
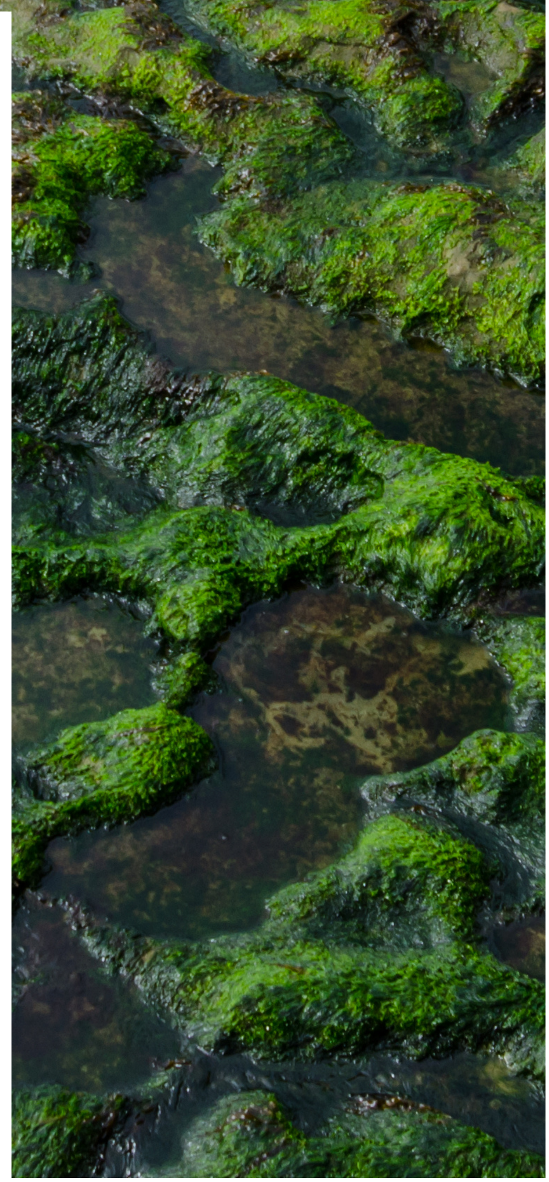

2021 Melbourne Project Center

A ROADMAP TO

Scaling the Algae Industry: A Study of Opportunities in Gippsland, Australia

By: Emily Baker, Kelly Makechnie, Meghan Sailer, and Jonathan Scribner

18 March 2021

A Roadmap to Scaling the Algae Industry: A Study of Opportunities in Gippsland, Australia

An Interactive Qualifying Project submitted to the Faculty of WORCESTER POLYTECHNIC INSTITUTE in partial fulfilment of the requirements for the degree of Bachelor of Science.

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Sponsor Organization:
Snowy River Innovation

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Abstract

Algae is an underutilized renewable feedstock due to major commercial barriers. Our project goals were to characterize the current global industry and develop a location assessment methodology for algae production, which was guided by interviews and peer-reviewed reports. Political acceptability, water accessibility, and land usage were identified as critical success factors. The assessment methodology was applied to Gippsland, Australia. Conclusively, algae operations can be financially feasible by pairing high-value and low-value products and/or using wastewater as a growth medium.

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Stakeholder engagement across the algae industry was conducted and the Authors would like to acknowledge the contribution of the industry experts who provided input.

The authors would like to acknowledge the Traditional Custodians of the land in the Melbourne region (where the MPC is located): the Bunurong Boon Wurrung and Wurundjeri Woi Wurrung peoples of the Eastern Kulin Nation and pay respect to their Elders past, present and emerging.

Abbreviations

ABO – Algae Biomass Organization
AUD – Australian Dollars
BGA – Blue-Green Algae (Cyanobacteria)
EIC – Energy Innovation Cooperative
GWF – Gippsland Water Factory
HRAP – High Rate Algal Pond
LCA – Life Cycle Assessment
MCDA – Multi-Criteria Decision Analysis
ORP – Open Raceway Pond
PBR – Photobioreactor
RAB – Revolving Algae Biofilm
USD – U.S. Dollars
WPW – Westernport Water

Executive Summary

WHAT IS THIS REPORT ABOUT?

Algae is an exceptional biofuel feedstock as it can commercially produce high-value coproducts while contributing to a circular economy. Common algae products include biofuels, animal feed, human food, fertilizer, cosmeceuticals, nutraceuticals, and pharmaceuticals. A beneficial characteristic of algae is that as a photosynthetic organism, it absorbs carbon dioxide and releases oxygen. This means that during biomass production, algae serves as a valuable carbon drawdown tool.

Growing and harvesting algae has been achieved in freshwater, saltwater, and wastewater. In addition, algae can thrive in both open and enclosed systems, but carbon drawdown is more significant when algae is grown outside in an open body of water. The type of growth medium and production system determines which products would be most financially and legally viable.

Growing and harvesting algae has been thoroughly researched and demonstrated, but there are major gaps between production and commercialization. Algae as a source for fuel has been researched since the late 1930's. However, due to high algae production capital costs and low oil prices, algae biofuels are currently a financially unsustainable pathway. Thus, more profitable non-fuel algae products must be produced alongside the biofuel to subsidize production costs. For example, fertilizer and animal feed can be developed simultaneously with the algae biofuel. Considerations in the extraction and processing steps must be made to ensure that as much of the biomass is utilized as possible. This will not only save costs but also minimize waste and environmental impacts. This report seeks to contribute to the promising, yet complicated study of algae by developing location selection criteria and focusing on possible pathways for commercializing algae non-fuel products.

INTENDED AUDIENCE

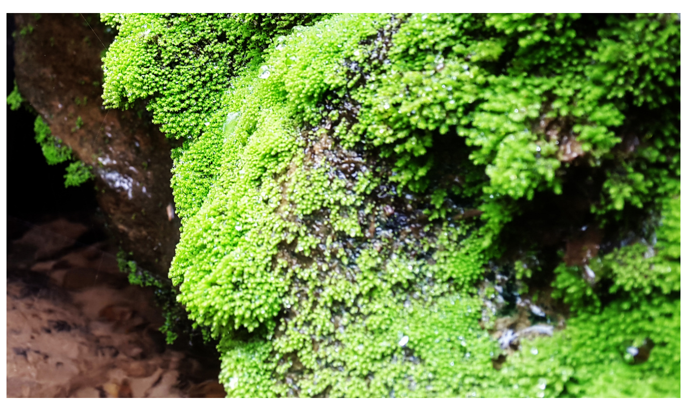
This report was developed for Snowy River Innovation, a consulting group interested in bringing sustainable initiatives to rural-regional Australia. The report provides an overview of the algae industry and an introduction to an algae location selection methodology for a range of interested parties. Developers, investors, and planning professionals may be interested in the methodology, as it can be applied to any location. The methodology created in this report can serve as a foundation for future related research. This research could include a feasibility analysis of integrating algae cultivation and wastewater treatment or a viability assessment of growing and marketing specific algae coproducts in a region.

KEY OBJECTIVES

The aim of this report is to identify commercial opportunities for algae and to develop and apply a location selection tool for industrial algae production.

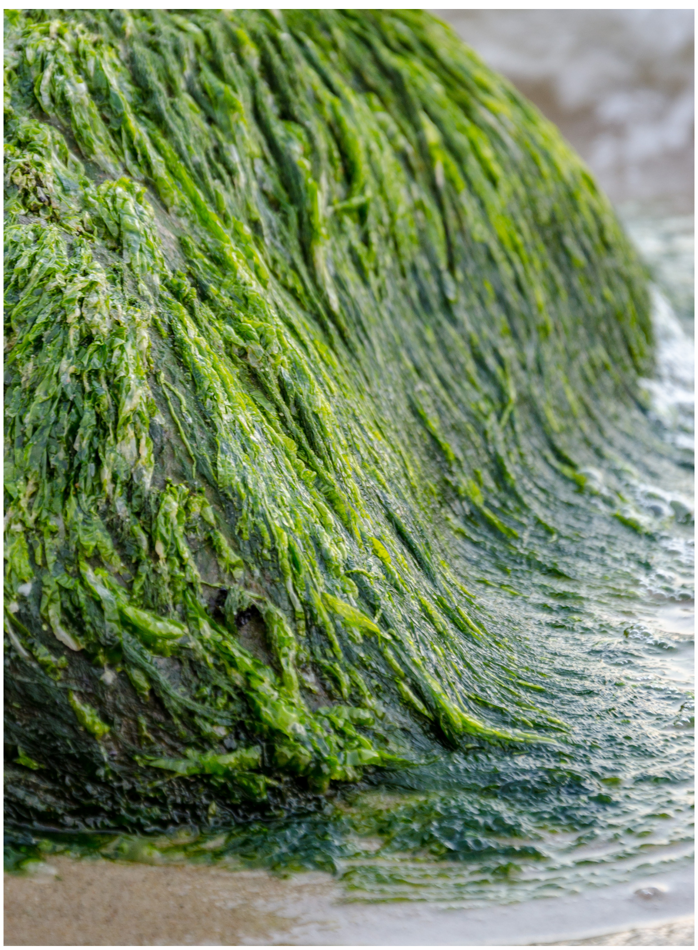
The key objectives are to:

1. **Characterize the current state of the algae industry**
2. **Design a methodology to assess the potential for an algae project location**
3. **Apply the methodology in a notional study in Gippsland, Victoria, Australia**



METHODS

1. Extensive research of peer-reviewed literature on algae growth conditions and production systems, including techno-economic and life cycle analyses.
2. Six semi-structured interviews were conducted with industry professionals worldwide to identify industry gaps and barriers as well as opportunities.
3. Data collection through desktop research and interviews.
4. Creation of a general location selection multi-criteria decision analysis (MCDA) methodology for algae production.
5. Application of the location selection methodology for two locations in Gippsland, Australia using academic and government sources.



WHY AUSTRALIA? WHY GIPPSLAND?

Gippsland, Australia was initially selected as a region of interest due to the sponsor of this project, Snowy River Innovation, being headquartered nearby. Gippsland has a high potential for the acceptance and success of several algae applications. There is public and government action to establish a diverse and low carbon economy, since currently the Latrobe Valley region has been generating electricity from brown coal, which is expected to stop over the next 20-30 years. The first of four brown coal generators closed unexpectedly in 2017 as it was commercially unsustainable. Across Gippsland there is both State and Federal government policy and financial support for industry expansion activities that comply with environmental objectives and plans. There has been considerable government encouragement for the industry and community to engage and invest in clean technologies, particularly in renewable energy.

In addition to an environmentally progressive mindset within the community and local government, Gippsland offers environmental and commercial conditions suitable for industrial algae operations. The region's abundance of available flat land and temperate climate support conditions needed to grow algae productively.

Gippsland's proximity to Melbourne provides a large market and population base for algae coproducts, and also an established network for electricity, road, and railways. The two regions of interest within Gippsland that were compared using the MCDA tool were Latrobe Valley and Bass Coast Shire.

KEY FINDINGS

- Algae biofuels are not commercially competitive on their own due to the high production costs of algae biofuel operations and low traditional oil costs.
- Government funding and a shift in renewable energy policies are required to enable and incentivize an algae biofuels market.
- High capital costs can be overcome by coupling the production with low-value and high-value products or by utilizing wastewater as a growth medium. This is also a means to maximize algae usage and become more aligned with circular economy ideals.
- Open pond systems are best suited for low-value, high-volume products. Photobioreactor systems are best suited for high-value, low-volume products.
- A globally applicable MCDA location selection methodology provides a useful tool to assess the potential for algae in a location, but it involves several assumptions and limitations.
- Project opportunity for a given location can be assessed through political acceptability, water accessibility, and land usage.
- The town of Morwell in Latrobe Valley and the town of Wonthaggi in Bass Coast Shire have a high commercial potential for algae operations in their respective regions.
- Wastewater treatment paired with algae biomass production of low-value products in an open pond system has high potential in Latrobe Valley and Bass Coast Shire. Producing algae animal feed for Latrobe Valley and algae biofertilizer for Bass Coast Shire align best with the local environmental needs and goals.

Algae couples sustainability and economic opportunity in a way that could address climate change and also provide green energy employment. Gippsland's focus on transitioning to sustainable initiatives for energy, food, and agricultural practices indicate that there are many investment opportunities for stakeholders. Algae fertilizer and animal feed are of relevance because there are many farms and crops grown within Gippsland.

A secondary income stream for algae that is relevant to both Gippsland and other areas is algae-based bioremediation. Algae bioremediation is a symbiotic partnership for both the algae company and regional water authority, as the algae company has a cost-effective way to grow biomass and the regional water authority gets a fast, sustainable, and low-surface area treatment option. Both parties would need to agree on if the priority of the partnership were to treat the wastewater or to produce algae biomass. This roadmap suggests a potential partnership with the wastewater treatment authorities of Gippsland to cultivate algae for biofuel use, wastewater treatment, and coproduct creation.

To reduce greenhouse gas emissions and support local job creation, a fund was established by the Victorian Government for Gippsland in late 2020 to incentivize renewable energy projects with the aim of reducing greenhouse gas emissions. Companies interested in algae biofuels would qualify to apply for this fund to support their business endeavors.

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Introduction

A surge in human population, commercial endeavors, and industrial endeavors has increased energy consumption around the world within the last century (Figure 1). Although there is energy available for the immediate future, the world's accelerated energy consumption can only lead to the day that the demand for energy outpaces supply.

This energy consumption is accompanied by anthropomorphic climate change. Energy sources release greenhouse gases, which block heat from escaping the atmosphere. This heat is then absorbed by the land and oceans, which raises the temperature of the Earth over time.

Global Primary Energy Consumption by Source

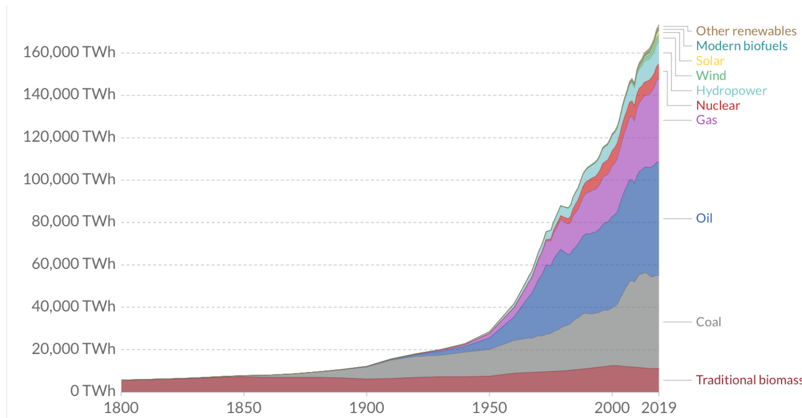


Figure 1: The world's energy consumption is growing at an increasing rate.
Source: (Ritchie, n.d.)

Atomospheric Carbon Dioxide and Earth's Surface Temerature, 1880-2019

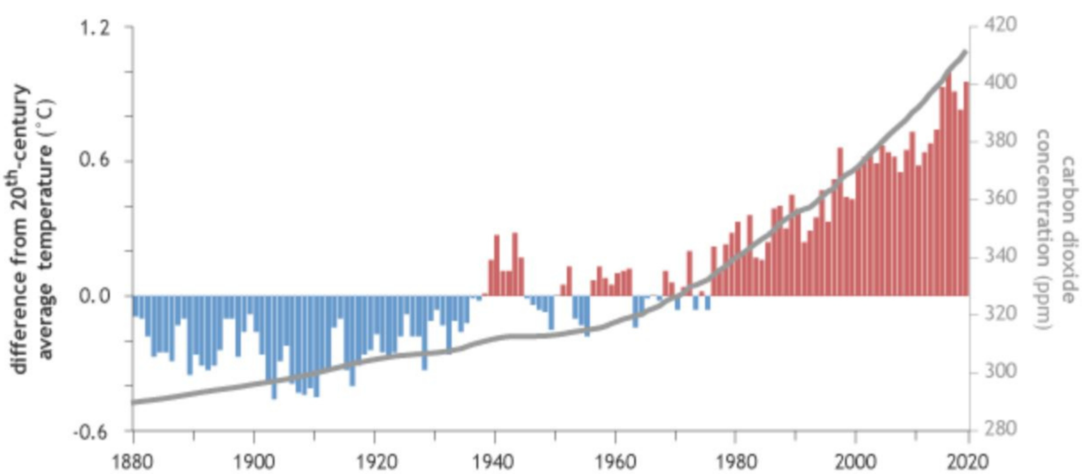


Figure 2: Since 1850, the average temperature of the Earth has risen 1.1 °C. The trend line indicates that the average temperature has risen nearly 0.8 °C since 1980. **Source:** (Lindsey, 2020)

Since 1850, it is estimated that the Earth has experienced an average temperature increase of 1.1 °C. Historical data estimates that 0.8°C of the 1.1°C change occurred within the last four decades (Ritchie and Roser, 2017). Although an increase of 1.1 °C over almost 200 years may seem negligible, the resulting implications are not. High carbon dioxide levels are destroying the Earth's ecosystems by polluting the air, water, and soils. In addition, the number of extreme weather conditions and events are increasing.

In Australia, anthropomorphic climate change has increased the frequency and severity of wildfires (Van Oldenborh et al., 2020). According to the United States Environmental Protection Agency, tropical storm activity has increased over the last two decades due to warmer ocean temperatures (United States Environmental protection Agency, 2020). Other weather events, such as flooding and extreme high and low temperatures have become more common in the United States over the most recent decades.

IMPORTANCE OF ALGAE

The fight against greenhouse gas emissions will require a sustainable and multi-faceted solution. Solar, wind, and other forms of renewable energy will need to be integrated together to provide power to the world. Algae is a source of bioenergy and has the potential to play a considerable role in providing for the world's renewable energy needs.

"I think that algae are part of the solution, it cannot be the solution, but it's part of it."
Catherine Legrand, Algoland Project & Marine Ecology Professor at Linnaeus University

The technology and science to produce and synthesize algae biofuels is well-established, but biofuels are not yet cost-competitive with traditional fossil energy sources. Many companies involved with algae biofuels in the United States, Europe, India, and Asia have failed to compete at a commercial level (Khan, 2018). Algae biofuels use the energy stored in the algae's lipids, which are composed of fats and oils. However, algae is also rich in carbohydrates, vitamins, and minerals, and these are currently being used to create more profitable and commercially competitive products like vitamins.

A novel idea to enable biofuel production is to develop other algae products alongside algae biofuels.
Source: (Gnansounou and Kenthora-Raman, 2016)

Algae products have the potential to support circular economies around the world.
Source: (Algal Biofuels: Long-Term Energy Benefits Drive U.S. Research, 2013).

A circular economy model is an alternative approach to the linear economy model, which has dominated the economies of most, if not all, countries (Figure 3). A product in a linear economy follows the "take-make-dispose" framework, which continually creates waste and the need for more natural resources. The goal of a circular economy is to reuse and extend the life of a product by repairing or re-manufacturing the product in order to close the industrial ecosystem loop (Alamerew et al., 1970). This places an emphasis on preserving products instead of creating new ones. The circular economy has the potential to support algae and algae products. Algae biofuel coproducts fit together to create a sustainable, closed-loop pathway.

Economic Structure: Circular vs. Linear

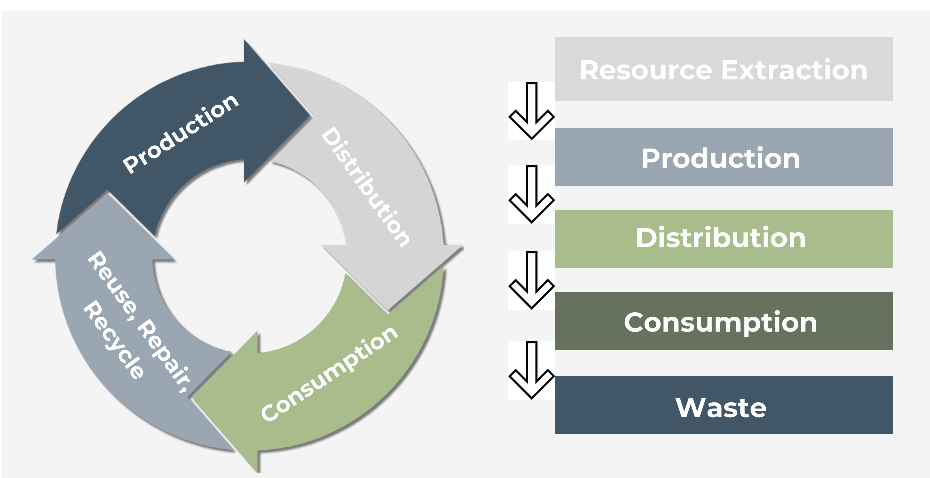


Figure 3: Circular economy model (left) vs. linear economy model (right). Circular economies provide a sustainable alternative to linear economies.

History of Algae Research

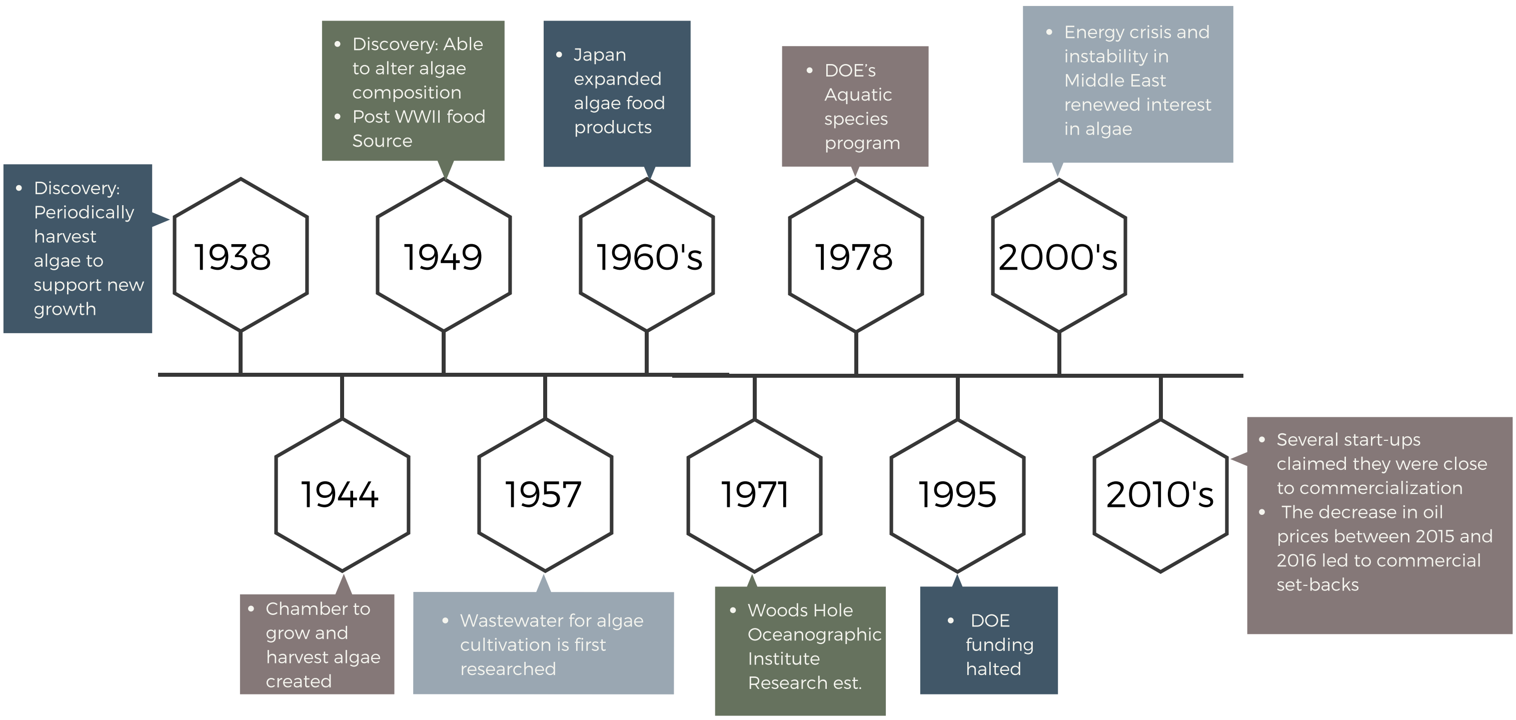


Figure 4: Algae research began in 1938, when Researchers Ketchum and Redfield discovered that periodically harvesting algae stimulated new growth. Since then, many academic and commercial entities have invested in algae research for its potential as a biofuel.
Source: (Office of Fuels Development, 1998)

Research into algae as an energy and food source began following World War II. Algae was selected for its high lipid content, which could be extracted and processed into usable fuel. In the 1970's, interest in algae research continued in the wake of the 1973 oil embargo and 1979 oil shock. In 1978, the U.S. Department of Energy established the Aquatic Species Program, which was tasked with researching algae for biofuel development. Algae strains were collected and cataloged throughout the United States (Figure 5). Although this initiative was successful, algae biofuels were abandoned as oil prices in the 1990's plummeted. In the present day, algae biofuels still face this same issue (Office of Fuels Development et al., 1998).

Microalgae Collection Locations within the Continental U.S. in the 1980s

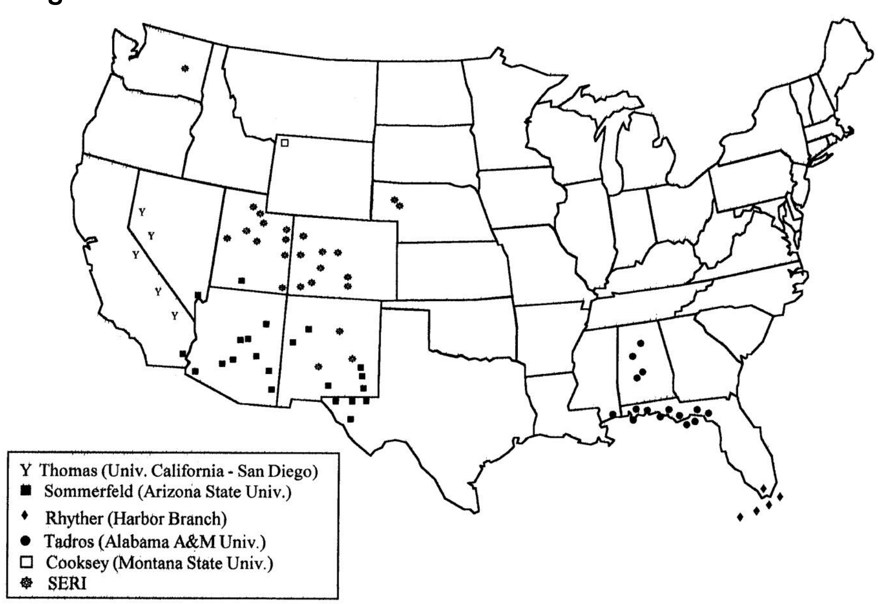


Figure 5: In the 1980s, approximately 3,000 different microalgae strains were collected across the continental United States. These algae strains were analyzed for lipid content in order to develop algae biofuels.
Source: (Office of Fuels Development, 1998)

NUTRIENTS IN ALGAE

It is well researched and documented that algae contains a myriad of bioactive compounds. Bioactive compounds are any molecules that encourage physical health. The documented bioactive compounds in algae are: carotenoids, chlorophyll, polysaccharides, polyunsaturated fatty acids, astaxanthin, antioxidants, vitamin A, B1, B2, B6, B12, C, E, potassium, iron, magnesium, calcium, and iodine. These compounds cover various therapeutic properties, including anti-cancer, anti-inflammatory, anti-diabetic, and antibacterial abilities, among others (Wells et al., 2017).

Table 1: Nutrients Found in Algae

BIOACTIVE COMPOUND	CLASSIFICATION	WHY IS IT GOOD FOR HUMANS?
Carotenoids	Antioxidant	Beneficial antioxidants that can protect you from disease and support your immune system
Chlorophyll	Pigment	May be helpful for skin conditions, body odors, and fighting certain kinds of cancer
Polysaccharides	Carbohydrate	Source of energy
Polyunsaturated Fatty Acids	Fat	Can help lower your LDL (bad) cholesterol, important for nerve function, blood clotting, brain health, and muscle strength
Astaxanthin	Keto-carotenoid	One of the most important vitamins when it comes to supporting the immune system, and can also reduce inflammation
Antioxidants	Compounds that inhibit oxidation	Absorbs free-radicals, which can damage cells
Vitamin A	A group of fat-soluble retinoids	Important for immune function, vision, reproduction, and cellular communication
Vitamin B1	Vitamin	Essential for glucose metabolism and it plays a key role in nerve, muscle, and heart function
Vitamin B2	Vitamin	Helps break down proteins, fats, and carbohydrates. It plays a vital role in maintaining the body's energy supply
Vitamin B6	Vitamin	Prevents and treats low levels of pyridoxine and anemia. It is also used for heart disease, premenstrual syndrome (PMS), depression, and many other conditions
Vitamin B12	Cobalamin, vitamin	Helps keep the body's nerve and blood cells healthy and helps make DNA. Vitamin B12 also helps prevent a type of anemia called megaloblastic anemia that makes people tired and weak
Vitamin C	Vitamins, Water-Soluble	Supports the growth, development, and repair of all body tissues, formation of collagen, absorption of iron, the proper functioning of the immune system, wound healing, and the maintenance of cartilage, bones, and teeth
Vitamin E	Fat soluble compound	Helps to protect cells from the damage caused by free radicals
Potassium	Mineral	Regulates fluid balance, muscle contractions and nerve signals
Iron	Mineral	Helps make hemoglobin and myoglobin
Magnesium	Alkaline earth metal	Maintains normal nerve and muscle function, supports a healthy immune system, keeps the heartbeat steady, and helps bones remain strong
Calcium	Alkaline earth elements	Calcium is important for bone and teeth structure
Iodine	Mineral	The body uses iodine to make thyroid hormones

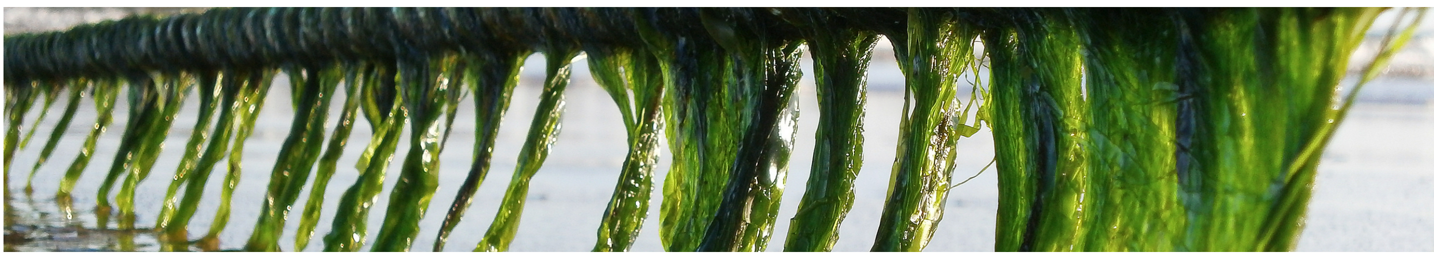
Sources: (Wells et al., 2017) and (Peñalver et al., 2020)

ALGAE COPRODUCTS

Algae species can be divided into two main categories: microalgae and macroalgae. Microalgae are unicellular microscopic algae best grown onshore, and macroalgae are seaweeds, kelps, and red algae best grown offshore. Generally, microalgae are used for more specialized products like cosmeceuticals, while macroalgae are best suited for base commodity products like fuels or feed (Federal activities report on the bioeconomy: algae, n.d.). There are also opportunities for algae-derived compounds to be utilized in pharmaceuticals, cosmeceuticals, nutraceuticals, human food, animal feed, and fertilizer. These non-fuel products have the potential to support the algae biofuel industry in the present day, as algae biofuels are not cost-competitive with traditional non-renewable fuel sources.

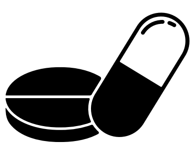
"The capacity of microalgae in producing various high-value by-products with wide application in medicine, food and cosmetic industries can significantly improve the prospects of algal biofuel production...These can provide a catalyst for the development of large-scale biofuel technologies that will not compete for land or freshwater resources."

Source: (Jingjing Li et al., 2015)

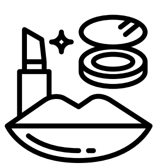


MICROALGAE CO-PROUCTS

Pharmaceuticals



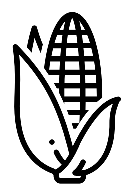
Cosmeceuticals



Nutraceuticals

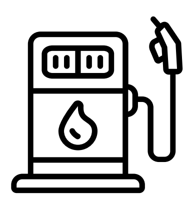
MACROALGAE CO-PROUCTS

Food, and Animal Feed



Fertilizer

Fuel



Pharmaceuticals

Pharmaceuticals are traditional medicines that are proven to be safe and effective. Algae's proven medicinal properties include antiviral and antioxidant traits. For example, research in brown algae yielded that some of its compounds inhibit viruses, which led to advances in antiviral chemotherapy. Vaccines for HIV, HBV, and HPV derived from algae compounds have been explored. A second potential application for algae is in antioxidants, such as marine polyphenols, which are able to prevent oxidative damage by free radicals. Free radicals are concerning as they can inflict DNA damage that leads to cancer (Aditya et al., 2016).

Presently, there is only one algae-derived pharmaceutical that has progressed to clinical trials, called GV-971. The dearth of algae pharmaceuticals is not because algae lack clinical relevance, but because of financial and regulatory reasons. Pharmaceuticals are highly profitable, but they require years of research and development, lots of capital, rigorous quality control, standards testing, and skilled individuals with highly technical knowledge (PR Newswire, 2020). A pharmaceutical derived from algae is conceivably possible, but should not be attempted by a company without knowing the full extent of the scientific and regulatory requirements.

GV-971

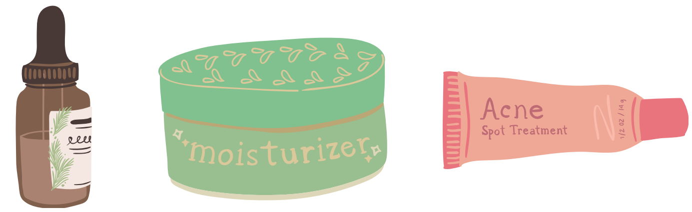
GV-971, developed by Green Valley Pharmaceuticals based in Shanghai, was formulated as a treatment for patients with Alzheimer's. One of its ingredients, sodium oligomannate, is made from marine brown algae. GV-971 works to treat Alzheimer's by changing the gut microbiome and reducing inflammation. Green Valley received New Drug Approval from China's National Medicinal Products Administration in late 2019. In April 2020, the United States Food and Drug Administration granted Green Valley approval for its Investigational New Drug Application, allowing Green Valley to conduct Phase III clinical studies through 2024 (Staff, 2020).

Marine Brown Algae

Figure 6: GV-71 is derived from marine brown algae, pictured above.
Source: (Turnbull, 2020)

Cosmeceuticals

Cosmeceuticals describe cosmetic products that purportedly have a medicinal benefit. Potential benefits a consumer could observe from algae-derived cosmetic compounds include under-eye correction and face-wrinkle reversal (Senevirathe and Skim, 2014). Oftentimes, these products are in the form of a cream or lotion. One company, Algenist, utilizes an algae-derived compound as its standout ingredient. Algenist alleges that their patented Alguronic Acid has a myriad of anti-aging skincare benefits (Thiyagarasaiyar et al., 2020).



The natural cosmetics market is growing, and algae-derived compounds could start to appear in many cosmetic products.

It is estimated that the natural cosmetics industry will grow from 34.5 billion USD in 2018 to almost 54.5 billion USD by 2027.

Source: (Thiyagarasaiyar et al., 2020)

Table 2: Examples of Algae Cosmeceutical Products

COMPANY	PRODUCT	ALGAE TYPE	BENEFITS
Algenist	BLUE ALGAE VITAMIN C Dark Spot Correcting Peel	Spirulina, a genus of blue-green algae	Visibly reduces the appearance of dark spots and discoloration, smooths texture
	GENIUS Collagen Calming Relief	Alguronic Acid® - a nourishing microalgae oil	Combats dryness and the look of redness, restores skin bounce & resilience
	GENIUS Ultimate Anti-Aging Cream	Alguronic Acid® - a nourishing microalgae oil	Combats line and wrinkles to visibly firm, smooth, brighten, hydrate, and nourish skin
OSEA	Undaria Algae Body Oil	Undaria Algae®	Lightweight, age defying, energizing, smoothing
	Red Algae Mask	Gigartina seaweed, or red marine algae	Cleanses, de-congests, and minimizes the look of pores
Skyn Iceland	Berry Lip Fix With Wintered Red Algae	Red algae	Repairs and hydrates lips
Chantecaille	Faux Cils Mascara	Red seaweed extract	Keeps lashes soft and elastic

Sources: (Thiyagarasaiyar et al., 2020)

Neutraceuticals, Food, and Animal Feed

Algae Nutraceuticals and Human Food

Nutraceuticals are essentially food with nutritional benefits. Nutraceuticals can be used to improve health, delay the aging process, prevent chronic diseases, increase life expectancy, or support bodily functions. Algae nutraceuticals and food have virtually limitless applications to human diets, including pasta, chips, smoothies, chocolate bars, protein powder, food coloring agents, and organic supplements like tablets, capsules, and pastes. Interest in algae-derived nutraceuticals has been catalyzed by consumer interest in sustainable and organic foods. Lower nutrient intakes stemming from busy lifestyles and steady diets of fast foods has heightened the need for nutraceuticals. Algae's high protein content is of the most interest in the human food market, as millennials are craving protein-rich products to build muscle quickly. The protein content of spirulina (genus of blue-green algae (BGA)) and chlorella (genus of green algae) are, respectively, 50%-70% of its dry weight and 50-60% of its dry weight. The abundance of algae protein can be understood when compared to the protein content of beef, which is 17.4% (Grand View Research, 2019). Vitamin A and Omega-3 and Omega-6 algae supplements are also an area of interest, as algae contains many bioactive molecules. Most of the algae grown for human consumption is harvested in freshwater.

Table 3: Examples of Algae Nutraceutical Products

COMPANY	PRODUCT	ALGAE TYPE	BENEFITS
Cyanotech Corp.	Hawaiian Spirulina	Blue-green algae	Health for the immune system, eyes, brain, cardiovascular system, and cells
	Cyanotech BioAstin, Hawaiian Astaxanthin	Microalgae	Powerful antioxidant, health for joints, tendons, skin, eyes, brain, cardiovascular system, and cells, recovery from exercise
Earthrise Nutritionals	Spirulina Natural	Blue-green algae	Antioxidants, brain health, cardiovascular health, cellular health, eye health, immune support
Nested Naturals	Super Algae	Spirulina and chlorella	Aids in healthy detoxification and helps maintain a healthy immune system

Sources: (Cyanotech Corporation, 2021) and (Earthrise, 2021) and (Nested Naturals Inc, 2021)

It is estimated that the global market size of supplements is worth upwards of 120 billion USD, with the potential to grow to 349 billion USD by 2026 as health-conscious consumers search for solutions to take their health into their hands.

Source: (Grand View Resarch, 2019)

North America is currently dominating the algae food supplement market (Grand View Research, 2019). Unlike pharmaceuticals, supplements do not require FDA-approval before they are marketed. However, the FDA does review and label certain food-additive ingredients as "Generally Recognized As Safe" (GRAS) (Center for Food Safety and Applied Nutrition, 2019). Depending on the supplement classification, ingredients, and marketing, GRAS designation might be necessary for an algae supplement. At least five algae species have already received GRAS designation. In Australia, supplement manufacturers do not require approval from the Therapeutic Goods Administration (TGA), but their supplement can only contain pre-approved ingredients.

Algae Animal Feed

Protein scarcity in animal feed has been exacerbated due to reduced land fertility and increased dependency on the existing land caused by expanding population. Therefore, environmentally sustainable and low cost alternative sources of protein such as algae have been generating significant traction in the animal feed sector. Algae animal feed products are mainly being incorporated by poultry, aquatic, pet, and cow feed manufacturing companies, owing to algae's rich protein and amino acid content (Grand View Research, 2019). A particular area of interest is replacing cattle consumption of soybeans with marine algae (seaweed). Several studies have revealed that marine algae helps cattle digest more efficiently, which in turn drops methane production from gut microbes and increases milk production. Methane emissions from cattle alone account for 4-5% of global greenhouse gas emissions (Madeira et al., 2017).

By replacing 2% of soy livestock feed with algae, the world could see an 8% decrease in nitrogen losses (soy consumes a lot of nitrogen), a 7% reduction in greenhouse gas emissions, and a 6% increase in available cropland. Preliminary research has indicated that adding a small amount of algae to cattle feed can reduce methane emissions by as much as 99% .

Source: (Nosowitz, 2019)

Table 4: Examples of Algae Animal Feed Products

COMPANY	PRODUCT	ALGAE TYPE	BENEFITS
Algea	AlgeaFeed	Ascophyllum nodosum, a brown algae	Fiber, minerals, and "sea-oligo" elements
Cellana Inc.	ReNew Feed	Marine microalgae native to Hawaii, not specified	Source of protein and Omega-3
AlgaPrime	AlgaPrime DHA	Marine microalgae, not specified	Source of Omega-3

Sources: (Algae, 2021), (Cellana, 2018), and (Corbion, 2020)

The algae animal feed market is projected to grow by 1.13 billion USD during 2020-2024, progressing at a CAGR of over 8% during the forecast period.
Source: (Business Wire, 2020)

The aquafeed market is gaining the most traction in Europe, mainly due to the expansion of marine aquaculture in countries such as Norway, Denmark, and Ireland. There are several algae companies around the world that are shifting towards animal feed, including Algae.Tec. Algae.Tec is an Australian algae company that shifted its efforts away from biofuels to animal feed in 2017. In its FeedMe product range, the most promising product is an algae powder for large fish farms. Another company is Cellana Inc., a Hawaii and San Diego-based algae coproducts developer that has recently begun a ReNew Feed program that works with cattle, chicken, and fish feed (Einstein-Curtis, 2017).

Fertilizer

An example of a non-consumable algae coproduct is fertilizer. The target markets for biofertilizers are the Asian Pacific and Africa, as these regions are the largest consumers of fertilizers. In addition, the Asian Pacific needs immediate sustainable solutions due to the rising population and severe pollution in the region. North America is also expected to see a large jump in the biofertilizer market due to national bans on harmful chemicals and certain fertilizers (Singh et al., 2019).

Due to the growth in the organic food industry, the global biofertilizer market is estimated to be valued at 2.3 billion USD in 2020 and is projected to reach 3.9 billion USD by 2025.

Source: (ReportLinker, 2020)

Traditional chemical fertilizers use lots of fresh water, do not replenish the soil's nutrients long term, and have nitrogen and phosphorus runoff which pollutes nearby waters and can create ocean dead zones. Algae biofertilizer has been proven to be a solution, as shown in a study in India with cyanobacteria, or blue-green algae (BGA). In this study, BGA was applied to paddy fields and the results showed that crop yields increased and cultivation cost per acre decreased, thus farmer income increased (Bhooshan, 2018).

Table 5: Examples of Algae Fertilizer Products

COMPANY	PRODUCT	ALGAE TYPE	BENEFITS
TrueAlgae	TrueSolum	Chlorella	Has metabolites to stimulate soil microrganisms
Ficosterra	cystium-k	Macrocysis pyrifera, a large brown algae (kelp)	Supports soil microbes
Pacific Biotechnologies	PlantJuice	Macroalgae	Growth promoting hormones

Sources: (TrueAlgae, 2021), (Ficosterra, 2021), and (Pacific Biotechnologies, 2021)

The major barriers for algae biofertilizers are: the ease of use of chemical fertilizers, lack of farmer awareness, relatively short period of shelf life, specific conditions required for storage, and limited seasonal effectiveness (biofertilizer needs warmth and moisture). In terms of Australian regulation, fertilizer sales are regulated by State Governments. The National Code of Practice for Description and Labelling of Fertilizer lists the maximum permissible concentration (MPC) for impurities and details the other information that should be included on labels. For biofertilizer specifically, imported biological agents require a permit from the Department of Agriculture, Water, and the Environment (DAWE) before they can be brought into Australia (Maurya et al., 2016).

ALGAE GROWTH CONDITIONS AND PRODUCTION SYSTEMS

General Growth Conditions

As a photosynthetic organism, algae requires sunlight, or solar insolation, to grow. Solar insolation describes the amount of solar radiation an area is exposed to and is dependent on factors like altitude and angle of incidence. Generally, algae needs 8 hours of sunlight per day and warm temperatures to be productive (S.P. Singh and P. Singh, 2015). Different algae species and strains have different ideal climate conditions, but one study identified that an average annual temperature of 29.2 °C and solar insolation of 14.5 MJ/m^2/d was ideal for microalgae growth (Schade and Meire, 2019). Increased heat does not always correlate with increased productivity, and too much heat can even kill the algae. The relationship between temperature and the growth rates of several microalgae species is illustrated in Figure 7:

Temperature Effect on Microalgae Growth Rates

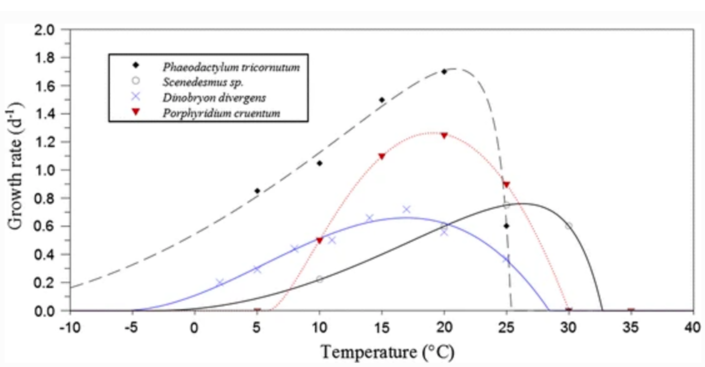


Figure 7: Very high temperatures decrease algae growth rates and eventually kill the algae. **Source:** (Ras, et al., 2013)

It should be noted from the figure above that while productivity drops at freezing temperature (0 °C), some algae species don't die. Many laboratory studies have concluded that consistent climate conditions are best for productivity, but several field studies have revealed that this may not entirely be the case. This can be seen with the concept of diurnal shift, which is the difference between the average daytime high temperature and the average nighttime low temperature. The Algoland project, created by researchers at Linnaeus University in Sweden, found that diurnal shifts could be effective for producing lipids for biofuels:

> **“Cold night[s] during warm days is actually systematically leading to higher lipids.”**
>
> Catherine Legrand, Algoland Project & Marine Ecology Professor at Linnaeus University

Unlike other sources of biomass, a unique quality of algae is that it thrives in aquatic environments. It can propagate in salt, brackish, fresh, or wastewater as long as a pH of 7.5-9.0 is maintained. This pH range can be narrowed down to maximize productivity once a specific algae strain and species are selected. Each algae type also has differing requirements for various nutrients, the most important being nitrogen, carbon, and phosphorus. Depending on the water source, these nutrients may have to be injected into the algae growth container. During photosynthesis, algae absorbs the carbon in the water and the carbon dioxide in the air and converts them into oxygen. Because algae consumes carbon and low carbon levels correlate to high pH levels, constant water recycling is needed to keep the pH low and in the ideal growth range (Weyer et al., 2009).

> **“To grow tons of algae there needs to be a lot of water because water contains carbon, which is one of the main elements to grow algae"**
>
> Nicholas Neveux, Research and Development Manager at Pacific Biotechnologies

Onshore vs. Offshore

Algae can be grown on land (onshore), in bays and harbors (nearshore), or in the deep sea (offshore). Microalgae are best grown onshore and macroalgae (seaweeds, kelps, and red algae) are best grown nearshore or offshore (Federal activities report on the bioeconomy: algae, n.d.). Onshore algae production has been heavily researched and there are many commercially successful industrial operations. While there are several promising designs, current offshore algae operations have not been tested at an industrial scale. In the past, the DOE (1970's) and NASA (2008) researched and designed offshore algae farms, but these designs were not constructed or deployed at a large scale. Additionally, there are initiatives in the Netherlands to grow seaweed in the North Sea, but their designs are still in the planning phase (Dijkstra et al., 2016). Current infrastructure consists of floating structures that either drift in the current or are anchored. The financial feasibility models and yields of industrial offshore algae cultivation are theoretical (Roesijadi et al., 2011). Onshore and offshore operations have unique benefits and drawbacks, and these are illustrated below.

Table 6: Onshore Benefits and Drawbacks

BENEFITS	DRAWBACKS
• Wide array of applications • Plentiful research on growth, harvesting, and extraction methods • Growth environments can be controlled year round in greenhouses and PBR's • Location access to the energy grid • Current and previous commercial operations ease investor's doubts • Established high-value product markets	• Freshwater operations stress water supplies • Competition for large areas of flat and inexpensive land • Struggle to meet energy efficiency requirements • Production rates are reliant on large amounts of phosphorus as fertilizer

Sources: (Schlarb-Ridley and Parker, 2013), (Hannon, 2010), (Renganathan et al., 2014), (Water management policy and legislation, 2019), (Davis, 2019)

Table 7: Offshore Benefits and Drawbacks

BENEFITS	DRAWBACKS
• Decreases ocean acidification • Restoration of marine ecosystems (reversing coral bleaching) • The ocean is the world's largest CO2 drawdown tool • No shortage of area for industrial operations • Ability to grow at lower sea levels • Use of macroalgal seaweeds for animal and human feed	• No current industrial infrastructure • All financials are theoretical estimates • Limited location access • Production is strongly governed by seasons • Unpredictable growth environment • Strict and nonunified marine permaculture regulation pathways • Risk of harming marine biodiversity • Nearly impossible to contain industrial waste • Product streams are less profitable

Sources: (Roesijadi et al., 2011), (Schlarb-Ridley and Parker, 2013), (Fernand et al., 2017), (Economic modelling and life cycle analysis, 2020), (Marine algae, 2019)

Offshore operations have more environmental benefits than onshore, but the lack of environmental and economic impact data makes it difficult to make measured industry assessments. In addition, research into nearshore operations face the same issues. Thus, this report focuses on onshore algae operations.

Open Pond Systems

The open pond system, located onshore, was the first proposed algae cultivation system (Costa, 2019). In the 1980's and 1990's, the U.S. DOE's Aquatic Species Program researched open pond systems to grow algae (Algae Biomass Organization, n.d.). In an open pond system, a shallow (between .2 and .8 meters) raceway or circular pond structure is created to mimic the natural habitat of algae. An open raceway pond (ORP) is advantageous as it allows for easier mixing of algae and nutrients, which prevents sedimentation, ensures consistent biomass, and increases productivity. Because the ponds are so shallow, the algae are subject to hot temperatures during the day and cold temperatures at night, thus water recycling and mixing are of utmost importance. This mixing is performed by paddle wheels. The algae and nutrients are placed in front of the paddlewheel in order to start the movement and are collected at the end of the raceway. Algae companies often choose the open pond system due to its relatively low cost and ease of operation. However, the open pond's exposure to the weather can decrease productivity and result in unpredictable product quality variations. Cloud cover and evaporation could foster conditions in the open pond that are not conducive to algae growth. Further, rainwater could deposit trace contaminants that permeate the algae (Tachoth and Rose, 2016). Due to product quality variations and relative ease of scale-up of open pond systems, they are better suited for low-value, high-volume coproducts that do not require strict monitoring and quality control, such as animal feed and fertilizer.

Open Pond System

Figure 8: This is an open raceway pond (ORP) built for Seambiotic in Israel.
Source: (WIlliams II and Pagan, 2018)

Integration of Wastewater Treatment

Increasing levels of environmental awareness paired with freshwater scarcity have placed a significant focus on sustainable wastewater treatment and water recycling initiatives. Research suggests that an open pond-like system with wastewater as a growth medium would be a sustainable solution to both treat wastewater and produce large quantities of algae biomass. There are three stages in wastewater treatment: primary (solid removal), secondary (bacterial decomposition), and tertiary (extra filtration). Algae can be used in either the secondary or tertiary stages, depending on the strength, or contamination, of the wastewater.

Nitrogen and phosphorous are the two most important nutrients for algae growth, both of which are abundant in wastewater. Thus, these nutrients don't need to be purchased separately and placed into the system. Using wastewater as an algae growth medium eliminates the need for freshwater, which is much more difficult to access and more expensive. In addition, the cost of the energy required for biomass production is covered by the value of the wastewater treatment function of the pond (S.P. Singh and P. Singh, 2015). Despite the advantages of using wastewater as an algae growth medium, there are limitations. One major challenge of algae wastewater treatment is the non-sterile environment associated with the process, which can lead to contamination and algae culture crashes. Another limitation is the lack of pH control, a growth parameter that needs to be kept consistent to ensure productive algae growth. In addition, a robust and dominant species of algae is needed to withstand the harmful contents in the wastewater. Harmful contents can include heavy metals, pathogens, toxic chemicals, oil and grease, sludge, acids and bases, and toxic organic compounds (Mohsenpour, 2021).

Using wastewater for algae growth reduces the coproduct opportunities to high-volume, non-human products due to the low quality of the biomass, the potential contamination of the biomass by pathogens in the wastewater, and the difficulty in maintaining monocultures in an open system (Mohsenpour, 2021). Although non-human products such as fertilizer and animal feed do not command the high market prices of cosmeceuticals or pharmaceuticals, open pond systems utilizing wastewater provide a much less cost-prohibitive production method.

The priorities of the wastewater treatment company and the needs of the community must be considered when pursuing algae as a bioremediation option. For example, wastewater is often produced and treated year-round. Thus, the climate conditions of the location would largely impact if algae could grow and be of service for the whole year. An important question to ask is:

"Are you growing algae just to grow algae, or do you have a duty to treat the wastewater too?”

Nicholas Neveux, Research and Development Manager at Pacific Biotechnologies

The two most common algae wastewater treatment systems are the revolving algae biofilm (RAB) system and the high rate algal pond (HRAP) system. Both systems are advantageous to conventional treatment systems, as they treat water faster using less surface area, resulting in a decrease in construction costs and evaporative water losses. In addition, because they require minimum power and management, operational costs are decreased (Young and Taylor, 2017). The RAB system, used by Gross-Wen Technologies in Iowa, uses vertically oriented conveyor belts that grow algae on their surface and dip into a shallow tank of wastewater (Gross-Wen Technologies, n.d.). Although Gross-Wen Technologies does not turn the leftover biomass into products themselves, it can be used by their customers as a revenue stream for fertilizers, bioplastics, and biofuels. The HRAP system is more heavily researched, has more potential, and has been commercially implemented in several countries. Research on HRAP systems has historically been centered on biofuels, but recently slow-release fertilizers have been an area of focus.

“HRAP-based wastewater treatment is currently the most economical and environmental approach to produce algal biomass for conversion to biofuels.”

Source: (Molazadeh et al., 2019)

The HRAP system is very similar to an ORP system, as it is composed of shallow ponds that are gently mixed around the oval-shaped infrastructure. One key finding of HRAP systems is that recycling the harvested algae biomass back into the system significantly increases biomass productivity, harvestability, energy content, and net biomass energy yield. Another finding is that CO2 addition promotes both nutrient recovery and algal productivity, and consequently energy production (Mehrabadi et al., 2015).

HRAP SYSTEM EXAMPLES

California Pilot Study for Dairy Farms

A pilot-scale HRAP operation was conducted by Quantitative Biosciences Inc. at Van Ommering Dairy farm in Lakeside, California in 2015. Quantitative Biosciences constructed and designed a fully integrated dairy wastewater solution using microalgae. Compared to traditional aeration wastewater treatment systems, this system had much higher effluent water quality and much lower operational costs. Although the technology developed by Quantitative Biosciences has not been commercialized, they are currently working on a "farm of the future" project with Fiscalini Dairy. The "farm of the future" would allow a farm to clean its own water, grow its own animal feed, generate its own electricity and fuel, and produce valuable algae co-products (Cookson, 2015).

Japan ABES R&D Center

The University of Tsukuba began the Algae Biomass and Energy System (ABES) R&D Center in 2015. They use abandoned farmland to develop mass production of fuel and other algae industry products like animal feed. A demonstration project was conducted in Fukushima that used waste heat, CO2, and wastewater in the cultivation process, and optimized the processes of drying, concentration, conversion, as well as the stage of residue recycling (Figure 9). This sustainable demonstration cut algae biofuel production costs by 75% (Herrador, 2016).

Algae Biofuel from Wastewater Demonstration

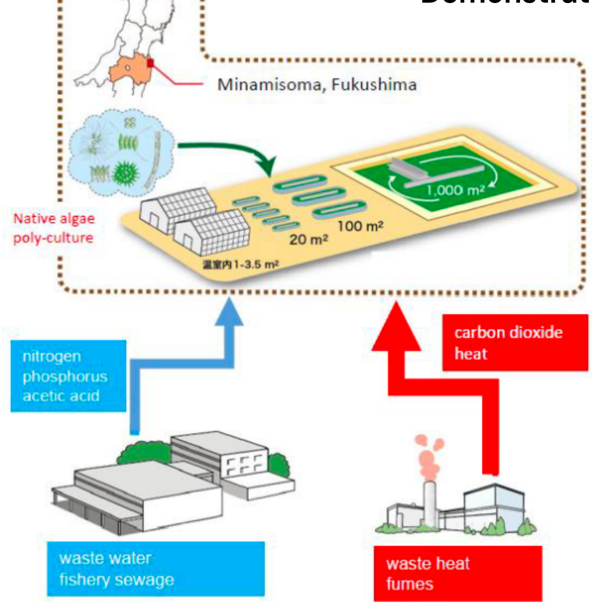


Figure 9: The ABES R&D Center's demonstration project on microalgae fuel production from wastewater in Minamisoma, Fukushima. **Source:** (Herrador, 2016)

European Union's All-Gas Project

In 2010, the European Union (EU) provided funding for a large-scale demonstration of algae biofuels in southern Spain (All-gas, 2017). The third-largest private water company in the world, Aqualia, coordinated with seven companies from six countries to research, construct and evaluate the feasibility of algae grown in wastewater for biofuel and coproduct development. This project is called "All-Gas'.

3.6-hectare HRAP systems were filled with municipal wastewater that had been pre-treated to remove oil, grease, and sand. Various processing phases resulted in end products of biodiesel, biogas, and biofertilizers. The All-Gas project proves that algae cultivation can be successfully integrated with wastewater treatment to create biofuels and coproducts. All-Gas has future plans to construct a 10-hectare facility, create a biomethane extraction pathway, and use thermal energy derived from burning excess algae biomass to generate electricity (All-gas, 2017).

Photobioreactor Systems

The second onshore cultivation system is a photobioreactor (PBR). This is a closed system where a biological reaction occurs due to exposure to light energy. Photobioreactors can be tubular, flat, or a column structure. Different structures might be more appropriate according to the quantity of biomass required (Raes et al., 2013). Photobioreactors are an advantageous container for algae growth as they allow for complete control over the algae's growing environment, unlike in an open pond system. Temperature, pH, carbon dioxide, evaporation of water, and sunlight exposure can all be moderated and monitored in a PBR (Oguchi, 1989).

Although PBR systems allow for more control over algae growth, they have higher capital and energy costs than open pond systems. One cost estimation concludes that a PBR system would account for at least 50% of an algae company's total capital investment (Zhu et al., 2018). In fact, energy inputs can even outweigh energy outputs.

"The energy input for constructing, operating and maintaining multiple photobioreactor units and associated equipment during upscaling could easily result in a negative energy balance." **Source:** (Raes et al., 2013)

In order to subsidize the high production costs and energy requirements of PBR systems, high-value algae coproducts for human consumption and renewable sources of energy are often recommended. Due to regulations, these high-value products would need to be grown in freshwater (Zhu et al., 2018). This type of system might be favorable for pharmaceuticals, nutraceuticals, and cosmeceuticals, as these products are specialized and require rigorous quality control at each step of production.

Photobioreactor System

Figure 10: This is a tubular photobioreactor built for IGV Biotech in Germany.
Source: (IGV Biotech, 2013)

OPEN POND VS. PHOTOBIOREACTOR

Photobioreactor or Open Pond?

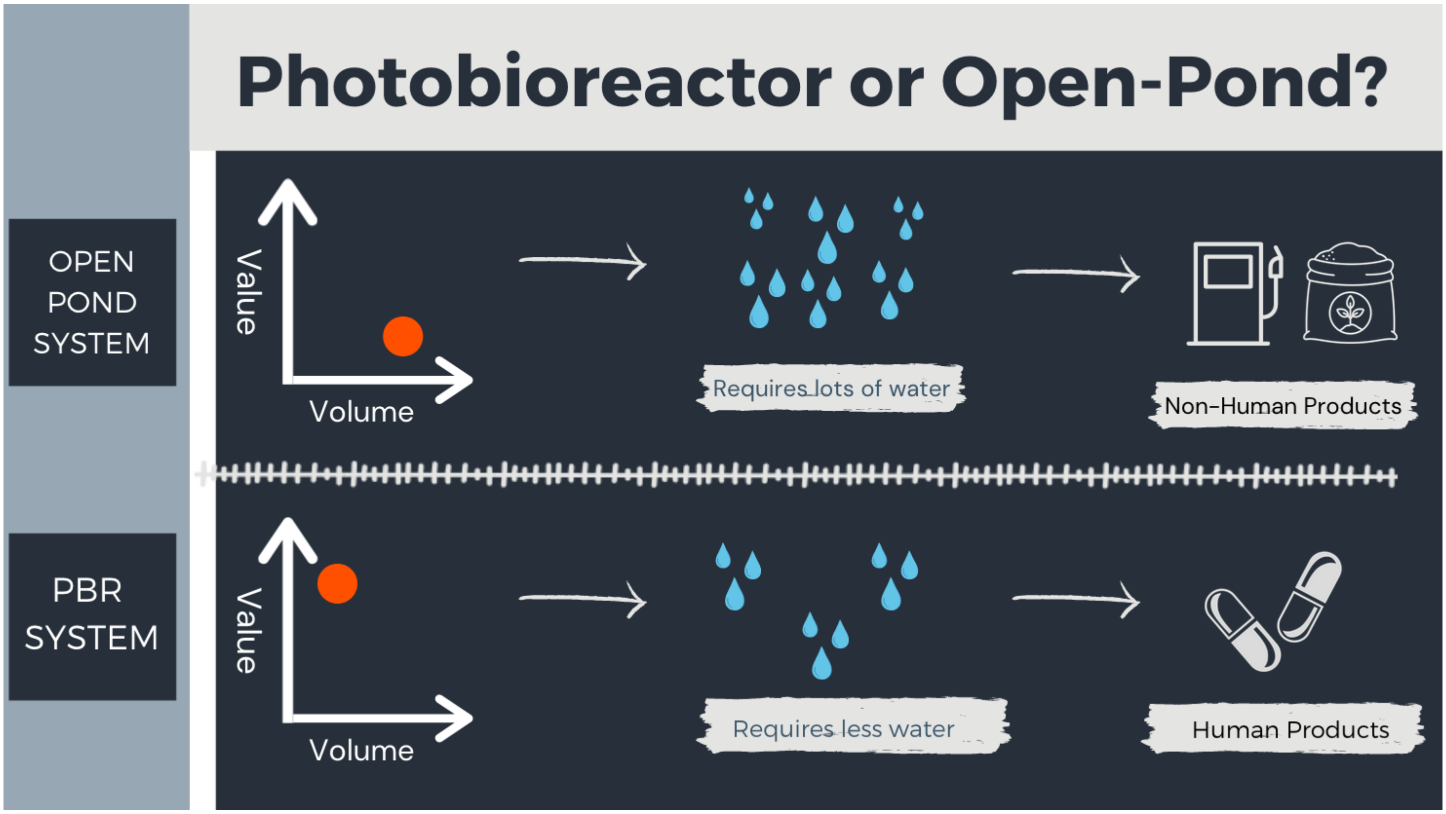


Figure 11: This is a graphic that compares the application and characteristics of open pond systems and photobioreactor systems. Due to its relative ease of scaling, an open pond system can support large quantities of algae biomass. In addition, open ponds have relatively low capital and operational costs. An open pond system is best suited for low-value, high-volume products. However, the open pond requires lots of water, which can be expensive and stress local water needs. To reduce expenses, wastewater can be used. The use of wastewater limits the algae coproducts to non-human products, as wastewater is not allowed for direct or indirect human consumption. PBR systems allow for more control over the algae's growth environment, thus capital and operational costs are higher. In addition, the total biomass yield capabilities and thus quantities of water required for PBR's are much lower than open ponds, and freshwater or saltwater is often used. High-value, low-volume human products that require minimal product variations are best grown in a PBR system. The profits from these products can offset the higher production costs of the PBR system.

State of the Algae Industry

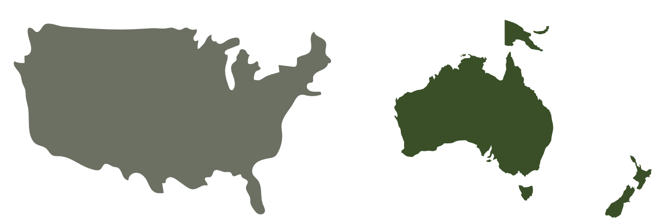
This research was completed over a seven-week period between January and March 2021. Algae initiatives located in the United States and Australia were of focus due to the location of the authors and sponsor. Information was gathered from peer-reviewed journals, government publications, and interviews with experts in the algae industry. The authors would like to acknowledge a potential bias towards the United States and Australian sources.

U.S. ORGANIZATIONS

There is an abundance of algae research in the U.S. Research groups across the U.S. include the Algae Biomass Organization (ABO), Ocean Foresters, Woods Hole Oceanographic Institution, and Algenol. Ocean Foresters is an organization that has developed an innovative approach to climate change using macroalgal seaweeds. They estimate that if seaweed forests covered about 5% of the earth's oceans, it would remove all of the atmosphere's excess carbon dioxide and the biomass could completely replace fossil fuels with biofuels. One of their projects, named Haven Atolls, is of particular interest. Atolls are ring-shaped reefs or islands formed of coral. Atolls feature sheltered bodies of water, which is ideal for macroalgal growth. Seaweeds would be grown near these reefs to not only save the reefs but to also lower sea levels and decrease ocean acidification through carbon sequestration (Restorative aquaculture, n.d.). Another organization, Woods Hole Oceanographic Institution, a research facility located in Falmouth, Massachusetts, is growing algae in wastewater that contains growth accelerating compounds (Who we are, 2018). Algenol is a former biofuel company that researched algae-derived fuels. They sought to derive ethanol from algae to synthesize gasoline, jet, and diesel fuel. While this technology was not commercialized, it was estimated that their product could reduce the carbon footprint of car emissions by 60% and their fuel was approximated to cost 1.27 USD per gallon (Bailey, 2015).

AUSTRALIAN ORGANIZATIONS

There are many exciting research organizations interested in algae within Australia. One group of researchers at James Cook University determined that a type of algae in Northern Australia has the potential to be used for jet fuel synthesis. James Cook University researchers developed a way to process algae and convert it to crude oil using freshwater-grown algae (James Cook University Research, 2021). Another group actively researching algae for biofuels is The Commonwealth Scientific and Industrial Research Organization (CSIRO). The CSIRO collects, cultures, and characterizes Australia's native microalgae to understand its ecological importance for biofuel production. CSIRO is working with industry professionals to select an efficient strain of microalgae for biofuel production. They have screened hundreds of strains of algae species including the green algae genus Nannochloropsis and others that produce high hydrocarbon quantities (About the Australian national algae culture collection, 2019).



"Interest in algae biofuels is rising in the United States, as the U.S. Renewable Fuels Standard expects the U.S. to produce 36 billion gallons of microalgae-derived fuels by 2022."

Source: (Khan, 2018)

GLOBAL INDUSTRY

The global industry has grown over the last decade and continued interest in algae indicates that this growth will continue in the future.

According to a report done by Grand View Research Inc., the biofuel market for algae is expected to grow to 10.73 billion USD by 2025. Globally, this puts the compound annual growth rate (CAGR) at 8.8%.

Source: (Algae biofuel market size worth $10.73 billion by 2025, 2017)

This increase is likely because algae has a higher biomass yield than other existing biofuel feedstocks such as corn, sorghum, and beet. With a 2-20x higher yield and an increasing interest in R&D by organizations, algae products are expected to appear more often in the near future (Algae biofuel market size worth $10.73 billion by 2025, 2017). The International Energy Agency (IEA) reported that by 2030 the use of biofuel will triple. In addition, it is forecasted that the transportation sector will be responsible for over 70% of the demand for biofuels by 2025 (Bhushan et al., 2020). Some transportation industries like automobiles are quickly shifting to electric vehicles, while the aviation industry is far away from electric airplanes. As a result, biofuels have more potential to make a lasting impact in the aviation industry (Doliente et al., 2020).

In the future, it is possible that algae biofuels could be used in the aviation industry, as electric airplanes are not feasible.

Source: (Doliente et al., 2020)

North America is expected to account for over 30% of the global supply for the algae market. The second-largest market is projected to be Europe and then followed by the Asia Pacific Region. The Asia Pacific region is expected to reach a revenue of over 2 billion USD by 2025, which would mean a CAGR of over 8%. This large increase is likely due to the low costs of raw materials and rapid technological advancements in the Asia Pacific Region (Algae biofuel market size worth $10.73 billion by 2025, 2017).

Most of the developed world is set to see an increase in their algae market, however, North America is expected to have the largest algae market due to high investments that have been made by start-up companies and the U.S. government.

Source: (Algae biofuel market size worth $10.73 billion by 2025, 2017)

COMMON FINDINGS FROM INTERVIEWS

Table 8: Algae Industry Experts Interviewed

INTERVIEWEE	COMPANY	PRODUCTS/WORK
Catherine Legrand	Algoland Project & Marine Ecology Professor at Linnaeus University	Cleaning cement industry emissions, cleaning Baltic Sea water, cleaning water of power station, feeding mussels algae and using the mussels to feed hens
Dan Mulder	Business Manager of Bioremediation Services at Pacific Biotechnologies	Prawn farm, AstraReef, PlantJuice, and bioremediation
Brian Von Herzen	Founder and Executive Director of the Climate Foundation	Marine permaculture
Martin Gross	President and Founder of Gross-Wen Technologies & ABO Board Member	RAB water treatment systems
Mark Allen	Vice President of Accelergy & ABO Board Member	Low carbon synthetic distillate liquids
Nicholas Neveux	Research And Development Manager at Pacific Biotechnologies	AstraReef, PlantJuice

The above interviews contributed information on algae growth conditions, harvesting methods, and industry gaps and trends. One finding across all interviews was that research on algae and algae production technologies has been heavily researched. The success of the algae industry is not governed by technology, but by the barriers involved with product commercialization. This point is illustrated by Mark Allen:

> **“The agencies and the scientists are very much on top of this in the national laboratory system and across the universities. So all of that is pretty much in place...and [the industry] is going to be driven by scale, and scale’s going to be driven by 'do we recognize algae as part of a pervasive climate response?'”**
>
> Mark Allen, ABO Board Member and Vice President of Accelergy

Although scale is key to the success of the algae industry, many algae operations have not made it to a commercial scale. One reason for this is the high initial investment required, caused by raw materials, cost of expertise, and technology. Scaling issues are also caused by a lack of algae awareness and a non-unified government and public response to climate change. Scaling the algae industry is important mainly because it is expected to follow Wright's Law of scale, explained by Dr. Brian Von Herzen:

> **"For every accumulating doubling of production volume per area, we should see an x% decrease in costs. This Wrights Law is what we need to project for this industry.”**
>
> Dr. Brian Von Herzen, Founder and Executive Director of the Climate Foundation

A DOE study estimated that the total capital investment of a PBR system for algae biofuel production would be over 133 million USD (Zhu et al., 2018). This high price severely limits the amount of companies that will be able to afford an algae biofuel business using PBR's. Capital costs must be lowered in order to increase proprietor and investment interest. Implementation of a circular economy or supplementing the capital costs with high-value algae coproducts are two options to address this barrier. Dr. Brian Von Herzen gives his model for current algae companies:

"I think effectively your first 2-4 years of operations are going to be on the coproducts, and then the biofuels can be done once you have everything else in a comfortable profit margin."

Dr. Brian Von Herzen, Founder and Executive Director of the Climate Foundation

Cost is the main barrier to industrial algae production. A significant operational cost is the large quantity of water required for industrial algae operations. Water must be constantly recycled throughout the system to encourage algae growth, and the extent of this recycling varies by production system and algae species. Open pond systems require even more water than PBR systems due to the large quantities of biomass needed for low-value products and climate factors such as evaporation (Richardson et al, 2012). Another expense that must be considered is energy. Mitigating energy costs is possible through on-site renewable sources, but that requires additional capital for construction if that infrastructure does not already exist. Companies producing sustainable products often begin by using non-renewable energy sources but are interested in transitioning to renewable sources. This is shown by Dan Mulder, when he was asked about the opportunity to supplement energy requirements with renewable energy:

"our prawn farm…has a big electric bill. We operate about 100 hectares of prawn farms…moving 20 megaliters of water in and out every day. The major project manager has developed a plan for solar energy for that location…that [renewable energy supplementation] is definitely possible and we have looked into it."

Dan Mulder, Business Manager of Bioremediation Services at Pacific Biotechnologies

One major barrier that was mentioned in multiple interviews was the fact that businesses and investors do not always want to integrate new technologies. Investors are usually risk-averse, meaning they will wait to invest until they are almost certain they can make a profit. There are many new algae production technologies at the testing stage, such as using algae to treat wastewater and using the same biomass for fuel and fertilizer coproducts. However, until successful commercial operations exist, the market is hesitant to commit to these innovative solutions. This point is illustrated by Dr. Martin Gross:

"… no one wants to be the first but everyone wants to be the second. So it's just a matter of the new technology being de-risked for the customers before you get widespread adoption. It [leads] to a long delay in the commercialization process."

Dr. Martin Gross, President and Founder of Gross-Wen Technologies & ABO Board Member

The competition related to algae research and infrastructure design in regards to commercialization is high between companies. This has led to a lack of detailed public publications and reports on the most current processes and methodologies for algae-based products. During multiple interviews, we encountered resistance from interviewees not wanting to disclose too much information about their products, cost and profit margins, and their designs. Mark Allen summarized this point:

"You strategically give out information and give presentations, but you don't write papers because it's a very competitive environment."

Mark Allen, ABO Board Member and Vice President of Accelergy

An agreement shared by the interviewees of this project was that there needs to be significant pressure from the general population and corporate interest before legislation will be placed in place by governments to lessen the regulatory barriers that currently stand in the way of algae focused companies. Further, the public local, and national governments must understand how algae can be part of a sustainable energy solution. One example of public engagement can be found in Sweden. The Algoland project has found that a "community of knowledge" and collaboration between commercial stakeholders in the industry, political stakeholders in the industry, academia, and the public are essential to raising awareness and support for sustainable products. Linnaeus University staff, such as professors, post-doctoral researchers, and previous PhD students at the university are the helm of this project. Algoland's three main objectives are to clean the air, clean the water, and produce sustainable feed from algae and mussels. They can achieve these objectives with the support of their extensive local network, which involves political and commercial stakeholders. Credit for the project's achievements largely goes to its community support. Algoland coordinates annual events like their Sustainability Safari, elementary school visits, and tours of their algae infrastructure. A new addition was their Algokidz program, which aims to inform the next generation about algae's oxygen output and carbon capture capabilities (Algoland, 2020). Algoland is very well received in the community, as illustrated by Catherine Legrand:

> **“We add also quite a lot of not directly commercial impact but impact with the politicians and the communities where they could basically increase their reputation due to the fact that they were supporting our research.”**
>
> Catherine Legrand, Algoland Project & Marine Ecology Professor at Linnaeus University

The desire to improve the environment is clear at Linnaeus University and the surrounding community. Unlike most environmental operations, they are solely focused on sustainable technological innovation, not on the profitability of their products. This genuine mindset is highlighted by Catherine Legrand:

> **“As long as [commercial entities] give [Algoland] credit for what they are doing, this is fine... because this is our impact as scientists so if you make money out of it fine I don’t mind.”**
>
> Catherine Legrand, Algoland Project & Marine Ecology Professor at Linnaeus University

One means to add value to low-value algae products was common across all of our interviews: use wastewater as a growth medium. This not only decreases algae operations' dependence on freshwater sources, but the wastewater provides "free" nutrients for algae growth, thus decreasing operating costs. In addition, wastewater treatment is an expensive process and a growing industry sector, so there are many opportunities for algae. Wastewater treatment coupled with algae biomass production has gained significant traction in the last decade. Four of our six interviewees were involved with algae wastewater treatment, including Catherine Legrand at Algoland, Dan Mulder and Nico Neveux at Pacific Biotechnologies, and Martin Gross at Gross-Wen Technologies. The global increase in population and industrial activities continues to raise the value of water and the need for sustainable treatment solutions. Dan Mulder shows his high hopes for bioremediation in the future:

> **“I think the value put on water is going to keep increasing...I think through force of population, there is going to be a really strong focus on water and the circular economy which then will flow onto the more commodity algae products.”**
>
> Dan Mulder, Business Manager of Bioremediation Services at Pacific Biotechnologies

ALGAE INDUSTRY GAPS AND BARRIERS

Table 9: Industry Gaps and Barriers

GAP/BARRIER	IMPLICATION OF GAP/BARRIER	PROPOSED ACTION/COMMENTS
1. Algae biomass production requires large amounts of water, especially open pond systems.	Algae grown in open ponds requires roughly the same amount of water per unit area as cotton or wheat to replenish the water lost in evaporation. Sources of freshwater are finite, and industrial algae production demands alternative water sources.	Grow algae in wastewater to both treat water and produce biomass for fuel or fertilizer.
2. Algae production requires large amounts of energy, which is mainly provided by non-renewable sources.	Non-renewable sources of energy do not support a sustainable business due to GHG emissions and costs.	Integrate solar or wind energy to subsidize or completely fulfill energy requirements of an algae company.
3. Non-standardized LCA methodology and conflicting long-term environmental impact data.	Distorts cross-comparison of LCA's and discourages risk averse investors. Data collected from the field and the lab are two different scales/environments that yield different results.	Establish or use existing standardized metrics when comparing emissions, energy, and money.
4. High capital costs for algae production.	Large initial investment required for production discourages investors. A DOE study estimated the total capital investment of a PBR system for algae biofuel production to be 133.4 million USD.	Algae production of low-value products must be integrated into a circular economy or supplemented with highly profitable products (eg. nutraceuticals). Algae production can be coupled with wastewater treatment to alleviate nutrient, CO_2, and water costs.
5. Algae product quality variations are inevitable, especially in open pond systems.	Climate conditions like temperature, light, and water quality affect the efficiency of algae photosynthesis.	Periodically and randomly conduct quality control tests on the algae. Have a monitoring system or an indicator that monitors pH and temperature.
6. Low levels of public awareness, and vastly different levels of acceptance across countries.	There has yet to be an industrial-scale algae biofuel/coproduct global model. The competition of the industry causes companies to withhold valuable information.	Educating the public is essential. A successful example of this is seen with Algoland's "Algokidz" program in Sweden.
7. Lack of funding for algae production.	Lack of connection between research entities and commercial companies.	Establish more organizations where potential investors and companies can collaborate to facilitate commercialization and market development. Model the Algae Biomass Organization's approach to networking and acting as an algae information hub.
8. Industrial algae production requires large areas of inexpensive, flat land with access to power and established roads.	Land policies and requirements can be strenuous. There is often resistance from local entities to give up valuable, protected, or farmable land.	Selecting a location for algae growth is critical to the success of the operation. A balance must be found between proximity to the energy grid, highways, railroads, ports, water sources, etc. and distance from indigenous lands, wetlands, and residential areas.

Sources: (Farag et al., 2011), (Schade and Meier, 2020), (Carneiro et al., 2017), (Zhu et al., 2018), (Collet et al., 2015), (Schlarb and Parker, 2013), and (Pilbara Development Commission, 2016)

MCDA Location Selection Methodology

WHY USE AN MCDA?

CHOOSING OPPORTUNITY AREAS FOR ALGAE IS COMPLEX, SO AN MCDA IS A GOOD TOOL TO GET STARTED

As discussed previously, there are many factors that contribute to choosing an appropriate location for algae production. It is up to the business stakeholders to decide which factors are more significant, as those decisions will likely result in different locations being the preferred location. Here it is proposed that a decision-making tool capable of comparing multiple criteria would help organize and analyze the environmental and commercial factors relevant to algae production. A methodology for complex decision making, the “Multi-criteria Decision Analysis” or MCDA, exists (Frazão et al., 2018). An MCDA is a method for simultaneously comprising, combining, and structuring complex information that is both qualitative and quantitative. MCDA supports deliberation and encourages dialogue about the necessary decisions by embracing the diversity of opinions among experts and stakeholders (MCDA, n.d*.)*.

In this roadmap, our MCDA analyzes criteria and factors for a geographic location. It is not an analysis on a specific plot of land, but an analysis for a location.

MCDA METHODOLOGY

In the first step of the MCDA, the context of the goal is identified. Following the goal, an iterative questioning process is employed. This process can be expressed as a flowchart, where there are different considerations depending on the answer to each question. The response to each of these questions also yields a score (MCDA*, n.d.)*. In this MCDA each question has four potential conditions, or answers, which are assigned a score of 0-3 to assess a location's potential for algae. A score of zero is the lowest possible score and means that the conditions do not support an algae operation, and a high score of 3 indicates that the conditions are suitable for algae production. Some questions warrant a quantitative answer, whereas others warrant a qualitative answer. For example, the average annual temperature is a numeric response, while public acceptability of renewable energy is a subjective answer. Questions are also weighted on importance and relevance. If a question is more critical than another, then that question will have a higher multiplier. For example, evaporation impacts an outdoor open pond system more than an indoor photobioreactor, so this factor would be weighted more in a scenario employing an open pond algae growth system.

GENERAL ASSUMPTIONS

Although the MCDA is an appropriate analysis tool for this project, its advantages and disadvantages must be recognized. The advantages include organizing outcomes, analyzing conflicting criteria in a meaningful way, and the opportunity to prioritize critical success factors by assigning different weights. The disadvantages of using an MCDA is that general assumptions must be made. These assumptions are often included because of ambiguity within the project goal. Assumptions also help simplify the decision-making process, as having too many decision-making pathways exponentially increases the number of possible considerations (MCDA, n.d.).

GENERAL MCDA STEPS

01 DEFINE THE CONTEXT

- The present situation
- Key players
- Stakeholders

02 IDENTIFY OPTIONS

- Multiple options are compared
- All options can be changed/influenced
- Options provide a go/no-go basis

03 DECIDE OBJECTIVES

- Varying consequences are tied to each option
- Multiple different criteria need to be established
- Criteria represent clearly defined standards and express the value of the options

04 MEASURE IMPORTANCE

- Each preference unit can have a scale of choice
- Relative importance of options is measured
- Criteria are weighted to show difference between options and relevance of difference

05 WEIGH THE SCORE

- Relative priority scores are calculated
- A weighted average of all criteria creates a general preference score
  - 1. Scores for each criterion are multiplied with their weighting
  - 2. Scores of each criterion are added together
  - 3. Total sum comprises the preference score

06 MAKE SUGGESTIONS

- The outcomes from weighing the scores can be compared to see which option is most suitable

Figure 12: The six steps of an MCDA decision-making tool are described above.
Source: (Janse, 2018)

LOCATION SELECTION FACTORS FLOWCHART

This flowchart is the culmination of an extensive academic literature review, interviews with algae industry experts, and independent analysis. The flowchart presents the factors that should be considered for a location's suitability for algae cultivation.

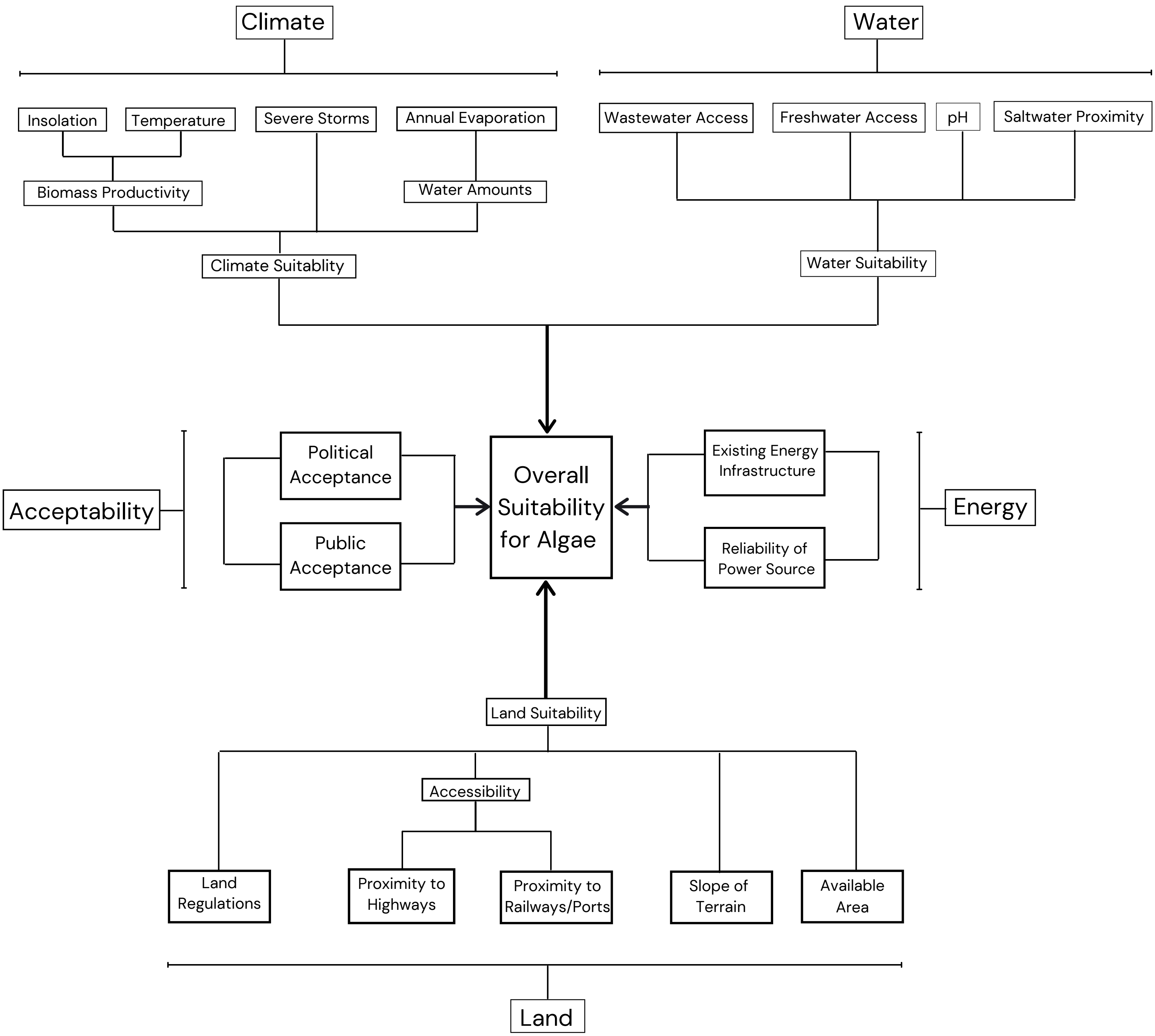


Figure 13: The five factors categories that contribute to a location's overall suitability for algae are listed above as climate, water, energy, land, and acceptability. The specific factors of our MCDA are shown beneath each of the categories.

MCDA METHODOLOGY ASSUMPTIONS

The following MCDA framework is presented through the lens of a hypothetical algae company looking to assess the potential for algae in a location. Different coproducts require different conditions, such as freshwater or wastewater, so an MCDA is necessary to select which location can provide adequate conditions.

It is assumed that the hypothetical algae company is interested in developing high volume, low value, coproducts that are not for human consumption ("non-human coproducts") at an onshore location.

Questions tailored to these non-human coproducts will be included in the MCDA for consideration. Questions tailored to human coproducts and offshore algae cultivation will not be included, as that would broaden the scope of this MCDA and not allow for necessary specificity in the analysis. If offshore algae cultivation was of interest, criteria such as the temperature and nutrient profile of the body of water, water regulations, and harvesting infrastructure would have an increased emphasis. Maintenance costs would be a greater concern in comparison to onshore, as turbulent water currents and severe storms could compromise the integrity of the growth structure. In addition, transporting goods and services to and from the offshore location would pose a significant cost.

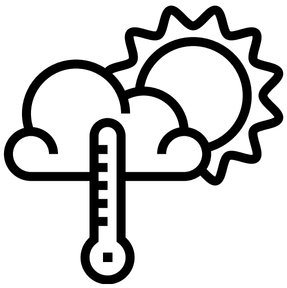
The sequential production of non-human products enables this hypothetical algae company to grow the algae in wastewater. As previously discussed, the nutrients in wastewater enable algae growth for biomass, while simultaneously the algae is removing pollutants from the water. Wastewater is an economically and environmentally sustainable pathway for the production of algae biofuels and non-human coproducts as it is generally less expensive and more accessible than freshwater. Although freshwater is scarce and expensive in many locations, this does not disqualify freshwater as a water source. Freshwater is more suitable for the development of human coproducts, such as pharmaceuticals or nutraceuticals, as potential trace pollutants found within wastewater would not allow human coproducts to pass regulatory and quality control testing.

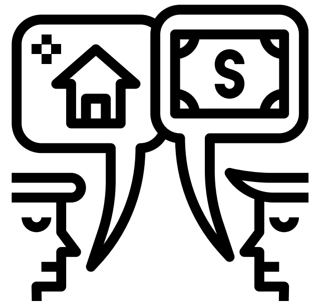
Because questions in this MCDA are focused on a high-volume, low-value products, an open pond is the most appropriate system for algae production.

The end result of this MCDA will be a numeric score. The locations of interest will be compared according to their potential to support a non-human algae product stream. A conclusion will follow the scoring to further clarify the factor scores and weighting.

LOCATION SELECTION FACTORS

Climate & **Commercial**





CLIMATE

Solar insolation describes the amount of solar energy per unit area per time unit. Synonyms for this phrase include solar irradiation or solar exposure. Solar insolation is critical to algae growth, as algae requires sunlight to perform photosynthesis. Factors that impact solar insolation include solar elevation, ozone, cloud coverage, ground reflectivity, and altitude. Generally, maximizing solar insolation is conducive for high algae productivity, but too much light can decrease productivity or even kill the algae.

Average annual temperature describes taking the mean average of the coldest month of the year and averaging it with the mean average of the hottest month of the year. Most algae species are capable of growth over a range of 15-30 °C, but the optimal conditions are 20-25 °C. Of course, these values differ between different algae species and strains.

Temperature variations are especially important for open pond systems, as the algae is more vulnerable to the environment. Measuring the months per year within a generally acceptable temperature range is one way to ascertain if year-round or seasonal algae growth is best for a particular location. Different pathways for algae will have different climate requirements. For example, an algae wastewater treatment facility would need to be operational year-round, whereas producing animal feed or fertilizer from a salt or freshwater pond could be a seasonal operation. The times of the year that an algae company decides to operate is largely dependent upon the net value between heating or cooling energy costs and revenue. The average amount of frost days per year is a key statistic because frozen algae can not propagate or be harvested. Due to the variability of this statistic's importance with the type of algae operation, it is omitted from this general MCDA.

Although terrain slope may not seem like an intuitive factor that affects algae growth, it does impact the cost of the operation. The greater the terrain slope, the greater construction costs are. When looking at location preparation costs, a 0% slope correlates to about 31,240 USD per hectare, while a 15% slope correlates to about 55,400 USD per hectare.

Annual evaporation in millimeters describes the amount of water lost to evaporation. Pan evaporation is the amount of water which evaporates from a Class A evaporation pan. The rate of evaporation depends on factors such as cloudiness, air temperature, and wind speed. This is of greater importance in an open pond system as the pond is (usually) directly exposed to sunlight. Water lost to evaporation must be replaced, but that incurs greater costs and stress on water sources.

The average annual amount of severe weather events is relevant as severe weather could endanger the algae and destroy infrastructure. A drought could stress the water supply, a hurricane could physically damage the operation location, and an electrical storm could compromise the energy source. Classifying "what is a severe weather event?" will change as you move around the globe. This MCDA is comprehensive in the metrics for a severe weather event, the list including thunderstorms, hurricanes, hail storms, snowstorms, tornadoes, floods, wildfires, dust storms, and landslides. To be considered a severe weather event in this MCDA, the weather has to pose a direct danger to the infrastructure of the industrial algae production.

pH is a scale of acidity from 0 to 14. More acidic solutions have a lower pH, while more alkaline solutions have a higher pH. Substances that aren't acidic or alkaline are neutral and have a pH of 7. Generally, algae can propagate in saltwater, freshwater, and wastewater as long as a pH of 7.5-9.0 is maintained. It has been found that a pH range of 8.2-8.7 is ideal for most algae species. The pH can be further narrowed down to maximize biomass productivity once an algae species is selected.

Table 10: Climate and Geographical Factors Scoring

FACTOR	MULTIPLIER	SCORE 0 CONDITION	SCORE 1 CONDITION	SCORE 2 CONDITION	SCORE 3 CONDITION
Average solar insolation per day (MJ/m2/d)	3	< 13 OR > 22	13 - 15 OR 22	15 - 18 OR 21	18 - 20
Months per year with average solar insolation per day > 18 MJ/m2/d	1	0	1 - 4	5 - 8	9 - 12
Average annual temperature (°C)	2	<5 OR >30	5 - 17 OR 28 - 30	17 - 22 OR 25 - 28	22 - 25
Months per year with average temperature 17-28 °C	2	0	1 - 4	4 - 8	8 - 12
Slope of terrain (%)	1	> 10	5 - 10	2 - 5	< 2
Annual pan evaporation (mm)	1	> 3000	2000 - 3000	1000 - 2000	< 1000
Average annual amount of severe weather events	1	> 20	10 - 20	5 - 10	< 5
pH of water source	2	< 4 OR > 12	5.5 - 4 OR 10.5 - 12	8.2 - 5.5 OR 8.7 - 10.5	8.2 - 8.7

COMMERCIAL

Public awareness is a qualitative factor used to measure the state of knowledge about climate change and environmentally sustainable ideas in the general public. This metric doesn't measure the public's expert knowledge on algae, but rather it measures the potential for the community to understand the implications of algae. Public awareness is important, especially for novel energy ideas, as the public has the power to pressure the local government into certain actions.

Political acceptability is a qualitative factor to measure if the local area is dependent on fossil fuels and if the local government is interested in supporting algae. High dependence on fossil fuels could indicate there is lobbying, old infrastructure, or that the economy is reliant on them for job security. A community that already has established renewable energy initiatives or waste free product streams is more likely to seriously pursue algae.

Existing energy infrastructure defines if the specific area has infrastructure such as a transformer or power distribution lines. It's also important to consider if an adequate amount of voltage is available for industrial purposes. If an area does not have existing energy infrastructure, then time and money will have to be spent to bring in infrastructure.

Power reliability refers to the number of brownouts or blackouts that occur during a year. It's important to distinguish that blackouts are a complete shutdown of power, whereas brownouts are 10-25% reductions in the system's power capacity. Brownouts or blackouts are not ideal, as breaks in electricity would stop algae production. If an area has unreliable access to energy, then the proprietor should consider installing a back-up source of energy, such as solar panels.

Proximity to main highways is a numeric value to score how close the algae operation would be to roads. Generally, more remote locations require more money to be spent on infrastructure construction and transportation of materials, especially if the roads are not well kept. Additionally, if the algae facility is in a remote location the company may have to pay for road construction to the location. Road construction is estimated to be 314,500 USD per kilometer for flat terrain and even higher for rough terrain (Maxwell et al., 1985).

Proximity to railroads or ports is a numeric value to score how close the algae operation would be to shipping locations. Although not crucial to a location's viability for algae production, shipping centers far away from the algae growth location results in higher costs. This factor is more relevant to low-value products, as the profit margins of high-value products can often absorb higher shipping costs.

Proximity to saltwater sources is a numeric value of how close the algae operation would be to the ocean. In general, the further away the water source, the higher the cost to transport the water. This is because you have to build pipe and pump infrastructure and pay high electricity operational costs for pumps.

Access and availability of fresh and wastewater sources involve geographic, climate, environmental, economic, and political considerations. For fresh water, the main consideration is to avoid disturbance of the local water supply (for the people and natural ecosystems). Water levels and reliability trends must be analyzed. In addition, the depth of underground water sources is linearly related to water suitability, as it affects both construction and operation costs. For wastewater, the main questions to ask are: how close is the existing wastewater treatment plant, what existing treatment steps does it use, is the wastewater domestic or industrial, and does the government feel comfortable allocating wastewater to algae operations?

The extent of land regulations for the region describes if land in the region is available for purchase. If available, the main questions to ask are: has that land been contaminated previously or are there existing restrictions on how that land can be used? Strict restrictions often arise from proximity to protected lands such as indigenous lands and wetlands. In addition, tourist and residential areas will dissuade the local government from selling land for industrial activity.

The operation expansion factor is a binary choice. This is based upon the current available area and the region's plans for industrial spatial expansion. In this MCDA, specific conditions for a yes or no response to this factor are not provided as they are dependent on the type of algae operation. Production at a large scale is advantageous, as cost per kg of algae biomass decreases with increasing scale.

Table 11: Commercial Factors Scoring

FACTOR	MULTIPLIER	SCORE 0 CONDITION	SCORE 1 CONDITION	SCORE 2 CONDITION	SCORE 3 CONDITION
Public awareness	2	Lack of environmental awareness AND negligence to act	Pockets of individuals are aware, but are not interested in change	Grass roots and activist activity AND nearby research individuals are knowledgeable	General population is aware AND community has progressive mindset
Political acceptability	3	Dependence on fossil fuels and a linear economy & community is not interested in diversifying energy sources	Dependence on fossil fuels, but community is interested in diversifying energy sources	Community has diversified energy sources AND is working towards a waste-free solution	Established waste free product streams and renewable infrastructure AND local and national government support
Existing energy infrastructure	3	No existing energy infrastructure AND no access to power	No existing energy infrastructure AND access to limited amounts of voltage	There is existing energy infrastructure AND limited access to adequate amounts of voltage	There is existing energy infrastructure AND limited access to adequate amounts of voltage
Reliability of power source	2	Not reliable, several blackouts or brownouts per year			Reliable power source with few to no brownouts or blackouts per year
Proximity to main highways (km)	1	> 80	25 - 80	8 - 25	< 8
Proximity to railroads or ports (km)	1	> 120	55 - 120	32 - 55	< 32
Proximity to saltwater source (km)	2	> 30	10 - 30	5 - 10	< 5
Access and availability of fresh water source	3	High drought risk AND several industrial operations dependent on water OR water source disturbance would be detrimental to the ecosystem OR no known groundwater	Above ground water levels are decreasing AND water source disturbance would be detrimental to the ecosystem OR groundwater is challenging to access (fractured or fissured aquifer, OR at a depth > 150 meters)	Consistent and abundant above ground water levels AND groundwater is easier to access (porous aquifer OR at a depth 75-150 meters)	Plentiful and independent above ground water source AND above ground water levels are increasing OR groundwater is easy to access (porous aquifer AND at a depth < 75 meters)
Access and availability of wastewater source	3	There is no wastewater facility OR wastewater is already designated for elsewhere AND local government is not interested in value-added product streams	Wastewater treatment plant is nearby, but local government is not interested in value added product streams and tertiary treatment	Wastewater from a wastewater treatment plant is available and the local government is interested in value added products and tertiary treatment, but accessibility would be costly OR wastewater supply is inconsistent	Wastewater from a wastewater treatment plant is abundant and easy to access AND local government embraces a value added product stream and tertiary treatment
Extent of land regulations for the region	2	Land is publicly owned AND/OR tourist area, wildlife reserve, near residential area, near indigenous peoples area, near wetlands	Private land available, but there are strict regulations on industrial activity due to previous environmental harm AND/OR near residential areas	Private land available and industrial activity is possible, but with some restrictions	Private land available and industrial activity is possible because there are no significant restrictions
Can you expand the operation?	1	NO			YES

Factor Limitations and Critical Success Factors

Although this MCDA provides pertinent factors for industrial algae production, it is not entirely comprehensive.

The majority of the commercial factors have qualitative score criteria, which can make the scoring process slightly ambiguous and less objective, as well as more challenging.
The factors “access and availability of freshwater sources” and “access and availability of wastewater sources” were written with qualitative criteria, but are better suited to have a numeric value. For example, analyzing the community's water usage and water supply trends and developing an estimate of the available volume of freshwater and wastewater would be helpful to cross-compare. In addition, while wastewater is generally less expensive than freshwater, it would be important to establish the actual cost difference between freshwater and wastewater. The factors “public awareness” and “political acceptability” are difficult to measure quantitatively.

The framework of this MCDA is to assess the overall potential for algae in a location or region, not a specific location. A focused location analysis would follow the analysis in this MCDA.
The factors “existing energy infrastructure”, “proximity to highways”, “proximity to railroads or ports”, “proximity to saltwater source”, “extent of land regulations”, and "operation expansion" would be better scored if a specific plot of land was pre-selected for an algae operation. For this MCDA, these factors can be scored based on the region's economic type, population, land usage, proximity to the ocean, and proximity to major cities.

The factor “reliability of power source” is difficult to score for several reasons.
Power reliability is impacted by severe weather and the state of the power grid technology and infrastructure. “Reliability” is not a standard metric, so different power distributors define reliability differently. Reliability could be an overall percentage of how often there are unplanned or planned energy restrictions for a given year. Reliability could also be described as an acceptability measurement. For example, many power distributors set an acceptability threshold for urban customers of 90 minutes per year of total unplanned power interruptions. If an algae operation requires constant power and cannot accept any interruptions, the company should consider integrating their own power source via batteries, solar, or wind energy. This MCDA did not consider the opportunity for renewable energy, as that would increase the complexity of the decision-making process.

CRITICAL SUCCESS FACTORS

The factors "political acceptability”, “proximity to saltwater source”, “access and availability of freshwater source”, “access and availability of wastewater source”, and “extent of land regulations” are highlighted in red because they are critical to the success of an algae operation. If all three of the water factors, or just political acceptability or land regulations receive a score of zero for a particular location, then that location should be disqualified from further consideration. This is because industrial algae production requires government approval, vast quantities of water, and large areas of flat land. The energy factors were not included as critical success factors as there is the opportunity to integrate renewable energy into the operation. It's important to note that there are no critical success factors under the climate category. While high levels of solar insolation and warm temperatures are crucial to algae productivity, these conditions can always be altered with artificial lighting and heating and cooling machinery, respectively. The importance of climate factors is more subject to the priorities and profit margins of the algae company. While altering climate conditions may not be the most financially sustainable solution, it should not completely disqualify a location from consideration for algae.

MCDA Case Study: Gippsland, Australia

The MCDA tool was used to notionally compare the potential of two locations in Gippsland, Australia for industrial algae production. This case study was notional in that it was conducted using limited resources and time. It serves more as a set of guidelines and opportunity assessment for algae in the region. The two locations that were compared are Latrobe Valley and Bass Coast Shire. The information was gathered from the Australian Bureau of Meteorology, the Bass Coast Shire Council Climate Action Plan, and the Australian Department of Agriculture. Context and reasoning for Gippsland and both Latrobe Valley and Bass Coast Shire are presented below.

GIPPSLAND GENERAL CONTEXT

Gippsland was initially selected as a region of interest due to the project sponsor, Snowy River Innovation (SRI), having a long-term engagement with Gippsland and its proximity to the city of Melbourne, Victoria. The region of Gippsland is suitable for algae development initiatives and policy settings are driving a rapid shift towards a sustainable, diversified, and non-linear economy.

Gippsland is a rural region of Victoria in the southeast part of the state with a considerable amount of State Forests and National Parks. Gippsland central is about a 2.5-hour drive east of Melbourne. Gippsland offers a diverse agricultural and industrial base as well as a variety of tourist attractions such as beaches, rainforests, and snowfields. The region is the powerhouse of Victoria's natural resources and commodities economy. It houses the state's brown-coal electricity industry and hosts other key sectors such as agriculture, forestry, dairy, fishing, tourism, engineering, finance, health care, and education (Victoria's Gippsland region, n.d.). Gippsland is divided into six local government regions: Bass Coast, South Gippsland, Latrobe, Baw Baw, Wellington, and East Gippsland.

- As of 2016, 274,600 people lived in Gippsland
- Gippsland is home to 14 National Parks.
- Agriculture and food production generates 2 billion USD annually from Gippsland

Source: (Accelerating growth for the Gippsland food and fibre industry, 2019)

Map of Gippsland Regions

Figure 14: This is a map of the Gippsland regions. This report will focus on the Latrobe and Bass Coast regions.
Source: (Victoria's Gippsland region, n.d.)

The impact of climate change and corresponding policies has deeply impacted the region's key industries such as farming, forestry, and mining. In particular, the energy sector is facing significant challenges resulting from a global shift to a low carbon economy. The electricity production from Gippsland has been mostly coal-fired, but the recent decommissioning of the Hazelwood Power Plant is sparking environmentally protective action. Similar closures have caused significant disruptions in the Gippsland community and economy (Hicks, 2019).

EFFORTS ARE UNDERWAY TO COORDINATE A PRODUCTIVE AND SUSTAINABLE ENERGY TRANSITION:

> "The Victorian Government is committed to establishing Victoria as a leader in renewable energy by implementing supportive policies to give the renewable energy sector the confidence needed to invest in renewable energy projects and jobs. Under the New Energy Jobs Fund, the Department of Environment, Land, Water and Planning (DELWP) has funded the development of regional renewable energy roadmaps in Barwon South West, Grampians, Loddon Mallee, Hume and Southern Gippsland".
>
> **Source:** (Hicks, 2019)

The Gippsland region has sustainability opportunities and challenges outside of energy. For example, effluent from industrial areas gives the opportunity for algae wastewater treatment. In addition, poor soil health from the overuse of chemical fertilizers could be improved by algae biofertilizer. Lastly, specialized algae dietary supplements could be produced in Gippsland and sold to a high-value and progressive market in Melbourne. However, analysis on the cost of transportation of products must be considered. For example, it may not be financially viable to transport low-value products, but financially viable to distribute high-value goods throughout the Melbourne market. Gippsland is attractive for industrial-scale algae production for analyzing the potential from multiple perspectives, including community, environment, economy, and infrastructure.

Table 12: Gippsland Strengths and Opportunities for Industrial Algae Growth

COMMUNITY	ENVIRONMENT
• Public action on environmental and sustainability issues • Local governments serve a leadership role in the community due to their desire to facilitate renewable energy initiatives • A community that supports health and well being • Strong community networks and high volunteer rates	• Abundance of flat open space for industrial operations (low population density of 6.5 people/km2) • Temperate climate: mild to warm summers (average maximum temperatures of 21-25°C) and mild winters near the coast (average maximum temperatures of 12-15°C)

→

ECONOMY	INFRASTRUCTURE
• Local agriculture, water, and tourism industries are interested in renewable energy • Proximity to Melbourne provides a large market and population base for algae products • Presence of energy-related skills & industries in Latrobe Valley	• Established networks for electricity, road, and rail • Existing electricity distribution network (high voltage transmission lines in Latrobe Valley) • Several small airports for state to state flights • New water treatment and management systems

Source: (Hicks, 2019)

Why Latrobe Valley?

Latrobe Valley is an inland district and the most urbanized area of the Gippsland, Australia region. The valley's approximate population is 125,000, most of which is spread between the four population centers of Moe, Morwell, Churchill, and Traralgon. Latrobe Valley is easily connected to Melbourne via the Latrobe Regional Airport and Princes Freeway. The Latrobe River flows eastward through the valley and into the Gippsland lakes (Latrobe Valley, 2021).

Map of Latrobe Valley

Figure 15: Latrobe Valley outlined within Gippsland's area.
Source: (*Latrobe valley*, 2021)

Latrobe Valley is an industrial hub, especially for energy, as it provides approximately 72% of Victoria's electricity using brown coal, and supplies some electricity to the National Energy Market (NEM), the eastern seaboard electricity grid. The valley contains one of the world's largest coal deposits and nearly 90% of Australia's brown coal reserves. Two brown coal mines feed three major power generating stations called Loy Yang A, Loy Yang B and Yallourn (Power drive, n.d.) Brown coal, or lignite, differs from black coal in that it has more ash and moisture and less carbon, thus it has a lower energy content (Brown coal, 2012). The decommissioning of the Hazelwood Power Plant in 2017 for commercial reasons was a significant moment, as it significantly decreased Latrobe Valley's carbon emissions. Hazelwood supplied up to 25% of Victoria's baseload electricity and more than 5% of Australia's total electricity and was one of the most polluting power stations in the world (Latrobe Valley, 2021).

In 2016 the Latrobe Valley Authority was established to coordinate Victorian Government action in Latrobe as the region transitions to a sustainable and diversified economy. The Latrobe Valley Authority is staffed by local people who have a vested interest in the community's long-term success and sustainability (Aberle, 2016). Environment Victoria, Victoria's leading non-government and non-profit environmental organization, explores "what a just, and well-managed, transition process for the Latrobe Valley" might look like in their document "Life After Coal" (Life after coal: pathways to a just and sustainable transition for the Latrobe Valley, n.d.).

Hazelwood Power Plant

Figure 16: Hazelwood Power Plant mines.
Source: (Aberle, 2016)

The large scale of industrial operations in the area requires large quantities of water and produces a copious amount of liquid waste, called effluent. From the 1950s to 2010 the solution for wastewater was to dump it into the environmentally detrimental Regional Outflow System (ROS). The ROS transported industrial and domestic untreated wastewater through towns and tourist areas from Latrobe Valley to Dutson Downs and the Tasman Sea in an open stream. Now, this wastewater is treated at the Gippsland Water Factory in the city of Morwell (Industrial water treatment, n.d.).

The Gippsland Water Factory treats 35 ML of wastewater a day from nine towns in central Gippsland and serves the needs of more than 48,000 domestic customers and 300 local businesses.

Source: (*Industrial water treatment*, n.d.)

It also treats wastewater from the Australian Paper Mill at Maryvale, the largest pulp and paper mill in Australia. The wastewater is treated in three stages. The first stage involves screens and grit systems, the second stage uses bacteria, and the third stage uses filters and disinfectants. Apart from treating wastewater, the plant can produce up to three billion liters of recycled water a year for potential reuse in industry. Water not used in industry is safely returned to the environment. In addition to the treatment facility at the Morwell location, there is the Vortex Education Centre which has interactive displays explaining the importance of the facility to the local environment and the water cycle. The Gippsland Water Factory won three Banksia Environmental Awards in 2011: in the water, education, and overall categories (Industrial water treatment, n.d.).

Another exciting development centred around the Australian Paper Mill in Maryvale is the possibility for an indoor aquaculture facility integrated with the current paper mill infrastructure. In 2019, Australian Paper entered into a partnership with fish farmers Mainstream Aquaculture for a 1.24 million AUD feasibility study into the proposed barramundi (Asian sea bass) farm. Due to COVID-19, this study was not completed in mid-2020 as planned. The plan is for the fisheries to use the spare capacity of the mill's wastewater treatment system (the Gippsland Water Factory) and freshwater supply, and to use the mill's hot water to supplement energy requirements (Slater, 2019).

If algae could be integrated into the existing tertiary water treatment stage, it could add value and further the sustainability of the operation through products made from algae biomass. Blue-green algae (BGA), or cyanobacteria, is commonly found growing natively in the Latrobe Valley in ponds and lakes. Because BGA is robust and it has been proven that the region's climate conditions are conducive for BGA growth, it is worth considering as a tertiary treatment for the Gippsland Water Factory. If additional wastewater treatment was needed for the Australian Paper-Mainstream Aquaculture project, algae could be used in a fashion similar to Pacific Biotechnologies' Pacific Reef Fisheries project. The algae would not only treat water but also capture CO2 and provide the opportunity for biomass production for low-value products.

Based on preliminary research, Morwell is a viable city in Latrobe Valley for industrial algae production. This is largely because available wastewater at the Gippsland Water Factory is located in Morwell. Morwell has a small population of approximately 14,000 and has received significant funding from the Latrobe Valley Authority for industrial expansion due to the closure of the Hazelwood Power Plant on the outskirts of the city. Princes Freeway, the Traralgon Rail Line, and Latrobe Regional Airport all run through Morwell (Latrobe Valley, 2021). In addition, elevation differences are relatively low as compared to other cities in the valley (Figure 16). This is important for industrial algae production, as flatter land decreases construction costs (Maxwell, 1985).

Topographic Map of Morwell

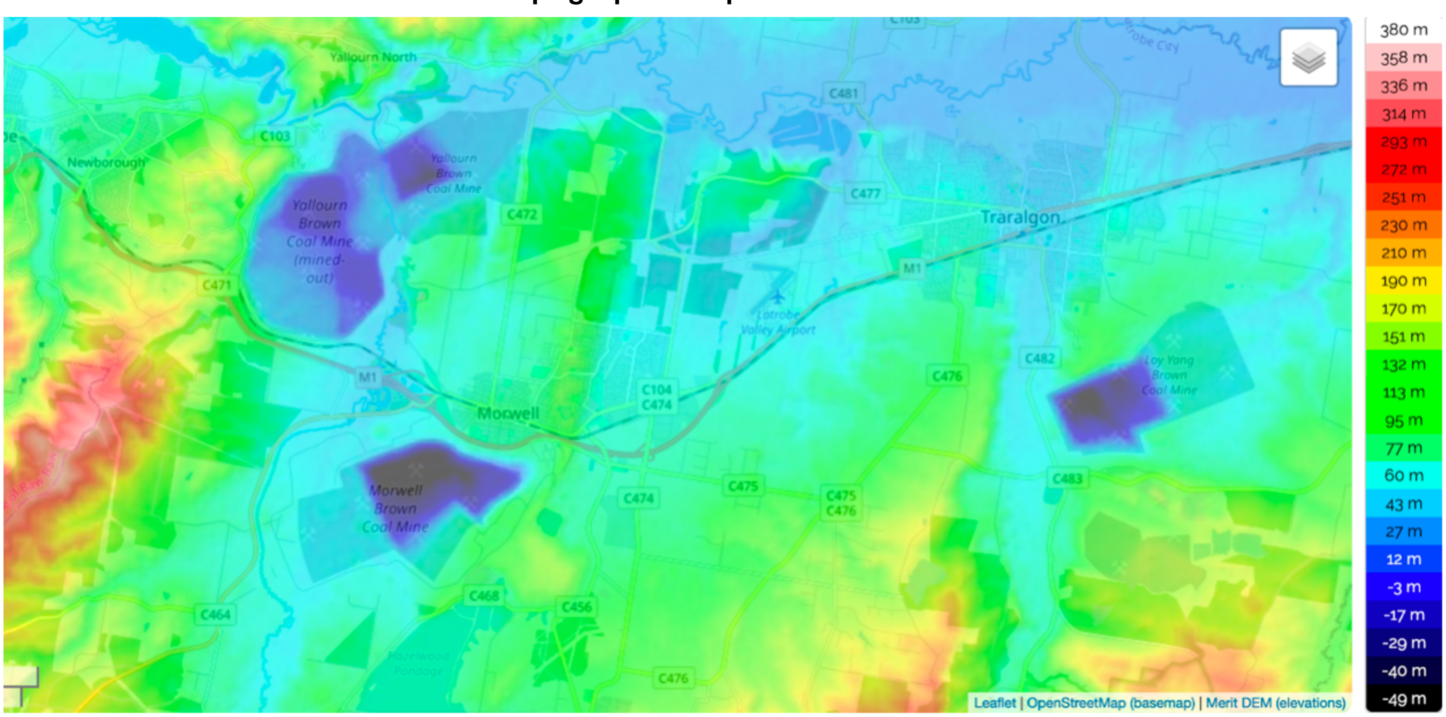


Figure 17: Morwell's elevation changes are not severe, making it a good candidate for algae cultivation.
Source: (Morwell topographic map, elevation, relief, n.d.)

Why Bass Coast Shire?

Bass Coast Shire is a rural government area in the southeastern part of Victoria, Australia. It is located only 1.5 hours southeast of Melbourne. The region's total population is 36,320, however during peak holiday periods the population can reach over 70,000. The residential population is growing as well, as by 2036 it is forecast to increase to over 47,000. 90% of the land is agricultural and as the economy continues to develop this land it is becoming a valuable food source for Victoria. The Shire consists of extensive coastal areas which attract a plethora of tourists and offers a variety of fishing opportunities. Phillip Island is an exciting tourist attraction, as it features wildlife like penguins and fur seals and a GP racing track for motorcycle and car racing (Climate change action plan: 2020-2030, 2019).

Map of Bass Coast Shire

Figure 18: Phillip Island is a large tourist attraction, and Wonthaggi is the region's largest town.

Bass Coast Shire Coastline

Figure 19: Bass Coast Shire is a small, coastal region near Melbourne. **Source:** (Chensiyuan, n.d.)

Bass Coast Shire is a connected zero-carbon community. Bass Coast Shire Council, which provides authority and represents the community's interest, declared a climate emergency and declared zero net emissions by 2030 as a response to a 1,000 strong community petition in 2019. In addition, in 2018, the "Totally Renewable Phillip Island" project was begun by the Energy Innovation Cooperative (EIC). The EIC is a long-established community energy group that covers both Bass Coast and South Gippsland shires. whose goal is to amplify the impact of community-owned renewable energy. Bass Coast Shire's renewable energy focus is on solar power, as a local company Island Energy on Phillip Island supplies solar panels to residential and commercial customers (Solar energy victoria, n.d.). Community action was sparked by environmental hazards such as increased average temperature and solar radiation, increase in extreme heat, decrease in annual rainfall, more severe weather events, and rising sea levels. Bass Coast Shire's current emission distribution can be seen below (Figure 19).

Bass Coast Shire Emission Distribution

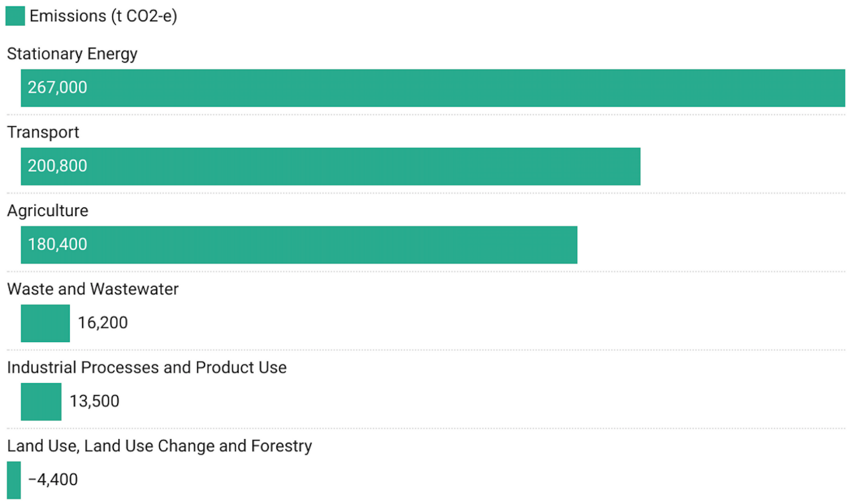


Figure 20: Bass Coast Shire's highest emission sectors are stationary energy and transportation.
Source: (Climate change action plan: 2020-2030, 2019)

Emissions Percentage by Economic Sector

Residential: 44.1%

Farming: 33.3%

Commercial: 16.7%

Industrial: 6.1%

Municipal: -.2%

Source: (Climate change action plan: 2020-2030, 2019)

Bass Coast Shire Council acknowledges that some emission sources are more difficult to address than others. For example, it is forecasted that until 2030 agriculture and transport emissions will stay relatively consistent with the current levels, but industrial, land use, and especially stationary energy are expected to see decreased emissions. The goal is for stationary energy to transition from a carbon emitter to a carbon drawdown tool, which appears within reach due to the community's large focus on residential renewable energy. Efforts are still being employed by farmers to reduce agricultural emissions: planting trees, controlling invasive species, participating in regenerative agriculture training, developing a water budget, installing solar, improving herd management, etc. Two recommendations for agriculture that the Bass Coast Shire Council listed in their Climate Change Action Plan were providing food supplements for cattle year-round and implementing soil carbon sequestration methods (Climate change action plan: 2020-2030, 2019). Both of these are of interest to algae, as algae have been proven to reduce cattle methane emissions as an animal feed, improve soil health, and sequester carbon as a biofertilizer. The animal feed from algae would not only provide a sustainable solution for agriculture, but also for the damaged ecosystem of Western Port Bay. As expressed in "Understanding the Western Port Environment", the combined effects of sea-levels rising and increased storm surges have eroded the coastlines. The eroded sediments remain suspended in the water, which has reduced ecosystem biodiversity. Algae paired with seagrass has been explored as an option to both slow erosion and sequester carbon dioxide (Understanding the western port environment, 2010).

A consistent and plentiful water supply is necessary for algae production. This was considered when analyzing the potential for algae production in Bass Coast Shire. Due to the anticipated population growth and impacts of climate change, Bass Coast Shire Council is committed to adopting an Integrated Water Management approach (IWM). IWM, developed in 2020, involves the management of all types of water, including stormwater, wastewater, and potable water sources. Among the IWM's values are: "freshwater is a limited and vulnerable resource that is prioritized for specific uses" and "wastewater systems are effective and affordable". The Bass River and Powlett River are the region's key freshwater sources, neither of which are large enough to support an industrial algae operation. In addition, both rivers suffer from low water quality and are home to wetland ecosystems filled with native wildlife (Bass Coast integrated water management plan – strategy document, 2020).

Bass Coast Shire has two wastewater treatment plants, both belonging to Westernport Water (WPW). The primary wastewater treatment plant is in the town of Cowes on Phillip Island, while the secondary plant (King Road Wastewater Treatment Plant) is in nearby Coronet Bay (Wastewater, n.d.).

WPW supplies wastewater services to **90%** of the properties, **commercial and residential**, in Bass Coast Shire that receive water. WPW also sells **recycled water** and reuses sewage biosolids for farming.

Source: (*Wastewater*, n.d.)

WPW Primary Facility
Treats 1148 ML of wastewater annually, and 90% of the waste by volume
WPW Secondary Facility
Treats 183 ML of wastewater annually

Source: (*Wastewater*, n.d.)

Based on preliminary research, Wonthaggi is a viable city in Bass Coast Shire for industrial algae production. This is largely because Wonthaggi has 5,730 hectares available for development and has been "identified within the Bass Coast Planning Scheme's settlement hierarchy as a regional center with high spatial growth capacity" (Urban development program - shire of Bass Coast, 2013). Wonthaggi is the largest city in Bass Coast Shire, with a population of approximately 5,000. Although it has several wetland reserves, the city has fewer land regulations, aesthetic infrastructure limitations, and spatial constraints than smaller, more coastal towns in Bass Coast Shire. The northeast outskirts of the city have the most available flat land for industrial algae production (Figure 20). The Wonthaggi Wind Farm, although it currently only supplies residential power, could potentially provide a sustainable energy solution for algae production (Wonthaggi wind farm, 2021).

Topographic Map of Wonthaggi

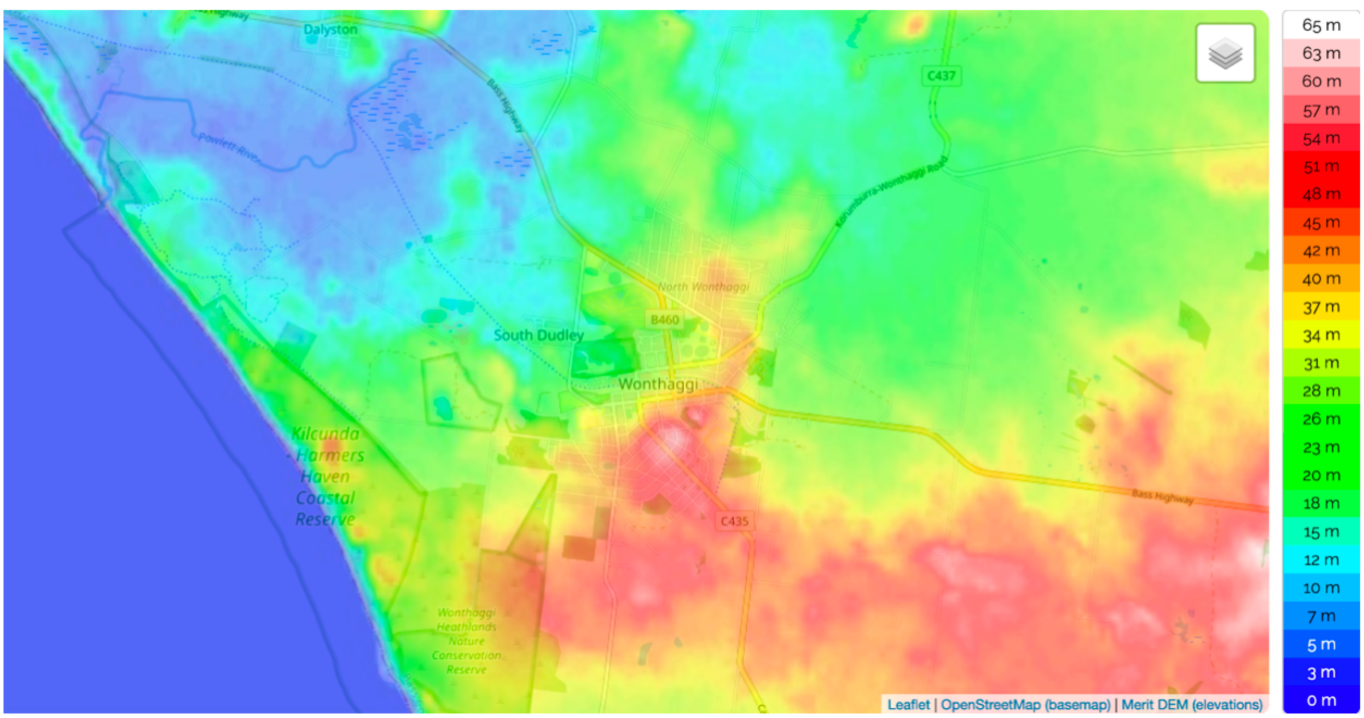


Figure 21: Bass Coast has areas of high and low elevation. The northeast quadrant of the city has a similar elevation, making it an ideal location for algae cultivation.
Source: (Wonthaggi topographic map, elevation, relief, n.d.)

MCDA RESULTS

LATROBE VALLEY

Table 13: Latrobe Valley Climate and Geographical Factors Scoring

Site Selection Criteria	Multiplier	Raw Score	Weighted Score
Average solar insolation per day ($MJ/m^2/d$)	3	1	3
Months per year with average solar insolation per day > 18 $MJ/m^2/d$	1	1	1
Average annual temperature (°C)	2	1	2
Months per year with average temperature 17-28 °C	2	1	2
Slope of terrain (%)	1	2	2
Annual pan evaporation (mm)	1	3	3
Average annual amount of severe weather events	1	3	3
pH of water source	2	2	4
		Total Score	20

The total score given is 20 for the climate and geographical factors of Latrobe Valley. The location selection criteria factor that contributed the highest score was the pH of the water source. This is because Latrobe was given a raw score of two, and the criteria factor was multiplied twice. On the other hand, the months per year with average solar insolation per day >18MJ/m^2/d contributed the lowest weighted score. Both the multiplier and the raw score were scored as one.

Table 14: Latrobe Valley Commercial Factors Scoring

Site Selection Criteria	Multiplier	Raw Score	Weighted Score
Public awareness	2	2	4
Political acceptability	3	1	3
Existing energy infrastructure	3	3	9
Reliability of power source	2	3	6
Proximity to main highways (km)	1	3	3
Proximity to railroads or ports (km)	1	3	3
Proximity to saltwater source (km)	2	0	0
Access and availiability of fresh water source	3	1	3
Access and availiability of wastewater source	3	2	6
Extent of region's land regulations	2	2	4
Can you expand the operation?	1	3	3
		Total Score	44

Latrobe earned a total weighted score of 44 for commercial factors. Out of the five critical success factors, proximity to a saltwater source was the only factor to score a zero. However, since freshwater and wastewater sources are available in the area, the Latrobe Valley location can still be considered. Existing energy infrastructure earned the highest weighted score possible, which is a nine. This is due to the factor having a three multiplier and the raw score also earning a three.

BASS COAST SHIRE

Table 15: Bass Coast Shire Climate and Geographical Factors Scoring

Site Selection Criteria	Multiplier	Raw Score	Weighted Score
Average solar insolation per day ($MJ/m^2/d$)	3	1	3
Months per year with average solar insolation per day > 18 $MJ/m^2/d$	1	2	2
Average annual temperature (°C)	2	2	4
Months per year with average temperature 17-28 °C	2	2	4
Slope of terrain (%)	1	3	3
Annual pan evaporation (mm)	1	3	3
Average annual amount of severe weather events	1	3	3
pH of water source	2	2	4
		Total Score	26

The Bass Coast Shire had a total weighted score of 26. This is six points higher than the Latrobe Valley scored in the climate and geographical factors. This also means that Bass Coast Shire earned 66% of the possible points that it could have. There is not much variation in the scores, as each of the criteria's weighted scores were between a two and a four.

Table 16: Bass Coast Shire Commercial Factors Scoring

Site Selection Criteria	Multiplier	Raw Score	Weighted Score
Public awareness	2	3	6
Political acceptability	3	3	9
Existing energy infrastructure	3	2	6
Reliability of power source	2	3	6
Proximity to main highways (km)	1	3	3
Proximity to railroads or ports (km)	1	3	3
Proximity to saltwater source (km)	2	2	4
Access and availiability of fresh water source	3	1	3
Access and availiability of wastewater source	3	3	9
Extent of region's land regulations	2	1	2
Can you expand the operation?	1	0	0
		Total Score	51

A total weighted score of 51 was earned for Bass Coast Shire's commercial factors. This is approximately 74% of the total possible points for this location since the highest possible score for commercial factors is a 69. Out of the five critical success factors, none received a zero. The two location selection criteria factors that scored the highest were the political acceptability and the access and availability of a wastewater source. Those factors were two of the four factors given a multiplier of three. The only location selection criteria factor that scored a zero was whether the operation could be expanded.

MCDA CONCLUSIONS AND IMPLICATIONS

Although Morwell, Latrobe Valley, and Wonthaggi, Bass Coast Shire share a similar climate and are in close proximity (~100 Km) to each other, their economic differences suggest that different algae co-products would be more relevant to one location over another.

LATROBE VALLEY

As stated previously, Morwell, Latrobe Valley is home to the Gippsland Water Factory (GWF). Presently, Gippsland Water Factory employs a three-stage sanitation method for the wastewater (Wastewater treatment, n.d). These steps were designed initially with the goal to recycle water back to the Maryville Mill and reduce wastewater odors. After these goals were achieved, GWF had shifted to prioritize sustainability (Gippsland water factor, n.d.).

This new priority makes GWF an ideal candidate for tertiary wastewater treatment through algae bioremediation. The tertiary stage of wastewater treatment serves to remove organic material through chemical or biological means. While a chemical-based tertiary treatment is effective, it is also expensive (Mohsenpur, 2021). A biologic-based tertiary treatment is inexpensive and performs similarly to chemical treatment. If algae could be integrated into or replace the existing tertiary water treatment stage at GWF, it would further the sustainability of the operation through value-added products from algae biomass. Blue-green algae (BGA) are commonly found growing natively in the Latrobe Valley in ponds and lakes. BGA is robust and it has been proven that the region's climate conditions are conducive for BGA growth, it is worth considering as a tertiary treatment for the Gippsland Water Factory. The algae would not only treat water but also capture carbon dioxide and provide the opportunity for biomass production for low-value products.

Coupling wastewater treatment for GWF with algae cultivation for an algae company is mutually beneficial. Algae as a tertiary wastewater treatment is inexpensive for the wastewater treatment plant and the algae company would have minimal costs associated with water. A potential suggestion would be the addition of an open pond on-site or near the GWF. This open pond would receive the wastewater following the second sanitation step. A paddlewheel would circulate the water through the algae, either BGA or another species, allowing the algae to come into contact with the wastewater to absorb excess nitrogen and phosphorus, among other substances. Absorbing these substances is important, as excess nitrogen or phosphorus could cause eutrophication if the wastewater effluent is deposited into a body of water.

There are additional opportunities for algae beyond wastewater treatment and biofuels in Morwell, Latrobe Valley. The many cattle, calf, lamb, and sheep farms for slaughter and dairy (3,165 as of 2018) indicate that animal feed derived from algae would be a potential coproduct appropriate for Latrobe Valley (About my region – Latrobe-Gippsland Victoria—Department of Agriculture, n.d). It is up to the algae company to decide if the animal feed will be developed subsequently or simultaneously with the algae biofuel. A subsequent development would require the lipids from algae to be extracted first, and the remaining vitamins, carbohydrates, and protein would be sequestered for animal feed packaging. A simultaneous development would require enough algae to be grown so that some would be siphoned for biofuel production and some would be developed into animal feed. This decision is based on extraction specificity and the nutrient profile of the potential animal feed.

Cattle, calves, sheep, and lamb production contributed approximately 700 million AUD between 2018-2019 to Latrobe Valley's overall agricultural production, which was valued at 2.2 billion AUD for the same period (About my region – Latrobe-Gippsland Victoria—Department of Agriculture, n.d). Algae-based animal feed is a healthy alternative to corn and soybean feed. It also is not a controversial feedstock for animal feed, as the "food versus fuel" debate does not qualify for wastewater algae products. For example, corn grown as a feedstock as a renewable source for ethanol is controversial, as corn is a human food. Algae grown in wastewater is not suitable for human products, so this issue is not encountered.

BASS COAST SHIRE

Similar to Latrobe Valley, there are opportunities in Bass Coast Shire for wastewater treatment. Unlike Latrobe Valley's GWF, Bass Coast Shire's WPW does not have a tertiary wastewater treatment step. Algae could potentially be integrated as a tertiary treatment for the people of Bass Coast Shire. This would further remove heavy metals, toxic chemicals, and other pollutants from the wastewater.

Bass Coast Shire's local leadership recognizes the emerging threat of global warming and climate change. In 2019, a Climate Action Plan was developed to address how the community of Bass Coast Shire will adapt to challenges resulting from climate change (Climate change--taking action, 2020). Algae biofuels, wastewater treatment, and algae coproducts will support Bass Coast Shire's sustainability goals.

Algae fertilizer is one coproduct appropriate for Bass Coast Shire, as farming is a primary driver of Bass Coast Shire's economy. Bass Coast Shire is home to a multitude of crops, including snow and sugar snap peas, cabbages, and grapes (Climate Change--taking action, 2020). Fertilizers are necessary to replenish soil nutrients and support crop productivity. Algae fertilizer is a sustainable alternative to traditional fertilizers and also answers a call to action outlined in the Climate Action Plan to modify agricultural practices into "Regenerative Agricultural" practices, which emphasizes biodiversity and nutrient recycling (Climate change--taking action, 2020).

Algae fertilizers allow farmers to grow high-value and high nutrient foods, such as organic food. Algae is recognized as an organic fertilizer, and paired with other organic farming practices, would benefit farmers. One concern of the Bass Coast Shire Council is decreasing income for their farmers, and suggests value-added practices to increase income (Climate Change--taking action, 2020). Organic food is one way to increase the farmer's income. Another benefit to farmers is that algae fertilizer supports soil health. Some algae fertilizers have been documented to improve soil structure and porosity, accelerate microbe activity, and promote root growth (Gimondo, 2018).

ALTERNATIVE CONCLUSIONS

The results outlined from the Gippsland case study are specific to an open pond system for algae biomass production, therefore, the factors are weighted towards the requirements associated with the open pond systems. The open pond systems and the PBR systems are suited to each produce different algae products. The PBR system has higher production costs than the open pond system, thus to offset these costs, PBR's are best suited for high-value, low-volume coproducts for human consumption. Due to the strict regulations on these human coproducts, more environmental control is needed than for high-volume coproducts produced in open pond systems.

For the MCDA, this means that the set of questions used to evaluate the climate and commercial can be given different weights based on the production system and products that a company is interested in developing. Therefore, if the hypothetical company in our case study compares the locations in Gippsland for a PBR system, the score distribution and total score would have likely changed.

In our case study, Bass Coast Shire had a higher score than Latrobe Valley for both the climate and commercial factors. This means that the company would have been recommended to choose Bass Coast Shire as the location to operate an open pond algae facility. It is possible that Latrobe Valley would have had a higher score if the questions and scores were altered, especially considering that questions such as access to fresh water and wastewater would not be as highly weighted for a PBR system. Suitable temperature and pH ranges would still be important from the perspective of minimizing energy costs, but not vital to algae growth as PBR systems can compensate for these environmental factors.

A similar conclusion can also be made for an offshore facility. Many of the climate factors would still be relevant, but the commercial factors would need to change. For example, the land regulations would have to be adapted to consider ocean regulations, and transportation of feedstock and biomass between sea and land would need to be considered. In addition, factors relating to the maintenance of infrastructure would be of heightened importance due to the unforgiving currents of the ocean. The most significant change would be eliminating the water availability factors in the MCDA, as offshore operations assume growth in saltwater. An MCDA would still be relevant to an offshore facility even with a significant change in critical success factors and barriers, as there would be many decisions and priorities to consider.

ALGAE IN A CIRCULAR ECONOMY: BASS COAST SHIRE

The goal of a circular economy is to reuse and extend the life of a product by repairing or remanufacturing the product in order to close the industrial ecosystem loop. This places an emphasis on preserving products instead of creating new ones (Alamerew et al., 1970).

The circular economy model has the potential to support the algae industry. In the below graphic, algae are first grown in wastewater as a tertiary treatment (Figure 21). Then, the algae are periodically harvested to allow new algae to grow and provide biomass for biofuel processing. Non-lipid-containing biomass would be further processed into fertilizer, which would be delivered to farmers. There is also the opportunity for the cleaned wastewater to be provided to farmers, as cleaned wastewater is typically not permitted for human consumption. This circular loop seeks to repurpose and recycle as much of the water and algae as possible. Additionally, this loop could be amended or expanded to include other coproducts.

Australia is implementing a circular economy to assist in reducing its greenhouse gas emissions by 26-68% by 2030. This goal will reduce its greenhouse gas emissions below the levels produced in 2005. **Source:** (Fleischmann, 2019)

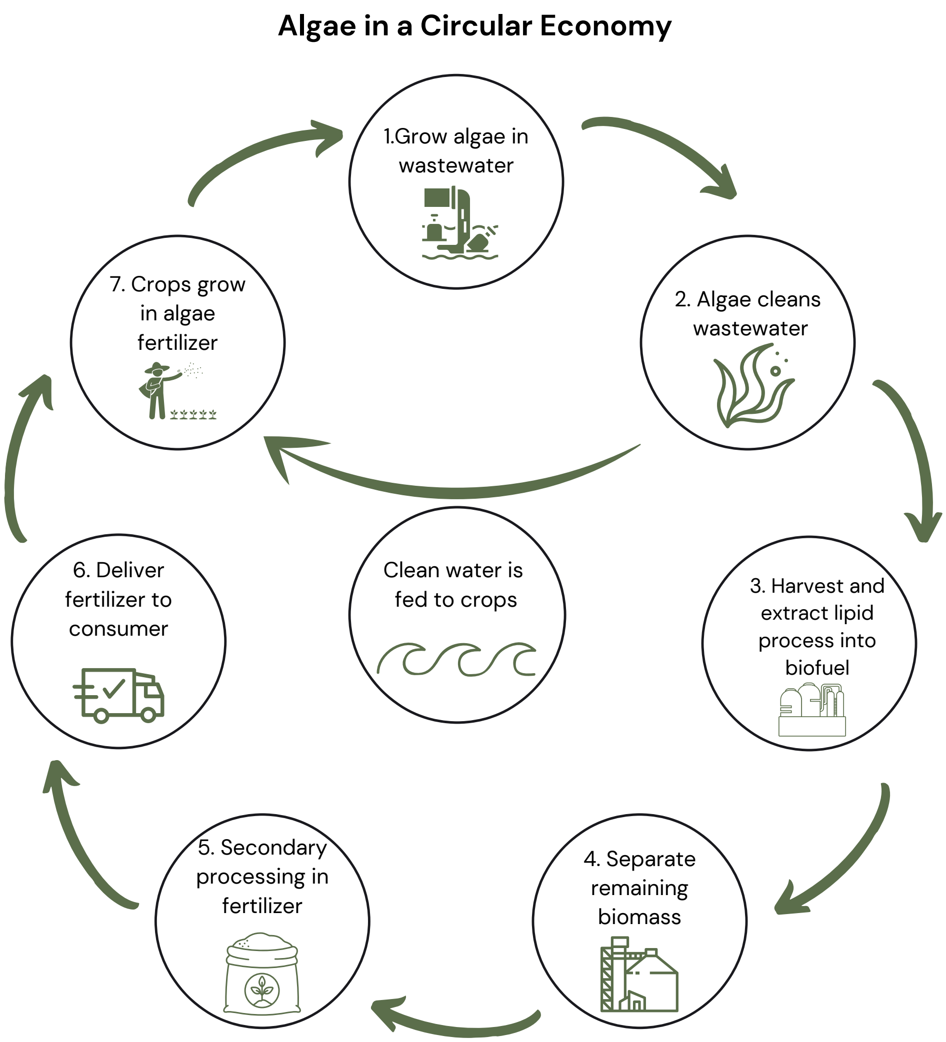


Figure 22: Algae supports the circular economy model as it can be developed into sustinable goods and services.

Conclusions

COMMERCIALIZING ALGAE PRODUCTS

Growing and harvesting algae have been thoroughly researched and demonstrated, but there are **major gaps** between **algae production and commercialization**. A key barrier to commercializing algae initiatives, as seen with algae biofuels, is high capital costs. This can be overcome by **coupling low-value and high-value products** and/or utilizing **wastewater** as a growth medium. This coupling maximizes algae usage and minimizes waste to align with circular economy ideals.

PRODUCT - PRODUCTION SYSTEM RELATIONSHIP

Varying algae production water requirements and product regulations lead to the following relationship: **low-value products** like fuel and fertilizer are more suited for **open pond systems**, while **high-value products** like nutraceuticals are more suited for **PBR systems.**

ASSESSING A LOCATION'S POTENTIAL FOR ALGAE

The algae industry currently lacks a globally applicable location assessment methodology for the potential of algae initiatives. The methodology developed in this report lays a useful foundation for assessing the overall potential for algae in a particular location, but it involves several assumptions and limitations**.** Political acceptability, water accessibility, and land usage are the **critical success factors** of this location assessment methodology. The city of Morwell in Latrobe Valley and the city of Wonthaggi in Bass Coast Shire have high commercial potential for algae operations. Wastewater treatment paired with algae biomass production of low-value products in an open pond system has high potential in Latrobe Valley and Bass Coast Shire. Producing **algae animal feed for Latrobe Valley** and **algae biofertilizer for Bass Coast Shire** align well with the local environmental needs and goals.

LOOKING AHEAD

The trends of anthropomorphic climate change hold grim implications for the future. A multifaceted and immediate response is required to address the consequences of climate change. Although commercializing algae products is challenging, algae can provide sustainable solutions that benefit the planet and people. Algae has the potential to simultaneously become a **valuable carbon sequestration tool a**nd make large impacts in **several product streams,** including fuel, food, fertilizer, and specialized human products.

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Appendices

APPENDIX A: INTERVIEW QUESTIONS

CATHERINE LEGRAND INTERVIEW

1. What led to the creation of Algoland? Were other renewable energy sources considered, or has algae/marine permaculture always been a passion of yours?
2. Because Algoland is university research, have there been commercial constraints on this project? We noticed that the university is partnered with several organizations and research groups, but has there been commercial interest?
3. What are Algoland's two, five, and ten year goals?
4. What are some of the major barriers you have encountered in the sustainable feed project? Has feeding the hens the algae-fed mussels produced positive results?
5. Your paper found that DS increased BPF in three temperature treatments (6, 10, and 12 C) compared to Nitrogen limited cultures. However, we have read that some algae species require much warmer conditions to grow (20C+). Would you say your temperature/DS algae treatment is species specific? Do you think all algae have species-specific conditions to maximize growth/lipids and there is not a one-size fits all approach? To your knowledge, would any algae species not produce more lipids in nitrogen limiting environments or DS?
6. How challenging is it to genetically engineer algae to express more lipids? For example, the DOE altered microalgae to overexpress SNRK gene, which increases photosynthesis. In this paper , you identify the DGAT gene as a potential controller of neutral synthesis. Would the increased expression of either of these genes synthesize more lipids in comparison to nitrogen limitation or DS?
7. Is it possible that the DS would cause any inconsistencies in the biomass product? The idea of DS contradicts other information we have read that states stagnant climate conditions are best for algae growth.
8. Your paper suggests a year-round algae cultivation method. This suggestion is interesting because previous life cycle assessments recommend growing algae only in certain months, primarily to avoid the energy requirements needed to heat the algae water in winter. Do you think your suggestion of nitrogen-limitation in winter and spring and DS in the summer and fall to cultivate algae year round is energetically "worth-it"? Would some locations have to shut down cultivation in winter months due to the energy required for heating?
9. In your opinion, which microalgae product(s) do you think are most valuable to the circular economy? One product we have encountered that is relevant to both microalgae and the circular economy is fertilizer, for example.
10. Sweden has been renowned for its progressive strides in terms of environmental awareness. Although algae biofuels are a bit of a challenge for the United States, do you have any recommendations, however small they might be, that would be feasible in the United States?
11. Have you seen the Algokidz Program bringing awareness to kids or the general public? What is its reception in Sweden?

DAN MULDER INTERVIEW

1. Was Pacific Biotech founded as a bioremediation company, and did the algae products come after? How long did it take for Pacific Biotech to develop RegenAqua?
2. What was the most difficult barrier to commercialization for RegenAqua? Did you have issues with regulations, funding, or product reception?
   a. How did Pacific Biotech choose their headquarter location? Was it based on regulations? Does Pacific Biotech research also take place at the headquarters?
   b. We very recently have been looking into Latrobe Valley as a location for potential algae water treatment and/or other algae production infrastructures in Australia. Do you have any information on whether this location is suitable for commercialization? (In your opinion, what factors (like rain and sunlight) are most important for algae growth?)
3. On the Pacific Biotech website, RegenAqua's is described as financially advantageous. From our readings, it is challenging for an algae product to be affordable. What enables RegenAqua system to be financially advantageous over other bioremediation products?
4. On your website it mentions that the RegenAqua system can be used for customers of all sizes, from municipal treatment plants to industrial companies. At what customer scale have you received the most interest? What industries do your customers represent?
5. What are Pacific Biotech's two, five, and ten year goals? Are there considerations for new algae products?
6. Do you foresee clean water algae products (eg. food, nutraceuticals, cosmeceuticals) or wastewater algae products (eg. fertilizer or bioplastics) being more successful in the next 10 years? Would your answer change if I asked you about the next 50 years?
7. What are Pacific Biotech's electricity requirements? Is there an opportunity for renewable energy to supplement those requirements?
8. Is the algae in the RegenAqua system the same algae used to synthesize ReefAqua?
9. Have RegenAqua or other Pacific Biotech products been featured in any peer-reviewed journals?
10. We are interested in the diagram on the Plant Juice webpage, but are not sure how the prawn production and PlantJuice create a closed loop. Could you please describe the closed loop for PlantJuice further?
11. What made Pacific Biotech develop an astaxanthin nutraceutical over other algae nutraceuticals? Is the astaxanthin extracted through solvent extraction, superfluid extraction, or another method?
12. If you are able to disclose, how do the profit margins of each of the different products produced (RegenAqua, Reefasta, PlantJuice, etc) compare?
13. As a manager, have you had to make compromises on the types of products developed by Pacific Biotech? For example, was an algae cosmeceutical pursued but not launched due to cost?

MARK ALLEN INTERVIEW

1. In your opinion, what are the biggest barriers to algae biofuels and coproducts? Are there any barriers that are U.S.-specific?
    a. In your work, what have you found is most difficult in process engineering? Systems integration? Systems architecture?
2. On Accelergy's website, your biography mentions that you have "frequent policy engagement on Capital Hill". We noticed that the Algae Agriculture Act Of 2018 was introduced to the House Of Representatives, but it doesn't seem that it was pursued further. Could you speak about any more recent developments in the United States government regarding the algae industry?
    a. How do you think the government's awareness of the potential of algae can improve? What about the general public?
    b. How much resistance or acceptance have you been met with by the public and government?
3. As a founding board member of the ABO, how have you seen the organization's international influence grow?
    a. What are the key future goals of the ABO?
4. What are Accelergy's two, five and ten year goals?
    a. Do declining oil costs concern accelergy? Is the algae biofuel product more of a long term business strategy in anticipation of a future need for renewable fuel sources?
5. We saw that Accelergy employs seven individuals, but there are many articles complimenting Accelergy for being a global leader in bio-speciality fluids. How is Accelergy able to be well renowned but maintain a small number of employees?
6. We have read that factors such as sunlight and temperature are important for ideal algae growth. Where does Accelergy research CO2 capture and algae production, and what went into that decision making?
7. We saw in one of Accelergy's patents that you selected to grow algae in a PBR, and that a closed PBR was optimal. What led you to decide on a closed PBR over an open PBR or open pond system?
8. We have read various algae reports that use clean water or waste water to cultivate algae. There are drawbacks and benefits to each water source. What type of water does Accelergy use?
9. We read that your company utilizes algae to capture CO2 and then that same algae is turned into fertilizer, among other products. What treatment or extraction process does your algae go through prior to becoming a fertilizer? Do you employ organic solvent extraction or supercritical fluid extraction?
10. What partnerships or agreements with multinational oil companies such as ExxonMobile or BP, who are also headquartered in TX, does Accelergy have? How receptive has the oil industry been to your carbon capture technology?

MARTIN GROSS INTERVIEW

1. We admire that your thesis research led to Gross-Wen's inception. What was the most difficult barrier to commercialization for Gross-Wen Technologies? Did you have issues with regulations, funding, or product reception?
2. On the Gross-Wen website, the RAB's affordability and efficiency is highlighted. From our readings, it is challenging for an algae product to be both efficient and affordable. What enables the RAB system to be both efficient and affordable?
3. On your website it mentions that the RAB system can be used for customers of all sizes, from small towns to industrial companies. At what customer scale have you received the most interest? What industries do your customers represent?
4. Can the RAB system be efficient in any environment, or are there constraints based on the amount of sunlight?
5. The Gross-Wen website promotes that the algae used in the RAB can be repurposed into fertilizer and bioplastics. From our readings, synthesizing fertilizer and other algae coproducts is capital intensive. To your knowledge, how many of your customers are able to or have repurposed the algae into other products? If so (and if you are able to disclose), what products have they developed?
6. Your thesis describes the potential for algae as a biofuel, but the RAB is marketed as a waster-water treatment system. Is Gross-Wen in the process of developing their own biofuel?
7. We are interested in the future products for Gross-Wen. We read your 2020 Patent and found it very interesting, especially since our research has revealed the potential for algae food products. What are the possible algae foodstuffs Gross-Wen is considering? Is the focus more towards nutraceuticals or standard food products (eg. algae spaghetti)?

BRIAN VON HERZEN INTERVIEW

1. We've learned about the abundance of legislation that regulates commercial ocean activity. What do you believe are the key regulatory barriers for the Climate Foundation's projects?
    a. How were you able to determine that you could cut out decades of permits by applying for a vessel that required just a few months instead of a permit for a seaweed forest that could have taken 3-10 years in the USA?
2. What species of kelp/algae has CF determined is best for marine permaculture? Does this answer change if the kelp/algae is primarily utilized as a carbon sink or if the algae/kelp is recycled into secondary products?
3. Does this answer change if the kelp/algae is primarily utilized as a carbon sink or if the algae/kelp is recycled into secondary products? How do you compare offshore algae/kelp cultivation in relation to onshore, in terms of potential and commercialization? For example, onshore algae cultivation trades greater control of the plant for cost. Is this trade off worthwhile?
4. What are some negative environmental effects that you have encountered with marine permaculture? Is there a potential for the upwelling pipes to disrupt natural currents, the kelp to sustain an invasive/non-native species, or increased chance for algae blooms?
5. Has The Climate Foundation noticed if costs for the marine permaculture cost decreases linearly or exponentially as you increase size? What are the cost differences if kelp is grown off the coast of California or Australia?
6. Do you have upcoming publications for CF sponsored research? If so, where could we find them?
7. Are there any emerging marine permaculture, algae biomass, or algae cultivation initiatives that we should be made aware of? (Eg. Marine Bioenergy, Makai Ocean Engineering, Fearless Fund, Catalina Sea Ranch and C.A.Goodey and Associates Autonomous Tow Vessels Program, Senator Whitehouse)
8. How do you see algae products contributing to Australia's circular economy?

NICHOLAS NEVEUX INTERVIEW

1. Your articles mention growing algae in only open containers. How did you and your colleagues decide that open containers would work best for algae cultivation? Were photobioreactors ever considered?
2. In your 2016 article titled "Adding value to the treatment of municipal wastewater through the intensive production of freshwater macroalgae", it is stated that a large and consistent water supply is needed. How do the water requirements (volume of water needed) of wastewater algae operations compare to solely freshwater or marine operations?
    a. Also in this article, a water dilution rate is discussed for low nutrient wastewaters. It's stated that when using freshwater macroalgae, a water dilution rate between 50 and 100% per day is sufficient for high productivity. Could you speak to what this 50-100% means?
3. We are aware that nitrogen starvation causes algae to increase lipid content. Is there research on how that affects other molecules found in algae, such as carbohydrates and PUFAs, for example?
4. We have read about the many ways to extract lipids from algae. Some methods include organic solvent extraction and supercritical fluid extraction (SFE). Your papers are the first source that described HTL as a means to create an algae biofuel. In your opinion, what factors lead you and your colleagues to choose HTL over other extraction methods?
5. In this article, "Adding value to the treatment of municipal wastewater through the intensive production of freshwater macroalgae" you and your colleagues grew and harvested algae over a year-long period. The resulting paper describes seasonal effects on biomass productivity, with the algae yielding increased productivity in the summertime. We have read other research that suggests growing algae only during the warmer months. How do you determine the point at which it is less productive (in terms of biomass, energy usage, costs) to grow year round as opposed to seasonally?
6. In the same article as above, the algae genus Oedogonium was selected because it can continuously propagate and did not need to be re-inoculated over the 12 month growth period. What is "re-inoculation", and what algae species can't continuously propagate?
7. In this article, "Comparing the potential production and value of high-energy liquid fuels and protein from marine and freshwater macroalgae" you and your colleagues describe sequential extraction steps for extraction of lipids and proteins. Would you be able to elaborate on what steps those are?
8. In your 2019 article "Selecting extraction conditions for the production of liquid biostimulants from the freshwater macroalga Oedogonium intermedium", your conclusions were that the biomass-to-solvent ratios and pH conditions (extraction time, biomass-to-solvent ratio, or temperature) had the greatest impact on the tomato plants for biostimulants. Why do you believe those were those more influential than the time and temperature of the extraction?
9. Going off of that same article, was light exposure/type of light ever considered to be studied as an extraction condition?
10. Pacific Biotech has products spanning several industries. We were wondering how the species and strain of algae change from the low value products, such as fertilizer, to the high value products, such as nutraceuticals?
11. We had briefly discussed Pacific Biotech's nutraceutical product ReefAsta with Dan Mulder a few weeks ago. We were hoping you could give us more insight into the details of the product. What type of solvent or extraction method is used to obtain the astaxanthin, and what specialized species did you consider and eventually decide on?