Biomass Feedstocks Innovation Programme:

Integrated Microalgae Biomass Production via Carbon Dioxide Sequestration

Final Report_Redacted

Contents

1. Executive Summary

This report presents the outcome of the feasibility study on the integrated microalgae biomass production via carbon dioxide sequestration, funded by the department for business, energy, and industrial strategy under the biomass feedstock innovation programme phase 1. The report is divided into seven sections.

The first section (desk study) presents an overview of the literature review conducted on various microalgae species, photobioreactor technologies and microalgae harvesting/dewatering technologies.

The second section (technical description) describes SEaB's anaerobic digestion products (FLEXIBUSTER™ and MUCKBUSTER™), and the integration of these products with the biosystem proposed to produce microalgae biomass. This section also contains an example scenario techno-economic analysis of the proposed system.

The third section (operational impact) evaluates the microalgae market and outlines how the project will support the sustainable biomass supply in the United Kingdom. The overview of the preliminary environmental analysis done on the FLEXIBUSTER™ and the proposed addition of the microalgae system are presented as part of the fourth section - Environmental Impact.

An overview of the risk register developed is presented in the fifth section of the report, highlighting the risks identified, impact, likelihood, risk rating, mitigation actions, residual risk rating (after mitigation has been applied) and contingency measures that can be implemented.

The sixth section (quality plan) contains an overview of the laboratory proposal, maintenance plan and key performance indicators (KPIs). It is worthwhile to note that the laboratory studies are a critical stage of the Phase 2 project and would be conducted at a university who has already agreed to collaborate with SEaB on this project. The seventh section (Project management and Implementation Plans) presents an overview of the main work packages, and how the project will be overseen and governed.

2. Desk Study

2.1 Readily Available Microalgae

This section outlined which microalgae are of primary interest for this study. Selection is based on the properties of the different microalgae and the potential to utilise these favourable properties in growing industries. A brief analysis on the different industries was carried out to understand the scope for the application of the microalgae of interest. Two of the main properties, carbon dioxide fixation and biomass productivity rates into further to understand how these measurements are taken and the significance of them on this study.

The European market consists of four main industries - nutraceuticals, cosmetics, animal feed, and ‘others’ such as fertilisers, biofuels, and bio-stimulants. However, the industries of particular interest to this study are the bioenergy and animal feed accounting for 52% of the market share. The others, accounting for 48% of the market share, were not considered, due to the nature of the process to cultivate the microalgae (Araujo and others, 2021).

Spirulina is rich protein source, with it making up around 55% of its dry weight composition. As a result, it can be considered as a valuable feedstock and/or supplement for animal feed (Tibbetts and others, 2015). Furthermore, biodiesel produced from *Spirulina* has high concentration of saturated fatty acid methyl esters (FAMEs) and low concentrations of unsaturated and polyunsaturated FAMEs. The high concentration of saturated FAMEs guarantees good oxidation resistance (Mostafa and El-Gendy, 2017). This is one of many benefits of using *Spirulina* as feedstock for biofuels.

Chlorella also has a sizeable protein content of around 53% and can also be considered as feedstock of high nutritional value for animals (Tibbetts and others, 2015). *Chlorella* has high lipid content of around 25%, suggesting it may be a valuable feedstock for biofuels. Studies comparing the use of *Chlorella* for biofuels compared to rapeseed, which is currently the primary feedstock for biofuels, showed chlorella fed biofuels performed better (Makareviciene and others, 2011).

Nannochloropsis is also rich in proteins and lipids, making them good candidates for the production of animal feeds and biofuels (Xu and others, 2004). They are high in omega-3 fatty acids, which have numerous health benefits which were observed in various studies of animals fed *Nannochloropsis*. On biofuels, although *Nannochloropsis* has a high lipid content, they are rich in polyunsaturated fatty acids. This negatively effects oxidation stability. However, there are options to manoeuvre around this problem which would make their use viable for biofuels (Porphy and Farid., 2011).

Scenedesmus is a protein rich microalga, making up around 50% of its dry weight. It can be hypothesised that it will be of high nutritional value for animal feed (Gonzalez and others, 2015). There are studies on animals fed *Scenedesmus* which agree with this theory. *Scenedesmus* has been investigated for use for biofuels production. In the same study with *Chlorella* and rapeseed, *Scenedesmus* performed better than both, highlighting its potential for use in biofuels (Makareviciene and others, 2011).

Therefore, for the reasons mentioned above and their relatively high carbon dioxide fixation and biomass productivity rates, *Spirulina*, *Chlorella*, *Nannochloropsis* and *Scenedesmus* were considered as microalgae of interest.

2.2 Carbon Dioxide Fixation Measurement

Carbon dioxide fixation rates can be measured via two methods – direct and indirect. Direct involves measuring the amount of carbon dioxide in the algal biomass whereas indirect involves measuring the carbon dioxide levels at the inlet and outlet. Direct methods are more commonly applied in laboratory studies, making up 70% of the literature reviewed. However, indirect methods have the advantage of being able to provide real time carbon dioxide data compared to direct methods. Examples of direct methods include assumptive values, elemental analysis, and total organic carbon analysis. Examples of indirect methods include gas chromatography and infrared sensors. Biomass productivity rates are measured mainly via two methods - total suspended solid and optical density.

2.3 Photobioreactor Technologies

Photobioreactors typically fall into one of two categories: open and closed volume systems. Open volume systems often take the form of ponds or raceways while closed systems focus on tubular, panel, or column construction methods.

The most common form of open volume bioreactors used for microalgae production is the open raceway pond. These ponds are typically elongated oval canals, constructed with a mechanical paddlewheel to maintain fluid motion, and introduce mixing. Construction materials and system simplicity make them less costly compared to closed volume systems. However, they do experience higher contamination and lower biomass production rates. Natural environment and geography have a large impact on the productivity of open raceway ponds. For example, temperature variation throughout the day can be extreme and so temperature control must be maintained. High temperatures can lead to evaporation. Evaporation affects pH and salinity with a negative impact on biomass growth.

Furthermore, the geographic location of the open raceways can determine the natural light intensity available. Mechanical mixing increases the fluid exposure to light, and artificial light installations can ensure ideal light intensity is achieved in wider geographies. Additional environmental controls, such as polytunnels and glass houses, can also improve biomass productivity.

2.4 Microalgae Harvesting and Dewatering Technologies

To aid with the overall system integration and design, a brief review of various technologies used for microalgae harvesting and dewatering was performed. The technologies analysed include a pressure filter, belt press, disc stack, decanter, and membrane filter. Criteria that impact the selection of the different technologies include dewatering efficiency, costs, energy use, biomass impact, capacity, species applicability, filtrate recycling, and operation/maintenance cost.

2.5 Parameters to Monitor in Photobioreactors

The important parameters monitored in photobioreactors, such as biomass concentration, temperature, pH, CO2/other gas concentrations, light intensity, and nutrients were analysed to understand which methods and equipment is required to accurately monitor process performance and microalgae growth.

3. Technical Description

3.1 Description of FLEXIBUSTER and MUCKBUSTER

The FLEXIBUSTER™ is a modular, containerised, fully automated, remotely monitored, patented organic waste management solution for converting waste to electricity, heat, and valuable fertiliser and water while being integrated into buildings. The award-winning small-scale closed-loop technology is based on anaerobic digestion, designed to process waste from mid-size food waste producers (between 500kg and 3000kg of waste per day). SEaB Energy's proprietary anaerobic digester reduces the carbon footprint and generates green energy, water and organic fertiliser from waste that normally would end up on landfills. FLEXIBUSTER™ is the solution to organic waste recycling in the cities of the future and we strive to take our solution to global markets. Onsite anaerobic digestion is the most sustainable and efficient organic waste management solution.

The main differentiation from all similar solutions is in the end-to-end integrity and the flawless operation of all of its subsystems and integration into building infrastructures. FLEXIBUSTER™'s highly innovative architecture and processes are patent protected and represent our most valuable intellectual assets. The MUCKBUSTER™ is similar to the FLEXIBUSTER™.

3.2 Process Flow Design: Integrated Microalgae Biomass Production

SEaB Energy's patented FLEXIBUSTER^{TM} and MUCKBUSTER^{TM} system would be used in this project for the valorisation of cow manure, slurry, and cattle feed waste to produce microalgae biomass as shown in the process flow diagram.

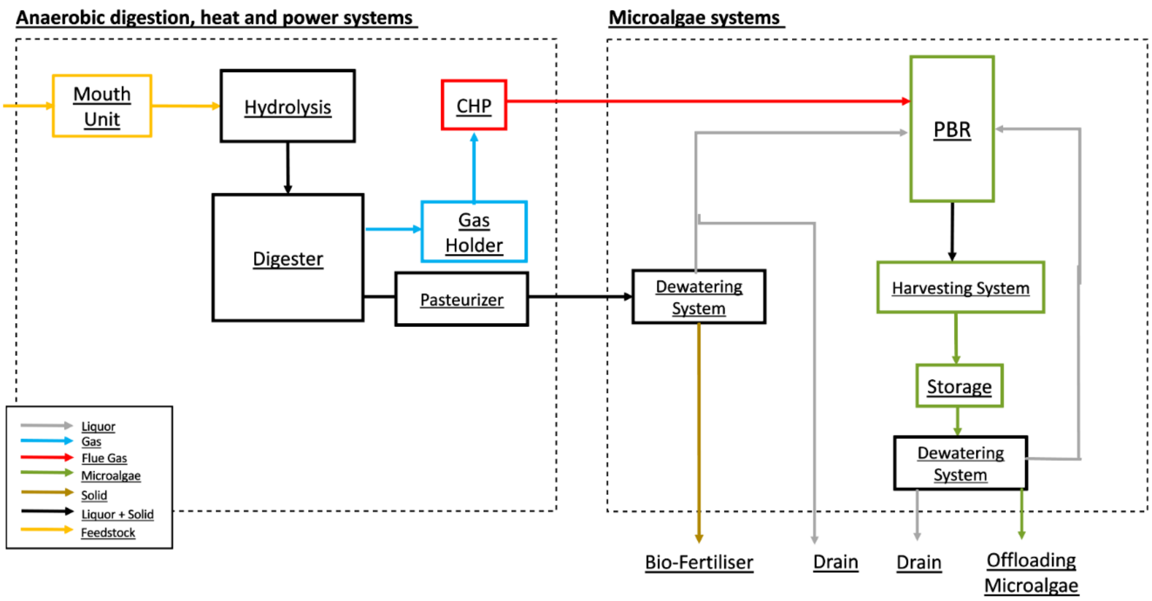

Figure 3-1 – Process scheme of anaerobic digestion system with heat and power systems integrated with microalgae systems

3.3 Photobioreactor Technology Selection Discussion

Multiple correspondence and virtual meetings were held with three major manufacturers of open raceway and closed tubular photobioreactor systems for microalgae production. Those manufacturers are referred to as manufacturer 1, manufacturer 2 and manufacturer 3 in this report. Feedback from these manufacturers is summarised in the tables 3-1 and 3-2.

Table 3-1 – Closed photobioreactor operation and cost assumptions from prominent manufacturers

	Manufacturer 1	Manufacturer 2	Manufacturer 3
Volume (L)	30,000	32,000	30,000
System biomass production (g/L/day)	0.225	0.30	0.20
Kg of CO2 capture per kg of biomass growth	2	2	2
Estimated footprint (m^2)	342	720	270

Table 3-2 – Open raceway photobioreactor operation and cost assumptions from prominent manufacturers

	Manufacturer 1	Manufacturer 3
Volume (L)	80,000	60,000
System biomass production (g/L/day)	0.03	0.10
Kg of CO2 capture per kg of biomass growth	2	2
Estimated footprint (m^2)	405	360

The assumptions and estimations provided by the manufacturers above were incorporated into a mass balance and techno-economic model for optimising system sizing, operation, and costs.

3.4 Harvesting and Dewatering Technology Selection

Multiple manufacturers were contacted in search of the proper dewatering solution. The belt press and membrane filtration technologies were identified as most appropriate for the current project based on the analysis in the prior deliverables. Organic flocculant will be applied prior to the inlet of the belt press filter to enable higher efficiency in the separation of liquid and solid digestates.

The table 3.3 summarises the feedback received from the manufacturers regarding the belt press filter and membrane filter. A supplier of organic flocculant for improving the digestate separation efficiency has also been identified.

Table 3-3 – Dewatering technology manufacturers identified project execution

	Manufacturer	
Attribute	**Manufacturer 1**	**Manufacturer 2**
Technology	Belt press filter	Membrane filtration
Process step	Digestate dewatering	Microalgae dewatering
Capacity (L/hr)	1000 to 6000	2000 (max)
Output concentration (g/L)	180 to 300*	30 to 150

3.5 Control and Monitoring Equipment for the Photobioreactor

The parameters to be monitored in the photobioreactor include temperature, biomass concentration, pH, flue gas composition and flow rate, light intensity, and nutrient composition and flow rate. A summary of the monitoring equipment can be seen in table 3-4.

Table 3-4 – Summary of the monitoring equipment and control measures for the different parameters in the photobioreactor

Parameter	Monitoring equipment
Temperature	Temperature transmitters
Biomass concentration	Spectrophotometry, Fluorometry, Nephelometric turbidity
pH	pH probes throughout different sectors of the photobioreactor
Flue gas composition and flow rate	Infrared sensors Flow transmitters
Light intensity	Light meters
Nutrient composition and flow rate	Spectrophotometers and colorimeters on lab samples. Flow transmitters

3.6 Techno-Economic Analysis

A techno-economic model has been developed in Microsoft Excel to evaluate the technical requirements and economic requirements of integrating the anaerobic digestion system and a microalgae bioreactor system. Using this model, multiple scenarios were considered based on SEaB Energy's internal knowledge of their anaerobic digestion systems and the manufacturers' assumptions described earlier.

The results of the model provided SEaB Energy with insight regarding expected capital and operational project costs, potential biomass revenues, estimated energy consumption, and expected payback period. These insights have enabled internal design and business decisions that will positively impact Phase 2.

4. Operational Impact

4.1 Market

The main routes to market are considered as business to business (B2B), business to consumer (B2C) and direct use on site. Directly using the microalgae on site offers potentially the simplest use and lowest biomass processing requirement. Two scenarios are being considered: Recycling the microalgae to form part of the anaerobic digester feedstock and using the microalgae to supplement animal feed. Following discussions with our university collaborator for the pilot site, they have agreed to offtake the biomass produced to supplement cattle feed on their farm.

4.2 Commercialisation Plan

4.2.1 Promotion of Innovation

Agreements are in place with our university collaborators to host the pilot site and run laboratory studies troughout Phase 2. Together this will aid in the understanding of certain parameters and allow improvements on the current commercialisation plan.

Following successful Phase 2 trials, our university collaborator is open to scaling up the capacity at their site, off taking all the microalgae as animal feed and make introductions to other potential customers in their network. Our commercial advantage with developing this technology is that we can upsell to existing clients who use SEAB's products. We have had initial discussions with these SEAB customers, and they have shown interest in using the technology.

4.2.2 Partner Interactions and Future Plans

SEaB's university collaborators will remain integral post Phase 2. Following successful trials, they will increase capacity at the site and remain a key partner to connect us with other farms in the UK. We also aim to create partnerships with organisations who will support us in promoting the technology. We will also tap into our existing network of clients.

4.2.3 Increasing Sustainable Biomass Supply

SEaB will look to achieve this by improving the efficiency and implementing cost reductions, increasing profitability. One avenue for increasing efficiency is by implementing an oscillating baffle reactor configuration. This will ensure thorough mixing. SEaB has been in contact with a supplier, and there are plans to conduct laboratory stuides using this solution to see how it compares to other technologies.

4.2.4 Trialling Delivery, Installation, Commissioning and Support Functions

Year 1 following the end of Phase 2, will be dedicated to expanding the production capacity at the university to trial the full potential of the technology. In Year 2, we aim to trial the technology with different types of feed, by establishing a photobioreactor in large sites of existing customers and other types of farms.

5. Environmental Impact

5.1 Inputs and Outputs

According to the proposed implementation model and project requirements, the SEAB Energy anaerobic digester coupled photobioreactor will be situated in a cattle farm or other livestock farm in the UK. The table below shows the modified inputs, processes, and outputs of a farming system with SEaB PBR technology. This can be compared to a farming system without SEaB technology.

Table 5-1: Inputs, processes, and outputs of the SEaB PBR technology implementation in a mixed farming system. Factors shown in grey cells are partially offset/reduced in comparison to current farming systems.

Inputs	Processes	Outputs
Animal feed	Biomass production in PBR	Animal feed (from microalgae)
Water	Dewatering	Grey water
Heating	Livestock digestion of feed (enteric fermentation)	Animal products
Electricity	Field preparation	Bio-fertiliser
	Crop stubble burning (occasional)	Methane emissions from enteric fermentation
	Anaerobic digestion of manure	CO2 emission from CHP
		Nitrous oxide emissions (from soil carbon loss)

In addition to this input/output summary, further evaluation is to be carried out on the methane emissions from cattle who have had their diets replaced or supplemented with microalgae. The nature of the evaluation can be conducted via a literature review or in conjunction with the university collaborators, using their resources. The university have already conducted studies regarding cattle methane emissions hence the desire to utilise their experience in our evaluation.

5.2 Assumptions

- All SEAB equipment has a working life of 20 years.
- The Processing Unit, Digestion Unit and Gas Unit are each contained within a re-used 20-foot shipping container weighing 2,200 kg; the CHP is not.
- Each FB120 Unit contains the following equipment:

  - 1x command module
  - 5 x digester module
  - 1 x gas holder
- Carbon footprints of any short-lived climate pollutants (SLCPs), measured in CO2 equivalent (CO2e), designated as the average CO2e value for the first 20 years of the SLCP release as this is the lifetime of the system

5.3 Environmental Impact Calculation

A PAS2050 analysis was carried out, including the following process steps – raw materials, manufacture, distribution, consumer use and disposal/recycling. This along with a WRATE analysis which has been conducted.

5.4 Summary

SEAB Energy's innovation can drive the reduction of emissions in the agricultural sector and other industries that create organic waste. Through coupling photobioreactors with a SEaB AD system, each site can progress towards being closed loop. The main environmental benefits of the innovation are:-

- Reducing emissions and land contamination from animal waste and thus increasing the biodiversity on site-.
- Producing microalgae in an energy neutral way and returning electricity to the grid once used for the needs of the system. Energy neutrality is a key project requirement to avoid the consumption of untraceable, potentially high carbon producing electricity from the grid-.
- Reduced nitrogen application to soils by replacing manure application and artificial fertiliser that will have downstream effects on eutrophication.-
- The water reclaimed from waste will offset irrigation use-.
- Reduced dependency on fossil fuel- derived chemical fertilisers.-
- Reducing animal feed transportation costs, reliance on unsustainable sources of feed and reducing methane emissions from cattle.

We have assessed the environmental impact with the information we have on hand, and we will re-assess at phase 2. This is the theoretical environmental impact based on the desk study, and once we have a more defined technology description, including manufacturing location, site requirements and raw materials a full life cycle analysis can be conducted for the SEaB photobioreactor technology and its impacts on UK farming systems.

6. Risk register

The potential risks identified for Phase 2 have been categorised into technical, commercial, environmental, and operational. Each section contains risks identified, impact, likelihood, risk rating, mitigation actions, residual risk rating (after mitigation has been applied) and contingency measures that can be implemented.

One of the key risks in every section are detailed below, along with likelihood (L), impact (I), mitigation and residual risk rating (RR):

6.1 Risk Area: Technical

TR1) Failure to source the different technologies and equipment (photobioreactor, belt press filter, etc.) [I=H, L=M]. Mitigation: Contacted several suppliers, procuring from well-established suppliers / manufacturers, Reference site visits to interact with other users of the equipment / technology [RR=L].

6.2 Risk Area: Commercial

CR2) Change in microalgae nutrient feedstock profile from AD process affecting value and consistency of microalgae product making it difficult to target certain markets. [I=H, L=M]. Mitigation: We will run regular sampling to determine consistency of product quality. We will identify and explore several uses / markets where control of microalgae characteristics is less tight. [RR=M].

6.3 Risk Area: Environmental

ER1) Digestate leakage contaminating sewer or ground [I=M, L=M]. Mitigation: Installed low level detectors in the digester. System to alert on potential leakages. [RR=L].

6.4 Risk Area: Operational

OR1) Estimating and/or scheduling errors. [I=M, L=L]. Ensure clarity of project timelines and milestones, hold regular team progress update meetings. Contingency has been built into project timelines in the event of delay. Divide this risk into two: 'cost estimating' and 'scheduling errors'. Apply two approaches of cost estimation and track costs and future costs at the end adjusting where necessary. Include a 10% contingency on cost and scheduling. Keep an eye on schedules and include schedule review as an agenda item in every project team meeting. [RR=L]

7. Quality Plan

7.1 Laboratory Study

The laboratory study will focus on developing a CO2, SOx and NOx fixation system using digestate from SEaB's systems. The studies would be conducted at the bench and pre-pilot scales. The laboratory study and pilot study will be conducted at the universities which have agreed to collaborate with SEaB on this project.

7.2 Action Plan for Process Deviation

An automated issue tracking and resolution system, such as Zendesk, will be utilised to record and monitor deviations during the pilot study.

7.3 Maintenance Plan

A maintenance register has been developed for all major equipment that would be used in both the laboratory study and pilot study under the following headings: maintenance task description, component, failure mode, frequency, existing revision or new, personnel, equipment condition (running, shutdown, partial shutdown, cold shutdown), and estimated time. The maintenance procedures for all equipment would be carried out in accordance with the requirements provided by manufacturers and suppliers of all major equipment to be utilised.

7.4 Key Performance Indicators

The performance indicators have been divided into the following categories: collaboration, laboratory study, technology readiness levels (TRLs), publications, knowledge exchange and dissemination, commercial readiness levels, steps towards commercialisation, suppliers, operation, emission control, energy demand.

Some of the main key performance metrics we have chosen to assess how the innovation proposed under Phase 2 will help increase sustainable biomass feedstock supply in the UK are:

Biomass production per day (kg/day): This metric will help us understand how much we can produce based on the feedstock at the site. It will help us identify the potential of the project when widely commercialised.

Net Income per volume (£/kg): The income per volume will help us understand what types of interventions have made improvements in the profitability, for example different PBRs.

Organic waste processed (kgs in waste): The organic waste processed is a key metric that will help us identify what are the results in the volume of microalgae produced from changes to the amount of feedstock processed

CO2 capture portion of CHP Total (%): The CO2 capture rate is a key metric that will show the improvement in the environmental impact of the technology and the efficiency During the Phase 2 demonstration

8. Project Management and Implementation Plan

8.1 Work Packages

This project SEAB's solution from TRL5 to TRL8 before taking the full solution to market. SEAB's innovative project combines their patented anaerobic digesters, producing heat and electricity to be returned to the grid, with a photobioreactor that will cultivate microalgae for harvesting.

A detailed project plan has been developed, with work packages (WPs), critical paths, dependencies, milestones, duration, and resources. Table 8.1 provide overview of the WPs and duration.

Table 8.1 Summary of project based on work packages and duration

Work Package	Start Date	End Date
Mobilisation Phase	02.05.22	07.09.22
WP1: Set-up and project management	02.05.22	07.03.25
WP2: Site preparation, laboratory studies and pilot design and procurement	02.05.22	07.09.22
WP3: Pilot study 1: Anaerobic digestion and digestate production for laboratory study	08.09.22	05.01.24
WP4: Laboratory tests- batch experiments and pre-pilot studies on three 400L photobioreactors	01.12.22	06.03.24
WP5: Pilot study 2: Anaerobic digestion and carbon sequestration	25.01.24	12.12.24
WP6: Economic/Cost benefit analysis and commercialisation plan	06.03.24	12.12.24
WP7 Environmental benefit analysis	31.10.24	23.01.25
WP8 Certifications	31.10.24	26.02.25

8.2 Project Oversight and Governance

The project has been designed by experts in the field who have a deep understanding of how to develop such a technology and prove it before moving to market. SEAB Energy will establish its rigorous quality control procedures and our data depository will be frequently updated and analysed. The project manager (PM) will manage WP owners to ensure activities are delivered, dependencies managed, and risks mitigated. The PM reports into the PD (project director) who oversees the project. A robust project management methodology will be used, based on PRINCE2 principles to ensure quality, with responsibility assignment matrix in place. Communication plans will ensure timely/effective information sharing. Digital tools (including Slack/Trello) and the use of cloud services for saving documentation will be promoted to encourage effective collaboration. A robust project management methodology will ensure risk is controlled, requiring the register to be updated by all personnel. Risk/mitigation will be a dedicated agenda item in meetings. The PM is responsible for risk management.

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