Research Needs in Ecosystem Services to Support Algal Biofuels, Bioenergy and Commodity Chemicals Production in the UK

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A Project for the Algal Bioenergy Special Interest Group
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Executive Summary

Products from micro and macroalgae have applications in a wide range of existing markets. Both algal forms may provide low value, high volume products such as livestock feeds, as well as high value, low volume speciality chemicals such as carotenoids and omega oils. Such speciality chemicals have a range of applications including use in pharmaceuticals, cosmetics and nutrition. Algae can also be used for bioremediation, for example in wastewater clean-up.

Recently, there has been considerable interest surrounding the use of algae for commodity products such as biofuels, bioenergy and commodity chemicals. While there has been a large amount of research focusing on improving the economic sustainability of algal production and use, environmental sustainability, including impacts on ecosystem services such as biodiversity, water, soil and air quality associated with the production of algal commodity products, has received considerably less attention.

The Algal Bioenergy Special Interest Group (AB-SIG) is a two year initiative (from January 2011), supported by the UK’s Natural Environment Research Council (NERC) and the Technology Strategy Board (TSB). The AB-SIG has three principle objectives:

1) to ensure that project developers fully understand the environmental implications of any planned algal commercialisation activity in the fields of bioenergy and commodity chemicals;
2) to connect academia and industry in developing the evidence base for the sustainable production of algal products;
3) to help UK businesses operating in the fields of algal bioenergy or using algal-derived products, to profit and grow through new biosciences-inspired innovation.

As part of the AB-SIG, NERC are funding two Fellowships, one in micro- and the other in macro-algae research. The appointment of these two new fellowships will ensure the expansion of NERC science in this strategically important area. A Knowledge Exchange Fellow is also being funded by NERC, who will work with project developers to assess business opportunities and the environmental implications of this activity. The Knowledge Exchange Fellow will also provide an interface between the Director, Research Fellows and stakeholders.

The AB-SIG has been Living With Environmental Change (LWEC) accredited. LWEC’s purpose is to ensure that decision makers in government, business and society have the knowledge, foresight and tools to mitigate, adapt to and benefit from environmental change through access to accredited activities including those funded by the UK Research Councils. The AB-SIG is also an external member of the Cross Council Bioenergy Strategic Co-ordination Group (BSCG), a sub-group of the UK Research Council’s Energy Programme Co-ordination Group. The BSCG has been formed to develop a strategy for and coordinate future bioenergy research to ensure that research into sustainable bioenergy, including algal biomass, is able to make the maximum contribution to future economic growth whilst helping move the UK towards a low carbon future.

The current report will be used to inform decisions on future activities undertaken by the AB-SIG. The report examines UK capabilities in this area, identifies current and future market dynamics and the potential environmental consequences of commercial algal projects. The report focuses on the implications of producing large scale commercial products.

The work presented is based on extensive consultation with stakeholders from academia, industry, government and research funders to elucidate the potential areas of strategic interest for the UK. It pulls together the opinions of stakeholders in the algal arena and those outside of it who may have a strategic interest in being involved in the future. The report merges opinions from microalgae and macroalgae stakeholders, covering different cultivation, processing and conversion technologies including thermochemical and fermentation based approaches.

Eleven research challenges are highlighted which are focused upon NERC’s strategic priorities, but they also are embedded in the wider research remit of the other Research Councils of the UK. Many are complementary to the current strategic priorities of BBSRC which includes bioenergy and industrial biotechnology. Research challenges have been identified as areas in which the UK could
develop a position at the forefront of research in this emerging area. It is hoped that the AB-SIG Research Fellows when in post will feed into these challenges. The eleven research challenges are:

- **Research Challenge 1**: Identify the key environmental factors influencing yield and biochemical composition.
- **Research Challenge 2**: Identify suitable sites for algal production.
- **Research Challenge 3**: Develop life cycle assessment capability including carbon balance and sustainability information suitable for aquatic and marine systems.
- **Research Challenge 4**: Assess the potential for algal diseases to affect both cultivated algae and wild stocks.
- **Research Challenge 5**: Identify the biosecurity issues associated with using non-native or improved algal strains.
- **Research Challenge 6**: Identify the role of algae in carbon and nutrient cycling.
- **Research Challenge 7**: Identify to what extent algal farms attract or repel marine mammals.
- **Research Challenge 8**: Understand to what extent algal cultivation affects biodiversity in the farm, the water column and benthic environment.
- **Research Challenge 9**: Understand the atmospheric effects resulting from trace gas emissions from algal growth.
- **Research Challenge 10**: Identify the best configuration for an algal farm to maximise yield and environmental benefits and minimise environmental impacts.
- **Research Challenge 11**: Identify mechanisms to overcome nutrient limitation in offshore environments.

Four market opportunities which the UK could exploit have been identified. In order to develop these markets, it will be vital that impacts on ecosystem services, i.e., air, water, soil, sand and biodiversity are considered. While these four opportunities are primarily focussed upon NERC’s remit, there will be significant cross over with other research councils in terms of engineering, cultivation and exploitation of algal strains (BBSRC), engineering of cultivation facilities (EPSRC) and social acceptance (ESRC).

The four market opportunities are:

1. **The near shore cultivation of macroalgae for bioenergy.**
   This opportunity will be developed first through the development of higher value food and nutraceuticals markets which have an existing and rapidly expanding market. Once novel high value products which the UK can produce competitively have been identified, this will facilitate the development of a UK high value products industry with the residues potentially being used for bioenergy through anaerobic digestion. The cost and rate of production of new goods typically change as experience is gained in a process known as experimental learning. As more experience is gained in the manufacture of a product, the unit cost often decreases and this may be translated into increased productivity. This analogy may be applicable to macroalgae cultivation, whereby as experience is gained in smaller scale markets, it is likely that costs will be reduced. Cost reduction, if feasible, will enable an increase in cultivation area, and subsequently bioenergy may emerge as a more prominent end product.

2. **The offshore cultivation of macroalgae for commodity chemicals.**
   This opportunity will initially build upon the commercial macroalgae cultivation expertise developed in market opportunity 1. Once cost effective routes to fermenting macroalgal carbohydrates to fuels (biobutanol and bioethanol) have been developed, this will promote the utilisation of offshore macroalgae farms for biofuels markets. The production of commodity chemicals from macroalgae will occur in the longer term, when cost effective routes to fermenting macroalgal carbohydrates to commodity chemicals have been developed.
3. **The heterotrophic conversion of sugars by microalgae to fuels**

   This opportunity will develop from the existing industry which is predominantly based upon omega oils production. The development of biofuels markets will occur when existing markets are saturated, costs of production reduced, for example through the identification of cheaper sources of organic carbon, and organisms developed which can produce products in both sufficient quantity and quality for biofuels markets.

4. **Using microalgae and bacteria from biofilms\(^1\) for wastewater treatment and biofuels production**

   This opportunity will initially develop through the wastewater industry as a way of reducing nitrogen and phosphates in treated discharge water. Given that the water industry already has anaerobic digestion capability at many wastewater treatment facilities, it is likely that wastewater companies will utilise algae for wastewater treatment, then utilise the residues in anaerobic digestion to increase biogas yields and bioenergy revenue. In the longer term, algal biomass grown on wastewater could be used in thermochemical conversion to produce a range of products which are currently produced from fossil oil sources.

There is an increasing emphasis on ensuring that bio-based products do not have negative effects on the natural environment, and as such, it is crucial that any issues surrounding the environmental impacts of biofuels, bioenergy and commodity chemicals production are addressed prior to the commercialisation of products.

The UK has a world leading capability in research relating to ecosystem services in marine and aquatic environments. This capability combined with the leading position that the UK has in assessing the sustainability of terrestrial biomass, could be applied to develop a leading international position in understanding the environmental implications of the large scale cultivation of algae for biofuels, bioenergy and commodity chemicals production. This report identifies the ways in which this position could be secured.

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\(^1\) Biofilms are populations or communities of microorganisms, including algae and bacteria, adhering to a surface material.
Scope

The UK has developed a world leading position in assessing the sustainability of land based renewables, and more recently, marine renewable devices. Given the UK’s enviable research strength in marine and aquatic ecosystem services research, it is in a prime position to develop a leading place in assessing the sustainability of algal based systems, both at home and abroad.

NERC currently funds a number of thematic action plans, covering the sustainable use of natural resources, climate, biodiversity, earth systems, natural hazards, environmental pollution and technology. These thematic plans have considerable synergies with the cultivation and production of algal commodity products. NERC have made a commitment to funding research on the topic of algal bioenergy and are supporting a Director and two research Fellowships (one on macroalgae, and one on microalgae) in this field. A Knowledge Exchange Fellow is also being funded through the AB-SIG to ensure that project developers fully understand the environmental implications of any planned activity.

In order to inform decisions on future activities undertaken through the group, the AB-SIG have commissioned this report to assess the opportunities and challenges to the UK in developing products based from algae. This report identifies research opportunities and impacts on ecosystem services, including impacts on biodiversity, water, soil and air quality, associated with the production of large scale commodity products (i.e., those products at a scale of over 10,000 tonnes at a single site) which could be exploited by 2025.

The terms of reference for the report were to provide information on:

- UK research-base and industry capacity,
- Current market dynamics: future market trends and opportunities,
- Possible or likely environmental consequences of algal commercialisation projects and risk mitigation approaches,
- Supply chain partners necessary to take strategic algal-based projects to market,
- Identification of commercial priority areas for UK.

This report identifies the key research challenges in the area of ecosystem services, with projected timeframes and budgets, thereby helping to inform the AB-SIG about how future projects could be developed between the research base and industry partners.
Introduction

Microalgae are currently cultivated to produce a wide range of economically interesting metabolites which are used for cosmetics, personal care and food ingredient markets. These include astaxanthin which has a market size of around $250 mn, beta carotene with a market size of $280 mn and omega oils such as DHA and EPA which can be used in nutraceuticals and for aquaculture, with a market size of $1,500 mn. Macroalgae have a wide range of existing applications including use in food, feed, fertiliser, chemicals and cosmetic ingredients. These include liquid fertilisers, which has a market size of around $5 mn, feeds for livestock with a market size of $300 mn and foods with a market size $500 mn. Macroalgae can also be used to produce higher value products including hydrocolloids (seaweed polymers), such as carageenan, alginate and agars, which together have a total market size of $1 bn.

Recently, there has been considerable interest surrounding the use of algae for fuels and energy uses, with Exxon Mobil committing up to $600 mn and BP committing $10 mn amongst other substantial investments in this area. However, while there has been a large amount of research focusing on improving the economic sustainability of algal fuels production, environmental sustainability, including impacts on ecosystem services such as biodiversity, water, soil and air, have received considerably less attention.

The Renewable Energy Directive stipulates that biofuels should be produced in an environmentally sustainable manner and as such, consideration of the environmental sustainability of biofuels and bioenergy production is an important pre-requisite for participation in member state support programmes. Similarly, while not specifically mandated at present, companies using both commodity chemicals and higher value products are becoming increasingly aware of the benefits of demonstrating environmental sustainability and maintenance or improvement of ecosystem services on consumer purchasing choices. Thus, the environmentally sustainable production of algae for biofuels, bioenergy and chemical products is of vital importance to the development of robust supply chains for algal products, both now and in the future.

The current report summarises the key research challenges which need to be addressed in order to develop an environmentally sustainable large scale algae to commodity products industry in the UK. It identifies the key stakeholders which need to be brought together and identifies the mechanisms by which strategically important research in this area could be developed.
The Algal Bioenergy Special Interest Group

The Algal Bioenergy Special Interest Group (AB-SIG) is a two year programme developed by NERC and TSB which started in January 2011. The AB-SIG has three principle objectives: to ensure that project developers fully understand the environmental implications of any planned activity, to connect academia and industry in developing the evidence base for the sustainable production of algal products, and to help UK businesses operating in this area, or using algal-derived products, to profit and grow through new biosciences-inspired innovation.

NERC are supporting a Director and two Fellowships (one on macroalgae, and one on microalgae). A Knowledge Exchange Fellow is also being funded through the AB-SIG to ensure that project developers fully understand the environmental implications of any planned activity.

Stakeholders from academia, industry and Government, both within and outside of the algal area, were questioned regarding the aims and objectives of the AB-SIG and what these stakeholders thought the AB-SIG could feasibly achieve during its 2 year duration. The salient points of these interviews are given below.

1. It was thought that the AB-SIG should bring together a group of experts to develop a UK national strategy for the sustainable use of algae, ensure that UK competitiveness in this area is maintained, and to develop a focussed research programme.

2. Many of the research challenges which need to be addressed, both within and outside of the environmental sustainability field, are intrinsically cross-disciplinary; however, stakeholders felt that cross-disciplinary projects often fall through the net of research councils. Stakeholders suggested that the AB-SIG should ensure that there is cross-research council buy-in to the group and that cross-disciplinary projects are not overlooked.

3. Stakeholders felt that the focus on industry-relevant research was a key advantage of the group.

4. It was felt by several stakeholders that the AB-SIG could play a useful role in information dissemination to the community, either through organising meetings or through providing news updates of important developments in the area. However, it should not simply be a talking shop, and thus needs clear aims and objectives.

5. It was suggested that the AB-SIG could function as a virtual centre of expertise in the sustainable use of algae, with UK experts acting as a focus for consultancy, for projects being taken forward both within the UK and internationally.

6. Some stakeholders expressed concern that the momentum built up by the group would dissipate once its funding period ends.

7. Stakeholders felt that initial meetings of the group should focus on identifying the terms of reference of the group, and these goals should be communicated to the wider community to bring in additional stakeholders.

8. It was highlighted that there are several other algal initiatives in the UK and that a joined-up approach is needed to ensure that there is no unnecessary duplication of effort, especially when funding is limited.

9. In general, there was a low awareness of the AB-SIG and its aims and objectives. While the academic community had a greater awareness of the existence of the group than other communities, awareness of the aims and objectives of the group, even amongst those directly involved in algal R&D, was relatively low.
Identifying Strategic Development Priorities for the UK

There is a variety of algal production methods available and a wide range of ways in which algae could be converted to biofuels, bioenergy and commodity chemicals. These routes are shown in Figure 1 on the next page.

Table 1 below is a qualitative assessment of the extent to which each of the possible routes for algae production and utilisation could be environmentally sustainable at the scales required for the production of commodity products in the UK.

Table 1 Summary Analysis of the Sustainability of Different Algal Production and Conversion Pathways for Biofuels, Bioenergy and Commodity Chemicals Production in the UK

<table>
<thead>
<tr>
<th>Technology</th>
<th>Availability / Potential</th>
<th>Environmental Risks</th>
<th>Environmental Benefits</th>
<th>UK Capability</th>
<th>UK Potential</th>
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<tbody>
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<td><strong>Inputs</strong></td>
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<td>Wastewater treatment</td>
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<td>Industrial CO₂ use</td>
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<td><strong>Biomass Production</strong></td>
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<td>Photobioreactors</td>
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<td>Open Ponds</td>
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<td>Macroalgae in Sea</td>
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<tr>
<td>Microalgae in Open Sea</td>
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<td>Microalgae in enclosed membranes in Sea</td>
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<td>Driftweed/Wrack</td>
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<td>On Land Tanks</td>
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<td>Standing Stocks</td>
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<td><strong>Conversion Processes</strong></td>
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<td>Heterotrophic</td>
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<td>Anaerobic Digestion</td>
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<td>Sugar Fermentation</td>
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<td>Hydrothermal Processes</td>
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<td>Extraction</td>
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Key: low availability/high or detrimental impact, high availability/low impact, intermediate availability / intermediate impact.

Table 1 suggests that, for large scale production and utilisation of algae, as required for biofuels, bioenergy and commodity chemicals production:

- The most sustainable input material is wastewater,
- The most sustainable methods for algae production at scale are likely to be biofilms and heterotrophic production in fermentation vessels on land, and the production of microalgae in membranes and macroalgae in the sea,
- All conversion processes are potentially suitable for the UK.

The technologies listed above, and highlighted in Table 1, form the priority sectors for the rest of this report. The following sections outline the supply chains, research needs, timelines and skills needed to develop these opportunities.
Figure 1 - Algal Biofuel and Bioenergy Pathways

Dashed lines represent microalgae only pathways.
Review of the Environmental Impacts Associated With Algae Cultivation and Utilisation

There is an increasing emphasis on ensuring that bio-based products do not have negative effects on the natural environment, and as such, it is crucial that any issues surrounding the environmental impacts of biofuels, bioenergy and commodity chemicals production are addressed prior to commercialisation of products. Ecosystem services are a crucial part of assessing the environmental impacts of a process. Ecosystem services can be defined as:

“the benefits that people obtain from ecosystems...and may include (but not be limited to), water quality and quantity regulation, soil protection especially with reference to erosion control, protection from fire and wind, maintenance of supply of natural goods to local populations (e.g. non-timber forest products) which have identified such goods to be important to their livelihood”

Round Table on Sustainable Biofuels (2010)

Both macroalgae and microalgae can potentially impact upon the environment. In contrast to the terrestrial environment, there has been relatively little consideration on the aquatic environmental impacts of large scale algal cultivation. This section briefly reviews the impacts on each of the main ecosystem services (air, water, biodiversity, soil) from algal cultivation and utilisation, focussing upon those areas which have the most potential for commercial deployment at a large scale in the UK by 2025.

Air

Algae can result in the release of a variety of gases either during its cultivation or its decomposition. These may be beneficial or detrimental. Cultivation of macro and microalgae in the sea can result in the release of halogenated hydrocarbons and dimethyl sulphide, which could promote a localised climate cooling effect. Decomposition of macroalgae can release noxious gases, so removal of macroalgae from shore lines can potentially prevent anoxic conditions or public concerns over the resultant odours. Detrimental effects from algal conversion technologies are likely to be minimal, especially as many conversion routes are technologically mature (albeit for other feedstocks) and the most viable systems should be used. Where solvents are used, these should be recycled to avoid the release of volatile organic compounds (VOCs). Even where algae pose a particular problem, for example the anaerobic digestion of the green seaweed Ulva lactuca can result in high hydrogen sulfide emissions, there are current techniques that can be used to overcome any potential issues. Addition of CO$_2$ is a necessity for the production of microalgae in open pond and photobioreactor systems and therefore algae cultivation has attracted attention as a route to mitigating CO$_2$ emissions from industrial sources. However, fuels derived from algae grown with CO$_2$ supplementation from fossil sources would not be biofuels owing to the fossil derived carbon contained within them. This would not be an issue with algae grown with CO$_2$ from biogenic sources.

Water

Land based algal cultivation systems can have a high water requirement. The limited availability and cost of freshwater has promoted the use of alternative water sources such as seawater and wastewater for algae cultivation. Algae can play an important role in wastewater clean-up, removing nutrients such as nitrogen and phosphates and trace elements such as copper from water effluents. This can help reduce potential downstream eutrophication of water ways, estuaries and marine environments and the associated negative effects on aquatic and marine biodiversity. Algae can also remove other potentially undesirable components from wastewater streams including heavy metals; help reduce the biological oxygen demand and chemical oxygen demand of the system and increase the oxygen content of the wastewater. The sea based cultivation of macroalgae and microalgae negates any need for fresh water use, except perhaps in the hatchery stage and for washing equipment. Nutrient demand by microalgae and macroalgae offshore may result in removal of nutrients from the water column, with adverse effects on other marine organisms. Exogenous fertilisation may overcome this, but in itself may be undesirable and if not carefully balanced to the amount of nutrients that the algae can take up, may result in eutrophication. In all cases, a site by site assessment on the carrying capacity of a specific location will be needed.
Biodiversity

Macroalgae provides an important habitat for a range of organisms and can act as a resting ground for fish. Macroalgae is a valuable food source for fish, macroinvertebrates and grazing sheep in isolated coastal communities (such as the Western Isles, Shetland and Orkney). The introduction of artificial structures into the marine environment (such as macroalgae farms or containers for cultivation of microalgae in the sea) could improve biodiversity, acting as a substrate for marine organisms to grow on, and, especially in the case of macroalgae farms, result in sediment and nutrient capture with possible beneficial effects on production in the water column and benthic environment. However, these positives must be balanced against potential negative effects including the potential for marine mammals to get caught in growth structures, detrimental effects from seabed preparation on benthic communities and shading implications on communities. The potential for disease transfer from cultivated macroalgae to native species is unknown. While there is no evidence of disease transfer at current sites of widespread macroalgal cultivation, the potential should be investigated experimentally.

There is the potential for the escape of algal material into the external environment from any algal cultivation system and non-native or improved strains may out-compete local species if not adequately managed. Such risks should be minimal if containment procedures are followed. The use of naturally occurring consortia, for example in biofilm systems, are likely to have minimal implications on local algal and microbial biodiversity. Significant benefits to biodiversity in an area could arise as a result of algae being used for wastewater treatment or in conjunction with aquaculture enterprises, such as salmon farming. Indeed, by removing excess nutrients in water, algae can prevent eutrophication and anoxia of aquatic species. In Sweden, research is identifying how the removal of filamentous red algae can help reduce eutrophication in the Baltic Sea.

Land and Sea Use

The amount of land used for most land-based systems, especially pond and tank systems, is likely to be inhibitory at the larger scales required for biofuels, bioenergy and commodity chemicals production, especially where cultivation systems need to be co-located with waste streams (CO₂ and wastewater) or specific water inputs. The requirement for open ponds to be located on flat land can add further siting restraints. Heterotrophic systems have a significantly lower direct land footprint than photoautotrophic systems, and except where wastewater is used, are relatively independent of location constraints and may therefore be a more feasible option for the UK. The upstream land use requirements of heterotrophic conversion for commodity products could be considerable, however it is considered more feasible for the UK to produce fermentable sugars for conversion to oils via this route than it is to produce algae directly in open ponds for production of oils for commodity product applications due to land constraints. Large scale cultivation of algae at sea may result in conflicts with other sea users, including fishermen, navigation, leisure users and other marine energy industries, especially given the areas needed. For example, a 100 kW anaerobic digestion plant, typical of the size of plant found on farms in the UK, would require a 50 ha farm of Laminaria sp. per year, while a bioethanol plant with an output of 400 million litres, similar to the capacity of the Ensus wheat to ethanol plant on Teesside would require a farm area of around 143,000 ha of Laminaria sp. each year. Stakeholders considered that marine spatial planning will be crucial to overcome potential conflicts with other sea users, especially given the scales needed for commodity products. The Crown Estate, as the owner of the UK seabed, NERC, and Government bodies such as Defra, the Marine Management Organisation, Marine Scotland, Welsh Assembly Government and Northern Ireland Assembly, will play a crucial role in resolving any potential conflicts over the use of the sea resulting from the large scale cultivation of algae.

Energy and GHG

There are few life cycle assessments (LCAs) for microalgae systems and those which are available cannot easily be compared due to a lack of consistency in system boundaries. There are currently a limited number of LCAs for macroalgal systems.

2 The full calculations and assumptions used are contained within the technical appendix which accompanies this report.
Direct energy requirements for heterotrophic systems are likely to be lower than both photobioreactors and open pond systems. Heterotrophic systems do not require a light source and can be grown with only carbon, oxygen and nutrients supplied. Indirect costs of algae cultivation can vary according to input, for example the large scale market adoption of heterotrophic systems would have similar issues to those surrounding the production of first generation biofuels. As a result, there is an increased focus on the use of waste materials and wastewater to provide these nutrient inputs to support algal growth, without increasing pressure on agriculture to supply organic carbon e.g in the form of glucose.

The harvesting step can add significant energy and GHG costs to algal production. Some downstream technologies are tolerant of feedstocks with high moisture content, for example anaerobic digestion and hydrothermal liquefaction, whilst other technologies may require a drier biomass, for example CO$_2$ extraction. Conversion processes such as thermal conversion routes (hydrothermal liquefaction and hydrous pyrolysis) and technologies using pressure (some natural extraction techniques e.g. CO$_2$ extraction) may require high energy inputs, especially compared to anaerobic digestion processes.
Ecosystem Services – A Possible Research Opportunity for the UK?

Many of the most important research challenges identified through stakeholder consultation focus on the need to ensure that ecosystem services are not adversely affected by algal developments. This is the principal remit of the AB-SIG through its stakeholder engagement and research activities.

This section investigates the research needs, timescales and collaborations which should be developed to further promote ecosystem services in the UK. The most important research challenges indicated by stakeholders are given below. These research challenges are not mutually exclusive, therefore there may be a high degree of overlap, or one challenge may be dependent upon other research challenges.

- **Research Challenge 1**: Identify the key environmental factors influencing yield and biochemical composition of algae.
- **Research Challenge 2**: Identify suitable sites for algal production.
- **Research Challenge 3**: Develop life cycle assessment capability including carbon balance and sustainability information suitable for aquatic and marine systems.
- **Research Challenge 4**: Assess the potential for algal diseases to affect both cultivated algae and wild stocks.
- **Research Challenge 5**: Identify the biosecurity issues associated with using non-native or improved algal strains.
- **Research Challenge 6**: Identify the role of algae in carbon and nutrient cycling.
- **Research Challenge 7**: Assess to what extent algal farms attract or repel marine mammals.
- **Research Challenge 8**: Understand to what extent algal cultivation affects biodiversity in the farm, the water column and benthic environment.
- **Research Challenge 9**: Understand the atmospheric effects resulting from trace gas emissions from algal growth.
- **Research Challenge 10**: Identify the best configuration for an algal farm to maximise yield and environmental benefits and minimise negative environmental impacts.
- **Research Challenge 11**: Identify mechanisms to overcome nutrient limitation in offshore environments.

In addition, three enabling actions were identified:

- **Enabling Action 1**: Improve techniques for maintainance of algae cultures.
- **Enabling Action 2**: Develop a series of pilot scale, near shore macroalgae farms in the UK in conjunction with aquaculture.
- **Enabling Action 3**: Develop infrastructure for offshore cultivation of algae followed by deployment of an offshore farm. This enabling action encompasses two parts: 3a) research on engineering of algae growth structures suitable for offshore environments and 3b) developing a series of pilot scale offshore macroalgae farms.

Indicative timescales as identified by the stakeholders, for each research challenge and enabling action are indicated in Figure 2 below. The timeframes for such actions are categorised as short term actions (i.e., those which can be completed within 5 years), medium term actions (i.e., those which can be completed within a 5-10 year time span), long term actions (those which can be completed within a 10-20 year time span) and longer term actions (more than 20 years).
<table>
<thead>
<tr>
<th>ENABLING ACTION</th>
<th>SHORT TERM (0-5 years)</th>
<th>MEDIUM TERM (5-10 years)</th>
<th>LONG TERM (10-20 years)</th>
<th>LONGER TERM (20+ years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enabling Action 1a: Improve techniques for maintenance of algal cultures</td>
<td>Research Challenge 1: Identify the key factors influencing yield and biochemical composition of algae</td>
<td>Research Challenge 2: Identify suitable sites for algal production</td>
<td>Research Challenge 3: Develop LCA capability including carbon balance and sustainability information suitable for aquatic and marine systems</td>
<td>Research Challenge 4: Assess the potential for algal diseases to affect both cultivated algae and wild stocks</td>
</tr>
<tr>
<td>Enabling Action 2: Develop a series of near shore pilot scale macroalgae farms in the UK in conjunction with aquaculture</td>
<td>Enabling Action 3: Develop a series of pilot scale offshore macroalgae farms in the UK.</td>
<td>Research Challenge 7: Assess to what extent algal farms attract or repel marine mammals</td>
<td>Research Challenge 8: Understand to what extent algal cultivation affects biodiversity in the farm, water column and in the benthic environment</td>
<td>Research Challenge 9: Assess atmospheric effects resulting from trace gas emissions from algal growth</td>
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<tr>
<td>Nearshore Cultivation</td>
<td>Research Challenge 10: Identify best configuration for an algal farm to maximise yield and environmental benefits and minimise negative environmental impacts</td>
<td>Research Challenge 11: Identify methods to overcome nutrient limitation offline</td>
<td>Enabling Action 2a: Research on engineering of algal growth structures suitable for offshore environments</td>
<td></td>
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</tbody>
</table>

Figure 2 - Indicative Timeline for Key Research Priorities in the Area of Ecosystem Services

Research challenges which depend upon a specific enabling action are shown below the respective enabling action.
Research Challenge 1: Identify the key environmental factors influencing yield and biochemical composition of algae

The amount of a biofuel, bioenergy or biochemical product produced will depend upon both the yield and the biochemical composition of the algae. Algal yield is influenced by a large number of abiotic factors, including turbidity, temperature, wave action, salinity and availability of nutrients and light. Yield can also be affected by biotic pressures in an area, for example the presence of predators and competing species. The biochemical composition of the algae can vary according to both abiotic factors and time of harvest. The factors needed for high yield and optimal biochemical composition of cultivated algae (for example light, temperature, nutrients and flow characteristics) need to be understood in order to develop a robust industry in this area and to identify suitable sites for algal production (c.f. research challenge 2) and to increase the carrying capacity of the environment.

A research programme in this area should be composed of two research strands. The first should draw upon algal cultivation expertise in macroalgae (Scottish Association for Marine Sciences, Newcastle University and Queens University Belfast) and microalgae (Scottish Association for Marine Sciences, Plymouth Marine Laboratory, National Oceanographic Centre, Newcastle University and Swansea University) and, through a series of trials, identify the optimal growth conditions for specific algal strains which are in demand by the market. This fits within the remit of NERC and BBSRC.

The second strand, linked to the first, should investigate how the biochemical composition of algae is affected by growth conditions and how it varies according to harvesting time. There has been some research in this area in the UK, which has investigated the biochemical variations in selected macroalgal species for both thermochemical and biochemical conversion processes. This includes work by Newcastle University and Scottish Association for Marine Sciences and by University of Leeds and Aberystwyth University under the SUPERGEN Bioenergy project. This background research should be extended to include a wider range of potentially useful species and should be focussed upon a wide range of potential uses including high value products (e.g. omega oils, carotenoids) which could be extracted from algae alongside biofuels, bioenergy and commodity chemicals as part of a biorefinery. This work fits within the remits of BBSRC and EPSRC.

Research Challenge 2: Identify suitable sites for algal production

There will be variation, both spatially and temporally, in the suitability of different sites for cultivation, affecting what species may be grown in an area, but also how much can be grown and when. In addition to these environmental factors a number of other constraints can also affect the suitability of an area for algae production, including anthropological constraints, such as a need to ensure that fisheries are not displaced from one area to another, and that cultivation does not interfere with shipping or leisure boats. Finally, constraints over potential sites may also arise from marine protected conservation areas and the need for access for maintenance and harvesting operations.

The scale of cultivation for bioenergy and liquid transport fuel production is likely to be large. We have estimated that a Laminaria sp. farm of around 143,000 ha would be needed to produce an equivalent amount of bioethanol as the Ensus wheat to ethanol plant on Teesside. The identification of suitable areas which have sufficient carrying capacity to allow high algal productivity without impacting on other uses could be a significant problem and modelling, which integrates each of these factors, will help provide indicative guidance for developers and regulators over which sites could be suitable for cultivation and under what circumstances. Modelling should be tailored to specific production systems and include modelling of nutrient flows, the need to reconcile the needs of different users of the marine environment, logistics, LCA criteria, weather and climatic factors. Research in this area should pull together marine spatial planning expertise available at The Crown Estate, Scottish Association for Marine Sciences (SAMS), Southampton Solent University, Heriot Watt University, University of Dundee, University of Stirling, and integrate this with expertise in hydrodynamics, biogeochemical cycling, and phyology modelling, available at Swansea University, University of Strathclyde, Newcastle University and UK Hydrographic Office and the Centre for Environment, Fisheries & Aquaculture Science (CEFAS) amongst others.
Research Challenge 3: Develop life cycle assessment capability including carbon balance and sustainability information suitable for aquatic and marine systems.

The Renewable Energy Directive stipulates that biofuels should be produced in an environmentally sustainable manner and, as such, consideration of the environmental sustainability of biofuels is an important pre-requisite for participation in member state support programmes. Similarly, while not specifically mandated at present, companies using both commodity chemicals and higher value products are becoming increasingly aware of the benefits in demonstrating environmental sustainability on consumer purchasing choices. The environmental sustainability of production should therefore be considered from the outset in all algal commercialisation projects. Sustainability criteria cover GHG balances of the fuels, effects on ecosystem services, including soil, water and air quality, potential processing issues including the effects of using GM organisms and broader social issues such as existing rights to resources from local communities and workers rights. Existing sustainability criteria have been based on terrestrial systems, and while there is a broad applicability of the themes to marine and aquatic systems, development of more appropriate standards for algal fuel and energy products is needed to facilitate the marketing of these products.

The UK has a strong capability in LCA, with particular academic centres of expertise at Imperial College London, University of Manchester, Sheffield Hallam University, University of Southampton, University of Aberdeen and the University of Bath were Professor Geoff Hammond leads on LCA for the BBSRC Sustainable Bioenergy Centre (BSBEC). The expertise at commercial companies such as North Energy and E4Tech is outstanding and these companies have played an important role in developing the evidence base for sustainability certification schemes. UK expertise is predominantly focussed upon terrestrial systems although there is some algal LCA expertise at Plymouth Marine Laboratory, University of Manchester, Bangor University, Swansea University and the University of Cambridge. Expertise in the sustainable management of marine resources exists in a range of Scottish institutions under the auspices of the Marine Alliance for Science and Technology Scotland (MASTS) consortium. The MASTS consortium are currently re-aligning their themes to include a marine energy group which will cover bioenergy applications. UK expertise in this area should be pulled together to develop a stronger capability in this area.

Research in this area should address the crucial need for solid data to underpin the development of robust LCA and sustainability criteria. LCA and sustainability of macroalgae to biofuels and bioenergy is being addressed under the BioMara and Energetic Algae Interreg projects, but while these projects are a crucial step in the right direction, the evidence base is immature especially with respect to environmental sustainability impacts of algal production in the marine environment. By combining the expertise in LCA and sustainability with information gained from addressing the research challenges indicated in this section, the UK can take a leading international position to advise on the development of robust carbon and sustainability criteria for algal biofuels and bioenergy chains.

There is a critical role for LCA and sustainability practitioners to be involved in the design of environmental research, setting the parameters for LCA, including the need for fundamental research on carbon, water and nutrient cycles as appropriate. Data collected should be consistent in both quality and quantity and should include final processing and use as well as production steps. The implications of environmental research for developing and meeting sustainability criteria should also be assessed by LCA and sustainability practitioners and development of a user friendly LCA tool kit would greatly benefit practitioners working in this area. This research challenges cuts across all of the other research challenges in this report, especially research challenges 6 and 9.

Research Challenge 4: Assess the potential for algal diseases to affect both cultivated algae and wild stocks

The mass monoculture of algae in farms could result in outbreaks of pests and diseases. This could both reduce yield and result in disease spreading to wild populations, potentially damaging marine biodiversity and food webs. It is therefore crucial to understand the potential for algal diseases to affect both cultivated algae and wild stocks so that methods for mitigating such risks can be developed prior to commercial scale production (c.f. research challenge 10).
A research programme in this area should draw upon modelling expertise available at the University of Stirling, National Oceanographic Centre, Plymouth Marine Laboratory and Scottish Association for Marine Sciences and assess the potential for developing disease and disease transfer in different sites. This should be based upon hydrodynamic information and site specific factors and draw upon the UK’s knowledge of algal pathology at Plymouth Marine Laboratory, Scottish Association for Marine Sciences and Newcastle University amongst others. Crucially, in view of the limited practical experience of growing algae at scale in the marine environment in the UK, collaboration with countries which already have extensive experience of algal cultivation at scale, for example China, other Asian countries and Chile, will be important in identifying possible solutions to this issue.

Research Challenge 5: Identify the biosecurity issues associated with using non-native or modified algal strains

Macro and microalgal strains used for the production of commodity products will need to demonstrate high productivity and tolerance to a wide range of abiotic and biotic pressures. There have been few attempts to domesticate algae and, as a result, they are undeveloped as a feedstock. There is considerable potential to improve both macro and microalgae through selective breeding, although stakeholders believe we currently lack the tools by which to exploit this opportunity at present and significant work is needed on the fundamental genetics and preservation of algae. Strain improvement (both breeding and GM) of algae falls within the remit of BBSRC. Likewise, non-native strains may be particularly robust and suitable for specific applications. In both cases, it will be crucial to assess the biosecurity issues associated with cultivation of improved or non-native cultivars, including the potential effects on local biodiversity of escapes of such cultivars or of gene transfer amongst algal species. This is a particular concern given that algal strains for cultivation should be robust and demonstrate high productivity under a wide range of environmental conditions. The protection of biodiversity is an area which fits within NERC’s remit.

Queens University Belfast have experience in the cultivation of a range of seaweed species and expertise in assessing the impact of invasive seaweed species that could pose a threat to indigenous communities while more broadly, the University of Portsmouth, Scottish Association for Marine Sciences, Plymouth Marine Laboratory and Marine Biological Association have capability in assessing the potential impact and dispersal of marine aliens and Swansea University have expertise in modelling biosecurity issues. There are also a number of groups working on this areas internationally including National University of Ireland, Galway, Station Biologique de Roscoff, France, Flanders Marine in Belgium, University of Aarhus, Denmark, University of Oviedo in Spain and Universities of Porto and Algarve in Portugal in the EU and further afield University of California, James Cook University Australia, and the University of Hawaii, USA. Stakeholders considered that an assessment of horizontal gene transfer potential could cost around £1 million and would need funding for at least 3 years.

Research Challenge 6: Identify the role of algae in carbon and nutrient cycling

Algae have the potential to fix large amounts of carbon from the atmosphere, however, little is known about how much of the fixed carbon ends up in benthic sediments, how much is locked up in the algae itself, how much is returned to the atmosphere and how much is lost as dissolved carbon in seawater. This organic matter has been shown to form an important component of marine food webs. The extent to which algal farming could affect marine carbon cycling and food chains is unknown and there is a need to understand how this could be affected by climate and temperature changes. Algae have the potential to affect the level of nutrients in the water column, having positive or negative effects on surrounding organisms and disturbing biogeochemical cycles. Indeed, in China, large scale cultivation of macroalgae has been shown to result in a decline in nutrient levels in the water column. The extent to which algal farming could affect nutrient levels in the water column will need to be addressed and, given that nutrient levels vary between different locations, should be assessed in multiple locations. This research challenge links with research challenges 3 and 9. Similarly, the potential for positively locking carbon into the land through harvesting algae and converting it to an organic fertiliser or biochar product needs investigation.

The UK has an excellent research base in algal carbon and nutrient cycling. Centres of expertise in biogeochemical cycling include the Centre for Environment, Fisheries & Aquaculture Science, (CEFAS), University of East Anglia and the University of Bristol, University of Portsmouth, University
of Essex, University of Glasgow and the University of Leeds, while Newcastle University and the University of Oxford have expertise in carbon cycling. A UK research programme in this area should be based around a number of pilot sites, and stakeholders suggested that this could cost around £5 million. It should bring together expertise in biogeochemical and carbon cycling, together with phycologists and hydrodynamic modellers to assess to what extent algal cultivation could affect cycling processes.

The research surrounding the opportunity for locking carbon into the land through hydrothermal processing and anaerobic digestion should bring together the centres of expertise in these areas, for example at the University of Leeds, Aston University, Newcastle University, with the agricultural research community, including Scottish Agricultural College, Harper Adams College, and ADAS and soil science community at Rothamsted Research and Cranfield University. It should draw upon existing land based renewables work on the potential to use biochar from pyrolysis as a carbon sequestration mechanism, for example the expertise of the UK Biochar Research Centre and University of East Anglia, and adapt it for algal systems.

**Research Challenge 7: Assess to what extent algal farms attract or repel marine mammals**

Marine projects have the potential to cause adverse effects on marine organisms, both in the construction phase, the operation phase and the end of life of the production facility. The largest issue regarding offshore wind, for example, is marine noise, especially for porpoise species which depend upon sonar for navigation. Marine activities can affect behaviour (in terms of feeding location, diving) and can affect the location of sensitive species. The effects of algal cultivation systems is unknown, but may vary according to the size of structures deployed, where they are located and the duration they remain in a given site.

The UK has a world leading capability in assessing the impact of renewables devices on marine biodiversity, and this complements the UK's leading position in developing marine mammal tracking systems and telemetry. UK capability includes expertise at the University of St Andrews (Sea Mammal Research Unit), Scottish Association for Marine Sciences, University of Aberdeen Renewable Devices Group, Bangor University, PRIMare (Peninsula Research Institute for Marine Renewable Energy), Bournemouth University and the University of Exeter. The Marine Renewable Energy Development in Scotland (MREDS) programme, based at Heriot Watt University has a work strand investigating the environmental and ecological risks of marine renewable devices and the COWRIE Project (Collaborative Offshore Wind Research Into The Environment) has investigated the effect of offshore wind turbines on marine mammals. The Sea Watch Foundation, Whale and Dolphin Conservation Society and the Marine Conservation Society have an interest in this area as do Joint Nature Conservation Committee (JNCC). International centres of expertise include the University of Kiel, German Oceanographic Museum and the National Environmental Research Institute (NERI) in Denmark.

A research project in this area is of high importance and the UK could develop a leading international position in this field. It should build upon the existing work already undertaken in the marine renewables sector from UKERC, Carbon Trust and SUPERGEN Marine, and apply this knowledge to a series of algal cultivation sites, in a number of locations, and over a number of years. Scottish Association for Marine Sciences have secured funding to assess the effect of macroalgae farming in Ireland on porpoises, but this is limited to a single small site, and a near shore environment. While this is useful as a 'look-see' experiment, the wider applicability of this work, due to the limited sample size will be restricted; therefore it is imperative that biodiversity impacts are assessed at a range of sites to provide the necessary replication needed. Stakeholders estimated that the costs for such a research project, assuming that experimental farms were available, would be around £1 million.

**Research Challenge 8: Understand to what extent algal cultivation affects biodiversity in the farm, the water column and benthic environment**

Artificial structures in the sea can affect biodiversity directly, by providing shelter for organisms or a substrate for growth, or indirectly, by affecting shading or by slowing wave action so sediments are deposited, resulting on effects on the benthic community. There is little data on these effects from algal cultivation and the best information available is from tropical environments and so may not be
immediately transferrable to conditions found in the UK. There is an urgent need to assess the potential direct and indirect effects of algal cultivation in marine environments in the UK context and how positive effects could be enhanced and negative effects mitigated (c.f. research challenge 10).

This research challenge would draw upon the UK’s world leading capability in assessing the impact of renewables devices on marine biodiversity, for example the Environmental Research Institute has expertise in assessing the impacts of renewable energy on benthic environments. This will also need to draw upon expertise in sediment dynamics at University of St. Andrews and Cardiff University, and the UK’s significant marine ecology expertise at Bangor University, Centre for Environment, Fisheries & Aquaculture Science (CEFAS), Swansea University, Scottish Association for Marine Sciences, Marine Biological Association, National Oceanographic Centre, University of Aberdeen, University of York and commercial companies such as APEM, Partrec, Marine Ecology Solutions and EMU amongst others. The British Oceanographic Datacentre should also be involved as the repository for UK benthic information. Effects on biodiversity in the water column and within the farm itself should be monitored alongside benthic effects.

A UK research programme in this area should be based around a series of experimental algal cultivation sites, which would be monitored over at least 4 years to ensure reproducibility. It would bring together phycologists with marine ecologists to assess the impacts of algal cultivation on the marine water column and benthic ecology. It should include a period of monitoring prior to project development to establish baseline data and monitoring throughout the cultivation operations.

Research Challenge 9: Understand the atmospheric effects resulting from trace gas emissions from algal growth

Algae, especially kelps, are known to release volatile organic compounds such as iodine, dimethyl sulphide and non-methane hydrocarbons such as organo iodines. Emissions can be increased significantly through exposure to stress such as grazing, UV radiation and when algae are removed from water, so there is a potential for release of volatile gases as a result of harvesting operations. These gasses can contribute to marine aerosol production and may have climate altering effects. Small-scale experiments at lab scale and on intertidal macroalgae have shown that emissions could potentially have a water nucleating effect; however this is of limited environmental concern in the UK context. There is limited knowledge of the emissions from sub tidal macroalgae stands or macroalgae farms. There is also a need to understand the emissions from different algal species and the factors which promote or mitigate emissions. In vivo monitoring is needed to establish what potential implications there could be on atmospheric chemistry from a macroalgae farm.

The UK has world leading expertise in atmospheric chemistry. Centres of expertise include the University of York (volatile gas emissions from macroalgae, and green tides), Plymouth Marine Laboratory (expertise in trace elements from microalgae), University of East Anglia (near surface trace gasses), National Oceanographic Centre, University of Essex, Scottish Association for Marine Sciences, University of the West of England (microbial volatiles), Newcastle University, University of Leeds and University of Manchester. Expertise in emissions from terrestrial plants, which could be applied to algal emissions, includes expertise at Centre for Environment and Hydrology and Lancaster University (CO₂ and methane emissions). Much of the expertise in this area was pulled together under the NERC Surface-Ocean / Lower Atmosphere Study (SOLAS) project.

A UK research programme in this area should be based around a series of experimental algal cultivation sites, which would be monitored over at least 4 years to ensure reproducibility. It would bring together atmospheric chemists with phycologists to ensure that monitoring best reproduces what would happen in a real facility. This research challenge has links with research challenges 3 and 10.

Research Challenge 10: Identify best configuration of an algal farm to maximise yield and environmental benefits and minimise negative environmental impacts

The farming of algae on a large scale in the seas and oceans is in its infancy, especially in the UK and Europe. There are still many ‘known unknowns’ about the realistic yields which could be achieved in UK waters and the environmental and ecological implications of cultivation. For example, densely packed macroalgae cultivation sites may be prone to disease, and poor yields may occur in the
centre, where water flow and hence nutrient delivery may be minimal. Further research will be needed to identify the best configuration of algal farms to both maximise yields and minimise environmental impact in order to develop a competitive and sustainable industry.

Stakeholders suggested that addressing this challenge will need an investment of £5 million over at least 5 years (including design and commissioning) and to be carried out at multiple sites to allow optimisation of farms through successive alterations to the farm layout. Cost effective harvesting and processing technologies should also be investigated alongside farm optimisation. This research challenge should build upon the expertise gained through mass cultivation of algae in China, other Asian countries and Chile in order to adapt best practice that has already been established in these countries.

**Research Challenge 11: Identify mechanisms to overcome nutrient limitation in offshore environments**

Offshore environments can vary in their nutrient distribution and may be less nutrient rich than near shore locations. Nutrient addition is desirable in terms of extending the growing season and increasing yields. However, this could impose significant costs both financially and environmentally in terms of the potential to cause eutrophication within the water column (impacting upon biodiversity, c.f. research challenge 8) and the environmental burden of fertiliser manufacture. Upwelling of nutrient rich deep waters may be an opportunity to provide nutrients for algal growth although the effects on ecosystem services from upwellings need to be better understood. The identification or breeding and selection of algal strains which have a reduced need for fertilisers is another potential avenue by which such limitations could be overcome. The latter option would need at least 10 years of research effort and thus would be a medium term opportunity.

The potential effects on ecosystem services from either of these options have not been considered and are areas where the UK could develop a significant capability. There are two parts to this research challenge: 1) research relating to potential effects on ecosystem services from upwelling; 2) research to develop new algal strains with improved nutrient use efficiency.

While the UK appears to have little practical involvement in nutrient upwelling, there have been some experiments in this area in USA, Japan and Norway. However, the UK is extremely well placed to consider the implications of artificial upwelling on biogeochemical cycles, with centres of expertise in biogeochemical cycling include Centre for Environment, Fisheries & Aquaculture Science (CEFAS), University of East Anglia, University of Essex, University of Glasgow and University of Leeds. A research programme on the effects of nutrient upwelling would have considerable synergies with any research programme on the effects of algal cultivation on biogeochemical cycles and would fit within the remit of both NERC and the AB-SIG. There is also a need to consider the implications of upwelling on biodiversity. This should consider to what extent harmful algal blooms could be stimulated by upwelling and the potential effects on marine life from any noise from upwelling systems. This should draw upon the expertise of the National Oceanographic Centre and others in assessing harmful algal blooms, and has synergies to the expertise required for research challenges 7 and 8. The UK is also well placed on both of these fronts and both of these areas are within NERC’s remit. As such, they could both form areas for further investigation when the AB-SIG fellowships are in place.

The breeding or selection of algal strains with increased nutrient use efficiency is within the remit of BBSRC. The UK has a world leading expertise in molecular biology of algae, bacteria and plants, which could be engaged to take forward this area of research for the potential benefit of UK industry. There is a huge diversity of algal strains and this diversity represents an untapped resource that could be exploited to identify industry-useful traits, either through selective breeding programmes or through biotechnology approaches. The UK culture collections, the Culture Collection of Algae and Protozoa (CCAP) at the Scottish Association for Marine Sciences and the Plymouth Culture Collection of Marine Microalgae at the Marine Biological Association, both of which are sponsored by NERC, will be a key resource in facilitating breeding efforts (c.f enabling action 1). The Chinese have been developing techniques for the genetic modification of macroalgae since the 1990s. The biosecurity

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issues associated with the utilisation of improved algal cultivars will need investigation \( (c.f.\) research challenge 5) as improved strains, bred for robustness, could potentially adversely affect ecosystem services through, for example, out-competing native strains or through horizontal gene transfer to native species. There is very little research on the biosecurity issues associated with algal cultivation. This could be an interesting area for NERC funded research, it is also highly relevant to BBSRC and would allow the UK to establish a leading position in this area.

**Enabling Action 1: Improve techniques for maintenance of algae cultures**

There is a huge diversity of algal strains and this diversity represents an untapped resource that can be exploited to identify industrially-useful traits, either through selective breeding programmes or through biotechnology approaches, which is clearly within BBSRC's remit. The UK has a world leading expertise in molecular biology of algae, bacteria and plants, which could be engaged to take forward this area to the benefit of UK industry, including potential uses for commodity products and higher value chemicals. Investment in UK culture collections will be an important way in which the diversity of algal species can be exploited to maintain UK competitiveness in this area.

There are currently no effective methods for the long term storage of master stocks for the vast majority of either microalgae or macroalgae strains. Techniques need to be developed to ensure that algal strains can be preserved in the long term and while some work in this area is ongoing, for example the Culture Collection of Algae and Protozoa (CCAP) are developing methods for the cryopreservation of *Ectocarpus*, more research is needed. The UK is considered a world leader in the area of protistan cryopreservation, however, international collaboration could help to further cement the UK position in this area, learning from the experience of others, preventing duplication of effort and speeding up the use of algae at industrial scales. International collaborators, in turn, could benefit from the UK’s experience. This work should include, amongst others, Sammlung von Algenkulturen Gottingen (SAG) in Germany for work on genotypic stability, the Australian National Algae Culture Collection (ANACC), National Institute of Environmental Studies (NIES) in Japan. Marbank, University of Bergen and Norwegian Institute for Water Research (NIVA) in Norway, amongst others, could add to any microalgae preservation work. Stakeholders suggest a research programme in the preservation of algae could take 4-5 years at a cost of around £1 million.

There is also a need to develop a comprehensive macroalgae culture collection, improving and expanding upon the so far limited culture collection resources, although this may be limited to the conservation of small gametophyte or sporophyte stages of macroalgae. In contrast to microalgae, the UK has a limited capability for storage of macroalgal strains with a limited number of strains maintained at the Culture Collection of Algae and Protozoa (CCAP) and at Queens University Belfast. There are few macroalgae culture collections world-wide. The Culture Collection of Algae and Protozoa (CCAP) and Roscoff collections are the only service collections within the EU, although the AlgiNet project in 2004 identified collections at the University of Konstanz, Germany, the Martin Ryan Institute, Ireland, Rijksbterarium, Netherlands, University of Oslo, Norway, University of Oviedo, Spain, Queens University Belfast, UK and Portuguese Seaweed at the University of Coimbra, Portugal. Internationally, the Kobe collection in Japan is the most formalised macroalgae collection. Collaboration between these facilities will be needed to share resources such as unique strains which have novel functionalities, techniques and to ensure redundancy in collections. Redundancy in collections is important in ensuring that if one collection is lost, the resource can be made available again from other collections.

These two research needs fall directly within the remit of NERC, with the culture collections being a key resource which could be drawn upon for biotechnology and strain selection work carried out through BBSRC grants \( (c.f.\) research challenge 11). Increased effort in this area would provide firm groundwork for the successful utilisation of algae in industrial applications.

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4 A service collection maintains strains, providing quality and standard cultures on an open access basis to the research community, commercial laboratories, industry and Government users upon payment of a fee.
Enabling Action 2: Develop a series of pilot scale, near shore macroalgal farms in the UK in conjunction with aquaculture

The cultivation of macroalgae in near shore locations is thought to be the most likely method by which macroalgae can be produced in the UK in the short term. The majority of cultivation systems used globally are long-line systems which consist of vertical strings, suspended from a horizontal string and held up by a series of buoys, and are analogous to the systems used in the mussel cultivation sector. Asia and Chile have significant experience with long line systems, but cultivation in the UK has been limited to a few, small scale trials.

The UK has a limited number of academic groups working in this area. The Scottish Association for Marine Sciences have performed a number of successful small scale trials (<1ha) on long lines over many years, predominantly in association with aquaculture, and Queens University Belfast also have expertise in this area. There is limited industrial activity in this area. Viking Fish Farms have a macroalgal hatchery in Scotland with the macroalgae subsequently grown in Loch Duart. Bød Ayre has a small number of long lines in Shetland.

There is increasing interest in the development of near shore facilities for algal cultivation, especially located alongside aquaculture enterprises where nutrient rich water streams can be cleaned by the algae. The resulting algae could be used for a range of existing or future applications including anaerobic digestion, food or chemicals. The Scottish Association for Marine Sciences have recently developed two small scale macroalgae farms in Scottish waters, while Queens University Belfast are developing a macroalgae farm in Strangford Loch as part of the £12.3 million Interreg IVB Energetic Algae project. The Crown Estate is also investigating the potential for developing a 30 ha macroalgae farm off the coast of Oban in Scotland. While there is growing momentum in this area, multiple sites, of around 10 ha are needed to ensure reproducibility and to negate site specific issues which could affect a farm. Any work in this area should be carefully integrated with the aquaculture industry, especially the mussel cultivation sector and the fisheries industries. Both of these sectors are strong in the UK.

The UK would benefit from working with international partners who have more expertise in this area. A key benefit from international collaboration is that the UK could benefit from a series of existing or developing facilities which could be monitored to assess effects on ecosystem services. Indeed, a number of other facilities are being developed throughout Europe, for example, the Centre d'Etude et de Valorisation des Algues (CEVA) in France, and Irish Seaweed Research Group in Galway, Ireland are developing macroalgae pilots as part of the Energetic Algae project. The Energy Research Centre of the Netherlands (ECN) and Norway have activities in this area which could be used to provide information. Collaboration with China and Chile will be vital to ensure that lessons learned in the commercial production of macroalgae in these countries are passed on to the UK, so the UK can learn from existing knowledge in this area. In turn, international partners would gain from the UK’s leading expertise in ecosystem services to improve the sustainability of their macroalgal cultivation operations.

A UK research programme in this area would draw upon industry and NERC expertise. Stakeholders suggested that it could cost around £ 2-3 million to establish and maintain 3-4 1 ha pilot farms for a 3 year period. Larger scale plants, of around 10 ha could cost significantly more. Consideration would need to be given to the application of the developmental infrastructure following programme completion. For example, would the the remaining infrastructure could become self-sustaining, be taken on by industry or be used as open access facilities?

Enabling Action 3: Develop infrastructure for offshore cultivation of algae and develop a series of pilot plants

The scale of material needed to support an algae to biofuels, bioenergy and commodity chemicals industry, combined with increasing conflict over near shore areas for other uses, has driven the interest in developing large scale macroalgae farms offshore. Offshore environments are, however, extremely high energy environments, and the cultivation systems used for relatively sheltered near shore environments are inappropriate for offshore projects. The US Marine Biomass Programme of the 1970’s tested the offshore cultivation of kelp in deep waters off the Californian coast. These
experiments failed, but there has been significant progress in our understanding of the offshore environment and the engineering requirements needed to exploit such environments.

The UK has considerable expertise in ocean engineering which could be applied to the development of such structures, and could leverage the UK’s world leading position in the development of offshore renewable devices. Academic expertise in this area is found at Newcastle University (Marine Sciences and Technology), University of Strathclyde (Naval Engineering and Technology), Plymouth Marine Laboratory (Ocean Engineering and Technology Group), University of Glasgow, Plymouth University, Liverpool John Moores University, University of Southampton (Coastal and Offshore Engineering Research Centre), Cranfield University (Offshore Engineering and Naval Architecture Group). Engineering expertise should be combined with wave flow modellers, such as Plymouth Marine Labs, Met Office and National Oceanographic Centre (who together form part of The National Centre for Ocean Forecasting), City University London and GL Noble Denton (who are working on the development of a wave modelling tool for applications in developing offshore renewables and structures), European Marine Energy Centre (EMEC) based in Orkney and algal biologists.

There is an increasing UK interest in the potential for developing offshore facilities for algal cultivation. Cranfield University, for example, are developing mesocosm facilities for the production of microalgae in the North Sea, while The Crown Estate have a long term vision to develop an offshore macroalgae farm in UK waters. As a first step towards achieving this vision, they have identified a potential near shore site close to Oban for a 30 ha test farm. The cultivation of the kelp *Laminaria hyperborea* on an offshore ring system has been successfully tested in the North Sea by the Alfred Wagner Institute in Germany, while Seaweed Energy Solutions in Norway have developed a flexible sheet-like structure known as the seaweed carrier.

A UK research programme in this area would draw upon both EPSRC and NERC expertise and stakeholders suggested that it would cost around £10 million to develop, build and monitor a pilot offshore plant. A pilot plant should aim to identify why previous efforts failed and should build upon the work in Norway and Germany, preferably as part of an international project.
Technology Roadmap and Supply Chains

Both micro and macroalgae have a wide range of existing markets including low value, high volume markets such as livestock feeds and higher value, lower volume markets such as speciality chemicals. Speciality chemicals, namely carotenoids, omega oils and antioxidants, have a range of applications including use in pharmaceuticals, cosmetics, nutrition, food applications and agrochemicals. In general, there are two principal routes envisaged for the scale up of algae production for commodity products. In the first proposed route it is considered that higher value products from algae will be commercialised first, and then will develop into increasingly lower value, higher volume markets such as biofuels, bioenergy and commodity chemicals production when sufficient scale of production can be achieved, and cost effectiveness assured. A second proposed route involving the utilisation of algae for bioremediation and carbon utilisation, would first target lower value markets such as fertiliser and substrates for anaerobic digestion, with the progressive addition of protein, oil etc to add value.

The timeline presented on the next page shows indicative timeframes for the deployment of bioenergy and biofuels from macroalgae and microalgal technologies in the UK and how these compare with the deployment of higher value markets. More information on the specific supply chains which are needed to develop each of the areas, and indicative timescales for addressing these challenges are presented in the following sections.

The principal focus of this report is to investigate those routes which could feasibly be commercial by 2025 (Figure 3). Quantification of deployment levels by 2025 are outwith the scope of this report. Thus, commercial deployment could refer to one or more facilities.

The most feasible use of algae in the period to 2025 covered by this report is for bioenergy through anaerobic digestion. This will initially draw upon macroalgae from near shore cultivation in the medium term, then offshore cultivation and algal biofilms as these are established in the medium to long term. The production of commodity products from algae in the UK may be a longer term opportunity, with the production of fuels via heterotrophic fermentation the first potential sustainable route to biofuels, perhaps being commercialised in the long term (10-20 years), with other fuels being commercialised in the longer term (beyond 20 years). For all potential opportunities, a concerted effort should be initiated now if we are to realise commodity chemical and energy production from algal feedstocks in the UK within these ambitious timescales. Even if this sector doesn’t develop in the UK, there is the opportunity for the development of UK technology and revenue generation through licensing and deployment of this technology abroad.
The section below considers in brief, by pathway, the current state of the art for production of each of these products, and the supply chain partners which need to be brought together to develop each opportunity.

**Pathway A – Macroalgae (near shore) to Bioenergy**

Pathway A, presented in Figure 4, represents the progressive deployment of nearshore cultivation of macroalgae from food products to high value chemicals and subsequently to a feedstock for the production of bioenergy by anaerobic digestion.
In 2009 approximately 15 million wet tonnes of seaweed biomass was harvested world-wide. The vast majority of this was from Asia and Chile. In contrast there is currently limited cultivation of macroalgae in the UK, with Scottish Association for Marine Sciences, Böd Ayre and Loch Duart actively cultivating macroalgae on a small number of long lines. There is an increasing interest into the farming of seaweed in the UK, with interest from The Crown Estate and Whitby Council amongst others. A pilot scale macroalgae farm will be established in Northern Ireland as part of the Energetic Algae Interreg IVB project.

**Short Term: Food**

There is an increasing knowledge of the important health benefits that certain species of macroalgae can bring for human food and healthcare. A small number of UK companies are harvesting macroalgae for human nutrition, including Böd Ayre, Seagreens (Hebridean Seaweed) and Irish Seaweeds. While these companies largely harvest their macroalgae resources from natural standing stocks, expansion of this market will require cultivation, both because it allows specific species to be cultivated, but also because it gives the potential for scalability in production which is not fostered by wild harvesting. Key researchers investigating the benefits of macroalgae as a food include Teesside University, University of Reading, Sheffield Hallam University, Scottish Crop Research Institute and Scottish Agricultural College. The Seaweed Health Foundation is an independent, not for profit organisation which provides commercially focussed and independent research on the health benefits of macroalgae as a food source and is playing an important role in expanding the markets for such products.

**Medium Term: High Value Chemicals**

Macroalgae is a high value resource for the production of a range of high value chemicals such as the hydrocolloids agar, carageenan and alginates. Macroalgae could potentially be used as a resource for the production of a range of high value bioactive substances and high value chemicals, which could be used in a variety of industrial applications, from consumer care to healthcare.

The closure of the Girvan alginate processing plant in 2009 means the UK currently has no commercial capability for the extraction of high value chemicals from macroalgae. While hydrocolloids are one possible market for macroalgae, there is increasing capability and competition from Asian producers. As a consequence, the UK may benefit more from the development of new markets based on the strength of its science and industrial base, e.g. bioactives which could be used in personal care products and the healthcare sector. The identification of marine bioactive molecules has been carried out at the Marine Biodiscovery Centre at the University of Aberdeen, University of St. Andrews and Plymouth Marine Laboratory. Wider work on bioactive molecule identification is carried out by Centre for Agriculture Bioscience International (CABI). CABI have formed a number of strategic research alliances to identify active products in biological materials, for example a collaboration with the British Antarctic Survey (BAS) aims to explore the BAS collection of microorganisms for bioactive molecules. While the majority of work on bioactive identification appears to be on microorganisms and microalgae, it is likely that the skills and expertise gained through such research could be transferable to macroalgae research. Few groups appear to work on the isolation of high value products from macroalgae, with perhaps the University of Leeds and University of York the most active this area. The UK has a strong capability in the isolation of high value products from other biomass materials, with particular centres of excellence in the isolation of natural products at the University of York, University of Nottingham, Biocomposites Centre (BC) and Aberystwyth University.
There are three principal issues which need to be overcome to improve the environmental sustainability of high value product isolation from macroalgae. The first is to reduce the energy demand of extraction technologies to ensure that the environmental and economic cost of processing does not outweigh the cost of the product obtained. Similarly, and related to the first challenge, is that there is a need to identify extraction mechanisms which are tolerant of higher moisture content feedstocks to negate the energy needed for drying wet material such as algae. Finally, the potential to use other solvents which may be equally effective yet less volatile, especially for products which will not be marketed as ‘natural products’ should be investigated. Engineering and chemical engineering expertise will be crucial to address these issues. Whilst all of these research challenges are highly applicable to the maintenance or improvement of ecosystem services, they are likely to fall under areas of research and development that are typically funded by the EPSRC or TSB, rather than NERC.

Long Term: Anaerobic Digestion

Anaerobic digestion is a technology favoured by the UK Government as a way of both treating waste materials and generating bioenergy. It can be deployed at a range of scales, and provides multiple benefits, including reducing landfill, producing a valuable digestate product which can be used in place of inorganic fertilisers and production of a range of energy products. Anaerobic digestion is a wet process, meaning macroalgae are particularly suitable.

Scottish Enterprise funded the Seaweed Anaerobic Digestion project which investigated the potential for using macroalgae as a feedstock for anaerobic digestion in the UK context. Through the Seaweed anaerobic digestion project a wealth of information regarding the economics and feasibility of using macroalgae for bioenergy in the UK was developed. Key researchers looking at the use of macroalgae in anaerobic digestion include Newcastle University, Aberystwyth University and Scottish Association for Marine Sciences. Wider expertise in anaerobic digestion is available at the University of Southampton and University of Manchester, and there are pilot and demonstration scale facilities at Newcastle University, University of Southampton, and at the Anaerobic Digestion Development Centre at the Centre for Process Innovation.

Anaerobic digestion is already a highly sustainable process; however, there are three issues which need to be addressed in order to further improve the environmental sustainability of macroalgae use in anaerobic digestion. The first is identification of how anaerobic digestion could be integrated into a biorefinery. For example understanding the extent to which residues from the extraction of specific materials and compounds could be used to feed anaerobic digesters considering the variation in chemical composition and volume between the residues. Such understanding would allow the production of high value chemical products from macroalgae while the residues could be valorised by anaerobic digestion if the scales of production were sufficient. The second is to establish to what extent macroalgae can be used in conjunction with other organic waste streams to achieve economies of scale in production or favourable economics, especially if there is a large disparity in scales between the amount of macroalgae residues produced from high value product isolation and the scales needed for anaerobic digestion. These issues are perhaps more suited to BBSRC and EPSRC than NERC and will require the focus of both engineers and biologists. The third issue is to identify potential markets for the digestate product other than simply spreading to land. Identification of new potential digestate produce markets would help overcome the current problem faced by farmers using digestate. At present the application of digestate to land is restricted both temporally and spatially by the Nitrogen Vulnerable Zone regulations. There are several anaerobic digestion facilities planned in the UK where the digestate will be used as a fertiliser source for microalgae, and perhaps the digestate from macroalgae production could be used in a similar way. Regulatory constraints could potentially limit the use of such algae for nutraceutical and feed applications, especially where manures are used as a feedstock for the anaerobic digestion plant, however, the use of algae grown on digestate for commodity products would represent a good opportunity to use these anaerobic digestion residues as a nutrient source for algal cultivation.
Pathway B – Macroalgae (offshore) to Commodity Chemicals

Pathway B (Figure 5) describes the potential development of offshore cultivation of macroalgae for commodity chemicals production, initially via bioenergy (anaerobic digestion) followed by biofuels (biobutanol and bioethanol) and finally commodity chemicals.

![Figure 5](image)

The offshore cultivation of macroalgae is perceived by many as the only plausible route in which the volumes of biomass required for biofuels, bioenergy and commodity chemicals production can be obtained. There is limited research experience world-wide in the offshore cultivation of macroalgae, with the bulk of work in this area carried out in the USA in the 1970s though the US Marine Biomass Programme. There is no commercial production of macroalgae in offshore environments.

Medium – Long Term: Anaerobic Digestion

Many of the supply chain issues associated with the offshore production of macroalgae will be common to the near shore production of macroalgae opportunity discussed above.

Long Term: Biofuels (Biobutanol and Bioethanol)

Macroalgae are rich in carbohydrates, and as such there will be potential routes for the development of fermentation based fuels such as biobutanol and bioethanol, which can be blended into transport fuels as a renewable biofuel. Internationally, there is an increasing research effort in this area. Bio Architecture Labs (BAL) and Dupont have received funding from the US Department of Energy to develop the production of biobutanol from macroalgae, which will be commercialised by Butamax, while projects in Chile, Norway and South Korea are investigating the potential for producing ethanol from macroalgae.

The UK capability in the development of microbial strains for fermentation processes is on par with leading countries world-wide. The UK has particular strengths in the development of microbial strains which can ferment C5 sugars to ethanol. There is expertise in fermentation of C5 sugars to ethanol at University of Ulster, Imperial College London, Aberystwyth University, University of Bath and University of Nottingham. There is expertise in the development of organisms for bio butanol production at University Nottingham, Edinburgh Napier University and Aberystwyth University. The University of Manchester has expertise in fermentation development. The UK also has a number of innovative companies in this area, particularly TMO Renewables and Biocaldol. Biocaldol are developing thermophilic organisms which can ferment C5 sugars to ethanol. Green Biologics are working on the manipulation of the acetone-butanol-ethanol (ABE) process to enhance butanol yield, and Kingston Research Limited are developing a bio butanol technology process which will be commercialised by Butamax. With the exception of Edinburgh Napier University, Scottish Association for Marine Sciences and Aberystwyth University, it is considered that all the above establishments are developing technologies based on terrestrial lignocellulosic biomass only; however, the potential to work on algal fermentation is also likely to exist at those institutions working on terrestrial biomass.
There are two principal research issues which could improve the environmental sustainability of the fermentation processes. The first is to identify potential ways to valorise the residual material remaining after the fermentation of the sugars within the macroalgae so as to both avoid a waste stream and to improve the economics of production. Such research could include investigating the potential to utilise residues in the animal feed industry, including livestock and aquaculture feed. The first opportunity would need to draw upon animal nutrition skills, for example at University of Leeds, University of Nottingham, University of Reading, ADAS and feed supply companies such as AB Agri. The second opportunity should draw upon recent work on the value of macroalgae as an aquaculture feed commissioned by Scottish Aquaculture Research Forum, and experts with aquaculture experience for example the University of Stirling, Centre for Environment, Fisheries & Aquaculture Science (CEFAS) and Swansea University.

The second challenge is to assess to what extent the carbon emissions arising from sugar fermentation could be re-circulated to algal cultivation, in effect, reducing the amount of CO$_2$ from the process, and closing the production loop. This research should draw upon microalgal cultivation skills available at various institutions, and process engineering expertise at University of Leeds, Cranfield University and Newcastle University. Research could also utilise the skills of engineering contractors such as Arup, Atkins and Black and Veatch.

**Longer Term: Commodity Chemicals**

The development of other commodity chemicals from macroalgae will require the isolation or development of microbial strains which can ferment macroalgal sugars to industrially interesting commodity chemicals such as succinic acid, lactic acid and polyhydroxyalkanoates (PHA). It will draw upon the same fermentation expertise as for bioethanol and biobutanol production described above and the same research challenges highlighted above will also apply to commodity chemicals production.

**Pathway C – Heterotrophic Microalgae to Biofuels**

Pathway C, shown illustrated in Figure 6, describes a scenario which draws upon the existing expertise surrounding the heterotrophic cultivation of microalgae for commercial production of high value chemicals and from the developing biofuel markets. Heterotrophic routes can be used to produce a wide range of chemicals and fuel products. These products include alkanes and vegetable oils (the latter of which can be converted to hydrogenated vegetable oils (HVO)) both of which can be used as a bio-kerosene, and non-fungible fuels such as bioethanol and biodiesel FAME which can be used in road transport.

**Current Markets: High Value Products**

The production of algae through heterotrophic routes is commercial, with around 10,000-20,000 tonnes of algae produced each year globally through this method. The principal market is for high value products such as omega oils (Martek, now part of DSM) and cosmetic products (Solazyme). Omega oils are in demand for healthcare and as a source of feed for aquaculture. There has been some interest in this area in the UK, for example Algacytes have stated that they will focus on the production of omega oils from algae. However New Horizons Global operated an omega oil production facility near Liverpool and have recently ceased trading. With the exception of the University of Liverpool and University of Hull, there appears to be few academics working on heterotrophic fermentation in the UK.
Long to Longer Term Markets: Biofuels

The key attraction of heterotrophic routes is the potential for mass production of chemicals from algal strains, by a method which is relatively independent of climatic factors. Heterotrophic production is a closed process and so this facilitates the utilisation of GM and exotic, non-native strains of algae. The production of oils suitable for biofuels from heterotrophic fermentation has been investigated by Solazyme. In 2010 Solazyme delivered 80,000 litres of algal-derived marine diesel and jet fuel to the U.S. Navy. Martek (part of DSM), have also recently formed a joint venture with BP to develop this technology.

In order to develop biofuels from algae, it will be necessary to bring together expertise in heterotrophic fermentation, molecular biology and industrial biotechnology. The UK has a considerable strength in molecular biology which could be used to develop strains with a high oil yield and high productivity (biomass) or develop novel strains of microalgae which can excrete biofuel precursors into their growing medium. Expertise in algal molecular biology is found at a number of different institutions, including Rothamsted Research, Durham University, Scottish Association for Marine Science, University of the West of England, University College London, Swansea University, University of Sheffield, Plymouth Marine Laboratory, Newcastle University, University of Manchester, Kings College London, Imperial College, University of Exeter, University of East Anglia, Coventry University, Cardiff University and Cambridge University, and could draw upon expertise in carbon partitioning (for example at the John Innes Centre, Rothamsted Research, University of York and University of Essex). Development of industrial production will need to draw upon the industrial biotechnology expertise of companies such as Novacta and Ingenza, and the scale up facilities available at the Centre for Process Innovation.

Stakeholders consider that there is a need to identify alternative sources of organic carbon which could be used as feedstocks for heterotrophic production to replace the current sugar feedstocks e.g. waste materials such as glycerol. Identification of alternative feedstocks could improve the environmental impact (and economics) of heterotrophic fermentation processes. Research should also consider how different feedstocks impact upon algal chemistry. This research fits within the remit of BBSRC.

Pathway D – Wastewater to Biofuels

Pathway D (Figure 7) describes a scenario by which microalgal biofilms from wastewater treatment could be developed, initially for bioenergy (anaerobic digestion) then for biofuels or commodity chemicals.

The potential for combining wastewater treatment with the production of microalgae is an area of considerable interest, especially in view of the ability of algae to remove nitrogen and phosphates from water. A number of concepts have been described, including biofilm technologies where wastewater is trickled over a solid structure on which algae and bacteria, have been immobilised. Although not commercial at present, the economic and environmental benefits of algal wastewater treatment suggest that there is significant scope for development in the future, should sufficient land be available near wastewater sources. Identification of the amount and suitability of land near to wastewater treatment facilities would be a useful topic for investigation and one which falls within the remit of NERC.
Medium Term Markets: Bioenergy (Anaerobic Digestion)

Many UK wastewater treatment plants have anaerobic digestion facilities for treatment of sludge. Therefore, algae biomass resulting from wastewater treatment, can be added to the existing anaerobic digestion infrastructure on site, and can increase biogas yields. The development of this opportunity will require the type of expertise in anaerobic digestion demonstrated by Newcastle University, University of Southampton, University of Greenwich and the University of Manchester and could draw upon the pilot and demonstration scale facilities at Newcastle University, University of Southampton, and at the Anaerobic Digestion Development Centre at the Centre for Process Innovation to demonstrate the potential optimal feedstock mixes of sludge to algae to maximise biogas yields. Newcastle University has expertise which could be used to determine whether natural consortia of microalgae and bacteria generated through biofilms would be digestible in anaerobic digestion processes and how this could be optimised.

Many of the research challenges pertaining to the environmental sustainability of using microalgae in anaerobic digestion have been covered in the macroalgae anaerobic digestion sections above (Figures 4 & 5).

Longer Term Markets: Biofuels, Bioenergy and Commodity Chemicals (Hydrothermal Conversion Routes)

In the longer term, it is possible that hydrothermal routes could be commercialised which could use algal biomass and produce a wide range of biofuel, bioenergy and commodity chemical products. Hydrothermal routes can utilise wet biomass (typically 25% slurry in water) and as such little water removal would be needed after harvesting of biofilm material for these processes. Among the benefits of hydrothermal processing routes for using algae which have been used for wastewater treatment is that a mixed feedstock can be utilised, which is a good fit for wastewater biofims as the composition can change based upon the composition of the wastewater, temperature, season etc. Hydrothermal processing also offers a route for utilisation of wastes which may contain impurities such as hormones or heavy metals.

Biocrude, produced through the hydrothermal liquefaction of wet biomass, could provide a route to exploiting the full range of products currently produced from fossil fuels, from plastics, to fuels and energy and more specialised chemicals. There are relatively few groups worldwide working on hydrothermal processing routes, and the UK is amongst the leaders in the field. Centres of expertise in this area include University of Leeds (predominantly liquefaction) and Aston University (predominantly pyrolysis). Wider expertise in thermochemical conversion technologies (albeit mainly on conventional dry thermal processes) which could be leveraged in this area include Newcastle University, Imperial College London, and the Centre for Process Innovation.

There are three key issues which need to be addressed to improve the environmental sustainability of hydrothermal conversion processes, all of which are based on the need to identify possible valorisation routes for the by-products from the process. Specifically, this should address 1) the potential to recycle nutrients from the waste processing water into other products, for example algae growth, 2) recycling or utilisation of the CO₂ stream, 3) the potential products which could be derived from the solid char material from pyrolysis and the residues from liquefaction. Addressing these challenges will require significant engineering expertise and fits within the remit of EPSRC.

Pathway E – Microalgae (offshore) to Biofuels

Figure 8 describes Pathway E in which the offshore cultivation of microalgae is developed for biofuels markets.

Although this is believed to be a longer term opportunity, with deployment on a commercial scale possibly more than 25 years away, it is included in this section given the considerable synergies which this area has with the production of macroalgae and the general marine renewables sector, for example wave energy devices such as Pelamis, from which much knowledge could be transferred.
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Figure 8 Pathway E - Commercialisation Pathway for the Production of Biofuels and Commodity Chemicals from Offshore Cultivation of Microalgae
Conclusions

There has been considerable interest surrounding the use of algae for biofuels, bioenergy and commodity chemical production in the past few years. There is also an increasing emphasis to ensure that these products are produced in an environmentally sustainable manner and demonstrating sustainability is a key requirement of European support schemes. This report was commissioned by the AB-SIG in recognition of the potential marketing advantages for industry in demonstrating sound environmental stewardship and the potential for the UK science base to develop an international standing in this emerging area. This report identifies the specific market opportunities which the UK could exploit and the research needs required to underpin the environmental sustainability of these opportunities.

The cultivation and processing of macro- and micro-algal biomass in the marine and terrestrial environments has not yet been performed on a large scale in the UK and there are many unknowns regarding the potential effects of upscaling from our current level of relatively small scale production. Many of these are ‘known unknowns’ surrounding the potential effects on ecosystem services in the environment and are directly relevant to the remit of the AB-SIG. Through the AB-SIG, NERC are funding new research areas through two Fellowships one in macro- and the other in micro-algae research. Appointment of AB-SIG Research Fellows will ensure the expansion of NERC science in this strategically important area. A Knowledge Exchange Fellow is also being funded by NERC, who will work with project developers to assess business opportunities and the environmental implications of this activity. The Knowledge Exchange Fellow will also provide an interface between the Director, Research Fellows and stakeholders.

Eleven research challenges have been identified which will provide the necessary evidence to ascertain the environmental sustainability of large scale production. Several of these challenges are dependent upon the development of a series of trial/demonstration facilities, of sufficient scale for representative data to be gathered. These include assessing the potential effects on marine mammals, impacts on benthic, water column and organisms associated with the farm, investigating biogeochemical and carbon cycles, and the potential climatic effects from the release of volatile gases. The UK has a significant strength in research relevant to marine and terrestrial ecosystems which could be leveraged to investigate the potential impacts on the environment from large scale algal cultivation and processing. The UK has significantly less expertise than other countries, both in Europe and the rest of the world, especially Asia, in macroalgae cultivation and should utilise international expertise to develop best practice in macroalgae cultivation. Such research could be facilitated through a collaborative agreement or project in this crucial enabling area or by the recruitment of international expertise.

This report has identified four market opportunities which could be developed for the sustainable production of biofuels, bioenergy and commodity chemicals from algae. These are:

- The near shore cultivation of macroalgae for bioenergy, via food and high value chemicals,
- The offshore cultivation of macroalgae for commodity chemicals, via bioenergy,
- Heterotrophic conversion of sugars to biofuels via high value chemicals,
- Algal biofilms for biofuels, via bioenergy.

These have been chosen based on potential scalability in the UK, low energy consumption and low environmental impact. It is likely that in the UK at least, a progressive, step-wise approach to the commercialisation to many of these opportunities will occur, first developing higher value markets, then as experience is gained and costs reduced, and if higher value markets become exhausted, progressing to lower value markets including biofuels, bioenergy and commodity chemicals production. None of these opportunities are currently commercial at the scales needed for biofuels, bioenergy and commodity chemicals production, and each require, to differing extents, further research and development work to improve their sustainability credentials. The progression of this area will be dependent upon a concerted effort between research-base and industry stakeholders to develop new technologies in a commercial framework to establish a competitive UK algal business sector.
In summary, the UK has the potential to develop an environmentally sustainable industry in the area of algal biofuels, bioenergy and commodity chemicals; however, this must be underpinned by sound science. The UK has an excellent research base in ecosystem services, and it is crucial that this expertise is utilised in assessing the ongoing development of this industry. As a starting point for the UK, NERC and TSB has made a commitment to research in this field by funding the AB SIG in the form of a Director, which NERC are further supporting through two independent research Fellowships and a Knowledge Exchange Fellow, whose work will support activities of the AB SIG.
Consultees

We are extremely grateful for the time and insights of the following people during the development of this study.

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<td>Vicky Jackson</td>
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