.

Assuming we borrow £ 4,000,000 from the bank to finance the project at the interest rate (r) of 5% p.a for 15 years (n), (neglecting inflation) it implies that;

Discount factor $[1 - (1+r)^{-n}]/r = [1 - (1+0.05)^{-15}]/0.05 = 11$

Therefore £ 4,000,000/11 = £363,636.

Thus £ 363,636 needs to be paid back to the bank annually to settle the loan.

£ 1,124,529 (profit) - £ 363,636 = £ 760,893 as the final profit after subtracting bank loan.

BUSINESS CASE

As described above the best case scenario for the production of algae biodiesel in the Cambois Peninsular is the foam column harvesting route. This paragraph will explore the advantages and disadvantages of this option for possible implementation by the local authority or business organisation.

PEST

This looks at the external factors of the macro environment that may affect this business case. The categories are Political, Economic, Social and Technological.

- Political
- There are political drivers concerning biofuels put in place by the EU and UK which favours the establishment of this kind of business. See chapter 3.
- Security of supply due to volatile Middle East as well as depleting world oil reserve calls for investment in the renewable energy sector for government and institutions to be self-subsistent.
- This document can also serve as regeneration option plan for the Peninsular that may be considered in the future by the local authority for implementation.

- Economic
- Close proximity of V fuel Biofuel Company to the algae farm can serves as economic advantage where the final biodiesel product can be dispose of easily. V Fuel Company has been the leading biofuel producers through 1st and 2nd generation biofuel technology in the Northumberland.
- Fossil fuel price hike may also serves as another economic incentive for the algae biodiesel business in the Northumberland County. Especially Blyth that recently witnesses the collapse of its coal fired power plant which provide job for the locals.

- Social
- The Business can provide the much needed job the local community need at this crucial time.
- It can also improve the local economy amidst the global recession currently hitting the world especially Europe.
- The business case can be used as an option to be presented to the local authorities for regeneration potential option of the land.
- Increase awareness of greenhouse effect by the community may also add credence to the business plan.
- Some of the drawback of this issue is competing land use as well as community objection to the overall business proposal.

- Technological
- Rapid advancement in the renewable energy technology.
- Algae biofuel R&D have been supported by government and multinational organisation.

CONCLUSION

Previous research and development work on microalgae biodiesel production has been centred exclusively on tropical areas where the coldest average temperature is 15^{o}C. For the first time this kind of study was conducted in the North East of UK (at least to my knowledge), and it was proven that given the right condition microalgae biodiesel could be produce on large scale economically. The techno-economic analysis presented in the project proves that biodiesel could be produced from microalgae and be viable if the bottle neck of harvesting and dewatering could be obviated. Close proximity of important algae production parameters such as CO_2 and water also aid in reducing the overall capital cost of the production system without which the business may not see the light of the day.

Finally it is important to test the foam column separation technique of microalgae at a commercial scale to validate its effectiveness in this field.

FUTURE RESEARCH

Future research work is to find the extent to which algae cell wall are broken during harvesting and to investigate the possibility of having 2 step harvester where insitu transesterification of the algae lipid could be conducted at the upper level where the algal cell wall breaks to produce biodiesel.To achieve the above-mentioned objective, activities on the research work are organised in to three phases. The initial phase will involve experimental growth of algae sp chlorella in a lab control condition of optimum temperature, light and nutrients deficient culture. The second phase involves the construction of portable foam column harvester that will be used to extract the chlorella from the culture medium using NaOH as surfactant. The last phase involves careful study of the algae cell activities as it travels from the culture medium through the foam column tube to the final collection point.

The research will investigate the feasibility of algae cell wall breakage by surfactant with a view to exposing the algae lipid necessary for biodiesel production. This will certainly reduce the overall production cost and makes algae biodiesel competitive with the fossil fuel in the long run.

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APPENDICES

Appendix 1: Algae Farm Nutrient Requirement @ 22 g $m^{-2}day^{-1}$ Productivity

Algae Equation

$\mathbf{106\ CO_2 + 16\ NO3^- + H_3PO4^- + 122\ H_2O + 17\ H^+ \rightarrow C_{106}\ H_{263}\ O_{110}\ N_{16}\ P + 138O_2}$

Biomass Molar Mass (**$C_{106}\ H_{263}\ O_{110}\ N_{16}\ P$**) = 3,551 g mol^{-1}
At the productivity of 22 g m^{-2} day^{-1} = 220,000g ha^{-1} day^{-1}
Thus productivity divide by the Biomass Molar Mass = 220,000 g ha^{-1} day^{-1} / 3,551 g mol^{-1} = 61.954 moles ha^{-1} day^{-1}

Thus Nutrient Req:
61.954 X 106 moles CO_2 = 6567.1 moles day^{-1}
61.954 X 16 moles NO_3 = 991.3 moles day^{-1}
61.954 X 1 moles H_2PO_4 = 61.954 moles day^{-1}
61.954 X 17 moles H^+ = 1053.2 moles day^{-1}

This produces:
61.954 X 1 mole Algae Biomass = 62 moles day^{-1}
61.954 X 138 moles O_2 = 8546.7 moles day^{-1}

For a 100 ha Algae Farm

- CO_2 = 6567.1 X 100 = 656712 moles day^{-1}
  CO_2 molar mass = 44.0096 g $mole^{-1}$
  Thus 656712 X 44.0095 = 28901632 g = **28.9 tonnes**
- NO_3^- = 991.3 X 100 = 99130 moles day^{-1}
  NO_3^- molar mass = 62.0049 g $mole^{-1}$
  Thus 62.0049 X 99130 = 6146545.7 g = **6.2 tonnes**
- H_2PO_4 = 61.954 X 100 = 6195.4 moles day^{-1}
  H_2PO_4 molar mass = 96.9874 g $mole^{-1}$
  Thus 6195.4 X 96.9874 = 600875.74 g = **0.6 tonnes**
- H_2O = 7558.4 X 100 = 755840 moles day^{-1}
  H_2O molar mass = 18.0153 g $mole^{-1}$
  Thus 755840 X 18.0153 = 13616684.4 = **13.6 tonnes**
- H^+ = 1053.2 X 100 = 105320 moles day^{-1}
  H^+ molar mass = 1.00794 g $mole^{-1}$
  Thus 105320 X 1.00794 = 10615.2 g = **0.11 tonnes**

Summary

CO_2 = 29 t
NO_3^- = 6.2 t
H_2PO_4 = 0.6 t
H_2O = 13.6 t
H^+ = 0.11 t

Appendix 2: Fertilizer Production Requirement

- **Phosphorous**

At 22 g m^{-2} day-1 production 100ha algae farm requires 0.6 t of P (Appendix 1). The cheapest and readily available source of P is Diammoniumphosphate [(P_2O_5) DAP]. DAP contains 46% P and 18% N.

Thus to supply 0.6 t of P we require 0.6 X (100/46) = 1.3 t DAP

- **Nitrogen**

Here we require 6.2 t of N for a daily production of 22 g m^{-2} algae in a 100 ha farm (Appendix 1). The cheapest source of Nitrogen is Urea which contains 46% N.

Thus to supply 6.2 t N we require 6.2 X (100/46) = 13.5 t Urea
But we have 18% N that comes from DAP = 1.3 t DAP X (18/100) = 0.234 t N
13.5 t – 0.234 = 13.3 t N