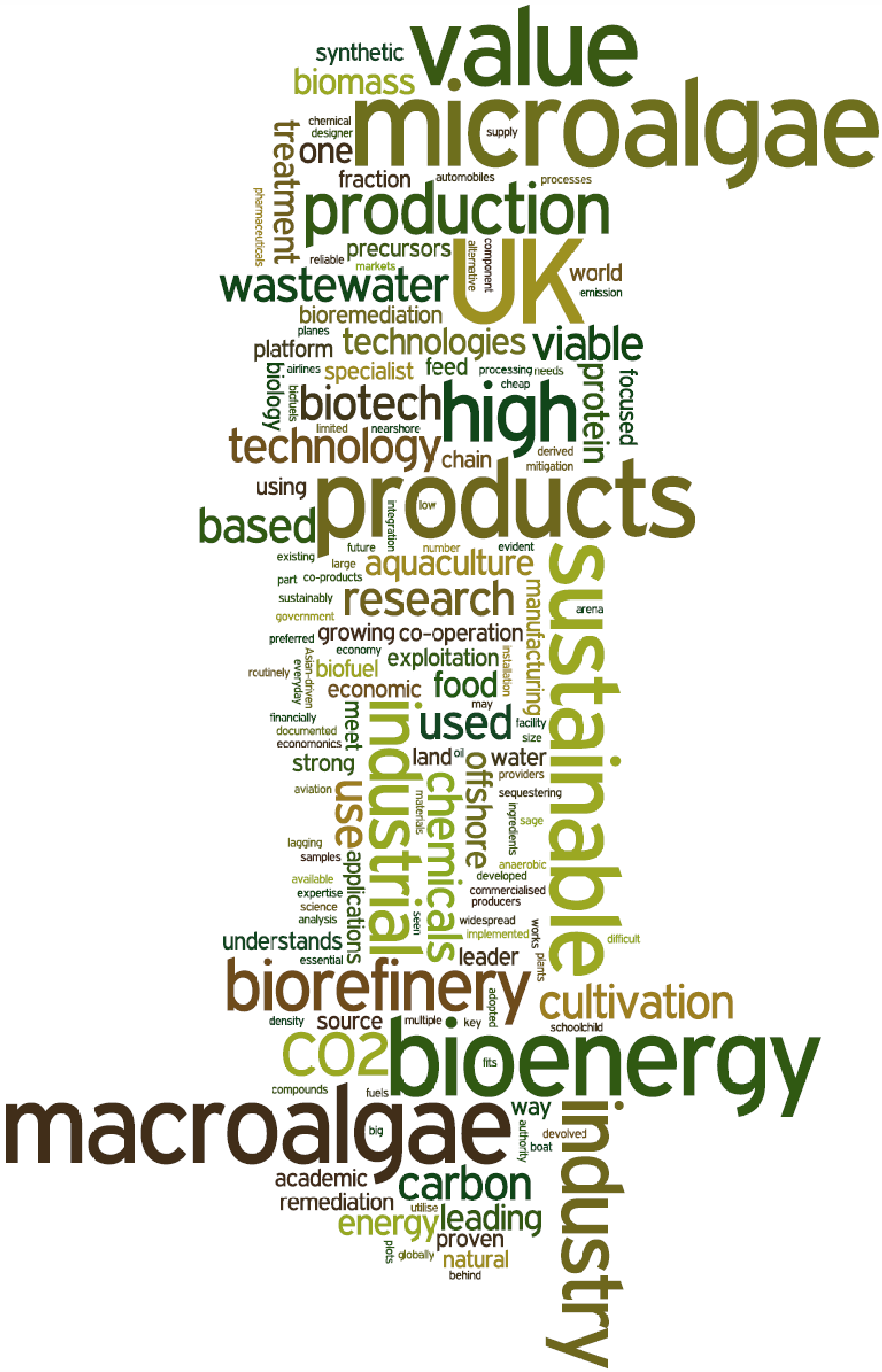
A UK Roadmap for Algal Technologies



May 2013

Collated for the NERC-TSB Algal Bioenergy-SIG
by B. Schlarb-Ridley and B. Parker, Adapt

NATURAL ENVIRONMENT RESEARCH COUNCIL

Technology Strategy Board
Driving Innovation

Research Councils UK
Energy
For a Low Carbon Future

Living With Environmental Change

Knowledge Transfer Network
Biosciences

Knowledge Transfer Network
Energy Generation and Supply

Knowledge Transfer Network
Environmental Sustainability

adapt

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the inputs of the participants of the Algal Bioenergy Special Interest Group (AB-SIG) Roadmapping Workshops October/November 2012. They provided the selection of the sectors most relevant to the commercialisation of algal technologies for the UK. A list of workshop participants, and summary of workshop outcomes, can be found in Appendix 1. We would also like to express our appreciation for the support of Dr Michele Stanley and Dr Tom Jenkins in writing this document, and for the co-ordination of the workshops by the Institute for Manufacturing, Cambridge. We are grateful for the feedback on draft versions of the roadmap received from the AB-SIG Programme Executive Board as well as from various stakeholders from academia, industry and the public sector.

TITLE PAGE

The wordle image[1] on the title page is based on the vision statements from participants of the two roadmapping workshops organised by AB-SIG in October/November 2012.

ABBREVIATIONS / *DEFINITIONS*

AB-SIG	NERC-TSB Algal Bioenergy Special Interest Group
AD	Anaerobic Digestion
BBSRC	Biotechnology and Biological Sciences Research Council
CCAP	Culture Collection of Algae and Protozoa
CEFAS	Centre for Environment, Fisheries & Aquaculture Science
CPI	Centre for Process Innovation
CSR	Corporate Social Responsibility
DECC	Department of Energy and Climate Change (UK)
GHG	Green House Gas
HACCP	Hazard Analysis Critical Control Point
HRAP	High Rate Algal Pond
HTL	Hydrothermal liquefaction
insolation	*Amount of solar radiation reaching a given area*
IP	Intellectual Property
KBBE	Knowledge-based bio-economy
KTN	Knowledge Transfer Network
LCA	Life Cycle Assessment
NOC	National Oceanographic Centre
MASTS	Marine Alliance for Science and Technology Scotland
MBA	Marine Biological Association
microalgae	*In this roadmap this term is defined to include cyanobacteria*
MREDS	Marine Renewable Energy Development in Scotland
NERC	Natural Environment Research Council
PBR	Photobioreactor
Pers. comm.	Personal communication
RD&D	Research, Development and Demonstration (Deployment)
ROC	Renewable Obligation Certificate
PML	Plymouth Marine Laboratory
PRIMare	Peninsula Research Institute for Marine Renewable Energy
PUFA	Polyunsaturated fatty acid
SAMS	Scottish Association for Marine Science
Seaveg	Sea vegetable
SRA	Strategic Research Agenda
STW	Sewage Treatment Works
TSB	Technology Strategy Board
yrs	Years

[1] Compiled using wordle.net. The size of the words is proportional to how often they were mentioned in the vision statements; shade of colour and positioning are random.

Disclaimer

The information provided in this report was collated between January and May 2013. The choice of sectors for the case studies is based on the ranking provided by participants of the two roadmapping workshops organised by AB-SIG in October/November 2012. Data and insights from the workshops have been used to build the business case studies. Assumptions that had to be made during the workshops were, as much as possible, checked with available literature, and corrected where appropriate to ensure the accuracy of information presented in this report.
A degree of harmonization was required to summarise the outputs of the two workshops, and we apologise if in the harmonization process some aspects that have been highlighted by participants have been omitted. Adapt carries no responsibility for the accuracy of information provided by referenced sources.

Contents

List of Figures

List of Tables

List of Case Studies

Algae have attracted considerable interest globally as a potential feedstock for a bio-based economy. The industrial and research communities in the UK have much to offer in this space: UK companies and academics have laid the foundations for several now globally-used algal biotechnology and engineering advances, and as an island nation we have a strong history in macroalgal commercial activities.

This roadmap has been commissioned by the NERC-TSB Algal Bioenergy Special Interest Group, to complement its Strategic Research Agenda of 2012. It focuses on the commercialisation potential of algae-related products, processes and services for the UK, being mindful of environmental implications. It builds on the outcomes of two workshops held by AB-SIG in October and November 2012 with a variety of stakeholders, whose contributions are gratefully acknowledged.

The report signposts the strengths of the UK science base, gives a snapshot of UK and global algal industries, and presents an overview of trends and opportunities for algae–derived products and services. Based on these, it assesses the UK's potential for profiting from international markets, and highlights actions required to compete in a global marketplace. It then presents seven sectors which the workshop participants had identified as being of particular relevance and value for the UK. Examples of products or processes in each sector are given in case studies which evaluate their commercial, technical and environmental strengths and weaknesses.

Roadmap Aims

To highlight which algal products, processes and services

- are on the market or close to deployment
- are under development
- require considerably more R&D
- have highest potential for UK, according to community

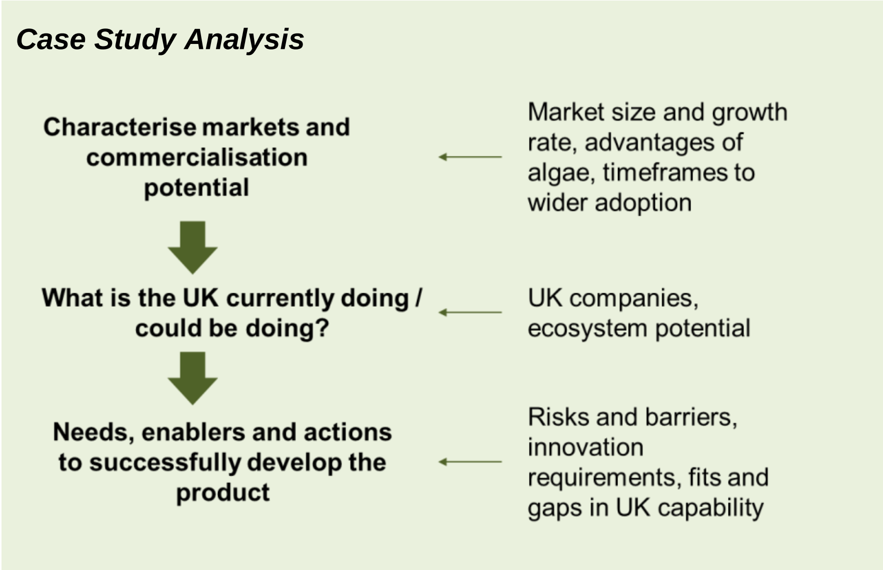
To identify interventions needed to seize opportunities in a

- timely
- economically and environmentally sustainable way

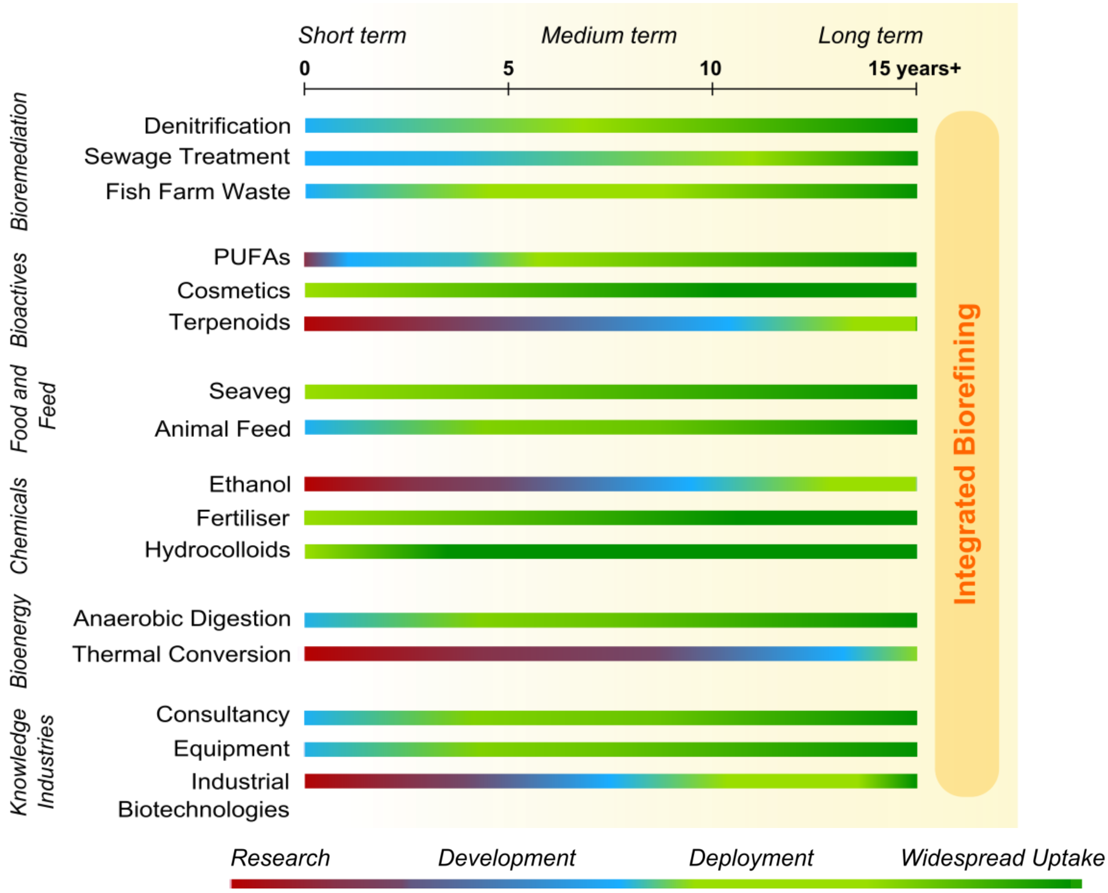
Sectors and their Case Studies (macroalgae: ; microalgae:)

Biorefining	*Lens through which business case studies can be viewed*
Waste water remediation	Denitrification of brine wash generated from groundwater purification
	Nutrient recovery from sewage treatment
	Remediation of fish farm waste
Bioactives	Nutraceuticals: Omega 3 PUFAs DHA and EPA
	Macro- and microalgae-derived cosmetics
	Pharmaceutical terpenoids
Food and feed	Premium sea vegetable and condiments
	Animal feed
Chemicals	Ethanol
	Organic fertiliser
	Hydrocolloids
Bioenergy and biofuels	Biomethane via Anaerobic Digestion
	Synthetic biofuels via thermochemical conversion
Algae knowledge & technology industries	Consultancy on Algal Know-how
	Technology suppliers for equipment and industrial biotechnologies

Each case study concludes with key actions required to develop UK competitive advantage relative to the global commercial landscape.



Indicative timescales to commercialisation for each case study are provided in the following figure:



Based on the available data, the report identifies the following areas to be **commercially most promising**:

In the short to medium term:

- high value products from both macro- (condiments and premium sea vegetables, high value uses of hydrocolloids) and microalgae (increased production of established and emerging bioactives, *e.g.,* DHA, EPA, pigments, antioxidants, sunscreens)
- bioremediation using macro- and microalgae linked to feed and fertiliser production and decentralized energy generation via AD
- knowledge industries for technology provision and consulting

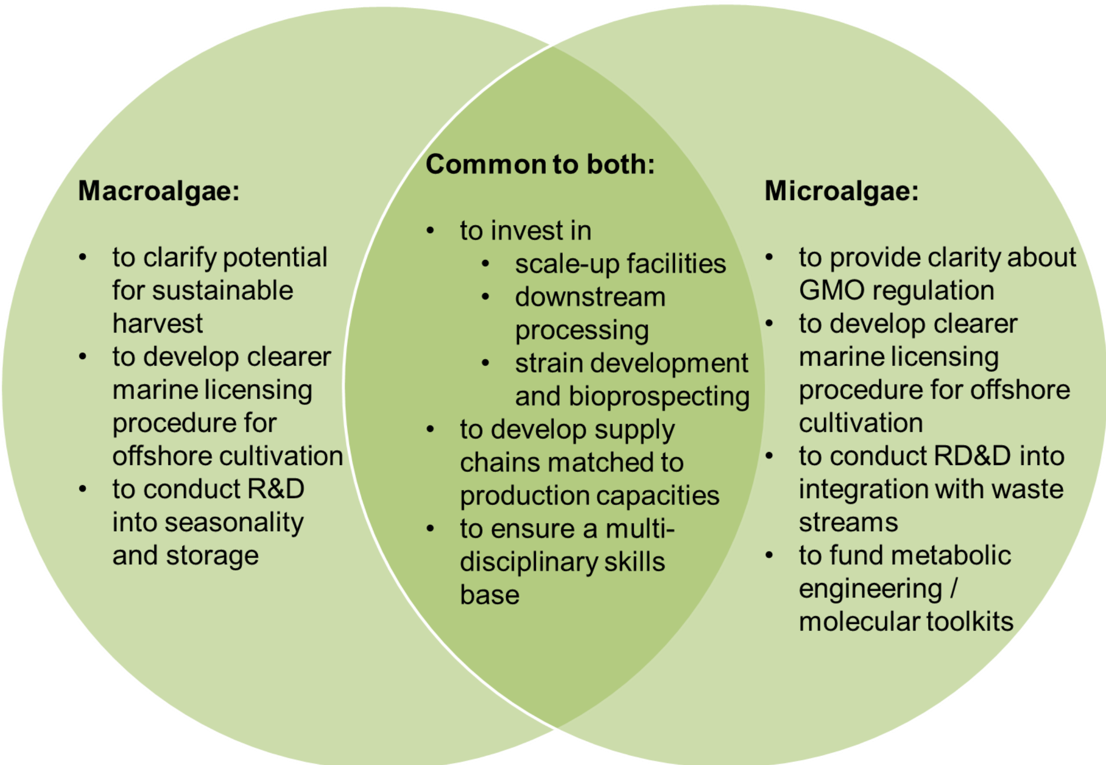
In the medium to long term:

- integrated biorefining of micro- and macroalgae coupled to fractionation or thermochemical conversion for a suite of chemical and energy products
- novel bioactives through bioprospecting (micro- and to some extent macroalgae) and metabolic engineering (microalgae) for pharma, cosmetics, nutrition

To realise these opportunities, the following were deemed by workshop participants to be **key enablers**:

Technical	• **Accessible test / pilot / demonstration facilities** to collect data on ecological impact, operational costs, life cycle parameters and variability of yields, all of which will underpin developing business case scenarios and scale-up • **Mapping potential sites** for sustainable cultivation across the UK • Encouraging **IP generation and interdisciplinary skill development** in these areas • Expertise in **bioprospecting, strain development and metabolic engineering** / algal synthetic biology toolkits • **Multi-disciplinary training** (biology, engineering, processing, biorefining, sales & marketing)
Financial	• **Security of funding for RD&D**, with increased accessibility for micro-SMEs, to attract and retain skilled personnel / entrepreneurs, and accelerate commercialisation • **Successful examples of algal biotechnology applications** leading to increased confidence and maturing supply chains • Attributing a **direct value to bioremediation** through financial incentives / penalties
Services	• Closer **interaction and knowledge transfer between academia and chemical & pharma industries**, to guide development of algal expression for platform chemicals and pharmaceutically interesting scaffold molecules • Algal bio-business **incubators and clusters** • **Marketing / increasing visibility of UK expertise and products** on the global stage: for environmental know-how, technologies and products • Customer / **public awareness** and acceptance to increase demand and avoid NIMBYism
Regulation	• Providing **clarity about regulatory context** (macroalgae: marine licensing; microalgae: GMO regulation) • Simplifying IP protection

The report concludes with a **set of recommendations** for actions by funding bodies and regulators:

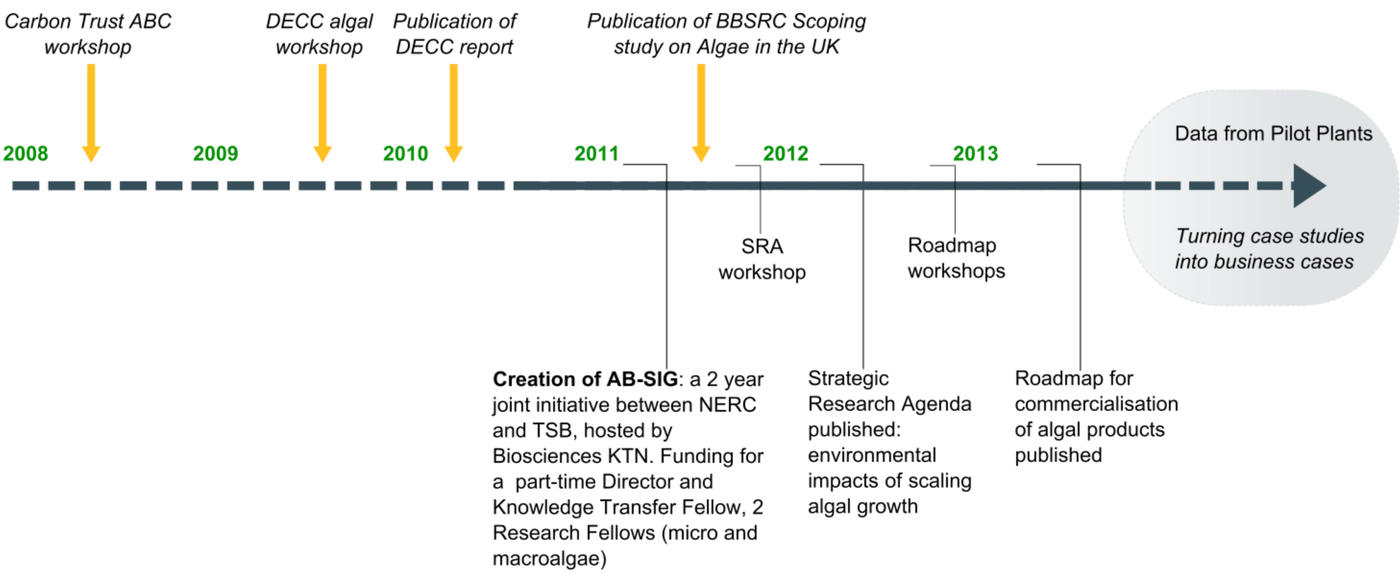


1. SETTING THE SCENE

Algae have attracted considerable interest globally as a potential feedstock for a bio-based economy. The industrial and research communities in the UK have much to offer in this space: UK companies and academics have laid the foundations for several now globally-used algal biotechnology and engineering advances[2], and as an island nation we have a strong history in macroalgal commercial activities. To assess how the UK might best respond to this interest and capitalise on opportunities offered by algal technologies, the UK community of stakeholders have gone through a process that was catalysed by workshops and consultations organised by, amongst others, the Carbon Trust, DECC, the Research Councils, and the NERC-TSB funded Algal Bioenergy Special Interest Group (AB-SIG, hosted by Biosciences KTN with support from the Environmental Sustainability KTN). A number of reports have been published which highlight the challenges, opportunities, strengths and gaps from different angles (see Figure 1). These include

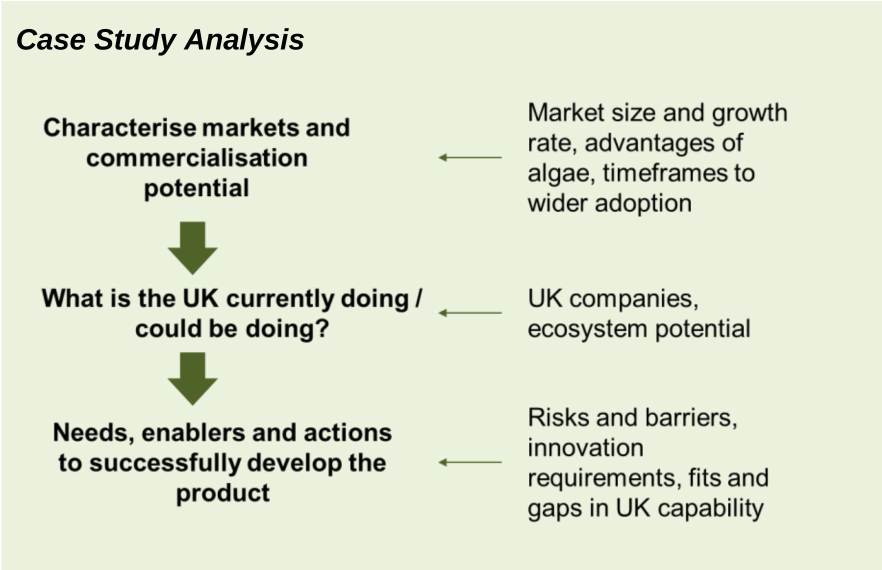
- the DECC report 'Assessing the Potential for Algae in the UK' from 2010[3] (which provided an initial assessment of UK strengths and weaknesses, and made early recommendations)
- the BBSRC scoping study 'Algal Research in the UK' from July 2011[4] (which emphasised challenges, opportunities and expertise around biological and biotechnological research)
- the AB-SIG strategic research agenda 'Research Needs in Ecosystem Services to Support Algal Biofuels, Bioenergy and Commodity Chemicals Production in the UK' of February 2012[5] (which highlighted challenges, opportunities and UK expertise around ecological implications of algal scale-up)

Figure 1: Timeline of activities building an algal community in the UK



[2] *e.g.,* the 'Biofence' photobioreactor design and microalgal fermentation: see BBSRC scoping study 'Algal Research in the UK' p. 4; pp. 19-20; available at bbsrc.ac.uk/web/FILES/Reviews/algal_scoping_study_report.pdf
[3] available at nnfcc.co.uk/tools/assessing-the-potential-for-algae-in-the-uk
[4] available at bbsrc.ac.uk/web/FILES/Reviews/algal_scoping_study_report.pdf
[5] available at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81879.pdf; appendix at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81878.pdf

To complement previous publications, this AB-SIG funded roadmap focuses in particular on the commercialisation potential of algae-related products, processes and services for the UK, taking into consideration the environmental implications of such commercial activities. It builds on the body of the above-mentioned reports, as well as on the outcomes of two workshops held in October and November 2012[6], which were run by the Institute for Manufacturing[7] to assist AB-SIG to develop a strategic roadmap with input from a variety of stakeholder groups. In Chapter 2, we present 15 business case studies for a range of sectors which were highlighted in the workshops as being of particular relevance and value for the UK. For each case study[8], information is provided on:

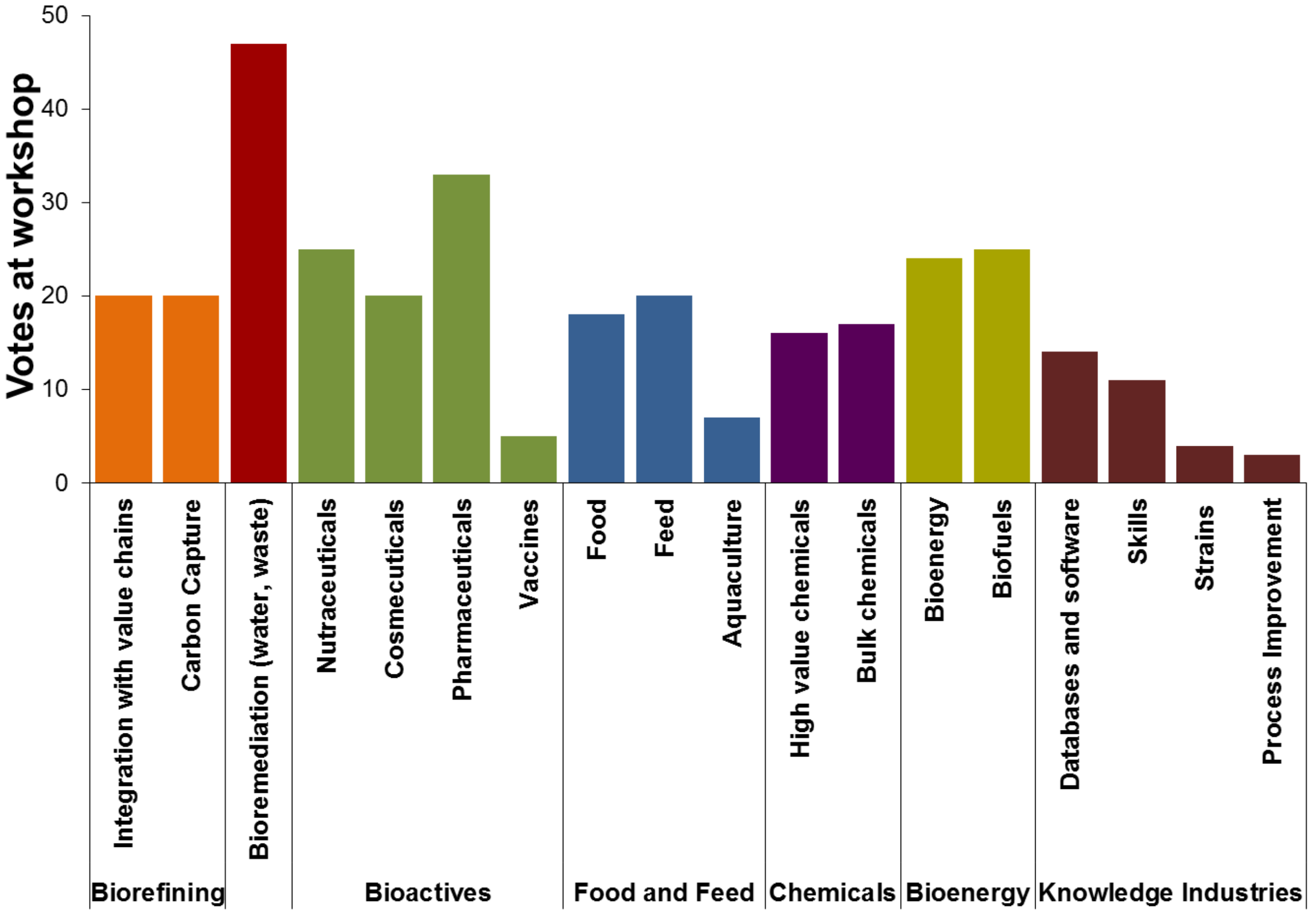


- why this is an important market
- how the technology could be commercialised
- indicative timescales to commercialisation
- advantages over incumbent approaches
- market size and growth rate
- companies operating in this sector
- the potential of UK ecosystems to contribute to commercialisation
- technological, commercial and other barriers and risks
- fit and gaps concerning relevant UK capability
- key innovation and R&D needs
- enablers for successful UK commercialisation
- key actions required to develop UK competitive advantage relative to the global commercial landscape

Figure 2 (overleaf) highlights the seven different market sectors identified as most relevant to the UK as commercialisation opportunities. It shows subcategories for the seven market sectors, and the number of votes attributed to these by workshop participants.

[6] 31 Oct - 1 Nov (Manchester); 5-6 Nov (London); a summary of the workshops can be found in Appendix 1.
[7] ifm.eng.cam.ac.uk
[8] All data has been collated in the same tabulated form; to make reading the document easier, some case studies have been summarised in text in the main body of the report. The detailed tables for those are provided in Appendix 2, to enable direct comparison of all case studies.

Figure 2: Overview of workshop votes for relevance by sector



This report aims to define the likely timeframes and actions required to establish a strong and sustainable Algal Biotechnology industry within the UK, through the sector overviews and business case studies described in Chapter 2.

The following introductory sections provide context of the current academic and industrial expertise in the UK, and the position of UK activity in the expanding global algae landscape, which inform the business case studies in Chapter 2.

1.1 UK science-base strengths

One of the great assets the UK has to offer is its knowledge base, and by incorporating this expertise into commercial ventures the UK can increase its competitive advantage. Furthermore, the UK could position itself as a global provider of advice services and consulting for environmental and sustainability assessments as well as biotechnology and engineering know-how, thereby further strengthening the knowledge-based bioeconomy (KBBE).

The landscape of algae-related expertise in biological and environmental sciences and engineering in the UK has been investigated both in the BBSRC Scoping Study of 2011, and in the AB-SIG Strategic Research Agenda of 2012.

The BBSRC scoping study describes the knowledge landscape as follows:[9]

- Academia in the UK has great expertise in the environmental and ecological sectors for both micro- and macroalgae, especially (but not exclusively) in the marine sector.
- The UK's expertise in life cycle assessment (LCA) is also of importance globally.
- The algal culture collections in the UK are internationally highly regarded.
- Both academia and industry are actively involved in designing photo bio-reactors (PBRs) and integrated systems for producing algal biomass.
- Fundamental biology is one of the UK's key strengths, and a wealth of experience exists in taxonomy, physiology, metabolism, biochemistry and molecular biology of algae. This expertise is now increasingly being employed in a biotechnological context, with high relevance to underpinning a bio-based economy.

The AB-SIG Strategic Research Agenda has identified UK-based expertise relevant to each of its research challenges; an overview of this is given in Table 1.

Further detail on snapshots of the expertise landscape can be obtained from Chapters 1 and 5 of the BBSRC scoping study, and up-to-date contact details and introductions to the relevant academic expertise can be obtained for example via the AB-SIG Knowledge Exchange Fellow, who will be in post until Dec 2015, and Biosciences KTN in general.[10]

The UK therefore has a highly valuable base of expertise, and current support networks (*e.g.,* AB-SIG, the KTNs) are providing a crucial role to facilitate access to this expertise for the benefit of algae-focused commercial ventures. However, continuity of funding is essential to maintain this advantage: both R&D funds to attract and retain academic excellence, and resources to provide continuity and expansion of the support networks that facilitate successful project development between academia and industry, will be essential if the UK is to establish a globally competitive algal commercial sector. With funding for the AB-SIG staff terminating in Dec 2015, it is essential that a lasting legacy, together with a platform for expansion, of the knowledge transfer activity in the algal sector are set up.

---

[9] p. 10 of BBSRC scoping study 'Algal Research in the UK', available at bbsrc.ac.uk/web/FILES/Reviews/algal_scoping_study_report.pdf; for more detail on the academic expertise reviewed see Chapters 1 and 5.

[10] Other networks that can facilitate introductions include the EnAlgae project (enalgae.eu), the InCrops Enterprise Hub (incrops.co.uk), the European Algae Biomass Association (eaba-association.eu), and the Algae Biomass Organization (algaebiomass.org).

Table 1: Overview of research challenges and associated UK expertise, as identified in AB-SIG Strategic Research Agenda (for abbreviations see glossary)

No	Research challenge	Associated expertise	UK institutions with said expertise (U=University)
1	Identify the key environmental factors influencing yield and biochemical composition of algae	- algal cultivation expertise in macroalgae - algal cultivation expertise in microalgae - biochemical variations in macroalgae for thermochemical / biochemical conversion processes	- SAMS, UNewcastle, Queens U Belfast - SAMS, PML, NOC, UNewcastle USwansea - UNewcastle SAMS, ULeeds, UAberystwyth
2	Identify suitable sites for algal production	- marine spatial planning expertise - hydrodynamics, biogeochemical cycling, and phycology modelling	- The Crown Estate, SAMS, USouthampton Solent, UHeriot Watt, UDundee, UStirling - USwansea, UStrathclyde, UNewcastle, UK Hydrographic Office, CEFAS, *et al*
3	Develop LCA capability including carbon balance and sustainability information suitable for aquatic and marine systems	- LCA - algal LCA - sustainable management of marine resources	- Imperial College London, UManchester, USheffield Hallam, USouthampton, UAberdeen, UBath; North Energy, E4Tech - PML, UManchester, UBangor, USwansea, UCambridge, ERM Ltd - MASTS
4	Assess the potential for algal diseases to affect cultivated algae and wild stocks	- modelling expertise - algal pathology	- UStirling, NOC, PML, SAMS - PML, SAMS, UNewcastle *et al*
5	Identify the biosecurity issues associated with using non-native or modified algal strains	- assessing the impact of invasive seaweed species - assessing the impact and dispersal of marine aliens - modelling biosecurity issues	- Queens U Belfast - UPortsmouth, SAMS, PML, MBA - USwansea
6	Identify the role of algae in carbon and nutrient cycling	- algal carbon and nutrient cycling - carbon cycling - locking carbon into the land through hydrothermal processing and anaerobic digestion (incl. agricultural expertise, soil science) - carbon sequestration via biochar	- CEFAS, UEast Anglia, UBristol, UPortsmouth, UEssex, UGlasgow, ULeeds - UNewcastle, UOxford - ULeeds, UAston, UNewcastle, Scottish Agricultural College, Harper Adams College, ADAS, Rothamsted Research, UCranfield *et al* - UK Biochar Research Centre, UEast Anglia
7	Assess to what extent algal farms attract or repel marine mammals	- assessing the impact of renewables devices on biodiversity, developing tracking systems, telemetry - assessing environmental/ecological risks of marine renewable devices - assessing effects of offshore wind turbines on marine mammals	- USt Andrews, SAMS, UAberdeen, UBangor, PRIMare, UBournemouth, UExeter - MREDS programme at UHeriot Watt - *general:* Sea Watch Foundation, Whale and Dolphin Conservation Society, Marine Conservation Society, Joint Nature Conservation Committee
8	Understand to what extent algal cultivation affects biodiversity in the farm, the water column and benthic environment	- assessing the impact of renewables devices on marine biodiversity - assessing impacts of renewable energy on benthic environments - sediment dynamics - marine ecology	- see above (challenge 7) - Environmental Research Institute - USt Andrews, UCardiff - UBangor, CEFAS, USwansea, SAMS, MBA, NOC, UAberdeen, UYork; APEM Ltd, Partrec, Marine Ecology Solutions, EMU Ltd *et al.*
9	Understand the atmospheric effects resulting from trace gas emissions from algal growth	- atmospheric chemistry - emissions from terrestrial plants	- UYork, PML, UEast Anglia, NOC, UEssex, SAMS, UWest of England, UNewcastle, ULeeds, UManchester - ULancaster
10	Identify best configuration of algal farm to maximise yield and environmental benefits	- farming of algae on a large scale	- CEFAS
11	Identify mechanisms to overcome nutrient limitation in offshore environments	- implications of artificial upwelling on biogeochemical cycles	- CEFAS, UEast Anglia, UEssex, UGlasgow, ULeeds

1.2 UK and global algal industries

The algae-related business community is expanding in the UK as well as globally, with a considerable degree of fluctuation. There are fundamental differences between macro- and micro-algal activities.

Macroalgae

Globally, macroalgae are both collected from the wild (*e.g.,* in the UK, Ireland, Norway, the US and Chile) and cultivated (esp. in China, Indonesia and the Philippines), predominantly for food, feed, fertilisers, chemicals and cosmetics. In Northern Ireland, where Anaerobic Digestion (AD) attracts quadruple Renewables Obligation Certificates (ROCs), macroalgae are becoming increasingly interesting as a component in mixed feedstock AD operations.

In the UK, macroalgae are a traditional crop. They have been wild-harvested and used for food, feed and as fertiliser in coastal communities for centuries. A core of commercial activity is hence well established: Companies such as the Hebridean Seaweed Company, Böd Ayre, Mara, Irish Seaweed, Viking Fish Farms, and Seagreens harvest seaweeds (2,000- 3,000 dry tonnes total harvest per year in the UK[11]) from the wild and produce food and feed products as well as speciality chemicals and fertilisers.

Particularly given the extended coastline, the opportunities for macroalgae in the UK extend beyond their current applications, both in terms of high value bioactives and (in the longer term) commodity products. In addition, they can contribute to bioremediation, and there is scope for expansion and a renaissance in traditional uses. Examples of opportunities are given in case studies three (bioremediation), five (cosmetics), seven (food), eight (feed), nine (chemicals/ethanol), ten (fertilisers), eleven (hydrocolloids) and twelve (bioenergy/methane) of Chapter 2. Some novel applications are already being commercialised, but fulfilling the wider potential will require increased production capacity, through wild harvest, but mainly through cultivation, for example on long-lines. Sustainable wild harvest is close to maximum capacity at the locations with current activity; expansion may be possible in some new geographical areas[12]. Barriers include accessibility of wild stocks and safety considerations for harvesting, access rights, and environmental considerations. In order to estimate the possible sustainable increase in wild harvesting, recent data on both stock availability and true long-term environmental impact will need to be consolidated and ideally expanded (the last thorough review of stocks was carried out by F. T. Walker in the late 1940s[13]; a more recent study focused just on the Outer Hebridies[14], further studies are under way at MBA[15] and at The Crown Estate, through the Natural History Museum[16]). Any environmental impact assessment needs to address both type and quantities of seaweed to be harvested, frequency of harvesting and recovery times[17].

Cultivation does not have a long-standing history in the UK; however, pilot scale-up on long-lines is under way (*e.g.,* at SAMS, Queens University Belfast, Böd Ayre, Hebridean Seaweed Company, and through The

---

[11] Pers. comm., Michele Stanley, Feb 2013

[12] Current data seems to indicate that large-scale and sustained harvesting of natural stocks of most (possibly all) seaweeds in most locations is unsustainable. (Pers. comm., Prof Michael Cowling, The Crown Estate, May 2013)

[13] Walker*,* FT (1947), A Seaweed Survey Of Scotland–Fucacae. *Proceedings of the Linnean Society of London*, 159: 90–99

[14] Michael T. Burrows, Martin Macleod, Kyla Orr: Mapping the intertidal seaweed resources of the Outer Hebrides, Scottish Association for Marine Science Internal Report No. 269 (2010)

[15] Monitoring abundance and distribution of rocky intertidal macroalgae, *e.g.,* mba.ac.uk/fellows/nova/

[16] 2 studies: (a) Aim: To document the biodiversity of the intertidal seaweeds of the Outer Hebrides, an area of interest for seaweeds and which has been identified as a major gap both in the Natural History Museum seaweed collections and The Crown Estate knowledge. (b) Aims: (i)To undertake a detailed review of evidence of changes in the large brown zone-forming seaweeds in the UK, and ii) to evaluate available satellite and bathymetry data and map the current status of the resource in order to create a baseline by which comparisons can be made. *Both reports should be published by the winter of 2013.* (Pers. comm., Prof Michael Cowling, The Crown Estate, May 2013)

[17] The Norwegians wild harvest 170000 wet tonnes of kelp annually. This is done in a strict five year rotation between the different areas which are licensed to ensure the minimum amount of environmental impact.

Crown Estate). Establishing how seaweed cultivation can be done at scale in an environmentally and economically sustainable manner is of paramount importance for developing this industry. The Bioenergy TINA estimates "up to 0.6Mha of sea would need to be used to grow macroalgae for energy production, in line with DECC 2050 pathways analysis. Future detailed analysis from The Crown Estate is expected to offer further insights into the area of the UK seabed which macroalgae could be farmed on. Initial insights from this indicate that significantly greater production might be possible, by a factor of two or three. However, increased production will not necessarily mean greater use as an energy source, owing to the higher profitability of macroalgae in pharmaceutical, chemical and food markets."[18] The Crown Estate has commissioned studies on ecosystem effects of large-scale seaweed farming. The report from Phase 1 was published in October 2012[19]; Phase 2 is due to be completed in 2014[20].

Microalgae

Microalgae are globally grown at significant scale for high value food, neutraceutical and cosmeceutical use, *e.g.,* in Australia (>650 ha of open ponds for beta-carotene[21]), the US, China and Israel. Microalgal-derived biofuels are currently developed both through heterotrophic cultivation (*e.g.,* Solazyme[22]), and phototrophic growth (*e.g.,* Algenol[23], Sapphire Energy[24]).

Microalgal cultivation in the UK is predominantly still at R&D scale. Although we have had a succession of highly innovative algal (bio)technology companies since the 1980s, that have been the cradle for heterotrophic DHA production as well as tubular photobioreactor designs (*c.f.* BBSRC Scoping Study "Algal Research in the UK", Chapter 1.3[25], for a history of UK algae companies), the volume of phototrophically grown microalgae has until recently been negligible. Widespread interest in commercialising microalgae has arisen in the UK community mainly over the last decade; initially through the global interest in algal biofuels, and more recently through their potential as an industrial biotechnology platform and for bioremediation. Examples of commercial opportunities are provided in case studies one (groundwater denitrification), two (sewage treatment), four (omega-3 polyunsaturated fatty acids (PUFAs)), five (cosmetics), six (pharmaceuticals), eight (feed) and 13 (synthetic fuels) of Chapter 2.

Microalgae are currently either being grown[26] by early stage companies that, although promising, do not yet have any significant production capacity (*e.g.,* Aragreen, AlgaeCytes; previously Merlin Biodevelopments and Scottish Bioenergy[27]), by research institutions at R&D scales, or by the aquaculture industry for their own use. By contrast, the heterotrophic growth of microalgae for DHA is commercially established in the UK at a capacity of 800,000L fermentation volume[28].

Despite the increased interest, the overall photoautotrophic production of microalgae in the UK is estimated to be only between one and five dry tonnes per year[29], mostly at pilot scale. With the possible exception of

---

[18] TINA Bioenergy Summary Report, September 2012, LCICG, page 11; available at carbontrust.com/media/190038/tina-bioenergy-summary-report.pdf

[19] Available at thecrownestate.co.uk/media/358662/initial_environmental_consideration_of_large-scale_seaweed_farming.pdf

[20] examining standing stock in certain areas so as to put the anticipated ecosystem effects due to large scale farming into context of existing natural processes (pers. comm., Prof Michael Cowling, The Crown Estate, May 2013)

[21] *e.g.,* Cognis *Dunaliella* plants at Whyalla (400ha) and Hutt Lagoon (≥250ha); also smaller facilities (*e.g.,* Aurora LLC at Karratha)

[22] solazyme.com/technology

[23] algenolbiofuels.com/; they are producing 8000 gallons per acre per year of ethanol for <$1 per gallon photoautotrophically with a marine cyanobacterium in a 36-acre closed demonstration facility

[24] sapphireenergy.com/; they are producing biocrude from algae grown in open saltwater ponds in a 300-acre demonstration plant

[25] bbsrc.ac.uk/web/FILES/Reviews/algal_scoping_study_report.pdf

[26] Unless specified, we use 'growth' synonymous with photoautotrophic growth.

[27] Technology providers such as Algenuity and Varicon Aqua, although they grow some biomass, do not aim at being producers.

[28] Pers. comm., New Horizons Global, Jan 2013

[29] Exact amount is unknown; the calculation is based on the 16,000L PBR at Boots, where the average productivity is 0.4 g/L/day (pers. comm., Steve Skill), with ca 200 days of operation per year, resulting in 1.3 dry tonnes per year. Swansea University have 1,600L PBRs, resulting in 0.13 dry tonnes, using the same assumptions. A few other

the Boots-PML venture at Nottingham, these pilots are too small to make meaningful projections. The UK does not currently have open-access facilities operating at adequate scale to enable innovative SMEs to demonstrate new commercial routes can operate with technical and economic viability at pilot scale. In addition, the volumes of algae currently produced are insignificant compared to the requirements of most industries interested in the material as a feedstock. This constitutes a serious bottleneck in the development of microalgal technologies. Urgent investment is needed into larger, strategically positioned open access test, pilot and demonstration facilities, to prove economic and technological feasibility, environmental sustainability and public acceptability of commercialisation opportunities such as those given in the case studies in Chapter 2.

Features common to macro- and microalgae

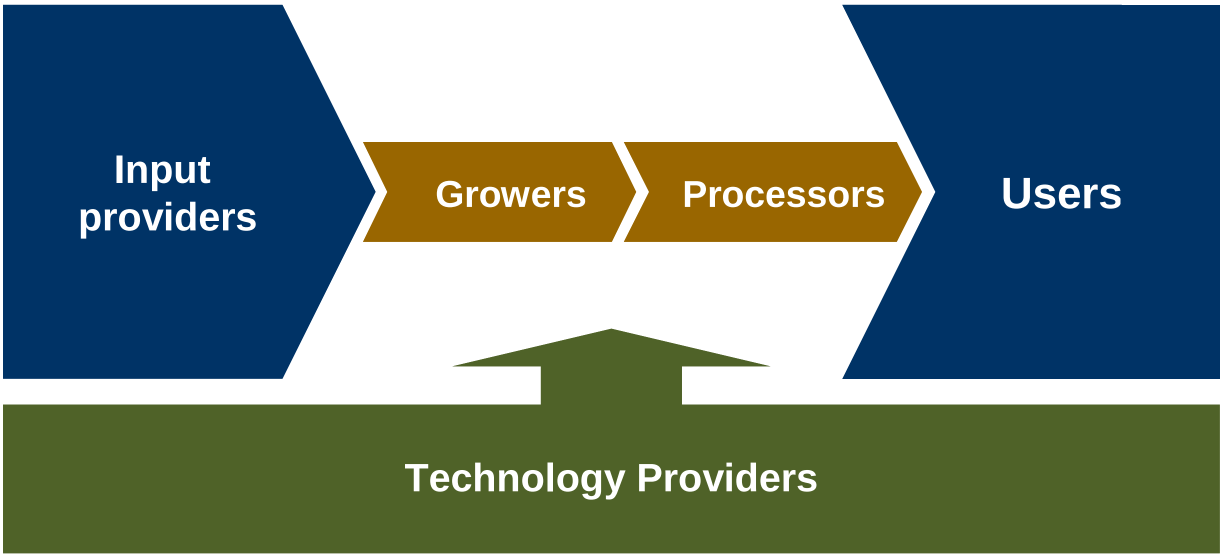
Despite their differences, the supply chains for macro- and microalgal products have several features in common:

- Many industries have resources to offer that could be used for algal growth (*e.g.,* nutrient waste streams, land / marine space, for microalgae also CO_2, low-grade heat). However, since turn-key solutions for algal growth and harvesting at commercial scale relevant to UK conditions do not exist as yet, these potential input providers hesitate to invest into pilot facilities or RD&D projects due to the associated risks.
- A multitude of companies are interested in using algal biomass, but they are held back by the high price of algae, and/or shortage of supply due to limited current production capacity.
- The UK is rich in technology providers who can underpin the transition of algal growth out of R&D scale into commercial production; however many are themselves still in the process of moving to industrially relevant technology readiness levels.

The limited current production capacity (and for microalgae, the shortage of test, pilot and demonstration facilities) constitutes a serious bottleneck in the supply chain. This leads to a marked imbalance along the supply chain (see Figure 3), which is more pronounced for micro- than macroalgae.

The need for accelerated scale-up of sustainable macroalgal cultivation on long lines, and for accessible test and pilot sites for microalgae (paving the way for demonstration and deployment) is a recurring theme throughout the report.

Figure 3: Current imbalance in the supply chain for algae in the UK



research institutions have similarly sized PBRs (*e.g.,* Queens University Belfast, Cranfield University, Birmingham City University, PML, Bath). The amount produced by the aquaculture industry for their own use, and by young companies such as Aragreen and AlgaeCytes, is unknown.

1.3 Trends and opportunities for algae–derived products and services

Products

Macroalgae

While the majority of macroalgal biomass grown in the UK is currently used for comparatively low value applications, such as fertilisers and animal feed (based on traditional use; *e.g.,* Hebridean Seaweed company; Böd Ayre, Uist Asco), there is a trend towards addressing higher value markets such as condiments for human food, and inclusion in cosmetics products (*e.g.,* 'Rest and be thankful' range by Made in Heaven[30]; Seaweed Organics and Scottish Botanicals by Diana Drummond Ltd[31]). Some biomass is also being used for processing into hydrocolloids (Marine Biopolymers, Cybercolloids). This trend should be encouraged, in order to develop this feedstock for further high value applications (such as novel uses for hydrocolloids in drug delivery, personal care and food, fucoidins for functional foods), especially in the context of industrial biotechnology and biorefining. In addition, companies and research institutions are preparing for scale-up of production on long lines, to underpin the longer-term development of this feedstock for commodity chemicals and bioenergy (*c.f.* Figure 4).

Microalgae

In response to the persistent challenges surrounding the commercialisation of microalgal biofuels, several companies that were founded as part of the biofuels wave are (re)positioning themselves towards

- providing technologies rather than bulk biomass (*e.g.,* Solix[32]; Heliae[33]; BioProcess Algae[34])
- dual value chains of health/feed and energy products (*e.g.,* Solazyme[35]; Cellana[36])[37]
- heterotrophic growth for high spec products (*e.g.,* Solazyme Roquette Nutritionals[38]).

Considerable potential exists to increase market penetration for currently successfully commercialised products, such as nutraceuticals and high value food and feed ingredients, cosmeceuticals and speciality chemicals (*e.g.,* pigments, antioxidants, fertilisers and polysaccharides). This is contingent on an increase in production capacity, and on successful marketing of the benefits of algae-derived products and ingredients, which provide justification for paying a premium price. In addition, both bioprospecting and metabolic engineering (using algae as a chassis for novel products) are expected to lead to a suite of new algae-derived high value products, particularly for pharmaceutical and chemical use. Any penetration beyond the speciality markets however requires a simultaneous increase in production capacity and reduction in cost of algal biomass or product (see Figure 4).

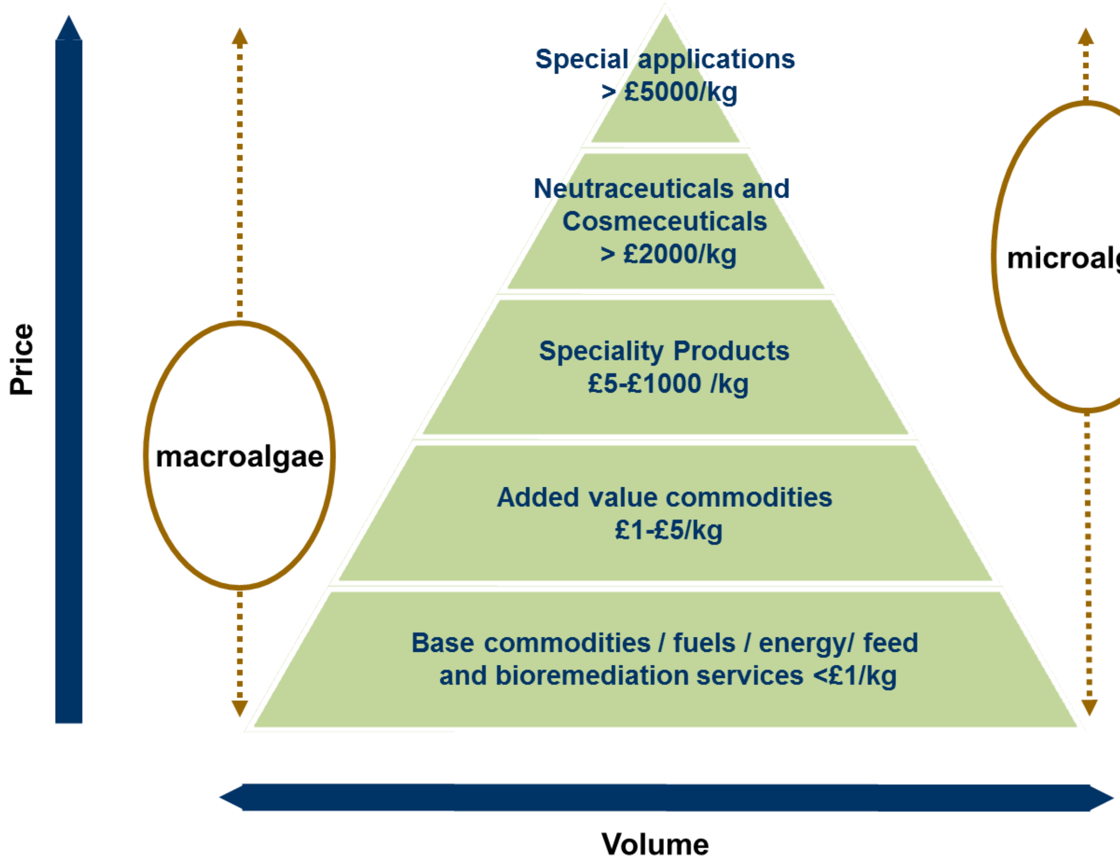
Due to increase in global population, and the move towards protein-richer diets, there is great need for protein for food and especially feed, and microalgal protein would be a logical potential replacement for the highly unsustainable feedstock fishmeal (*c.f.* Case Study 8 in Chapter 2). The price for fishmeal in 2012 was £1.36/kg (£2/kg digestible crude protein)[39]. Economic modelling of microalgal biomass produced on small scale in the EU[40] predicts a minimum price of £20/kg dry biomass[41], while *e.g., Chlorella* can be imported from China for €5/kg dry weight[42]. The EU prediction is based on an R&D facility, and costs would be reduced through economy of scale in commercial operation, including savings in personnel costs.

---

30 madeinheavenuk.co.uk/product-category/rest-and-be-thankful/
31 seaweedskinfoods.co.uk/
32 solixbiofuels.com/
33 heliae.com/
34 bioprocessalgae.com/
35 solazyme.com/market-areas
36 cellana.com
37 Qualitas Health, focusing on commercialisation of EPA, has arisen from the ashes of the 1st algal biofuels company GreenFuel Technologies; *c.f.* algaeindustrymagazine.com/aim-interview-dr-isaac-berzin/
38 srnutritionals.com/
39 World Bank Commodity Markets "Pink Sheet" worldbank.org/prospects/commodities
40 Based on yields 16 tonnes per hectare per year
41 Pers. comm., Chris de Visser, EnAlgae project.
42 BBSRC Algal Scoping Study, Chapter 3, p. 36; bbsrc.ac.uk/web/FILES/Reviews/algal_scoping_study_report.pdf

Savings in terms of land use efficiency and material costs are less pronounced when scaling up on surface area (as is required when harvesting sunlight) compared to scaling on volume (in heterotrophic growth, or internally lit photobioreactors), and are technology-dependent. Proof of concept will have to be provided to see if larger-scale production, coupled with technology innovation and optimized cultivation techniques, can lead to sufficiently low costs to be able to address the fishmeal market. This applies also for any other commodity and value-added product derived from microalgae. In the meantime, there are opportunities to couple staged scale-up of production capacity[43] with addressing specialty feed markets such as supplements and premium pet feed.

Figure 4: Current capacity and pricing of products from micro- and macroalgae[44]



Technologies

In order to overcome the challenges currently associated with scaling algal growth up, such as optimizing productivity and lowering the cost and energy requirement of growth, harvesting and processing, innovative technologies are essential. Globally this is an expanding and successful field. Due to its strong R&D profile and innovation record, the UK is well placed to produce relevant game-changing technologies. These also include molecular toolkits and methodologies to develop algae as a platform for industrial biotechnology. The challenge will be to pull these innovations through to the market (traditionally many UK inventions have not emerged from the 'Valley of Death' due to lack of funding to move from proof of concept to product), and then provide global visibility to achieve market penetration.

[43] Current production capacity in the UK is struggling even to meet the quantities of biomass required by the feed industry to conduct feed formulation trials, and would have to grow by several orders of magnitude for the market to be able to embrace algae as a staple feed ingredient. Targeting supplements and niche feeds will still require further increase in production capacity, but can be achieved more realistically in the near term.

[44] Adapted from Figure 2, SRA Appendix p. 61; available at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81878.pdf

Know-how

A significant new development is the increasing global awareness of the importance of sustainability factors in scale-up of algal growth. The US Department of Energy, for example, commissioned a report in 2012 on "Sustainable Development of Algal Biofuels in the United States"[45], which highlights the importance of life cycle assessment, cumulative impact analysis and ecosystem service analysis. The UK's extensive expertise in these areas could and should be used to provide consultancy services on an international level. A key challenge lies in marketing the benefits of such services to increase uptake.

In addition, a number of niche markets exist where UK expertise can play a consulting role. Algae are increasingly being embraced by the creative industries. Architects and designers exhibit a strong desire to incorporate biological materials in the built environment[46]. The potential algae have for bioremediation of nutrient rich wastes, for air purification, and (in the case of microalgae) natural shading, whilst at the same time producing biomass which could be used for *e.g.,* energy generation or as soil improver, has captured their imagination. UK algae experts have started to engage with these ideas, and – while injecting realism – work with the creative industries to harness their enthusiasm and to test which of the futuristic ideas could be developed at which timescales. Consultancy services with openness for such cross-disciplinary work could lead to innovative products and solutions, and successful follow-on businesses.

1.4 UK potential for profiting from markets

Macroalgae

Due to the extensive coastline, macroalgae have a high potential for scaled growth in the UK. There are legal limits, informed by sustainability requirements, on how much seaweed can be collected from the wild[47]; some expansion of wild harvest may still be possible (levels of wild harvest in areas where companies currently operate are close to the sustainability limit; further expansion may be possible in new geographical areas, but may be limited by issues such as accessibility and ecological impact; see Section 1.2). Substantial increase can be achieved by near-shore (in the short- and medium term[48]) and off-shore (long-term[49]) cultivation on long-lines (if possible to be developed in conjunction with other infrastructure such as wind farms, see Section 2.1). In the first instance this would satisfy demand for high-value products which do not require intensive or novel processing; as the field matures the biomass could be fed into biorefining, with a variety of potential product streams, including energy (*c.f.* Sections 2.1 - 2.6).

Microalgae

Given the high population density of the UK, and the strong emphasis on a knowledge-based bioeconomy, the UK is best suited to developing algae for high value applications, where our biotechnology and metabolic engineering expertise comes to the fore, and where medium-sized production capacity is appropriate. There are significant opportunities for developing distributed microalgal cultivation, in the context of integrated biorefining and bioremediation, for high value and value-added products. This will be elaborated in Sections 2.1 - 2.5. In addition, there is great potential to export underpinning technologies and know-how by working collaboratively with partners abroad who have sufficient space and higher insolation for extensive large-scale microalgal cultivation on land (*c.f.* Section 2.7).

---

[45] Available at download.nap.edu/catalog.php?record_id=13437
[46] Currently this is led by Germany and France; see algaeindustrymagazine.com/hamburgs-biq-house/ and algaeindustrymagazine.com/ennesys-launches-green-building/
[47] In addition, permission has to be granted by the owner of the beach to harvest from wild
[48] Pathway A in AB-SIG SRA, available to members of AB-SIG at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81879.pdf
[49] ≥10 years; pathway B in AB-SIG SRA, available to members of AB-SIG at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81879.pdf

Large scale land-based microalgal cultivation is possible in the UK if the biomass is grown heterotrophically in fermenters that are scaled on volume rather than surface area. This is already established[50], and has been highlighted in the AB-SIG SRA[51] as a near-term market opportunity for the UK. Although this option removes one of the great selling points of algae, *i.e.,* harnessing the energy of sun light (like other fermentations it depends on sugars from another photosynthetic process), it is a biotechnologically exciting and profitable[52] way to provide sought-after microalgal products such as DHA, and to add microalgae to the available toolkit for deriving fermentation products.

Substantial opportunities for producing bulk commodity products will arise once technologies are available that allow off-shore microalgae cultivation. Due to the technological challenges and environmental risks associated with off-shore cultivation, the expected timescale for commercialisation is ≥25 years (*c.f.* AB-SIG SRA[53], where microalgae cultivated in enclosed off-shore systems for biofuel production is described as one of the pathways for bioenergy in the UK).

Services

The UK's algae-related expertise, be it in biotechnology, environmental sciences or (chemical) engineering, has a great potential to be harnessed for a vibrant knowledge industry. The increased focus on impact in the funding landscape is encouraging university staff to become involved in consultancy projects. In many cases this still happens haphazardly rather than in a structured manner, and culturally there are still hurdles to be overcome to unlock more of the potential for the benefit of a sustainable algal industry in the UK. Again important development factors include building a portfolio of service offerings, and increasing visibility of these services on the national and international stage.

1.5 Actions required to compete in the international market place

*The most urgent action relates to **capacity building**, both in terms of production volume and trained personnel, enabled by relevant **funding streams**.*

Capacity building & funding: Production

For **macroalgae**, cultivation (near- and eventually off-shore) needs to be expanded in an environmentally sensitive way to grow feedstocks for high-value products and, if production costs and ecological considerations allow, eventually base commodities. Further information is needed on the environmental risks of scale-up, as has been detailed in the AB-SIG SRA. Such data needs to be collected in publically (co-)funded pilot and demonstration projects, so that the data will be unbiased and fully available. This is essential for de-risking, and will pave the way for building solid business cases and attracting private investment.

Microalgae need to move out of the lab into an increasing number of test and pilot sites in order to allow collection of commercially relevant data on yield, process resilience, scalability and costs, as well as provide sufficient quantities of biomass to allow potential end users to conduct trials. Multiple sites are needed across the UK to test different ways of integrating into a spectrum of existing infrastructure (*e.g.,* with AD, coal-/oil-/gas-/biomass-based combustion, groundwater denitrification, sewage works, thermochemical conversion and fractionation infrastructure; *c.f.* Section 2.1 and microalgal case studies).

[50] The Liverpool-based company New Horizons Global, who have changed ownership in 2012, have a fermentation capacity of >1000m3, with a production capacity of 3500-4000Mt of biomass/year
[51] Pathway C of AB-SIG SRA; available to members of AB-SIG at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81879.pdf
[52] As evidenced by the success of Martek / DSM
[53] Pathway E of AB-SIG SRA; available to members of AB-SIG at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81879.pdf

Test programmes need to target different strains, nutrient sources (different industrial nutrient / flue gas waste streams, nutrient-rich marine or freshwater sources, different nutrient regimes to optimize composition of biomass for desired end uses), growth technologies (a variety of open and closed PBRs) and a spectrum of harvesting, dewatering and processing options, to provide a sufficiently resolved picture of which combinations lead to best yields, quality, resilience and lowest costs. The dependence of photoautotrophic growth on geographical factors such as insolation, rainfall (for open ponds) and local biodiversity (competing microalgae, predators, disease carriers) means that a network of pilot sites in a variety of strategic locations will be more valuable than one large national facility. For heterotrophic growth, this dependency on geographical location does not exist, and the excellent facilities at CPI can provide the necessary open-access testing for the UK as a whole.

Currently microalgal technologies sit in the dangerous 'Valley of Death' – they are ready to exit the lab and enter scale-up, but without a sound body of commercially relevant data from test and pilot facilities the economic risks associated with this first step are prohibitive for securing investment from industry. To enable entrepreneurs and companies to draw up firm business cases, it will require public sector funding to provide test growth facilities where relevant data can be collated that will help to define the risks better and mitigate against them.

Capacity building & funding: Personnel

It is internationally recognised[54] that we need more **skilled personnel** that are able to work across a large spectrum of disciplines. To develop the full potential of algae for a bio-based economy, teams are needed that combine expertise in biotechnology, environmental sciences and (chemical) engineering, and in addition have a sound grasp of market dynamics and business reality, as well as a true entrepreneurial spirit. Structures need to be put in place that allow these disciplines to interact, and that train and inspire a cohort of well-rounded 'algaepreneurs'.

To establish a UK algae-based knowledge industry which unlocks more of the relevant available expertise, it will be necessary to encourage structures which increase the **flexibility** of moving between commercial activities and academic positions, *e.g.,* through secondments.

Finally, **marketing** plays an important role: both in terms of highlighting the benefits of algal products to increase uptake as production capacity expands, and as regards advertising the expertise we have to offer to the world stage.

[54] The Algal Industry Survey 2008 (published February 2009), available at: ascension-publishing.com/BIZ/algal-industry-survey.pdf

1.6 Context of previous reports

In the BBSRC Scoping Study of 2011, one chapter was dedicated to an overview of algal products and their indicative market value, and another chapter summarized opportunities for future commercialisation arising from algae-related R&D. Together with highlighting the UK's academic expertise relating to algae, it also gave a brief snap-shot of the algal industry landscape. However, the report focused on early technology readiness levels, in line with being commissioned by a research council. No business case studies were given, and the topical emphasis was placed on industrial biotechnology without significant consideration of ecological impacts.

The Strategic Research Agenda commissioned by AB-SIG in 2012 highlighted research challenges in the first instance, giving prominence to environmental considerations. It also provided five different pathways towards a variety of macro- and microalgae-based products, with a focus on larger scale production (in the order of 10 ha for macroalgae) for bioenergy and bulk chemicals. These pathways will be cross-referenced in the more detailed case studies which are presented in Chapter 2. In contrast, this roadmap is agnostic about scale and presents a range of sectors, including but not focused on energy or chemicals, which through the roadmapping workshops have been identified as commercially significant opportunities for the UK.

The authors are indebted to the participants in the AB-SIG roadmapping workshops[55], who have provided valuable data and insights which have been used to select the sectors or relevance, and build the business case studies.
Assumptions that had to be made during the workshops were, as much as possible, checked with available literature, and corrected where appropriate to ensure the accuracy of information presented in this report.

Roadmap Aims

To highlight which algal products, processes and services

- are on the market or close to deployment
- are under development
- require considerably more R&D
- have highest potential for UK, according to community

To identify interventions needed to seize opportunities in a

- timely
- economically and environmentally sustainable way

A degree of harmonization was required to summarise the outputs of the two workshops, and we apologise if in the harmonization process some aspects that have been highlighted by participants have been omitted.

The roadmap is to be seen in the context of previous reports, see Figure 1. Going forward, we envisage that the data from scale-up facilities on operational costs, variability of yields, life cycle parameters and ecological impact, once it is available, will make it possible to turn the case studies into fully developed business cases.

[55] Participants are listed in Appendix 1.

2. Results and Outputs

During two roadmapping workshops which AB-SIG organised in Nov 2012, several market sectors were highlighted by the participants as particularly relevant for the UK in commercial terms (see Figure 2). The most highly ranked examples will be presented and analysed in turn in the following sections.

2.1 Biorefining: Integration with existing infrastructure and value chains (1-15 yrs)

Why is this important?

Algal biomass, be it macro or micro, is currently expensive, and produced in small quantities, servicing mainly high value markets. In order to reduce production costs, it is imperative that

- inputs are wherever possible derived from waste streams
- energy use and capital expenditure are minimised
- no waste is produced during growth and processing, *i.e.,* nutrients are recycled, and every part of the biomass is developed into a saleable product.

This concept is at the heart of integrated biorefining, and provides the lens through which all following business cases need to be viewed. This section will provide an overview and make reference to case studies in following sections.

Wider advantages that adoption of integrated algal biorefining are likely to offer include

- more control over the supply chain (and its ecological impact, as the biomass would be grown, harvested and processed in the UK)
- provision of employment across a section of skill levels, training opportunities for technical staff
- the opportunity to provide ecosystem services.

How can it be achieved?

As far as **growth and harvesting** are concerned, the opportunities for integration vary considerably between macro- and microalgae (*c.f.* Figure 5).

For **macroalgae**, where prospects for larger-scale cultivation are positive due to the UK's extensive coastline[56], inputs from waste streams could stem from integration with fish farming, leading to elevated nutrient levels and hence enhanced growth, while at the same time providing valuable ecosystem services (this is elaborated in Case Study 3 of Section 2.2). Reduced capital expenditure could be achieved in the long term by co-developing algal farms with off-shore wind farms[57], providing this can be achieved safely without impinging on maintenance access for the farm.

[56] However, restrictions on algal growth arise from multiple uses of sea space for recreation, shipping, fishing etc. In addition, the ecological impacts of growth at sea will need to be carefully monitored throughout staged scale-up.
[57] Oil rigs are sometimes also mentioned, however most oil rigs are in much deeper water than would ever be likely to be contemplated for farming macro-algae. Some wind turbines are in shallower water but developers have borrowed £bn to develop such windfarms and understandably are not prepared to add further risk factors. In 20 yrs time co-existence of nearshore windfarms and aquaculture facilities may have become routine. Currently developers do not have a lease from The Crown Estate to do anything other than develop a windfarm. (Pers. comm., Prof Michael Cowling, May 2013)

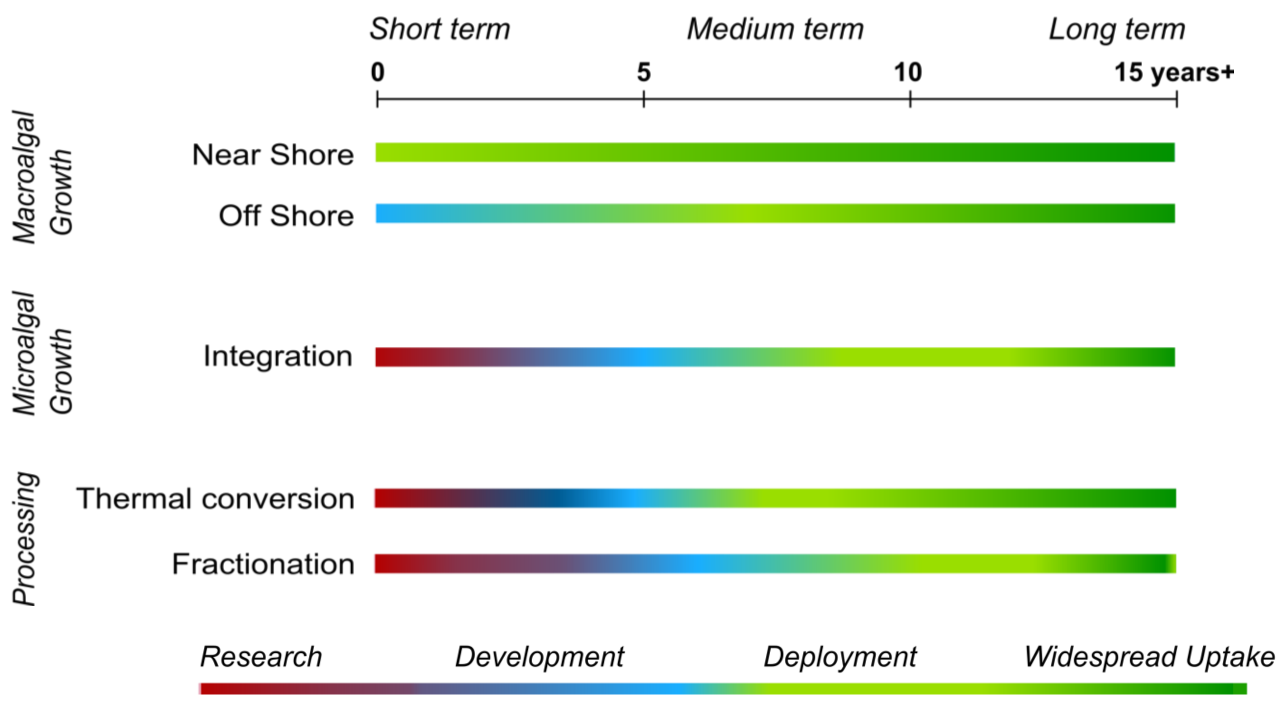
For **microalgae**, the geographical and socio-economic situation of the UK does not lend itself to large-scale land-based production. This means that there is a limitation to the savings that can be achieved through economy of scale[58], and it is even more important to achieve savings in other ways. Key opportunities exist if medium-sized facilities can be integrated with other industrial processes, which can

- provide inputs (such as CO_2, nutrients, water, sugar for heterotrophic growth, low-grade heat, cheap electricity/lighting),
- directly use some of the products (*e.g.,* fresh algae as live feed in aquaculture), and/or
- where infrastructure can be shared (provision of utilities such as electricity, gas, water, sewage, steam, DI water).

In many cases this integration can also provide benefits for environmental sustainability: CO_2 from flue gasses can be used instead of bottled CO_2, and although this does not provide permanent carbon storage for emitted CO_2, it does diminish the carbon footprint of algal growth compared to having to purify, compress and transport bottled CO_2. It can also lead to sequestration of NO_x from flue gasses.[59] Examples of coupling algal growth to water remediation are given in Section 2.2.

Although the general technologies will be applicable in most settings, there is an opportunity to tailor each setting to provide customised solutions to specific issues facing a range of industries, therefore enhancing or restoring local ecosystem services.

Figure 5: Indicative biorefining timeframes for macro- and microalgae



Once harvested, requirements for **processing** macro- and microalgal biomass are more similar, and within each group will be heavily dictated by the properties of the chosen strain and the desired suite of end products. The production volumes and costs in the short term will require a focus on low volume, high value markets as the main financial driver; examples are given in Section 2.3. The residual biomass after

[58] These savings are smaller than in fermentation-based technologies, as scale-up for autotrophic growth has to occur on area rather than volume.
[59] SO_x have to be removed from flue gasses prior to bubbling through algal cultures, as they would acidify the medium and harm the algae.

extraction of the main target compound will need to be put to best use; this will be heavily dependent on the process and the strain. Care will have to be taken to develop appropriate HACCP[60] procedures if one of the end products is to enter the food chain; this will not be compatible with all inputs or processing protocols.

Once production capacity has increased to a level that is relevant for value-added or commodity products, a more general approach can be taken, in which the biomass is either thermochemically converted into syngas, bio-oil and/or biochar[61], or fractionated into its key components (proteins, lipids, carbohydrates, metabolites and nucleic acids). A schematic overview is shown in Figure 6.

Thermochemical processes have the great advantage that they are largely insensitive to the nature of the feedstock; they hence provide a 'one size fits all' solution across the vast spectrum of algal strains with their differing physical and biochemical properties. This is achieved by applying a thermal 'sledge hammer' to the biomass, thereby destroying the complexity (and some of the intrinsic value) of the molecules. The three key thermochemical processes gasification, pyrolysis and hydrothermal liquefaction (HTL) differ in their reaction conditions and the relative abundance of gaseous, liquid and solid products. The products are less complex chemicals that can be used as building blocks for desired molecules (*e.g.,* syngas to fuel via Fischer Tropsch), as a saleable product (*e.g.,* biochar for horticulture) or directly for energy generation (*e.g.,* bio-oil). As a water-based process HTL is well suited for algal feedstocks, since no energy penalty for drying the biomass is incurred; nutrients can also be easily recovered.[62] In addition, R&D on HTL catalysts could lead to production of sought-after hydrocarbons with specific chain lengths or branches.

In principle integration with existing thermochemical plants is possible; process optimisation will be required especially if algal feedstocks are to be mixed with other forms of biomass. Even if a separate thermochemical conversion step should be deemed necessary, the products from algae and other feedstocks could be combined and processed further using the same infrastructure, hence reducing capital expenditure. Given adequate R&D support, this path could move towards deployment within the next five to ten years.

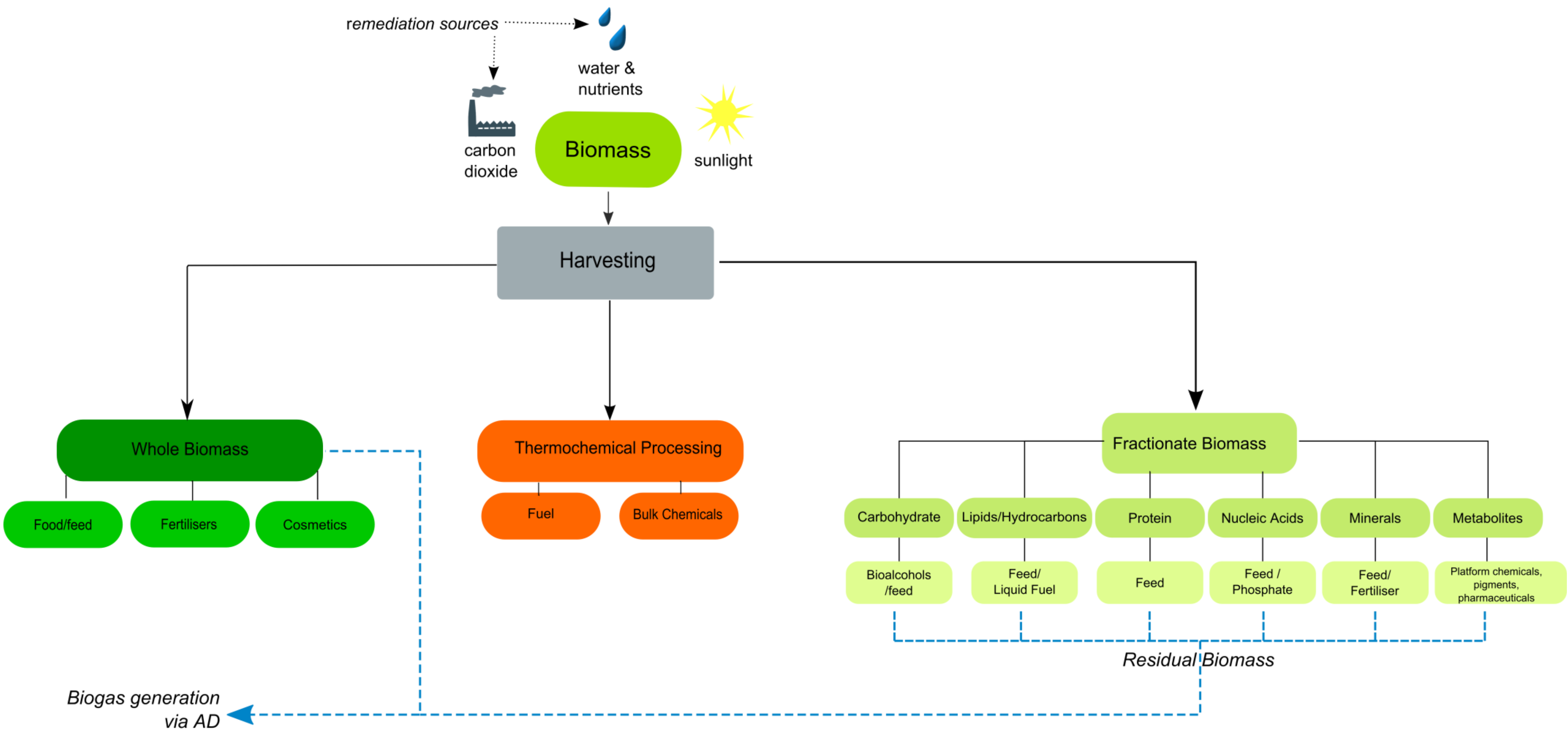
If **fractionation** is used, the intrinsic value of the complex biological molecules can be preserved. Technologies will have to be developed that work at scale, are economical and allow for the degree of functional integrity and purity needed for each end product. For economic viability it is of vital importance to match the value and market size of each co-product, so as to avoid flooding the market for a speciality product and thereby devaluing it, as was the case with glycerol from biodiesel. Given appropriate R&D support, this path could move towards deployment within the next ten years.

It is paramount that **life cycle and sustainability analyses** are embedded in any development and deployment, to ensure that any new algal technology provides an overall improvement, or is at the very least not less sustainable than established processes that lead to the same products. As in all areas, research and commercialisation have to go hand in hand to achieve maximal impact.

To capitalise on the opportunities posed by integrated biorefining, it is essential to provide feasibility studies and test, pilot and demonstration facilities. CPI's facilities at Wilton are highly valuable, and should be made use of as much as possible for downstream processing. Integration with existing infrastructure upstream of growth, however, cannot be done centrally, and therefore a number of test facilities piloting integration with various input-providing industries have to be established across the UK, with immediate effect, in order to stay competitive on the international scene. Examples will be given in the following sections.

[60] Hazard Analysis Critical Control Point: principles used by the retail food industry to prevent, eliminate or reduce food safety hazards
[61] The proportion of each depends on the reaction conditions; a schematic overview is given in Figure 13 / Section 2.6.
[62] Biller P, Ross AB, Skill AC, Lea-Langton A, Balasundaram B, Hall C, Rilley R, Llewellyn CA (2012) *Nutrient recycling of aqueous phase for microalgae cultivation from the hydrothermal liquefaction process*. Algal Research 1(1):70-76

Figure 6: Schematic of integrated biorefining options for algal biomass



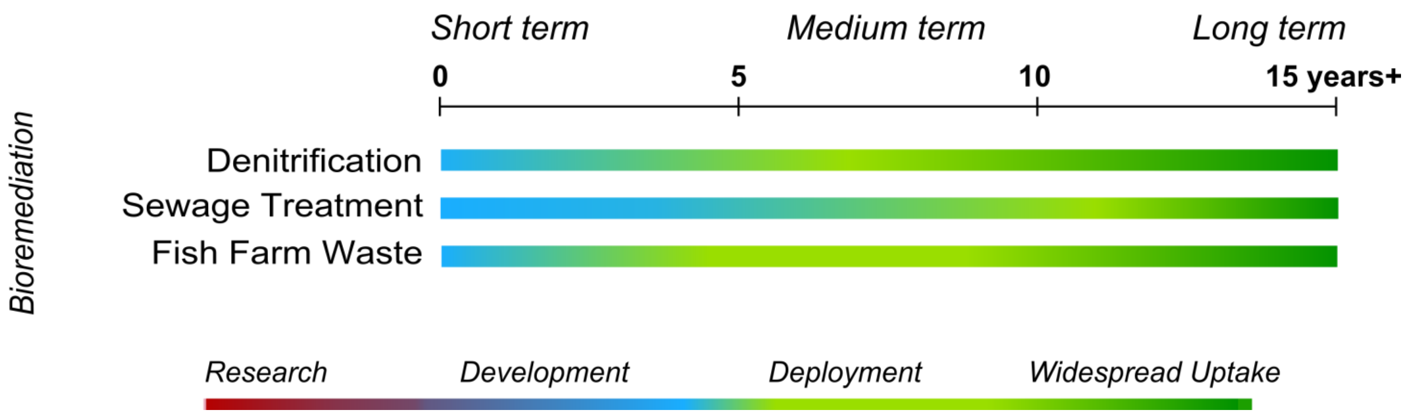
2.2 Waste water remediation (1-10 yrs)

Intensive agri- and aquaculture as well as high population density are putting increasing pressure on our water infrastructure and marine as well as freshwater eco systems. Elevated nutrient levels lead to eutrophication, while de novo synthesis of fertilisers has a high price and carbon footprint, with phosphate being a globally limited resource. UK regulations to implement the Water Framework Directive[63] *and the Nitrate Directive*[64] *provide strong drivers for preserving and maintaining water quality.*

The value of algae as a means to clean waste waters has already been highlighted in the AB-SIG SRA[65]. Opportunities exist not only to prevent eutrophication, and avoid the expense of mitigation, but to derive value from the biomass grown on the waste stream. In addition, bioremediation provides positive publicity which has a high PR value.

Here we present three different case studies for business opportunities arising from the use of micro- or macroalgae for bioremediation of waste water streams: Denitrification of brine wash generated from groundwater purification, nutrient recovery from sewage treatment, and remediation of fish farm waste in Integrated Multi-Trophic Aquaculture (IMTA) systems. In addition, other bioremediation options are already on the market[66] which specifically target problematic waste streams such as heavy metals, toxic organic compounds and other industrial wastes. Here we focus on cases where the biomass grown on the waste streams can be used for saleable products in a variety of markets, depending on the purity of the inputs. Estimated timescales for deployment and widespread uptake are given in Figure 7.

Figure 7: **Indicative commercialisation timescales for bioremediation case studies**



[63] Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32000L0060:EN:NOT
[64] Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources, eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31991L0676:EN:NOT
[65] p. 13, available at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81879.pdf
[66] *e.g.,* algalturfscrubber.com/; microalgal biofilms for waste water remediation have also been included in the AB-SIG SRA in Pathway D

Case Study 1: Microalgae for denitrification of brine wash generated from purification of groundwater[67]

Why will this be an important market?	• Increasing nitrate levels in groundwater due to agricultural activity mean that drinking water abstracted from this source must be treated prior to going into supply to meet EU regulations. • At present, nitrate extracted from ground water is concentrated when ion exchange columns are regenerated using a brine wash. This saline nitrate solution cannot be spread onto fields and is currently disposed of into sewage, resulting in a wasteful cycle of energy-intensive nitrate production and then re-reduction to nitrogen in the sewage works. • Discharge consents require dilution of the brine wash before introduction into the sewage works. This is associated with operational costs, which can be mitigated through algae-based nitrate remediation. • The operational costs of sewage disposal range from £50,000-£250,000 per year per site[68], plus possible additional capital costs depending on whether the brine wash is tankered offsite or a pipeline is built to the STW.

How will the algal technology be commercialised?	• Marine microalgae are normally grown on freshwater augmented with salts, or else purified seawater, which represents a cost factor. This, and the cost of nitrate fertiliser, could be saved if the nitrate-rich brine wash was used in the growth medium.
	• Unlike most other waste streams, this groundwater-derived brine wash is compatible with the end use of the biomass in the food chain.
	• New infrastructure for denitrification will need to be built in the next decade; this offers the opportunity to integrate algal growth facilities seamlessly.
	Steps include:
	• Initially, collaboration between the water industry, algal growth experts and PBR technology providers will be necessary to provide proof of concept: R&D in test facilities will be necessary to
	    • test strain performance and optimise growth conditions using a brine-derived medium
	    • collect data for LCA and economic assessments, to demonstrate the cost benefits over conventional technology.
	• Based on which algal strains can be grown at what yields, target markets (such as high value feed ingredients) will need to be identified, a detailed business case needs to be developed (taking into account space requirements for scale-up co-located with denitrification, and the need for cheap CO_2 provision), and partnerships with end users will need to be formed.
	• For pilot operation and further scale-up, the water industry would best form a partnership with the provider of denitrification infrastructure and an algal growth company, in which the water industry provides the waste stream as a feedstock, the infrastructure provider ensures smooth integration with the denitrification process, and the growth, harvesting and marketing of algal biomass are dealt with by the algal company.
	• After successful demonstration at scale, a turn-key solution can be developed by a joint venture between the denitrification infrastructure provider and an algal growth company. This can be marketed to suppliers of drinking water in the UK (and abroad, taking into consideration adaptation needed to accommodate the effect of different climatic and environmental parameters on algal growth; this will require another demonstration phase).

Timescale to commercialisation	• 2-5 yrs with existing technologies to demonstration phase; 5-10 years for turn-key solution
Advantages of Algal Biotechnology over incumbent approaches	• No alternative for resource recovery currently in operation • Relative ease of integration with existing infrastructure • Potential to use biomass as saleable high-value product (as waste stream is clean) • Sustainable: green approach, lowered carbon footprint, higher energy efficiency (to be proved by sustainability analysis based on data from test/pilot site)

[67] Initial trials of this process are carried out in a collaboration between Cambridge Water, the InCrops Enterprise Hub and the University of Cambridge, co-funded by the INTERREG NW Europe Strategic Initiative EnAlgae.
[68] Pers. comm.., confidential industry source, 2012

Market size	• In the UK, the nitrate removal technology that produces the brine is already in use by regional water companies in at least 13 sites. The combined output of these is over 67 million litres per day. The number of these plants will increase in line with published rising national trends of nitrate in groundwater[69].		
Growth rate	• More denitrification plants are planned for the UK to enable drinking water to meet EU regulation on nitrate levels.		
UK companies operating in this market sector	• Cambridge Water – pilot test facility in conjunction with INTERREG NW Europe Strategic Initiative EnAlgae • Other water companies with denitrification plants, who could adopt the technology, include Anglian Water and Thames Water.		
UK Ecosystems potential to commercialise	**High:** • Breaks wasteful cycle currently in operation (turning nitrate back into nitrogen at sewage works under energy expenditure) • Turns an environmental problem into an opportunity • Provides a solution to problem at point of origin • Environmental risk from algal species is low, as they will be marine species grown in closed systems on land		
	Technological	**Commercial**	**Other**
Barriers	• Turn-key integration with infrastructure of water industry has to be developed	• Requirement for land, and proximity of CO_2 source • Need for training & skills in industry • Cost of scaling up • Risk averseness and inertia of water industry - hesitant to invest in test facilities	• Low insolation during winter requires artificial lighting for continued processing of waste stream
Risks	• Productivity on brine-derived medium is low for most desirable strains (low)	• CapEx and OpEx may dictate a price that will only service speciality product markets; scale-up without lowered costs could then flood the market (medium)	• LCA might show that overall the process is not greener than current practice (low) • If intensive fertilising were to stop, the need for denitrification of ground water would decrease, leading to under-used capacity (very low)
Fit with UK capability	• Good existing R&D base (biology & engineering)	• Large market potential • Export of technology possible • Industry interest	• Research funding priorities fit (*e.g.,* RCUK)
Gaps in UK capability	• Urgent need for scale-up facilities (test / pilot / demonstration plants) • Data availability	• Translation of existing research into market place	• Lack of agenda / strategy • Needs change of mindset in industry from treatment as waste to resource recovery / revenue generation
Key innovation and R&D needs	• Strain cultivation at scale • Low cost harvesting • Process integration and refinement • Data for models – economic/technological/environmental/ecological/LCA • Need for demonstration • Establishing HACCP procedures		

[69] Stuart, M.E.; Chilton, P.J.; Kinniburgh, D.G.; Cooper, D.M.. (2007) Screening for long-term trends in groundwater nitrate monitoring data. *Quarterly Journal of Engineering Geology and Hydrogeology*, 40 (4). 361-376. Doi:10.1144/1470-9236/07-040

	Requirement for technology partnerships	Support needs	Other
Enablers for successful UK commercialisation	• Collaboration between industry, technology providers and academia • People: skill transfer to end users	• Funding: public sector 'push' • TSB grant for globally recognised pilot and demonstration facilities (£5 - 10 Million)	• Academic skills & existing algae industry • Economics and LCA / sustainability models
Key actions required to develop UK competitive advantage in the global commercial landscape	• Build (and fund) pilot plants, assess performance, refine through R&D • Proceed to demonstration stage • Develop turn-key solution for global market		

Case Study 2: **Nutrient recovery from sewage treatment through High Rate Algal Ponds (HRAP) or microalgal biofilms**[70]

Both High Rate Algal Ponds (HRAP) and biofilms are a means of growing algae on municipal wastewater. They allow retrieval of nutrients such as nitrate and phosphate which are currently not recovered from sewage treatment works (STW). This increases resource efficiency, and turns an environmental problem (eutrophication potential of water leaving the facility) into an opportunity for lowering the cost of inputs into algal biomass production. Unlike the example given in Case Study 1, biomass generated this way would not be appropriate for the food chain, but would be ideally suited to feed into biorefining via thermochemical conversion or fractionation to produce chemical feedstocks or energy products. As a first step, the latter could also be achieved by feeding the biomass into AD, which tend to be associated with sewage works, thereby making optimal use of existing infrastructure. It could be one way of generating commodities such as bulk chemicals, biofuel or bioplastic from algae that cannot enter the food chain.

Two ways exist in which a HRAP step can be incorporated into STW: through Advanced Integrated Wastewater Pond Systems[71] (which entirely replace traditional STW), or as a final polishing step after conventional activated sludge systems. The first scenario is best suited in cases where new treatment plants have to be built, to avoid the capital expenditure of adaptation of existing infrastructure. Although these facilities are larger than conventional plants, they have lower construction and operational costs. They have been successfully demonstrated in the US and in developing countries[72]. The second scenario would be appropriate to add to existing STW, but will require considerable land area as volumes of tertiary wastewater are large; this constitutes a barrier for the UK.

Pilot and demonstration facilities are necessary to prove the reliability of the technique in a given climatic region, to predict the area required for scale up, and to test if there are adverse side effects such as odours. One example of an existing demonstration project is the NIWA plant in Christchurch, New Zealand. It operates a 5 hectare facility with High Rate Algal Ponds and extraction of algal lipids using supercritical water[73]. Depending on uptake by the water industry, this technology could be within 2-5 yrs of commercialisation. According to DEFRA in 2012, the UK has approximately 9000 sewage treatment works. Converting a percentage of these to a HRAP system would be a first step to generating bulk volumes of biomass for non-food applications.

---

[70] Information is also provided in Appendix 2 in the same tabulated format as in the previous case study, to allow a direct comparison.

[71] Eg: ibcinc-enviro.com/main/page_aiwps.html

[72] United States Environment Protection Agency (2011). Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers. EPA/600/R-11/088

[73] NIWA website – niwa.co.nz/sites/default/files/algaeoilproduction_-_hrap.pdf

An alternative to pond-based algal growth that is already commercialised in the US (*e.g.,* by The Algal Turf Scrubber®[74]) is based on biofilms; there is also interest in the UK in trialling this type of technology. Again it could be used for polishing, or to replace the activated sludge systems.

For the UK to adopt these technologies, lessons should be learned from HRAP and biofilm projects in similar climates, and pilot and demonstration facilities need to be constructed to test performance, ecosystem compatibility (which should be high if native strains are used), and public acceptance. Collaborations between academia and industry need to continue and intensify to develop the concept further within the biorefinery model.

Case Study 3: **Macroalgae for the remediation of fish farm waste: Integrated Multi-Trophic Aquaculture (IMTA)**[75]

Farmed species such as salmon, trout and halibut account for around 47% of all fish directly consumed by humans worldwide. In the UK, finfish aquaculture is typically conducted near shore, creating nitrate-rich waste that disperses in the local coastal environment. As aquaculture production in the UK continues to expand (it has risen from 152,000 tonnes live weight to 201,000 tonnes between 2001 and 2010, representing an average annual growth of 3.5%), the potential for ecosystem damage increases. Finfish producers seeking to acquire new licences will need to demonstrate that they are taking steps to mitigate ecological effects, and one means of doing so is to install macroalgae longlines adjacent to aquaculture sites. This system is known as Integrated Multi-Trophic Aquaculture (IMTA).

At present, the Loch Duart salmon company in Scotland uses this system and commercial operations also exist in Canada, Chile and Portugal. Wider uptake could be achieved within 2-5 years, if economic viability can be demonstrated. Multi-trophic aquaculture is being investigated for the potential to retrieve nutrients currently lost (and acting as pollutants) via projects such as the EU FP7 programme IDREEM (Increasing Industrial Resource Efficiency in European Mariculture). The ecosystem service benefits can be quantified and computer modelling applied to predict how much nitrate/phosphate can be sequestered.

The potential to use algal biomass produced by IMTA as saleable product for feed or other applications increases the sustainability of the operation and the potential to generate revenue. In the case of carbon and nitrogen credits the markets are forcibly created as a result of regulation and become more attractive under a cap-and-trade scheme. A nitrogen/nutrient credit market currently only exists in the US (namely Connecticut). However it is unknown whether fish farms are already able to sell credits into a market.

As a coastal nation, aquaculture is of importance to the UK, and IMTA could minimise changes in the benthic environment due to waste build up from aquaculture, and mitigate effects on ecosystems. Building on aquaculture expertise in the UK, and creating pilot facilities to test and model the economic and ecological impacts of this approach would enable reliable data to be generated. Ensuring biosecurity is paramount – operating an integrated system could provide reservoirs or vectors for disease in fish – so this must be verified. Bioaccumulation of any toxins by macroalgae must also be tested for.

Working with marine licensing authorities to raise awareness of the potential benefits of an IMTA system is important as this could be a key driver for wider adoption.

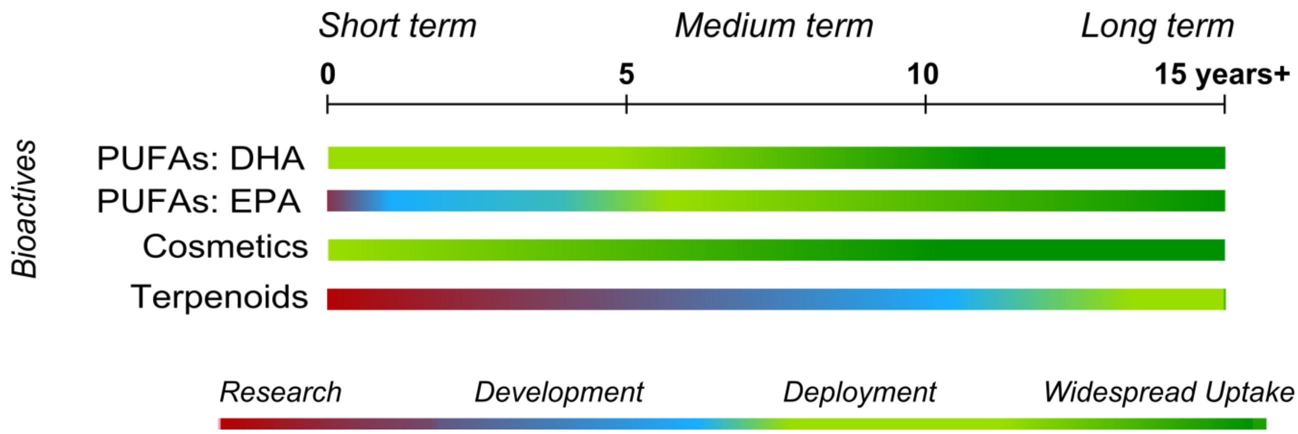
Globally, tank-based recirculation systems are also used for remediation of fish waste from land-based aquaculture; this is of less interest to the UK, but UK expertise could flow into international projects for such systems (*c.f.* also Section 2.7 / Case Study 14).

[74] algalturfscrubber.com/point.htm
[75] Information is also provided in Appendix 2 in the same tabulated format as in Case Study 1, to allow a direct comparison.

2.3 Bioactives: nutraceuticals (1-5 yrs), cosmeceuticals (1-5 yrs), pharmaceuticals (5-20 yrs)

As has been highlighted in the introduction, the highest potential for commercialisation of algae in the UK in the near term lies with high value / low volume products, where the UK's industrial biotech expertise can come to the fore. Indeed, globally an algal industry exists that markets algae for their content of bioactives; *Spirulina* and *Chlorella* are being grown *e.g.,* in the US, China and Germany, and are sold as whole cells in nutraceutical products[76]. Pigments with anti-oxidative effects such as the carotenoids beta-carotene and astaxanthin[77] are produced *e.g.,* in Australia, Israel and New Zealand, with applications in nutrition and for vibrant colouration in high value fish. Blue Smarties are back on sale thanks to a *Spirulina* extract, and the cyanobacterial pigment allo-phycocyanin commands a staggering price of up to €50/mg for use as an ultra sensitive fluorescent tracer in protein labelling. Increasing interest also exists to exploit the astounding diversity of algae for the discovery of new pharmaceuticals through bioprospecting, and for establishing especially microalgae, including cyanobacteria, as expression platforms for complex biomolecules. To showcase some of this immense potential which the UK is well placed to exploit, we provide one case study each for nutraceuticals (Omega 3/6 fatty acids DHA and EPA), cosmeceuticals (seaweed extracts in cosmetics), and pharmaceuticals (terpenoids expressed in microalgae). Estimated timescales for commercialisation are given in Figure 8.

Figure 8: **Indicative commercialisation timescales for bioactives case studies**



[76] As tablets *e.g.,* from Rainforest Foods (rainforestfoods.co.uk), Pink Sun Organics (pinksun.co.uk), Nature Complete (naturecomplete.com), as powder *e.g.,* from Buy Wholefoods Online Ltd (buywholefoodsonline.co.uk), Bobby's Health Shop (bobbyshealthyshop.co.uk), Lifestream (lifestream.co.nz), Synergy Natural (synergynatural.com)
[77] Others comm.30noids examples include lutein, canthaxanthin and fucoxanthin; for market sizes and prices see Chapter 3 of BBSRC Algal Scoping Study, available at: www.bbsrc.ac.uk/web/FILES/Reviews/algal_scoping_study_report.pdf

Case Study 4: **Microalgae-derived nutraceuticals: Omega 3 PUFAs DHA and EPA**

Why will this be an important market?	• Demand for Omega 3 supplements is increasing (rising middle class spending power for nutrition in BRIC and globally). • Questions over long term supply of fish oil and the sustainability of this source • Certain species of algae are able to make EPA, which is sought-after as a dietary supplement. • Highly purified versions of EPA and DHA are used in pharmaceuticals. • Increasing introduction of green labelling (LCA will need to demonstrate this is a 'greener' option than fish oil.)
How will the algal technology be commercialised?	**DHA:** • Heterotrophic growth for DHA production is already established in the UK. • Expansion through working with existing nutraceutical suppliers who currently rely on fish oil; demonstrate added value compared to fish oil • Strong international competition through Martek: UK industry will have to demonstrate added value of product or partnership. **EPA:** • Yields need to be increased through R&D, potentially making of use of metabolic engineering, to become competitive in terms of price and production capacity. • Through algal start-ups as well as existing biotech companies, exploring photo- and heterotrophic growth options.
Timescale to commercialisation	• Heterotrophic DHA is already commercial; 4-10 yrs for EPA
Advantages of Algal Biotechnology over incumbent approaches	• longer term sustainability, vegan source • EPA can only be provided by fish or algal oil, it is not made in higher plants whereas there are a number of sources of DHA • fish oil has problems of heavy metal contamination
Market size	• In 2009, algae oil was priced at $80 to $175/kg in the United States[78]. However, the market has witnessed a significant drop in price due to new entrants flooding the market in the US following the approval of Martek's algal DHA product to be used in infant formula. • The price of 30% (EPA+DHA) fish oil is $7.43/kg, with this price rising to $149.45 for 85-95% concentrates. Algae oils are still considered a premium product and command $87.85/kg.[79] • The global revenues for marine and algae omega-3 ingredients markets were valued at $1,447.5 million in 2009, the European market revenues at $473.2 million.
Growth rate	**Predicted compound annual growth rate from 2009 to 2015:** • Global market: 12.0% • European market: 9.0% • There is growing demand in the pharmaceutical sector for Omega 3 concentrates, for drugs such as Omacor/Lovaza and over-the-counter products such as E-EPA 90/Vegepa E-EPA 70/Omegaflex which are currently made from purified and concentrated fish oil.
Companies operating in this market sector	• Algae-based: Martek (DSM), New Horizons Global (UK-based), Fermentalg, Qualitas Health (EPA) • Fishoil-based: BASF, Croda, Igennus (EPA)
UK Ecosystems potential to commercialise	• For phototrophic growth (EPA) especially if coupled to bioremediation (under HACCP): excellent • For heterotrophic growth: neutral / equal to other fermentations

[78] Frost and Sullivan (June 2011), Global Analysis of the Marine and Algae Omega-3 Ingredients Market (reference does not specify the source strain or composition of the algae oil)
[79] ibid

	Technological	Commercial	Other
Barriers	• Strains with high yields of EPA still have to be developed.	• Cost of getting regulatory approval	• HACCP / GMP regulations
Risks	• High EPA yields might only be achievable using GM, making the product less desirable for some markets (medium)	• Oversupply of product would drive price down (medium) • Lack of investors (high)	• Public perception (medium for GM) • IP race / IP competition (high)
Fit with UK capability	• Good existing R&D base (metabolic engineering, synthetic biology, strain improvement, heterotrophic growth)	• Commercial capabilities for DHA production already exist. • Strong commercial interest in EPA (producers and end users)	• Fit with research funding priorities (synthetic biology, industrial biotech)
Gaps in UK capability	• Pilot / demonstration plants for phototrophic growth • Training in downstream processing	• Further scale-up for heterotrophic growth	• Risk averseness in funding landscape
Key innovation and R&D needs	• Open access pilot plant / scale-up • Genetic stability in target strains • Model organisms • Yield improvements • Development of low cost effective techniques for cultivation, harvesting, extraction and downstream processing • Improvements in basic biology and biotechnology knowledge • Data for models – economic/technological/environmental/ecological/LCA		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Mechanism to transfer technology from universities • Reducing barriers to releasing technologies to SMEs • Cross collaboration - domestic / international • Need for more 'united' research efforts across UK universities	• Funding: Non equity, for international collaborative activities, government investment • Smaller contribution requirement for UK Plc for UK grants • IP assistance • Commercial interest in the UK for algal biotech from SMEs, VCs • Training programs in downstream processing	• GMO legislation - PR campaign on GM and algae • Mechanism to grow small into medium sized companies • More algal technology companies • Simplification of patenting process
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Advocate introduction of incentives / legislative drivers to move away from unsustainable feedstocks such as fish oil • Build open access pilot plant(s), assess performance, refine through R&D • Provide non-equity funding • Utilise existing UK industry expertise for commercialisation		

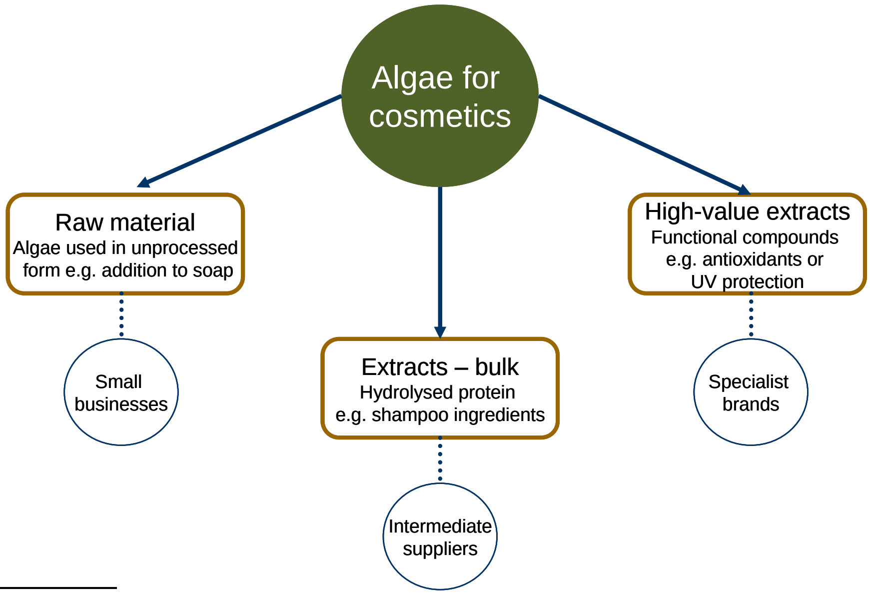
Case Study 5: **Macro- and microalgae-derived cosmetics**[80]

Spending on natural personal care and cosmetic products is growing steadily globally, and especially in BRIC countries. Natural and organic products have a 2% share of global personal care product sales. In some countries – such as the USA, Germany and Austria – the market share is reaching 10%[81], and for the UK market revenues have been increasing by about 6% per annum since 2008, despite the financial crisis. Global revenues in the personal care market are predicted to climb to USD 14 billion in 2015, and many UK brands look to export to markets where growth is faster. Rising average life expectancy leads to increased popularity of anti-ageing products and exotic natural ingredients have strong marketing power and can command a premium price. Research is being conducted into novel functional ingredients from macro- and microalgal sources: Compounds such as mycospoine-like amino acids, terpenes and carotenoids, tocopherols and pyrenoine (an extract from the macroalga *Fucus*) are all under investigation as photo-protective ingredients.

There are three main routes for algal products to enter the cosmetics market (*c.f.* Figure 9): as raw materials; as bulk extracts for formulation; and as specialised functional ingredients. Each of these is associated with a different size of industry. Small businesses with innovative products based on raw materials (*e.g.,* seaweed soaps from Rest and be Thankful or Irish Seaweeds) may provide local employment and there could be potential for acquisition by larger entities if the product is promising. Cosmetic ingredient suppliers are increasingly interested in non-petrochemical derived surfactants so products can be labelled as "natural"; bulk extracts are an attractive source. On the specialist, high value end of the scale, large multinationals invest heavily into R&D and patent protection of functional extracts from seaweed and microalgae. A search of the US Patent Collection database in Feb 2013 for "cosmetics AND (algae OR seaweed)" yielded 1834 patents. Companies operating in this market include Boots, L'Oreal, Nivea, Body Shop (products containing seaweed are best sellers according to their website), Garnier, Clarins and Estee Lauder; UK companies include Seaweed Organics, The Scottish Fine Soap Company, Rest and be Thankful and the Highland Soap Company.

Sustainable harvesting and price competitiveness against Asian imports are two important challenges for a UK-based algal cosmetic industry. Collaborations between academic institutions and commercial enterprises (such as Boots and PML for the production of microalgae with a view to bioprospecting novel photo-protective compounds) are key to enabling the UK to capitalise on the high value end of the market. Linking with bioremediation (denitrification / IMTA, see Section 2.2) may be one means of sustainably generating raw material.

Figure 9: Process opportunities for inclusion of algal biomass in cosmetics



[80] Information is also provided in Appendix 2 in the same tabulated format as in Case Study 1, to allow a direct comparison.
[81] Organic Monitor (December 2011). Global Market for Natural & Organic Personal Care Products (3rd edition), Organic Monitor #1003-60.

Case Study 6: Microalgae as an expression platform for pharmaceutical terpenoids

Why will this be an important market?	**Cost of production of existing pharmaceuticals:** • Plant-derived terpenoid compounds have been an important source of drug scaffolds, or represent direct pharmaceutically active compounds (such as the anti-cancer drugs paclitaxel and ingenol-3-angelate, forskolin for treatment of heart failure and glaucoma, or the antimalaria drug artemisinin). • Due to the structural and stereochemical complexity, chemical synthesis is technically possible, but economically not feasible. Paclitaxel, for example, requires >25 steps with a yield of 0.02%. As a result, most are extracted from the native plant species in minute quantities. • Algal biotechnology could produce these compounds at much increased levels, making production cheaper. **Novel active compounds:** • In addition, terpenoid biosynthesis pathways are interesting candidates for bioprospecting. • The marine environment has been a fruitful source of novel terpenes[82]. • Due to the patent cliff the pharma industry is looking to diversify; novel terpenes with new functionalities could be produced by / in algae. **General advantages:** • Meets health drivers (ageing population; increasing concern about dementia; healthcare costs) • Aligned with: a. drive for knowledge-based biotech economy b. CSR drive for sustainability • Developing terpene scaffolds in algae for pharma will develop latent ability to make other valuable terpenoid compounds for broader application (analogous to Amyris, where development of increased efficiency/reduced cost of isoprenoid production for pharma in yeast has paved the way for economically viable production of other isoprenoid family members *e.g.,* for flavour fragrance compounds and fuels).
How will the algal technology be commercialised?	• Using metabolic engineering and synthetic biology toolkits, expression pathways for terpenoids can be introduced into microalgal strains (proof of concept exists for cyanobacteria[83]). • Yields and cultivation regimes need to be optimised through R&D, to become competitive in terms of price and production capacity. • Through spin-outs from academia; collaboration between spin-outs and pharmaceutical companies for scale up (R&D for innovation outsourced by pharma) • A clear regulatory route will be essential. • In addition, algal culture collections and new strains discovered through bioprospecting should be screened for novel terpenes to develop further product pipelines.
Timescale to commercialisation	• 5-15 years to determine commercialisation potential
Advantages of Algal Biotechnology over incumbent approaches	• Diverse range of species for bioprospecting: Potentially enormous, but largely untapped pool of novel bioactives • Algae are a versatile chassis for expression. • Some species are already registered as GRAS. • Algae are perceived to be naturally 'green' (LCA of production process required to prove green credentials). • Algal expression is expected to be more cost effective than extracting compounds from trees, roots, corals, sponges *etc*. • Some drugs must be made via semi-synthetic routes, and the starting material is costly, *e.g.,* Ingenol-3-angelate which is derived from a compound found in the latex of *Euphorbia* species, costs €605 per 10 mg dose. • Possibility for higher titres and more controlled manufacturing • Microalgae naturally produce the GDPP (geranylgeranyl-diphosphate) precursor for diterpenoid synthesis in large amounts.

[82] Wang G, Tang W and Bidigare RR (2005) *Terpenoids As Therapeutic Drugs and Pharmaceutical Agents* in *Natural Products: Drug Discovery and Therapeutic Medicine* pp 197-225. eISBN: 1-59259-920-6

[83] Pers. comm., Bjoern Robert Hamberger / Poul Eric Jensen (unpublished data; May 2013); Lindberg *et al.*, (2010) *Engineering a platform for photosynthetic isoprene production in cyanobacteria, using Synechocystis as the model organism.* Metab Eng.12(1):70-9 doi: 10.1016/j.ymben.2009.10.001.; Reinsvold *et al.*, *The production of the sesquiterpene β-caryophyllene in a transgenic strain of the cyanobacterium Synechocystis.* (2011) J Plant Physiol. 168(8):848-52. doi: 10.1016/j.jplph.2010.11.006

Market size	• The global market for terpenoids is **>€8 billion per year**, comprising three segments: fragrances/food ingredients, fine chemicals and therapeutics[84].		
Growth rate	• The market for terpene-based healthcare products globally is set to rise, with an increase in global population, in average life expectancy, and increasing spending power esp in BRIC countries. • An indication of the growing interest in alternative sources for plant metabolites is given by the recent $13.5 million investment of BASF into Allylix (US), who produce essential oils using industrial biotechnology rather than extraction from plant materials.		
UK companies operating in this market sector	• Pharma Nord UK, Norkem		
UK Ecosystems potential to commercialise	• As this application requires the use of metabolically engineered microalgae, and as pharma applications are tightly regulated, cultivation will need to occur in indoor closed PBR systems, without coupling to bioremediation, and most likely with artificial illumination. The application would not be offering any ecosystem service, but (provided containment is not compromised) would not be of disadvantage to ecosystems. As a fail-safe the expression strain would need to be engineered so as to not survive in the wild. • High yield expression in algae would displace extraction from plant or marine materials with low natural terpene levels. This can lead to better resource efficiency of solvents, and ecological benefits if the material has to be wild harvested from ecologically sensitive locations (*e.g.,* coral reefs) and transported over long distances.		
	Technological	**Commercial**	**Other**
Barriers	• Expression of terpenoid biosynthesis pathways in microalgae is still at R&D stage.	• Containment strategies, validation and approval for new GM host strains of algae required which will make scale up costly.	• Competition from other sources, *e.g.,* bacterial expression[85]
Risks	• Microalgae growth at scale-up introduces growth/expression characteristics that differ from those observed in lab tests (medium).	• If there are poor titres of terpenoid at scale up it could mean that product is not competitive (medium).	• Public acceptance of GMO (low for pharma)
Fit with UK capability	• Expertise in industrial biotechnology and downstream processing	• Fits high value, low volume profile appropriate for production in the UK	• Research funding priorities fit: Industrial biotechnology; healthy ageing (funding opportunities for elucidating mechanisms of action)
Gaps in UK capability	• Proof of concept is being developed in Denmark (in collaboration with UK partners).[86] • GM-compatible open access test facilities for phototrophic growth	• Supply chain	• Risk averseness in funding landscape
Key innovation and R&D needs	• Genetic stability in target strains • Model organisms • Yield improvements • Improvements in basic biology and biotechnology knowledge • Development of low cost effective techniques for cultivation, harvesting, extraction & downstream processing • Open access pilot plant with GM facilities for scale-up • Data for models – economic/technological/environmental/ecological/LCA • Bioprospecting		

[84] Wang G, Tang W and Bidigare RR (2005) *Terpenoids As Therapeutic Drugs and Pharmaceutical Agents* in *Natural Products: Drug Discovery and Therapeutic Medicine* pp 197-225. eISBN: 1-59259-920-6
[85] Cane DE, Ikeda H (2012) *Exploration and mining of the bacterial terpenome* Acc Chem Res. Mar 20;45(3):463-72 doi: 10.1021/ar200198d
[86] Pers. comm., Bjoern Robert Hamberger / Poul Eric Jensen / Colin Robinson (May 2013)

	Requirement for technology partnerships	Support needs	Other
Enablers for successful UK commercialisation	• Mechanism to transfer technology from universities • Reducing barriers to releasing technologies to SMEs • Cross collaboration - domestic / international • Need for more 'united' research efforts across UK universities, with good links to expertise abroad	• Funding: Non equity, for international collaborative activities, government investment • Smaller contribution requirement for UK Plc for UK grants • IP assistance • Commercial interest in the UK for algal biotech from SMEs, VCs • Training programs in downstream processing	• GMO legislation - PR campaign on GM and algae • Mechanism to grow small into medium sized companies • More algal technology companies • Simplification of patenting process
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Provide funding for further collaborative R&D into stable expression of terpenoids in algae • Build strong partnerships between research community and pharma industry • Support formation of spin-out companies • Utilise existing UK industry expertise for commercialisation		

2.4 Food and feed (1-10 yrs)

> *Food security is a tremendous global concern; with the population of our planet expected to rise to 9.1 billion by 2050, food production will need to increase by up to 70%[87]. At the same time agriculture is a major contributor to greenhouse gas emissions, both through the energy-intensive production of fertilisers, and through direct and indirect land use change leading to carbon emissions from the soil. Pressure on land and freshwater resources is rising.*

Marine algae can and are being used as a source of food that is grown without needing arable land or freshwater. It is hence an ethical imperative to explore if the UK, with its large coastal area, can contribute to meeting the increasing demand for food, by producing algae in a sustainable manner for food and feed.

Established markets for algae-based foods exist: especially in Asian societies algae are a staple food; Sushi would be unthinkable without the seaweed wrapping Nori. Even in the UK traditional recipes such as Welsh Laver Bread use macroalgae (of the same genus as Nori, *Porphyra*). Macroalgae are generally rich in iron, zinc, iodine as well as vitamins A, B and C, and therefore are valuable contributors to a balanced diet. Indeed their mineral profile has led to their use as flavourings and salt replacements[88]. As indicated in Section 2.3, microalgae such as *Chlorella* and *Spirulina* are being used as health supplements for their protein composition and content, and heterotrophically grown *Chlorella* is being developed by Solazyme Roquette Nutritionals as a source of oil, protein and gluten-free flour.

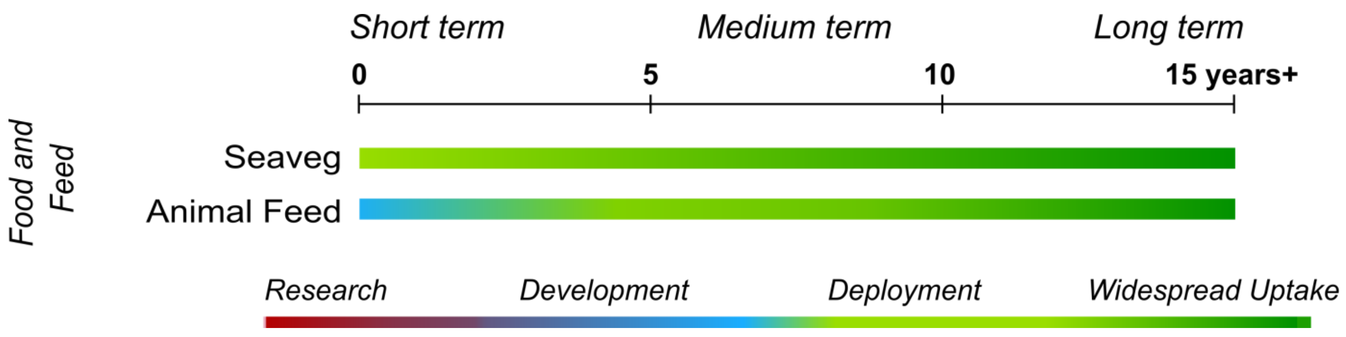
To showcase how algal technologies in the UK might contribute to sustainable food and feed supply, as well as economic growth, we present two case studies: macroalgae as premium sea vegetable, and microalgal biomass and protein for aquaculture and animal feed. Estimated timescales for commercialisation are given in Figure 10.

---

[87] Source: fao.org/news/story/en/item/35571/

[88] *e.g.,* SeaSpice (seaveg.co.uk/salts.html); Artisan Seaweeds Sea-Spice® Collection (maraseaweed.com); Seagreens® salt replacements (seagreens.com/Products/FoodmanufacturingingredientsSaltreplacement2.aspx), *kombu* seaweed / umami (en.wikipedia.org/wiki/Umami)

Figure 10: **Indicative commercialisation timescales for case studies on food and feed**



Case Study 7: **Macroalgae as premium sea vegetable and condiments**[89]

There is considerable potential for expansion of the use of macro- and microalgae for human consumption, both in unprocessed form and as a feedstock for food ingredients. Sourcing macroalgae for food from the coastal areas in a sustainable form, as it has been done traditionally in the UK for centuries, could displace a proportion of more carbon-intensive agri- and horticulture, diversify the food chain, and provide local employment. Despite the traditional use, seaweed is a relatively under-used culinary resource in the UK. However, growing awareness of diet – both in terms of health and traceability (fuelled further by the recent food scandals) – a growing vegetarian population, and a desire for speciality ingredients in the West mean that the market for algal-based foods and condiments is expanding. It has been highlighted that the UK has a growing problem of iodine deficiency[90] and the use of macroalgal replacements for salt may be one means of addressing this issue.

Premium macroalgal products can command high prices, such as £8.97 per 100g of a macroalgal condiment[91] which is produced in Scotland. New enterprises could be formed in coastal communities to expand the range of products and suppliers. This would need to be accompanied by effective marketing, for example through partnerships with celebrity chefs, and in association with the research community to provide evidence of health benefits and sustainability credentials.

In addition, after the disaster at Fukoshima, the Asian market is looking for alternative producers to feed into their supply chain, in particular those with Soil Association organic certification. Although the species of highest interest to the Japanese market are not native to the UK, there is an opportunity to brand European seaweed products, such as dulse, as exotic high-value foods for the Asian market.[92]

Case Study 8: **Algal biomass for animal feed**[93]

The global demand for protein-rich food is growing, as spending power in emerging economies increases. Meat consumption is suggested to rise from 233 million tonnes (2000) to 300 million tonnes (2020)[94], with a concomitant 23% increase in milk production and 30% increase in egg production. Sustainable animal feed, especially from vegetarian sources and for non-GM markets, is highly sought after. Both macro and microalgae can contribute to this in a significant way, an overview is given in Figure 11. The benefits of macroalgae in animal feed formulations have been highlighted at the AB-SIG conference 'Opportunities for

[89] Information is also provided in Appendix 2 in the same tabulated format as in Case Study 1, to allow a direct comparison.
[90] Vanderpump M Lazarus J Smyth P Burns R Eggo M Han, T et al. *Assessment of the UK iodine status: a national survey.* Endocrine Abstracts. Presented at the Society for Endocrinology BES 2011: 11 April 2011-14 April 2011
[91] Source: Böd Ayre website (seaweedproducts.co.uk), Feb 2013
[92] Pers. comm., Derek Przybycien, Clearspring Ltd. April 2013.
[93] Information is also provided in Appendix 2 in the same tabulated format as in Case Study 1, to allow a direct comparison.
[94] Source: fao.org/docrep/007/y5019e/y5019e05.htm

algal commercialisation' on 20 June 2012, they include: reduced infection and mortality rates, improved taste, better colouration and texture, higher weight gain, as well as reduced need for chemical pre-mixes, synthetic additives and antibiotics[95]. AB Agri Ltd market a macroalgae feed for cows, Simple System Ltd include macroalgae in some horse feed formulations, and Ocean Harvest Technologies Ltd provide macroalgae feeds for pigs and pets as well as salmon and shrimp.

Microalgae are rich in protein and many strains possess a desirable amino acid profile[96]. Indeed for the hatching stages of aquaculture they are an essential food, and are well suited to displace the highly unsustainable protein source fishmeal in aquaculture and across the food chain. This is an established industry, but due to the high current price of microalgal biomass its full potential is far from being realised. To broaden the use of algal protein and biomass beyond high value applications, and to respond to the increasing need, production capacity has to increase. Economy of scale, integrated biorefining for increased resource efficiency, and innovation through continued R&D will contribute to lowering the price.
One example of an initiative which seeks to improve algal feedstocks for use in aquaculture is a collaboration between Eminate Ltd, Skretting, Liverpool University, Anglesey Aquaculture and the University of the Highlands and Islands. With funding from the TSB's sustainable protein call, this consortium investigates fermentation as a means of making proteins from a variety of plant sources, including algae, more bioavailable in animal feed.

Figure 11: Overview of algal product categories in animal feed

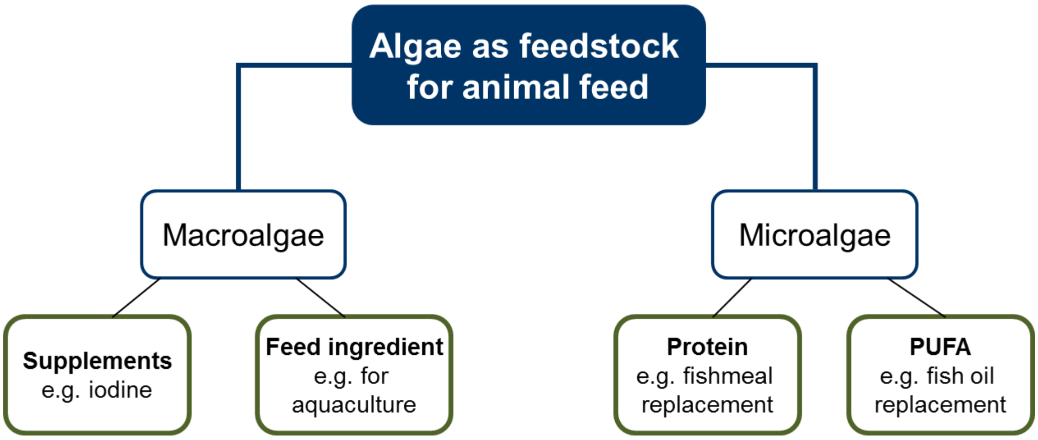


Table Case Study 8: Microalgal biomass and protein for aquaculture and animal feed

Why will this be an important market?	• Quest to find a sustainable source of protein to replace fishmeal • Aquaculture production / consumption of aquaculture products is rising • Algae can deliver added benefit: omega oils and desirable amino acid balance (strain dependent) • There is appetite within the aquaculture industry to reduce the reliance on fishmeal
How will the algal technology be commercialised?	• Through integrated biorefining: initially using all biomass as speciality feed, as production capacity increases: fractionation, targeting protein fraction for feed • Coupling with bioremediation as far as possible (while satisfying HACCP; *c.f.* Case Study 1) • Partnerships between feed producers and pilot facilities throughout scale-up
Timescale to commercialisation	• 2-10 yrs

95 Presentation slides with details available at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=8580598&name=DLFE-87643.pdf
96 Becker EW. 2007. Microalgae as a source of protein. Biotechnology Advances 25: 207-210.

Advantages of Algal Biotechnology over incumbent approaches	• Sustainable source (to be proved by LCA) • Potential to reduce carbon footprint of feed • Benefits of omega oil content • Under the transmissible spongiform encephalopathies (England) regulations 2010, fishmeal can only be fed to non-ruminants (pigs and poultry), algal protein would not be subject to such restrictions and could offer a means of enriching the diet of other animals with omega 3/6		
Market size	• Globally: Fish farming: USD150 billion; shrimp farming: USD80 billion; pig farming: USD200 billion[97] • In 2010 the UK consumed 135,400 tonnes of fishmeal, most of which it imports from Peru and Denmark[98]. • The aquaculture sector is the biggest user of fishmeal in the world, globally consuming 3.72 million tonnes in 2008[99]. • Non-aquaculture uses for fishmeal replacement (livestock in the UK[100]): 4.5 million pigs; 47 million laying or breeding fowl; 103 million table chickens; 9.9 million cattle and calves.		
Growth rate	• World total aquaculture production has grown from 47.3 million tonnes to 63.6 million tonnes from 2006 to 2011[101].		
Companies operating in this market sector	• Skretting, EWOS, Ocean Harvest, Biomar in aquaculture feed market		
UK Ecosystems potential to commercialise	**High:** • If it can be coupled to bioremediation of suitably clean nutrient-rich waste streams (*c.f.* Case Study 1; denitrification of ground water); for that, HACCP must be established		
	Technological	**Commercial**	**Other**
Barriers	• Handling of algal biomass needs to be made compatible with current feed machinery. • Incorporation rates in animal feed need to be determined – might not be a direct replacement.	• Cost and volume of biomass (currently too expensive to substitute for bulk feed, and insufficient production) • Cost of raw materials / nutrients	• HACCP regulations (expensive to establish)
Risks	• If whole biomass with high DNA content is used: may cause gout (species-dependent) (medium)	• Potential issues around stability of supply due to seasonality unless supplemented with light in winter (medium)	• Raw protein may have limited bioavailability (medium)
Fit with UK capability	• Knowledge base (CCAP) for strains screening • Integration with existing aquaculture industry	• Industry could develop and adapt existing good knowledge base	• Recent/current initiatives: FPI, Energetic Algae, Biomara, IDREEM, FFINN (TSB sustainable protein call) • UK leading on Global Ocean Commission – sustainable management of marine resources may encourage a move away from fishmeal
Gaps in UK capability	• Pilot / demonstration plants • Availability of algal biomass for testing • Cost effective cultivation and harvesting at scale	• More R&D on choice of appropriate strains is needed to reduce investment risks	• Awareness of feed manufacturers of the full potential and spectrum of benefits algae offer

[97] Ocean Farvest Technology; connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=8580598&name=DLFE-87643.pdf
[98] Seafish (October 2011) Fishmeal and fish oil figures,
[99] FAO State of World Fisheries and Aquaculture Report 2012 available at www.fao.org/docrep/016/i2727e/i2727e00.htm
[100] Defra UK. (2012) Farming Statistics Final Crop Areas, Yields, Livestock Populations and Agricultural Workforce at 1 June 2012
[101] FAO State of World Fisheries and Aquaculture Report 2012

Key innovation and R&D needs	• Determining health benefits of algal feed (justification for price) • Screening algal strains for optimum yields and composition to get best feed results • Integrating with waste streams (nutrients, surplus heat/ energy) and existing technologies/infrastructure for cost effective cultivation and harvesting • Scaling up of growth, harvesting, processing • Environmental impact assessments for scaled growth • Develop / explore new value chains outside of aquaculture		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Integrating with waste streams and existing technology/aquaculture industry • Utilising knowledge base (strains, environment)	• Understanding of market conditions • Pilot plants (investment) • Educating investors	• Successful communication • Acceptability and appreciation • Excellent research base
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Trials – demonstration with salmon and other species • To develop a financial measure for the damage done by overfishing, in order to allow competitive pricing of algal protein • Scale-up of microalgal production to achieve economy of scale and satisfy demand		

2.5 Chemicals (5-10 yrs for speciality, >10 yrs for commodity)

The majority of the chemicals which are the building blocks of so many of the consumer items we take for granted are based on fossil resources. Long-term sustainability can only be ensured if, in addition to reducing, re-using and recycling our resources we also develop alternative, renewable feedstocks. While in some cases direct replacements are possible, in other cases it will be necessary to focus on functional equivalents rather than identical molecules.

As a general trend, platform chemicals from renewable sources struggle to be price competitive with incumbent petrochemicals. It is, therefore, desirable to provide added benefits in terms of improved functionality. The immense – and as yet virtually untapped – diversity of micro- and macroalgae provides a rich treasure chest to bioprospect for molecules with desirable functionalities[102]. Arriving at a candidate molecule and organism compatible with industrial scale-up is a laborious and risk-laden process: the timescales until an organism with a desirable metabolite is discovered cannot be predicted. Once it is found, there are no guarantees that it can be cultured. However, given the astounding diversity of algae, the probability of discovering interesting chemicals is very high. Even if the strain that produces them naturally is found to resist cultivation and scale-up, the ever-increasing tool-kit of metabolic engineering and synthetic biology, where the UK has considerable strengths, can open paths towards production of the desired molecule in an established algal expression platform.

In order not to lose out in the race for novel chemicals from algae, the UK needs to invest in extensive bioprospecting, and in thorough mining of existing culture collections. In addition, the algal metabolic engineering and synthetic biology communities should work closely with the chemical industry to identify lead molecules which could be expressed in algal platforms within the concept of integrated biorefining.

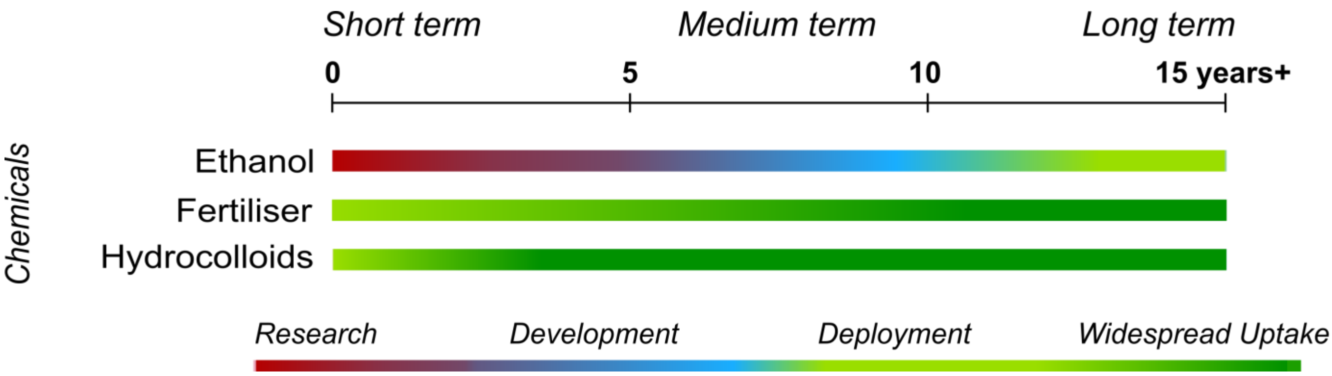
In addition, as outlined in Section 2.1, algal biomass can be fed into thermochemical conversions, and the breakdown products used for chemical synthesis of desired end molecules. This potential is not unique to algae, but is shared with other sources of biomass.

[102] This is elaborated in Chapter 4 of the BBSRC Scoping Study "Algal Research in the UK" ; available at bbsrc.ac.uk/web/FILES/Reviews/algal_scoping_study_report.pdf

Overall, considerable R&D and effective communication between the algal and chemical communities in the UK are still necessary to develop the large, but as yet mainly theoretical potential algae have in providing sustainable feedstocks for the chemical industry.

However, cases exist where algae can now already provide a feedstock for renewable chemicals; an example for a direct replacement product is ethanol (a platform intermediate for a host of products) derived from macroalgae. This has also been highlighted in the AB-SIG SRA as a route to commercialisation[103]. A functional equivalent with added benefits is fertiliser from macroalgae, and an existing example of a group of molecules exclusively found in algae, with particular functional traits, is hydrocolloids from macroalgae. These are described in more detail in case studies 9-11. Estimated timescales for commercialisation are given in Figure 12.

Figure 12: **Indicative commercialisation timescales for case studies on chemicals**



Case Study 9: **Macroalgae to ethanol for chemicals**[104]

Demand for non-petrochemical based / 2nd generation bio-derived chemicals is ever-increasing. Ethanol is one example of a platform chemical used for many solvent applications in pharmaceuticals, toiletries and cosmetics, detergents and household cleaners, coatings and inks, and processing solvents. It also serves as a chemical intermediate for the manufacture of ethyl acetate, ethyl acrylate, acetic acid, glycol ethers and ethylamines, amongst others; it will hence continue to be an important building block in future.

Recent developments[105] using an engineered strain of *E.coli* have yielded 0.281 weight ethanol per dry weight macroalgae (equivalent to ~80% of the maximum theoretical yield from the sugar composition in macroalgae). However, there is a significant challenge to make ethanol derived from macroalgae competitive with other sources on a financial basis.

Developing large-scale cultivation of macroalgae for this purpose (if not in conjunction with fish farming for bioremediation, *c.f.* Case Study 3) may deplete nutrients and influence the ecosystem. Fertilisation may remediate that, but may cause other side effects[106]. Testing of cultivation by pilot facilities and scale up is necessary to collect more data and evidence. Preliminary data suggests that savings of greenhouse gas emissions can be achieved by using macroalgal biomass as a feedstock for biogas and bioethanol production in Denmark[107], but there is considerable scope for reducing energy consumption in the process. Proof of concept needs to be established now in order to pave the way for commercialisation within the next 10-20 years. This includes further research into the fermentation step to improve the viability of the process.

[103] under pathway B
[104] Information is also provided in Appendix 2 in the same tabulated format as in Case Study 1, to allow a direct comparison.
[105] Wargacki et al. (2012) An Engineered Microbial Platform for Direct Biofuel Production from Brown Macroalgae *Science* Vol. 335 no. 6066 pp. 308-313 DOI: 10.1126/science.1214547
[106] *c.f.* AB-SIG SRA, p. 13
[107] Merlin Alvarado-Morales et al. (2013) Life cycle assessment of biofuel production from brown seaweed in Nordic conditions *Bioresource Technology* Volume 129, February 2013, Pages 92–99 doi:10.1016/j.biortech.2012.11.029

Case Study 10: Macroalgae for organic fertiliser

Why will this be an important market?	• Proven performance benefits for horticulture • Demand for non-synthetic fertiliser • High carbon footprint of producing synthetic fertiliser • Increase in organic agriculture		
How will the algal technology be commercialised?	• Collaboration between seaweed producers and fertiliser companies • Expansion of existing fertiliser ranges		
Timescale to commercialisation	• Now – ongoing		
Advantages of Algal Biotechnology over incumbent approaches	• Qualifies as organic – enables certification • Scientific studies show added benefit to fruit setting and disease protection[108] • NPK source as well as trace nutrients • Improvement in soil characteristics[109]		
Market size	• The European fertiliser market had total revenue of $30.4 billion in 2011[110].		
Growth rate	• The European fertiliser market had a compound annual growth rate of 13.9% between 2007 and 2011[111].		
UK companies operating in this market sector	• Maxicrop (source seaweed from Norway), Böd Ayre, Hebridean Seaweed, Leili – Alga600 (Chinese)		
UK Ecosystems potential to commercialise	• Capitalising on our large coastal region • High if in conjunction with fish farming for bioremediation, *c.f.* Case Study 3		
	Technological	**Commercial**	**Other**
Barriers	• Need for long-line infrastructure for scale-up	• Competition on a price basis with chemical fertiliser	• Transition from wild harvest to cultivation to allow scale-up
Risks	• If growth is integrated with bioremediation: vectors for disease need to be controlled (low)	• Market saturation; price decay (medium)	• Ecological considerations may limit scale-up (medium)
Fit with UK capability	• Strong horticultural and plant science research base	• Small-scale industry already in existence	• Existing traditional method used by coastal farmers
Gaps in UK capability	• Cost effective cultivation and harvesting • Scale up	• Transition of industry from wild-harvest to cultivation	• Limited ecological data concerning risks of scale-up
Key innovation and R&D needs	• Scale up of macroalgal growth facilities • Demonstration of fertiliser use at scale on farms to prove efficacy and dosing		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Between growers and fertiliser industry • Between growers and technology providers: investigate novel low cost, environmentally friendly harvesting and processing options	• Clarity about options for sustainable scale-up	• Increase in organic farming • Consumer awareness of the environmental impact of chemical fertilisers

[108] Reviewed in: Seaweed extract stimuli in plant science and agriculture J Appl Phycol (2011) 23:371–393
[109] Reduction of nitrate leaching from soil treated with an *Ascophyllum nodosum* based soil conditioning agent – Leach *et al.* Journal of Applied Phycology 12-1999, Volume 11, Issue 6, pp 593-594
[110] Research and Markets report, 2012: "Fertiliser in Europe"
[111] ibid

Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Identify where in the UK seaweed can be farmed sustainably • Put in place partnerships which will allow scale-up of growth in these areas • Verify amount of biomass that can be produced sustainably • Use biomass for higher value purposes (such as speciality fertilisers) first, without flooding the market • In parallel, develop partnerships and processing options for lower value, higher volume products, to capitalise on increase in capacity

Case Study 11: Macroalgae for hydrocolloids

While the bulk market for hydrocolloids for food processing is nearing maturity, there is scope for products using the same materials for pharmaceutical and other high-grade applications. UK companies such as Cybercolloids and Marine Biopolymers are leading innovation on this front.

Why will this be an important market?	• Carrageenan has long enjoyed a small share of the personal care toothpaste binder market and has started to make inroads into cosmetics and pharmaceuticals, *e.g.,* drug capsules and excipient formulations. • Alginate is used in a variety of industries beside food, *e.g.,* textile printing, pharmaceuticals, welding rod manufacture, paper industry as well as a substrate for immobilised biocatalysts
How will the algal technology be commercialised?	• Through scale up of macroalgae operations, integration with biorefinery approach
Timescale to commercialisation	• now – ongoing
Advantages of Algal Biotechnology over incumbent approaches	• already used, established market and demand • occupies a unique niche
Market size	• The global hydrocolloids market was worth $3.30 billion in 2010, mostly dominated by gum arabic. Emulsifiers command between $3-8 /kg, while gelling agents are worth $5-22/kg. • Carageenan had a European market value of $127.9 million in 2012, with prices between $10-12/kg. • Agar had a European market of $29.6 million in 2012 with prices between $20-23/kg[112].
Growth rate	• Compound Annual Growth rate of emulsifiers is 6% • Compound Annual Growth rate of gelling agents is 2.5%[113]
Companies operating in this market sector	• ISP Alginates (Sco) – now owned by FMC (Norwegian) • Algas Marinas (Chile), Agarindo Bogatama (Indonesia), Setexam (Morocco), MSC co (Korea), Hispanager (Spain), Huey Shyang Seaweed Industrial Company (China), Iber Agar, ROKO, FMC international, Danisco, Cargill, Food Chemifa Co, Hebridean Seaweed Co. CP Kelco, FMC Biopolymer, Danisco Dupont, Shemberg Corporation, Cargill
UK Ecosystems potential to commercialise	**High:** • If based on sustainable use of natural stocks and farming • Long coastline enables scale-up

[112] Frost and Sullivan (2013) Sensory and Textural Food in Europe
[113] Ibid

	Technological	Commercial	Other
Barriers	• If considered as part of a biorefinery, the methods of treating biomass would have to be compatible with hydrocolloid production and vice versa (*e.g.,* use of harsh chemicals not acceptable to food chain)	• Cost and volume of biomass (currently too expensive, and insufficient production) to compete with imports from elsewhere • Difficult to compete against an established international industry	• Potential regulatory barriers if novel hydrocolloids are developed for pharmaceuticals
Risks	• IP protection by larger industries may mean it is difficult to innovate without infringing IP (low)	• Price, Volumes, Stability/ seasonality (medium) • This is a mature market, and entry of a new player is likely to depress value of the product especially if hydrocolloids were produced in large volumes.[114] (low)	• Delays to entering market if regulatory approval was necessary for new products (low)
Fit with UK capability	• Pharma and drug delivery R&D	• Industry could develop and adapt • Existing good knowledge base • Seaweed industry exists but small scale	• Integrate this with recent/current initiatives: FPI, Energetic Algae, Biomara, IDREEM
Gaps in UK capability	• Small scale harvesting, would require scale up to produce a significant volume	• UK companies operating in this industry have been acquired by other multinationals	• Lack of awareness of innovation potential for seaweed products
Key innovation and R&D needs	• Scale up • Pilot / demonstration plants • Availability of algal biomass • Cost effective cultivation and harvesting • Increase in evidence base for potential health benefits of hydrocolloids, and of range of value-added functionalities for speciality applications, *e.g.,* in pharma		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Fine chemical companies working with academic base to unlock innovation potential for seaweed products	• Understanding of market conditions • Understanding of regulatory restrictions for pharma use • Pilot plants (investment) • Educating investors	• Development of macroalgal biorefining concept, with pilot operations
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Integrating with waste streams (nutrients, surplus heat/ energy) and existing technologies/infrastructure for cost effective cultivation and harvesting (*e.g.,* IMTA, see Case Study 3) • Environmental impact assessments • Develop/ explore new value chains, *e.g.,* drug delivery		

[114] Lewis, J., Salam, F., Slack, N., Winton, M., Hobson, L. 2011. 'Product options for the processing of marine macro-algae – Summary Report'. The Crown Estate, 44 pages. ISBN: 978-1-906410-31-5

2.6 Bioenergy and biofuels (5-20 yrs)

Like food security (see Section 2.4), energy security is an increasingly urgent global issue, with great impact on national economies and politics. Rising energy prices have a profound impact on industry as well as individual households. Fossil fuels are not only increasingly expensive to extract (for technical and/or geopolitical reasons), but are linked to carbon emissions which accelerate climate change and the concomitant incidence of extreme weather events, with further destabilising effects on the economy.

Renewable sources such as wind, solar and geothermal energy are associated with expensive infrastructure, and are mostly not available on demand, while nuclear power (especially post-Fukoshima) poses other environmental challenges. Biomass as an energy source can be stored (albeit for a limited time in the case of algae), and unlike the other non-fossils can be a feedstock for liquid transport fuels.

Reducing energy consumption through improvements in efficiencies and a change in consumer mindset is essential, but biomass will need to play its role if the UK is to meet its carbon reduction targets and renewable obligations. The potential of bioenergy, and innovation required to fulfill that potential, have been discussed in the recent Bioenergy TINA[115]. 1st generation biofuels are controversial due to possible competition with food and feed[116], the pressure on arable land (leading to direct or indirect land use changes) and on freshwater supplies. Alongside lignocellulosic biofuels, algae-derived liquid transport fuels have attracted a large amount of interest and funding on a global scale. However, it has become clear that substantial challenges still have to be solved before large-scale economically and environmentally sustainable production of biofuels from algae can become a reality[117].

However, within the context of integrated biorefining (*c.f.* Section 2.1), various forms of energy can be a co-product also in the near- and medium term. In this concept, the energy burden of processing[118] is justified by the suite of products derived from the processed algae.

Figure 13 illustrates how algal biomass can be converted to energy. Most favourable will be those pathways which do not require the energy-intensive step of drying the biomass, such as AD and liquefaction.

Of the pathways given in Figure 13, conversion into methane through Anaerobic Digestion (AD) has been highlighted in the AB-SIG SRA as a medium- to long-term option for bioenergy production (pathways A and B); liquefaction as a long-term choice for biofuel production (pathways C and D).

Indeed, opportunities for use of macroalgae in mixed feedstock AD are emerging already now, especially in Northern Ireland, where AD attracts quadruple ROCs, and in combination with sewage AD plants in areas of high seasonality. *E.g.,* in coastal holiday towns, where sewage production is considerably higher in summer, macroalgae could be a supplemental feedstock in winter. This could ensure that the full capacity of the AD plant can be used around the year[119]. Issues around seasonal harvesting and storage will need to be addressed. In addition, photosynthetic microbes can also add considerable value to AD operations

---

[115] Published Sept 2012; available at lowcarboninnovation.co.uk/document.php?o=9

[116] although the protein portion/DDGS after fermentation of grain to ethanol, and the press cake after extraction of oils for biodiesel from seeds, can be used as animal feed

[117] US Department of Energy report "Sustainable Development of Algal Biofuels in the United States", 2012, available at https://download.nap.edu/catalog.php?record_id=13437

[118] which especially for many microalgal strains can be substantial; for an example quantification see Stephenson AL, Kazamia E, Dennis JS, Howe JH, Scott, SA, Smith AG, 2010. Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors. *Energy & Fuels*, 24(7), 4062-4077 doi: 10.1021/ef1003123

[119] This has been discussed at the AB-SIG conference in June 2012 (for presentation slides see: connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=8580598&name=DLFE-87878.pdf.) The economics depend on scale, and on revenue from the digestate. Overall, the economics of using macroalgal biomass for anaerobic digestion are still very much under investigation. An Irish study on the current feasibility based upon a commercial gas price of €8/GJ in August 2008 and REFIT tariff available for electricity from biogas in Ireland of €120/MWh concluded that the biomass feedstock would have to cost less than €63 per tonne for the process to break even. A separate study commissioned by The Crown Estate stated the value must be less than £300 per dry tonne for the process to be financially sustainable.

primarily as a means to upgrade digestate[120]. This is of increasing relevance as AD is being adopted by agri, food, waste and retail entities in urban locations, where transportation of digestate for land application is not feasible.

Further details are given in case studies 12 (Macroalgae for AD) and 13 (Microalgae to synthetic fuels via thermochemical conversion). Estimated timescales for commercialisation are given in Figure 14.

Figure 13: Biomass processing options (simplified) for energy products

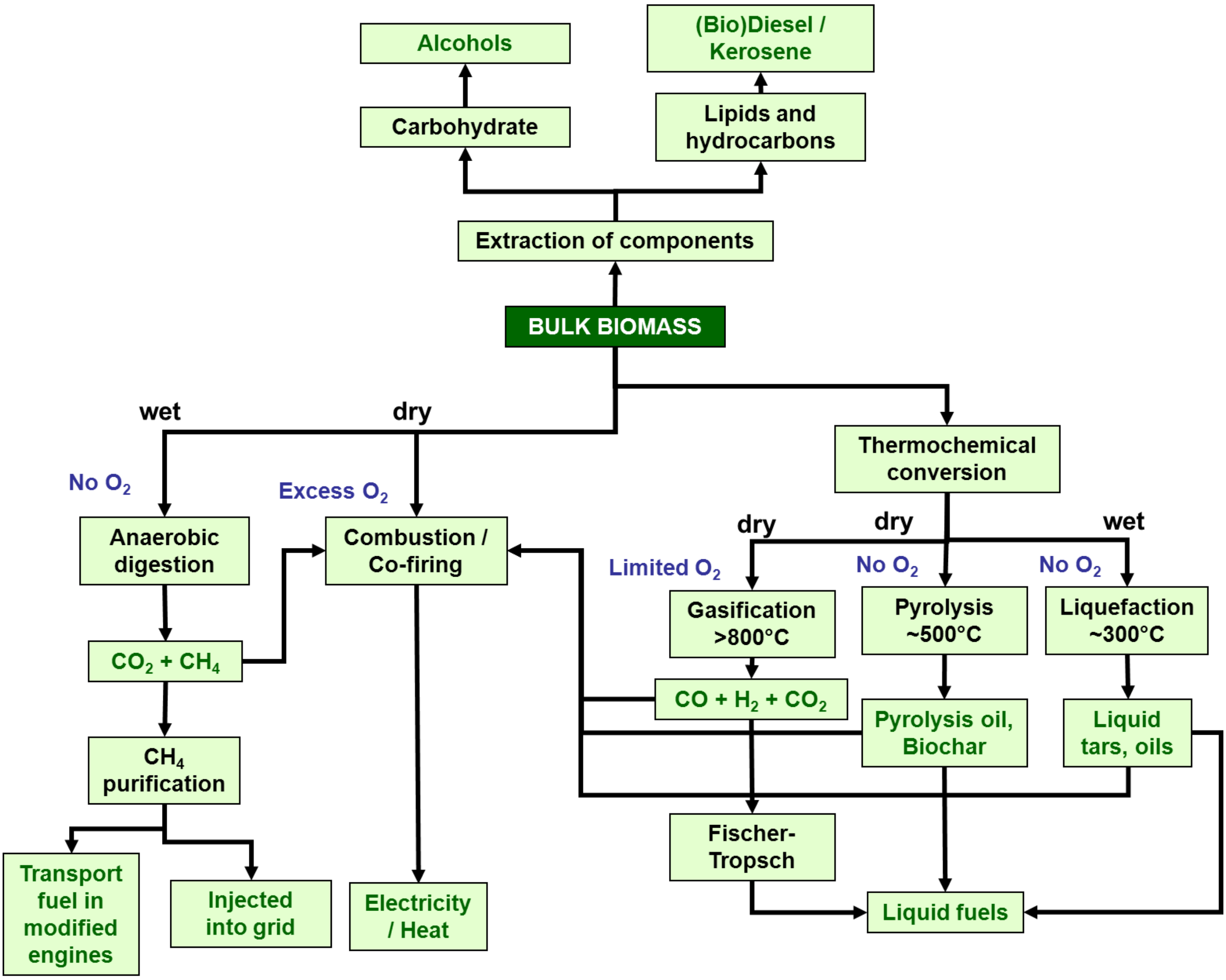
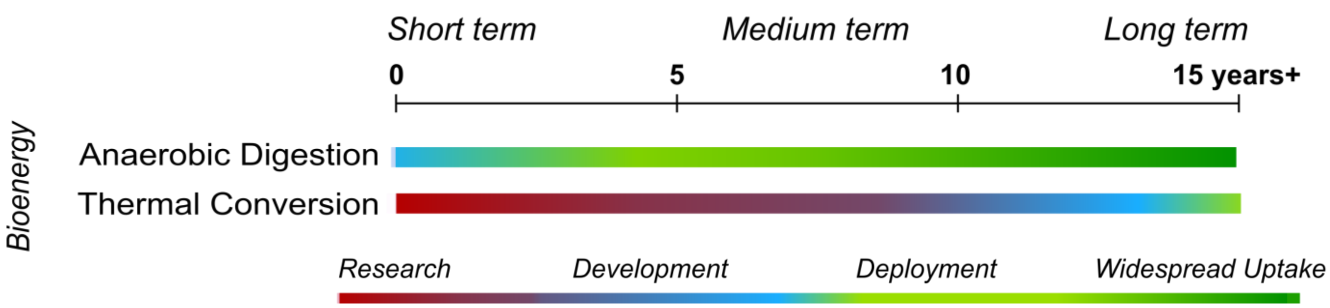


Figure 14: **Indicative commercialisation timescales for bioenergy case studies**



---

120 Pers. comm., Steve Skill, April 2012

Case Study 12: Macroalgae for Anaerobic Digestion (AD)

Why will this be an important market?	**AD:** • AD is becoming an important means of generating biogas (if coupled to CHP: electricity & heat) and reduces reliance on fossil fuels. • Means of retrieving value from waste (*e.g.,* food waste, farm waste); for scale-up additional feedstocks are needed, which macroalgae can provide • Provides a means for decentralised energy generation; could reduce energy cost for remote communities. *E.g.,* to provide all the households on Mull in Scotland with domestic gas from macroalgae (they currently have no domestic supply) would require the methane from 430 ha of macroalgal cultivation based on 200 tonnes/ hectare production[121]. • Contributes to energy mix, leading to higher resilience in energy supply
How will the algal technology be commercialised?	**For algal growth:** • Make full use of sustainable natural harvest (including ecologically responsible beachcast harvest) • For further scale-up on long lines: As far as possible integration with remediation / waste treatment / fish farming **For AD:** • Integration with existing operations dealing with food / farm waste, or other energy crops, to provide an additional / alternative source of feedstock • Recovery of nutrients in digestate – potential for use as fertiliser
Timescale to commercialisation	• 5-10 yrs[122] (small scale addition to existing AD facilities could start immediately)
Advantages of Algal Biotechnology over incumbent approaches	• Use of macroalgae reduces reliance on other feedstocks for AD which may compete with food. • Co-digestion of macroalgae with food waste provides a viable financial route for the utilisation of macroalgae in a sustainable bio-energy based energy platform. This applies to energy schemes from < 500 to 2000 kWe with macroalgae gate prices ranging from £100 – 300 per dry tonne. • Overall, the scenarios that appear to be commercially possible at the present time require that seaweed be delivered to the operating plant at between £125-300 per dry tonne. Under the right criteria for macroalgae and food waste, anaerobic digestion is an investable proposition with efficient returns for both the project developer and macroalgae harvester[123]. • Importantly, biomethane has the potential to reduce GHG emissions (21.9%) and fossil fuel depletion (58.6%) for seaweed farmed for bioenergy relative to natural gas[124]. • Reduces pressure on land, as it acts as a replacement for energy crops • Possibility for near shore and offshore cultivation
Market size	• Currently 106AD plants are in operation in the UK outside of the water industry, in additon 146 plants are run by the water industry as part of sewage operations[125]. • 222 planning applications for AD plants have been submitted.
Growth rate	• The installed capacity in the worldwide market for biogas plants will increase from around 4,700 to about 7,400 MWel between 2012 and 2016[126].
UK companies operating in this market sector	Some AD examples (currently no macroalgae-focused operation, but a demonstration facility is in planning in Scotland): • Biogen-Greenfinch, AWS, Andigestion Ltd / Summerleaze Group • water companies (sewage treatment) • numerous independent farms

121 Hughes *et al*. (2012) Biogas from Macroalgae: is it time to revisit the idea? *Biotechnology for Biofuels*, 5:86 doi:10.1186/1754-6834-5-86
122 *c.f.* pathways A and B in AB-SIG SRA
123 Lewis, J., Salam, F., Slack, N., Winton, M., Hobson, L. 2011. 'Product options for the processing of marine macro-algae – Summary Report'. The Crown Estate, 44 pages. ISBN: 978-1-906410-31-5
124 Langlois *et al.* (2012) Life cycle assessment of biomethane from offshore-cultivated seaweed, *Biofuels, Bioproducts and Biorefining* Volume 6, Issue 4**,** pages 387–404, doi: 10.1002/bbb.1330
125 Figures collated by NNFCC and WRAP in 2013 available from www.biogas-info.co.uk/index.php/ad-map.html
126 thebioenergysite.com/articles/1345/european-biogas-market-grows-but-german-market-slumps

UK Ecosystems potential to commercialise	• High, if algal farms can be sighted in eutrophication zones • But: potential ecological changes could arise due to intensive cultivation of macroalgae, *e.g.,* changes to local hydrodynamics and resulting sedimentation patterns, benthic impacts from increased organic matter supply, changes to water column nutrient availability and from shading of the sea-floor • While beachcast material mostly plays an important ecological function, the removal of some odour-producing red algae can have environmental benefits[127].		
	Technological	**Commercial**	**Other**
Barriers	Algae: • Overcoming seasonal supply/availability of feedstock • Development of lower cost methods of macroalgae farming AD: • Need to upgrade biogas and clean up, non compressibility of methane • Need for infrastructure to export products to point of use	• Price of algae supplied must be <£300 per dry tonne to make the business case for AD stand up. Many AD operations currently run on waste products / charge gate fees, rather than paying for feedstock. • Energy end product not very high value but could be more valuable in rural areas for decentralised energy supply. • Using a scale of 100,000 dry tonnes of biomass per year macroalgae costs would need to be less than €63 per tonne of dry weight biomass for the process to be economically viable[128]. • Technology exploitation limited by resource scale (but could be transferred) • Market is constrained by location of resource.	• Marine spatial planning issues • Limited number of appropriate sites for production are close to location of demand
Risks	• Different strains of macroalgae may have differing impacts on AD process – optimisation of conditions may be required • Macroalgae bioaccumulate heavy metals – could impact use of digestate as a fertiliser	• Security of supply of algal feedstock	• Change in government policy regarding feed in tariffs • Potential ecological changes due to intensive cultivation of macroalgae (see above)
Fit with UK capability	• Growing expertise in macroalgae cultivation	• Links to aquaculture industry -> bioenergy from waste • Growing AD industry	• Marine special planning expertise
Gaps in UK capability	• Pilot / demonstration plants for algae-fed AD • Fragmentation across expertise sectors: needs integration pull	• It is still difficult to attract funding for AD operations	• Funding landscape for scale-up
Key innovation and R&D needs	• Supply route security (available biomass; sustainable increase in yields with minimum inputs at reduced cost) • Selective breeding of macroalgae • Understanding environmental and ecological consequences of growth at scale • Process intensification • Mechanisation of macroalgal biomass production • Storage options for harvested biomass (*e.g.,* silage)		

[127] *c.f.* http://wabproject.pl/index.php?ver=en
[128] Bruton, T., H. Lyons, Y. Lerat, M. Stanley and M. B. Rasmussen (2009). A review of the potential of marine algae as a source of biofuel in Ireland. Dublin, Ireland, Sustainable Energy Ireland

	Requirement for technology partnerships	Support needs	Other
Enablers for successful UK commercialisation	• Links to other existing industry frameworks • Knowledge/ technology dissemination (innovation and industry sector linked)	• Pilot facilities • Funding for RD&D on needs identified above	• Public awareness • Devolved/ localised mass cultivation: Grow locally where demand • Successful examples and case studies (demonstration of scalability)
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• A demonstration facility should be built in the West or North East of Scotland on one of a number of sites identified for this purpose, to prove the concept and showcase the potential for further exploitation.[129] • Such a facility should be fed with seaweed based on the harvesting of the existing standing crop to prove the yields, economics and impact on the overall environmental sustainability.[130] • Further development of potential seaweed cultivation activities should then be considered to improve the economics and sustainability of such activities.[131]		

Case Study 13: **Microalgae for synthetic biofuels via thermochemical conversion**[132]

The drivers for producing biofuels from algae are clear: renewable liquid transport fuels will have to be a part of the energy landscape of the future, as sectors like aviation cannot be electrified. The only non-petrochemical source is biomass, and the trend (encouraged by regulation[133]) is away from 1st generation biofuels. Other advanced biofuels are mainly based on fermentation of lignocellulosic materials, leading to bioalcohols with low energy density. Microalgae are an ideal source of high-density fuels, with all the attractions that they do not depend on freshwater or arable land, can scrub CO_2 from flue gasses and nutrients from waste streams, have the potential for higher biomass yields than land plants, and can be cultured quasi-continuously, in contrast to seasonal harvesting. These intuitive advantages have led to substantial private and public investments. Much progress has been made, and some ventures are at demonstration (Sapphire Energy[134] are producing biocrude from algae grown in open saltwater ponds in a 300-acre demonstration plant). However, in the UK, microalgal biofuels are currently produced at lab scale, and are predicted to become competitive in terms of price or scale within 15-20 years (AB-SIG SRA[135], Pathways D and E). Large-scale production in the UK will depend on the development of environmentally and economically sustainable off-shore cultivation; this is under way at Cranfield University. In the meantime, the expertise that has been developed in the UK through the Carbon Trust's Algae Biofuels Challenge, short-lived though it was, and through R&D projects funded by the oil industry, can and should be put to good use to develop biofuels as one product of integrated biorefining, as described in Section 2.1. For maximum flexibility concerning both feedstock and end product, thermochemical conversion should be explored (AB-SIG SRA, Pathway D).

There is considerable scope for innovation relating to algal cultivation at scale to improve the efficiency of production markedly, especially on harvesting and processing. Close collaboration with technology providers will be essential (*c.f.* Section 2.7). Investment in pilot facilities is necessary to allow data collection for LCA and process modelling, a vital step towards sustainable deployment.

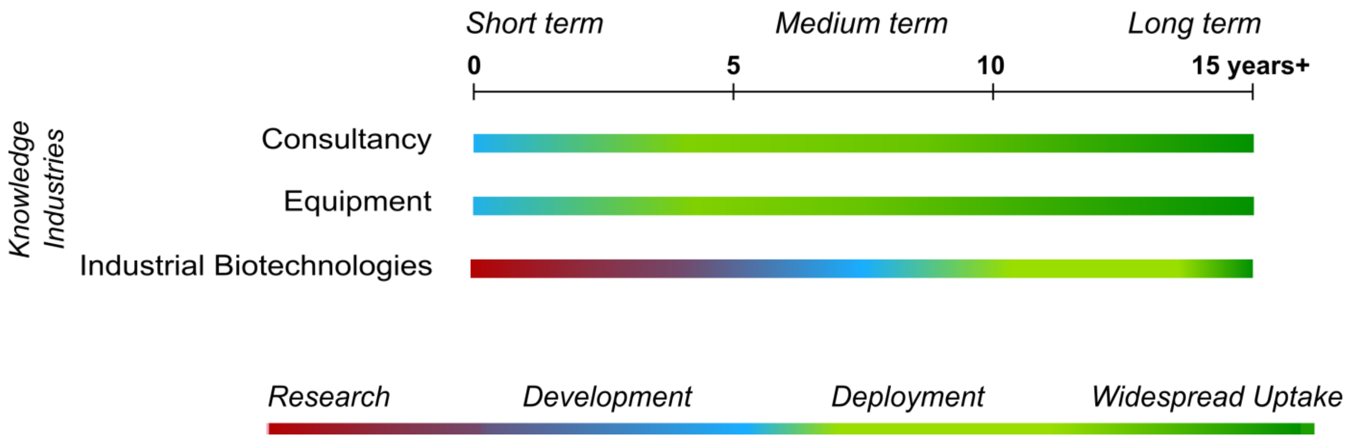
[129] Lewis, J., Salam, F., Slack, N., Winton, M., Hobson, L. 2011. 'Product options for the processing of marine macro-algae – Summary Report'. The Crown Estate, 44 pages. ISBN: 978-1-906410-31-5
[130] ibid
[131] ibid
[132] Information is also provided in Appendix 2 in the same tabulated format as in Case Study 1, to allow a direct comparison.
[133] The EU Biofuels directive stipulates that the use of food-based biofuels to meet the 10% renewable energy target will be limited to 5%.
[134] sapphireenergy.com/
[135] available at connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81879.pdf

2.7 Algae knowledge industries and technology providers (1-10 yrs)

As highlighted in the introduction, the UK possesses a wealth of expertise and know-how which could and should be developed into a vibrant, globally active knowledge industry. This expertise falls broadly into two categories: consultancy (on markets, environmental factors, algal IP/publication landscape), and technology provision (biotechnology methods, growth/harvesting/processing technologies). Details on both are given in case studies 14 and 15 below, respectively. Estimated timescales for commercialisation are given in Figure 15, with two separate timelines for equipment and industrial biotechnology methods for Case Study 15.

In addition, the creative industries have started to embrace algae. A number of designers and artists have been using macro and microalgae as a raw material in their work. The Victoria and Albert museum in London has an artist in residence[136], Julia Lohmann, who has called her tenancy the "Department of Seaweed". Her aim is to develop craft products that can be made from macroalgal fronds. High profile architectural projects have included algal elements as a design feature. Examples include the Alga(e)zebo by Marcos Cruz, Director of the Bartlett School of Architecture, which was commissioned for London 2012 and exhibited at Euston station[137]. An exhibition in 2013 in Paris, entitled "Alive", will showcase two pieces from UK-based designers that incorporate microalgae[138].

Figure 15: **Indicative commercialisation timescales for case studies on knowledge industries**



136 vam.ac.uk/whatson/event/2414/product-design-residency-julia-lohmann-3702/
137 bartlett.ucl.ac.uk/architecture/news/london-2012
138 thisisalive.com/exhibits/

Case Study 14: **Knowledge industry for consultancy on algal know-how**[139]

Building a strong knowledge industry to complement technical research is important for a number of reasons. Firstly, market intelligence is essential for commercialisation of any algal product or hardware. A consultancy industry that has strong links to primary data producers and who can translate these into the commercial context is highly valuable. Secondly, long-term survival of any industry demands minimizing environmental impacts. Understanding these allows risk to be minimised and enables responsible management of resources. Demonstrating this in the context of Corporate Social Responsibility is also a very important factor for PR and branding, with relevance to consumer confidence and staff morale. Feasibility studies and desk-based modelling will be required in future to ensure project success from environmental and economic standpoints. Finally, consultancy on general algal know-how and sharing of best practices accelerates how fast the industry can move. This includes developing teaching tools, training programs from grass-roots level for learning about the industry, but also working on policy advice and public perception to ensure that there is community buy-in and engagement.

> *Knowledge-intensive services have become the predominant source of jobs in the UK economy, and have been responsible for a large proportion of new jobs over the last 30 years*[140]*.*

Creating a knowledge industry in parallel to industrial biotech can also contribute to retaining a larger pool of skilled graduates with training relevant to algal technologies. This reduces the brain drain and builds an interdisciplinary pool of expertise that UK-based algal IB industries, as they develop and expand, can then tap into for recruitment.

> *Lack of skilled workforce has been identified as a key bottleneck in developing an algal industry internationally*[141]*.*

Commercialising the service offerings for the algal industry will involve addressing not just the UK but a global market. There are opportunities to work with industry, policy makers, NGOs, teaching and training institutions and communities. One essential role for a knowledge industry is to promote positive interactions between players in the supply chain and underpin commercialisation of ideas. Through offering reports, reviews, advice, feasibility studies and training programmes, algal consultancies can play a varied range of roles. Commercial activity can begin at a small scale immediately, and will grow alongside the industry.

Knowledge transfer between academia and industry is vital, and this cannot be assumed to take place without mediation. Likewise, buy-in from stakeholders (planning / regulatory bodies, communities) for introduction and expansion of algal technologies requires a third party to assist with this process. At present a number of UK bodies operate in this sector, and most of these are embedded in academia or have strong academic links – *e.g.,* NNFCC, InCrops, SAMS and PML offer commercial consultancy. The AB-SIG and KTNs also act as a gateway to academic expertise. Retaining skilled graduates in a number of fields including LCA, marine spatial planning and biotechnology will become increasingly important as the field develops.

Companies starting up in the algal sector can benefit enormously from the knowledge industry to support their businesses. Currently, this is assisted *e.g.,* by Regional Development Funds and TSB Innovation Vouchers. Schemes such as these enable entrepreneurs to take their developments further and assess risk. Maintaining the access to pilot data is crucial to a knowledge industry for both macro and microalgae.

---

[139] Information is also provided in Appendix 2 in the same tabulated format as in Case Study 1, to allow a direct comparison.

[140] Work Foundation Report: A plan for growth in the knowledge economy Technical Annex A Knowledge Economy Programme Paper June 2011 – figures based upon ONS workforce jobs data, 1978 to 2010

[141] The Algal Industry Survey 2008 (published February 2009), available at: www.ascension-publishing.com/BIZ/algal-industry-survey.pdf

Case Study 15: **Technology suppliers for equipment and industrial biotechnologies**

Why will this be an important market?	• Innovations needed to improve yields, economics and productivity of systems – enabling technologies to overcome specific hurdles • UK has significant research base – novel algal products / capabilities in science and engineering • Innovations to reduce energy consumption and increase productivity are essential for the field to become economically competitive		
How will the algal technology be commercialised?	• Via SMEs, start ups, academic spin-outs • Via collaborations between academia and industry (*e.g.,* aquaculture / water / chemical / biotech / pharma industry)		
Timescale to commercialisation	• Equipment: some already commercial, others in development (1-10 years) • IB methodologies: 5-10 years		
Advantages	• Capitalise on strong research base within UK universities, and on expertise of technology companies in related fields • Engineering and bioprocessing expertise		
Market size	• Dependent on invention – either as enabling a new market or as a component in an existing one.		
Growth rate	• The number of patents granted on algal-related technologies has been growing steadily – over 600 patents granted worldwide every year since 2008		
UK companies operating in this market sector	• Algenuity, Varicon Aqua, Sphere Fluidics, Enlightened Design, EDTE, Aragreen, Photobioreactor.co.uk, AlgaeCytes, Supreme Biotech, Xanthella; previously Seasalter, ExAlga / Merlin Biodevelopments, PDX		
	Technological	**Commercial**	**Other**
Barriers	• Algae are slow growing, compared with other industrial microorganisms • genetic toolkits are still under development • Range of species is vast – difficult to know where to start	• No coherent supply chain • Capital intensive • Investors are risk averse	• A lot of industry data / research generated in multinationals does not get developed
Risks	• GM algae may never be licensed / growth in contained environments negates CO_2 benefits?	• Return on Investment may not be guaranteed	• Regulations • Negative public perception (GM)
Fit with UK capability	• Algal culture collections • Industrial Biotech experience • Engineering and technology expertise	• tax breaks for R&D / Patent Box initiative	
Gaps in UK capability	• Graduates with appropriate skill sets - multidisciplinary • Access to operational macroalgae farms / microalgae production for testing • Access to raw material for testing	• Difficult to find investors – perceived as high risk	• Small algal community
Key innovation and R&D needs	• Access to affordable R&D/ analytical facilities • More rapid development of metabolic engineering and synthetic biology toolkits		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Introduction of technology experts in (bio-)processing to algal field	• Partnering platforms: We need technology to solve problem X – who can help?	• Contact between Foreign and Commonwealth Office and service providers to increase international visibility of service offerings
Key actions required to develop UK competitive advantage	• Open access analytical / demonstration facilities • Retention of skilled graduates in field / encouragement of interdisciplinary training		

3. CONCLUSIONS

What this roadmap set out to achieve

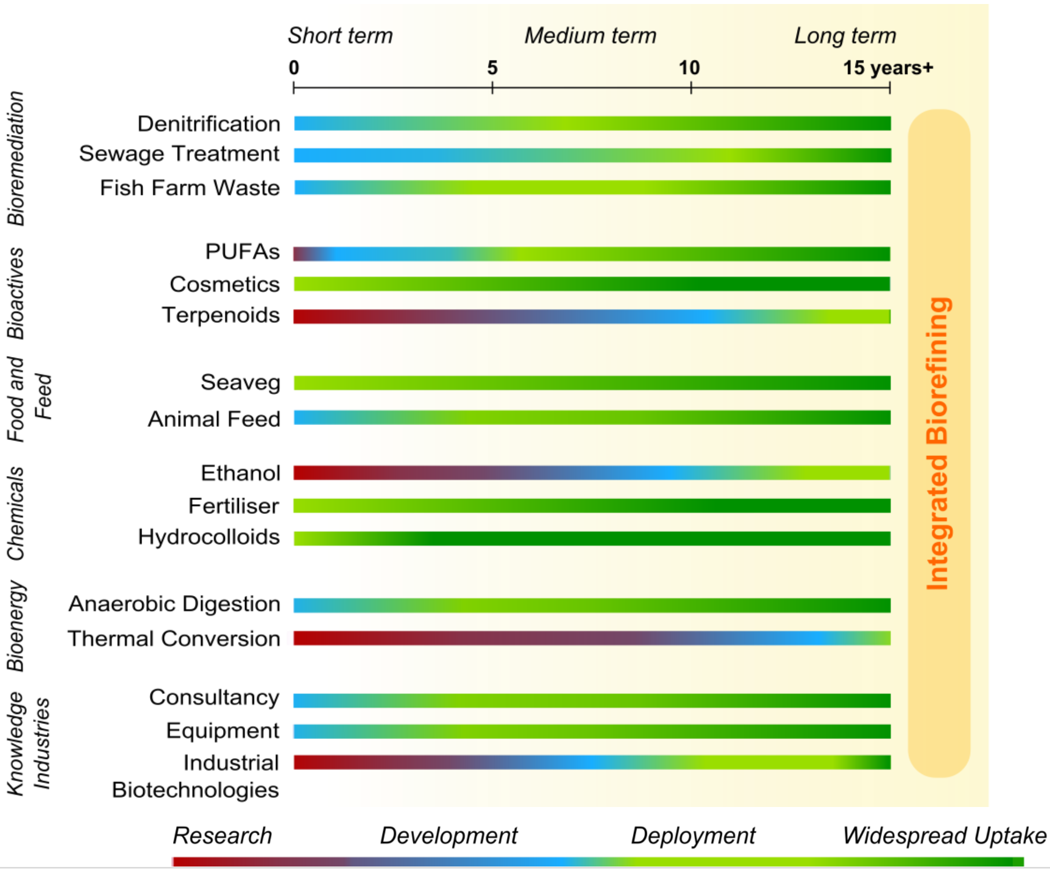
This document aims to identify how the UK can develop a sustainable and internationally competitive algal industry, and how algal technologies might help to address economical, environmental and social challenges facing the UK.

It attempts to paint a picture of which algal products, processes and services
- are already on the market or have the potential to be commercialised in the near future
- are expected to come online medium term
- will require considerably more R&D before a realistic assessment of deployment potential can be made.

It emphasizes where the community sees the highest potential for the UK, and what interventions will be needed to make sure opportunities can be seized in a timely, economically and environmentally sustainable manner. The potential is illustrated with 15 case studies. The level of reliable data and detail available for these case studies varies considerably. Those areas with as yet sparse information would benefit from being addressed in further detail, for example through ongoing AB-SIG / KTN workshops with respective sector specialists, incorporating data from test and pilot growth facilities as they become available.

Figure 16 depicts the predicted timelines to commercialisation for the 15 case studies which have been introduced in Chapter 2, moving from research (in red), via development (blue) and deployment (light green), through to widespread uptake (dark green). Nutraceuticals (such as the PUFA DHA, antioxidants and functional algal food and feed ingredients), cosmetic products, hydrocolloids, fertilisers and some technologies and consultancy services are already being deployed, with a spectrum of options for increasing market shares for UK-based companies and introducing novel products. Research is still required for pharmaceuticals (and the PUFA EPA), platform chemicals, biofuels and ongoing technology innovation. Areas in development include bioremediation solutions, animal feed, Anaerobic Digestion and a broader suite of consultancy services.

Figure 16: Expected timeframe for development of commercialisation opportunities for case studies



Most likely areas to develop commercial success in the UK

> *Factors that influence the potential for success include market pull, technology readiness and existing expertise, international competitive landscape, fit with legislative and regulatory drivers, as well as geographical, financial and environmental competitive advantages.*

Overall, the UK has a strong portfolio of existing expertise in algal industrial biotechnology and molecular biology which can be applied for the development of mainly micro-, but also some macroalgal applications[142] for a knowledge-based bioeconomy. This is well aligned with UK and EU policy and research funding priorities. Despite the strong international competition, we expect algal industrial biotechnology and associated services to develop into a commercially successful sector in the UK, provided the political and funding support is not withdrawn, as regrettably was the case for the Carbon Trust Algae Biofuels Challenge. International competition could benefit the UK if strong transnational collaborations can be built. This sector will thrive through generation of IP and high value products and services, and is comparatively independent of geographical and environmental parameters, although for economic and environmental sustainability integrated biorefining solutions need to be sought as much as possible even for high value products.

> *The largest market pull is found for products and services that in the current techno-economic assessments are most challenging to achieve: biofuels, bulk feed and chemicals, and large-scale bioremediation, e.g., for CO_2 capture and storage. Existing UK expertise needs to be used, strengthened and expanded to address these challenges in the context of internationally collaborative R&D with strong commercial underpinning, so the UK can stay in the race for developing long-term step-changing solutions.*

The UK possesses a geographical competitive advantage through its extensive coast line, which offers opportunities for cultivation of macroalgae at larger scales, provided environmental sustainability can be demonstrated throughout scale-up. These ecosystem capabilities are complemented by strong expertise in environmental sciences that should be exploited to build a knowledge industry with global reach.

Mapping the above onto the case studies of Chapter 2, we expect the following areas to be commercially most promising:

In the short to medium term:

- high value products from both macro- (condiments and premium sea vegetables, high value uses of hydrocolloids) and microalgae (increased production of established and emerging bioactives, *e.g.,* DHA, EPA, pigments, antioxidants, sunscreens)
- bioremediation using macro- and microalgae linked to feed and fertiliser production and decentralized energy generation via AD
- knowledge industries for technology provision and consulting

In the medium to long term:

- integrated biorefining of micro- and macroalgae coupled to fractionation or thermochemical conversion for a suite of chemical and energy products
- novel bioactives through bioprospecting (micro- and some extent macroalgae) and metabolic engineering (microalgae) for pharma, cosmetics, nutrition

[142] including development of 'Algae Omics' and molecular toolkits

Key enablers to allow the UK to exploit identified market opportunities

To assess fully how the UK could derive most benefit from algal technologies, it will be necessary to know

- the potential scale of production that the UK could support
- how much is needed should all the opportunities for use be realised
- whether the UK would be able to sustain security of supply or depend on imports.

These questions are both highly important and – particularly in the case of scale of production and security of supply – rather frustratingly impossible to answer with any degree of accuracy based on currently available data.

> *The most vital enabler, common to both macro- and microalgae and relevant to the whole value chain of products, would hence be the immediate provision of scale up and demonstration plants that allow collection of reliable data on yields and financial as well as environmental sustainability. Complemented by mapping of sites across the UK where the biomass could be grown sustainably, this would enable a meaningful projection of the potential scale of production.*

Having access to realistic and regional data from scale up facilities is essential to exploiting any of the market opportunities described in Chapter 2; it is paramount that the risk factors are reduced for industrial stakeholders who are interested in investing but are not prepared to commit funding based upon literature or extrapolated data. These facilities need to have critical mass and concentrate on both upstream (growing) and downstream (processing) activities so that more precise estimations of yield, cost and environmental impact can be made.

Allied to the idea of demonstration facilities is the need for modelling of cost, yield and sustainability based on real data. At present the margins of error are large, increasing the risk in forecasting business performance and viability. Particularly for bioenergy, where the business cases rely on reductions in GHG emissions, it is vital that this can be demonstrated *in situ* through reliable LCA. Other technical, financial, service- and regulation-related enablers are detailed in Table 2.

Table 2: Overview of enablers

Technical	• **Accessible test / pilot / demonstration facilities** to collect data on ecological impact, operational costs, life cycle parameters and variability of yields, all of which will underpin developing business case scenarios and scale-up: *Upstream:* Macro: long line growth facilities in different geographical and ecological settings Micro: facilities across the country where a variety of open and closed growth technologies can be trialed in conjunction with a spectrum of input providers (nutrients, CO_2, waste heat from a range of sources) and low energy/low cost solutions can be developed *Downstream:* **Macro**: equipment for and R&D into • ecologically sensitive low-energy mechanized harvesting • low-energy drying and processing • wet preservation (silage) **Micro**: equipment for and R&D into • low-energy harvesting (flocculation, milking, sedimentation, floatation) and processing (green solvents, enzymes, mechanical methods) **Both**: thermochemical conversions (particularly hydrothermal liquefaction[143]: catalyst selection for production of specific chain length and branched hydrocarbons) • **Mapping potential sites** for sustainable cultivation across the UK[144] • Encouraging **IP generation and interdisciplinary skill development** in these areas • Expertise in **bioprospecting, strain development and metabolic engineering** / algal synthetic biology toolkits • **Multi-disciplinary training** (biology, engineering, processing, biorefining, sales & marketing)
Financial	• **Security of funding for RD&D**, with increased accessibility for micro-SMEs, to attract and retain skilled personnel / entrepreneurs, and accelerate commercialisation • **Successful examples of algal biotechnology applications** leading to increased confidence and maturing supply chains • Attributing a **direct value to bioremediation** through financial incentives / penalties
Services	• Closer **interaction and knowledge transfer between academia and chemical & pharma industries**, to guide development of algal expression for platform chemicals and pharmaceutically interesting scaffold molecules • Algal bio-business **incubators and clusters** • **Marketing / increasing visibility of UK expertise and products** on the global stage: for environmental know-how, technologies and products • Customer / **public awareness** and acceptance to increase demand and avoid NIMBYism
Regulation	• Providing **clarity about regulatory context** (macroalgae: marine licensing; microalgae: GMO regulation) • Simplifying IP protection

Recommendations for actions and investment

Macroalgae

For macroalgae, two fundamental options exist for expanding commercial activity: firstly, to harvest wild stocks more widely and diversify the small industry based on that, by exploring new markets for traditional and novel products; and secondly, to establish commercial longline cultivation. To ascertain the degree to which wild harvest could be expanded sustainably, an updated version of the seaweed maps of Walker from the 1940s[145] is urgently needed. A number of regional mapping initiatives are being carried out across the UK; these should be brought together so that gaps can be filled and that an up-to-date overall picture

[143] Where wet biomass can be used as feedstock and nutrients can be easily recovered (*c.f.* Biller P, Ross AB, Skill AC, Lea-Langton A, Balasundaram B, Hall C, Rilley R, Llewellyn CA (2012) *Nutrient recycling of aqueous phase for microalgae cultivation from the hydrothermal liquefaction process*. Algal Research 1(1):70-76).
[144] For microalgae this is partially under way through the EnAlgae project; some regional mapping initiatives exist for macroalgae
[145] Walker, FT (1947), A Seaweed Survey Of Scotland–*Fucacae*. Proceedings of the Linnean Society of London, 159: 90–99

can be presented. Small-scale cultivation is under way in some companies such as Böd Ayre and the Hebridean Seaweed Company, and pilot facilities are being established at research institutions through projects such as EnAlgae and IDREEM. To build on expertise gained on these sites, investment will be needed for further scale up of macroalgal farming, and concomitant data collection. This is essential for establishing reliable projections for feedstock costs, as well as environmental sustainability.[146] More clarity about costs at scale will enable building business cases for those processes (*e.g.,* bioethanol production) which are technically feasible, but where the cost benefit still has to be proven. Furthermore, funding is needed for processing and biorefining of macroalgae, to broaden the spectrum of potential endproducts.

In addition, investment should be targeted towards feasibility studies for local energy generation in remote areas, *e.g.,* by supplementing sewage-based or mixed feedstock AD with macroalgal biomass[147]. Operation of pilot schemes would demonstrate whether this can be accomplished and if it could provide a stable and reliable source of domestic gas, while at the same time boosting employment opportunities. A list of recommendations, linked to the enablers given above, is presented in Table 3.

Table 3: **Summary and rationale of recommendations for macroalgae**

Recommendation	Rationale
Clarify potential for sustainable harvest from wild and cultivated stocks	• The last comprehensive study on wild stocks (for Scotland only) was carried out by Walker in the 1940s[148]. • More recent, UK-wide data is needed to assess if/how wild harvest could be expanded sustainably. • Available data from regional studies needs to be collated, gaps need to be filled and all data needs to be made available in a unified format. • Sites suitable for cultivation and their potential yields need to be identified.
Invest in pilot and scale up facilities	• Majority of case studies lack data to model financial feasibility. • Margin of error projecting from lab scale is too great, deters investment and possibly leads to shelving of promising technologies. • Impact and yields of intensive cultivation are currently mainly theoretical. • Scarcity of biomass is a bottleneck in developing biorefinery processes.
Develop clearer marine licensing procedure for offshore macroalgae cultivation	• Current procedures are lengthy, without a unified approach. • Macroalgae are currently considered under same criteria as mussel farms.
Conduct R&D into seasonality	• Overcoming seasonal production • Research into storage of macroalgae

Invest into downstream technologies	• Develop extraction methodology / processing
	  • to improve yields of fermentation products
	  • to extract high value molecules and enable use of residual biomass

Invest into strain development and bioprospecting	• Improving domestication of commercially relevant strains • Screening and R&D to identify promising candidates
Ensure a skill base	• Encouraging multidisciplinary research • Attracting and retaining skilled graduates
Develop supply chains matched to production capacities	• Joining up producers and processors • Diversifying product range

[146] Similar recommendations are also made by the Bioenergy TINA (2012), p. 34; available at carbontrust.com/media/190038/tina-bioenergy-summary-report.pdf

[147] Building on the results of Strathclyde University in conjunction with Scottish Water, SAMS, CREW and MASTS, *c.f.* presentation given by B. Postlethwaite at the AB-SIG conference 'Opportunities for Algal Commercialisation' on 20 June 2012; slides available at https://connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=8580598&name=DLFE-87878.pdf

[148] Walker, FT (1947), A Seaweed Survey Of Scotland–*Fucacae*. *Proceedings of the Linnean Society of London*, 159: 90–99

Microalgae

Microalgal cultivation in the UK is largely still at R&D stage. At present pilots (with the possible exception of the Boots-PML venture at Nottingham) are too small to make commercially meaningful projections, and the volumes of algae produced are insignificant compared to the requirements of most industries interested in the material as a feedstock. Urgent investment is needed into larger, accessible test, pilot and demonstration facilities. Furthermore, to guide the choice of strains, processing options and end products for scale-up, market intelligence will be required on the value, market size and purity requirements of products that could be derived from algae in the context of integrated biorefining. Supply and demand for the various co-products needs to be balanced to avoid flooding the market.

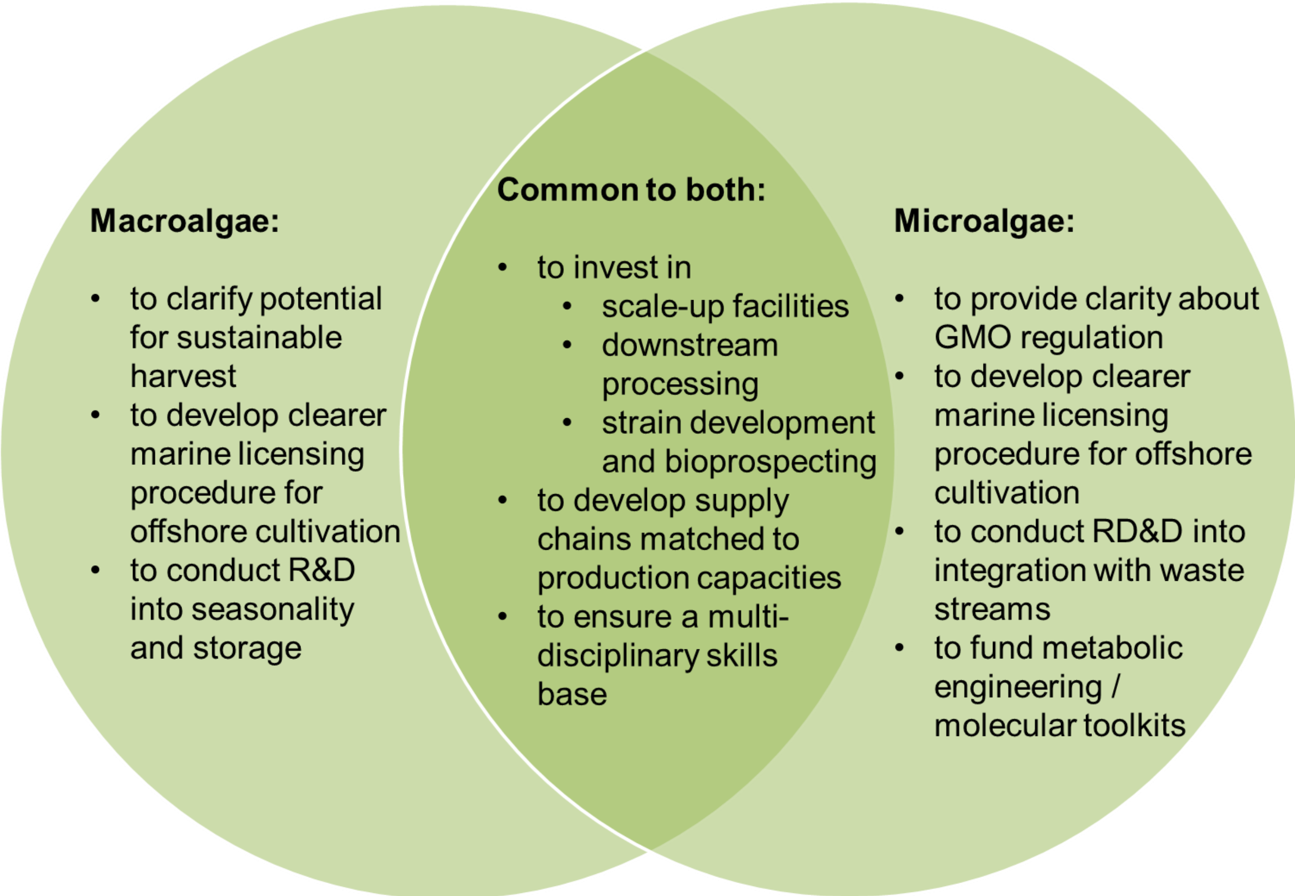
Investment is also needed in underpinning upstream and downstream technologies: synthetic biology, metabolic engineering, strain development and bioprospecting, harvesting, dewatering and fractionation technologies, and thermochemical conversions. A list of recommendations, linked to the enablers given above, is presented in Table 4.

Table 4: Summary and rationale of recommendations for microalgae

Recommendation	Rationale
Provide consolidated investment in pilot and scale up facilities	• Majority of case studies lack data to model financial feasibility. • Margin of error projecting from lab scale is too great, deters investment and possibly leads to shelving of promising technologies. • Impact and yields of intensive cultivation are currently mainly theoretical. • Lack of feedstock availability presents a bottleneck in testing possible products and technologies, and in developing biorefinery processes.
Provide clarity about GMO regulation	• Productivity, ease of handling and product spectrum can be greatly enhanced through GMO methods; clarity needs to exist as to how GMO algae can be grown at industrial scale.
Conduct RD&D into integration with waste streams	• Enabling greater collaboration and coordination to access resources needed for algal growth • Underpinning economic sustainability • Providing bioremediation
Fund metabolic engineering, strain development and bioprospecting	• Expression toolkits for a variety of strains • Algae Omics • Improving domestication of commercially relevant strains • Expanding strain collections, screening programmes • Strengthening and expanding international collaborations
Invest into downstream technologies	• Harvesting, dewatering and fractionation technologies • Thermochemical conversions (*e.g.,* hydrothermal liquefaction catalysts)
Ensure a skill base	• Encouraging multidisciplinary research • Attracting and retaining skilled graduates
Develop supply chains matched to production capacities	• Joining up producers and processors • Identifying needs of users (*e.g.,* HACCP, FEMAS) and matching the production processes accordingly • Closer collaboration with existing industries to understand if algae can provide a valid alternative feedstock

Algal technologies have considerable potential to contribute to economic growth in the UK. To realize this potential for delivering sustainable products and services, and for expanding the knowledge-based bio-economy, it is essential to invest into scale-up cultivation facilities for macro- and microalgae, to develop the concept of integrated biorefining, and to harness UK expertise for the development of a thriving, globally relevant industrial biotech and knowledge industry.

Figure 17: Overview of recommended actions



APPENDIX 1

Summary of Roadmapping Workshops

In Oct and Nov 2012, two roadmapping workshops were held by AB-SIG, facilitated by IfM, which have directly fed into this document. The text below, provided by IfM, gives a high-level overview of process and key outcomes. Participants and their affiliations for both workshops are given in the subsequent to tables.

Participants identified priority Drivers, Market Needs, Opportunities, Capabilities and Enablers in the Short, Medium and Long timeframes. The most important market opportunities were then highlighted and explored in more detail.

In prioritising relevant Trends & Drivers, there was a strong emphasis on resource and environmental challenges to which Algal Biotechnology might provide solutions, including the drive for renewable fuels; energy pricing and scarcity; climate change and food supply and pricing. Pressures caused by an expanding and ageing population; resource scarcity and land availability were also stressed. Legislative challenges included CO_2 reduction targets; tighter waste regulation; Nitrate directive and GMO legislation.

Enabling drivers in the value chain included

- a clear regulatory landscape;
- interaction with existing industries;
- successful examples of algal biotechnology applications leading to market demand and
- a clear business case for commercial scale production.

A world-class research base was considered highly significant: the potential to exploit Synthetic Biology synergies also being important. It was recognised that increased customer awareness and acceptance was key, with additional research into environmental factors being an associated requirement.

In support of these prioritised opportunities, a wide range of capabilities were identified, the most relevant of which were: lower cost production and harvesting; scalability modelling and downstream processing; greater energy efficiency and lower cost bioreactor design; systems and processing; and accessible strain development.

The workshop also identified other key enablers for success, underpinning these capabilities as: pilots and demonstrators; secure funding; science skills development; life-cycle analysis/eco-system impact of harvesting and large scale cultivation; clear GMO regulation; academic/industry facilitation and knowledge transfer.

Participants of AB-SIG Roadmap workshop in Manchester:

Name		Organisation
Rebecca	Allen	Eminate
Michelle	Carter	Biosciences KTN
Blanche	Coleman	NERC
Jane	Garnett	Technology Greenhouse Ltd
Jim	Gilmour	University of Sheffield
Merlin	Goldman	Technology Strategy Board
Sheila	Heymans	SAMS
Adrian	Higson	NNFCC
Tom	Jenkins	Biosciences KTN
Tim	Kruger	University of Oxford
Marco	Lizzul	University College London
Paul	Lucas	AB Sugar
Joanne	MacDonald	SAMS
Joe	McDonald	Varicon Aqua Solutions
Jenni	McDonnell	Environmental Sustainability KTN
Jagroop	Pandhal	University of Sheffield
Jean	Phillips	Biosciences KTN
Jon	Pittman	University of Manchester
Mark	Randle	ETDE
Shaun	Richardson	University of Swansea
Andrew	Spicer	Algenuity
Michele	Stanley	AB-SIG
Jim	Trueman	IfM
Seetharaman	Vaidyanathan	University of Sheffield
Marit	Valseth	Innovation Norway
Jon	Williams	Aquapharm Biodiscovery
Kate	Willsher	IfM

Participants of AB-SIG Roadmap workshop in London:

Name		Organisation
Catherine	Ainsworth	University of Durham
Richard	Burt	Chelsea Technologies Group
Jodie	Clarke	NERC
Duncan	Eggar	BBSRC
Rodney	Foster	CEFAS
Chris	Franklin	NERC
Irina	Guschina	University of Cardiff
Patricia	Harvey	University of Greenwich
Graham	Howes	BP Alternative Energy
Imoh	Ilevbare	IfM
Tom	Jenkins	Biosciences KTN
Hans	Kleivdal	Uni Environment Norway
Carole	Llewellyn	Plymouth Marine Laboratory
John	Love	University of Exeter
Joanne	MacDonald	SAMS
Gill	Malin	University of East Anglia
Gianluca	Memoli	National Physical Laboratory
John	Milledge	University of Southampton
Nadia	Munday	URS Infrastructure & Environment UK
Jean	Phillips	Biosciences KTN
Saul	Purton	University College London
Nander	Robertson	Glenside
Beatrix	Schlarb-Ridley	InCrops Enterprise Hub
Steve	Skill	Plymouth Marine Laboratory
Michele	Stanley	AB-SIG
Alastair	Sutherland	Glasgow Caledonian University
Joanna	Szaub	Algenuity
Campbell	Tang	Centre for Process Innovation
Patricia	Thornley	University of Manchester
Jim	Trueman	IfM
Isabella	Van Damme	Mars Chocolate
Mike	Weston	UKERC
Narumon	Withers Harvey	Defra
Michael	Yates	Algenuity

APPENDIX 2

TABLES ON CASE STUDIES 2, 3, 5, 7, 9, 13 AND 14

Table Case Study 2: Nutrient recovery from sewage treatment works (STW) through High Rate Algal Ponds or microalgal biofilms

Why will this be an important market?	• Need to retrieve nutrients such as nitrate and phosphate in future, rather than synthesise fertilisers from scratch. • In line with Defra's mitigation and adaptation plans to help deliver the UK obligation to reduce greenhouse gas emissions by 80% by 2050 and work to carbon budgets stemming from the Climate Change Act 2008, within the context of the EU Emissions Trading System[149]. • Climate change adaptation is adequately included in waste water infrastructure planning. For instance, climate change may also result in reduced annual or seasonal river flows which may in turn require higher standards of sewage treatment in order to meet statutory environmental requirements[150]. Tertiary waste polishing with algae could be a means of achieving this.
How will the algal technology be commercialised?	• Through pilot schemes and demonstration facilities • Example is NIWA plant in Christchurch, New Zealand. They have a 5 hectare demonstration facility with High Rate Algal Ponds and extraction of oil using supercritical water[151].
Advantages of Algal Biotechnology over incumbent approaches	• Algal production for low value/high volume bulk chemicals or commodities such as biofuel or bioplastic where material does not enter food chain. Lower cost means of generating biomass. • Adaptation of an existing problem, but will require a change in infrastructure for the UK. Advanced Integrated Wastewater Pond Systems have been widely demonstrated. Plants are larger than conventional STW, but have lower construction and operational costs. They have been successfully demonstrated in the US and in developing countries[152].
Timescale to commercialisation	• 2-5 yrs with existing technologies
Market size	• The UK has approximately 9000 sewage treatment works in total (Defra 2012). • Every day in England and Wales the public sewerage system collects approximately 10 billion litres of waste water from households and industry[153].
Growth rate	• The number of households in the UK is predicted to grow to 27.5 million in 2033, an increase of 5.8 million over 2008[154] • Household water consumption in England has been rising since the 1950s and is now • approximately 150 litres per person per day (l/p/d)[155]
Companies operating in this market sector	• STW: UK Water companies: Anglian / Northern Ireland / Northumbrian / Severn Trent / South West / Southern / Thames / Wessex / Yorkshire Water; United Utilities • Algal Turf Scrubber

[149] National Policy Statement for Waste Water: A framework document for planning decisions on nationally significant waste water infrastructure (Defra 2012): ISBN: 9780108511486
[150] ibid
[151] Rupert Craggs *et al*. (2012) Hectare-scale demonstration of High Rate Algal Ponds for Enhanced Wastewater Treatment and Biofuel Production *Journal of Applied Phycology* pp. 1-9, doi:10.1007/s10811-012-9810-8
[152] United States Environment Protection Agency (2011) Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers. EPA/600/R-11/088.
[153] National Policy Statement for Waste Water: A framework document for planning decisions on nationally significant waste water infrastructure (Defra 2012): ISBN: 9780108511486
[154] Laying the Foundations: A Housing Strategy for England November 2011 available at communities.gov.uk/documents/housing/pdf/2033676.pdf
[155] Based on Waterwise data, 2006

UK Ecosystems potential to commercialise	**High:** • Turns an environmental problem into an opportunity • Increases resource efficiency • Provides a solution to problem (eutrophication potential) at point of origin • Environmental risk from algal species is low, if native species are grown		
	Technological	**Commercial**	**Other**
Barriers	• New system for the UK, unproven in these conditions	• Requirement for land (3-5x area of conventional sewage works[156]), and proximity of CO_2 source • Need for training and skills in industry • Needs complete exchange of infrastructure • Risk averseness of water industry -hesitant to invest in test facilities	• Regulation / discharge consents • Short day lengths, low temperature in winter • Inertia of existing facilities / utility companies
Risks	• Would need to demonstrate year-round reliability (medium)	• Need a secure market for biomass (low)	• Public perception (low)
Fit with UK capability	• Good existing R&D base (biology & engineering)	• Large market potential	• Fit with research funding priorities
Gaps in UK capability	• Proof of concept in UK conditions • Pilot / demonstration plants • Data availability	• Adoption of technology that has been successfully commercialised abroad	• Lack of agenda / strategy • Needs change of mindset from treatment to resource recovery / revenue generation
Key innovation and R&D needs	• Strain development / adaptation; consortia • Process integration and refinement • Data for models – economic/technological/environmental/ecological/LCA • Need for demonstration		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Collaboration between industry, technology providers and academia • People: skill transfer to end users	• Funding: public sector 'push' • Demonstration facility – as per Christchurch example	• Academic skills & existing algae industry • Economics & LCA / sustainability models
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Build demo plant • Assess performance • Refine through R&D • If LCA and economic assessment are promising, deploy at new STWs/wherever refurbishment of STW infrastructure is needed		

[156] Pers. comm., Steve Skill (Dec 2012)

Table Case Study 3: Macroalgae for the remediation of fish farm waste: Integrated Multi-Trophic Aquaculture (IMTA)

Why will this be an important market?	• Fish consumption is growing, and farmed species such as salmon, trout and halibut account for up to half of total human consumption. • Farmed fish produce nitrate-rich waste, which disperses in the local coastal or offshore environment. • While there is no specific levy on nitrate pollution due to waste from aquaculture, farms are monitored by the regional environmental protection agencies under the Water Framework Directive. For example, in Scotland, applicants for marine aquaculture licenses are expected to conduct computer modelling to show how waste will be dispersed from the site. In this instance IMTA could be a strategy to mitigate against pollution from fish farm waste. • Run off from agriculture also contributes to locally increased nutrient levels.
How will the algal technology be commercialised?	• Intensified research to lead to pilot and then demonstration projects • Example: the IDREEM (Increasing Industrial Resource Efficiency in European Mariculture) EU FP7 program is looking at multi-trophic aquaculture to retrieve nutrients currently lost as pollution from aquaculture[157].
Timescale to commercialisation	• 2-5 yrs with existing technologies to demonstration phase (commercial operations exist in Canada)
Advantages of Algal Biotechnology over incumbent approaches	• At present excess nutrients are released into the water and are not recovered; *i.e.,* there are no incumbent approaches. • Computer modelling (FARM - Farm Aquaculture Resource Management model) demonstrates quantitatively how much nitrate/phosphate can be reduced[158]. • Potential to use biomass as saleable product (could enter food chain, if HACCP was established / appropriate accreditation obtained) • Sustainable: green approach, offers ecosystem services (to be proved by sustainability analysis based on data from test/pilot site)
Market size	• In 2012 around 47% of all fish directly consumed by humans worldwide is produced in aquaculture (value: Seafish UK). • According to Cefas the total UK value of aquaculture finfish production in 2010 was £484 million, an increase from 2009 of £29 million[159]. • In the case of carbon and nitrogen credits the markets are forcibly created as a result of regulation and become more attractive under a cap-and-trade scheme. The only place where there is a nitrogen/nutrient credit market is in the US (namely Connecticut). However it is unknown whether shellfish farms are already able to sell credits into a market.[160]
Growth rate	• Aquaculture production in the UK has risen from 152,000 tonnes live weight to 201,000 tonnes between 2001 and 2010[161] (average annual growth of 3.5%).
UK companies operating in this market sector	• UK: producers of Atlantic Salmon (Scotland), rainbow trout, sea trout and halibut • The Scottish Salmon Company have begun trials with IMTA at their site at Loch Roag[162]
UK Ecosystems potential to commercialise	**High:** • The UK is a coastal nation, aquaculture is important. • Turns an environmental problem into an opportunity • Provides a solution to problem at point of origin • IMTA would minimise changes in the benthic environment due to waste build up from aquaculture and mitigate effects on ecosystems.

[157] cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=13107002
[158] longline.co.uk/site/products/aquaculture/farm/
[159] Finfish News, Number 13, Summer Autumn 2012. Published by Cefas (cefas.defra.gov.uk/publications/finfish-news.aspx)
[160] Pers. comm., Rui Gomes Ferreira, Longline Aquaculture / IDREEM. February 2013 ftp://ftp.wcc.nrcs.usda.gov/wntsc/mktBased/nitrogenCreditTrading.pdf
[161] Eurostat (from http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Fishery_statistics)
[162] sams.ac.uk/news-room/news-items/scottish-salmon-company-starts-excellent-trials

	Technological	Commercial	Other
Barriers	• Turn-key integration with infrastructure of aquaculture industry has to be developed • Sites need to be compatible with macroalgae growth – current, light attenuation etc	• Need for training and skills in industry • Lack of hard economic data on the viability of IMTA	Regulatory and marine licensing – on a case by case basis
Risks	• Biosecurity – concerns that an integrated system could provide reservoirs or vectors for disease in fish (medium)	• Economics might not be favourable (Full economic case can only be made once data from pilot sites is available) (low)	• LCA might show that overall the process is not greener than current practice (low) • If intensive fertilising were to stop, the need for denitrification of ground water would decrease, leading to under-used capacity (very low)
Fit with UK capability	• Expertise in aquaculture research in Scotland	• Commercial aquaculture already established	• Research funding priorities fit *e.g.,* RCUK
Gaps in UK capability	• Urgent need for scale-up facilities (test / pilot / demonstration plants) • Data availability	• Translation of existing research into market place	• Lack of agenda / strategy • Needs change of mindset in industry from treatment as waste to resource recovery / revenue generation
Key innovation and R&D needs	• Better understanding of scale and species • Understanding of loading rates, bioaccumulation of antibiotics or pathogens • Data for models – economic/technological/environmental/ecological/LCA • Need for demonstration • Establishing HACCP procedures for biomass produced in this manner		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Collaboration between industry, technology providers and academia • People: skill transfer to end users	• Funding: public sector 'push' • TSB grant for globally recognised pilot and demonstration facilities (£5 - 10 Million)	• Academic skills & existing algae industry • Economics & LCA / sustainability models
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Build (and fund!) pilot plant, assess performance, refine through R&D • Economic modelling • Proceed to demonstration stage • Develop turn-key solution for global market		

Table Case Study 5: Macroalgae-derived cosmetics

Why will this be an important market?	• Growing middle class spending power for cosmetic products in BRIC countries and globally • Rising average life expectancy leads to increasing popularity of anti-ageing products • Increasing consumer awareness of the benefit of natural products • Exotic natural ingredients have strong marketing power and can command a premium price[163] • Existing body of R&D: Search of US Patent Collection database for "cosmetics AND (algae OR seaweed)" yielded 1834 patents • Novel functional ingredients from macroalgal/microalgal sources include: mycospoine-like amino acids, terpenes and carotenoids, tocopherols, pyrenoine (extract from macroalga *Fucus*) – all are under investigation as photo-protective ingredients
How will the algal technology be commercialised?	• Collaborations between cosmetic manufacturers and academic institutions • Commercialisation of bioprospecting • R&D by cosmetic ingredient suppliers/ replacement of petrochemical products • Acquisition of smaller companies by larger multinationals
Timescale to commercialisation	• 1-5 yrs
Advantages of Algal Biotechnology over incumbent approaches	• Customer preference for "natural" ingredients • Consumer awareness / concern over synthetic ingredients such as nanoparticles used in sun screens. • In the case of sunscreens, there is clinical evidence of mycosporine-like amino acids from algae as effective UVA protectants[164] (product: Helioguard, *Porphyra* extract[165]).
Market size	• Natural & organic products have 2% share of global personal care product sales. In some countries – such as the USA, Germany, Austria – the market share is reaching 10 percent[166].
Growth rate	• **UK market**: Revenues have been slowly increasing by about 6% per annum since the financial crisis started in 2008. Many UK brands look to export market where growth is faster[167]. • Global revenues in the personal care market to climb to USD 14 billion in 2015
UK companies operating in this market sector	• Boots, L'Oreal, Nivea, Body Shop, Garnier • Seaweed Organics, Highland Soap Co
UK Ecosystems potential to commercialise	**High:** • If biomass can be grown in conjunction with bioremediation of nutrient-rich, but non-toxic / non-harmful waste streams • If harvesting from wild is carried out in ecologically sensitive way to manage stocks, without depleting nutrients from ecosystems

[163] *e.g.,* Crème de la Mer serum concentrate with sea kelp retails for £620 for 100 ml (cremedelamer.co.uk/product/CAT9090/PROD12421/The+Concentrate)
[164] F. de la Coba, *et al*, Prevention of the ultraviolet effects on clinical and histopathological changes, as well as the heat shock protein-70 expression in mouse skin by topical application of algal UV-absorbing compounds, *Journal of Dermatological Science*, Volume 55, Issue 3, September 2009, Pages 161-169 doi:10.1016/j.jdermsci.2009.06.004
[165] mibellebiochemistry.com/common/search.php
[166] Organic Monitor (December 2011) Global Market for Natural & Organic Personal Care Products, (3rd edition), Organic Monitor #1003-60.
[167] ibid.

	Technological	Commercial	Other
Barriers	• Providing evidence of the mechanism of action	• Competing against raw material from Asian markets	• Getting organic certification
Risks	• reliable supply of high quality feedstock may not be guaranteed (low)	• Oversupply of product / loss of exclusivity and associated price (medium) • Lack of investors (medium-high)	• Pollution events can make natural stocks unsuitable (low)
Fit with UK capability	• Cottage industry in UK but also some high-end premium product developers • Existing industry of manufacturers of cosmetic ingredients keen to have "natural" replacements	• Fits high value, low volume profile appropriate for production in the UK	• Research funding priorities fit: Industrial biotechnology; healthy ageing (funding opportunities for elucidating mechanisms of action)
Gaps in UK capability	• Access to sufficient quantities of raw material • Bioprospecting activities could be much stronger	• Stronger alignment between research/ bioprospecting and industry would be helpful	• Lack of agenda / strategy
Key innovation and R&D needs	• Development of low cost effective techniques for cultivation, harvesting, extraction and downstream processing • More proof of efficacy and mechanism of action / benefit to skin health		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Collaboration between industry and academia on formulation • More macroalgae farmers, and partnerships with processors	• Funding: Non equity, for international collaborative activities, government investment • Smaller contribution requirement for UK Plc for UK grants	• Academic skills & existing algae industry • Economics & LCA / sustainability models • Mechanism to grow small into medium sized companies
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Provide non equity funding • Utilise existing UK industry expertise for commercialisation		

Table Case Study 7: Macroalgae as premium sea vegetable

Why will this be an important market?	• Asian market: Since Fukoshima concerns about health of Japanese products; market demand for products from alternative sources • New trends in eating for domestic market		
How will the algal technology be commercialised?	• Feeding into existing market, meeting demand from abroad (export) • Creating new interest (domestic) • Via strong branding, promotion of UK product as superior • Move from hand-harvested to cultivated seaweed		
Timescale to commercialisation	• Immediate opportunity; window of export is likely to close if market demand is being met by expanded production from competing countries (*e.g.,* Israel)		
Advantages of Algal Biotechnology over incumbent approaches	• Advantage of UK product: premium for branding • Possibility for organic certification • Opportunity to scale growth in ecologically sensitive manner		
Market size	• In France, the only European country which has established a specific regulation for the use of seaweeds as vegetables or ingredients, the consumption is estimated at 27 tonnes of dry products per year[168]. • 99.6% of global cultivated macroalgae production comes from just eight countries: China (58.4%, 11.1 million tonnes), Indonesia (20.6%, 3.9 million tonnes), the Philippines (9.5%, 1.8 million tonnes), the Republic of Korea (4.7%, 901,700 tonnes), Democratic People's Republic of Korea (2.3%, 444,300 tonnes), Japan (2.3%, 432,800 tonnes), Malaysia (1.1%, 207,900 tonnes) and the United Republic of Tanzania (0.7 %, 132,000 tonnes).[169]		
Growth rate	• The premium sea vegetable has seen year on year growth in the UK, but the biggest increase in demand is for the export market[170].		
UK companies operating in this market sector	• Seaweed Health Foundation, Böd Ayre, Hebridean Seaweed, Irish Seaweeds (N.Ireland) • Clearspring (source from multiple countries)		
UK Ecosystems potential to commercialise	• Capitalising on our large coastal region and clean water – in particular for Soil Association organic certification • Larger scale production (if not in conjunction with fish farming for bioremediation, *c.f.* Case Study 3) may deplete nutrients and influence ecosystem; fertilisation may remediate that, but may cause other effects[171]		
	Technological	**Commercial**	**Other**
Barriers	• Considerable scale-up required in short timescale in order not to miss window of opportunity, with associated infrastructure challenges	• Cost and volume of biomass relative to what is currently available	Need for premium marketing and distribution network in Asia
Risks	• Species that are desirable for export may not be native to UK; *e.g.,* the species of *Porphyra* popular in Japan is not currently cultivated here. (high)	• High capital venture, need to spend on brand visibility and consumer education (high)	• Ecological concerns if scale-up happens too quickly to evaluate impacts (low-medium)
Fit with UK capability	• Ecology expertise for environmentally responsible scale-up	• Industry could develop and adapt existing good knowledge base • Seaweed industry exists but small scale	• Image • Good expertise in marine special planning

[168] Fleurence, J. et al (2012) What are the prospects for using seaweed in human nutrition and for marine animals raised through aquaculture? Trends in Food Science & Technology Volume 27, Issue 1,Pages 57–61 DOI: 10.1016/j.tifs.2012.03.004
[169] FAO (2012) State of World Fisheries and Aquaculture, available at www.fao.org/docrep/016/i2727e/i2727e00.htm
[170] Pers. comm., Derek Przybycien, Clearspring Ltd, 2013
[171] *c.f.* AB-SIG SRA, p. 13

Gaps in UK capability	• Cost effective cultivation and harvesting – for this market has not been explored for the UK, as current demand can be satisfied from material harvested from the wild	• Link to Asian marketing is missing	• HACCP if integrated with fish farming / bioremediation • Need to educate public about the health benefits of algae foods and ingredients
Key innovation and R&D needs	• Scale-up • Environmental impact assessments • Integrating with waste streams (nutrients, surplus heat/ energy for drying) and existing technologies/infrastructure for cost effective cultivation and harvesting (*e.g.*, IMTA, see Case Study 3) • Determining health benefits of algae from UK waters • Updated and accurate surveys of stocks of accessible wild harvest material		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Integrating with existing technology/aquaculture industry, utilising knowledge base (species, environment)	• Understanding of market conditions • UKTI links to Asian markets/companies that could be distributers • Educating investors	• Successful communication within UK: press, celebrity chefs, Japanese restaurants, • Establish demand for exports
Key actions required to develop UK competitive advantage relative to the global commercial landscape	**Immediate:** • Identify which species attractive to the Asian market can sustainably be grown in the UK • Existing seaweed producers to work with UKTI and Japanese restaurants on an offering for the Japanese premium market, then to make introductions to potential distributors for Asian markets **Longer term:** • Existing producers, and any new ventures, to work with celebrity chefs in parallel to scaling up production • Develop and expand flavour products based on algae • Work on public perception to move algae products from niche towards wider adoption		

Table Case Study 9: Macroalgae to Ethanol for chemicals

Why will this be an important market?	• Demand for non-petrochemical based material • Important to establish a sustainable source: at the moment largely petrochemically derived, or from 1st generation carbohydrate feedstocks • Ethanol is used in many solvent applications in pharmaceuticals, toiletries and cosmetics, detergents and household cleaners, coatings and inks and processing solvents. • There is a growing market for "eco" household products which use bio-based chemicals, and often command a significant price premium. • Ethanol is a chemical intermediate for the manufacture of ethyl acetate, ethyl acrylate, acetic acid, glycol ethers and ethylamines, as well as other products.
How will the algal technology be commercialised?	• Collaborative R&D on integrated biorefining: Identification of suitable feedstocks and processing • Provide detailed technical and economic feasibility study • Scale-up of production, harvesting and processing to increase production volumes and lower costs through economy of scale • Industry follow up from research programmes such as EnAlgae • Buy-in from chemical companies specialising in intermediates
Timescale to commercialisation	• High value/speciality chemicals: 5-10 years for appropriate production capacity to be reached • Base commodity chemicals: >10 years for appropriate production capacity to be reached Recent developments[172] using an engineered strain of *E.coli* have yielded of 0.281 weight ethanol/weight dry macroalgae (equivalent to ~80% of the maximum theoretical yield from the sugar composition in macroalgae). However, if the entire present harvest (6000 tonnes) were converted to ethanol that would equate to approximately 2 million litres of ethanol.
Advantages of Algal Biotechnology over incumbent approaches	• Sustainable feedstock (to be proved by LCA) • Truly renewable • No competition for arable land / food crops
Market size	• 96% beverage grade is worth £66-70/hl gross price UK • 99% industrial grade is worth £870-930/tonne gross price UK[173]
Growth rate	• Ethanol consumption for fuel increased by 19 percent in 2012, from 652 million litres in 2011 to a record high of 774 million litres in 2012[174]. • Sales of eco-cleaning products increased from £3 million in 2000 to £42 million in 2010[175].
UK companies operating in this market sector	• TMO Renewables, Ensus, British Sugar, Vivergo, Vireol, - none as yet on algal bioethanol
UK Ecosystems potential to commercialise	• Capitalising on our large coastal region • Larger scale production (if not in conjunction with fish farming for bioremediation, *c.f.* Case Study 3) may deplete nutrients and influence ecosystem; fertilisation may remediate that, but may cause other effects[176]

[172] Wargacki et al. (2012) An Engineered Microbial Platform for Direct Biofuel Production from Brown Macroalgae *Science* Vol. 335 no. 6066 pp. 308-313 DOI: 10.1126/science.1214547
[173] ICIS Market Intelligence, November 2012
[174] UK Department of Energy & Climate Change, 2013
[175] Co-Operative Bank Ethical Consumerism Report 2011 available a co-operative.coop/PageFiles/416561607/Ethical-Consumerism-Report-2011.pdf
[176] *c.f.* AB-SIG SRA, p. 13, available at: connect.innovateuk.org/c/document_library/get_file?p_l_id=2244614&folderId=7863898&name=DLFE-81879.pdf

	Technological	Commercial	Other
Barriers	• Scale up of process has to be established	• Lack of funding • Lack of proof of concept	• Ecological soundness of scaled growth has to be established
Risks	• LCA may show there is little improvement compared to 1st generation bioethanol (very low)	• May prove too expensive compared to 1st generation bioethanol (medium) so therefore only suitable for premium applications[177] • A Crown Estate commission report estimates that manufacture of ethanol from seaweed is likely to be in the region of £200/te more expensive than from corn[178].	• Race with lignocellulosic bioethanol production (medium-high)
Fit with UK capability	• CPI fermentation infrastructure • Ecology expertise for environmentally responsible scale-up of cultivation	• Existing chemical industry • Industry could develop and adapt existing good knowledge base	• Good expertise in marine special planning
Gaps in UK capability	• Cost effective cultivation & harvesting • Scale up	• Seaweed industry exists but only at small scale	• Low-cost, efficient seaweed storage and/or transport
Key innovation and R&D needs	• **Pilot scale facilities** - proof of concept • Integrating with waste streams (nutrients, surplus heat/ energy) and existing technologies/infrastructure for cost effective cultivation and harvesting (*e.g.,* IMTA, see Case Study 3) • Develop appropriate low carbon / low cost downstream processing, *e.g.,* by modifying pre-existing processes • Environmental impact assessments of growth at scale		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Integrating with existing technology/infrastructure, utilising knowledge base (species, environment, fermentation)	• Funding for proof of concept	• Legislation
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Determine LCA of processes to evaluate which is the overall 'greenest' option • Integration with UK-based manufacturing, incentives to displace fossil-based ethanol		

177 US Dept of Energy study (Macroalgae as a Biomass Feedstock: A Preliminary Analysis, US Dept of Energy 2010**)** reports that for a plant operating at 500,000 dry tonnes per day input the price per dry tonne of macroalgae feedstock is $28 to make an ethanol product which is $0.48 per litre

178 Lewis, J., Salam, F., Slack, N., Winton, M., Hobson, L. 2011. 'Product options for the processing of marine macro-algae – Summary Report'. The Crown Estate, 44 pages. ISBN: 978-1-906410-31-5

Table Case Study 13: Microalgae for synthetic biofuels via thermochemical conversion

Why will this be an important market?	• EU Biofuels directive – to incorporate 10% biofuel by 2020, but 5% must come from non-food sources • Provides a means for decentralised energy generation • Contributes to energy mix, leading to higher resilience in energy supply • Opens opportunity for community energy systems (micro generation)		
How will the algal technology be commercialised?	**Growth of algal biomass:** • Integrated biorefining: growth coupled to remediation / waste treatment • Exploitation of "brownfield" land and existing infrastructure **Thermochemical processing:** • Partnerships between algae producers, thermochemical process experts and existing liquid transport fuel suppliers • Needs to be based on outstanding science • Need to produce fuel we use, not just fuel we can produce - understanding of downstream applications		
Timescale to commercialisation	• 15-20 years		
Advantages of Algal Biotechnology over incumbent approaches	• Does not need to compete for food/arable land/fresh water • Fit with reuse, recover, recycle at different levels (infrastructure, land, nutrients, resources, etc) • Potential for higher biomass yields than land plants, and quasi-continuous culture rather than seasonal harvesting (but proof of concept is still outstanding)		
Market size	• Price is €900 per tonne (2011)[179] • EU: 10,842,655 tonnes of oil equivalent (2011)[180]		
Growth rate	• Overall biofuel consumption in Europe grew by only 3.1% from 2010 to 2011 representing a slowdown (possibly due to interim targets for incorporation into transport fuel being reached)[181]		
UK companies operating in this market sector	• UK Players: Argent, Harvest Energy. EU Players: Diester (Fr), Neste (Fi), ADM Biodiesel (DE)		
UK Ecosystems potential to commercialise	• Could provide ecosystem service if biomass could be grown on nutrients from waste water, *e.g.,* sewage works.		
	Technological	**Commercial**	**Other**
Barriers	• Scale up – energy consumption of production and harvesting are currently prohibitive	• Exclusive biofuels too expensive for the free market	• Higher value markets for algal biomass are not saturated, hence growing algae for a low value product like fuel is less attractive
Risks	• LCA may stay unfavourable (medium)	• Volatility in oil prices (medium-high)	• Instability in political drivers (medium-high)
Fit with UK capability	• Strong academic research base	• Links to waste water industry for remediation > creating bioenergy from by-products	• Existing momentum through project like BioMara, EnAlgae
Gaps in UK capability	• Scale up • R&D into downstream processing	• Data for reliable economic modelling	• Low insolation during winter • Restrictions on growing GM algae

[179] FO Licht
[180] EurObserv'ER Biofuels Barometer report, July 2012
[181] Ibid

Key innovation and R&D needs	• Supply route security (available biomass: sustainable production of higher yields with minimal inputs at lower costs) • Strain selection and development of GM tools • Better understanding of biology and biochemistry • Closed systems: light penetration, light colour and dosage, downflow reactors • Open systems: local ecology, dynamics of the microcosm, fertilisation/mixing, co-siting; pilot plants • (Micro-)process intensification • More economic harvesting / dewatering / processing technologies • Alternative processing, *e.g.,* hydrothermal • Data for LCA, sustainability and economic analysis • Knowledge / technology dissemination (innovation and industry sector linked) • Matrix of complementary sciences / technologies		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Links to other existing industry frameworks • Harvesting technologists and thermochemistry experts	• Pilot scale demos • Funding • Return on Investment	• Demand for bio-based alternatives by industry, and by consumers
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Develop a number of pilot sites for integrated biorefining, in differing industry integration contexts, to collect reliable data for LCA, sustainability and economic analysis • Proceed to demonstration scale for whole system analysis		

Table Case Study 14: Knowledge Industry for Consultancy on Algal Know-how

Why will this be an important market?	**Consultancy on markets / economics:** • Market intelligence is essential for commercialisation • Data = Knowledge = Profits **Consultancy on environmental factors:** • Long-term survival of any industry demands minimizing environmental impacts • Understanding of environmental impacts allows de-risking • Ensuring responsible management of resources / CSR • Feasibility studies (incl desktop) will be required to ensure project success **Consultancy on general algal know-how:** • Acceleration of learning; development of teaching tools • Policy advice • Work on public perception; outreach tools for community engagement and buy-in (preventing NIMBYism in relation to algal installations) • Preventing duplication / reinventing the wheel (maximise use of existing community knowledge)
How will the algal technology be commercialised?	• Selling knowledge (standard techniques) • Addressing a global market • Working with industry, policy makers, NGOs, teaching and training institutions, communities • Promote positive interactions between players in the supply chain • Through offering reports, reviews, advice, feasibility studies, training programmes
Timescale to commercialisation	• 1-5 yrs
Advantages of Algal Biotechnology over incumbent approaches	• Industry imperative: Underpins entire commercialisation and value chain • Cannot assume the translation of knowledge from academia to industry without mediation • Cannot assume buy-in from stakeholders (planning / regulatory bodies, communities) for introduction and expansion of algal technologies without mediation

Market size	• Policy makers, developers, regulators; consumers, community groups, neighbouring countries • knowledge-intensive services have become the predominant source of jobs in the UK economy, and have been responsible for a large proportion of new jobs over the last 30 years[182]		
Growth rate	• Follows growth of industry, and of environmental concerns where algae can offer remediation		
UK companies and organisations operating in this market sector	• InCrops, NNFCC, PML Applications, SRSL (SAMS), Centre for Process Innovation • AB-SIG, KTNs		
	Technological	**Commercial**	**Other**
Barriers	• Knowledge gaps • Technology impacts (ROI/ LCA)	• Start-up companies often do not have capital to access services of knowledge providers	• Need for marine test sites (macro) and pilot/scale up plants (micro) for real life data on which to base modelling
Risks	• Lack of access to basic data, especially on scale up	• Commercial sensitivity/IPR	• Growing amount of non-vetted / potentially misleading information in public domain
Fit with UK capability	• Algal collections • Marine ecosystem modelling • Biotech experience • Broader systems modelling	• Innovation vouchers / collaborative R&D awards which include a partner in this industry	• UK participates in many major algal research networks
Gaps in UK capability	• Existing training (PhDs/ next generation) • Data on operational macroalgae farms / microalgae pilots • Competition for numerical skills	• Funding / grants to enable start ups to access market analysis and advice	• Small algal community
Key innovation and R&D needs	• Very high resolution numeric ocean models • Validated data from test and pilot sites • More global outlook		
	Requirement for technology partnerships	**Support needs**	**Other**
Enablers for successful UK commercialisation	• Built in role for knowledge transfer within grants	• Investment in pilot sites, giving access to knowledge providers for data acquisition and analysis	• Promotion • Bringing it up agenda • National programme • Perceptions, information gap, understanding
Key actions required to develop UK competitive advantage relative to the global commercial landscape	• Investment in pilots and scale up • Retention of skilled graduates in field • Encouragement of interdisciplinary training		

182 Work Foundation Report: A plan for growth in the knowledge economy, Technical Annex A Knowledge Economy Programme Paper June 2011 – figures based upon ONS workforce jobs data, 1978 to 2010