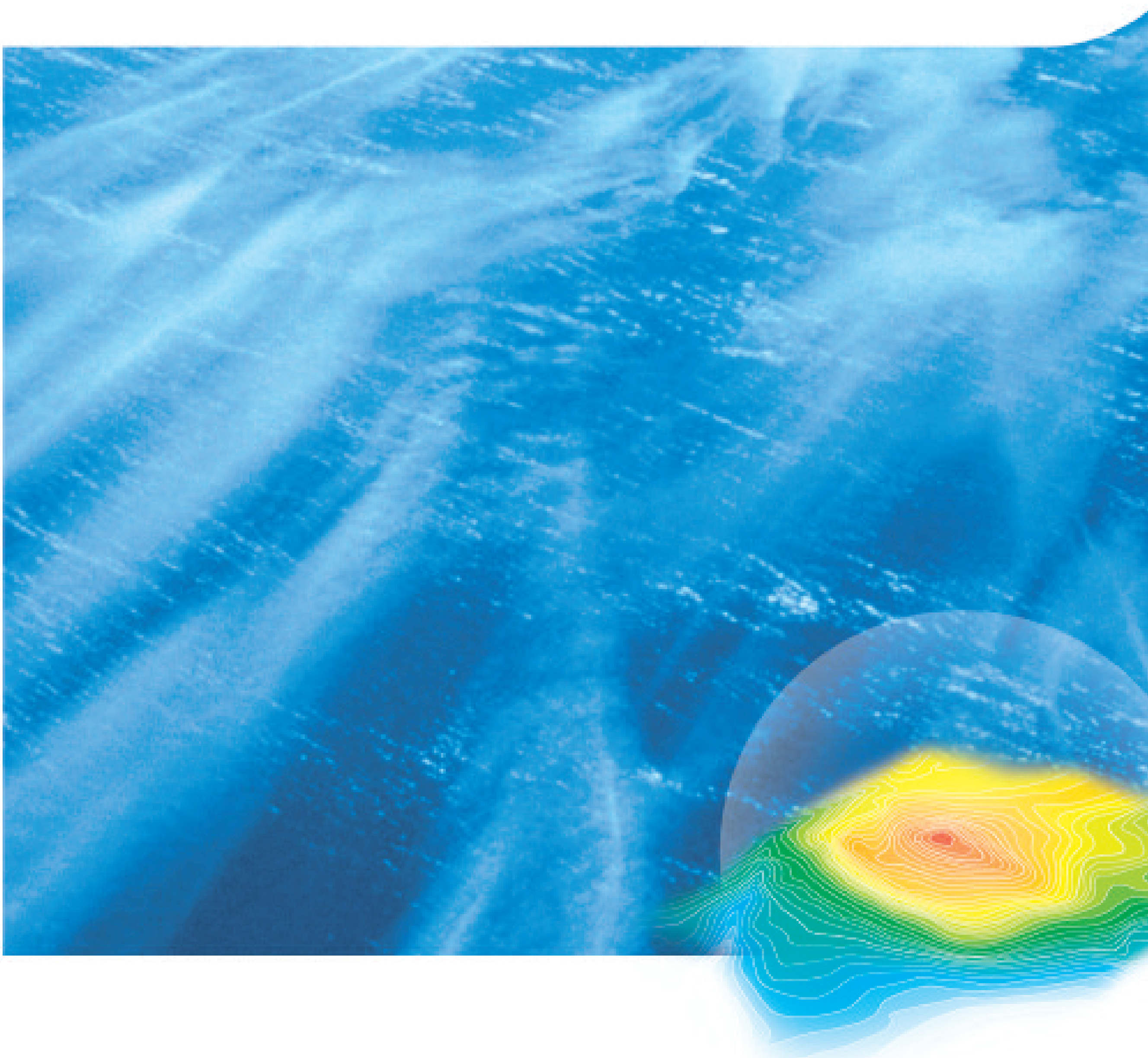

A Review of the Potential of Marine Algae as a Source of Biofuel in Ireland

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Executive Summary

This report has been commissioned by Sustainable Energy Ireland in order to provide an overview of marine algae as an energy resource, from either macroalgae or microalgae. It is also required to assess the potential resource in Ireland, determine the level of activity and identify research and development knowledge gaps.

A biofuels obligation scheme is being proposed in Ireland which will see a percentage of fossil-fuels for transport being displaced by biofuels, ultimately reaching 10% (on an energy basis) by 2020. The achievement of this ambitious target is contingent on finding and commercialising new resources for transport fuel, as current feedstocks are not sufficient to meet the target.

Microalgae are being widely researched as a fuel due to their high photosynthetic efficiency and their ability to produce lipids, a biodiesel feedstock. Macroalgae (or seaweeds) do not generally contain lipids and are being considered for the natural sugars and other carbohydrates they contain, which can be fermented to produce either biogas or alcohol-based fuels.

A supply-chain analysis was carried out for both macroalgae and microalgae, technologies identified and research topics proposed to evaluate commercialisation potential of these resources for energy. For the purposes of this report tentative roadmaps based on high, medium and low scenarios are hypothesised for development of these resources by 2020.

Macroalgae

Among macroalgae, the *Laminaria spp* and *Ulva spp* are the most important prospects from an energy perspective. The five kelp species which are native to Ireland are *Laminaria digitata, L. hyperborea, Saccharina latissima, Sacchorhiza polyschides* and *Alaria esculenta*.

The vast majority of seaweed is collected for human consumption and for hydrocolloid production. Seaweed exploitation in Europe is currently restricted to manual and mechanised harvesting of natural stocks. The majority of Asian seaweed resources are cultivated. The traditional markets for seaweed products sustain a much higher price for raw material than that likely for biofuel production.

In Europe, the main harvesters are Norway and France. Mechanised systems for harvesting *Laminaria spp* have been utilised for many years. The sustainability of harvesting natural stocks is a major challenge for these countries. Ireland and Scotland have large resources of brown seaweeds. In Ireland the access to wild stocks is controlled by the state. A deeper understanding of the impact of large-scale harvesting of wild seaweeds is required before any consideration of commercial exploitation is made. There will be a burden of proof on the industry to monitor stocks in any future exploitation. Mechanised harvesting would be essential to development also. In Ireland, the only existing harvest of significance is the *Ascophyllum* harvested manually for Arramara Teo. In 2006, 29,000 wet tonnes were harvested for the state-owned company.

Ireland has an estimated 3 million tonnes of standing kelp stock although the accuracy of this figure is poor as it is largely based on regional survey data in Galway Bay that had a margin of error of ±40%. Many barriers exist to high levels of exploitation of natural stocks, particularly recognising the significant contribution of macroalgae in supporting marine biodiversity.

There are some seaweeds available as drift material. Significant quantities of *L. Hyperborea* and *Ulva spp* are washed up annually. This resource is seasonal and unpredictable and its extent is yet to be fully assessed.

In the longer term cultivation is the most likely means to generate significant volumes of seaweed biomass. This can happen, subject to appropriate licences, either at nearshore locations, or offshore. This is likely to be initially deployed through integration with existing aquaculture enterprises or in conjunction with new offshore engineering projects. Trials to date have concentrated on small-scale applications for niche high-value products. In an optimistic scenario, developed for the purposes of this report, up to 700 ha of seaweed aquaculture could be established by 2020. Large-scale cultivation projects of up to 41 km^2 have been envisaged elsewhere, notably in the USA and Japan, but cost and engineering barriers have not been surmounted. Costs for the large scale development of seaweed aquaculture in Ireland are unknown.

Seaweed is normally sold in modest volumes and delivered fresh for further processing at local factories. It has about 80-85% moisture content and is costly to transport. It has a negative lower heating value, so processes which do not require drying would be favoured. The principal energy process considered for seaweed is fermentation, either anaerobic digestion (AD), to create biogas, or ethanol fermentation. The presence of salt, polyphenols and sulphated polysaccharides would need to be carefully managed in order to avoid inhibition of the fermentation process.

Biogas production is a long-established technology and previous trials have indicated that anaerobic digestion (AD) of seaweed is technically viable. It should initially be possible to incorporate seaweed resources into existing AD plant to allow for smaller quantities and seasonal availability. This is the closest process to commercialisation for conversion of macroalgae to energy, though there is still a need to reduce the cost of the raw material by at least 75% over current levels.

Alcoholic fermentation is more difficult. The lack of easily fermented sugar polymers such as starch, glucose or sucrose means there is little point in pursuing standard sugar fermentation processes. The polysaccharides that are present will require a new commercial process to break them down into their constituent monomers prior to fermentation, or else a direct fermentation process will have to be developed. Promising work has been initiated in Ireland and elsewhere to isolate marine lyases which would do this efficiently. Theoretically up to 60% of the dry biomass in *Laminaria spp* could be fermented with the right process. *Ulva spp* are also of interest due to their starch content.

The competitiveness of macroalgal biomass for alcohol fermentation must be viewed in the context of other available cellulosic biomass such as wood, straw and dry organic waste which are also potential ethanol feedstocks.

There is much speculation that integrated biorefinery solutions would allow sufficient scale to enable economic production of fuel from macroalgae. The only industrial product of significance from macroalgae is hydrocolloids, and there is no production based in Ireland currently. Extraction of energy from waste-streams is a valid commercial biorefinery concept. If the cost of seaweed permits, a dual production of ethanol and biogas is also possible. There are many other opportunities for extraction of high-value niche products from seaweeds. Each would have to be assessed on commercial terms and demonstrate the feasibility for co-production of energy alongside the higher-value product, with particular attention to whether the scale of operation is appropriate.

Ireland has a long track-record in macroalgal research. There are several existing research programmes identified within the report for which algae as a biofuel feedstock could be a good complement.

The estimates produced for the purposes of this report show that up to 447 TJ of energy might be generated from macroalgae by 2020. This is about 0.2% of current national road-fuel demands.

Microalgae

There are at least 30,000 known species of microalgae. Only a handful are currently of commercial significance. These are generally cultivated for extraction of high-value components such as pigments or proteins. A few species are used for feeding shellfish or other aquaculture purposes.

One of the key research tasks for commercialisation of algae for energy purposes is to screen species for favourable composition and for ease of cultivation and processing, among other criteria. The main focus of screening is currently on lipid productivity, and subsequent esterification, but fermentation options should not be ignored. Most screening programmes include freshwater species.

There is no consensus concerning optimum systems for microalgae cultivation. Scientists disagree over whether open or closed or some combination of cultivation systems is most favourable. Open-pond systems, such as raceways, entail low capital and operating cost, but also low productivity and lack of control over cultivation. Closed systems, such as photo-bioreactors (PBR) are much more expensive but offer higher productivity.

In existing commercial applications, artificial light and sometimes heat are used. This can be justified on a small-scale for high-value product manufacture. For energy purposes, only natural light and sometimes waste heat should be considered. The biggest unknown in Ireland or other similar climates is whether it is possible to achieve reasonable productivity in view of prevailing natural light and temperatures. For regions at higher latitude, it may be possible to identify local strains requiring low light intensities and lower water temperatures but giving satisfactory growth rates and yields.

Short term growth rate is often mistakenly extrapolated to annual productivity. It is likely that a large seasonality penalty will exist if microalgae are to be cultivated in Ireland where the latitude is 53°N. Despite this limitation, microalgae production for biofuel cannot be ruled out without further research and validation of the concept in Ireland. Stakeholders in Ireland from the academic, industrial and entrepreneurial community wish to demonstrate this technology. An optimistic scenario is outlined within the report where 100 ha of microalgae production is achieved by 2020. Several significant research advances would be required if this were to be achieved.

There is a consensus that the photosynthetic efficiency of terrestrial plants is 1% or less. Promoters of algae technology for biofuel expect the limits of microalgae photosynthetic efficiency to be pushed out to somewhere between 3 and 6%. 6% can be set as an absolute maximum theoretical efficiency that is unlikely to ever be obtained under real conditions. Productivity claims for microalgae systems are often overstated.

Based on the fundamentals of photosynthesis, anything above 53 t/ha/yr of dry biomass in the Irish climate should be treated with caution.

A research goal for Ireland could be to demonstrate biomass areal productivity rates of 25 dry t/ha/yr and to obtain 25% of useful lipids, yielding 6.25 m^3/ha/yr. Expectations should be modest until at least these preliminary targets are met.

Nutrients and carbon are other key requirements for microalgal growth. For carbon, exhaust gas from power plants which contain significant quantities of low-cost CO_2 can be used. This is part of the business model of most biofuel projects, which also allows power plants to recycle CO_2.

Algal slurry is 15-25% dry weight after collection. Dry lipids are necessary for esterification and removal of water is expensive. Development of lipase for direct esterification or other extraction techniques could remove the drying step. Unsaturated fatty acid content is high in algal oils and their presence lowers esterification yields.

Microalgae have significant lipid content and even very high lipid content under certain stress conditions. Research laboratories have shown that some microalgae strains are able to generate 70% lipid in their biomass. However this has not yet been found in real conditions where maximum yields of 30% are encountered.

There may be opportunities for applying biorefinery-type processes to extract and separate several commercial products from microalgal biomass. Besides lipids, microalgal biomass offers opportunities for obtaining additional commercial materials. These include fermentation to obtain ethanol and biogas. It is also possible to produce protein-rich feed for both animal and human consumption. Poly-unsaturated fatty acids (PUFAs) are a potential co-product of biodiesel production from microalgae. PUFAs are a vegetable origin alternative to e.g. fish oils and other oils rich in omega-3 fatty acids. Bulk markets for the co-products potentially available via a biorefinery process have not been demonstrated, and this is a research need if the biorefinery concept is to prove a valid business model.

Due to the small initial scale of any pilot production of microalgal oil, it is likely that feedstocks would first be used in existing biodiesel refineries in order to trial the concept. The aviation industry is particularly interested in algal biodiesel, due to its superior cold-temperature performance, energy density and storage stability.

Current cultivation costs only justify extraction of high-value niche components. A reduction by at least a factor of five is necessary to make microalgae attractive for their lipid content.

There is significant activity worldwide, with news about investments and research programmes emerging on an almost daily basis. There are likely to be over 30 new US patent applications submitted during 2008, which will exceed the total for the preceding 6 years. The low number of patents is an advantage for researchers and potential investors as it leaves opportunities for further developments and innovation protection. Current Irish research activities remain modest in the international context. Unless the key challenge of obtaining microalgae suited to the Irish climate is solved, this is likely to remain the case.

About 79 TJ could come from microalgae resources by 2020 based on the most optimistic scenario developed for the purposes of this report. This is a fraction of 1% of national road-fuel demand.

Conclusions

Many barriers to development and areas of research were identified. There may be potential for energy generation from both macroalgae and microalgae. It is however difficult to understand the high levels of commercial activity and investment in marine algae at present as a biofuel resource, in light of the research advances still required.

The large-scale exploitation of wild seaweed stocks, as required to support a biofuel production process, appears unlikely until its role in supporting and maintaining marine biodiversity is clarified. Seaweed produced from aquaculture is therefore the most likely source.

The energy contribution from marine algae by 2020 is likely to be modest. The opportunities for generation of new technology, spin-off activity, jobs, investment and the potential for new intellectual property creation have not been considered in this review. The interest for non-energy products such as nutraceuticals, pigments, proteins, functional foods and other chemical constituents is currently commercially more important than energy.

Greater research capacity and competence could enable a more complete exploration of the potential of marine algae for energy. Other countries in north-west Europe face similar challenges throughout the supply chain and collaborative research internationally and domestically could be encouraged.

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1. Introduction

This report has been commissioned by Sustainable Energy Ireland in order to provide an overview of algae as an energy resource, from either marine macroalgae or microalgae. It is also required to assess the potential resource in Ireland, determine the level of activity and recommend research and development priorities.

Algae essentially harness energy via photosynthesis. They capture CO_2 and transform it into organic biomass which can be converted to energy. Like other biomass resources it is theoretically a carbon neutral source of energy. Whilst the different technologies will be described in greater detail, the principal energy processes being considered for aquatic biomass are shown in Figure 1. Microalgae are being widely researched as a fuel due to their high photosynthetic efficiency and their ability to produce lipids, a biodiesel feedstock. Macroalgae do not generally contain lipids and are being considered for the natural sugars and other carbohydrates they contain, which can be fermented to produce either biogas or alcohol-based fuels.

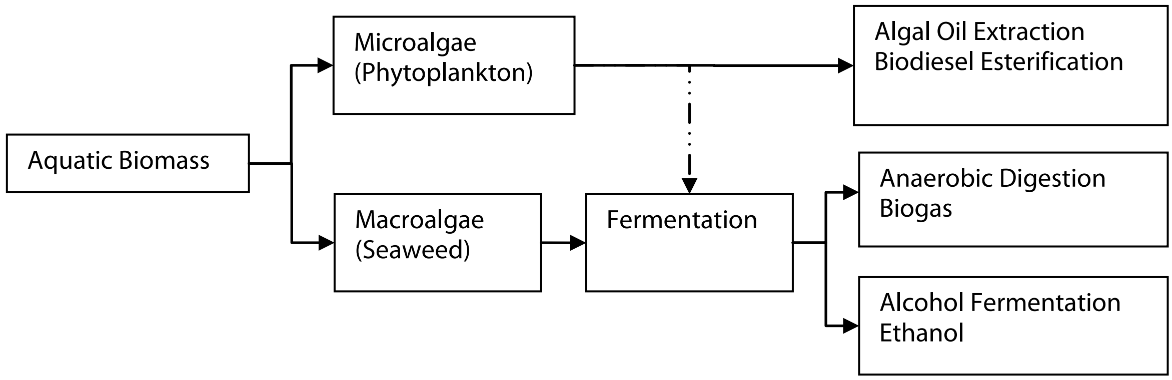

Figure 1: Principal Energy Processes Being Developed for Aquatic Biomass

1.1. Policy Context

Marine biomass is attracting a great deal of commercial and political interest as a feedstock for biofuel production. The International and Irish policy context is well outlined in a recent paper by the Irish Government on a biofuels obligation scheme (DCENR, 2008). A biofuels obligation scheme is being proposed in Ireland which will see a percentage of fossil-fuels for transport being displaced by biofuels from 2010, ultimately reaching 10% (on an energy basis) by 2020. The 2020 target coincides with that set out in a draft European Union Directive on Renewable Energy (European Commission, 2008).

What is clear is that the achievement of this ambitious 2020 target is contingent on finding and commercialising new resources for transport fuel, as current feedstocks are not sufficient to meet the target. Additionally, sustainability criteria governing acceptable forms of biofuels are being introduced as part of the proposed EU Directive, and eventually in Irish legislation, which will place constraints on the availability of biofuels from conventional land-based crops, such as oilseed rape and wheat. Biofuels from conventional sources are frequently referred to as 1st generation biofuels. Concerns are being raised over the impact of previous biofuels policy supports on food commodity prices, their impact on land-use change, their effect on habitats and eco-systems. The greenhouse gas profile of all biofuels is also likely to be regulated, so that initially, at least a 35% reduction in lifecycle greenhouse gas emissions must be demonstrated for biofuels. This topic is also well addressed in the Irish biofuels obligation scheme document.

New sources of biofuel feedstock, such as marine biomass, cellulosic biomass and other 'non-food' biomass are commonly referred to as next generation (or sometimes 2nd or 3rd generation, depending on the technology employed and ones subjective view) biofuel feedstocks. In general, they promise higher productivity, a lower greenhouse gas profile and improved sustainability performance when compared with 1st generation feedstocks. They do not directly impact on arable crop commodity markets.

Marine biomass, the subject of this review, is thought to be a promising next generation biofuel feedstock. Ireland has a long maritime tradition and significant potential for exploitation of marine resources, and it is timely to review possible biofuel production from this resource.

1.2. Scope and Methodology

The focus of this report is the main biomass resources in the marine environment - marine algae, either macroalgae (seaweeds) or microalgae (phytoplankton). Freshwater species were excluded from the brief.

The scope of the study adheres generally to the original tender request, which includes the following key items which are addressed within the report:

- Review international developments in marine algae as a source of biofuels
- Identify technologies to grow, harvest and convert marine algae to biofuel
- Present illustrative examples
- Highlight barriers to commercialisation which need to be addressed
- Identify co-product/residue issues
- Provide outline cost estimates for commercial projects
- Identify potential applications in the Irish context
- Highlight factors that favour a site for algae production and the types of algae that might be suitable
- Estimate the potential for development to 2020
- Identify important research topics in order to realise potential for biofuel from marine algae in Ireland

A methodology was developed to address these questions. Below the activities undertaken and the sections laid out for this report are outlined.

A team of experts was assembled to address the consultancy brief, comprising both Irish and International researchers. The project was managed and lead by BioXL, a specialist energy consultancy firm in Ireland, with partners in the Shannon Applied Biotechnology Centre (Ireland), the European Research Centre for Algae (France), the Scottish Association for Marine Science (Scotland) and the National Environmental Research Institute (Denmark).

The entire project team attended a week-long conference of the International Society of Applied Phycology in Galway in June 2008. A team workshop was held during this conference. A follow-up workshop was held at the European Research Centre for Algae (CEVA) in France in September 2008. The team consulted with many stakeholders in Ireland and overseas. An extensive literature review was undertaken and several other conferences attended.

Kick-off, mid-term and final review meetings were held with the Steering Group. A draft report was submitted to a peer review group and to the Steering Group and their feedback incorporated in the final version.

The report contents have been set out in logical sections which address the consultancy brief as set out below, in addition to this introductory section.

- Section 2: This section sets out a supply-chain review in order to give a complete picture of the resources, technologies and barriers to commercialisation. Case studies are elaborated for macroalgae and microalgae.
- Section 3: This covers costs and productivity estimates. There is no existing commercial technology. The estimates are not based on reliable data in an Irish context, and for this reason are set out as a stand-alone section.
- Section 4: This estimates the potential for development in Ireland, where factors favouring (or limiting) production in Ireland are outlined and tentative roadmaps out to 2020 described for macroalgae and microalgae.
- Section 5: This section outlines a number of research programmes and commercial developments, building on earlier sections to present a point in time overview. This highlights the international context within which any Irish projects must be viewed and the need for collaborative research.
- Section 6: The research priorities which need to be addressed in order to commercialise marine algae for biofuel are outlined. This is done by first addressing issues globally and then by attempting to identify specific priorities for an Irish R&D programme.
- Section 7: Draws some overall conclusions and highlights the principal findings of the report

2. Supply Chain Review

This section sets out an overview of the complete supply chain required to derive energy from both micro and macro-algae. The first step is Biomass Generation. It can be via natural generation or cultivation and applies to seaweed as well as microalgae. The second step is harvesting, from manual harvesting, still used for seaweeds in Ireland, to methods using continuous automated flow for some microalgae. The third step is Biomass Pre-treatment, including cleaning, desalination, dewatering and drying (when needed). A further step is grouped under Downstream Processing that can vary depending on the energy generation route selected. Finally the market aspects from a biofuel end-user perspective are considered. Table 1 presents an overview of the supply chain for both resources and the aspects which need to be considered.

Table 1: Supply Chain Overview

Resource Type	Biomass Generation	Harvesting	Pre-treatment	Downstream Processing	Market
Macroalgae (Seaweeds)	Natural stocks Aquaculture Nearshore Offshore	Manual Mechanisation	Cleaning Dewatering Desalination	Biogas Bioethanol Biorefinery Residues	Logistics Infrastructure Engines
Microalgae (Phyto-plankton)	Cultivation Photo bioreactor Open ponds Species selection	Filtration Sedimentation Centrifuge Flocculation	Dewatering Drying	Biodiesel (lipids) Fermentation (biomass) Biorefinery Residues	Logistics Infrastructure Engines Aviation
Overall Strategy					
Policy, Leadership, Vision Investment, Public funding R&D programme, Systems analysis, Life-Cycle Assessment Sector networks					

2.1. Macroalgae - Seaweeds

Marine macroalgae or seaweeds are plants adapted to the marine environment, generally in coastal areas. There are a very large number of species around the world, belonging to several phylogenic groups. Broadly, three types of seaweeds are defined according to their pigments e.g. the brown seaweeds (e.g.: *Laminaria, Fucus, Sargassum*), the red seaweeds (e.g. *Gelidium, Palmaria, Porphyra*) and the green seaweeds (e.g. *Ulva, Codium)*.

With the exception of green seaweed, terrestrial and marine plants have little in common. This partly explains the unique chemical composition observed in seaweeds. The marine environment also induces the production of unique chemicals to resist the environmental stresses plants are subjected to. In one way, seaweeds can be considered as extremophile organisms, especially those located in places with long daily periods of dryness (i.e. inter-tidal species).

The vast majority of seaweed is collected for human consumption and for hydro-colloid production. The FAO Guide to the Seaweed Industry provides an excellent overview of the seaweed resource and markets worldwide (McHugh, 2003). A worldwide survey performed in 1994/5, listed 221 species of seaweed collected for human applications (145 for food and 101 for hydrocolloid extraction).

The various brown seaweeds have since the early 20th century, been used for industrial applications, and now attention is turned in many regions with brown seaweed resources to the production of energy. Also green seaweeds, in particular *Ulva spp* are being researched as potential renewable fuel feedstocks.

2.1.1. Biomass Generation

Seaweed exploitation in Europe is currently restricted to manual and mechanised harvesting of natural stocks. The majority of Asian seaweed resources are cultivated. There is a marked difference in the cost of seaweed between the two regions. Costs are discussed in a later section along with productivity. Seaweed is normally sold in modest volumes and delivered fresh for further processing at local factories. It has about 80-85% moisture content and is costly to transport.

2.1.1.1. Natural Stocks

The most common system in Europe to obtain seaweed biomass is by harvesting natural stocks in coastal areas with rocky shores and a tidal system. The natural population of seaweed is a significant resource. Depending on water temperature, some groups will dominate, like brown seaweeds in cold waters and reds in warmer waters. In 1995 about 3.6 million tonnes wet weight were collected globally from natural stocks (*Lithothamnion* not included). This was about 48% of the total global seaweed biomass harvested with the balance produced by aquaculture. More recent numbers (FAO, 2006) give about 1 million tonnes harvested annually from natural stocks, making up only 6% of the global resource, with over 15 million tonnes produced by aquaculture.

In Europe the main harvesters are Norway and France. Around 120,000 tonnes of *Laminaria* spp are harvested annually in Norway. The standing stock is estimated to be 10 million tonnes (Jensen, 1998). France harvests about 50,000 – 70,000 tonnes annually, mainly *Laminaria* species for hydrocolloid production. Estimates of exploitation of natural stocks globally are shown in Table 2.

Table 2: Seaweed Wild Harvest Estimates for Selected Countries *(FAO 2006)*

Country	'000 tonnes wet seaweed capture (Estimates 2006)
China	323
Chile	305
Norway	145
Japan	113
France	75*
Ireland	29

* CEVA estimates

In Norway the industry is highly regulated. It has been estimated that the current level of industrial usage of standing stocks can be maintained using sustainable wild harvesting. Somewhere between a 6 and 17% extraction rate and a 7 year inter-harvest rest are legislated for. In some locations a higher growth rate was found after harvesting with a trawler.

In France, a survey of the *Laminaria* stock has not been carried out recently but some decrease of population density has been observed at sites supporting frequent harvesting. Discussions are ongoing regarding the overall management of natural stocks.

Methods of obtaining global data on seaweed stocks are available. Specific sonar technologies can generate large amounts of data drawing maps identifying underwater stocks of *Laminaria*. CEVA have developed this technology (Mouquet, et al., 2007). Research is underway in Ireland to develop marine biomass assessment methods (Blight, 2008). Hyperspectral technologies are available to monitor the intertidal zone. It is based on aerial capture - flights can cover very large zones in a short time, allowing precise maps to be quickly defined. Hyperspectral technology is commonly used to evaluate green tides, but has also been used to evaluate brown seaweed stocks. At some locations it was observed that stocks decrease in some years. The factors involved are not yet understood.

New regulations for coastal area management require demonstration that human activity in coastal zones is sustainable. Without appropriate methods to monitor the level of seaweed stocks and their evolution, harvesting of seaweed is likely to be banned in France.

Producing significant amounts of biofuel from natural stocks involves the harvesting and processing of large volumes (millions of tonnes) of seaweeds. This could have a negative public image which would influence investment and political decisions. To harvest higher amounts in Norway or in France may not be sustainable. If for any reason hydrocolloid production decreases or ceases, part of the unused seaweed resource could be redirected towards biofuel production.

In Europe, not all seaweed stocks are used commercially. This is true of Ireland and Scotland which have large brown seaweed stocks with no commercial application. The potential for exploitation in Ireland is considered in more detail in a later section.

2.1.1.2. Drift seaweeds

Another primarily natural source are drift seaweeds. Some reports suggest as much as 20% of *L. hyperborea* stocks are washed up on shore every year in Ireland. The location and seasonal availability of these resources are unpredictable. It has traditionally been collected by coastal communities on a small scale to use as fertiliser or soil-conditioner.

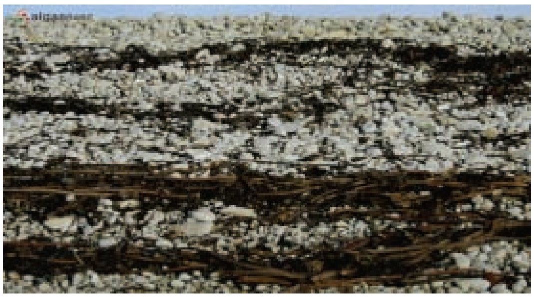

Figure 2: Drift *L. hyperborea* in Galway *(M Guiry/algaebase)*

Figure 3: Harvested *L. hyperborea* in Clare *(G Blunden/Algaebase)*

Drift *Ulva* spp are commonly encountered and often known as 'green tides.' They tend to develop at more and more locations along European coasts (including Ireland's), due to eutrophication. Drift *Ulva spp* are not yet used for industrial applications.

Figure 4: Drift Ulva spp *(CEVA)*

When collected on the foreshore drift seaweeds are considered a waste product. Developing an application for a waste has very positive connotations. Annually green tides in France generate about 60,000 tonnes of wet *Ulva spp*, which is about 8,000 tonnes dry weight. Although this is not a large quantity it can contribute to local energy production. However, it can be difficult to build a local enterprise based on wastes which are desirable to eradicate. This problem was encountered several times by local initiatives in France to use drift seaweed. This biomass provides an opportunity, as and when it is available, to be integrated in a broader process using other type of biomass raw materials.

2.1.1.3. Cultivation - Aquaculture

The second possibility for seaweed biomass generation is through cultivation. Only a few genera have been commonly cultivated for many years. The main genera cultivated include: *Laminaria, Porphyra, Undaria, Gracilaria, Euchema, Ulva and Chondrus*. The seaweed harvested from natural stocks has decreased significantly, while cultivated seaweed has sharply increased. The overall amount of seaweed harvested has almost doubled in the last 10 years to 15 million wet tonnes (FAO, 2006). Over half of cultured seaweeds, or 7.4 million wet tonnes, are brown *Laminaria* spp, mainly *L. japonica*.

The global industry turnover also increased from US $6.2 billion in 1994 to US $7.2 billion in 2006. Values have not been inflation-adjusted, but the trend is of increased volume and static turnover. It reflects the significant cost-reduction brought about by cultivation practices. There is a much larger amount of seaweed available and mechanized operations have improved productivity allowing lower market prices.

Table 3: Seaweed Aquaculture Estimates Main Producers *(FAO 2006)*

Country	'000 tonnes Seaweed Aquaculture (Estimates 2006)
China	10,800
Philippines	1,300
Indonesia	900
Others	2,000

In Europe, knowledge of seaweed cultivation is scattered across several R&D groups and a few industrial groups. The amount of cultivated seaweed is very low, mainly very small companies with local facilities for cultivating high value species. Existing industries having large scale cultivation plants are located in Asian countries (China, Philippines, Korea, Indonesia, and Japan) and in Chile. Estimates of global seaweed aquaculture are summarised in Table 3. If cultivation is to increase in Europe, technology transfer from these countries will need to be considered. The main obstacle in European countries will be labour cost. Development of mechanized seaweed cultivation will be required in Europe to achieve cost objectives. In Ireland also the aquaculture sector is gradually building know-how and basic infrastructure for *Laminaria spp* cultivation.

Figure 5: L. Japonica Cultivation on Long Lines in Japan *(M Ohno/Algaebase)*

Technologies to cultivate *Laminaria spp* are well known. For instance, the FAO published a guide to *Laminaria* culture which is very detailed (Chen, 2005). The main producers of *Laminaria spp* are located in China, Korea and Japan, where preservation of natural stocks is not always sustainably managed. The main reason for an increased harvest is increased productivity due to selection of the best performing strains, improved crop-care, less variability, fertilizing techniques and faster harvesting. This strategy will also be required to achieve the low material cost needed for biofuel applications.

There are potential economic advantages and opportunities for developing aquaculture facilities in conjunction with off shore wind farms. Anchorage of long-lines, ropes and rafts has been a major problem for pilot seaweed cultivation projects (including those carried out in Ireland) with numerous reports of structures being swept away by tides and currents. Sharing infrastructure with a wind farm or other offshore enterprise would seem to make economic sense from planning, design and operation points of view. The right conditions for cultivation of seaweed would need to be present. Previous studies outline this concept in depth. The 2-year Bio-offshore analysis carried out by the Dutch research centre ECN (Reith, et al., 2005) is one example. The study considered the feasibility of offshore cultivation of seaweed species in the North Sea, using 1,000 km^2 of offshore wind farm infrastructure envisioned by 2020. This considered chemical, biological and thermal processes for conversion of seaweed into energy products and platform chemicals. The economic modelling considered scales of 100,000 tonnes and 500,000 tonnes at an onshore processing site, transporting seaweed from up to 100 km offshore, grown on long-lines suspended between wind-turbines. The results of this economic modelling are presented in the section on costs.

In Germany, researchers have carried out technical studies on new offshore structures for cultivation of *Saccharina latissima*. An innovative floating ring structure anchored to offshore wind-turbines is proposed (Buck, 2007). They conclude it is not possible to assess the potential for economic returns from aquaculture as insufficient data and experience is available.

The marine biomass programme in the US considered the use of seaweeds, in extensive research that was carried out in the 1970's and 1980's. The programme is reviewed in full by key research staff involved (Chynoweth, 2002). A fast-growing kelp native to the pacific, *Macrocystis* was the subject of a number of aquaculture trials. In 1973 a 3 ha grid structure was deployed off California. It did not survive its first winter and is thought to have lost an anchor and been destroyed by passing ships. Several further attempts at smaller scale succumbed to engineering failures, and highlighted many technical issues which need to be addressed in offshore aquaculture of biomass. In 1981 two plots of 0.2 ha grid structures survived long enough to give yield data for *Macrocystis*. It also demonstrated that artificial upwelling of nutrients is a suitable method for cultivation of seaweed. Large-scale cultivation systems were envisioned both for the marine biomass programme, and also in Japan. In Japan a design for a marine farm of 41 km^2 area, 5 km wide and 8 km long has been proposed at a distance of 8km from the coast and estimated to produce up to 1 million wet tonnes of *Laminaria japonica* (Yokoyama, et al., 2007). Highly engineering-based concepts were devised, which would operate on a large scale. An example concept is shown in Figure 6.

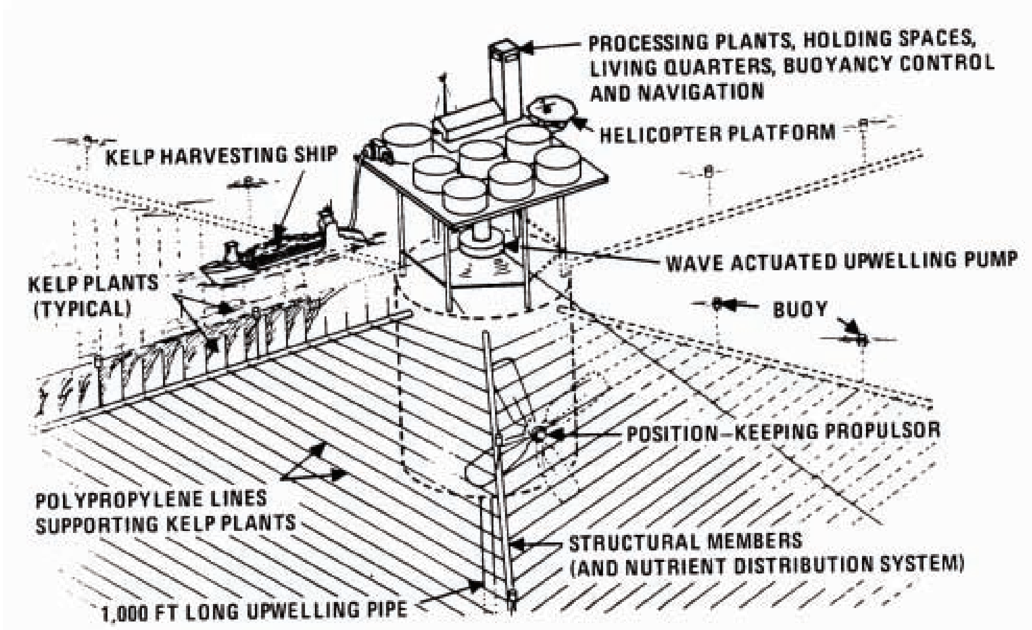

Figure 6: Conceptual Design of 400 ha Ocean Food and Energy Farm *(Chynoweth, 2002)*

Later the strategy of the US marine biomass programme switched to *Laminaria spp* which could grow in Atlantic waters, and *Gracilaria spp* which are suitable for warmer waters. Multi-crop systems were also considered to take advantage of seasonality and the differing light requirements of each species. The emphasis also switched to nearshore cultivation which reduced or eliminated many of the engineering risks of offshore development. The design of one such system is shown in Figure 7. Successful trials were carried out in New York and Florida which gave preliminary productivity data, which is reported in a later section.

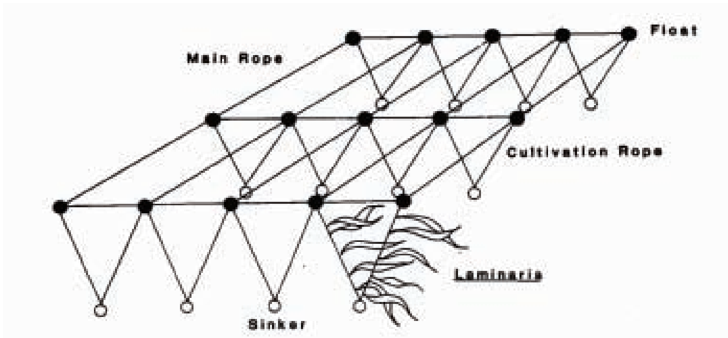

Figure 7: Hanging Rope Curtain *Laminaria* Cultivation System *(Chynoweth, 2002)*

In Ireland, so far seaweed aquaculture trials have been carried out mainly on *Alaria sp* and *Palmaria palmata* for the sea vegetable market. The most significant grow-out trials took place in Roaring Water Bay on 1.75 ha of existing mussel lines. These trials were supported by Bord Iascaigh Mhara (BIM) and the Irish Seaweed Centre. The trials lasted one season and suffered several setbacks which included adverse weather conditions, plant losses and plant bleaching (Werner, et al., 2003). The techniques used for *Alaria spp* cultivation and detailed results are described in a previous BIM report (Arbona, et al., 2006). Trials are also ongoing at Carna as part of the research programme at the Irish Seaweed Centre. New initiatives in seaweed aquaculture are summarised in a later section on commercial activity and research programmes.

Other relevant examples and productivity data will be discussed later.

2.1.2. Harvesting

Figure 8: Hand Harvesting of Ascophyllum *(M Guiry/Algaebase)*

Manual harvesting has been used since the pre-industrial age. This is still used for harvesting natural stocks of *Ascophyllum nodosum* and *Fucus* species, as they are located in the intertidal zone on the shore. At low tide, terrestrial vehicles can access the shore and seaweeds are accessible for manual harvesting. Prototypes for mechanical harvesting of fucales were tested in the past, but none gave significant results.

Manual harvesting was used for *Laminaria* in France and Norway, but the emergence of large scale application for hydrocolloids, stimulated the development of mechanical systems. Trawlers are used in Norway to cut the large size adult canopy, leaving the small size seaweed attached to the rocks. Re-growth is stimulated by the increased light reaching the small size seaweeds. Surveys have shown that kelp forests in Norway are very stable even in locations with high harvesting pressure. The trawler system is operated from a boat.

Another system operated by boat is used in France. This is the Scoubidou (See Figure 9). It twists *Laminaria* around a rotating hook and breaks holdfasts by traction. The tool is then rotated in the reverse direction to release seaweeds inside the boat.

Figure 9: Scoubidou System Used in France *(CEVA)*

In 2000, harvesting trials on *L. digitata* using the French equipment were conducted in Bantry Bay, Co. Cork, by the company Seaweed South-West with the assistance of BIM. Initial trials indicate that the length of the stipes in Ireland is likely to be the reason behind a reduced efficiency in collection compared with similar harvests in France (Werner, et al., 2004).

Using either a dredge or the Scoubidou allows one man in a boat to collect several tonnes of seaweed per day. This is a significant improvement over manual harvesting. These two examples are the most widely known mechanized harvesting techniques currently used for industrial applications. The main problem with these systems is the necessity for a boat. Seaweed harvesting is a seasonal activity in Europe. There is a need to find another use for the boat during non-harvesting periods, otherwise the cost of idle boats may impact upon the seaweed price.

Figure 10: Harvest of Drift Seaweed at Sacca di Goro, Italy *(Internet)*

Drift seaweeds are collected in beach tidal zones. Examples of drift seaweed collection equipment are shown in Figure 10 and Figure 11.

2.1.3. Biomass Pre-treatment

The first step of pre-treatment is to remove foreign objects from the seaweed biomass. The most regularly encountered debris are stones collected with the holdfast of *Laminaria* and snails on the surface of the seaweed. However, other objects are often found such as plastic bags and other rubbish. Debris screening is mandatory for all applications, especially where the next step is chopping or milling. If the biomass is used as it is, for instance in fermentation, the debris screening can be at a higher tolerance as the impact on downstream processes is low. Downstream yield may be decreased by using large seaweed pieces instead of smaller particles (with a large reactive surface), but it has to be balanced against the cost of a debris removal step and chopping or milling.

With the exception of *Laminaria spp* and some drift seaweeds, seaweeds are collected manually. Manually harvested seaweeds usually contain less debris and the volume for processing is smaller.

Figure 11: Amphibious Drift Ulva Harvester with a Salad Washer in Brittany *(BioXL)*

Drift seaweeds often contain large amounts of sand (about 1/3 by weight) if collection is done using standard vehicles. Removing this sand can be very tedious for green seaweeds. Sand levels can be lowered by using customized waste collection vehicles which collect seaweed in shallow water or at the surface of the water. Systems like salad washing machines were successfully tested but have a very low productivity rate and a high cost (capital and operational). An example of such a system is shown in Figure 11. The simplest system is to suspend green seaweed biomass in a large tank/pond of seawater by mixing. Sand will settle to the bottom. Some processes may not be impacted by sand. For instance fermentation or composting is not impacted directly. However, the mass balance and efficiency of the overall process is impacted by the amount of sand.

The shelf life of brown seaweeds is comparatively long. They can be stored at ambient temperature for hours or even days without starting to deteriorate. They resist microbial degradation due to the polyphenols present. This is considered to be beneficial for conventional manufacturing or extraction purposes. Quite often farmers harvest seaweed during the week-end, but deliver it to the factory only on the following week-day. During this period some natural dewatering of the seaweed occurs. However, this resistance to fermentation becomes an inhibitory factor for downstream microbial processes leading to biogas and alcohol formation.

Green seaweeds are the most difficult candidates for dewatering. They have high water content and they are very sensitive to microbial degradation. They need to be processed immediately. If storage is required, a suspension in seawater is the best choice (it can even continue to grow), or cold storage. Dewatering for green seaweeds requires pressing. There are numerous presses available on the market, either working on a batch or continuous flow basis. The best choice would probably be pressing conveyors used during seaweed collection on the shore. This would leave water on the shore and minimize water transportation.

Dewatering to 20-30% water content is usually a good objective. It stabilizes the biomass, allows transportation without too much water and reduces the energy required for any further drying step. The current practice in Ireland for industrial seaweed processing is to dry it down to a low moisture content, to allow for stable storage and cost-effective transportation to its customers. Arramara Teoranta currently use coal-fired boilers for drying of seaweed to a powder or meal product with about 10% moisture content.

If used, drying brings a severe increase in the cost of the overall process, as energy is required to evaporate the water. For biofuel applications, avoiding drying is the logical choice, providing seaweed biomass can be stabilized to fit downstream process flows or these processes can be adapted to the seasonal variations of seaweed biomass. Fresh seaweed actually has a negative Lower Heating Value, calculated to be -0.7 MJ/kg for an 88% moisture content (Reith, et al., 2005), which would have negative implications for any overall process energy balance. Biofuel processes compatible with seaweed biomass include biogas and bioethanol generation. Both are fermentation processes. There is no technical need to dry the biomass prior to a fermentation process. It requires water to operate efficiently. For this reason drying techniques are not considered in this report.

In terms of pre-treatment requirements, no differentiation is made between cultivated seaweeds and seaweed harvested from natural stocks. The processes apply in the same way, with the advantage of having a more homogeneous material in cultivated seaweeds and probably less debris.

Desalination is not discussed in this report, because it requires washing with freshwater which entails unnecessary costs both to get the water and to treat effluents rich in salts. Downstream processes for biofuels should be adapted to avoid a desalination step where possible. For example, a simple dilution with freshwater may be sufficient to allow adequate fermentation yields.

2.1.4. Downstream Processing

Selection of the fuel to be produced and the appropriate process is largely determined by the chemical composition of seaweeds. As it is the single largest resource and one of the most likely candidates for energy processing, brown seaweed is considered in some detail, including an assessment of its composition. Green seaweed composition will also be presented.

2.1.4.1. Composition of Brown Seaweed

The composition of brown seaweeds varies according to species, location, salinity and season so it is usual to give either an average or range of values. A simple analysis in Table 4 indicates that brown seaweeds have high moisture content, typically around 85%, and high ash content, typically around 25%.

Table 4: Basic composition range of brown seaweed

Moisture and dry-matter	Moisture 75-90%	Dry Matter 10-25%
Breakdown of dry matter	Organic 62-78%	Minerals 22-37%

Table 5: Representative *Laminaria* Species Biochemical Profile *(Reith & al)*

Component	Unit	Value
Cellulose*	% w/w d.b.	6
Hemicellulose	% w/w d.b.	0
Lignin	% w/w d.b.	0
Lipids	% w/w d.b.	2
Proteins	% w/w d.b.	12
Starch	% w/w d.b.	0
Alginates*	% w/w d.b.	23
Laminaran*	% w/w d.b.	14
Fucoidan*	% w/w d.b.	5
Mannitol*	% w/w d.b.	12
Total Fermentable Sugars*	% w/w d.b.	60
Total organic matter	% w/w d.b.	74
Ash content	% w/w d.b.	26

A representative biochemical profile of *Laminaria spp* is given Table 5. An expanded version of this showing a range of values for a variety of *Laminaria* spp are given in Appendix 4 along with an ultimate and elemental analysis.

It is apparent that the "woody" matter – lignin and cellulose – are very low in seaweeds compared to wood, suggesting that a similar processing approach to cellulosic fermentation may not be best suited to seaweed. The low lipid content does not lend itself to fatty-acid fuel production. The lack of easily fermented sugar polymers such as starch, glucose or sucrose means there is little point in pursuing a standard sugar fermentation processes. The polysaccharides that are present will require a biochemical or thermo-mechanical process to break them down into their constituent monomers prior to fermentation, or else a direct fermentation process will have to be developed.

The proximate and ultimate analyses highlight the trace elements, particularly heavy metals that may place environmental restrictions on any industrial application. It also shows high ash content (26% d.b.) and a lower heating (LHV) value of 12.2 MJ/kg d.b. which indicates that seaweed would be a poor combustion fuel even if dried.

2.1.4.2. Composition of Green Seaweed

The moisture content of green seaweed is even higher than that of brown seaweeds, and it has similarly high ash content. The species is attracting interest as an energy resource due to the comparatively high level of accessible sugars, specifically starch. It also has high cellulose content. In these respects it resembles some of the properties of terrestrial plants, suggesting it is compatible with a cellulosic and starch fermentation process. There is some potential for manipulation of the components in favour of energy production. The high sulphate content will cause high yields of H_2S during fermentation, which is a fermentation inhibitor.

Table 6: Composition of Ulva Species *(CEVA)*

Component	Unit	Minimum	Maximum	Typical
Water	% w/w w.b.	78	90	85
Ash content	% w/w d.b.	12	38	24
Proteins	% w/w d.b.	10	33	19
Lipids	% w/w d.b.	0	6	2
Cellulose	% w/w d.b.	10	20	18
Ulvan	% w/w d.b.	8	30	20
Starch	% w/w d.b.	1	4	2
Sulphates	% w/w d.b.	4	12	8
Pigments	% w/w d.b.			<1

2.1.4.3. Biogas

Figure 12: Anaerobic Digestion Tank at a Farm in Germany *(BioXL)*

Fermentation technology for biogas has seen significant industrial development. This is now a turn-key technology for which performance and economical data are available for conventional substrates. Use of seaweed biomass has been insignificant to date. However the organic matter composition is close to other organic material sources and there is no major technical barrier to the process, particularly as an additional feedstock for existing anaerobic digestion (AD) plants. The presence of salt, polyphenols and sulphated polysaccharides needs to be carefully managed in order to avoid inhibition of the fermentation process and a lowering of yields.

Fermentation to biogas has been studied by several authors, but there are very few large scale industrial applications in operation. There is one example involving the Tokyo Gas Company in Japan for drift seaweed which is outlined as a case study below.

Another example is the plant installed by SOPEX (a Belgian company) in Morocco. This was designed to treat agar production wastes. There is very little data for this plant, but it was designed to process 12 T of waste/day. Expected biogas generation was 100,000 m^3 /year. Residues were planned to be used as fertilizers (Morand, et al., 1991).

A full-scale experiment was carried out using *L. digitata* in Brittany, France in summer 1984. The seaweed was used in a 30 m^3 continuously mixed anaerobic digester designed for and normally running on animal manure. The seaweed was successfully digested and showed high yields of biogas. Chopped seaweed and juices were introduced at the rate of 1 m^3/day for the first 25 days and at 1.5 m^3/day for the next 31 days. However, the results have not been validated scientifically, as an insufficient number of cycles were used to provide reliable results. The trials need to be repeated to avoid any doubt as to whether previous substrates are responsible for methane yields (Morand, et al., 1991).

Other examples, even at large scale can all be considered as research and development projects.

2.1.4.4. Ethanol

Alcoholic fermentation of seaweed is not straightforward. For millennia man has succeeded in making alcohol from almost any plant growing on earth. Despite this, seaweed was never fermented to alcohol to give a traditional beverage.

The most readily accessible sugars in *Laminaria spp* are mannitol and laminaran.

The composition of seaweed varies with species, season and other factors, but a typical specimen might contain 26% of accessible sugars (Table 5). Factors which would favour seaweed over woody biomass are the lack of lignin in seaweed and the low cellulose content.

It is also possible that a thermal or biochemical process will be developed to release the sugars in the cellulose and alginate components of seaweed, in addition to the more obviously accessible sugars.

Alginate is a polysaccharide which cannot be fermented using conventional micro-organisms. Either hydrolysis prior to fermentation or adapted microorganisms are required. There is no cheap commercial enzyme to break it down. Researchers at Trondheim University and CEVA have isolated their own enzymes for this purpose. The production of alginate lyase at industrial scale, may reduce costs sufficiently to make it a viable pre-fermentation step. Chemical pre-treatment should also be considered as polysaccharide hydrolysis can be achieved by acidic digestion at high temperature.

Promising work was initiated in Norway to generate ethanol by fermentation of brown seaweeds using a single yeast *P. angophorae* (Horn, et al., 2000). However yields were poor and further research is needed to optimise this microbial process. Irish researchers in National University of Ireland Galway (NUIG) have isolated an enzyme from the thermophilic aerobic fungus *Talaromyces emersonii* which seems to have good prospects for the breakdown of complex sugars into simple sugars. A research group in China is also investigating alginate lyases (Zhang, et al., 2004).

Fermentation of green seaweed has also been initiated in Denmark (NERI/DMU) to produce bioethanol. This seaweed contains some starch which is similar to terrestrial plant starch. It is straight-forward to convert it to bioethanol using standard bacteria or yeast strains. The level of starch is naturally low in *Ulva spp*, but DMU is working on cultivation conditions under stress to increase this level.

Ethanol fermentation of seaweed biochemical components will be considered further in the section on R&D priorities and some further activities are outlined in the section on macroalgae research programmes.

2.1.4.5. Biorefinery and Integrated Manufacturing

In attempting to carry out an economic evaluation or feasibility study on the use of marine algae for biofuel production many researchers and commentators state that concentration on a single product is unlikely to make economic sense. Obtaining ethanol as well as biogas from brown macroalgae would be an obvious bonus if and when it can be introduced on a commercial scale. Both products would have global applications as transport biofuels or for electricity generation. An additional opportunity is to combine energy production with extraction of alginates, a concept which is outlined in Figure 13.

Alginic acid/alginates constitute 20-30% of the total dry matter content of brown seaweeds. This is the only component of commercial importance to date. 16 tonnes wet/fresh seaweed gives 1 tonne of alginate. The world market for alginates is roughly 30,000 tonnes at an average of 6 -10,000 US$ per tonne. Only 0.5 million tonnes fresh brown seaweed would be required to meet this market. The world market for phycocolloids has so far grown at a few percent a year. In the long term, market saturation is a possibility (Reith, et al., 2005). Gelatine and starch are the main competing materials in the colloid market, and gelatine use is declining.

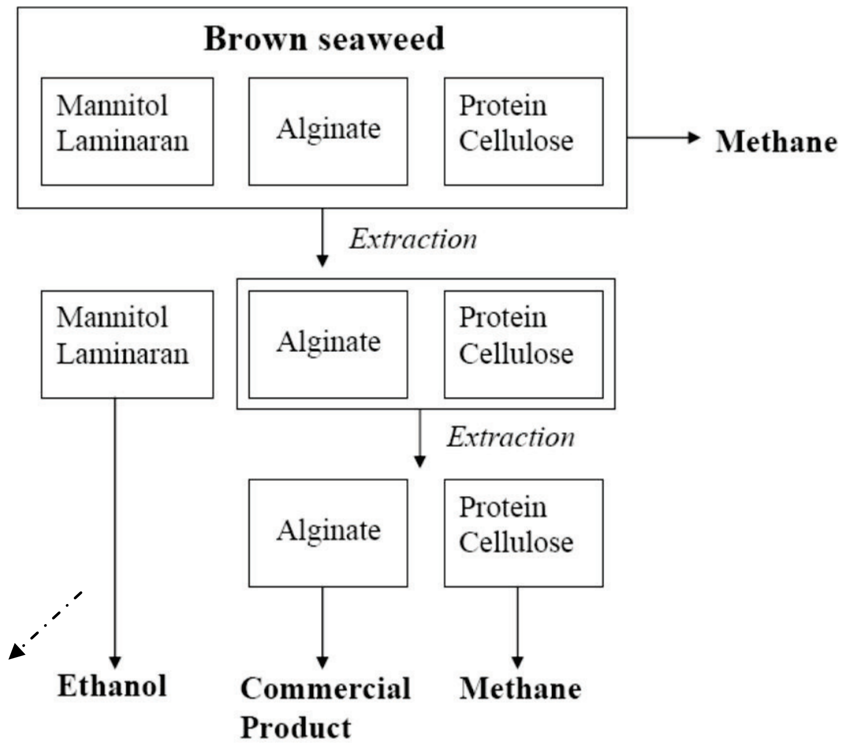

Figure 13: A Biorefinery Concept for Brown Seaweed *(After Horn,2000)*

It should also be noted for all biorefinery concepts considered that any extraction step is likely to lower the potential energy yield from seaweeds. For example extraction of alginate, laminaran and fucoidan would lower by almost 50% the amount of fermentable compounds in seaweed.

2.1.4.6. Residues

The anaerobic digestion processes used in biogas production leaves sludge containing bio-solids very similar to that formed in waste water treatment plants and having the same range of applications. It is likely that it would be considered to be superior to other sludges because of its origin (no animal waste), mineral content and possibly some natural ingredients which would have applications as bio-stimulants in the agriculture or horticulture sectors. Direct land application or conversion to compost-like materials for use as soil additives or ingredients for organic fertilisers are possible outlets as well as additives for animal feeds.

However, it should be noted that this involves the handling, processing and transport of very large amounts of a low-value material.

2.1.5. Market

Some promoters of algal biofuel products describe the market for fuel as "binary" – a vision in which there is unlimited demand for the product once available. For this reason the vast majority of research has to-date focussed on cultivation and processing, without much consideration of the full supply-chain. It is an aspect that should be considered, particularly at a policy level, and some outline of the market outlet issues is given here.

Concerning biogas production as a transport biofuel, this is a relatively widespread concept in some countries (Sweden, Denmark and Austria are good examples), but in Ireland the use of biogas as a fuel is not demonstrated to date. In order to utilise significant quantities of biogas it is necessary to upgrade biogas to natural gas quality, a distribution system is necessary and vehicles capable of running on petrol and biogas or exclusively on biogas are required.

There are no major technical barriers to the combustion of biogas in an internal combustion engine. Many of the vehicles currently fuelled by biogas use retrofitted kits to allow petrol engines to be fuelled by biogas. A big challenge is creating sufficient demand among end-users to encourage original equipment manufacturers (OEM) of vehicles to adapt engines and deliver new models to the market at an affordable cost.

There is not yet an EU standard for transport biogas, though a number of national standards exist. An Austrian standard OVGW[1] G31 for upgrading of gas and injecting it into the natural gas network is being used by many as a quality assurance standard.

Experience so far has indicated that a local supply agreement with a large user, such as a city bus-fleet or a haulage fleet is the most likely initial application of biogas as a transport fuel. Bus-fleets will consider biogas or other fuels due to favourable reduction of local emissions compared to diesel.

The market for biogas as a transport fuel is currently limited. However it is reasonable to assume that as seaweed begins to be harnessed as a resource for biogas, that parallel developments will stimulate a market for transport biogas.

Use of bioethanol is much more widespread, as it can be blended with petrol. According to current regulations, this can be done to a 5% blend and still maintain petrol fuel quality standards (EN228). Ethanol can also be used in Flex-fuel vehicles (FFV) at blends of up to 85% with petrol, commonly referred to as E85.

There is a large world-wide market for ethanol. Ethanol is a standardised industrial chemical with many applications. About 45 million m^3 of ethanol were produced worldwide in 2006. The market is expected to grow five-fold by 2020 to in excess of 200 million m^3 based on a series of mandatory blending obligations and other ethanol programmes worldwide (Bruton, 2007).

Development of the ethanol market is not without its challenges, but it is reasonable to assume that there is sufficient demand for all the possible production of ethanol from seaweed for the foreseeable future.

Initial exploitation of seaweed resources is unlikely to be at a scale sufficient to support a stand-alone biogas or ethanol process. It is likely to be more efficient to introduce the raw material into an existing facility where other biomass raw materials can be processed.

Regarding the multiple proposed product outputs from a biorefinery, it is of some concern that projections about the economic extraction of seaweed are based on products yet to be developed with no proven market outlets. Interdependence between industries creates its own risks. A full exploration of the biorefinery concept is beyond the scope of this report; however this topic is discussed further in the chapter on research and development knowledge gaps.

In particular it should be noted that the competitiveness of algal biomass for hydrolysis and subsequent fermentation must be viewed in the context of other available cellulosic biomass such as wood, straw and dry organic waste.

2.1.6. Case Study - Tokyo Gas

Recent trials in Japan were carried out on the anaerobic digestion of cast *Laminaria* and *Ulva* species (Matsui, et al., 2006). Drift seaweed, mostly Green *Ulva* causes social problems in Japan. They pile up on the shore and rot quickly. Local governments have been collecting and incinerating large amounts. *Laminaria* is also cultivated for coastal remediation through nutrient uptake, but there is no obvious market for the seaweed. It was decided that AD was the best process for this due to the high concentration of water (c. 90%). As only laboratory or short term data were available on AD of seaweeds, a pilot plant was built to test the concept on a larger scale, with a maximum capacity of 1 tonne of seaweed per day.

The test plant consisted of four main components: pre-treatment, fermentation, biogas storage and generation. A schematic overview is given in Figure 14. In pre-treatment, the seaweed was chopped and diluted with water to create a slurry. Water was added to decrease the salinity. The total solid concentration after dilution was 1 to 5%.

A two stage AD step is used. In a 5,000 L pre-fermentation tank preliminary acid conversion occurred. Retention time here was 2-3 days at 25 – 35°C. The fermentation tank is 30,000 litres and the retention time 15 to 25 days. It contains a porous matrix to encourage microbial degradation. A 55°C temperature was maintained. The biogas produced contained about 60% methane and 40% carbon-dioxide. Several thousand ppm of H_2S were also produced. This was removed by passing through iron-oxide. The optimum pH was determined to be 7.5. For *Laminaria*, 1 tonne yielded 22 m^3 of methane gas. The trial was run continuously for 150 days. The residues were dried and used as fertiliser.

A similar trial was carried out for cast *Ulva* over a 70 day period. The *Ulva* required washing due to the sand and debris content. In this instance, Ulva yielded 17 m^3 of methane gas.

The biogas is desulphurised and stored in a 30,000 litre tank. It is mixed with natural gas prior to supplying a gas CHP engine. The gas engine has a 10 kW_e capacity which powered the AD plant. The 23kW heating

[1] Österreichische Vereinigung für das Gas- und Wasserfach

capacity was also used internally to maintain tank temperatures. The gas engine displayed 10% higher thermal efficiency when running on a mix of natural gas and biogas, than on biogas alone. This is due to the variability in supply and quality of the biogas, as well as the lower calorific value compared with natural gas.

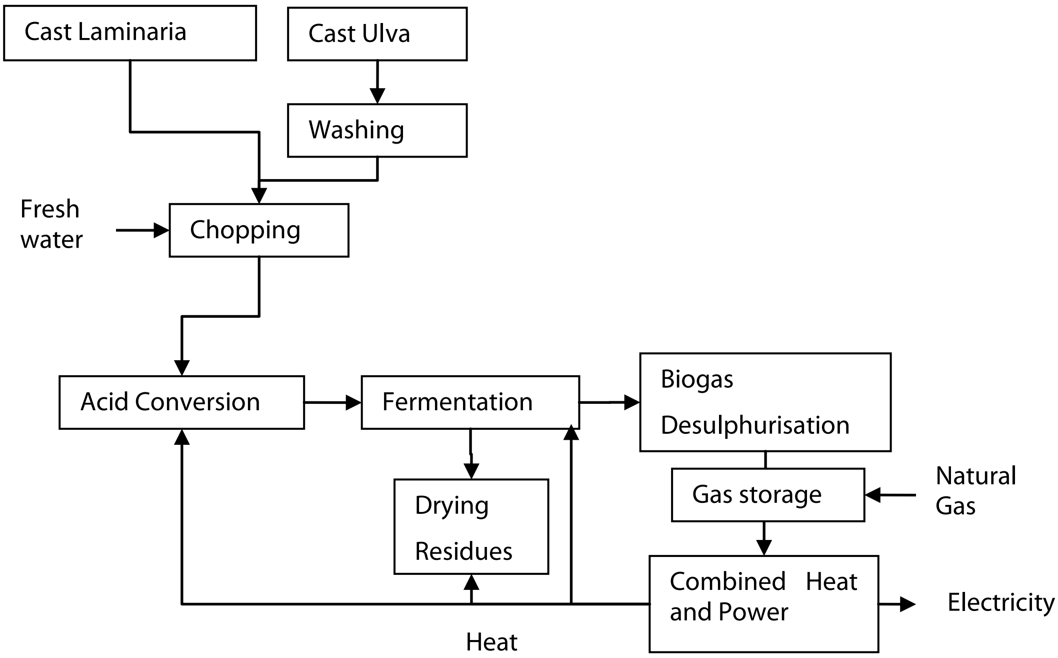

Figure 14: Schematic of Tokyo Gas Case Study Process

2.2. Microalgae

There are at least 30,000 known species of microalgae. Microalgae are defined as photosynthetic cells mostly unicellular, although some complex associations give colonies with larger structures. This is a very heterogeneous group comprising prokaryotic organisms similar to bacteria (cyanobacteria, also called blue-green algae) and eukaryotic organisms, such as diatoms. The number of blue-green species is very large and probably not fully explored.

From the vast number of known marine and freshwater species, only a handful are currently of commercial significance. These include *Chlorella, Spirulina, Dunaliella* and *Haematococcus*. Of these only *Dunaliella* is predominantly a marine species. These are generally cultivated for extraction of high-value components such as pigments or proteins. A handful of marine species such as *Isochrysis, Nannochloropsis, Skeletonema, Chaetoceros* etc. are also used for feeding shellfish or other aquaculture purposes.

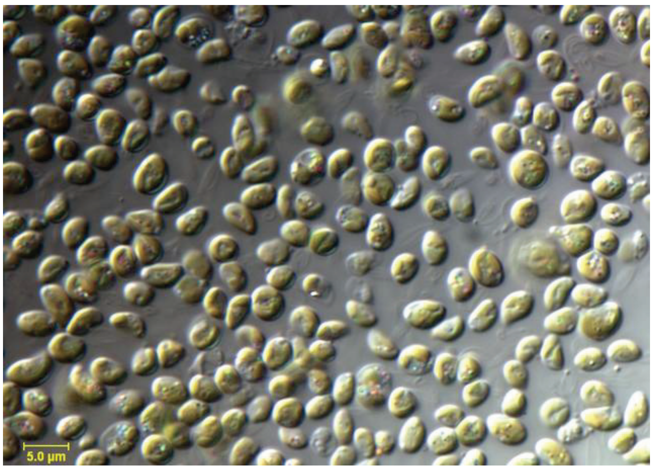

Figure 15: Microalgae Nannochloropsis salina *(Roscoff Plankton Group)*

There are many more species, and one of the key research tasks for commercialisation of algae for energy purposes is to screen species for favourable composition and for ease of cultivation and processing. This should certainly include freshwater species, even if the brief for this report is confined to marine algae.

The most applicable species of microalgae for production of alternative forms of energy derive from the groups of green algae or diatoms. So far the production of microalgae has concentrated on particular species with a special tolerance to growth under extreme conditions, which has made possible the production in open cultures in ponds or raceways. Future production of microalgae for energy purposes will probably focus on more advanced types of facilities, where cultivation of pure monocultures of selected species having specific capabilities for the production of carbohydrates, lipids or hydrogen will be applied. The topic of species selection will be discussed further in a later section on research knowledge gaps. In this section, the different technology options being considered for biofuel production from microalgae are set out and the opportunities and barriers to commercialisation described. The supply-chain approach is followed which is outlined in Table 1.

2.2.1. Biomass Generation

2.2.1.1. Naturally Occurring

As for seaweed, primary biomass generation can be via natural blooming of marine microalgae in salty lakes or ponds. There are examples of opportunistic harvesting of microalgae overgrown in these areas. This is similar to drift seaweed. The artificial eutrophication of water by human activities generates local modification of the ecosystems and may end in large unexpected blooms of microalgae. The negative impact of these blooms is the high amount of organic matter generated. The algal organic matter will undergo microbial degradation, significantly reducing oxygen levels in the water. During some algal blooms, the oxygen level can fall below acceptable limits for the rest of the local ecosystem, so wide mortality of fish and other animals is observed. Collecting algae blooms resulting from eutrophication is a good opportunity to use the biomass and to avoid later negative impacts on the ecosystem. This is likely to be a limited localised activity.

However, natural phytoplankton blooms occurring in open coastal waters are quite different. Harvesting these natural blooms has been considered in some biofuel projects. This may have knock-on effects on the entire ecosystem which could not survive without them. This option should not be pursued without a thorough review of potential ecosystem impacts.

Marine microalgae populations are dominated by phytoplankton in suspension in seawater. However forms which attach to a substrate also exist. This is known as biofouling when the colonized surfaces are man-made items such as boats or piers.

Although bacterial biomass can be grown industrially in the form of a biofilm, most industrial applications for microalgae use the planktonic form with suspension of cells. So the focus will be on this form in this report.

2.2.1.2. Cultivation

Cultivation is the main way to generate biomass from microalgae. This has been done at industrial scale for many years. The Handbook of Microalgal Culture (Richmond, 2004) gives a good overview of mass cultivation. There are two main cultivation systems: open pond and closed photobioreactor (PBR).

"Open pond" refers to anything from a simple open tank up to large natural ponds. Algae are grown in suspension. Fertilizers can be added to the water. Gas exchange is via natural contact with the surrounding atmosphere. Lighting is through natural solar light. The highest productivity in open systems is obtained in raceway systems. A shallow depth pond with an elliptical shape (like a raceway) is mechanically mixed with a paddle wheel. This moves the water along the raceway, ensures vertical mixing of water to avoid algae settlement and to maximize gas exchange. Large industrial production facilities currently use raceway systems for non-biofuel applications.

The raceway entails comparatively low capital investment. Simple lined earthen-bank ponds, mixed with a paddle wheel are the basic setup. Depths are shallow at 30 - 50cm. Operational costs are also low as weekly monitoring is enough to survey the biomass and nutrients. Energy is mainly consumed by mixing. Some raceways were designed with artificial light, but this design is not practical or economic for large units. Mostly solar light is used. The main drawback to a raceway is the low productivity yield. High light intensity causes cell mortality. Contamination by fast growing micro organisms often happens. High biomass density cannot be achieved with these systems.

The Seambiotic case study outlined (page 33) is a good example of open-pond algae cultivation.

The other commonly encountered system to grow microalgae is known as a closed photobioreactor (often abbreviated to PBR). Algae are also cultivated in suspension, but the system is closed. Water is circulated by pumps. In existing commercial applications, artificial light and sometimes heat is used. For energy or biofuel purposes, only natural light and sometimes waste heat are being considered. Nutrient and gas levels are monitored continuously and adjusted.

Figure 16: Example of Photobioreactor Design *(Greenfuel)*

Closed photobioreactors have the advantages of high productivity, low contamination, efficient CO_2 capture, continuous runs, and controlled growth conditions. The major drawbacks are the high capital and operating costs. An example of a photobioreactor design, installed as a pilot at Massachusetts Institute of Technology is shown in Figure 16.

There are many design and operational challenges which need to be resolved before low-cost microalgae production using PBR's can be considered. Some of the design challenges are considered here, but many systems are being trialled worldwide.

Fouling and cleaning of any system of both external and internal walls is a problem. Over time accumulation of dirt (external) or algae (internal) will prevent light from penetrating the PBR. Mixing to ensure optimum photosynthetic efficiency is a challenge. In order to maintain turbulent flow, energy needs to be supplied, generally for pumping, or for sparging with gases. Any parasitic energy load must be minimised in order to keep a positive energy balance on the overall process. Equally the embodied energy used in e.g. steel, glass, plastics and other system components must be considered.

The morphology of the PBR, its orientation and in particular the depth of the substrate are key considerations, in order to allow sufficient light to penetrate the PBR. Poor design can restrict light access and reduce areal productivity, but equally algae suffer photoinhibition through over-exposure to sunlight. Systems must be designed to allow efficient mixing of CO_2 and other nutrients. Indeed PBR design may not be a "one-size-fits-all" approach, as different microalgae species will thrive in different systems and be subjected to different climatic conditions.

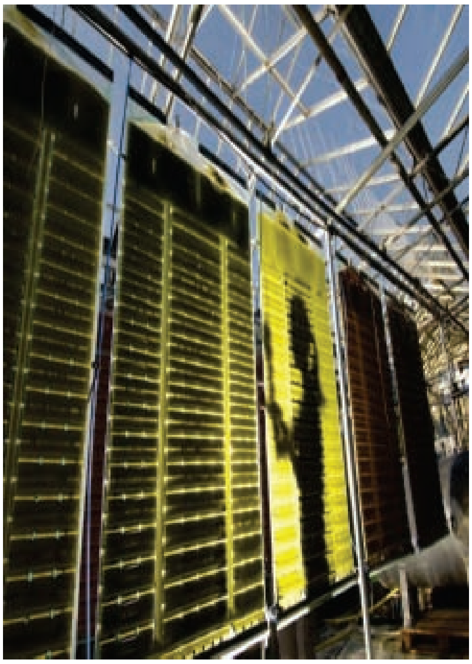

Figure 17: Flat Panel Airlift Reactor in Stuttgart, Germany *(Subitec)*

Intermediate systems have also been designed: Open ponds under greenhouses allow a more controlled environment. In the same way designers of photobioreactors have reduced costs by using simple materials, such as transparent pipes, using natural solar lighting and gravity feeding of the growth medium. Mixing by CO_2 bubbling is another way of maximizing CO_2 capture and reducing mixing costs. Examples of this are being demonstrated by the Algatech Company in Israel and by Subitec in Germany (See Figure 17).

There are numerous pilot and R&D projects on microalgae cultivation for biofuel production. The key parameters which influence microalgal growth are light and temperature. Only natural solar light is expected to give viable commercial operating conditions, except where energy for artificial lighting is free. Given this, the most appropriate locations to grow high biomass should be tropical and equatorial regions (roughly between 35°N and 35°S). However this is the subject of much debate and will be considered further in the section on productivity.

Assuming the light source is sufficient, the next important parameter is nutrient supply (inorganic nitrogen, phosphorus etc). There is strong demand for fertilizers in terrestrial agriculture. Having a new large scale demand for microalgae may results in fertilizer shortages. Particularly potassium availability could be a problem if a significant part of transportation fuel is replaced by microalgae fuel. At concentrations below 0.2 µmol P/l availability of phosphates in the growth medium will be a growth-limiting factor. Equally nitrates availability will be a problem for growth when concentrations are below 2 µmol N/l (Rasmussen, et al., 2007). For diatoms, in addition to N and P, silicate is essential. Silicon washed out from land to sea by freshwater run-off, will under normal conditions be available in sufficient amounts. Silicon will be a limiting factor for growth of diatoms in concentrations lower than 2 µmol Si/l. However for all nutrients, there are opportunities to use run-off fertilizers from cropland in river waters and estuarine systems.

Carbon is a key requirement, as the composition of microalgae is about 45% carbon. This is generally supplied as CO_2. For each kg of microalgae, at least 1.65 kg of CO_2 are required based on a mass balance (Berg-Nilsen, 2006). In existing microalgae industrial applications pure CO_2 is typically purchased at significant expense. Injection of CO_2 results in high gas losses if used in an open pond. If the end-use is not a food or pharmaceutical product, it is possible to use exhaust gas from power plants which contain significant quantities of low-cost CO_2. This is part of the business model of most biofuel projects, which also offer the opportunity to power plants to recycle a portion of their CO_2 emissions

When natural constituents of algae cells are used, biomass generation by cultivation is quite a straightforward process: light, nutrients and time are needed. If an increase of a particular chemical component is required, for instance lipids, specific growth conditions should be applied. High oil content in algae is not a naturally occurring condition. It happens when the algae experience a nitrogen deficiency through deliberate stress cultivation. Excess carbon is then stored in intracellular lipids. Changing operating conditions in large ponds is quite difficult.

A two-step cultivation process has been developed. This involves a combination of raceway and photobioreactor designs. The first step is the fast cultivation of biomass in the PBR; the second step is stress cultivation in open ponds. A photoreactor first step allows good protection of the growing biomass during early stages. CO_2 capture is maximized. The microalgae suspension is transferred to open ponds with nutrients low in nitrogen, but maintaining high CO_2. The open raceway in the second step has fewer problems, because a higher algae biomass density is more resistant to external contamination and this phase is nutrient depleted, avoiding the growth of contaminating species. The combination of photoreactor and open pond cultivation has proved efficient for astaxanthin production (Huntley, et al., 2006). It is currently being tested by companies developing biofuel applications. The University of Florence has undertaken considerable research into this topic (Rodolfi, et al., 2008).

2.2.2. Harvesting

The literature review on microalgae harvesting technologies does not reveal any revolutionary advances since the first comprehensive study by Golueke & Oswald (1965). Nevertheless, optimizing various processes can significantly reduce the harvesting cost. The existing literature is not conclusive enough to propose such optimal harvesting processes, and further R&D work will try to establish the optimal processes.

Planktonic microalgae can be considered as particles in suspension. Some strains tend to agglomerate naturally and to settle at a well-defined sedimentation rate. However, other strains synthesize chemicals excreted outside cells which will make a colloidal suspension without settlement properties. Moreover, some algae strains are motile and will not settle in a natural fashion. The amount of water in such a system is very high. Efficient harvesting is often the key to good economical yield of the overall process. The best expertise in microbial biomass harvesting to date comes from operators of waste water treatment plants. Initial work described in the literature comes from this application area.

Basically there are four methods to harvest microalgae: sedimentation, filtration, flotation and centrifugation. Pre-treatment of the biomass may also be necessary (e.g. flocculation) to improve harvesting yield. The aim of harvesting is to obtain slurry with at least 2 - 7 % algal suspension (total solid matter). When operated on raceway cultures, the concentration factor is about 100 to 200, as algal concentration in ponds is typically 0.02 - 0.06% (total solid matter).

Formation of stable colloidal suspensions is less likely to happen in the marine environment, as salts prevent and destabilize colloidal systems

The simple sedimentation system is suitable for microalgae which have naturally high sedimentation rates. This is performed in thickeners or clarifiers, standard processes in water treatment plants. Capital and operation costs are low. If the strain has poor sedimentation properties, a flocculation agent can help. There are numerous flocculants on the market either inorganic or organic, having negative or positive charges and working at different pH levels. The appropriate choice of flocculation and harvesting combination is mainly an economic consideration.

Flotation is a harvesting technique often overlooked in research projects. Some strains naturally float at the surface of the water. Oxygen generation under light by algae generates gas bubbles, assisting the flotation. Some chemicals can be added to modify the surface tension of particles in order to increase bubble attachment. Also fine air bubbling at the bottom of the pond can increase flotation behaviour. The other interesting characteristic is that as the microalgal oil content increases, the algae tend to float. Compared to sedimentation the flotation process is very fast. It only requires a few minutes instead of hours for sedimentation. Capital and operating costs are low. Biomass is collected at the surface of the pond. In shallow-depth ponds, the efficiency may be poor.

These harvesting techniques mainly apply to open pond cultivation systems. Biomass cultivated in photobioreactors is generally concentrated by filtration or centrifugation.

Centrifugation is an accelerated sedimentation process. It can operate with rotating walls (the most common type) or with fixed walls in systems called hydrocyclones. Capital and operation costs are usually high, but efficiency compared to natural sedimentation is much higher. Again the economics will dictate the choice of separation technology.

Filtration is a very common practice in industry. This process can range from simple screening or micro strainers to dewatering up to complex vacuum or pressure filtration systems. The more complex the system is, the more it costs. The main limitation of filtration is plugging. To solve this, vibrating screens are used or tangential filtrations. Deep bed filtration is also commonly used to avoid plugging, but it requires mixing the solution with sand. Some combined systems use pressing and screening belts, having the advantage of continuous operation.

2.2.3. Biomass Pre-treatment

Harvesting produces a slurry material with 2 - 7 % algal concentration. The next step is dewatering in order to get 15 to 25% concentration. This is usually achieved by pressing or centrifugation as described above. These steps are normally integrated in the harvesting operation.

Concentration by heating is possible to reduce water content, but the operating cost is usually high unless cheap heating is available (e.g. geothermal).

Compared to seaweed, microalgae suspensions are more akin to standard solid liquid mixtures where there is a lot of industrial experience. Technology and equipment choices are numerous. Techno-economical data are available to choose the best solutions**.**

Drying may be necessary for some applications. The lipid route to biodiesel is possible with microalgae. Existing chemical esterification processes require a lipid-rich material without water. So drying of microalgae biomass is considered in some processes. From 15-25% algal concentration, at least a 90% concentration should be obtained. Drying requires a lot of energy and is the economical bottleneck of the entire process. It can account for 70% of the total cost. Whatever the technology, evaporating 1 kg of water will always require at least 800 kcal of energy.

Several technologies are available for drying: spray drying (widely used but the most expensive), rotating drum dryer and flash drying (pressure and rapid vacuum) are among the systems normally considered.

A very important issue in biomass treatment is the preservation of chemical quality. After harvesting, chemicals in the biomass may be subject not only to degradation induced by the process itself but also by internal enzyme activity in the microalgae. For instance, lipase enzymes are well known to hydrolyse cellular lipids to free fatty acids after cell death. This reaction is fast enough to significantly reduce the part of the lipid content suitable for biodiesel production. This is a general statement applying to microalgae cultivation under stress. After the stress period, the entire cell metabolism will be dedicated to restoring the initial state of the cells before stress. Enzyme reactions can go on for a long time after cell death and can significantly impact downstream process yields.

In obtaining biofuel from microalgae, this only applies to lipid formation. Fermentation routes use the whole algal biomass grown using standard non-stress cultivation methods.

2.2.4. Downstream Processing

Downstream processes are neglected in many algae projects. There are a wide number of options available on the market to process the biomass; e.g. for dewatering, concentrating and drying. A significant part of biofuel development projects should be devoted to equipment testing both from an operational and economical point of view. Poor choice of equipment can ruin a very elegant system for biomass production. Equipment manufacturers should be involved and may be asked to customize their systems to achieve low cost operation.

A modelling approach is very important at this level to take into account the overall system performance. The work presented by Sazdanoff (2006) is a good example.

2.2.4.1. Composition of Microalgae

Figure 18: *Dunaliella salina* at 400x magnification *(Brooklyn College)*

Microalgae biomass has a chemical composition which varies depending on the algae used. It can be rich in proteins or rich in lipids or have a balanced composition of lipids, sugars and proteins. Species selection should be made according to the desired biofuel route.

A characteristic of microalgae is to have significant lipid content and even very high lipid content under certain stress conditions. A selection of lipid-producing species is shown in Table 7(Becker(ed), 1994). It should be noted that these species and cultivation techniques have not necessarily been optimised for lipid production. It should also be highlighted that several of these are freshwater species. Most screening and phycological studies include both marine and freshwater species. The purpose of presenting this data is to show indicative microalgal components of interest for energy purposes, not to set out a prescriptive list of species, which is beyond a short review. A longer list with some preliminary priority ranking for biofuel production in South Africa is shown in Appendix 6 (Griffiths, et al., 2008).

Table 7: Chemical Composition of Selected Microalgae Expressed on a % Dry Matter Basis

Strain	M/F	Protein	Carbohydrates	Lipids	Nucleic acid
Scenedesmus obliquus	F	50 - 56	10 - 17	12 - 14	3 - 6
Scenedesmus quadricauda	F	47	-	1.9	-
Scenedesmus dimorphus	F	8 - 18	21 - 52	16 - 40	-
Chlamydomonas rheinhardii	F	48	17	21	-
Chlorella vulgaris	F	51 - 58	12 - 17	14 - 22	4 - 5
Chlorella pyrenoidosa	F	57	26	2	-
Spirogyra sp.	F	6 - 20	33 - 64	11 - 21	-
Dunaliella bioculata	M	49	4	8	-
Dunaliella salina	M	57	32	6	-
Euglena gracilis	F	39 - 61	14 - 18	14 - 20	-
Prymnesium parvum	M	28 - 45	25 - 33	22 - 38	1 – 2
Tetraselmis maculata	M	52	15	3	-
Porphyridium cruentum	M	28 - 39	40 - 57	9 - 14	-
Spirulina platensis	F	46 - 63	8 - 14	4 -9	2 – 5
Spirulina maxima	F	60 - 71	13 - 16	6 - 7	3 - 4.5
Synechoccus sp.	M	63	15	11	5
Anabaena cylindrica	F	43 - 56	25 - 30	4 - 7	-

Note: M/F indicates marine or freshwater species.

2.2.4.2. Biodiesel

The basic chemical reaction required to produce biodiesel is the esterification of lipids, either triglycerides or oil, with alcohol. The result is a fatty acid alkylester which is the biodiesel material used in engines (e.g. Fatty-acid methyl-ester – also referred to as FAME). This reaction is performed at high pH. Alcohols used are methanol and to a lesser extent ethanol. The main by-product is glycerol. This chemical reaction is sensitive to water. In the presence of water, saponification reactions occur (soap formation) which affects both production yield and biodiesel quality. Free fatty acids cause similar problems during the reaction.

The main limitation of microalgae oil is the unsaturated fatty acid content. Excess unsaturated fatty acid levels are a major problem for biodiesel production, because they may induce cross linking of fatty acid chains, causing tar formation. The levels of unsaturated fatty acids in microalgae are sometimes very high (up to 30% of fatty acids). They have useful applications in the nutraceuticals market. This parameter is important to consider in species selection.

Research laboratories have shown that some microalgae strains are able to generate 70% lipid in their biomass. However this has not yet been found in experiments at industrial scale which have resulted in maximum yields of 30%. There is room for improvement in strain selection and culture conditions.

2.2.4.3. Fermentation

Another possibility is to use either the by-products or the entire microalgae biomass in a fermentation process to generate ethanol or biogas. Higher lipid content may increase biogas generation yield, but then this is unavailable for esterification. Several projects are exploring this route, but no commercial application is running as yet.

2.2.4.4. Biorefinery path

Many recent projects integrate multiple products in their business models. This is close to the biorefinery concept where all components of processed material are integrated in a global business model. Biofuel is one application, but feed, food and other materials which are more valuable than fuel can be produced.

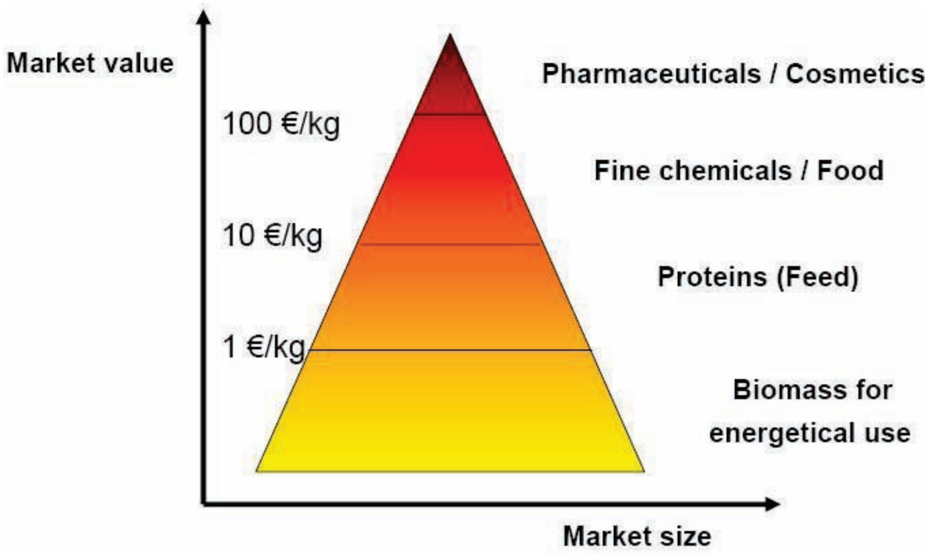

Figure 19: Value Pyramid for Algae Product Markets *(Subitec)*

An important feature of microalgae is the flexibility in controlling the composition of the cultivated biomass using techniques such as stress levels and light control to achieve the desired levels of lipids (by nitrogen starvation), proteins (e.g. spirulina), pigments (e.g. astaxanthin), nutraceuticals (e.g. β-Carotene) and other commercially significant materials.
There are opportunities for applying biorefinery-type processes to extract and separate several commercial products from microalgal biomass. Microalgal biomass cultivated for its lipid content for conversion to biodiesel offers several choices for obtaining additional commercial materials. These include fermentation to obtain ethanol (low conversion rates) and biogas. It is also possible to produce protein-rich feed for both animal and human consumption.

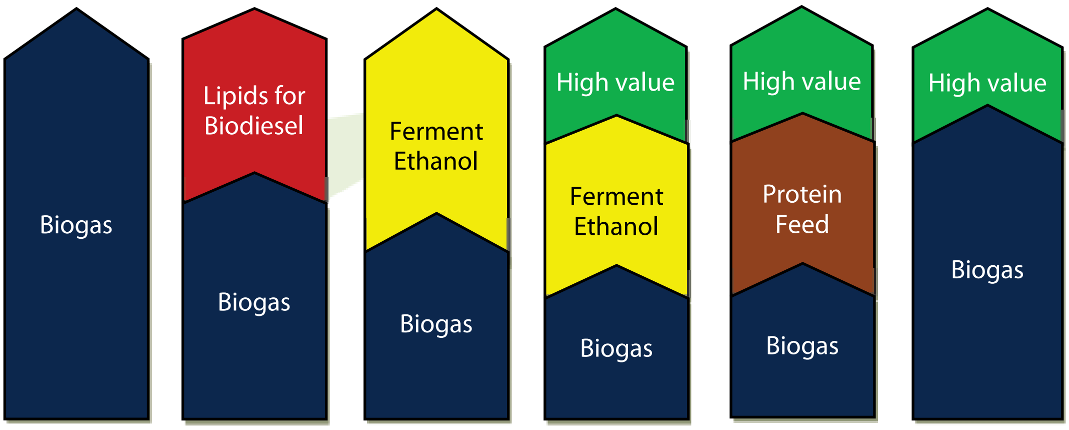

Figure 20: Biorefinery Concepts for Algae

Poly-unsaturated fatty acids (PUFAs) are a potential co-product of biodiesel production from microalgae. PUFAs from microalgae are a vegetable origin alternative to e.g. fish oils and other oils rich in omega-3 fatty acids. In a biodiesel process, the PUFAs would be extracted prior to esterification, as these fatty acids are not the most suitable raw material for esterification. See also the case study for Seambiotic on page 33.

2.2.4.5. Integration with other Enterprises

After sunlight the next most important requirements for algal biomass production are carbon dioxide and nutrients. These are also free but are present at low concentrations in seawater so they are limiting factors to be considered in trying to achieve optimum growth rates. Location of an algal enterprise adjacent to a power station which uses fossil fuel would be ideal for not only obtaining carbon dioxide at no cost but for the environmental benefits of sequestering it from the atmosphere. Likewise proximity to water treatment plants, food industries, fish farms or other source of suitable waste nutrients would be an added bonus. This is another type of 'integration' that would have a major influence on the economic feasibility of an algal enterprise. Potential locations for microalgae enterprises are considered further in a later section on potential in Ireland.

2.2.5. Residues

Algae processing residues are very rich in nutrients. Some bioremediation experiments have already run successfully on such wastes. There may be an opportunity to avoid artificial fertilizer use and even build integrated systems which reduce significantly the ecological impact of microalgal production.

Extraction of lipids from microalgae leaves a by-product comprising around 70% of the total biomass. It consists of proteins and polysaccharides. Disposing of this by-product as a waste will significantly impact the overall economics of a production plant. The simplest application is direct usage as a soil enhancer or as a base for organic fertilisers or as animal feed. There is increased demand for protein-rich substances available for human food and animal feed. Using microalgal proteins could reduce the pressure on land crops both for fuel generation and animal feed.

However in a more integrated approach, algal residues can be fermented as outlined above, or have further high-value products extracted in a biorefinery type concept.

As far as biodiesel esterification is concerned, the main by-product is glycerol. Glycerol is a versatile chemical with over 1,500 known commercial applications, though this market has become somewhat saturated due to strong growth in worldwide biodiesel production. Glycerol could be used for mixed fermentation together with sugar and protein residues from the lipid extraction step.

2.2.6. Market

There is a very large global demand for biodiesel in the European Union. Virtually all commercial vehicles and at least 40% of passenger cars run on diesel. In the EU 5.7 million tonnes of biodiesel were produced in 2007, which represented a 17% year-on-year growth (European Biodiesel Board, 2008). It can be used as a blended product with fossil diesel which conforms to existing diesel fuel standards (EN590) at blends of up to 5%. This is known as B5. It can also be used at higher blends and in its pure form (B100) in engines which provide warranties for operation on higher blends of biodiesel. The existing European standard for biodiesel is EN14214. It is likely that some modification of the standard may be required to accommodate algal feedstocks. The technical obstacles to use of biodiesel in all diesel engines are relatively minor.

To the knowledge of the authors, at least one manufacturer has reported pilot-scale production of an algal biodiesel which conforms to US biodiesel standards. Algal lipids will have a lot more variety than conventional biodiesel feedstocks and some work will be needed to achieve a standardised product. This should not prove a major obstacle to development of the industry.

Due to the small initial scale of any pilot production of microalgal oil, it is likely that feedstocks will first be used in existing biodiesel refineries in order to prove the concept.

The aviation industry is particularly interested in algal biodiesel, due to its superior cold-temperature performance, energy density and storage stability. Rapeseed Methyl Ester (RME) and Soy Methyl Ester (SME) have poor low temperature performance which poses a risk to airplane operators. As is generally the case for the automobile industry, there is a noted reluctance within the aviation industry to consider redesigning engines and fuel storage strategies to accommodate renewable fuels. The energy density of fuels is a major consideration for aircraft design. For this reason ethanol is receiving scant consideration and algal biodiesel is considered one of the only renewable fuel options under development suitable for aviation (Dagget, 2008).

Bulk markets for the co-products potentially available via a biorefinery process have not been demonstrated, and this must be a priority for research if the biorefinery concept is to prove a valid business model.

2.2.7. Case Study – Seambiotic Israel

Seambiotic was founded in 2003 in Israel. The founders had a long track record in algae research and commercial cultivation, primarily through a related company called Nature Beta Technologies Ltd (NBT) in Eilat, Israel.

A brief overview of NBT ltd is worthwhile, to demonstrate current commercial reality and known markets for microalgae. Since 1988 NBT cultivates *Dunaliella*, a salt-loving algae species, at 10 ha of open-pond facilities. The algae is processed, dried and inserted in capsules. The food supplement or "nutraceutical" is high in β-carotene, and it is sold via door to door sales in Japan at a retail price of about $4,000/kg. The cost to produce is $17/kg and about 70 t/year are produced. The operational costs are $1.1m per year, which are further broken down in Figure 21. Of note are the high charges for supply of pure CO_2 and charges for supply of clean seawater.

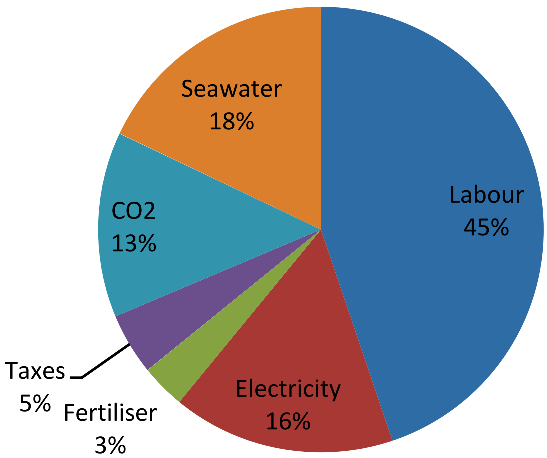

Figure 21: Production Costs of Microalgae for Nutraceuticals *(Ben-Amotz)*

Seambiotic was established to develop new environmental end-uses for microalgae. R&D pilot studies have been carried out at the Israeli Electric Corporation's power station located on the Mediterranean shore near the city of Ashkelon. Open-pond facilities were built, with the facility to use flue gas from the power-plant stack and to have sea water without charges.

Figure 22: Open-pond Test Facility at Ashkelon *(Seambiotic)*

According to the company (Ben-Amotz, 2008), trials on several species have been successful, with some species productivity of 20 g/m2/day. Using abundant flue gas instead of purchasing CO_2 has pushed productivity up by 30%. Maintaining original inoculation species proves a challenge, the whole culture sometimes changes to a diatom species. The algae are harvested via low-cost self-flocculation technique. Samples have been converted to biodiesel and showed 12% w/w daf yield of biodiesel from microalgal biomass. Seambiotic are of the opinion that production costs could be as low as \$0.34/kg, based on a comparison with the NBT operating cost and scale of operation. At 12% yield, this is still over \$2.80/kg of biodiesel feedstock. The intention is to make the process profitable through the co-production of omega-3 poly-unsaturated fatty acids (PUFAs) which are a valuable human and animal feed additive. If natural selection of the species is allowed to occur, maintaining consistency in output and oil quality will prove a significant challenge.

3. Productivity and costs

It is important to have in mind some key figures about primary production of biomass. This will help to define approximate boundaries of the potential. It is not an exaggeration to report that there are many examples put forward by proponents of algae which flout the basic laws of science.

3.1. Fundamental Photosynthesis Productivity

To get key figures of photosynthesis described in a simple way, one approach is described in the paper published by Palligarnai *et al* (2008). This is a global approach based on potential energy. Photosynthesis involves the capture of photons by organic molecules. The energy of photons is used to absorb CO_2 and to build the elementary units used to synthesize organic matter. Scientists agree that at least 8 photons are required to integrate 1 molecule of CO_2 into the organic matter of a photosynthetic organism.

These photons are captured by chlorophylls. Not all visible wavelengths can be captured. Other pigments can capture at different wavelengths and pass the energy to chlorophylls. Wavelengths ranging from 400 to 700 nm can be used by photosynthesis. It is usually considered that 43% of solar light can be captured by photosynthesis. This is the Photosynthetically Available Radiation (PAR).

From these simple statements, a crude analysis is possible. The light energy captured by photosynthesis is roughly 1 736 kJ/molecule of CO_2 (8 photons between 400 and 700 nm). A simple carbohydrate unit like (CH_2O), is 1/6th of a glucose molecule $(CH_2O)_6$. The potential energy contained in this (CH_2O) unit is 467 kJ.

In this example only 26% of the photon energy is converted to carbohydrate. Using solar light gives a global yield of roughly 12% (43% of 26%). Actual yields are lower as other metabolic steps are also used, which have their own energy consumption in the cell. For instance, it requires much more energy to build a long chain fatty acid from initial carbohydrate blocks.

Real experiments measuring the global efficiency of photosynthesis give 1 to 3 % as a theoretical yield, instead of the 12% given above. The difference is due to the quantum requirement for CO_2 fixation, poor light absorption, reflection on culture surface, respiration, photorespiration and other factors. It is impossible to have 100% of the plant under sunlight. Some parts are always shaded. Even for plants exposed to almost 100% light, there is another limitation due to photoinhibition. The plant is receiving more light than it can process, so part of the light energy is wasted. Nutrients, including CO_2, can also be limiting factors, decreasing the global efficiency of light energy conversion to organic matter. There is a consensus that the photosynthetic efficiency of terrestrial plants is 1% or less.

Microalgae growth is one exception to this calculation, because of cultivation methods. They are microscopic organisms (10 to 50 μm) that are in suspension in a growth medium with mixing. So they do not present a constant flat surface to incident light. The mixing is moving cells from light to shade and the reverse, so the total surface of the biomass is much higher than the flat surface of the pond. The penetration depth of light inside the pond is the key parameter. This is not a constant, as penetration will decrease when the cell number is increasing.

Various sources report, and evidently many promoters of algae technology for biofuel expect, the limits of microalgae photosynthetic efficiency to be pushed out to somewhere between 3 and 6% (Borowitzka, 2008). Another research group suggests that 4% is the maximum realistic photosynthetic efficiency attainable in photobioreactors (Grobelaar, 2008). In any case it seems that 6% can be set as an absolute maximum theoretical efficiency that is unlikely to ever be obtained under real conditions.

3.2. Macroalgae Productivity

3.2.1. Biomass Productivity

There is a large amount of reported productivity data for a range of seaweed species worldwide. These data need careful interpretation in an Irish context. A search of the literature yielded a selection of data, which are converted to consistent units and summarised in Table 8. An extended version of this is available in Appendix 5. Nonetheless, there is a lack of long term trial data. Many of the reported values are based on experimental plots, or short term trials which were not continued over an entire growing season.

The only yield which can be reported as commercially achieved and sustained is the cultivation of *Laminaria japonica* in China, which yields 25 t/ha/year dry matter. This is via the long-line cultivation of seaweeds which are artificially fertilised or naturally fertilised through integration with other aquaculture.

Availability of nutrients is a key productivity factor. Some reported yields assume no external nutrient supply, others propose siting to take advantage of coastal run-off or fish-farm effluent (Kelly, et al., 2008), while yet more yield assumptions are based around the artificial upwelling of deep ocean water (Chynoweth, 2002). Other yield assumptions are based around the development of precision nitrogen dosing techniques (Reith, et al., 2005).

There is a range of further literature reporting on productivity trials, but at a scale, or using methods which preclude extrapolating the figures to areal yields. One example of this is the grow-out trials of *Alaria* spp carried out in Ireland, where productivity is measured in wet weight per linear metre (Arbona, et al., 2006). A range of trials are reported in Western European countries and in Ireland in a review carried out on behalf of the Marine Institute, however bulk production was not considered and most of the data cannot be extrapolated to areal productivity (Werner, et al., 2003).

There are many other factors which impact upon seaweed cultivation productivity rates, which have been described in an earlier section. There is a wide diversity in the range of species considered and the geographical climate. It is clear that the only reliable data that could be used for estimating the Irish resource and developing a business model in Ireland would be the results of grow-out trials of relevant species under low-cost cultivation conditions here.

For the purposes of preparing indicative productivity figures for Ireland, a standard rate for cultivating *Laminaria* species could be 20 dry t/ha/yr and an optimised rate could be 35 dry t/ha/yr, based on the literature review.

Table 8: Selected Macroalgae Cultivation Productivity

Species	Yield t/ha/yr dry	Location	Origin	Source	Notes
L japonica	31	Japan	Cultivation	Yokoyama et al, citing Japan Ocean Industries Association	Corrected from dry ash-free value
L japonica	25	China	Cultivation	Kelly, citing China Fish Annals 2003	Commercially achieved yields
L japonica	60	China	Cultivation	Kelly, citing Tseng 1987	Experimental plots. High cost and poor quality
Alaria	12	Ireland	Cultivation	Kelly, citing Kraan 2007	Hybrid species
Saccharina latissima	15	Scotland	Cultivation	Kelly, citing Sanderson 2006 unpublished	Experimental plots near fish farms as nutrient source
S polyschides	25.5	Scotland	Cultivation	Kelly, citing Sanderson 2006 unpublished	Experimental plots near fish farms as nutrient source
Ulva	22.5	Pennsylvania	Cultivation	Rasmussen 2007, citing Moll 1998	Converted to annual yields using 6 months growth
Ulva	45	Denmark	Cultivation	Rasmussen pers. Comm. 2008	Based on extrapolation of 4-month trials

Concerning natural stocks of *Laminaria spp*, the potential for exploitation in Ireland will be discussed in a following section, but some productivity information is useful to report here also.

Previous Scottish research by Gao & McGinley, cited in Kelly & Dworjanyn (2008), reports typical standing stock of 15 kg/m^2 wet of brown seaweed in sub-littoral zones, which equates to approximately 22 t/ha dry basis. Estimates of the *L hyperborea* stock dating from 1947 are also typically c. 30 dry t/ha in Scotland. Harvestable yields of wild stocks are notoriously difficult to establish, due to wide variation in both sampling techniques and the harvest system they are trying to reflect. For example, some systems harvest the whole plant, while others leave the holdfast intact. Density figures may be converted to annual yields provided crops are harvested in a sustainable manner, which among other constraints would suggest leaving a minimum period of five years inter-crop. Previous Irish surveys report the plant density, but do not convert this to mass (Hession, et al., 1998). However, uncertainty regarding access to and exploitation of Irish wild stocks exists.

3.2.2. Energy Productivity

One approach is to use empirical data from trials. In the case study above, 1 T of fresh *Laminaria* gives 22 m^3 of methane. This is based on trials carried out over a period of 150 days. The disadvantage with this approach is that variations in moisture content and volatile solids (VS) content cannot easily be accounted for.

Previous research reported in Japan (Yokoyama, et al., 2007) gives a methane yield of 0.25 m^3/kg-VS, based on a typical VS content of 11.2% for *L. japonica*. Such an approach would give a higher figure of 28 m^3/tonne of fresh *Laminaria spp*.

The marine biomass programme in the US (Chynoweth, 2002) reports a range of yields from *Saccharina latissima*. These are averaged over the range of conditions to give a yield of 0.27 m^3/kg-VS. The findings of the commercial trials and the research broadly support each other. An empirical yield of 22 m^3 methane yield per fresh tonne of *Laminaria spp* is used as a productivity assumption.

There are no reliable productivity data concerning ethanol fermentation that demonstrate yields that could be considered viable. Based on the readily accessible sugars in brown seaweeds, up to 26% w/w dry basis is available for ethanol fermentation. Technical developments may increase the available sugars and demonstrate commercial yields, but for the purposes of this review, productivity assumptions on seaweed are restricted to anaerobic digestion technology.

3.3. Macro cost examples

Seaweed exploitation in Europe is currently through manual and mechanised harvesting of natural stocks. The majority of Asian seaweed resources are cultivated. There is a marked difference in the cost of seaweed between the two regions. Seaweed is normally sold in modest volumes and delivered fresh for further processing at local factories. It has high moisture content and is costly to transport. An indication of commercial seaweed prices in selected regions is given in Table 9. This table shows the lowest costs are achieved with production systems in Asia with an estimated dry cost of €165/t dry basis. Irish harvest of natural stocks is three times more costly at approximately €330/t for *Asco* species. If mechanised harvesting systems such as those in Norway or France are employed for *Laminaria* species, it is likely that the cost would be similar to that reported in France.

It is often claimed that the low cost of seaweed in Asian countries is due to low labour cost and lack of regulatory hurdles and environmental restrictions. Whilst these are cost advantages, much of the improvement can be attributed to advanced cultivation techniques and improved productivity.

Table 9: Cost of Seaweed in Selected Countries

Country	Species	€/t Wet	€/t Dry	Origin	Harvest
Ireland	*Asco/Fucus*	50	333	Natural	Manual
France	*Laminaria*	40	267	Natural	Mechanised
France	*Asco/Fucus*	30	200	Natural	Manual
Philippines	Carrageen		165	Cultivated	Manual

Notes:

- French wet prices based on 2007 harvest
- Irish harvest 2008 Arramara Teo. contractors wet price
- Philippines $-value converted using €/$=0.66
- Typical moisture content of 85% assumed for conversion

All of the above prices are based on current production on a modest scale for high-value non-energy end-uses. Reports by Chynoweth (2002) and Reith *et al* (2005) have projected lower costs for seaweed aquaculture based on improved productivity and large scale cultivation, either near-shore or offshore. Any consideration of cost improvements must be considered in tandem with reported productivities and advances in cultivation methods. A range of low cost seaweed resources are predicted in modelling undertaken during the US Marine Biomass Program for near-shore, tidal and floating cultivation systems. These systems were expected to deliver costs under $50/ton d.b. based on large scale cultivation. Off-shore cultivation of *Gracilaria* and *Laminaria* species were expected to cost between $112-409/t d.b. mostly dependent on the productivity assumed (Chynoweth, 2002).

Concerning the costs to establish *Laminaria* aquaculture, there is little reliable data available. As was the case for much productivity data, many trials are carried out on too small a scale to extrapolate on an areal basis, or to consider any economies of scale that might be achieved. One estimate in the UK puts the cost of long-lines for the growth of *Laminaria* at £2,300/ha (Kelly, et al., 2008).

The most recent and relevant cost model for this study is that prepared during the 2-year Bio-offshore analysis carried out by the Dutch research centre ECN (Reith, et al., 2005). The study considered the feasibility of offshore cultivation of seaweed species in the North Sea, using 1,000 km^2 of offshore wind farm infrastructure envisioned by 2020. This considered chemical, biological and thermal processes for conversion of seaweed into energy products and platform chemicals. The economic modelling considered scales of 100,000 tonnes and 500,000 tonnes at an onshore processing site, transporting seaweed from up to 100 km offshore, grown on long-lines suspended between wind-turbines. The actual area covered by an individual cultivation would depend on the site and the productivity. The estimated productivity is 20 dry t/ha for unfertilised sites and 50 dry t/ha for fertilised sites.

The cost models focus on downstream processing costs with the goal of estimating a maximum sustainable seaweed price. This decouples the seaweed cultivation system costs from the processing plant, though it is reported that the cultivation system could comprise 66-92% of total investment costs. This is similar to the business model for conventional agriculture where the cost of land and on-farm investment is not considered directly, but is factored into raw material costs.

The results of the analysis in Table 10 indicate that seaweed costs would need to be less than €63/t d.b. for anaerobic digestion of seaweed to generate electricity at a scale of 100,000 dry tonnes/year. This is less than 25% of the cost of Laminaria feedstock for the alginate industry in France, with reference to Table 9.

In the model presented in Table 11, co-production of electricity and ethanol are considered. The model is based on fermentation of switch grass, which is a cellulosic fermentation process and not directly comparable. None-the-less, it indicates that alcoholic fermentation at the 100,00 tonnes/year scale is far from commercial, with feedstock costs needing to be either free or attracting a modest gate-fee of €2/t to supply them to the factory.

Table 10: Estimated production and "break-even" cost for methane and electricity from anaerobic digestion of seaweed *(After Reith et al, 2005)*

Item	Remarks	Case 1	Case 2
Scale (Tonnes/yr d.b.)		100,000	500,000
Hydraulic residence time (HRT) in days	30 days also in model	20	20
Investment cost (2005) €m		9.6	31.9
Operational cost (2005) €m/yr		0.96	3.2
Gross methane production (million m3/yr)		14.8	74
Net methane production (million m3/yr)	After upgrading to natural gas	12.4	61.8
Production cost methane €/GJ	Excluding raw material cost	2.29	1.53
Production cost methane €/m3	Excluding raw material cost	0.08	0.05
Break-even cost of seaweed €/t d.b.	Based on €8/GJ and 4.93 GJ/t	21	25
Production of electricity (MWh)	At 40% elec. Efficiency	60,570	302,850
Production cost of electricity €/MWh	Excluding raw material cost	16	11
Break-even cost of seaweed €/t d.b.	Based on €120/MWh	63	66

Notes and assumptions:

- Production costs of either methane or electricity are reported excluding raw material cost. These are then deducted from market prices to obtain a maximum raw material price that can be supported. Profit margins have not been considered.
- Investment and operating costs are in 2005 values and have not been adjusted
- Investment and operating cost of offshore seaweed farms has not been incorporated in the model.
- The model was updated to use Bord Gais commercial gas price of €8/GJ in August 2008
- The model was updated to reflect the REFIT tariff available for electricity from biogas in Ireland of €120/MWh

Table 11: Estimated production and "break-even" cost for ethanol and electricity production from *Laminaria (After Reith et al, 2005)*

Item	Remarks	Case 1	Case 2
Scale (Tonnes/yr d.b.)		100,000	500,000
Size of CHP plant (MW_{th})	Using algal residues	39	193
Investment cost (2005) €m	Scale factor of 0.7 is used	71	187
Operational cost (2005) €m/yr		4.5	22.5
Intermediate products			
Fermentable sugars (t/yr d.b.)	80% w/w hydrolysis conversion	48,000	240,000
Final products			
Ethanol GJ/yr	90% fermentation yield	607,200	3,036,000
Electricity export MWh/yr		42,556	212,778
Conversion to ethanol w/w %		49.8	49.8
Conversion to electricity %		12.6	12.6
Total conversion efficiency %		62.3	62.3
Production cost of ethanol €/l	**Electricity exported at €127/MWh**	**0.41**	**0.24**
Biomass "break-even" cost €/t d.b.	Ethanol at €0.40/l	-2	44

Notes and assumptions:

- Model is based on an economic evaluation of cellulosic ethanol production from switchgrass carried out by Reith et al (2005). A 10-fold reduction in commercial enzyme costs is assumed.
- Investment and operating cost of offshore seaweed farms has not been incorporated in the model
- A 49.8% ethanol yield from seaweed would require a significant R&D advancement
- The process includes electricity generation from combined heat and power using residues
- The model data have not been altered, as they are sufficiently similar to current market data, with a REFIT tariff available in Ireland at just €7/MWh below the model estimate. €0.40/l is a reasonable assumption on ethanol prices
- In calculating the maximum feedstock cost supported, no profit margin is included
- Investment and operating costs are in 2005 values and have not been adjusted

3.4. Microalgae Productivity

Using the fundamental photosynthetic efficiency assumptions outlined above, it is possible to estimate the theoretical production yield of oil from plants. Solar light incident energy at Eilat in Israel is compared with typical values in Valentia, Ireland. Average solar irradiation values in Ireland are c. 9,600 kJ/m^2/day and in Israel 19,300 kJ/m^2/day. This is across the entire wavelengths of the spectrum.

The next step is applying a 1%, 3% and 6% conversion yield to incident energy. A maximum 50% of this biomass is assumed to be lipid that can be converted to diesel. This energy can be transformed into equivalent litres using the calorific value[2] 36 MJ/l to get estimated algal oil yields. Yield figures are converted to more convenient units of t/ha/yr[3] of dry biomass and m^3/ha/year of algal oil and displayed in Table 12. These calculations are crude, but serve as a useful barometer for comparison with reported and projected yields from various species and systems.

Table 12: Limits of Biomass productivity based on fundamentals of Photosynthesis

Location	Incident Energy	1 % PP[4] yield	3% PP yield	6% PP yield
	(MJ/m2/year)	Low	Optimal	Maximum Theoretical
Valentia Biomass t/ha/yr	3,500	9	28	53
Valentia Lipids m^3/ha/yr	@ 50% lipids	5	15	29
Eilat, Israel Biomass t/ha/yr	7,045	18	53	108
Eilat Lipids m^3/ha/yr	@50 % lipids	10	29	59

The values for oil and biomass production are estimated at the boundary conditions of available light and photosynthesis yields. Keeping in mind that the values are overestimated this gives ultimate limits that production will never reach, even in ideal conditions with no other limiting factors.

A range of reported productivity data are set out below, but both the theoretical limits imposed by availability of photons and the energy-consuming metabolic processes to turn photons into biomass in a given climate must be borne in mind at all stages.

An example of the productivity projections of German technology developer Subitec is given in Table 13 (Ripplinger, 2008). The system under development is a flat panel airlift photobioreactor. It is clear that the assumed annual yields are around the maximum theoretical production levels, if the Stuttgart climate can be compared with the Irish one.

Table 13: Microalgae Productivity Projections in Flatpanel Airlift Reactor *(Subitec)*

Climate zone	Productive days per year	Yield (t DW/ha/yr) at 1.0 g/L/d	Yield (t DW/ha/yr) at 0.8 g/L/d
Tropical	365	137	110
Mediterranean	300	113	90
Central Europe	240	90	72
Stuttgart	200	75	60

In one research review by Griffiths *et al* (2008) the current limit of long term productivity trials is given as 0.15 g/l/d, with the potential through research and development to extend this to 1.0 g/l/d. A current upper lipid level is given as 25%, with the potential to reach 50%. Currently areal lipid productivity would be limited to 21.6 m^3/ha/year using open-pond technology in an optimal climate for microalgae cultivation.

A leading expert on the subject reports a range of trials which lasted more than 3 months using open-pond raceway systems and reported biomass yields ranging from 2 to 37 g/m^2/d, though advises that these cannot be extrapolated to annual values, and that all productivity calculations must be treated with caution (Borowitzka, 2008).

Commercial cultivation of *Haematococcus pluvialis* species in Hawaii is reported over a year-long period to yield 420 GJ/ha/yr of microbial oil, which equates to approximately 11.7 m^3/ha/yr (Huntley, et al., 2006). A 2-stage system using photobioreactors and open-pond was used. The authors are of the opinion that a yield of 3,200 GJ/ha/yr or 89 m^3/ha/year is theoretically feasible in the Hawaiian climate, which would be exceedingly high.

[2] For the purposes of this calculation the gross calorific value of rapeseed oil is used as a proxy for algal oil.
[3] A density of 920 kg/m3 is used for algal oil
[4] Primary Photosynthesis

Recent trials in Italy using *Nannochloropsis* species in outdoor trials using a 2-stage nitrogen starvation strategy report final lipid yields as high as 60% and extrapolate the results to suggest that 20 t/ha/yr lipid yield is realistically achievable in the Italian climate (Rodolfi, et al., 2008). This is using a photobioreactor design called green wall panels.

A presentation from the same research group served to clarify the confusion surrounding microalgal productivity (Tredici, et al., 2008). Short term growth rate is often confused with annual productivity. For instance it is correct that certain microalgae can double their mass in a day in laboratory conditions, however this cannot be extrapolated to annual yields. According to the authors, an upper limit of algal oil productivity in outdoor systems should be 50 t/ha/yr. A goal for lipid yield of 40 t/ha/yr should be set, and a goal for overall biomass productivity of 80 – 100 t/ha/yr is a realistic research target.

Researchers in the Netherlands (Reith, et al., 2004) have developed a bubble-column photobioreactor which is estimated to yield 40 t/ha/yr of biomass based on successful scale-up. Current microalgae culture systems are reported to yield 30 t/ha/yr and with optimisation of the photosynthetic process this might be improved to 60 t/ha/yr. This is at latitude of 53° N in a climate which should be comparable to the Irish one.

Other researchers have considered substantially higher yields in recent reviews. Based on 50% lipid yield and a high daily productivity of 50 $g/m^2/day$ due to advances in photobioreactor designs yields of up to 98 $m^3/ha/year$ are suggested (Schenk, et al., 2008). Another review (Chisti, 2007) suggests lipid yields of up to 137 $m^3/ha/yr$ are possible based on experimental lipid yields of 70% and an areal productivity of 48 $g/m^2/day$. These yields are not considered obtainable under long-term conditions with any technology currently known and would be the result of a very significant technological break-through. These yields would also exceed currently assumed limits to global photosynthetic efficiency for microalgae of 6%.

The Aquatic Species Programme is one of the longest running research projects on microalgae and carried out long-term outdoor trials in open-pond raceway systems in Hawaii, California and New Mexico (Sheehan, et al., 1998). The results of the final trials are shown in Table 14, carried out in two 1,000 m^2 open ponds at Roswell, New Mexico. Only biomass yield was measured, with no long-term lipid data collected. The primary limitation of this site was temperature, which turned out to be too low for more than 5 months of the year for the more productive species identified during earlier trials. The most promising trial showed biomass yields of 38.3 t daf[5]/ha/yr. Assuming a typical lipid content of 20% this would indicate yields of c. 8 $m^3/ha/yr$. It should be noted that one of the main lessons learnt during this trial is that survivability and strain selection is as important as productivity. Ponds inoculated with non-native species were sometimes invaded by native species. The researchers concluded that a long-term productivity goal for this type of system should be 70 t/ha/yr of biomass.

Table 14: Results of Aquatic Species Programme Long Term Trials

Date from	Date to	Productivity (g daf/m2/d)	(t daf/ha/yr)
01/10/1988	30/09/1989	9.8	35.8
01/10/1988	30/09/1989	8.3	30.3
01/10/1989	30/09/1990	10.5	38.3
01/06/1990	30/10/1990	19	-
01/05/1990	30/09/1990	18	-

In conclusion, a review of the literature would indicate that assigning or predicting productivity rates for the Irish climate is not possible with any accuracy, as there is a lack of reliable trial data in Irish or comparable climates. A short term productivity goal (2010) for Ireland might be to demonstrate biomass areal productivity rates of 25 t/ha/yr and to obtain 25% of useful lipids, yielding 6.25 $m^3/ha/yr$. A medium-term target (2020) could be to raise this to 35 t/ha/yr and to obtain 50% useful lipids, yielding 17.5 $m^3/ha/yr$. It should be noted that lipid content is not the only potentially useful energy resource in microalgae.

This is the status with actual microalgae strains used in industrial applications. Some new strains adapted to low light may be selected and developed. For instance, a freshwater strain like *Haematococcus* is used to produce astaxanthin. It grows better at low light during its green phase and in cold water. Then in its red

[5] Dry and ash-free

phase light is used as a stress factor to generate astaxanthin overproduction by cells. It is possible that local microalgae strains may be adapted to grow well in temperate regions with less light. Some heterotrophic strains are actually capable of reproducing without light (external energy is delivered entirely as nutrients and without sunlight).

3.5. Micro Cost Examples

The cost of biofuel production from microalgae is not well defined in the public domain. It is clearly not a developed industry with a trading history and tradable commodities. A review of costs is redundant without bearing in mind the key variables to be considered, which include the assumed areal productivity and the production system to be used. This review will consider interpretations of two different comparable systems for which costs have been reported in the United States. It does not take account of recent advances in industry that have not been reported in the scientific literature. There is a large commercial investment wave underway into microalgae and multiple patents being filed, which are reported in the section on commercial activity.

The examples presented below are based on the assumption of successful scale-up on current commercial microalgae production for non-biofuel markets. If present cultivation systems and strains were used, production costs are an order of magnitude above conventional biofuel feedstock costs. The most significant challenge to commercialising microalgae for biofuel production is to address this cost gap. This cost gap, shown graphically in Figure 23, is estimated to be over $4,000 per ton in a recent sector review (Borowitzka, 2008).

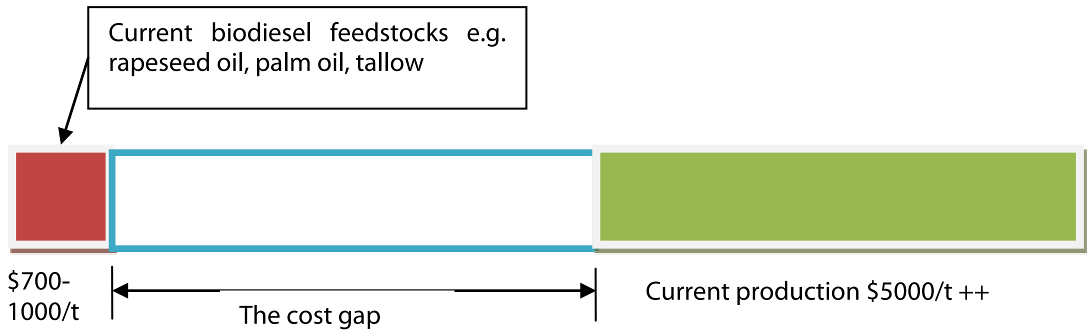

Figure 23: The Cost Gap with Current Microalgae Cultivation *(Borowitzka, 2008)*

3.5.1. Open Pond

The Aquatic Species Program (ASP) was funded by the United States Department of Energy for over 20 years and is a good source of cost data on open-pond systems (Sheehan, et al., 1998). The cost information is a little out of date and has been presented inflation-adjusted as in the Epobio project (Bowles (Ed), 2007). The capital cost estimates presented in Table 15 indicate a present-day $-denominated capital investment of just under $100,000/ha. The operational cost model estimates in Table 16 show a theoretical algal oil production cost of $157/bbl at 20% lipid content, with the potential to decrease costs to $78/bbl based on an elevated 40% lipid content in an open pond cultivation system.

This model is indicative only, and the authors are of the opinion that an updated feasibility study be prepared for the euro-zone business environment and temperate climate. Additional cost information is presented in the context of the Seambiotic case study outlined on page 33.

Table 15: Open-pond Capital Estimates for 400 ha Site *(NREL)*

Cost Item	Remarks	Cost US$/ha
Land preparation, grading, compaction	Percolation control by natural sealing	2,500
Building of pond walls & levees		3,500
Paddle wheels for mixing		5,000
CO_2 transfer sumps & carbonation		5,000
CO_2 supply (pipelines and scrubbers)	Assuming use of flue gas	5,000
Harvesting and processing equipment	Settling	7,000
	Flocculation	2,000
	Centrifugation and Extraction	12,500
Anaerobic digestion and nutrient recycling	Lagoon	3,250
Other capital costs	Water and nutrient supply	5,200
	Waste treatment	1,000
	Building, roads, drainage	2,000
	Electricity supply & distribution	2,000
	Instrumentation & machinery	500
Subtotals of above		**56,450**
Engineering, contingencies	15% of capital	8,450
Total direct capital		64,900
Land costs		2,000
Working capital	25% operating cost	2,700
Total capital investment		**69,600**
Total capital investment Inflation corrected	**2.5% inflation (12 years) 1996 to 2008**	**97,500**

Notes and assumptions:

- The productivity assumed in the model is 30 g/m2/day, which equates to c. 110 t/ha/yr of biomass or about 44 toe/ha/yr of algal oil (expressed in fossil oil equivalence). This is high and would need an R&D breakthrough. The proposed site for the model is Imperial Valley, California.
- Economies of scale have been assumed in the original model based on a 400 ha site.
- Co-location with a power plant is assumed. If a power generator were required, capital costs would increase by about 6.5%
- Original cost assumptions have not been reassessed. Land costs, even after inflation correction would be $2,800/ha which would seem too low for any Irish-based project. Other costs would equally need to be addressed for a site-specific business model.

Table 16: Operating Cost Estimates for 400 ha Site *(NREL)*

Cost Item	Remarks	Cost US$/ha
Power, excluding CO_2 supply		1,870
Power, flue gas supply	Fans, scrubbers etc.	1,000
Nutrients N, P, Fe		900
Flocculant		1,000
Labour & Overheads		3,000
Waste Disposal		1,000
Maintenance, Insurance, tax	5% of direct capital cost	3,246
Credit for Power or fuel	Power @ $0.065/kWh	-1,150
Total Net Operating Costs		**10,866**
Capital Charge	15% of Principal	10,443
Total Annual Costs		**21,309**
Total Operating costs Inflation corrected	**2.5% inflation (12 years) 1996 to 2008**	**29,832**
$\$_{2008}$/t biomass	Based on 30 g/m^2/day	272
$\$_{2008}$/barrel algal oil	Based on 40% lipid	78
$\$_{2008}$/barrel algal oil	Based on 20% lipid	157

Notes and assumptions (as above with the following additional remarks):

- This model considered anaerobic digestion of residues, generating methane and putting this in a gas engine. This leads to a credit for power produced on-site.
- The productivity and lipid level of 40% assumed in the original model is very high. The authors of this current report have inserted a cost based on 20% lipid content in the biomass, whilst maintaining the productivity of 30 g/m2/day.
- The costs per barrel have been estimated using an assumed algal oil density of 0.92 kg/m3 and 8 bbls of algal oil/m3.
- Operating costs have not been reassessed, but simply inflation-corrected. Nutrients, electricity charges, waste disposal and other costs may have exceeded headline inflation.

3.5.2. Combined Photobioreactor and Open Pond

A comparison can be made with the combination of photobioreactor and open-pond system reported by others (Huntley, et al., 2006). The model below refers to a commercial production of *Haematococcus pluvialis* carried out in Hawaii in a period spanning December 1997 through September 2001. The data reported was for the final year of operation only from September 2000 to September 2001, during which 182 individual pond cultures were harvested.

The assumed productivity is high, and would require significant R&D breakthroughs. The results indicate that a combined Open-pond and photobioreactor system would have a capital investment of just under $450,000/ha and would produce algal oil at $140/bbl in present-day $-denomination. The results and accompanying notes are presented in Table 17 and Table 18.

A reduction in the cost of the photobioreactor component by 75% would have the effect of reducing the cost of algal oil to approximately $83/bbl.

Table 17: Open-pond and PBR Combined Capital *(Huntley et al, 2006)*

Cost Item	Remarks	Cost US$/ha
Open pond component		74,500
Photobioreactor component		197,000
Subtotals of above		**271,500**
Engineering, contingencies	15% of above	40,725
Total direct capital		**312,225**
Land costs		2,000
Working capital	25% operating cost	2,700
Total capital investment		**316,925**
Total capital investment Inflation corrected	**2.5% inflation (12 years) 1996 to 2008**	**443,700**

Notes and assumptions:

- The model reported by Huntley et al (2006) did not include for contingencies, land cost or working capital. However the analysis was done largely based on the methodology in Sheehan & al and using 1996 figures in order to allow direct comparison. The capital estimates have therefore been adjusted upwards to maintain consistency.
- The capital estimates for PBR are based on an earlier estimate of $100/m2, and scale up from Huntley & al's experience of systems up to 25,000 l.

Table 18: Open-Pond and PBR Combined Operating Costs *(Huntley et al, 2006)*

Cost Item	Remarks	Cost US$/ha
Total Net Operating Costs		15,270
Capital Charge	15% of Principal	47,539
Total Annual Costs		**62,809**
Total Operating costs Inflation corrected	**2.5% inflation (12 years) 1996 to 2008**	**87,932**
$\$_{2008}$/toe	Based on 72.4 toe/ha/yr	1,215
$\$_{2008}$/barrel algal oil		140

Notes and assumptions:

- The productivity estimate of 72.4 toe/ha/yr is quite high, despite the authors own year-long trials showing a mean production in Hawaii of 9.5 toe/ha/yr and a maximum daily production, which if maintained would yield 22.9 toe/ha/yr.
- Algal oil productivity is expressed in tonnes of oil equivalent (toe)
- The annual costs excluded capital charges related to land, engineering and working capital and have been adjusted upwards to include this, making the models comparable.

4. Potential for Ireland

Although the brief for this report is to primarily assess the technical challenges and research barriers which might face the development of algae as a biofuel resource, it is important to highlight that no development will be possible without the right economic conditions and regulatory environment.

Some of the policy issues which will generally affect the development of the industry include:

- The contribution of macroalgae in supporting marine biodiversity
- The level of taxation of transport-fuels and policy supports for biofuels
- The tariff paid for renewable electricity from a biogas plant
- The availability of capital for biotechnology ventures
- The lengthy and costly planning process for energy projects in Ireland, especially one which may incorporate waste resources
- Difficulties in obtaining marine foreshore licences and any environmental legislation or sustainability criteria that might curtail marine developments and limitations for environmental reasons that would restrict the amount of seaweed harvested
- The availability of infrastructure to integrate with and incentives for hosting algae projects (e.g. offshore windfarms for microalgae; a suitable CO2 emitting site for microalgae)

Bearing in mind the policy and economic background, an analysis of the potential for marine macroalgae and microalgae for biofuel production is put forward in this section.

4.1. Macroalgae Current and Potential Application in Ireland

There are at least three separate sources to consider. These include the exploitation of natural seaweed stocks, the use of drift seaweed, and the cultivation of seaweed at either coastal sites or using offshore infrastructure such as that used for wind farms, ocean energy systems or other aquaculture. *Laminaria spp* are the most abundant in Ireland and among the most productive species. It contains several components which may be extracted for energy use. For this reason this is the species predominantly considered in this report for energy applications in Ireland, but it does not preclude other species, especially *Ulva spp* from being exploited.

4.1.1. Natural Stocks

In Ireland, the only existing harvest of significance is the *Ascophyllum* harvested manually for Arramara Teo. In 2006, 29,000 wet tonnes were harvested (See Table 2). This is all dried to seaweed meal at Arramara's manufacturing plant in Cill Chiaráin, Co. Galway. According to a survey by the Irish Seaweed Industry Organisation (ISIO) (Hession, et al., 1998), there are up to 75,000 tonnes of *Ascophyllum nodosum* that could be sustainably harvested each year, so less than half the natural *Ascophyllum* resource is being exploited. It is spread along 1,220 km of coastline along the Western seaboard and most abundant in Galway, Mayo and Donegal. The estimated potential is given in Table 19. According to the National Seaweed Forum (National Seaweed Forum, 2001), the fallow period of 4-5 years practised in Ireland for the last 50 years on the same *Ascophyllum* areas is ample evidence that this resource is sustainably harvested using manual harvesting.

Table 19: *Ascophyllum* Harvested and Potential from Natural Stocks *(Hession, 1998)*

County	1996 Harvest (wet tonnes)	Potential (Wet tonnes)
Donegal	8,250	16,430
Leitrim	-	-
Sligo	-	430
Mayo	4,400	16,600
Galway	21,200	37,470
Clare	100	1,140
Limerick	-	210
Kerry	1,800	1,140
Cork	-	1,425
Total	35,750	74,845

Due to the high cost of manual harvesting and the high polyphenol content, *Ascophyllum* may not be the ideal candidate for energy exploitation. Kelp species are more abundant and more likely to be suited to energy uses.

At present there is very little use being made of Irish kelp. Estimates as to the available resource are much less certain. The ISIO survey, referenced above, reports that Ireland has a natural kelp resource covering approximately 56% of the west coast. The survey defined 22% of the western coastline as being abundant with dense kelp. The five kelp species which are native to Ireland are *Laminaria digitata, L. hyperborea, Saccharina latissima, Sacchorhiza polyschides* and *Alaria esculenta*.

The ISIO study further listed the factors which affect the occurrence and distribution of *Laminaria spp*, which is reproduced in Table 20 below. A number of dive surveys were carried out, but an overall estimate of kelp occurrence was not quantified.

Table 20: Factors Affecting Occurrence of *Laminaria spp (Hession)*

Attribute	Detail
Substrate	Substrates composed of rocks and boulders are most suitable for kelp occurrence. Sand, mud and gravel substrates are less stable and do not provide a suitable anchorage for the kelp holdfast.
Illumination	Illumination will generally dictate the lower limits of the kelp forest. Green light penetrates more readily than blue or red and is most useful for photosynthesis by brown algae. The normal depth limit of kelp forests in western Europe lies at about 17-20 m below chart datum (Where green light declines to about 1% of its surface value).
Exposure	Exposure to extensive wave action can reduce the abundance or even occurrence of kelp.

The National Seaweed Forum Report gave no consideration to energy applications, but did conclude that there were sufficient volumes of brown seaweeds available from natural stocks to support a large alginate plant. An increase in the amount of seaweed being harvested would be required, and this could be achieved by the introduction of mechanical harvesting methods as employed in either France or Norway, and described earlier.

A study carried out by the Irish Seaweed Centre considered the topic of mechanised harvesting in some depth and began the task of quantifying the kelp resource (Werner, et al., 2004). Based upon surveys carried out in Galway Bay, an estimated average annual kelp biomass standing stock of 7.63 kg/m^2 is reported, which equated to about 81,000 wet tonnes of kelp in Galway Bay. Using the previous coastal survey by the ISIO, which reported that 56% of the western coastline supports kelp beds, and assuming an average kelp bed width of 100m, an overall figure of 3 million wet tonnes is estimated for standing kelp beds. The accuracy of this estimate is poor, as the original survey data in Galway Bay had a margin of error of about +/- 40%. However it is probably the most recent and best estimate of the natural kelp resource. The Irish Seaweed Centre is currently working on a revised estimate which could put the resource at as much as 10 million wet tonnes (Kraan, 2008).

Preliminary investigations were carried out to mimic the effect of both the "Scoubidou" and dredge harvest systems using manual clearing. These were monitored for one year only and good recovery had commenced. However the authors conclude that long term trials and careful monitoring of seaweed stocks, the surrounding ecosystem and the environmental consequences of mechanised harvesting will be required. The difficulties in monitoring natural stocks of *Laminaria spp* are highlighted, as most remote-sensing techniques are currently unable to distinguish between e.g. *L. hyperborea, L. digitata* and *S. polyschides* due to their similar morphology and texture. Equally, extrapolating a small sample to a national context most likely gives an inaccurate species profile. Separate estimates are required for the different kelp species due to their differing properties, end-uses and manner of sustainable harvesting.

In other countries with significant exploitation of natural stocks such as Norway and France, it is considered that a natural kelp bed must be allowed at least 5 years to regenerate after harvest, so a figure of 20% harvest of natural stocks would be a reasonable upper limit to sustainable annual harvest. This would indicate a combined potential annual sustainable kelp harvest of 600,000 wet tonnes at various locations along the west coast, based on 3 million tonnes of standing stocks.

A study by Duchas (Heritage Service in Ireland), considered the environmental impact of seaweed harvesting (Heffernan, 1999). It reported that the current environmental impact from manual harvesting is minimal, but with the likely advent of mechanised harvest, there is an increased risk of negative environmental impact.

A position statement by the Environment and Heritage Service in Northern Ireland sets out a series of matters that need to be addressed in any planned harvest of natural seaweed (Environment and Heritage Service, 2007). They point to the biodiversity benefits, the coastal erosion benefits and other ecological concerns regarding seaweed beds. Drift seaweeds play an important role in the beach ecosystem. Any commercial activity should use environmentally sustainable methods of seaweed harvesting and adhere to a code of conduct, yet to be developed.

As a driver to the business model developed later an optimistic estimate of potential exploitation of 50% of sustainable natural stocks by 2020 would supply up to 300,000 wet tonnes of *Laminaria* for industrial processing.

4.1.2. Drift Seaweed

Figures are not available for drift seaweed, which would primarily comprise cast *Laminaria hyperborea* and also *Ulva* spp. In Courtmacsherry Bay in West Cork, 60,000 tonnes of wet *Ulva spp* resulting from an algal bloom have been recorded (Kraan, 2008). This is likely to be a limited, local and highly seasonal resource, which may be integrated as an opportunistic feedstock into biomass processing plants based on other feedstocks, such as anaerobic digesters. In some years up to 20% of standing stocks of *L. hyperborea* are washed up on the Irish coast. NERI report summer densities of *Ulva spp* in Skive Fjord in Denmark of 2 dry t/ha (Rasmussen, et al., 2007).

An effort is required to quantify the drift seaweed resource. A 50,000 tonne estimate is put as an upper limit to reclaiming drift seaweed for energy purposes by 2020.

4.1.3. Nearshore Seaweed Aquaculture

A study by the Marine Institute considered the feasibility of nearshore seaweed aquaculture in detail (Werner, et al., 2003). Although the study did not quantify the potential volumes of seaweed from aquaculture, it did consider site selection in detail and also listed a number of potential sites for seaweed aquaculture. It is worthwhile reproducing an edited section of the report which considers the specific site suitability criteria. A section on potential production will be added.

Table 21: Selected Species Requirements for Optimal Growth *(Werner, 2003)*

Species	Light	Salinity	Optimum Temperature ^{0}C	Exposure/ Tidal current
Alaria esculenta	medium	normal	10 to 12	high
Saccharina latissima	high	low	10 to 15	medium
Ulva spp	high	low	10 to 20	low-medium

For the selection of the most appropriate seaweed aquaculture sites two key areas of consideration must be balanced:

1) Suitability of a site with respect to requirements of the target seaweed species.

2) Feasibility of aquaculture development with respect to availability of space and competition with other interest groups and coastal resource users (e.g. shellfish and finfish farmers, fishermen, shipping, yachting, tourism, protected areas).

4.1.3.1. Biotic and abiotic factors for site selection

Natural, high abundance of a particular species is the best indicator for the suitability of a potential cultivation site for that species. In most cases, these sites, for different reasons, would not be the first choice for an aquaculture operation. Often farming is conducted at sites where the target species is not highly abundant due to a lack of suitable substrata (e.g. sandy or muddy bottom substrata). The primary environmental factors, which have to be considered for successful growth of seaweeds, are discussed below. They are the availability of light and nutrients, the salinity, temperature and exposure of a given site as well as any pre-existing pollution of the local environment.

Light is essential for photosynthesis and consequently growth. The quantitative light demand for photosynthesis and growth depends on the algal species, its morphology and adaptation mechanisms. Species inhabiting the upper euphotic zone (intertidal) are well adapted to exposure to high irradiances and are referred to as “sun plants”. Species of the deeper euphotic zone (subtidal) lack adequate adaptation mechanisms but have developed strategies to cope with low light intensities and overall annual quantities.

The type of seaweed (sun plant or shade plant), the season (light intensity), the turbidity of the water body all must be considered during the design of a cultivation system.

Nutrients determine productivity and biomass yield but also the abundance of epiphytes in aquaculture systems. Nutrients essential for growth are divided into three main categories: macronutrients (e.g. nitrogen, phosphorous, carbon; N, P, and C, respectively), micronutrients or trace elements (e.g. iron, zinc, selenium, copper, manganese, molybdenum) and vitamins (vitamin B12, thiamine and biotin), which are required in different concentrations. Micronutrients and vitamins are rarely a limiting factor for seaweed production in coastal waters. The most important nutrients for high productivity are nitrogen (ammonium, NH_4^+, and nitrate, NO_3^-) and phosphorus (orthophosphate, PO_4^3). In coastal waters the concentrations of N and P can become limiting for seaweed growth. They vary significantly during the year with highest concentrations in autumn/winter and lowest in spring/summer. In many coastal areas (e.g. semi–enclosed bays, estuaries, inlets with restricted water exchange) the concentrations of inorganic nutrients are increased by anthropogenically derived inputs of nitrogen and phosphorus from urban sewage treatment works, intensive agriculture and aquaculture plants and run–off from agricultural land.

Seaweeds differ in their response to elevated N and P levels. The uptake efficiency depends on the form of N (NH_4^+ vs. NO_3^-) available in ambient waters and the N:P ratio. Some seaweeds (especially kelps) are able to take up NO_3^- and NH_4^+ simultaneously and at the same rate. By contrast, other seaweeds (e.g. *Ulva spp.*) take up NH_4^+ preferentially over NO_3^-.

The application of seaweeds as biofilters for removing inorganic nutrients from effluents of finfish and shellfish aquaculture systems, or from urban sewage, requires a good knowledge of the ecophysiological demands of a species to identify one with a potential for maximum nutrient removal efficiency that are additionally, commercially valuable species for aquaculture.

Fluctuations in salinity can be a critical factor for aquaculture sites located in bays with restricted water exchange and high fresh water inflow, in estuaries and in shallow areas. Most seaweed species grow optimally at salinities of around 30% but tolerate some fluctuations in salinity. Some intertidal algae however, such as *Ulva* spp, show optimal performance at lowered salinities (e.g. sites with a small fresh water inflow).

Each seaweed species has an optimal temperature range for growth and reproduction. For most native species the average optimal range for growth is between 10ºC and 15ºC with a survival temperature range between 0ºC and 25ºC. This is well within the range of average sea surface temperature of the west and south coast of Ireland, which is 6–8ºC in February /March and 14–17ºC in August. In certain shallow areas, however, summer temperature may well rise over 20ºC. Elevated temperatures, especially in combination with high irradiance, can be critical for some seaweeds (e.g. kelps and *Palmaria palmata*) and may lead to deterioration and bleaching of the thalli. To avoid this aquaculture sites should be located in areas with a minimum depth of 4–6 metres and good water exchange.

The demands of the commercially important seaweeds with respect to exposure and tidal current vary considerably. Whereas *Alaria esculenta* inhabits very exposed sites, *P. palmata* grows on less exposed sites with a good tidal current. Other algae such as *Saccharina latissima* and *Porphyra spp.* are found in more sheltered areas. The demands have to be balanced with the feasibility for an aquaculture operation to work efficiently at any season and weather condition and to avoid damage to the farm.

Therefore very exposed sites have to be excluded. Semi–sheltered areas with a strong tidal current (up to 3 knots) can significantly increase growth rates of *Alaria spp* and *Palmaria spp* in comparison to sites with prevailing currents of 0.5–1 knots as shown in cultivation trials. An increased water velocity at the algal surface enhances nutrient uptake and algal productivity. (Water motion is an essential factor for algal growth and has also to be considered in tank cultivation).

Seaweeds have the ability to remove nutrients from surrounding waters and also internally accumulate heavy metals (e.g. mercury, arsenic, cadmium, copper, lead, and zinc), radionuclides (e.g. Caesium–137 and Technetium–99) and other contaminants.

In Ireland, assessments of water quality data of estuarine and coastal waters have indicated generally satisfactory conditions. Overall inputs of effluent containing chemical contaminants other than inorganic nutrients are moderate with few cases with serious pollution. In general, the Irish Sea and Celtic Sea are loaded with more contaminants than the Atlantic Seaboard. On the west coast the main centres of anthropogenically derived inputs are Shannon Estuary, Galway Bay, Sligo Bay and Donegal Bay.

The effect of the environmental factors on the productivity and biomass yield of cultivated seaweeds mean that potential aquaculture sites should be examined with these criteria. Trials would be required initially to verify if the site is suitable for production of a target species.

4.1.3.2. Know-how and Research Capacity

This is an often-overlooked aspect and worth highlighting. Technology transfer, the availability of research facilities and training programmes are the key to successful alga aquaculture. This is discussed in a later section on commercial activity and research programmes. There is considerable know-how in Ireland in this regard and the aquaculture programmes supported by BIM and the Marine Institute are vital to development of the industry.

4.1.3.3. Availability of suitable aquaculture sites

Several other criteria have to be met for selection of an aquaculture site with respect to logistical operation of a farm. These criteria include exposure of a site, pier access, access to the hinterland and other activities in the potential area.

In the study some potential seaweed aquaculture sites are listed and generally described according to certain selection criteria. Some examples are given interpreting the selection parameters and implications, which can be drawn from them. Only major bays, loughs etc. are considered.

The highest potential for seaweed aquaculture development is clearly on the west coast, followed by the north, southwest and south coasts. In contrast to the coast of the Irish Sea these coasts provide:

- A large number of sheltered to semi–sheltered sea loughs, bays, inlets and estuaries.
- Good water exchange and different strength of tidal currents.
- Generally unpolluted water.
- Different degrees of nutrient enrichment.
- On average, lower water turbidity than at the east coast due to different bottom substrata.

With respect to the availability of space and competition with other coastal resource users, two major issues are highlighted: the opportunity for a close link of seaweed, shellfish and finfish aquaculture, and the implications of the presence of Special Areas of Conservation (SACs) and Special Protected Areas (SPAs).

4.1.3.4. Integrated polyculture

Integrated polyculture is an approach for the advancement of sustainable aquaculture, which brings the coordination of aquaculture activities to a stage of close collaboration between finfish, mussel and seaweed farmers. The underlying rationale brief is:

- Fish consume oxygen and release substantial amounts of nutrients (mainly NH_4^+) and organic matter (faeces). Significant concentrations of N and P are also released by non–consumed feed.
- Molluscs as filter–feeders take up organic matter, but also consume oxygen and excrete NH_4^+.
- Seaweeds remove nutrients released by fish and molluscs from the system and channel them into enhanced growth. They produce oxygen and therefore contribute to balance the dissolved oxygen levels of the system. The biomass produced in turn can be used to feed fish and/or herbivorous molluscs, or other value–added applications.

In a well balanced system, the nutrient release into the environment is minimal and the integration of fish, molluscs and seaweed can increase the economic output.

The first successfully developed polyculture systems were land based cultivation systems, using fish, abalone and seaweed. There is an increasing effort to apply the same principles in open sea aquaculture operations against the background of the rapid expansion of salmonid aquaculture worldwide, and Atlantic salmon in Norway, Chile and United Kingdom in particular. There is growing concern about the continuing deterioration of coastal ecosystems and intensive fish cage cultivation may contribute to the degradation of the environment. It is estimated that 9.5 kg P and 78 kg N per tonne of fish per year is released to the water column. For nitrogen, which is the nutrient of major concern in marine environments, there is a consensus that at least 80% of total losses (dissolved and organically bound) from fish farms are plant available and are potentially eutrophicating substances. In the worst case, they can generate severe disturbances, including eutrophication, toxic algal blooms and green tides. However, only a few cases of increased primary phytoplankton production in the vicinity of marine cage farms have been reported. This is not surprising considering the water exchange rate in relation to the doubling time of phytoplankton. Due to time lags and the buffering capacity of ecosystems, the eutrophication process in an area may be slow, acting over time scales of several years.

In order to utilise the nutrients released from fish farms, several studies have been conducted where seaweeds were grown in the direct vicinity of salmon cages. In Chile, for example, rope cultures of *Gracilaria* *chilensis* were co–cultivated with a coastal salmon cage farm. The growth rate of *Gracilaria* cultivated at 10 m from the farm was up to 40% higher than those of plants cultivated 150 m and 1 km away from the farm. In other pilot trials different *Porphyra* species, and *Saccharina latissima* and *Nereocystis luetkeana* (Pacific kelp species) have been tested showing that the co–cultivation of seaweed and salmonids can be feasible.

In Ireland, salmon production was about 11,000 tonnes in 2006 (MERC Consultants, 2007), which is significantly lower than the tonnage produced in Scotland and Norway. The majority of Irish farming sites are located in moderate to exposed areas which have good water exchange by strong tidal flushing resulting in high dilution effects of released nutrients.

Extensive environmental monitoring of the water bodies around the farming sites and the seabed below the cages confirmed that the impact of organic nutrient enrichment due to farming activity is minor.

Additionally, the application of novel fish feeding techniques is contributing substantially to the reduction of nutrient release from unused fish feed into the environment. To ensure the maintenance of the healthy status of seabeds around farming sites, the Department of Communications, Energy and Natural Resources (DCENR[6]) has defined acceptable levels of impact and has introduced annual benthic surveys monitoring protocols for all finfish farms. If impact levels are breached the DCENR has the option to take action against the operation.

If the concept of integrated polyculture is defined in a very narrow sense, i.e. to counteract potential eutrophication caused by offshore fish farming, then there would be no immediate need for application in Ireland as the data of environmental monitoring are showing. However, integrated polyculture is not just a tool for reducing potential or existing pollution:

- It has been shown that algal growth rates are enhanced, when seaweeds are cultivated in the direct vicinity of salmon cages, due to the inorganic nutrients released by the fish. The availability of nutrients at times when concentrations in ambient seawater are naturally low (spring/summer) may be advantageous to prevent a drop in growth rate.
- Seaweeds produce oxygen through photosynthesis and therefore increase levels of dissolved oxygen in the water, which may have beneficial effects for the fish.
- From a practical point of view, the co–cultivation of seaweed and finfish could lead to a share of infrastructure, labour and licensed aquaculture sites.

In seaweed cultivation a similar approach could be applied connecting seaweed aquaculture and mussel farming. Interest has already been expressed by several mussel farmers and existing structures could be used for seaweed aquaculture. The productivity of a licensed area could be increased and income improved through species diversification.

4.1.3.5. Special Areas of Conservation

In recent years a substantial number of designated marine Special Areas of Conservation (SACs) have been implemented and candidate SACs drawn up. Within these areas:

- Existing traditional activities (e.g. seaweed cutting) may be continued but a substantial increase of harvesting seaweed and any new activities must be approved by the Minister.
- Any mechanisation of seaweed harvesting within the designated areas would need the approval of the National Parks & Wildlife Service (NPWS), Department of the Environment, Heritage & Local Government.
- Seaweed aquaculture is permitted subject to the usual licensing considerations but the NPWS has to be consulted by the Department of Communication, Energy and Natural Resources for approval.

According to the statement there is no obligatory hindrance as such for the establishment of seaweed aquaculture in a Special Area of Conservation. Although the applicant for an aquaculture licence may have to prove that the construction of the farm will not have adverse impacts on the habitat. Therefore an environmental survey may need to be conducted before license issue.

[6] Formerly the Department of Communications, Marine and Natural Resources, in 2007 the name was changed to Department of Communications, Energy and Natural Resources (DCENR). The marine portfolio is now part of the Department of Agriculture, though marine development is influenced by the policy of several departments including DCENR

4.1.3.6. Potential Nearshore Production

The previous analysis (Werner, et al., 2003) listed 55 potential sites and some tentative assessment of their suitability for seaweed aquaculture. Some examples were outlined in a little more detail. For example, Clew Bay is identified as being suitable for *Saccharina latissima* and *Porphyra* species in parts of the inner bay. The *Laminaria spp* are more interesting for energy applications. The total area spanned by Clew Bay is 31,250 ha. Only a fraction of this area is likely to be suited to aquaculture. Currently 274 ha are under aquaculture for both finfish (70 ha) and shellfish (177 ha). The most interesting potential at least initially in this instance may be for polyculture of seaweed with fish-farming.

In the same report, an outline strategy for a seaweed aquaculture development programme was proposed over 10 years. This envisaged up to 8 commercial seaweed operations, including 2 tank-based systems. It is clear that the authors had small-scale nearshore applications for high value-added seaweed products in mind. It was also proposed to have a seaweed hatchery established and 3 pilot scale operations which would support extensive fundamental research into the development of new products. The species to be targeted included *Palmata, Alaria, Porphyra* and *Asparagopsis*. From an energy perspective, the goal should be the cultivation of *Laminaria* species in larger volumes at a lesser number of sites.

An optimistic scenario might see 500 ha of nearshore seaweed cultivation developed over a 10-year time horizon in Ireland.

4.1.4. Offshore Seaweed Aquaculture

Seaweed aquaculture can be considered as a stand-alone activity, building the required infrastructure to cultivate seaweed on a very large scale offshore. Such schemes have been proposed in the US (Chynoweth, 2002) and in Japan (Yokoyama, et al., 2007) as outlined earlier.

It is unlikely that a programme on such a scale would be undertaken prior to 2020 in Ireland, without trials being conducted at smaller scales and the very significant engineering challenges posed by offshore seaweed aquaculture solved.

Ireland has expertise in offshore finfish aquaculture. Due to the relatively shallow depths of the continental shelf, nearly all fishfarm operations include some mixture of inshore and offshore sites. There is some potential for integration of offshore seaweed aquaculture with existing finfish production. However, the environmental remediation effect of seaweed aquaculture is likely to be of most benefit in coastal zones.

Other opportunities exist to share infrastructure with offshore wind and wave energy sites. There are about 2,000 MW of offshore wind-generation capacity in various stages of planning (NOWIreland, 2008). There is also a target to achieve 500 MW of installed ocean energy capacity by 2020 (DCENR, 2007).

The extent to which seaweed aquaculture might piggyback on still to be deployed infrastructure is uncertain. The majority of offshore wind under development is at sites along the East Coast, where it is not known if the salinity, turbidity, tidal conditions and other factors will support productive seaweed aquaculture. However offshore wind turbines cover a large footprint and are good candidates to share supporting infrastructure. For ocean energy, especially wave energy, the locations are likely to be more compatible with existing natural seaweed stocks.

An optimistic scenario for offshore seaweed aquaculture is that the concept could be initially demonstrated at offshore wind, ocean energy or finfish cultivation sites, and by 2020 that up to 200 ha of cultivation is achieved.

4.1.5. Possible Development Scenarios

For the purposes of preparing indicative potential figures for Ireland, a standard rate for cultivating *Laminaria* species could be 20 dry t/ha/yr and an optimised rate could be 35 dry t/ha/yr, based on the literature review. Output will be considered initially in wet tonnes. A standard moisture content of 85% is used to convert to dry tonnes. For the purposes of achieving an energy output, all scenarios are assumed to use the seaweed biomass for anaerobic digestion, where one wet tonne of seaweed yields 22 m^3 of methane with a gross calorific value of 39.8 MJ/m^3. This takes account only of biogas fermentation yield and will give only primary energy supply from seaweed, independent of the application.

The hypotheses developed for the purposes of this report of low, medium and high development scenarios for the exploitation of macroalgae for biofuel in Ireland are characterised in Table 22 in a speculative roadmap for development to 2020. This coincides with national and EU biofuels policy goals to displace 10% of fossil-fuel in transport with renewable fuels.

Table 22: Roadmap for Development of Biofuel from Macroalgae in Ireland

Low	• Ongoing research programmes are continued • By 2015 cultivation of Laminaria species has been demonstrated and yields of 20 dry t/ha/yr confirmed • Various other trials including poly-culture with finfish and the testing of mechanical harvesting of natural stocks are carried out by 2020 • There is no significant commercial exploitation of seaweed for biofuel • Area under cultivation is < 5 ha.
Medium	• By 2010 Laminaria aquaculture trials have shown yields of 20 dry t/ha/yr • Mechanical harvesting of natural stocks is fully assessed • By 2015 up to 20,000 wet tonnes of natural Laminaria stocks are being exploited for anaerobic digestion (AD) • Small quantities of drift seaweed are also being collected (< 5,000 wet tonnes) and used for AD • 10 ha of Laminaria aquaculture are established at nearshore sites, ideally to supplement natural Laminaria, and produce c. 1300 wet tonnes • Polyculture with fishfarms is also demonstrated • By 2020 up to 100,000 wet tonnes of natural Laminaria stocks are being harvested • This is supplemented by up to 30,000 wet tonnes of cultivated Laminaria on c. 150 ha, produced on a combination of sites, some demonstrating higher yields of up to 35 dry t/ha/yr • The extraction of multiple products from Laminaria is demonstrated
High	• By 2010 Laminaria and Ulva aquaculture trials are initiated and show promising results • Mechanised harvesting of natural stocks is fully assessed and shown to be viable • By 2015 up to 100,000 tonnes of natural Laminaria stocks are being harvested • Up to 30,000 wet tonnes of cultivated Laminaria and Ulva are produced on less than 150 ha at yields of up to 35 dry t/ha/yr • Demonstration of integration with offshore infrastructure is achieved • The Laminaria and Ulva from natural stocks, aquaculture and drift seaweed primarily go into AD • By 2020 higher processing yields, demonstration of fermentation to ethanol and advanced biorefinery concepts are achieved • Up to half the sustainable harvest of Laminaria is exploited (300,000 wet tonnes) • Up to 500 ha of nearshore aquaculture are developed • An additional 200 ha of offshore cultivation is achieved • Up to 160,000 wet tonnes are produced by aquaculture • Up to 50,000 wet tonnes of drift seaweed are collected • Ethanol and other products besides biogas are being produced commercially

A summary of the seaweed biomass available under the scenarios hypothesised is presented in Table 23. For comparative purposes this is converted to GJ of primary energy supply (Table 24) based on anaerobic digestion yields for seaweed. From an energy-policy perspective, the 2020 outlook is too short a term to expect a significant contribution of biofuels from macroalgae in absolute terms. In the most optimistic of the scenarios outlined earlier, 447 TJ of energy could be contributed from macroalgae by 2020. The 2020 target of 10% transport fossil-fuel displacement would require about 22,000 TJ of biofuels (Sustainable Energy Ireland, 2008).

Table 23: Scenarios for Available Seaweed Biomass

Wet tonnes/year	2010	2015	2020
Low total estimate	-	20	200
Natural *Laminaria* stocks	-	-	100
Aquaculture	-	20	100
Drift Seaweed	-		
Medium total estimate	120	26,300	140,000
Natural *Laminaria* stocks	100	20,000	100,000
Aquaculture	20	1,300	30,000
Drift Seaweed	-	5,000	10,000
High total estimate	1,120	150,000	510,000
Natural *Laminaria* stocks	100	100,000	300,000
Aquaculture	20	30,000	160,000
Drift Seaweed	1,000	20,000	50,000

Table 24: Scenarios for Primary Energy Supply from Seaweed Biomass

GJ/year	2010	2015	2020
Low	-	18	175
Medium	105	23,000	123,000
High	981	131,000	447,000

Notes:

- Rounded to nearest '000 GJ (for > 1,000 GJ)
- Based on 22 m^3 of methane per wet tonne with a gross calorific value of 39.8 MJ/m^3

4.2. Microalgae Current and Potential Application in Ireland

There is little or no existing research which attempts to quantify the potential scale of microalgae for biofuel applications in Ireland.

A short discussion of the location-specific variables is given below, followed by an estimation of the potential scale of application. One possible development route will be shown, but due to the early stage of maturity of the technology, many other development scenarios may be extrapolated based on the implementation of ongoing research and development, which is outlined elsewhere in this report.

4.2.1. Marine Environment

The scope of the study is restricted to marine algae applications. Whilst there are many potential freshwater algae species worth pursuing, marine species have the advantage of not competing with other freshwater demands. Additionally marine algae species will not be prone to contamination by non salt-water algae species. However both freshwater and marine species should be pursued in order to facilitate inland developments and to exploit the vast range of freshwater species.

4.2.2. Carbon

A critical growth-limiting factor is the availability of carbon, usually supplied as CO_2. Commercial micro-algae facilities for production of nutraceuticals or other high value products supply pure CO_2 into their cultivations. This is costly and not a likely option for cultivation of biofuel raw material. Exhaust emissions from fuel combustion are the most likely source of CO_2 for algae production. Not only is this a lower cost option, but it also opens up the possibility of recycling CO_2.

For this reason it is thought that the most likely sites for implementation of microalgae technologies are high CO_2 emissions plants, particularly those which use coal or peat. An additional requirement is that they are registered under the Emissions Trading Scheme (ETS) to accrue carbon credits (Environmental Protection Agency, 2008). There are about 120 such sites.

Smaller sites may also be considered, particularly as part of the demonstration of sustainable concepts. For example, in Germany micro-algae pilot facilities have been installed at both a large coal-fired power plant near Hamburg, and also at a smaller biogas power plant in Bavaria (Ripplinger, 2008).

There is only one coal-fired power plant in Ireland operated by the ESB at Moneypoint. There are 915 MW_e of generation capacity at Moneypoint. There are three peat-fired power stations in the midlands, distant from the marine environment. There are a number of gas-fired power plants at coastal locations, including one under development by Bord Gais. In theory any of the large industrial sites including the cement manufacturers, pharmaceutical manufacturers and all those registered under the ETS would be potential sites for CO_2 offsets via the use of microalgae.

4.2.3. Climate

The photosynthesis process requires both light and heat. The ideal growth environment combines long periods of daylight with good mixing (Grobelaar, 2008). Most commercial microalgae production to-date has occurred in low-latitude regions. Israel, Hawaii and southern California are home to several commercial microalgae farms. For a description of typical current commercial microalgae cultivation see the Seambiotic case study presented earlier.

Developers of microalgae technology are focussing their development effort in warm climates. Solix biofuels, for example do their development work in Denver, but wish to concentrate their initial installations in the range of +/- 20 degrees latitude to avail of a favourable year-round climate. They estimate a 33% yield penalty by moving to 40°N (Willson, 2008).

Where microalgae cultivation has been demonstrated at higher latitudes, it has been done with the use of waste-heat and expensive greenhouse infrastructure to maintain productivity.

It is likely that a large seasonality penalty would exist if microalgae were to be cultivated in Ireland where the latitude is 53°N. However, stakeholders in Ireland from the academic, industrial and entrepreneurial community have a clear interest in further research of the potential of microalgae as an energy source.

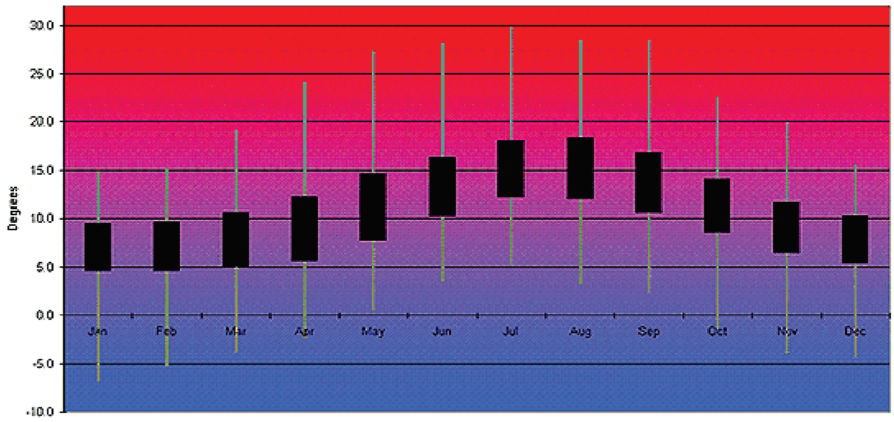

Figure 24: 1971-2000 Valentia Temperature Range *(MetEireann)*

The temperature profile at a coastal weather station at Valentia Observatory is shown in Figure 24. Both the extremes of daily temperature are shown and the mean daily minimum and maximum temperatures in a given month. Also shown are the average daily solar irradiation values at Valentia and a comparison with Eilat, Israel, an example of a climate with an established microalgae cultivation industry.

Table 25: Average Daily Horizontal Solar Irradiation *(RETScreen)*

Month	Average Daily solar radiation - horizontal	
kWh/m2/day	Valentia, Ireland	Eilat, Israel
January	0.61	2.85
February	1.25	3.78
March	2.19	5.23
April	3.86	6.36
May	4.89	6.99
June	4.89	7.67
July	4.67	7.64
August	3.83	7.07
September	2.78	6.08
October	1.53	4.59
November	0.86	3.33
December	0.5	2.67
Annual Average	2.66	5.36

4.2.4. Nutrient Source and Disposal

Microalgae require fertiliser, primarily nitrogen (N), but also phosphorous (P) and potassium (K). This is typically added as a synthetic fertiliser, though there may also be scope for using sludges and waste-water, with the added benefit of disposal of unwanted organic matter. There may be environmental restrictions linked to the requirement to apply nutrients, but additionally to dispose of any residues generated during the growth and or processing of microalgae.

The integration of processes to maximise the use of biomass and avoid waste must be considered, but conventional disposal methods suggest that a large land bank in a location capable of supporting sustainable application of sludge is required.

4.2.5. Environment and Ecological Stability

The ecological stability of a culture is important. Certain locations may facilitate contamination by competing algae species. Additionally local climate may have a significant impact on algae productivity. With thousands of species of algae to choose from, it should be possible to optimise systems to local conditions, but there is a need for constant screening and characterisation of algae species, as well as to understand the long-term performance of any given strain.

4.2.6. Know-how and Research Capacity

A key part of developing any new technology are the skills and training required for people to understand, develop and implement the technology. Technology tends to be initially deployed where it is developed. Virtually all of the demonstration plants built to-date have evolved from research at leading universities and research centres worldwide.

This will be discussed in a later section on research and development. Irish stakeholders would like to see more funds allocated to algal research.

4.2.7. Development Scenarios

The hypotheses developed for the purposes of this report of low, medium and high roll-out of microalgae technology in Ireland are characterised. This sets out a speculative roadmap for development of microalgae for biofuels.

Table 26: Roadmap for Development of Biofuel from Microalgae

Low	• There is little or no development outside of lab-based research by 2015 • One demonstration unit with nominal output is implemented at a power plant by 2020 • Reliable yield data begins to be demonstrated at site(s) of <<1 ha.
Medium	• Screening programme is carried out with moderate success • The concept is proven in the Irish climate via trials at a power plant on a site of up to 1 ha as early as 2010 • Yields of 25 t/ha/yr of biomass are demonstrated at 25% lipid yields • About 3 sites will demonstrate different concepts on a cumulative area of up to 3 ha and yields of 35 t/ha/yr at 50% lipid content are achieved • By 2020 a cumulative 10 ha of microalgae is established and maintaining these yields
High	• Multiple trials are initiated by 2010 • Extensive screening of strains and other areas of required research are actively pursued and start to yield promising results • Yields of 35 t/ha/yr at 50% lipid content are achieved • By 2015 a further 10 ha are developed • Biorefinery concepts are actively researched to include for non-lipid components • Higher value products are considered • By 2020, Ireland has achieved ground-breaking research in the area to become a world-leader in microalgal technology • Over 100 ha are in production at several sites • Biorefinery concepts are being demonstrated using multiple products from microalgae

The scenarios outlined above are hypothetical. They are based on the successful conclusion of a theoretical programme of research and using technologies with a wide range of capital costs. What is clear, from an energy point-of-view, is that the contribution, in the opinion of the consultants, will be quite low, with at most 1,750 toe (or 79,400 GJ) of production achieved by 2020. The estimates in tonnes of oil equivalent (toe) and GJ are shown in Table 27. The substantial opportunities for generation of new technology, spin-off activity, jobs, investment and the potential for new intellectual property creation have not been considered in any detail and are outside the scope of this report to quantify.

Table 27: Scenarios for Primary Energy Supply from Microalgae in Ireland

Scenarios	2010	2015	2020	2020
	toe	toe	toe	GJ
Low	0	0	<10	<500
Medium	<10	50	175	7,900
High	<50	175	1,750	79,400

Note: This does not adjust for the lower calorific value of microalgal oil compared to standard oil equivalent. It should not alter the estimates materially.

5. Commercial Activity and Research Programmes

The objective of this section is to give a brief overview of the existing commercial and research activities which consider both microalgae and macroalgae for biofuels. This is in addition to the examples and instances referred to previously in the report. There is an enormous amount of activity, mostly on microalgae, with news about new investments and research programmes emerging on an almost daily basis.

A brief overview of general energy research policy context is given here, prior to looking at specific activity both in Ireland and internationally on algal biofuels.

In Ireland, the Charles Parsons Awards scheme was announced in 2006. The awards totalled funding of €20 million for the development of energy research centres. Of the seven projects currently in progress as a result of Charles Parsons' awards, four projects relate to biofuels and/or biomass.

In 2008, Science Foundation Ireland (SFI) adopted an additional pillar in the area of sustainable energy research and energy efficient technologies. This has been a very successful initiative in the past for supporting innovation in other fields and so is a very promising development for the sustainable energy sector in Ireland.

The Irish Energy Research Council[7] recently published an Energy Research Strategy for Ireland (Irish Energy Research Council, 2008). The Strategy proposes five strategic lines, one of which is RD&D in sector-specific fields, including sustainable bioenergy.

5.1. General Research Programmes

The EU FP7th Framework Programme for research[8], under call 3 of the Food, Agriculture and Fisheries, and Biotechnology theme contains a specific indicative topic on "Sustainable uses of seas and oceans- Biomass from micro- and macro-algae for industrial applications". This, and future similar calls under the themes of biorefineries and marine biotechnology, present a clear opportunity for Irish-based researchers to collaborate with international researchers to solve common issues regarding the exploitation of algal resources for bioenergy.

A valuable forum for technology transfer and sharing of know-how in the UK is the government-funded (Department for Innovation, Universities and Skills) Bioscience for Business Network[9]. A special interest group has been set up for marine bioresources, which acts as a dissemination point for marine biotechnology information. They host a number of physical and virtual seminars and most of these have been on the topic of marine algae. Members outside the UK are also able to participate.

Enterprise Ireland has established a number of competence centres[10]. An area of research that Enterprise Ireland are addressing, in conjunction with Industry, is the possibility to develop a Competence Centre in the area of Bioenergy and Biorefining. One research theme to this Competence Centre could be in the area of algae as a biomass source for both energy and higher value co-products. Businesses and research groups may also form an Innovation Partnership with Enterprise Ireland and avail of a host of support processes for commercialisation, patenting and other activities which foster innovation.

Bord Gais have established a €10 million Alternative Energy Research and Development Fund[11] to support research into emerging energy-related technologies. Bord Gáis intends, through the establishment of this research and development fund, to support an increase in the quantity and quality of research in alternative energies in Ireland's colleges. It also intends to invest in campus/technology companies in prototyping and bringing technologies to market. This fund is open to both micro and macroalgae technology demonstrations.

5.2. Macroalgae Research Programmes

Investment in seaweed use for biofuel is much less intensive than in microalgae. Hectic activity in the 1970s greatly slowed down as soon as the price of oil began to drop and most R&D programmes were phased out by the end of the decade apart from a few exceptions such as the US Marine Biomass Project (Chynoweth, 2002). However this has been reversed over the past five years due to the steady increase in oil prices.

[7] http://www.dcenr.gov.ie/Energy/Office+of+the+Chief+Technical+Advisor/Irish+Energy+Research+Council.htm
[8] http://cordis.europa.eu/fp7/home_en.html
[9] http://www.biosciencektn.com
[10] http://www.enterprise-ireland.com/CompetenceCentres/
[11] http://www.bordgais.ie/corporate/index.jsp?1nID=93&pID=94&nID=707

There is a Danish research project (NERI – National Environmental Research Institute at the University of Aarhus) to investigate the conversion of cultivated green seaweeds into bioethanol (Rasmussen, et al., 2007). NERI is a collaborator in this current review project.

Other large projects have commenced in both the EU and Japan to develop offshore seaweed farms. For instance EU companies investing in marine wind farms are studying the possibility to use the area restricted to boat navigation for fish farms or seaweed farms. Significant research projects on this theme have been described earlier (Reith, et al., 2005) (Buck, 2007).

Previous research in Brittany has undertaken preliminary investigations into the suitability of *Laminaria spp* for AD (Briand, et al., 1997). Japanese trials, as described earlier in the Tokyo Gas case study have demonstrated this also (Matsui, et al., 2006).

In the UK and Ireland, efforts are underway to harness the stocks of naturally available *Laminaria* for fermentation. The Supergen II[12] consortium brings together a significant body of expertise to investigate macroalgae (among other things) as a bioenergy resource. A new 4-year programme commenced in 2008 and includes a theme to evaluate marine biomass production, transport and utilisation in the UK. The Supergen project is an initiative of the Engineering and Physical Sciences Research Council in the UK. The marine biomass theme receives £0.5m of the budget to carry out an 18 month research project investigating both ethanol production from seaweed and hydro-liquefaction processes. The gut flora of seaweed-grazing sheep (from the Orkney Islands) are being investigated for their ethanol fermentation capability. It is lead by researchers at the University of Leeds, but includes the Irish Seaweed Centre (ISC) as a research partner, the Scottish Association for Marine Science (SAMS), Aberystwyth University and others.

An INTERREG IVA project is currently pending funding of up to €6m, which will see collaboration between Scottish and Irish researchers on sustainable production of algae on a large scale for biofuel production. This project is being lead by SAMS and includes the Centre for Renewable Energy at Dundalk Institute of Technology (CREDIT) and the Institute of Technology Sligo as partners.

The National University of Ireland Galway (NUIG) has a prominent role in macroalgae research in Ireland. The Martin Ryan Institute for marine research and the Irish Seaweed Centre are located at NUIG and have carried out several research projects related to the harnessing of natural algae resources, and more recently on cultivation trials. The Marine Institute has been a key supporter of this research.

Bord Iascaigh Mhara (BIM) has been a key supporter of the development of seaweed aquaculture, particularly species with potential food applications. Seaweed hatcheries have been supported in Galway, Cork and Down and grow-out trials have been funded. This is valuable experience and will form a key part of further research on seaweed aquaculture. A new three year marine research programme was given funding of €750,000 and commenced in March 2008. This is a partnership between the state sector, academics and seaweed industry groups. The main objective is the development and demonstration of viable hatchery and on-growing methodologies for seaweed species with identified commercial potential. *L. digitata* is one of the three species prioritised for this research (Edwards, et al., 2008).

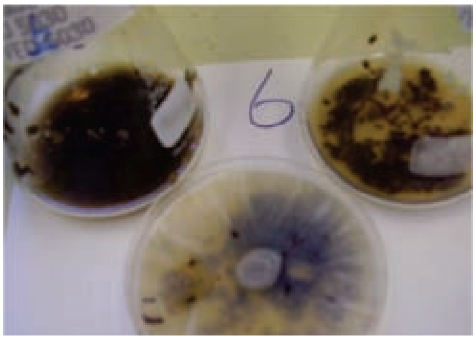

Figure 25: Enzymatic Fermentation Laboratory Trials on Macroalgae at NUIG *(AER)*

At NUIG, significant work has been undertaken on the development of enzymatic processes for the fermentation of seaweeds and other substrates. Several species of macroalgae have been tested and demonstrated technical viability for enzymatic fermentation to ethanol.

C-Mar[13] is a marine research and outreach centre within the School of Biological Sciences at the Queen's University of Belfast. C-Mar has developed hatchery and ongrowing methodologies for marine macroalgae. Other groups active in macroalgae research and demonstration include the Daithi O'Murchu Marine Research Station (DOMMRS[14]), part of University College Cork and the Institutes of Technology at Tralee, Waterford and Limerick.

There are also a range of ongoing research programmes and policy supports related to biofuels, primarily managed and funded by Sustainable Energy Ireland and the Department of Communications, Energy and Natural Resources.

[12] http://www.supergen-bioenergy.net/
[13] http://www.c-mar.eu/
[14] http://www.dommrc.com/

5.3. Microalgae Research Programmes

Due to the much larger amount of activity on microalgae, it is logical to split this section into programmes of regional relevance and a section with a more global outlook. Thus far, most activity has been concentrated outside of Ireland and even outside of regions with similar climates, due to the favourable growth conditions for microalgae in warmer climates, and also a long track-record in microalgal research and development in these regions.

5.3.1. Regional Activity

Businesses including Alternative Energy Resources (AER), Bord na Mona, Green Cell, Biodiesel Production Ireland, Bord Gais and others have indicated that they wish to demonstrate microalgae technology for biofuel production, mostly on a pilot basis at a source of CO_2.

Bord na Mona are interested in Microalgae and will be investigating options for microalgal biomass cultivation on cutaway peatlands, using freshwater species. As an operator of fossil-fuel power plants, there are opportunities to offset CO_2 emissions, and also to consider the use of algal residues either as a fuel for co-firing, or as a constituent in a range of horticultural products. The company has recently taken a decision to invest €50m in research and development over the coming five years and to setup an Innovation centre within the company with a full-time staff of 40 to pursue opportunities such as this.

AER is a biofuel company currently producing and distributing bioethanol in Ireland. They would be interested to demonstrate pilot-scale operation of a photobioreactor on an industrial site.

Green Cell, a start-up created to develop microalgal biomass opportunities, has prepared costs and a preliminary design of a photobioreactor system. They have collaborated with both the Centre for Freshwater Studies and CREDIT at Dundalk Institute of Technology.

Biodiesel Production Ireland is a supplier of biodiesel in Ireland and currently developing a production facility in Co. Louth. They are investigating microalgal oil as an alternative feedstock and as a means to utilise waste CO_2.

Figure 26:Microalgae Cultivation at C-Mar *(C-MAR)*

Other Irish research centres with existing expertise and interest in microalgae for biofuel include the Genetics and Biotechnology research group at University College Cork, the Bioresources Research Centre at University College Dublin, the Genetics Department at Trinity College Dublin, the Carbolea research group and the Industrial Biochemistry Department at the University of Limerick, among others. C-Mar, the marine research centre of Queens University have a laboratory with microalgal culturing facilities, primarily for use in bivalve mollusc farming.

The FP7 programme outlined above should directly stimulate new microalgae research projects for biofuel.

The Carbon Trust[15] in the UK has recently launched an Algae Biofuels Challenge. Concentrating primarily on microalgae, the objective of the programme is to de-risk commercial investment into large-scale algae biofuels production via a coordinated and focussed programme of research and development that will generate value for the UK. Over the next 4-6 years, Carbon Trust plans to invest several million pounds in projects to address the challenge of developing algal bioenergy systems. The initial focus of the programme is expected to be on algal screening.

There are many research centres in Northern Europe which are facing similar issues to Ireland for the viability of microalgae production – the primary concern being the productivity rates and availability of suitable strains for temperate climates. Among the researchers involved in this review, the European Algae Research Centre (CEVA), the Scottish Association for Marine Science (SAMS) and the Danish National Environmental Research Institute (NERI) are active in microalgal research for biofuel applications. Others of note encountered in this review are the Nordic Innovation Centre in Norway, the Energy Research Centre of the Netherlands (ECN) and the Alfred Wegener Institute in Germany.

5.3.2. Global Activity

Both global activity and sources of information are numerous on biofuels from microalgae. Below (Table 28) are listed some internet links with useful information on a global basis. Readers must bear in mind that

[15] http://www.carbontrust.co.uk/technology/directedresearch/algae.htm

information on these sites is not reviewed either as a scientific publication or a patent. This information evolves continuously and more data is presented on these websites than is possible to appropriately place within any one report.

Table 28: Recommended Internet Resources for Biofuel from Microalgae

http://peswiki.com/index.php/Directory:Algae
http://www.oilgae.com/
http://en.wikipedia.org/wiki/Algaculture

By pooling a combination of resources including the internet resources outlined above and the consultants' own expertise, about 30 companies were identified, mainly operating in the US, which have invested significantly in microalgae production facilities.

Table 29: List of companies having significant production plants for microalgae

Company	Location(s)	Year of Creation
IGV Institut für Getreideverarbeitung	Germany	
Algae Biofuels	USA (Az), Australia	2006
Imperium Renewables	USA	2007
Aquaflow Bionomic	USA	2007
Kent SeaTech Corp.	USA (Ca)	1972
Diversified Energy	USA (Az)	2005
Solazyme, Inc.	USA	2008
AlgaTechnologies	Israel	2006
Seambiotic	Israel	2003
Cyanotech	USA (Hawaii)	1995
FujiChemical	USA (Hawaii), Sweden	2000
Mera Pharma	USA (Hawaii)	2004
Amyris Biotech.	USA (Ca)	2008
Yamaha Motor	Japan	2007

From Table 29 above it is apparent that most production companies were created recently. The longer-established businesses generally cultivate microalgae for high-value applications. The Kent Sea Tech Corp established since 1972 is producing microalgae for fish feeding for many years. Several Hawaii based companies, Cyanotech, Mera, Fuji Chemical (Bioreal sub.) are operating microalgae production for high added value applications in cosmetics, nutraceuticals and pharmaceuticals. Some are highly specialized in astaxanthin production, such as Bioreal Inc. (belonging to Fuji Chemicals). The Natural Energy Laboratory of Hawaii Authority (NELHA) has been very active on microalgae projects for years. This partly explains the number of production companies at this location. It also demonstrates the benefits of having an algae research centre in a given country or region, and how it can stimulate innovation and investment.

Seambiotic and Algatechnology in Israel are investing heavily in development. Seambiotic activities are presented in an earlier case study. Algatechnology have set up a bioreactor culture using the clear pipe technique. They are based in a very sunny region. Pipes are simply laid out on the ground to maximize use of solar lighting. The first return on investment at their facilities is expected to be from astaxanthin production.

The Aquatic Species Programme (ASP) in the US, as earlier described, is still one of the longest-running research projects on microalgal biomass (Sheehan, et al., 1998). Although it is now closed since the early '90s, it is the precursor of much of the current activity around microalgae, and a prominent source of information and experience on microalgae. Many current developments employ former researchers of the ASP, as does the National Renewable Energy Laboratory (NREL) in the US. NREL has entered into a partnership with Chevron to develop transport biofuels from microalgae as part of a 5-year strategic alliance on biofuels research.

Newcomers are numerous. Of particular note is a large scale facility being setup in Japan by Yamaha Motor, using a closed photobioreactor system. Again the initial commercial focus is on astaxanthin production. A 37,000m^2 R&D lab has been setup.

Large petroleum industries are investing in research collaborations on microalgae biofuels. For instance Shell has announced projects with NELHA in a joint venture with HR Biopetroluem called Cellana. Construction of a demonstration facility has begun on the Kona coast of the Big Island of Hawaii. The site, leased from NELHA, is near existing commercial algae enterprises, primarily serving the pharmaceutical and nutrition industries. They plan to expand the 2.5-hectare pilot project to a 1,000-hectare facility after two years and later to a full-scale commercial 20,000-hectare plant. The facility will grow only non-modified, marine microalgae species in open-air ponds using proprietary technology. Algae strains used will be indigenous to Hawaii or approved by the Hawaii Department of Agriculture. Once the algae are harvested, the vegetable oil will be extracted. The facility's small production volumes will be used for testing.

British Petroleum has injected a large amount of money into Berkeley University for research on Biofuels. Also a co-operation between NREL and Chevron was mentioned in an earlier section.

The number of research projects and commercialisation efforts underway internationally are too numerous to mention. A synopsis, which cannot be considered complete, is listed in Table 30. The list is much longer than the previous one as many projects only started in the last few years.

Table 30: List of Companies and Institutes with R&D projects in Algae as biofuel

Company/Institute	Location
NREL	USA
Chevron	USA
C2B2	USA
A2BE Carbon Capture	USA
Inventure Chemical	USA (Co)
Aurora BioFuels Inc.	USA
Bodega Algae	USA
Kwikpower	USA (Ma)
HR Biopetroleum	USA (Ha)
Community Fuels	UK
OriginOil	USA (Ca)
PetroAlgae	USA (Nv)
Enhanced Biofuels & Technologies	USA (Az)
SeaAg Inc	USA
General Atomics	USA (Ha)
Global Green Solutions	USA (Ca)
Solix Biofuels Inc.	USA
Green Star	USA
Texas Clean Fuels	USA
Greenfuel	USA
Trident Exploration	USA
GreenShift	Canada
Valcent Products	USA
GS Cleantech	USA
XL Renewables	USA
Alganol	USA (Az)
Subitec	Germany
Ifremer (Shamash)	EU/France

5.4. Intellectual Property Status

Most of the patents filed in the '70s are now in the public domain (after 20 years have lapsed) or will be very soon. As petroleum prices decreased, projects were stopped and patents were not updated to keep Intellectual Property (IP) protection. A renewed interest in biofuel for the last few years has generated a growing interest in IP filing for alga-related projects, but it is too early to have a global picture. A search of the main patent databases has been undertaken for this study. The keywords used for searches were generic: "Algae" and "Fuel" were used though sometimes fuel was replaced by "fermentation". Where possible, the search was restricted to Claims.

The results refer to both microalgae and macroalgae. It is difficult to distinguish as the term algae is common to all the patents. It is safe to assume that the majority of recent filings are for microalgae-related applications, as the overwhelming majority of development activity is occurring in microalgal technology.

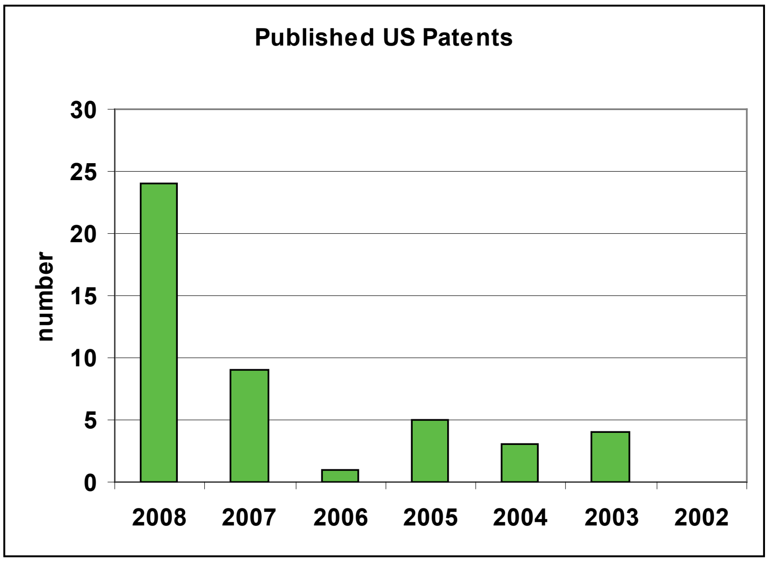

Figure 27: Number of US Patents Published Annually

A search of the US patent database indicates that there were 46 published US Patents between 2001 and 2008. Over the longer 1976 to 2008 period, 27 US Patents were granted related to algae and biofuels. The US patent publication trend is shown in Figure 27. The search only includes the first 10 months of 2008. The final number for 2008 will probably be above 30 patents. It shows the very recent interest of companies and research centres in algae-derived fuels. To cross-check the search, the term "fermentation" was used instead of "fuel". It gives approximately the same number of patents (26 granted since 1976). Appendix 1 lists the US patents granted and Appendix 2 lists published US patents.

The same search was performed on the Japanese database (PAJ). It gives 28 patents published over the period 1986 to 2008). A brief review did not show any key patents. The list of Japanese published Patents is given in Appendix 3.

The European database was searched (Espacenet) and gave no European patents published to date. In World Intellectual Property Organisation (WIPO) international patents, there are 53 patents related to Algae and Fuel. The higher number is likely to be due to an overlap between national and WIPO patents. The same publication trend is observed, with a high number of publications in 2008 and 2007.

Among the patent list WO2008/034109 was identified as a key patent for lipid conversion to biofuel. It covers both microalgae and seaweeds. It contains a lot of process innovation. The 98 claims submitted with this filing may not be all granted in final patent, but a lot of technology is disclosed which will prevent others patenting it.

Astaxanthin production using microalgae has 292 US patents published (search being restricted to claims). The worldwide market size for astaxanthin is over US$200 million. Biofuels from algae have a much larger potential market size and might generate significant patent potential.

There is poor visibility on actual patents filed but not published. Large well-funded companies are entering the biofuel sector. They have proprietary knowledge and the capacity to file a wide number of patents in a short time frame. This may pose a problem for smaller investors and for research projects.

6. R&D Knowledge Gaps

There are many issues which have to be studied and solved for progress to be made in obtaining biofuels from marine algae on a commercial scale. Most of these are common to all countries but there are additional questions to be asked and answered regionally and nationally. For this reason, a summary of research areas through the supply-chain is given, followed by specific topics relevant to Ireland.

6.1. Macroalgae

6.1.1. Biomass Generation

For seaweed biomass generation, an important area is the selection of best species and strains to optimise growth rates, biomass yield and quality of fuels. Compared to terrestrial crops, selection processes have not yet been well developed for seaweeds. In Northern Europe it is currently *Laminaria* and *Ulva* species that are being investigated.

Up to now the main focus has been biogas yields in most demonstration activities but the attractions of generating ethanol for transport fuel purposes has lead to strong interest in species of seaweed containing elevated levels of starch or similar polysaccharides suitable for fermentation to ethanol. This is the object of research projects in Denmark which will concentrate on the green alga *Ulva lactuca*. Researchers have also demonstrated ethanol fermentation from *Laminaria spp.* (Horn, et al., 2000).

Genetic Modification (GM) is an option that could be used to produce strains yielding enhanced levels of easily fermentable polysaccharides in seaweed. However, applying this technology to marine plants is likely to be controversial in many countries and may only be pursued after thorough consideration of the environmental and political consequences.

If offshore cultivation is to be developed, infrastructure design in difficult environmental conditions must be improved. Locations exposed to seasonal storms require specific engineering to avoid loss or damage of material and structures. There have been several reports of whole seaweed farms being swept away after years of operation and major investments (Chynoweth, 2002).

Substantial variations have been reported in the chemical composition of biomass from the same species grown in different locations at varying times of the year under variable saline, current and temperature conditions. The reasons for this are not well understood in many cases. In an energy context it would be desirable to explore the factors that determine the relative levels of carbohydrates and to find ways of maximising the amounts of readily fermentable sugar molecules.

Site trials in Northwest Europe with relevant species to instil confidence and provide real data for the development of an industry would be important. Sites should ideally address both the nearshore and offshore cultivation and engineering challenges.

Technology transfer from Japan, China, Korea and the U.S is a potential starting point for any cultivation trials. However the methods used in Asia are labour-intensive and unlikely to be economical in Europe. Mechanized cultivation and harvesting techniques would need to be developed in order to decrease the cost of seaweed biomass.

Solutions are required for nutrient supply at large-scale production facilities. The most innovative approach to this problem has been the 'up-welling' one developed in both Japan and the USA in which seawater is pumped upwards from the lower depths of the ocean to provide nutrients. The practice of spraying nitrogen solution is both expensive and unsustainable. Others have considered the development of techniques for precision-application of nutrients, which would be less wasteful.

The integration with suitable enterprises at coastal locations could bring economies of scale, synergies, sharing infrastructure and transport and energy costs, and bioremediation benefits to estuarine areas experiencing eutrophication. Finfish aquaculture enterprises in particular generate surplus nitrogen which could be taken up by seaweed aquaculture.

Recycling residues from the fermentation of seaweed, to use as nutrients for seaweed growth would need further research.

6.1.2. Harvesting and Pre-treatment

Collection, storage and distribution systems need to be considered in detail and with reference to legislation. The high moisture content in seaweed is a major obstacle to centralised processing, as it contains up to 90% water at harvest. Some level of dewatering may be achieved mechanically, or through natural drying. Systems which require thermal heat for drying should not be prioritised, unless a positive energy balance can be demonstrated. Consideration would have to be given to the optimum scale for downstream processes, and whether seaweed could be combined with other resources to achieve economic efficiency.

Chemical or enzymatic pre-treatment is required to maximize seaweed fermentation. This is largely a process issue, but the option to commence the process at harvest or shortly after could improve yields. For example, it has been reported that storage of *Ulva* biomass at 4°C for four weeks led to an increase of 45% in downstream biogas yields. In this case no enzymes were applied. The improvement is most likely due to natural hydrolysis of the *Ulva*.

In the case of *Laminaria spp.,* hydrolysis of alginate gives low molecular weight compounds and oligosaccharides accessible to fermentation. Alginate lyase pre-treatment, or chemical hydrolysis of the alginate merit further investigation.

There are a number of cell disruption techniques used in the bioprocessing of terrestrial plant materials which may have application for macroalgae e.g. ultrasonics, Microwaves and fine milling or homogenisation. Other methods under development include pressure changes to cause the material to rupture.

6.1.3. Down-stream Processing

6.1.3.1. Ethanol fermentation

The selection of industrial microbial strains isolated from or adapted to the marine environment would be a key step towards fermentation of seaweed with commercial yields. Commercial enzymes such as amylases, cellulases and proteases are available, but they are more efficient in depolymerising polysaccharides from terrestrial sources. A number of research laboratories such as those at SAMS in Scotland, CEVA in France, and indeed NUIG in Ireland, are building up libraries of marine bacteria from which commercial alginate lyases[16] may be developed during the next decade.

Recently a single step process was demonstrated to convert both mannitol and laminaran (polysaccharides in brown seaweeds) into ethanol (Horn, et al., 2000). An yeast (*Pichia angophorea)* and a bacterium (*Zymobacter)* are capable of this conversion in salty environmental conditions. However these micro-organisms are not marine organisms. The search through library collections for appropriate marine organisms from either mutant or wild type selection could be included in marine biodiscovery programmes.

The polyphenols in brown seaweeds are another challenging issue which needs solving. They are the main inhibitors of the fermentation processes for both ethanol and biogas production. In the alginate industry they are removed by precipitation using formaldehyde before the alginate is extracted. This chemical is known to be carcinogenic so the search for suitable alternatives has been ongoing. For biofuel production from seaweeds it is necessary to remove or deactivate these chemicals. There is a potential market for polyphenols if they are extracted from seaweed prior to fermentation.

In particular it should be noted that the competitiveness of algal biomass for hydrolysis and subsequent fermentation must be viewed in the context of other available cellulosic biomass such as wood, straw and dry organic waste.

6.1.3.2. Biogas Fermentation

For most biogas fermentations, the natural microbial bacteria of seaweed are the fermentation agents. Selection of specific microbial strains may bring less variability and higher yields, particularly where marine origin material is concerned.

Whilst seaweed anaerobic digestion trials have been carried out in Japan, trials in Europe so far have been inconclusive on *Laminaria spp*. Yields of *Laminaria spp* grown in Europe and in Ireland would need to be demonstrated, as composition varies with location, season and other variables. The co-digestion of seaweed with other substrates could be demonstrated and its impact on the process assessed. Integration with other substrates is important due to the limited and seasonal availability of brown seaweeds. It would also be of benefit for using macroalgae resources if small-scale cost-effective anaerobic digestion methods and equipment are further developed.

Previous experiments have shown that green seaweeds generate large amount of H_2S, which reduces biogas production and creates safety issues (Briand, et al., 1997). Similar problems occur from time to time in waste-water treatment. Iron-based chemicals are used to fix the H_2S. The same technology is potentially applicable to biogas.

[16] A lyase is an enzyme that catalyzes the breaking of various chemical bonds by means other than hydrolysis and oxidation

6.1.3.3. Thermal Processes

Combustion processes involving seaweed are inherently uneconomic because of the energy required to dry the seaweed and the high ash content. Research based upon thermal processes is unlikely to yield a viable energy solution. Nonetheless research is ongoing into gasification, pyrolysis and other thermal processes for processing a wide range of biomass including seaweed.

Hydroliquefaction involves the transformation of biomass to liquid fuels using high temperature and pressure. This area is being researched for seaweed species as part of the Supergen II project (See section on commercial and research activities, page 58) by researchers at Leeds University. Again, there are concerns about the energy balance of such a process, but the research activity could be useful for other biomass materials with lower moisture content.

6.1.3.4. Management of Residues

Management of residues is a common theme for all processing of algae. The option of disposal in landfill or at sea which has been the practice up to recently is not sustainable.

An area which could be considered is the combination of residues with other material (e.g. peat, pine bark) to obtain 'designer' composts. This could be used as added-value disease suppressive composts in large quantities for use in horticulture. Seaweed residues present opportunities to find alternatives to synthetic fungicides. A range of biocontrol products have been developed by e.g. Goemar, in St Malo, France.

Mixing residues with a low moisture content material such as sawdust could be studied for the manufacture of fuel briquettes - crude alginate was used as a binding agent for this purpose in Scotland in the 1950s (for combination with coal dust) and patented by Cyril Bonicksen who set up a company which later became Alginate Industries Ltd, Girvan.

The recovery of nutrients from seaweed residues for cultivation of seaweed could be investigated. This may present a 'closed-loop' in terms of nutrient life cycle.

6.1.3.5. Biorefinery and Integrated Manufacturing

The biorefinery approach may have limited prospects in processing brown seaweeds for biofuel production as there is a large market for only one high value component (alginate) and a part of Ireland's seaweed biomass would on its own supply the world market. There is no alginate manufacturing plant in Ireland but there are a few small companies producing liquid extracts with waste streams similar to those arising from the alginate process. The feasibility of fermenting waste solids and liquors from seaweed processing plants to generate biogas on site is worth studying.

It is possible to separate a number of high value by-products from the Alginate process which are outlined below with some comment as to the relative markets and scale.

For production of Fucoidan, several papers and patents have been published over the past five years with two significant manufacturers (Marinova in Tasmania and UBE in Japan). It is too soon to gauge world market figures but total production is still less than 1,000 tonnes. Potential applications as food ingredients, nutraceuticals, pharmaceuticals, anti-oxidant and skin lightening agents in cosmetics are interesting prospects but even if fucoidan becomes the next omega-3 or aloe vera the quantities of such a high value product which could be marketed are modest. The fucoidan content is c. 3 to 7% by dry weight.

Laminaran has one commercial application at present - as an inoculant for crop disease prevention (Goemar, St Malo, France) but the total market size is small. Polyphenols have several potential niche applications e.g. as anti-oxidants, anti–ageing, free radical scavengers, sunscreens etc. Integrated extraction/separation processes for polyphenols, fucoidan, laminaran and alginate have been patented for lab scale studies but have not been scaled up for commercial production (WO/2005/014657, 2005).

Other possibilities include pigments, iodine etc., but as of now there are no obvious commercial opportunities on the horizon for large markets for any of these materials.

As oil resources become restricted, the platform chemicals obtained from petroleum will need to be replaced by alternative basic chemicals derived from terrestrial and marine plants. In addition to ethanol, a range of other chemicals, such as lactic acid, propionic acid, acetic acid, citric acid, 2-3 butane-diol, succinic acid, adipine acid and butanol can be derived from biomass. This topic is considered further in a Dutch research report (Reith, et al., 2005). Both fresh seaweed and fermentation residues are potential raw materials for these platform chemicals.

6.1.4. Macroalgae Knowledge Gaps for Ireland

In an optimistic scenario developed for the purposes of this report 447 TJ or about 0.2% of Irelands current road fuel needs may come from macroalgae by 2020 (See Table 24). It is clear that the main focus concerning macroalgae utilisation for energy in the short term should be research and development.

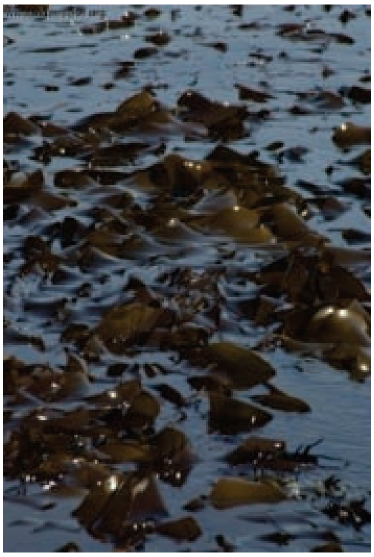

Figure 28: Naturally occurring L. digitata *(M Guiry/Algaebase)*

A longer-term potential may exist for macroalgae to make a significant energy contribution, particularly with development of aquaculture. The 2020 estimates developed for the purposes of this report are not very accurate, based as they are on a paucity of real production data.

Arramara Teoranta was set up as a semi-state company in 1947 to develop seaweed products from natural resources. It is currently harvesting almost exclusively *Ascophyllum* species. A strategic review is currently underway, and this could present an opportunity to re-orient the company towards more advanced biotechnology, a greater diversity of seaweed resources, and in particular to focus on new opportunities such as the energy sector.

The focus hitherto of most commercial and research activity in Ireland has been on seaweeds for human consumption and as plant nutrients. For development of biofuels, new research would need to be initiated with a focus on *Laminaria* and *Ulva* species as raw materials.

The accuracy of estimates of standing kelp stocks are poor, and based on short surveys in Galway Bay. More detailed survey work would be required to establish the level of existing stocks and the appropriate quantity that could be sustainably harvested.

Advanced survey techniques could be developed and employed to provide more robust data, and to survey large areas in a short time period.

The impact of mechanical harvesting of natural stocks would need to be assessed to understand any environmental impact of introducing this process.

Figure 29: Establishment of L. digitata Gametophytes at MRI Carna *(M Edwards)*

In light of the substantial but ultimately limited natural stocks, aquaculture of seaweeds could be a research topic. In particular the feasibility of both nearshore and offshore aquaculture could be revisited with a view to large scale production of *Laminaria spp*. Previous trials have concentrated on *Ascophyllum* and various edible seaweeds. An optimistic scenario developed for the purposes of this report of 700 ha of seaweed cultivation has been hypothesised in this analysis for 2020 (to include offshore cultivation trials). Significant research break-throughs in the technology and costs associated with seaweed aquaculture would be required.

Industrial yields of *Laminaria spp* have not been demonstrated. Trials on a scale of hectares need to harness international best practice in aquaculture. China in particular has achieved yields from *Laminaria spp* of typically 20 dry t/ha and optimally about 35 dry t/ha. Mechanisation would need to be introduced due to the high cost of labour in Ireland. Research to demonstrate sustainable yields of *Laminaria spp* cultivation in Ireland is required.

Laminaria aquaculture could also be an opportunity to demonstrate integration with other enterprises, such as marine enterprises (finfish aquaculture), food processing, waste treatment plants or other sources of waste nutrient supply.

Ireland has unique offshore marine experience. Offshore finfish aquaculture has been pioneered in Ireland and indeed Ireland is at the centre of international developments in ocean energy either through wave or tidal energy systems or through the development of offshore windfarms. This experience may be harnessed and put to good use in development of offshore aquaculture solutions.

Cast seaweed is not well quantified. Coastal local authorities could be surveyed to assess the species, quantity and disposal methods and seasonal availability of the resource.

The Environment and Heritage Service in Northern Ireland have produced a position statement on environmentally sustainable seaweed harvesting, on foot of a stakeholder consultation. This considers the valuable role played by natural and cast seaweed in the ecosystem. A similar exercise in the Republic of Ireland might provide some additional insights concerning the exploitation of seaweed resources.

In terms of downstream processing, anaerobic digestion of seaweeds is the most realistic commercial activity in the short term. Trials could be encouraged, ideally in existing anaerobic digestion facilities, to demonstrate the concept and gain operational data on seaweed supply.

Logistics is a key consideration, due to the geographically disperse location of the resource. The identification of resource clusters, possibly for integration with other biomass for processing could be undertaken. Ideally a project could be located to take advantage of natural, cultivated and cast seaweed.

Substantial research (at NUIG) has been carried out on enzymatic fermentation of seaweed to produce ethanol. The possibility of isolating marine lyases for the breakdown of marine biomass is a future area of research.

It should be hoped that many of these issues will not be solved in isolation, as many other countries with similar climate and seaweed resources are motivated to resolve the same barriers to commercialisation. Support could be given to those engaging in collaborative research efforts, and sharing best-practice with researchers in other countries. Several of the international research programmes and commercial projects have been outlined earlier.

6.2. Microalgae

For microalgae the key research issues are identified here, again following the supply-chain concept outlined earlier. The knowledge gaps for Ireland will be discussed at the end of the section.

6.2.1. Biomass Generation

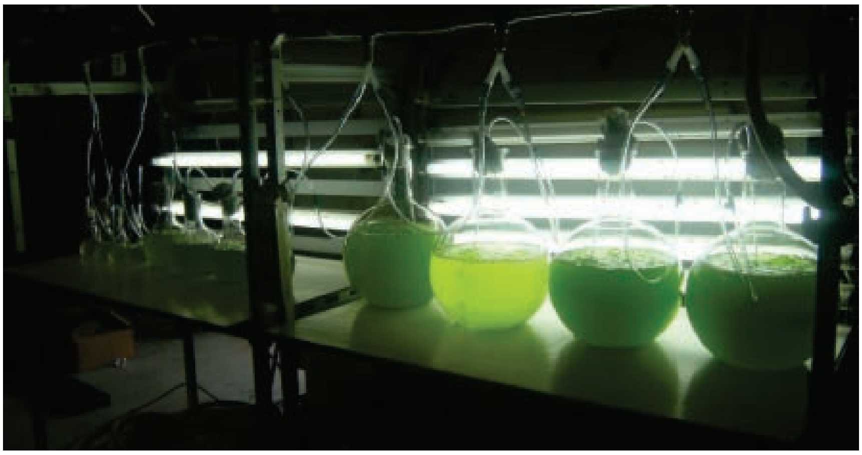

Figure 30: Laboratory Scale Cultivation of Microalgae at CEVA *(BioXL)*

The selection of strains having high growth rate and high chemical yield is an important area of research. It is a significant task because of the very large number of microalgae to be considered but progress to date has shown promising lipid yields and other desirable characteristics. The desired chemicals in current projects are lipids for conversion to biodiesel and although this will continue to be the case for the near future it is possible that strains which produce ethanol, butanol, methane and other hydrocarbons including hydrogen will receive increased attention in the longer term. This could also open up a wider variety of strains to investigation, which may yield results across diverse climatic zones.

Up to now the emphasis has been on strains suitable for cultivation at low latitude and elevated temperatures – e.g. Israel, Hawaii and Southern California. For regions at higher latitude, it would be critical to identify local strains requiring low light intensities and lower water temperatures but giving satisfactory growth rates and yields.

Species selection programmes are ongoing in all research organizations having strain libraries. These high cost research projects have to be supported by a viable industrial application. For instance astaxanthin production was reported in almost 20 species of microalgae, supported by real laboratory work. Only one species (*Haematococcus)* is currently used in industrial applications to produce astaxanthin.

A research area would be to identify the most suitable cultivation system: raceway, photobioreactor, or a combination? The relative merits of these options were discussed earlier. Scientific opinion is divided as to the most appropriate system. As further research is carried out there may be some significant developments which will favour one system over another. New designs and improvements in operations may result in increased efficiencies. This research area is heavily funded (outside Ireland) at present and is generating a large proportion of the publications over the past three years.

The key barrier to be addressed is the cost gap between current practice and what is required for biofuel production. Data reviewed here indicates that a five-fold cost reduction is needed, coupled with a productivity goal of 35 dry t/ha/yr for the Irish climate.

Key considerations, outside of the economics of biomass production, are both the embodied energy in any infrastructure developed and also the ongoing energy and raw materials needed for operations. Some laboratory based analysis has shown a negative life-cycle energy balance for pilot-scale photobioreactors (Tredici, et al., 2008).

Optimising stress conditions to obtain the highest possible yields of lipids in the cells is important. There is scope for additional research leading to further increases in yields.

Stimulated evolution is another option commonly used for bacteria. Stress conditions can induce spontaneous mutation in cultivated strains. Selection of these natural mutants can improve production yields. Another option is to select wild local species that are already adapted to local growth conditions.

Genetic modification (GM) is another option to improve production efficiency. One current example is the Algenol Company which is developing a strain of GM cyanobacteria capable of producing ethanol. The microalga was designed in Canada and the production site is operating in Mexico. Above a given temperature, ethanol is secreted by the alga, directly linked to the photosynthesis mechanism. This skips the normal metabolism process, so growth rate is impacted during this phase. Below the trigger temperature, the ethanol secretion is turned off so normal photosynthetic growth can start again.

For large-scale production systems, nutrient sources, especially phosphate, would be critical as is the case for seaweeds. Similar options will continue to be explored, such as options for recycling of nutrients from alga-processing residues, or harnessing nutrients in waste-water from another source. In all cases, the ability to harness freely available or naturally present nutrients could be explored in order to minimise both costs and the environmental impact of biomass production.

6.2.2. Harvesting and Pre-treatment

Improved harvesting technologies are needed. The solution may lie in adapting and refining separation technologies already being used in the food, biopharmaceutical and waste water treatment sectors.

Lipid extraction prior to esterification is an area for further research. It would be an important advance if methods of avoiding drying or solvent extraction of the algae slurry could be developed as it would significantly reduce the cost of biomass pre-treatment. This could be overcome if water-tolerant downstream processes are developed.

6.2.3. Downstream Processing

Research areas for commercialising downstream processes for biofuel from microalgae are identified here.

6.2.3.1. Biodiesel Esterification

Using existing biodiesel production processes requires a lipid material free of both water and free fatty acids. This leads to high processing costs to dry the microalgae material. Alternative esterification processes are being investigated using the acidic reaction route or enzymatic reactions. However they are still at the research stage.

Enzymatic esterification with lipases may be worth pursuing as it has the added advantage of running at low temperatures (60°C). A key problem with this process is that esterification generates a glycerol by-product which inhibits lipases. Studies are running with methylacetate as a substrate which avoids glycerol formation and lipase inhibition.

Management of unsaturated fatty acids which can be present in large quantities in microalgae requires further investigation. These fatty acids will reduce esterification yield. Technologies such as catalytic hydrogenation used in the food industry could be adapted to provide solutions. Certain polyunsaturated fatty acids (PUFA's) are a potentially valuable nutritional by-product of biofuel processing of microalgae. If new markets could be developed through extraction of PUFA's while simultaneously improving biodiesel yields, the process economics could improve.

6.2.3.2. Biogas fermentation

It is a good idea not to focus efforts entirely on lipid-producing strains and processes. Microalgal biomass is a potentially valuable fermentation substrate, and to concentrate on lipids only will exclude the majority of microalgal species. Concerning the fermentation process, similar issues will need to be addressed as for macroalgae to determine the inhibitory factors and both optimise species selection and make adjustments to the process for fermentation.

6.2.3.3. Biorefinery and Integrated Manufacturing

The most obvious opportunity for integrated manufacturing is by production of algae at a power-plant, in order to take advantage of waste CO_2 and possibly also waste heat. Much work needs to be done to demonstrate this concept successfully. The issues to be resolved include identifying any flue-stack emissions properties (or those from any particular industries or fuel) which might inhibit algae growth or affect downstream properties. It is already known for example that SO_2-scrubbing is a prerequisite. Systems to verify the quantity of recycled CO_2 need to be developed. The environmental compliance requirements of this process need to be well understood.

As outlined previously, there are many potential high-value products that could be co-produced with biofuel from microalgae. Proteins, pigments, cosmetics, nutraceuticals are all possibilities. The most suitable products for co-production need to be identified. PUFA's in particular seem promising. For non-fuel markets, especially human or animal consumption, regulatory compliance needs to be fully considered, especially if flue-gas emissions are introduced in the supply chain. Market scale must be considered as there is a mismatch in scale between bulk commodities such as biofuel and niche high-value products.

The biorefinery concept minimises residues, but what remains could be considered as a fermentation substrate. Also the possibility for nutrient recycling could be developed. The integration of microalgae cultivation with, for example, fish-farms, food processing facilities, waste water treatment plants etc., offers the possibility for both remediation and low-cost nutrient supply. These options could all be explored as part of an integrated biorefinery concept.

6.2.3.4. Other processes

Several projects are investigating the use of microalgae in direct hydrogen generation. The fermentation route is also being investigated, as anaerobic digestion can also generate hydrogen. Compared to the more conventional routes being considered (biodiesel, biogas and bioethanol) this technology is at present far from commercial application.

Other routes to renewable fuel generation exist for microalgae. Some species are able to synthesize hydrocarbons that could be used as a new petroleum source in the fuel industry. This has been extensively studied for *Botyrococcus braunii*. Hydrocarbons synthesized have the advantage of being extra-cellular, and therefore easily separated. Performances are not yet viable for industrial applications, but the technology is promising.

6.2.4. Microalgae knowledge gaps for Ireland

From an energy perspective, very similar conclusions can be made as for macroalgae resources. In an optimistic scenario developed for the purposes of this report as outlined earlier, only 79 TJ of energy would come from microalgae resources by 2020. In the context of a 22,000 TJ target by 2020 this is small. Other non-quantifiable and non-energy related opportunities could be considered in setting a research agenda for microalgae.

The most pressing issue to resolve is whether the Irish climate can support viable production of microalgae for biofuel. The elevated latitude, relatively low water and air temperatures and solar irradiation raise legitimate concerns that microalgae should best be cultivated at lower latitudes. Expectations should be modest unless these concerns are addressed.

This is a problem for other regional climates – researchers in Germany, Norway, Denmark, Holland, France and the UK have all given some consideration to the matter and none have succeeded in demonstrating significant yields without artificial light and/or heat.

Researchers in Ireland should screen their own strain collections in order to identify natural species that may be productive in this climate. This should ideally be done as part of a co-ordinated effort with other centres holding significant strain libraries.

Despite the advantages of marine species, the scope of any research activities should best be widened beyond the marine environment. This will achieve a few objectives. It will widen the number of potential strains, and increase the probability of finding one with suitable characteristics. It is also apparent from stakeholder consultations that freshwater species should be included. Bord na Mona in particular is interested in microalgae opportunities located in cut-away peat bogs. Other researchers also include freshwater strains within their objectives.

Although one of the primary objectives of screening should be to identify strains which can produce lipids reliably and at elevated levels, the opportunity to use the non-lipid material should not be ignored. Again this will widen the potential suitable strains for energy end-use which may be adapted to the Irish climate.

Stakeholders in Ireland have indicated a desire to pilot photobioreactor technology, usually at a power plant or close to some other source of CO_2. There is clear industry-led demand for this kind of research, and it would be beneficial for the development of microalgal technology in Ireland. It may also inform future R&D topics as there is a lack of quality information available on microalgal cultivation in temperate climates.

Downstream processing requirements should be considered in any strain selection programme. Efficiencies from integration with other enterprises should be considered even in trials, where the most obvious integration opportunity is with industrial CO_2 sources. Also the opportunity to extract other high value products should be actively considered in the design of any energy process.

Many other countries with similar climates to Ireland are motivated to resolve the same barriers to commercialisation. Support could be given to those engaging in collaborative research efforts and sharing best-practice with researchers in other countries. Several of the international research programmes and commercial projects have been outlined earlier.

An attempt has been made here to highlight issues of direct relevance to Ireland and to determine appropriate research themes in an Irish context. This should not preclude Irish researchers from attempting to address the very substantial research challenges faced by the industry on a global basis and outlined earlier in this section.

7. Conclusions

7.1. General

- The focus of activity until 2020 at least is likely to remain in the research or demonstration domain.
- It is worth exploring the energy potential of both macroalgae and microalgae. It is however difficult to understand the high levels of commercial activity and investment in marine algae at present as a biofuel resource, in light of the research advances still required.
- The interest for non-energy products such as nutraceuticals, pigments, proteins, functional foods and other chemical constituents is currently commercially more important than energy.
- The non-energy benefits, the opportunities for intellectual property development, for spin-off technology, jobs creation and export potential could also be considered in any follow-on activity.
- For both microalgae and macroalgae, exploitation of the resource need not be restricted to the marine environment. There are many freshwater opportunities which could be pursued.
- The biorefinery concept's main challenge is that demand for all co-products is very small compared with biofuel process scale requirements. The fundamental economics of the biofuel feedstock need to improve and cannot rely on niche co-products to subsidise them.
- In addition to the technical barriers and knowledge gaps identified in this report, there are many policy issues which could affect the development of algal biomass resources.
- There are several existing research programmes identified within the report for which algae as a biofuel feedstock could be a good complement.
- There is a need to further develop research capacity and competence in order to fully explore the opportunities presented by both microalgae and macroalgae.
- Other countries in north-west Europe face similar challenges throughout the supply chain and collaborative research internationally and domestically could be encouraged.

7.2. Macroalgae

- The exploitation of the natural resource is likely to remain constrained due to environmental concerns. Ultimately cultivation may present the greater long-term potential.
- For seaweed aquaculture, competition for space with other marine industries, protected conservation areas and other designated land-uses must be taken into account.
- The significant contribution of macroalgae in supporting marine biodiversity needs to be recognised. For mechanised harvesting, long term trials and careful monitoring of seaweed stocks, the surrounding ecosystem and the environmental consequences would be required.
- Laminaria spp and Ulva spp are the most interesting prospects from an energy perspective. The five kelp species which are native to Ireland are Laminaria digitata, L. hyperborea, Saccharina latissima, Sacchorhiza polyschides and Alaria esculenta.
- Anaerobic digestion is the most likely initial application for seaweeds, though alcoholic fermentation is a likely application if suitable marine lyases are isolated or organisms which can directly ferment algal polysaccharides are identified.
- Costs for seaweed cultivation need to reduce by at least 75% in order to make anaerobic digestion of cultivated seaweed of commercial interest.
- The competitiveness of seaweed for alcohol fermentation must be viewed in the context of other available cellulosic biomass such as wood, straw and dry organic waste.
- For the purposes of this report it was optimistically estimated that up to 447 TJ of energy could be generated from macroalgae by 2020. This is about 0.2% of current national road-fuel demands.
- There is a lack of data available for Laminaria cultivation in Europe.
- There are offshore marine activities underway in Ireland which present opportunities for integration with seaweed aquaculture. Offshore engineering solutions for seaweed aquaculture could be explored in any future research programmes.

7.3. Microalgae

- A review of the literature would indicate that assigning or predicting productivity rates for the Irish climate is not possible with any accuracy, as there is a lack of reliable trial data in Irish or comparable climates. Clearly the biggest unknown is whether it is possible to achieve reasonable productivity in view of prevailing natural light and temperatures.
- The limits of microalgae photosynthetic efficiency could be pushed out to somewhere between 3 and 6%. An absolute maximum theoretical efficiency of 6% is unlikely to ever be attained under real conditions.
- Current cultivation costs only justify extraction of high-value niche components. A cost reduction of at least a factor of five is necessary to make microalgae attractive for their lipid content.
- It is not possible to identify appropriate species for Ireland without a rigorous screening programme using genetic selection criteria. There are over 30,000 known species worldwide.
- The main focus of screening is currently on lipid productivity. Fermentation options should not be ignored, especially where growth is restricted by climate.
- Only a handful of species are of commercial value presently.
- There is no consensus concerning optimum systems for microalgae cultivation. Stakeholders from all communities will disagree over whether open or closed or some combination of cultivation systems is most favourable.
- Industrial stakeholders would like to participate in pilot production trials.
- Productivity claims for microalgae systems are often overstated. Based on the fundamentals of photosynthesis, anything above 53 t/ha/yr of dry biomass in the Irish climate should be treated with caution.
- For the purposes of this report, it was optimistically estimated that about 79 TJ could come from microalgae resources by 2020. This is a fraction of 1% of national road-fuel demand.

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9. Appendices

9.1. Appendix 1 : Patent list: US Patents Granted

(Terms “Algae” AND “Fuel” in Claims)

1 7,422,816 Fuel cell system

2 7,191,597 Hybrid generation with alternative fuel sources

3 7,101,410 Method for the microbiological desulfurization of fossil fuels

4 7,029,506 Organic cetane improver

5 6,986,323 Inland aquaculture of marine life using water from a saline aquifer

6 6,702,948 Mobile diesel fuel enhancement unit and method

7 6,676,954 Controlled release compositions

8 6,610,282 Polymeric controlled release compositions

9 6,569,332 Integrated anaerobic digester system

10 6,299,774 Anaerobic digester system

11 6,221,374 Controlled release compositions

12 6,149,927 Solid biocidal compositions

13 6,100,600 Maritime power plant system with processes for producing, storing and consuming regenerative energy

14 6,030,536 Disposal method for fuel oil and crude oil spills

15 5,659,977 Integrated microalgae production and electricity cogeneration

16 5,614,097 Compositions and method of use of constructed microbial mats

17 5,558,783 Supercritical oxidation reactor

18 5,551,956 Superheavy oil emulsion fuel and method for generating deteriorated oil-in-water superheavy oil emulsion fuel

19 5,219,875 Antimicrobial compositions comprising iodopropargyl butylcarbamate and 1,2-benzisothiazolin-3-one and methods of controlling microbes

20 5,160,526 Alkene stabilizers for 3-isothiazolone compounds

21 5,156,665 Antimicrobial compositions comprising iodopropargyl compounds and isothiazolones and methods of controlling microbes

22 5,127,934 Stabilized compositions comprising isothiazolones and epoxides

23 5,110,822 Synergistic combinations of 4,5-dichloro-2-n-octyl-3-isothiazolone or 2-methyl-3-isothiazolone with ferric dimethyl dithiocarbamate fungicide

24 5,049,677 Bismuth salt stabilizers for 3-isothiazolones

25 4,954,338 Microbicidal microemulsion

26 4,910,912 Aquaculture in nonconvective solar ponds

27 4,589,925 Methods for cleaning materials

28 4,368,056 Diesel fuel by fermentation of wastes

9.2. Appendix 2: Patent List: US Patents Published

(Terms “Algae” AND “Fuel” in Claims)

1. 20080268302 ENERGY PRODUCTION SYSTEMS AND METHODS

2. 20080257781 METHOD OF MANUFACTURING ALCOHOL ESTERS FROM TRIGLYCERIDES AND ALCOHOLS USING HETEROGENEOUS CATALYSTS BASED ON PHOSPHATE OR AN ORGANOPHOSPHOROUS COMPOUND OF A GROUP 4 METAL

3. 20080250715 Process and apparatus for carbon capture and elimination of multi-pollutants in fuel gas from hydrocarbon fuel sources and recovery of multiple by-products

4. 20080228542 Method and apparatus for cultured sea algae

5. 20080190024 SYSTEM AND METHOD FOR PRODUCING SUBSTITTUE NATURAL GAS FROM COAL

6. 20080182325 SYSTEM INCLUDING A TUNABLE LIGHT AND METHOD FOR USING SAME

7. 20080176304 Designer Organisms for photosynthetic production of ethanol from carbon dioxide and water

8. 20080176303 Farm Scale Ethanol Plant

9. 20080155985 Heat Energy Recapture And Recycle And Its New Applications

10. 20080155888 Methods and compositions for production and purification of biofuel from plants and microalgae

11. 20080149550 Filter fuel assembly

12. 20080135475 System and Method for Biological Wastewater Treatment and for Using the Byproduct Thereof

13. 20080135474 System and Method for Biological Wastewater Treatment and for Using the Byproduct Thereof

14. 20080135457 Method and apparatus for recovering oil from oil shale without environmental impacts

15. 20080131958 Energy production with hyperthermophilic organisms

16. 20080118964 Continuous-Batch Hybrid Process for Production of Oil and Other Useful Products from Photosynthetic Microbes

17. 20080102503 SYSTEMS AND PROCESSES FOR CELLULOSIC ETHANOL PRODUCTION

18. 20080052987 Hydroponic Growing Enclosure and Method for Growing, Harvesting, Processing and Distributing Algae, Related Microrganisms and their By Products

19. 20080052983 OPTIMAL ENERGY PATHWAY TO RENEWABLE DOMESTIC AND OTHER FUELS

20. 20080050800 METHOD AND APPARATUS FOR A MULTI-SYSTEM BIOENERGY FACILITY

21. 20080034645 METHODS FOR PRODUCING FUELS AND SOLVENTS

22. 20080028671 Alternative organic fuel formulations including vegetable oil and petroleum diesel

23. 20080022584 Alternative organic fuel formulations including vegetable oil

24. 20080009055 Integrated photobioreactor-based pollution mitigation and oil extraction processes and systems

25. 20070227493 INJECTOR-IGNITION FOR AN INTERNAL COMBUSTION ENGINE

26. 20070196892 METHOD OF CONVERTING A FERMENTATION BYPRODUCT INTO OXYGEN AND BIOMASS AND RELATED SYSTEMS

27. 20070178569 Systems and methods for producing biofuels and related materials

28. 20070157614 Hybrid Generation with Alternative Fuel Sources

29. 20070114476 Low radiocarbon nucleotide and amino acid dietary supplements

30. 20070113467 BIODIESEL FUEL COMPOSITIONS HAVING INCREASED OXIDATIVE STABILITY

31. 20070104761 Low radiocarbon nucleotide and amino acid dietary supplements

32. 20070017864 Process and system for converting biomass materials into energy to power marine vessels

33. 20070012041 HYBRID GENERATION WITH ALTERNATIVE FUEL SOURCES

34. 20060008868 Production method of biochemical coal

35. 20050260553 Photobioreactor and process for biomass production and mitigation of pollutants in flue gases

36. 20050244701 Fuel cell system

37. 20050239182 Synthetic and biologically-derived products produced using biomass produced by photobioreactors configured for mitigation of pollutants in flue gases

38. 20050120715 Heat energy recapture and recycle and its new applications

39. 20050064577 Hydrogen production with photosynthetic organisms and from biomass derived therefrom

40. 20040168648 Inland aquaculture of marine life using water from a saline aquifer

41. 20040144338 Low emission energy source

42. 20040040913 MOBILE DIESEL FUEL ENHANCEMENT UNIT AND METHOD

43. 20020100836 Hydrogen and oxygen battery, or hudrogen and oxygen to fire a combustion engine and/or for commerce.

44. 20020079266 Integrated anaerobic digester system

45. 20020014178 Biocide compositions and methods and systems employing same

46. 20020001618 Controlled release compositions

9.3. Appendix 3: Patent List: Japanese Patents Published

(From PAJ, Algae AND Fuel in Text)

1. 2008 - 011721 METHOD FOR PRODUCING BIOMASS FUEL, AND METHOD FOR PRODUCING SUPERHEATED-STEAM PROCESSED PRODUCT

2. 2006 - 204264 LARGE-SCALE CO2 REDUCTION SYSTEM USING MARINE BIOMASS

3. 2006 - 147348 FUEL CELL POWER GENERATION DEVICE AND WATER QUALITY CONTROL METHOD OF THE SAME

4. 2006 - 141385 SHELLFISH ADHESION-INHIBITING ADDITIONAL LIQUID

5. 2006 - 061071 METHOD AND APPARATUS FOR PREVENTING ATTACHMENT OF SHELLFISHES, ALGAE, OR THE LIKE

6. 2004 - 123820 BIOMASS CONVERTIBLE GAS GENERATOR

7. 2003 - 088838 RECYCLING SYSTEM OF FOOD WASTE

8. 2002 - 270194 FUEL CELL COGENERATION SYSTEM

9. 2001 - 315125 INTERMEDIATE TREATMENT METHOD FOR WASTE PLASTIC AND ARTIFICIAL FLOATING ALGAE SHELTER

10. 2001 - 313058 POWER GENERATING SYSTEM USING PLANT

11. 2001 - 262162 METHOD FOR PRODUCING FUEL FROM BIOMASS

12. 2001 - 225093 SEWAGE TREATMENT METHOD

13. 2000 - 284212 LIGHT CONVERGING DEVICE USING CONDENSER LENS, ACCUMULATING DEVICE FOR LIGHT ENERGY CONVERTED BY SAME LIGHT CONVERGING DEVICE, PRODUCTION OF GAS USING SAME ACCUMULATING DEVICE, SEPARATING METHOD FOR GAS PRODUCED BY SAME PRODUCTION,…

14. 2000 - 087054 PREPARATION OF GASEOUS FUEL FROM ALGA

15. 10 - 277569(1998) WATER QUALITY PURIFYING CERAMIC MATERIAL IN WHICH TITANIUM DIOXIDE IS MIXED

16. 09 - 276648(1997) RECYCLING OF CARBON DIOXIDE

17. 09 - 175912(1997) STABILIZATION OF HALOGEN-FREE 3-ISOTHIAZOLONE

BIOCIDE

18. 09 - 173050(1997) CULTURE OF MICROALGAE BELONGING TO GREEN ALGAE

19. 08 - 120287(1996) MOLDED FUEL, AND PROCESS AND APPARATUS FOR PRODUCING SAME

20. 07 - 126668(1995) EFFICIENT APPLICATION OF SUSPENDED PHOTOSYNTHETIC MICROORGANISM

21. 07 - 087986(1995) PROCESS FOR PRODUCING ETHANOL FROM FINE ALGA

22. 06 - 299179(1994) FUEL FOR INNER COMBUSTION ENGINE

23. 06 - 221235(1994) HARMFUL DISCHARGING GAS ELIMINATING METHOD FOR AUTOMOBILE AND FILTER FOR ELIMINATION

24. 05 - 304945(1993) FINE ALGA BELONGING TO GENUS CHLORELLA FOR IMMOBILIZING CO2 IN HIGH CONCENTRATION

25. 04 - 110395(1992) RECYCLING OF CARBON DIOXIDE

26. 03 - 178969(1991) STABILIZED COMPOSITION COMPRISING METAL SALT AND 3-ISOTHIAZOLONE

27. 03 - 154616(1991) RECOVERY AND FIXATION OF CARBON DIOXIDE

28. 63 - 035402(1988) PRODUCTION OF HYDROGEN GAS

9.4. Appendix 4: Composition of Brown Seaweeds

The following tables (Table 31, Table 32, Table 33 and Table 44) are selected translated data from the Bio-Offshore project (Reith, et al., 2005).

Table 31: Abbreviations Used

d.b.	Dry Basis
w.b.	Wet Basis
daf	Dry and ash-free
LHV	Lower Heating Value
HHV	Higher Heating Value

Table 32: Composition of *Laminaria* Species in Literature *(Reith et al, 2005)*

Component	w/w % d.b. min	w/w % d.b. max	w/w % d.b. median
Ash content	22	37.6	26
Volatile Solids	78	62.4	74
Protein	6	19	12
Lipids	0.92	4	2
Cellulose	3	9	6
Alginates	17	30	23
Laminaran	14	14	14
Fucoidan	5.5	5.5	5
Mannitol	7	18.25	12
Total % w/w			100

Table 33: Proximate Analysis of *Laminaria* Species *(Reith et al, 2005)*

Variable	Unit	Value
Moisture content	% w/w w.b.	88
Ash content	% w/w d.b.	26
Volatile solids	% w/w d.b.	74
C	% w/w d.b.	34.6
H	% w/w d.b.	4.7
O	% w/w d.b.	31.2
N	% w/w d.b.	2.4
S	% w/w d.b.	1
Cl	% w/w d.b.	-
F	% w/w d.b.	-
Br	% w/w d.b.	-
HHV	MJ/kg d.b.	13.2
LHV	MJ/kg d.b.	12.2
HHV daf	MJ/kg d.b.	17.9
LHV	MJ/kg w.b.	-0.7

Table 34: Ultimate Analysis of *Laminaria* Species in Literature *(Reith et al, 2005)*

Element	mg/kg db min	mg/kg db max	mg/kg db median
N	16,700	28,250	22,475
P	1,860	5,500	3,542
S	6,650	12,000	10,117
Al			7
Ca	5,525	22,700	11,606
Na	31,110	45,300	38,122
K	45,800	127,000	95,758
Mg	5,700	9,000	7,292
I	1,400	6,700	4,540
Fe	36.5	1,400	511
Mn	1.2	5	3
Se	4	5.7	5
Co			0
Mo			<0.01
Cu	2	<5	<5
As			76
Cr	<0.5	2	1
Cd			3
Hg			<0.05
Ni			1
Pb			<0.01
V			1
Zn	1	13.1	5

9.5. Appendix 5: Selected Macroalgae Productivity Data

Macroalgae productivity data from selected sources are presented here.

Species	Yield t/ha/yr dry	Location	Origin	Source	Notes
Ulva sp	22.5	Pennsylvania	Cultivation	Rasmussen 2007, citing Moll 1998	Converted to annual yields using 6 months growth
Ulva sp	2	Odense Fjord	Natural stock	Rasmussen 2007	Measurements in summer
Ulva sp	45	Denmark	Cultivation	Rasmussen Pers. Comm. 2008	Based on extrapolation of 4-month trials
L japonica	31	Japan	Cultivation	Yokoyama et al, citing Japan Ocean Industries Association	Corrected from dry ash-free value
L japonica	25	China	Cultivation	Kelly, citing China Fish Annals 2003	Commercially achieved yields
L japonica	60	China	Cultivation	Kelly, citing Tseng 1987	Experimental plots. High cost and poor quality
L hyperboria	30	Scotland	Natural stock	Kelly, citing Walker 1947	Have taken average between 48 t/ha and 7 t/ha. Needs to be rested >5 years inter-harvest.
Brown shallow sublittoral	22.5	Scotland	Natural stock	Kelly, citing Gao & McKinley 1994	Species not specified. Average of 10-20 kg/m2 wet. Needs to be rested inter-harvest
Alaria spp	12	Ireland	Cultivation	Kelly, citing Kraan 2007	Hybrid species
Saccharina latissima	15	Scotland	Cultivation	Kelly, citing Sanderson 2006 unpublished	Experimental plots near fish farms as nutrient source
S polyschides	25.5	Scotland	Cultivation	Kelly, citing Sanderson 2006 unpublished	Experimental plots near fish farms as nutrient source
Laminaria Gracilaria Multicrop	11	Southern USA	Cultivation	Chynoweth 2002	Base case commercial production. Dry and ash-free value
Laminaria Gracilaria Multicrop	45	Southern USA	Cultivation	Chynoweth 2002	Optimised production. Dry and ash-free value. Experimental yields only
Ulva	34.6	Florida	Cultivation	Chynoweth 2002, citing Hannisak 1987	Range 25 to 44 t/ha/yr
Laminaria sp	38	New York	Cultivation	Chynoweth 2002, citing Brinkhuis et al 1987	Range 28 to 48 t/ha/yr. Dry and ash-free value
Laminaria japonica	60	Japan	Cultivation	Chynoweth 2002, citing Brinkhuis et al 1987	Range 40 to 85 t/ha/yr. Dry and ash-free value
Red, green, brown multicrop	20	North Sea	Cultivation	Reith et al 2005	Theoretical yields. Layered cultivation. No nutrient supply.

Species	Yield t/ha/yr dry	Location	Origin	Source	Notes
Red, green, brown multicrop	50	North Sea	Cultivation	Reith et al 2005	Theoretical yields. Layered cultivation. Precision nitrogen dosing
Laminaria sp	20	North Sea	Cultivation	Reith et al 2005, citing Buck & Bucholz 2004	Theoretical yields. No nutrients other than coastal runoff.

9.6. Appendix 6: Example Ranking of Microalgal Species

The table below is an example of a preliminary desktop screening exercise prepared by researchers in South Africa (Griffiths, et al., 2008)

Species	Media	Lipid content (% d.b.)				Biomass prod (g/l/day		lipid productivity (g/l/d)	Ease of cultivation (Score)			Manipulative potential (score)		
		avg	N deficient	Si deficient	highest	avg	highest	lipid productivity	Resist contamination	Tolerate environ	Ease of Harvest	GM system	Heterotrophic	Score
Chlorella	fresh	23	44		70	76	260	88	10	10	0	10	10	91
Chlorella pyrenoidosa	fresh	14	64		86	21	42	14	10	0	0	0	10	39
Navicula acceptata	fresh	33	35	46	49	35	35	58	10	0	0	0	0	39
Navicula pelliculosa	fresh	28	45	34	45	40	40	56	10	0	0	0	0	39
Cylindrotheca	marine	27	27	?	37	38	55	50	10	0	0	10	0	38
Nitzschia	marine	35	41	47	80	16	25	28	0	0	0	0	10	37
Navicula	fresh	21	45	47	58	25	35	26	0	0	0	10	0	35
Amphora	marine	51	?	?	82	8	13	20	0	10	0	0	10	35
Navicula saprophila	fresh	26	44	?	44	25	28	32	0	0	0	10	10	33
Chaetoceros muelleri	marine	17	27	36	53	24	55	20	0	10	0	0	0	32
Cyclotella cryptica	marine	18	34	38	59	17	27	16	0	10	0	10	10	31
Monodus subterraneus	fresh	27	13	?	34	34	34	46	10	0	0	0	0	30
Monoraphidium minutum	fresh	22	52		52	13	13	14	10	0	0	0	10	28
Euglena gracilis	fresh	20	35	?	55	16	22	16	0	0	0	10	10	28
Nannochloropsis sp.	marine	40	32	?	68	7	12	15	0	0	0	0	10	28
Chlorella vulgaris	fresh	23	42		63	9	17	10	0	0	0	10	10	28
Chlorella sorokiniana	fresh	17	18		22	24	44	21	10	0	0	10	10	27
Crypthecodinium cohnii	marine	25	?	?	30	25	27	31	0	0	0	0	10	26

Species	Media	Lipid content (% d.b.)				Biomass prod (g/l/day		lipid productivity (g/l/d)	Ease of cultivation (Score)			Manipulative potential (score)		
		avg	N deficient	Si deficient	highest	avg	highest	lipid productivity	Resist contamination	Tolerate environ	Ease of Harvest	GM system	Heterotr ophic	Score
Nannochloris sp.	marine	26	30		63	11	16	15	10	0	0	0	0	26
Chlorella emersonii	fresh	29	63		63	3	6	5	0	0	0	0	0	26
Thalassiosira pseudonana	marine	16	26	?	26	25	40	21	0	0	0	10	0	25
Amphiprora hyalina	marine	22	28	37	37	13	27	15	10	0	0	0	0	25
Nannochloropsi s salina	brackish	27	46	?	72	2	2	3	0	0	0	0	10	24
Chlamydomona s	fresh	16	33		33	17	17	14	10	0	0	10	10	24
Dunaliella	salt	24	9		55	12	12	14	20	0	0	10	0	24
Chlorella minutissima	marine	31	57		57	2	3	3	0	0	0	0	0	23
Dunaliella salina	salt	19	9		35	15	16	14	20	0	0	10	10	23
Scenedesmus obliquus	fresh	21	42		53	3	10	4	0	0	0	0	10	22
Prymnesium parvum	marine	30	?	?	38	12	12	19	0	0	0	0	10	22
Spirulina platensis	fresh?	13	10		22	13	31	8	20	0	10	0	10	21
Oscillatoria	fresh	7	13		13	33	39	12	10	0	10	0	0	21
Isochrysis galbana	marine	24	29	?	40	10	21	12	0	0	0	0	0	21
Thalassiosira weissflogii	marine	22	24	?	24	16	20	18	0	0	0	10	0	20
Phaeodactylum tricornutum	marine	22	26	?	37	7	14	8	0	0	0	10	10	20
Ankistrodesmus	fresh	23	31		40	7	14	8	0	10	0	0	0	20
Synechococcus	marine	11	?		11	26	30	14	10	0	0	10	0	20
Dunaliella tertiolecta	salt	15	18		37	10	12	8	20	0	0	0	10	20
Skeletonema costatum	marine	14	25	?	30	16	22	11	0	0	0	0	0	18

Species	Media	Lipid content (% d.b.)				Biomass prod (g/l/day		lipid productivity (g/l/d)	Ease of cultivation (Score)			Manipulative potential (score)		
		avg	N deficient	Si deficient	highest	avg	highest	lipid productivity	Resist contamination	Tolerate environ	Ease of Harvest	GM system	Heterotr ophic	Score
Scenedesmus dimorphus	fresh	26	?		40	10	10	13	0	0	0	0	0	17
Porphyridium cruentum	marine	11	?	?	15	14	21	8	0	0	0	10	10	16
Spirulina maxima	fresh?	7	?		7	14	22	5	20	0	10	0	0	15
Dunaliella primolecta	salt	23	14		23	1	2	1	20	0	0	0	0	13
Tetraselmis sp.	marine	18	12		23	4	6	3	0	0	0	0	10	11
Chlorella protothecoides	fresh	13	23		23	2	4	1	0	0	0	0	10	11
Dunaliella bardawil	salt	?	10		10	5	7	?	20	0	0	0	0	11
Hymenomonas carterae	marine	20	14	?	20	5	6	5	0	0	0	0	0	11
Tribonema	marine	12	16	?	22	8	10	4	0	0	0	0	0	11
Anabaena cylindrica	fresh	5	5		7	9	9	2	0	0	0	0	0	6

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National Development Plan 2007 - 2013

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