Phyco-F

Fine Chemicals, Food, Feeds and Fuels

PHY-303 BEIS Biomass Feedstocks Innovation Programme: Public Report

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Executive Summary

Microalgae are used for an extremely wide range of industrial applications, from pharmaceuticals to fuels. Global production of microalgae biomass is, however, only around 130,000 tonnes dry weight per annum. The reason for the huge disparity between the economic potential of microalgae and the reality is simply down to costs of producing the biomass. Existing manufacturing systems are not cost effective except for small, high value markets. Without economies of scale to help drive down costs, access to larger commodity markets and thus economic significance is unachievable.

Costs can be reduced through the development of less expensive, more productive growth systems and reducing feedstock costs. The 3Gs project aims to significantly reduce the cost of producing microalgae through innovative, disruptive design of the manufacturing systems and a novel symbiosis with the whisky industry.

In Phase 1 the 3Gs team looked at the state of the art in microalgal production systems, trends in the markets for algae and how best to work with the whisky industry to produce mutually beneficial outcomes. Options were explored and a Phase 2 plan developed, informed by the Phase 1 results – some of which were unexpected and caused significant shifts in thinking.

A number of significant technical innovations were developed that will deliver a world-leading algal production system based around the algal production system and its component Advanced Photobioreactors (APBRs). The 3gs system is the modular building block of an industrial scale manufacturing system that significantly reduces both cost and carbon footprint of producing algal biomass.

Whisky production is an excellent source of high grade CO_2, nutrients and water that can be used to reduce the costs of feedstocks for algal production. It was assumed that distilleries would be partners rather than customers but as the Phase 1 project progressed it was recognised that algal production could offer them a significant value proposition, making sales to distilleries a real option. This is a significant business innovation as it changes the model from one of relying on organic growth through biomass sales to one driven by sales of technology. If the value proposition is sufficiently strong, distilleries will rapidly adopt the technology. As the biomass production is only part of the value proposition this will make it much easier to expand the industry and access newer markets, driving a virtuous cycle of sustainable growth, as economies of scale take effect. This will eventually lead to the biomass production becoming commercially viable even without the involvement of the distilleries. This will allow algal production to reach the scale at which it can support much larger, strategic markets such as the phytostimulant, salmon and animal feed markets.

The proposed 3Gs system has the potential to transform the UK into a leader in European microalgae biomass production while delivering significant environmental benefits, including direct carbon capture of distillery CO_2 emissions. The symbiosis with distilleries will help the whisky industry achieve their sustainability objectives and strengthen rural economies.

1. Introduction

Microalgae have the highest productivity of any photosynthetic organism and represent the most flexible source of industrial biomass. Rich in bioactive compounds, lipids and proteins, they are used in a wide range of industrial applications from agriculture to pharmaceuticals; food supplements to cosmetics; dyes to biofuels and bioplastics. Global production of microalgae biomass is, however, only 130,000 tonnes dry weight per annum with an estimated value of €2.6Bn[1] (CAGR ~ 10%). China accounts for almost 75% of this production, European output is <0.5% of global production and the UK has virtually no industrial production of microalgae.[2] This market has huge potential for growth.

The reason for the glaring disparity between the economic potential and the reality is simply down to production costs. Viable markets for microalgae and too small for economies of scale: without economies of scale, access to larger commodity markets is unachievable. Costs can be reduced through the development of less expensive, more productive growth systems and through reducing feedstock costs. The 3Gs project aims to significantly reduce the cost of producing microalgae through innovative, disruptive design and a novel symbiosis with the whisky industry. In Phase 1 the state of the art in microalgal production systems, trends in the markets for algae, and how best to work with the whisky and renewable energy industries to produce mutually beneficial outcomes were examined. The results were sometimes unexpected and caused significant shifts in thinking.

The proposed 3Gs system has the potential to transform the UK into a leader in European microalgae biomass production while delivering significant environmental benefits.

2. Technical Innovation

The 3Gs Phase 1 project started with an in-depth review of:

- The state of the art in microalgal production systems.
- The UK and international markets for algae.
- Opportunities and drivers for collaboration with the whisky industry.

These reviews were used to inform the Phase 2 proposal that aims to give the UK a strong competitive advantage through significantly reducing the cost of algal production.

2.1 Production Systems

Most microalgae is produced in raceway ponds, using sunlight as the energy source. Raceway ponds have very poor area to volume ratios making them unsuitable for the UK where space is at a premium and they are not considered further here.

The UK is not renowned for its sunshine – we receive about half the annual sunshine hours of Portugal and while we sometimes have good insolation in early summer, winter sunshine is insufficient to support microalgal growth. Using sunlight to grow microalgae at scale in the UK would be highly seasonal and would struggle to compete with production systems based in southern Europe. To produce microalgal biomass in the UK 24/7/365 thus requires the

[1] European Association for Algae Biomass 2020 Annual report
[2] Global Microalgae Market Study Report 2020

use of artificial light. Once this has been accepted, however, the many advantages of using artificial light can be embraced. An analogous case is that of vertical farming where the advantages of LED lights are changing the paradigm for food production. Sunlight constantly varies with time of day, season and cloud cover. Too much light and the algae become photo-inhibited, too little and they are photo-limited. Sunlight also contains ultraviolet (UV) radiation and infra-red (IR). UV is not much of a problem to algae grown in PBRs but the IR means that the heat load is constantly varying, resulting in fluctuating temperatures. Constantly changing light levels means that photosynthesis rates vary resulting in changing levels of CO_2 (with accompanying pH changes) and of O_2. Artificial light changes the process from one of farming to biotechnology, where the critical parameters can be controlled to produce optimised growth.

There are many designs of industrial photobioreactor (PBR) but the most commonly used is the tubular reactor (TPBR). TPBRs are comprised of transparent acrylic or borosilicate glass tubes joined together by end couplings to form an array [Figure 1]. Main advantages of TPBRs are the relative ease of scaling them and that they can be used for either sunlight or artificial light. As the most common industrial PBR type we benchmarked 3Gs designs against these, using published data and our own calculations.[3]

Figure 1: Commercial, externally lit tubular photobioreactors. Very low light coupling efficiency and large area per unit volume biomass.

Figure 2: Current state-of-the-art APBR. 700l system using LED light tiles to internally illuminate photobioreactors.

An Advanced Photobioreactor (APBR) is defined as one that uses an artificial and internal light source – maximising the efficiency of light delivery. The award-winning Pandora 1000l APBR (developed for the Zero Waste Scotland ENBIO project) was considered the state of the art [Figure 2]. Design innovations were explored to improve on this. Specific areas of innovation identified for the APBR were the LED lighting system and the APBR vessel.

TPBRs are at a significant disadvantage against APBRs, as summarised Table 1 below. TPBRs have limited tube diameter (usually 5-10cm) and so are unsuitable for internal lighting. External LED lighting for tubular PBRs is very wasteful because of poor coupling leading to light spill and much of the light never entering the PBR - see Figure 1. By using APBR designs,

[3] F.G. Acién, J.M. Fernández, J.J. Magán, E. Molina Production cost of a real microalgae production plant and strategies to reduce it; Biotechnology Advances, 30:6:1344-1353. https://doi.org/10.1016/j.biotechadv.2012.02.005

100% of the light can be delivered to the algae (see Figure 2) and any excess heat from the LEDs can be recovered. APBRs use approximately 90% less materials than tubular PBRs and have excellent space utilisations (<10% of the space needed per $1m^3$ for TPBRs). Freed from being tethered to sunlight, compact, energy-dense and highly efficient APBRs can be built anywhere.

Tubular PBR	APBR
Poor space utilisation	Maximum space utilisation
Energy inefficient due to light spill and heat losses; needs heavy use of pumps to maintain water flow	Highly energy efficient: 100% light within PBR and heat management. Mixing produced by low energy gas injection
Large material usage	Low material use
Vulnerable to damage	Robust design with long life
Recycling poor (borosilicate glass or PMMA)	Recycling good (Stainless steel)
Difficult to clean	Easy to clean

Table 1: Summary of design advantages of an APBR system vs industry standard TPBR system.

The ENBIO APBR LED light tiles (Figure 2) delivered high levels of light and were generally found to be robust when immersed. However, significant problems arose from the considerable use of PMMA (acrylic) boxes to keep the LEDs from contact with water. The tiles could only be used with the APBR housings they were designed for: A change in APBR architecture meant new light sheets needed to be designed and manufactured. A two-stage manufacturing process was required with LED boards being manufactured by one contractor then shipped to an acrylic specialist who encapsulated the LED boards. An expensive silicone optical resin had to be used to fill the acrylic casings and the need for structural strength meant that thick acrylic was required. The sheets were of a significant weight requiring a stainless steel cradle to support the light tiles (Figure 3).

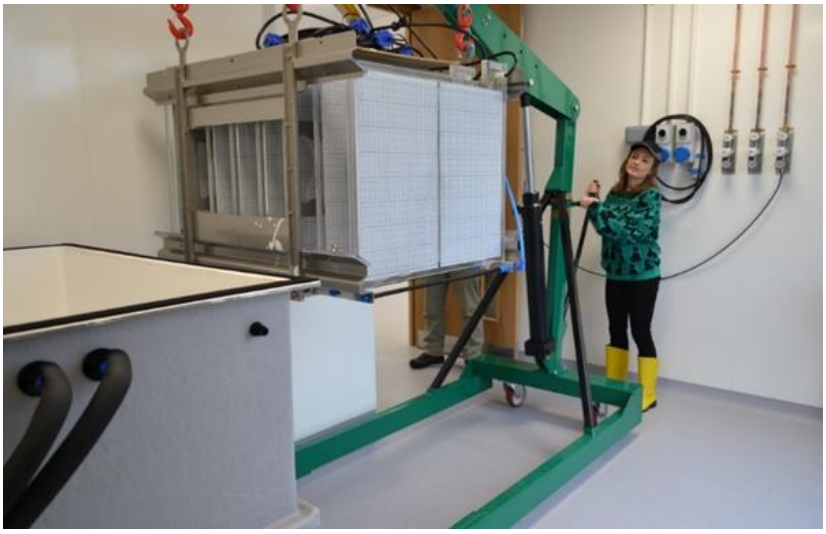

Figure 3: Current APBR design requiring a stainless steel hoist to support heavy LED light tiles and insert them into the APBR tank.

The light tiles are irreparable if internal components fail or if the seal breaks. The acrylic housing was difficult to sterilise and extremely difficult to recycle. Large tile volume meant less internal space available which also hindered fluid movement. Replacement of the acrylic housing with an inexpensive “shrink wrapped” plastic coating did remove many of the problems associated with the original light tile design but not all of them.

A number of technical challenges had to be addressed to improve the lighting system for the APBR:

- Distribution of illumination within the growth volume
- Electrical power delivery
- LED encapsulation

CAD modelling was used to examine combinations of LED power, spacing and APBR size (diameter vs height). Small prototypes of the novel lighting systems were built and tested.

The LED lighting systems designed in the Phase 1 project have substantive advantages over the ENBIO light sheets:

- Greatly increased productivity from of the light to volume ratio, illumination uniformity and better culture circulation.
- Material choices possible to make sterilisation and cleaning easier – reduced operational costs, and biomass suitability for feed markets
- Reduced hardware material mass and manufacture costs – reduced CAPEX and carbon footprint.
- Easier to repair and maintain – improved life and easier to recycle at end-of-life.

The ENBIO APBR used GRP water tanks for the PBR housing (Figure 3) with a special food grade gel coating. Because the light tiles were immersed, the electrical gland fittings also had to be of food grade plastic making them expensive. During Phase 1, many improvements over the ENBIO APBR were established. The simplest cost-saving design change was to replace the 1000l, cuboid APBRs with a 5000l cylindrical tank design. This reduces the number of some components (such as sensors) by up to 80%. The amount of material needed for the APBR housings per volume is also greatly reduced (by ~50%). Moving to a circular design increases the strength of the APBR over a cuboidal design and simplifies manufacturing.

Stainless steel was chosen for the APBR vessel being the material of choice for food grade applications. It is less expensive than GRP but also much easier to sterilise, reducing down time and production costs. It is simple to fabricate and is much more robust - increasing lifetime and reducing relative CAPEX costs. The carbon footprints of GRP and stainless steel are similar (~3-4kg CO_2 per kg) but stainless steel is much easier to recycle, reducing the LCA carbon costs. The lighting system design means that there is no requirement for the stainless steel cradle, offsetting the slightly increased weight. The use of stainless steel moves the APBR closer to the biotechnology “norm” and will increase its commercial acceptance.

2.2 Production System Integration

A major impetus to the Phase 1 project was the addition of Ross-shire Engineering Ltd (RSE) to the project team. The attractive technology options that RSE bring to the project, coupled with the results of studying integration with the distilleries, led to a decision that the Phase 2 demonstration scale should be 50,000l and consist of ten APBRs. This size (including all control systems and fluid handling) can be contained within two of RSE's standard, road-transportable, pre-built modules. RSE have over 25 years' experience in modular construction techniques, primarily for the water industry – see Figure 4. This significantly de-risks the project's engineering aspects.

Figure 4: RSE modular processing units being built and transported to clients' sites

Larger facilities can be created simply by adding more units. Using prefabricated units reduces the associated carbon footprint associated with manufacture and installation by 70% [RSE LCA estimate]. It also greatly reduces the risk of weather-related delays.

Control System

Control of the production unit requires a Programmable Logic Controller (PLC) which also couples the unit to the distillery operations and the local electricity network. Study of the distillery operations and discussions with companies engaged in grid balancing, led to the design of the system controller. This will extend LED control capability to multiple APBRs as well as integrating the motor control centre that will govern liquid and gas flows between the distillery and the production unit. The control system will also respond to the local electrical environment and to external electrical grid requests.

Systems for delivering electrical demand side management services are commercially available at relatively low cost so there was no obvious benefit in seeking to duplicate these. The system therefore only needs to be able to communicate with the chosen external energy platform via its supplied systems.

There is a wide range of commercial PLC hardware available. The actual specification and selection will be made in Phase 2 as current international supply chain issues impacting all electronic supplies, make it difficult to determine what systems will actually be available for the project. The system will be ENA EREC G99 compatible so that it can provide maximum flexibility and future proofing.

3. Distillery and Energy Integration

An obvious way to reduce the cost of microalgal production is to co-locate with industrial facilities that produce as by-products the necessary feedstocks for algal growth. There is extensive literature around using waste CO_2 and nutrients from a wide variety of processes (e.g. fossil fuel combustion; cement manufacture; anaerobic digestors; waste water treatment plants). The attraction of "free" feedstocks is clear, though the economics of their use may prove problematic if significant processing is necessary before they can be used. Using "waste" resources can also severely limit the uses of the algal biomass because of regulatory limitations, especially in regard to food, feed and pharmaceutical applications.

The production of spirits is a major and globally significant industry for the UK with an annual production of around 900 million litres - mostly whisky. Whisky production is the UK's most valuable food and drink export (~ £5Bn GVA annually). The industry has developed an ambitious sustainability plan, focussed on reduction of GHG emissions by 40% by 2030 and to Net Zero by 2040.

The 3Gs project is fortunate in having two blue chip whisky companies as partners and both companies are very interested in innovative technologies that will help them achieve their sustainability goals. A successful demonstration of the 3Gs concept offers the prospect of rapid adoption of the technology both within the UK and globally. During Phase 1, both companies shared a large amount of data concerning their operations that was critical in reaching a better understanding of their operations and how microalgal production could be integrated onto distillery sites to the mutual benefit of the distillery and the algae production.

Discussions with both companies have allowed us to understand their operational priorities and guide how best the 3Gs project can integrate with their operations. It is important to ensure that the operation and siting of the system has no detrimental impact on current or future distillery operations.

In addition to ensuring that the algae operations have no detrimental impact on the distillery, positive benefits from the operation of the systems or the algal biomass were examined in detail.

Fermentation of alcohol produces very pure (95%-99%) streams of CO_2. For every million litres of spirit (100%) produced, 755 tonnes of fermentation CO_2 is released – over 600,000 tonnes annually from the UK. Except in a few cases, this CO_2 is simply vented to the atmosphere as the quantities produced at single distilleries are usually too low to justify investing in the equipment needed to remove impurities (particularly oxygen) that would allow the fermentation CO_2 to be sold for industrial uses. Distillery co-products are not considered waste and remain “food grade” making it much easier to produce algal biomass that can address all markets. Co-location of algal production with distilleries or breweries means that they can access secure supplies of high-quality CO_2. Industrial CO_2 usually costs £100 to £200 per tonne though the recent shortages saw prices exceed £1,000 per tonne. Depending on the capture efficiency, it takes between 3 and 10 tonnes of CO_2 to produce a single tonne (DW) of algae. At the larger distilleries CO_2 is continuously available other than during occasional shutdowns. There is no need to purify or concentrate the CO_2 making integration with the algal production simply a matter of moving the low-pressure CO_2 to the nearby APBRs. Fermentation CO_2 does not count as a GHG because it originates from plant material. However, its sequestration can be considered an offset.

Distilleries produce liquid nutrients, either in the pot ale (3 billion litres annually) or through AD treatment. The available AD digestate at the demo distillery is sufficient to support large scale algal production but a number of challenges were identified in Phase 1. The high nutrient levels and dark colour of the digestate means that dilution and filtration would be necessary but this entails high costs. Pot ale has similar problems but the whisky industry is looking for better solutions to the existing uses of both AD digestate and pot ale.

Distilleries also use large amounts of water in making the whisky and in industrial processing. This is seen as increasingly important in regard to good stewardship of natural resources but also because of possible impacts to water supply caused by climate change. Process water from distilleries can be recycled by the algae, reducing residual nutrient loads in effluent streams and increasing the circular economy of the site. This removes the necessity to utilise “virgin” water sources. Existing distillery water treatment facilities bring the discharge levels below regulatory limits so improved purification coming from the algae using the process water is more of an added benefit than a necessity for the distilleries.

When the 3Gs project was envisaged, little attention was paid to the electrical environment at the distillery beyond obvious considerations of capacity. The emphasis was squarely on the use of fermentation CO_2 and nutrients from the distillery, with electricity considerations essentially focused on using the algal production system as a transactive load to reduce overall costs.

The systems can be used to provide grid balancing services (DSM) and extensive discussions were held with energy aggregators who are very interested in the capability of the production units to flex their electricity usage as LEDs can be turned up or down, on or off, very rapidly

Local and national electricity constraints can dramatically change the price of electricity. 'Constraint management’ is an additional service offered by the National Grid. The amount of constrained electricity is very large (3.6 TWh was curtailed in 2020) and has a high cost (estimated to reach £1Bn annually by 2025). The prices for this electricity can be well below the average wholesale values and sometimes becomes negative. Unsurprisingly, this has been seen as an opportunity to significantly reduce energy costs.

As part of the BEIS Green Distillery competition one project aimed to acquire constrained electricity at very low prices and use it to provide power to a heat store that would then be used to provide high temperature heat to operate the stills at Highland Park on Orkney. The electricity prices at the point of constraint were very low, ranging from a high of £26.20 per MWh to £1.76 per MWh (against a “normal” wholesale cost of ~£70 per MWh). However, accessing constrained electricity at low prices is problematic. Constraint is both spatial and temporal. The spatial aspects mean that to be able to access the electricity you usually need your asset to be near the constraint. This was a major limitation in the Highland Park project as the distillery was 22km from the constraint. The availability of constraint is difficult to predict as it depends on local generation and demand. New developments may also remove the constraint leaving electricity at normal prices. These uncertainties mean that an operational strategy that relied on accessing only curtailed electricity would be highly challenging even for standalone algal production systems and entirely unsuitable for a distillery where electricity supply must be reliable. For the 3Gs project there appears to be no mechanism by which the demo plant could reliably access the constrained electricity. It is, however, prudent that the systems have sufficient flexibility to take advantage of curtailment if significant opportunities arise in the future.

The remaining opportunities fall into two main categories: Power Optimisation (PO) and Tariff Negotiation (TN). The latter is straightforward: larger users enjoy lower tariffs for their electricity use. By using the distillery’s electricity supply a more favourable tariff for the site as a whole can be negotiated. This particularly benefits the algal facility as the cost of electricity is more sensitive for the production of the algae than it is for producing whisky. The algal production enjoys further benefits because the distilleries have existing grid supply infrastructure that would otherwise be expensive to obtain.

The study identified a use for the algal production units to help secure the local energy environment and this may provide significant benefits to the distilleries. Distilleries are very much part of plans to reduce Scope 2 emissions by enabling and strengthening renewable networks (e.g. the *North of Scotland Hydrogen Programme 'Distilleries Project*'). The scale of possible savings, and the wider environmental benefits that algal production can deliver, makes co-location at distilleries an attractive proposition to the distilleries themselves with the added benefit of the production of valuable algal biomass.

Distillery companies enter into a wide variety of external relationships to valorise co-products. The Phase 1 study did identify a number of possible uses of the microalgae that could indirectly benefit the distillery. Products of wider interest would include microalgae produced bio-inks with lower carbon costs than traditional inks currently used to label single-use cardboard boxes.

Distilleries traditionally supply co-products to farmers with either cattle feed (e.g. Distiller’s Dark Grains) or as low grade fertilisers (pot ale or AD digestates). Microalgae have considerable potential as phytostimulants; animal feeds and aquaculture feeds. Distilleries could use the algae produced by on site to support other local industries (i.e. farming and aquaculture).

4. Environmental Benefits

The 3Gs demo system designed during this Phase 1 project will produce up to 7,000kg DW biomass per MPU per year.

The 3Gs proposed process of growing microalgae in partnership with the distillery industry has a number of notable environmental benefits beyond the generation of biomass.

Significant savings in carbon emissions will arise directly as a result of the 3Gs photobioreactor system design and operation. Comparing the 3Gs system with artificially lit, tubular bioreactors currently used in industrial microalgae production, results in calculated carbon savings of almost 54kg CO2 per kg biomass.

Source	**Calculated Reduction**
CO_2 from the distillery process that would otherwise be discharged into the atmosphere will be captured and removed from the distilleries' carbon footprint.	7kg CO_2 / kg biomass
Further, reduction in CO_2 produced from non-renewable sources arises as a direct result of this displacement of industrially produced CO_2 distributed in tanks, which is the normal source for biomass production.	7.7kg CO_2 / kg biomass
In addition, the use of AD digestate as a nutrient source versus the typical use of chemical nutrients also reduces the carbon footprint of the operational process.	5kg CO_2 / kg biomass
50% increase in biomass production efficiency resulting from the 3Gs APBR will save CO_2 emissions associated with the operational energy source.[4]	34kg CO_2 / kg biomass
Total carbon savings	**53.7kg CO_2 / kg biomass**

Table 2: Calculated reduction in CO_2 from the operation of the 3Gs, distillery-integrated system compared to an industry standard tubular photobioreactor. Additional carbon savings through using a lower volume of materials and better recyclability are not shown here.

There are additional savings from materials usage as the APBRs use ~90% less material than an equivalent TPBR system; more detailed calculation to be made in Phase 2 LCA once system is manufactured and operational.

Applications of the biomass will have their own positive impact on carbon emissions reduction, whether that is through displacement of chemical ingredients, fertilisers, plastics, or fuels, currently produced from petrochemical products. The carbon savings of these have not been calculated during Phase 1 but will be significant in their own right. A number of microalgal biomass applications have additional environmental benefits that are not considered here. For example, displacement of wild fish caught to act as a source in of Omega-3; improvements in soil quality and crop yield through the use of microalgae as phytostimulants or replacement of meat proteins.

Integration with the distilleries will have further environmental benefits beyond CO_2 emissions reduction. These will include improvements in the quality of water discharged

[4] Non-renewable electricity assumed in both cases

from the distillation process. This water will be recycled and used to form the growth medium for the microalgae biomass. Research has demonstrated that algae will capture nutrients from wastewater.[5,6] Recycling of the water for a number of growth cycles could further minimise impact on this valuable resource.

5. Business Model Innovation

The 3Gs project has a host of technical innovations that will deliver a world-leading algal production system based around the production system and its component APBRs. This will result in an industrial scale system that significantly reduces the cost of producing algal biomass. The project's most significant innovation is, however, the symbiotic integration of the algal production with distilleries. At the start of Phase 1 it was assumed that the distilleries would be partners rather than customers but as the project progressed it was recognised that production systems could offer them significant value propositions. This was a major turning point in the development of the commercialisation plan. With distilleries now seen as target customers, the project has developed a clear business focus and set of goals.

This is changes the business model from one relying on organic growth through sales of biomass to one driven by sales of technology where the rapid increase in biomass production is a welcome by-product. If the value proposition is sufficiently strong then distilleries will rapidly adopt the technology. Even a modest adoption by the whisky industry would result in the UK rapidly becoming Europe's largest producer of microalgal biomass. As the biomass production is only part of the value proposition, this will make it much easier to expand the industry to access newer markets, driving a virtuous cycle of sustainable growth as economies of scale take effect. This will ultimately lead to the biomass production becoming commercially viable even without the involvement of distilleries, opening the way for algal biomass production becoming a significant industry for the UK and capable of supporting much larger, strategic markets such as the salmon feed market.

6. Commercialisation Plan

6.1. Opportunity

Market research confirmed that microalgae is a global market worth more than $2.5b per annum and growing at around 10% CAGR[7] across a diverse range of applications. The UK has virtually no industrial production of microalgae at scale and yet it is the third largest consumer of Spirulina in Europe (~300 tonnes pa) and the second largest consumer of Chlorella.[8] This demand is currently met entirely from imports. Retail values vary widely

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[5] Escudero A, Blanco F, Lacalle A, Pinto M. Ammonium removal from anaerobically treated effluent by Chlamydomonas acidophila. Bioresour Technol. 2014 Feb;153:62-8. doi: 10.1016/j.biortech.2013.11.076.
[6] Uggetti E, Sialve B, Latrille E, Steyer JP. Anaerobic digestate as substrate for microalgae culture: the role of ammonium concentration on the microalgae productivity. Bioresour Technol. 2014;152:437-43. doi: 10.1016/j.biotech.2013.11.036.
[7] European Association for Algae Biomass 2020 Annual Report
[8] Spirulina market and Chlorella market analysis by Meticulous Research 2019

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from as low as £15 per kg/DW equivalent to £485 per kg/DW depending on species, product type and country of origin / organic status. Displacing these imports is an obvious target for a UK microalgae biomass industry. Primary market research undertaken with producers of microalgae products in the UK confirmed that their microalgae are all imported but that they would be very interested in having UK supplies rather than relying on imported material.

Even more compelling are the very large nascent markets for microalgae in the UK which are currently inhibited by lack of availability of biomass at attractive prices. A good example of this is the salmon aquaculture feed market. Atlantic salmon is the UK's most valuable food export but feed ingredients are almost all imported. Whilst the industry is moving to plant based protein sources, fish oils remain the dominant source for lipids. Developing a UK based source of phototrophic algal oils would be of great benefit to the aquaculture industry's sustainability agenda. Further, it would secure their oil feedstocks, reduce imports and improve biosecurity and quality. The likely volumes required would be in the tens of thousands of tonnes.

Animal feed is a similar story where there is a lot of interest in using microalgae in feed formulations but it is difficult to find enough supply to even undertake scale studies. Phytohormones and other bioactive compounds produced by microalgae can also be used in arable agriculture; for example, phytostimulants used at 1kg per annum per hectare of barley would require approximately 500 tonnes DW of microalgae per annum for UK production.

Integration of production with distilleries will allow the UK industry to reach a critical mass driven by the added value that the production systems can deliver to the distilleries. The 3Gs system design will make it easier to deliver quality biomass at cost effective scale, growing the UK microalgae production industry. Beyond this, there is an opportunity to export both biomass and the production technology, worldwide.

6.2. Business Model

A number of potential business models were investigated through secondary research and discussions with biomass end users and distillery partners, to understand the benefits and value proposition for them.

Revenue streams considered included:

1. Production, marketing and sale of microalgae biomass.
2. Production, marketing and sale of specific bioactive compounds or extracts from microalgae biomass.
3. Sale, service and support of production systems – UK and export sales.
4. Operation of facilities for system owners – Plant owned by distilleries and operated as a service.
5. Licensing of MPU technology and / or business model to export markets.

An analysis was undertaken of each of these and key findings are summarised below, grouped into biomass and technology systems. This work informed the business model taken forward to develop an outline financial plan.

Sale of biomass and related compounds

Extensive market research has identified species of interest, applications, customers and target pricing.

Biomass markets would be addressed through a step wise strategy of supplying into high price / low volume markets then extending to lower price / higher volume markets as production efficiencies and economies of scale take effect. The ultimate opportunity lies in unlocking nascent, high volume markets. Discussions with UK-based animal and aquaculture feed suppliers, and arable research institutes has indicated an interest in partnering on developing these markets where a route to scale can be demonstrated.

Phyco-F plans to further develop partnerships with strategic end users of the biomass during the next development stage and to work with them on the biomass quality and stage of post-processing required to enable them to extract components of value and use these within their final products. This is preferred as the initial biomass sales model over undertaking in-house compound extraction and refinement which would require additional post-processing resource and would constrain target applications. Seven potential end-user partners who are interested to trial biomass produced in the next development phase were identified during Phase 1 and letters of support secured.

Sale and / or Management of Technology

Although distilleries are widespread, there are areas of significant concentration. In Speyside there are over 40 distilleries in a small area producing almost 50% of malt production. Smaller but still significant clusters are seen in Islay, Ross-shire and Sutherland and in the Scottish Central Belt, particularly associated with the large grain distilleries (Figure 5). These clusters offer the potential of further reducing production costs through staff sharing and location of centralised downstream processing facilities that would receive algal biomass from multiple distilleries.

This proposed route to market is quite similar to companies selling vertical farming systems. The value proposition is focused on cost and environmental impact reductions to customers who do not have microalgae as their core activities.

The details of this business model – operational management fee for profit sharing vs free operation for biomass ownership – will be refined in Phase 2

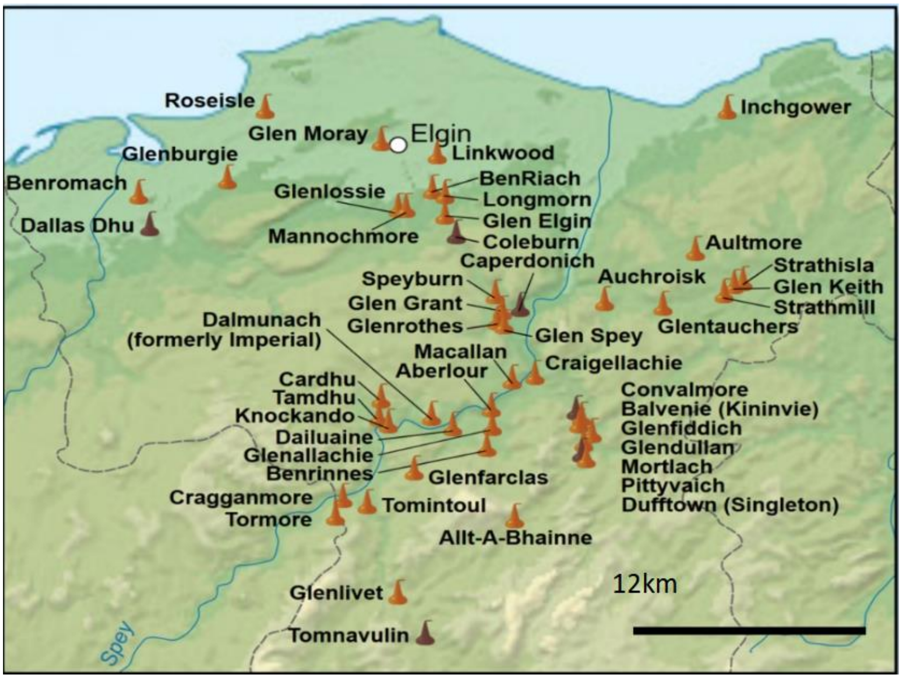

Figure 5: Example of geographic clustering of distilleries in Speyside. This will allow operational management cost savings through multi-site management.

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6.3. Strategic Partnerships

The association of this project with the whisky industry will ensure it is high profile. Phyco-F will leverage its association with the distilleries to promote joint campaigns around the environmental benefits of the innovation and the benefits to distilleries in their journey to achieving Net Zero. Phyco-F will also use the distilleries international profile to help promote international sales and licensing opportunities for the technology.

RSE and its engineering capabilities is a significant asset both for the project and post project commercialisation as they have the capacity to support rapid production of MPUs.

- 20% decrease in MPU manufacture costs over 5 years through design optimisation and increased volume.
- 45% reduction in biomass price as higher volume, lower value markets become accessible.
- Subcontract manufacture employed.

7. Phase 2 Project

7.1. Project Aim

To demonstrate the economic potential and technical feasibility of industrial scale, microalgae biomass production in the UK through the use of innovative, class-leading technology integrated with a whisky distillery.

The project has been shaped to minimise risk and maximise speed of delivery. It has been divided into 8 well-defined Work Packages (WP) each with a designated lead and clear lines of reporting to a dedicated Project Manager who will chair meetings, manage the Risk

Register, take the lead on IP and Quality Management and ensure timely submission of all reporting to BEIS.

7.1.1. Risk Management

A Project Risk Register has been created with input from all project partners. This identifies and quantifies key risks, outlines mitigating measures and assigns risk owners.

Key risks identified for Phase 2 were defined in 5 categories [Commercial, Financial, Operational, Technical, Environmental] and scored 1, 2 or 3 [low, medium or high] for Likelihood (L) and Impact (I). Risks where the final Risk Rating [L x I] after mitigation remains above 2, will be observed most closely.

The Risk Register will be a live document. It will be reviewed at Phase 2 project kick-off and pro-actively managed thereafter through monthly risk review meetings, or earlier if required.

7.1.2. Quality Management

Phyco-F is an early stage start-up business and as such, does not yet have independently accredited quality management certification however RSE, the key project engineering subcontractor, has multiple ISO certifications including ISO9001 (Quality Management), ISO14001 (Environmental Management) and ISO 45001 (Health and Safety).

Quality management will follow a recognised Plan - Implement - Monitor - Review structure with bi-annual Quality Review meetings scheduled throughout the project.

7.2. Project Team

A professional and highly experienced team has been assembled to deliver a Phase 2 demonstration project. This will comprise Phyco-F (led by Dr Douglas McKenzie, CEO, and Co-founder Dr Sébastien Jubeau, R&D Director). Dr McKenzie has previously founded, grown and exited technology SMEs. He has been instrumental in developing the core underlying system technology and has previously coordinated a £2m Scottish Government funded microalgae project. Dr Jubeau spent six years as Project Manager at AlgoSource Technologies where he was responsible for all downstream processing and microalgae valorisation. He has worked with systems development for the last 4 years.

Phyco-F will be complemented by key subcontractors and partners:

- Genmhor [Project Management] – Innovation and technology management consultancy that successfully managed the Phase 1 project.
- RSE Group [Engineering design and fabrication] – Specialist engineering services company, with over 25 years' experience of delivering multi-million pound engineering projects, will joining the team for Phase 2.
- The two global whisky brands who supported the Phase 1 project will become fully embedded within the team for Phase 2, at no cost to the project.

8. Conclusions

Market research confirmed that there is unmet demand for algal biomass produced in the UK across a wide range of industrial sectors and at significant scale. To meet this demand, however, the UK needs to create an industry that is capable of producing high quality biomass at an affordable price and at sufficient scale to be of interest to commodity markets. The UK does not have any such capability at present and almost all of the microalgae used in the UK is imported. To change this situation and move the UK to being a globally significant producer of algal biomass requires smart and disruptive innovation at both technical and business levels.

The Phase 1 project identified a number of technical innovations which promise to make the algal biomass production system the most cost effective, energy-saving industrial scale system in the world. These system innovations will put the UK at the front of algal biomass production technology and enhance its reputation for green technology innovation. The project's most significant innovation is, however, the integration of the MPUs with distilleries. This could provide the impetus that is necessary to drive growth in algal production in the UK to the point where it will have the necessary industrial capacity and human capital to start to open up much larger markets for algal biomass. The business model changes from one relying on organic growth through sales of biomass to one driven by sales of technology where the rapid increase in biomass production is a welcome by-product. Even a modest adoption by the whisky industry would result in the UK rapidly becoming Europe's largest producer of microalgal biomass. The integration of algal production with distilleries opens up the exciting but also credible prospect of a rapid expansion of algal production in the UK as the distilleries have both the scale and resources to enable them to do so.