MICROALGAE TECHNOLOGIES & PROCESSES FOR BIOFUELS / BIOENERGY PRODUCTION IN BRITISH COLUMBIA:

Current Technology, Suitability & Barriers to Implementation

Final Report Submitted to

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by

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EXECUTIVE SUMMARY

Microalgae (algae) are currently being promoted as an ideal next generation bioenergy feedstock because they do not compete with food or feed crops, can potentially produce much higher areal oil yields than current agricultural crops, and can be produced on barren land. Algae have broad bioenergy potential as they can be used to produce liquid transportation and heating fuels, such as biodiesel and ethanol, or anaerobically digested to produce biogas[1].

Three main technologies are currently being pursued to produce algae for bioenergy applications. These are:

- Phototrophic cultivation in open raceways,
- Phototrophic cultivation in closed photobioreactors[2] (PBRs), and
- Heterotrophic cultivation in closed fermenters.

Raceways have lower capital costs and energy requirements than PBRs. However, their open nature makes them more susceptible to contamination by undesirable species and environmental conditions (such as low temperatures and precipitation). This severely restricts the number of algal species that can be successfully cultivated as well as the cultivation periods in temperate climates. PBRs can cultivate more, possibly bioengineered, algal species and because of their heat retaining capabilities, can be used for longer periods in temperate climates. However, PBRs can overheat the cultures during the day and the pumping and mixing requirements preclude the culture of some fragile species.

Some algae can be grown heterotrophically using organic substrates in the absence of sunlight. This production mode has the advantages of a readily available technology and fermentation knowledge base, a high degree of process control and independence from environmental conditions. Furthermore, heterotrophic cultivation has been shown to achieve higher volumetric productivities and lipid content than phototrophic modes of cultivation. However, not all species of algae are capable of heterotrophic production.

One of the major cost factors in bioenergy production from algal biomass is harvesting[3]. Harvesting from open raceways is usually undertaken as a two-step procedure in which the algae are first concentrated to a suspension of roughly 1% solids, followed by an energy intensive concentration to 15-25% solids Currently, bio-flocculation is the least expensive method for achieving the first concentration step. However, its unreliability has led many to use organic polymers (polyelectrolytes) instead. [4]

Extensive review of the literature and information obtained from industry insiders resulted in the identification of cost parameters for expected biomass yields, algae oil content, capital, labour and operational costs. A thermodynamic model was developed that uses hourly solar insolation and temperature values in BC to predict maximum biomass yields for the two phototrophic

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[1] Biogas can be burnt to generate electricity and / or heat, or it can be upgraded to biomethane (> 96% methane) for injection into the natural gas grid or compressed and used as a transportation fuel.

[2] PBRs may also be mostly closed, with a small opening to the environment for gas exchange.

[3] This is because the relatively low concentrations of algae in the culture broth need to be concentrated prior to use.

[4] Other methods such as filtration and microstraining are only effective for larger or chain-forming algae species.

technologies. Using this model, the resulting cost per liter of algae oil produced were determined under the following scenarios:

Table ES1 Scenarios Examined for Algal Biomass Production in British Columbia (see Chapter 4 for detailed description).

Technology	Base Case	Scenario 2	Scenario 3	Scenario 4
Raceway	Unheated raceway (run year round)	Heated raceway (run year round)	Unheated raceway (run April to September)	Unheated raceway (run April to September with half the capital costs of Scenario 3)
	Location: Prince George	Location: Prince George	Location: Vancouver Island	Location: Vancouver Island
	9.38 $g.m^{-2}yr^{-1}$	15.47 $g.m^{-2}yr^{-1}$	22.89 $g.m^{-2}yr^{-1}$	22.89 $g.m^{-2}.yr^{-1}$
	15% oil	15% oil	15% oil	30% oil
PBR	15.3 $g.m^{-2}yr^{-1}$ 25% oil	15.3 $g.m^{-2}yr^{-1}$; 35% oil	6,000 $gal.ac^{-1}yr^{-1}$ Ethanol secretion	n/a
Fermenter	50 $g.L^{-1}$;	100 $g.L^{-1}$;	n/a	n/a
	50% oil	60% oil		

RW: Raceway; PBR: Photobioreactor; FER: Fermenter; CC: Capital Costs; PG: Prince George, BC; VI: Vancouver Island.

The results of the economic analysis for each scenario, expressed both in terms of cost ($) per kg of biomass produced and in cost per litre of oil produced, are shown in Figure ES-1. One option to produce ethanol in a PBR was also included. For comparison, the cost per kg of canola, and cost per litre of canola oil are included.

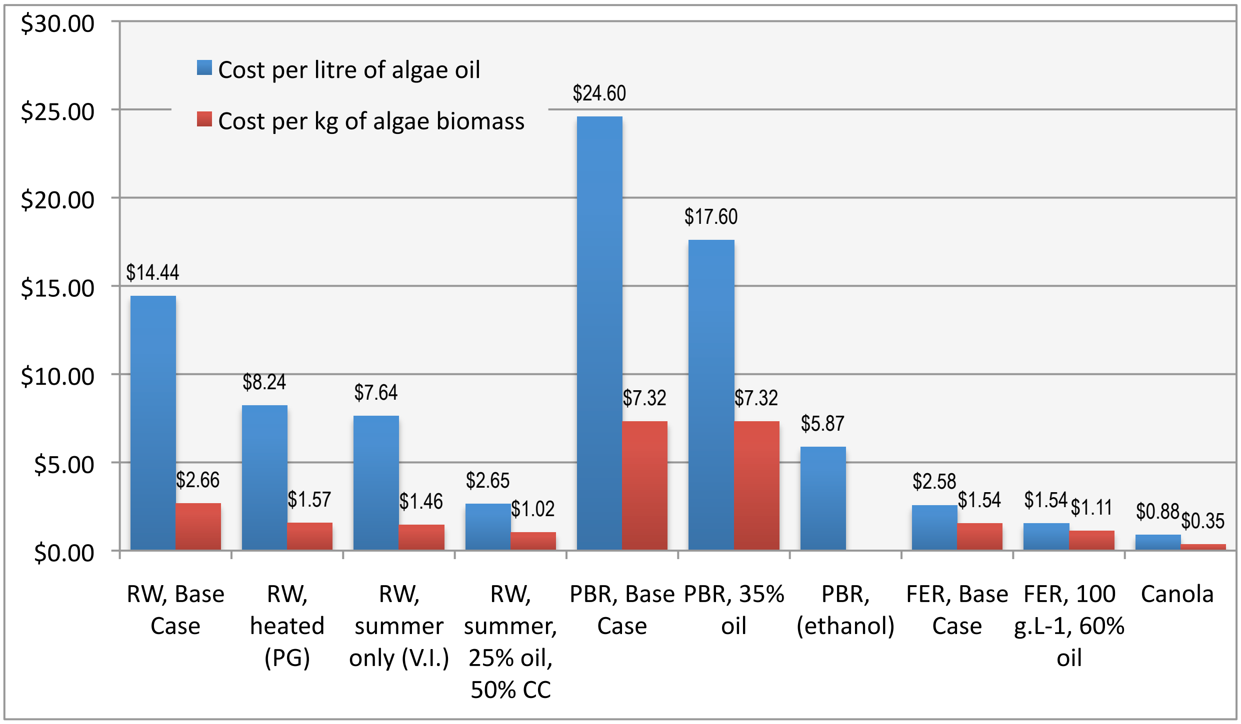

Figure ES-1 Cost per kg of Algal Biomass and per Litre of Oil/Ethanol Produced Using Different Systems and Different Scenarios.

The base case costs for the three different production processes are illustrated in Table ES-2. Raceways have total production costs of $14.44 per litre of algal oil. The majority of this cost is capital (49%) and labour costs (27%)[5]. However, operational costs, such as power and fertilizer, are also substantial (25%)[6]. PBRs have a higher production cost of $24.60 per litre of algal oil. As with raceways, the majority of this cost is capital (63%). Fermenters have the lowest production cost of $2.58 per litre of algae oil. This time the majority of cost is operational (78%) – mainly from the power (31%) and the organic carbon substrate (23%).

Even under the optimistic scenarios in Figure ES-1, currently, none of the processes examined in this study can achieve price parity with fossil fuels. Furthermore, while fermentation appears closest, achieving cost-effective algal biomass production through fermentation still requires significant R&D to generate greater yields and oil content.

Table ES-2 Comparison of Base Case Costs for Three Algal Biomass Production Technologies (US$ per Litre of Algal Oil Produced)

	Raceway		**Photobioreactor**		**Fermenter**	
Initial Investment ($.L^{-1})	52		111		2	
Production Cost	**($ per liter of oil produced)**					
Labour cost	$4.03	26.69%	$2.96	11. 90%	$0.29	10.88%
Other production cost	$3.71	24.59%	$6.37	25.59%	$2.06	78.45%
Capital cost	$7.35	48.71%	$15.56	62.50%	$0.28	10.66%
Total Cost	$15.09		$24.89		$2.63	
Credit from the sale of algae cake*	$0.65		$0.29		$0.05	
Net total cost	**$14.44**		**$24.60**		**$2.58**	
Lipid content	15%		25%		50%	
Cost per kg of algae	$2.66		$7.32		$1.54	

* including revenues from selling the algae cake after oil extraction

Table ES-3 shows the energy balances and GHG performance of the three algal cultivation technologies considered. While not an accurate life-cycle analysis, this shows that in BC all three technologies reduce GHG emissions and have a positive energy balance.

As a consequence of the high yields achievable, the GHG balance for fermentation outperforms both phototrophic options. All technologies compare favourably with the GHG balances of corn ethanol (around 1,400 g.L^{-1}) and biodiesel from canola (2,800 g.L^{-1}). However, this is mainly due to the electricity being almost carbon neutral in BC and might not hold true in most other jurisdictions. Likewise, the energy balance of the fermentation process is also better than both the phototrophic technologies[7], and at 1.93 (i.e. for one unit of energy input, 1.93 units are gained) compares favorably to both corn ethanol and biodiesel from canola oil (which have energy ratios of around 2).

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[5] While high labour costs differ from previous work, this has been confirmed by two independent sources.

[6] Algae cultures in raceways require the constant operation of paddle wheels or pumps to move the growth medium and prevent algal settling.

[7] The low energy balance for phototrophically grown algae is due to much greater energy input requirements, i.e. the need for continuous mixing, pumping, harvesting, and CO_2 insertion. The balance would be improved if cultivation were in more southern areas with higher insolation.

Table ES-3: Energy and GHG (CO_2) Balance per Liter of Oil Produced Using Three Different Technologies (see Chapter 5 for detailed description)

	Raceway	**Photobioreactor**	**Fermenters**
CO_2 Balance (Grams per liter)			
CO_2 Balance ($g.L^{-1}$)	6,097	4,108	3,117
Energy Balance (MJ per liter)			
Energy balance ($MJ.L^{-1}$)	-39.7	-11.5	-21.9
Energy ratio	1.76	1.23	1.93

Algae cultivation has also been attractive because of its potential to fix atmospheric or fossil fuel derived CO_2 into biomass, potentially enabling the generation of carbon credits through sequestration of the biomass or by the production of carbon neutral fuels[8]. However, if algae were cultivated to capture and sequester CO_2 in BC, based on current costs of production, this would cost around $793 per tonne of CO_2[9]. Furthermore, if the algae were used to make biofuels, this activity would only be eligible for offsets if enough biofuel could be produced to exceed the BC mandated level of 5%. How this would be determined is as yet unknown.

One possibility to improve the economic feasibility of bioenergy production from algae is to adopt a biorefinery model and co-produce additional (ideally, high-value) products. An initial analysis on eicosapentaenoic acid (EPA), an omega-3 acid ester, showed substantial potential for algae oil cost reductions[10]. The production of this or other high value products could help make algae bioenergy more economically feasible.

In summary, analysis based on ***current*** algae production technology shows that:

- While potentially feasible in geographic locations with cheap labour and high insolation, raceways are unlikely to produce algal oil at prices competitive with fossil fuels in BC or Canada. While the production of a specialty product may improve the economics of raceway production, its susceptibility to contamination is a major limitation to its use.
- PBRs are unable to economically produce bioenergy from algae.
- Fermentation appears to be the most promising option to make biofuels from algae. In addition, it is independent of climatic conditions, while the costs and energy balances may be equivalent to first-generation biofuels (if yields and oil content can reach high levels).

Algae-to-bioenergy technologies are still pre-commercial, and will require significant R&D to increase productivity and reduce costs. Consequently, successful commercial-scale bioenergy production from algae is unlikely in BC in the near term.

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[8] By displacing fossil fuels

[9] This calculation only considers the carbon fixed in the algae biomass. If carbon losses and costs from electricity, fertilizer use, transportation, deep burial etc. were included, this cost per would be even higher.

[10] The size of the EPA market at current price levels, however, would need to be confirmed in order to sustain the validity of this finding in the context of large-scale algae oil production.

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Glossary and Abbreviations

Air floatation	Process of floating clumps of algae cells using minute bubbles which attach to the clumps and make them float
Anaerobic digester	A sealed vessel or vessels in which microorganisms break down biodegradable material in the absence of oxygen, producing methane and biogas
Bcf	Billion cubic feet
Bcfd	Billion cubic feet per day
Bcm	Billion cubic meters
Biodiesel	A substitute for diesel fuel made from organic products
Bioenergy	Renewable energy made from organic sources
Bioethanol	Renewable ethanol made from organic sources
Biofuels	Solid, liquid or gas fuel derived from biological material
Biogas	The mixture of gases, including methane, formed during the anaerobic digestion of organic wastes
Biomethane	Methane portion of biogas, after upgrading to natural gas quality
Butanol	A primary alcohol that can be used as a substitute for gasoline with no modifications
Cyanobacteria	Prokaryotes microbes having characteristics of both bacteria and algae
Decarboxylation	The removal of a carboxyl group from an organic compound
Degasser	Section of a closed photobioreactor where gas exchange occurs
Desulphurization	Catalytic chemical process used to remove sulfur from natural gas and refined petroleum products
Electroflocculation	Process of inducing flocculation by electrical current
Feedstocks	Input (raw) materials required in the production of biodiesel
Fermenter	A closed vessel for aerobic culture of algae using organic carbon sources as nutrients
Flocculate	The aggregation of materials (e.g. algae cells) together to form large clumps
$g.L^{-1}.d^{-1}$	Grams per liter per day
$g.m^{-2}.d^{-1}$	Grams per square meter per day
GL	Giga liters
Gt	Giga tonne
Heterotrophic	Mode of producing microorganisms on organic substrates in the absence of light
Hydrocarbon dew point	The temperature at which the hydrocarbon components of a hydrocarbon rich gas mixture will start to condense out of the gaseous phase
Hydrogenase	An enzyme that catalyses the reversible oxidation of hydrogen
IEA	International Energy Agency (http://www.iea.org/)
IPCC	International Panel on Climate Change (http://www.ipcc.ch/)
Isoform	A protein that has the same function as another one but is encoded by a different gene sequence

kWh	Kilowatthour, a unit of energy
Lignocellulose	Biomass composed of cellulose, lignin and hemicellulose
Lipid	Fat soluble molecules
Mb/d	Million barrels of oil per day. One barrel = 34.97 imperial gallons = 158.99 liters of oil
$\mu E.m^{-2}.s^{-1}$	Microeinsteins per meter square per second, unit of irradiance. 1 einstein = 1 mole of photons
Mesophilic	Organism that grows best at moderate temperatures (typically between 15 to 40°C
Microalgae	Microscopic single celled plants
Mixotrophic	A culture mode whereby a cultured photosynthetic organism (e.g. algae) utilizes both inorganic carbon dioxide in the presence of light as well as organic carbon.
ML	Megalitres
MLS	Multiple Listing Service® of the Canadian Real Estate Association
μmole photon.$m^{-2}.s^{-1}$	Micro mole photons per meter squared per second
Mwh	Megawatthour, a unit of energy
NOx	Nitrogen oxides
OPEC	Organization of petroleum exporting countries
PBR	Photobioreactor
Continuous perfusion	Process whereby cell free media is continuously removed from a culture (usually through a hollow membrane) and fresh media added thereby enabling removal of toxic metabolites
Photoinhibition	A reduction in photosynthetic capacity caused by exposure to excess light.
Photon	A quantum unit of light energy
Photon fluence	Total number of photons hitting a given area
Photo oxidation	Oxidation under the influence of light
Planktonic	Microorganisms that inhabit the water column
Polyelectrolyte	Polymeric organic compounds with an electrolyte group, which, upon dissociation in water, makes the polymers, charged. They are used to neutralize the surface charges of materials (e.g. algae cells) during flocculation
Psychrophiles	Organisms capable of growing and reproducing in cold temperatures
Pyrolysis	The decomposition of organic materials by heat
Quantum	The smallest realizable unit of something
Stillage	The residue at the bottom of a still after fermentation containing solids but no alcohol
Syngas	A hydrogen and carbon monoxide-rich gas obtained through heating a carbon feedstock, such as biomass to very high temperatures
Thermophiles	Organisms which thrive at higher temperatures
Transesterification	The process of exchanging the alcohol group of an ester compound with another alcohol
Turbidostat	Continuous culture device with a feedback between the turbidity of the culture and the dilution rate

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1 Introduction

Microalgae (algae) are microscopic plants that are the primary synthesizers of organic matter in aquatic environments. They have high surface area-to-volume ratios, enabling the rapid uptake of nutrients and carbon dioxide (CO_2) and a much faster cell growth rate than land-based plants. Algae have been used in human food and health food products (50; 101; 102), feeds for fish larvae, shellfish and livestock (13; 17; 64; 102), and have been cultured for their high-value oils (16; 52; 53; 130; 131; 148; 169; 198), chemicals, pharmaceutical products (35; 72; 84; 148; 169) and pigments (18; 95; 110; 148; 169).

In the 1980s and 1990s, extensive research into the mass cultivation of algae biomass for the production of biofuels was conducted (26; 166; 195; 196). While the research showed this to be technically feasible, it also showed that, at the time, it was not economically feasible. As such, much of the research was discontinued. However, recent concerns about increasing costs and decreasing availability of fossil fuels, the impacts of CO_2 emissions on climate change, and the shortcomings of first-generation biofuel feedstocks, has led to renewed interest and research into algae cultivation for bioenergy production [11].

The following study was undertaken to provide a robust evidence base of factual information to validate decisions for the strategic development of algae for biofuels in BC. This was undertaken in light of controversies arising from widely varying claims regarding the productivity of algae. What follows is an impartial investigation into the current state of algae technologies and research to determine the feasibility of algae cultivation in BC as bioenergy feedstocks[12].

1.1 *Market Potential for Bioenergy/Biofuels*

The following analysis of the market potential of energy products from algae is limited to biodiesel, bioethanol and biomethane: products for which the technologies for large-scale production exist. By-products, which can impact the economic potential for producing algae biomass, are also considered.

1.1.1. Introduction

The potential market for bioenergy is currently driven by government mandates. However, as energy prices increase, demand for bioenergy may become more price-driven. Technological and regulatory developments, such as the production of more fuel efficient cars, hybrids and battery-powered cars or increased GHG emission reduction targets may also impact demand. What follows is an analysis of global demand for three bioenergy markets: bioethanol, biodiesel and biomethane.

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[11] This research is being conducted by several research groups / companies around the world who are taking advantage of newer technologies and increased cultivation and biotechnology knowledge (48; 117; 129; 143; 163; 189; 201).

[12] Since no commercial algae-to-biofuel operations currently exist and startup companies are generally not forthcoming with their data, this study relied mainly on information published in the literature and numerical calculations. However, to ensure validity, the key findings were confirmed through direct communications with algae experts and industry insiders.

1.1.2. *Global Demand for Bioenergy Products*

1.1.2.1. *Ethanol*

Estimates for international automotive fuel and biofuel production are summarized in Table 1. These estimates show that any fuel efficiency gains in North America and Europe will likely be erased by increased motorization in the developing world (Figure 1).

The range in ethanol production by 2030 in the forecast by Walter et al. (194) (Table 1) represents two scenarios. The lower forecast assumes E10 use in most regions (E20 in Europe), while the higher forecast assumes the use of E16 in the US. The difference between the forecasts made by the IEA (93) and Walter et al. (194) is because the latter assumes that lignocellulosic material will provide the bulk of ethanol feedstocks. None of the forecasters in Table 1 expect the contribution of biofuels to overall transportation fuel consumption to be significant.

Table 1: Current and Projected Future World Fuel and Biofuel Production from various Studies

Fuel Type	**World Production**		**Source**
	2005	**2030**	
Gasoline	1,213 GL.yr^{-1} 21.4 mb.d^{-1} (1,211 GL.yr^{-1})	1,924 GL.yr^{-1} 27.8 mb.d^{-1} (1,613 GL.yr^{-1})	Walter et al. (194) OPEC (139)
Ethanol	33 GL.yr^{-1} 17.1 Mt.yr^{-1} (21.4 GL.yr^{-1})	272.4 – 444.1 GL.yr^{-1} 78.5 – 125 Mt.yr^{-1} (98 – 156 GL.yr^{-1})	Walter et al. (194) IEA (93)
Diesel	22.2 mb.d^{-1} (1,288 GL.yr^{-1})	37.8 mb.d^{-1} (2,194 GL.yr^{-1})	OPEC (139)
Biodiesel	3.8 GL.yr^{-1} 2.9 Mt.yr^{-1} (3.5 GL.yr^{-1})	- 13.9 – 22.1 Mt.yr^{-1} (16.5 – 26.3 GL.yr^{-1}) 51 GL.yr^{-1}*	Walter et al. (194) IEA (93) Johnston and Holloway (96)
Biodiesel & Ethanol	0.7 mb.d^{-1} 40 GL.yr^{-1} +27 GL.yr[1]	2.8 mb.d^{-1} (162 GL.yr^{-1}) -	OPEC (139) Field et al. (69)
Aviation fuel	238 Mt.yr^{-1} 6.4 mbd^{-1}	426 Mt.yr^{-1} 8.5 mb.d^{-1}	IEA (93) OPEC (139)
Marine bunker	3.6 mb.d^{-1} 2.8 mb.d^{-1}	4.3 mb.d^{-1} 5.1 mb.d^{-1}	IEA (93) OPEC (139)
Middle distillates[2]	28 mb.d^{-1}	46 mb.d^{-1}	OPEC (139)

GL: gigaliters (10^9); mb.d^{-1}: million barrels per day; Mt: megatonnes

* maximum potential from agricultural and animal sources, without algae

[1] in addition to current production, from abandoned farmland

[2] Middle distillates include both heating oil and diesel fuel

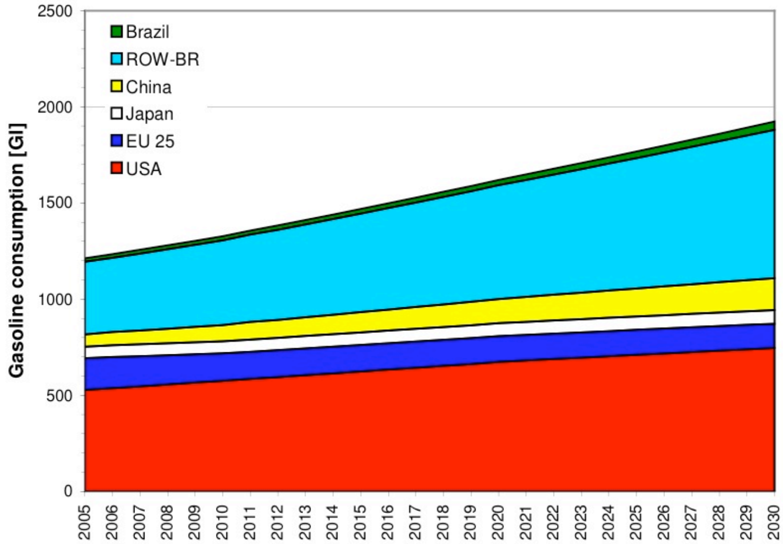

Figure 1: Projected World Gasoline Consumption through 2030 [Walter et al. (194)]. ROW-BR = Rest of the World

1.1.2.2. Biodiesel

The biodiesel market can be broadly classified into four main end-use applications: transportation, non-road applications (mining, forestry, construction, etc), marine, and to a lesser extent, space heating (125). Johnston and Holloway (96) estimated the worldwide potential for biodiesel production by 2030 to be above 50 billion liters[13] and with improved yields, could increase to more than 600 billion liters (primarily from palm oil). These estimates suggest that for algae to gain a market in biodiesel production depends on pricing, not on resource availability, as alternative sources can adequately satisfy market demand for the foreseeable future[14]. However, if all automotive fossil fuels are to be replaced with biofuels, new feedstocks such as algae will very likely be required (46).

1.1.2.3. Biomethane

While unrefined biogas is unlikely to become an internationally traded commodity, it can be refined to biomethane and used as a natural gas substitute. As such, and because biogas could replace LNG, the LNG market can be seen as a proxy for the global biogas market.

Currently, 14 countries import LNG, and this is expected to increase to more than 35 by 2010 (with the main importers being the US, China and to a lesser degree, Europe and India)(30). World exports are estimated to reach 110 Mt by 2010, and 346 Mt by 2030 (94) (Table 2), with imports to the US and Canada increasing from almost net-zero during the 1980's and '90's to more than 147 Mt by 2020 (125).

Table 2: Worldwide Liquefied Natural Gas (LNG) Trade [IEA (94)]

Year	**2004**	**2010**	**2030**
Amount	90 bcm	150 bcm	470 bcm
	(66 Mt)	(110 Mt)	(346 Mt)
% of total natural gas use	7%	9%	23%
Algae required (dry tonnes)	0.5 Gt	0.8 Gt	2.4 Gt

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[13] Estimates of world worldwide biodiesel production based primarily on vegetable oil production and animal fat residues.

[14] Increased demand for sustainable/ethical biodiesel feedstocks may alter this.

1.1.3. Biofuels Market Potential Discussion

The estimates for future biofuel production compared in Table 1, diverge substantially for the year 2030. However, two of the sources agree fairly well on future numbers (125; 139). Since 2005, current (2007) biodiesel production has doubled to 8 GL (127) and ethanol production has increased from 33 to 46 GL, thus vindicating the higher estimates. Based on these most optimistic and pessimistic estimates, and the estimates that algae can produce 267 litres of ethanol (assuming a 40% starch content) and 190 litres of biodiesel per dry tonne, worldwide algal biomass demand in 2030 could be up to 416 million tonnes per year. Twenty times more would be needed to replace all diesel and gasoline by 2030[15].

The anaerobic digestion of algae can achieve methane yields of about 250 $m^3.t^{-1}$ of algae (76; 202). Therefore, if algae were digested for biogas production alone, a conservative production capacity of 400 m^3 biogas per tonne (200 m^3 of methane) of algae can be assumed. This, based on predicted LNG trade in 2030, results in a theoretical worldwide methane market of at least 2.4 billion (dry) tonnes of algal biomass.

1.2 The Bioenergy Market in British Columbia

1.1.4. Biofuels:

The market for biodiesel and bioethanol in BC is currently driven by the 2007 BC Energy Plan's target of 5% renewable fuels in blends by 2010, and the federal government mandate of 5% ethanol in gasoline by 2010 and 2% biodiesel in diesel by 2012. The estimated sizes of the biodiesel and bioethanol markets in BC and Canada resulting from these mandates are shown in Table 3.

As little of BC's arable land base (less than 5% of the total land area) is available to cultivate energy crops, future increases in biofuel mandate targets will likely depend, in large part, on the feasibility of obtaining new second generation biofuel feedstocks that do not require arable land (such as algae).

Table 3 Biofuels Markets in Canada and BC due to Government Mandates

Fuel Type	Canadian Market in 2012	BC Market in 2012
Bio-ethanol	2.9 GL	245 ML
Biodiesel	0.6 GL	183 ML[16]

GL: gigaliters (10^9); ML: megaliters (10^6)

1.1.5. Biomethane:

The natural gas market in BC is 215 billion cubic feet (bcf) per year (171) (6 bln $m^3.yr^{-1}$), with an additional demand of 17.3 bcfd (179 bln $m^3.yr^{-1}$) in the Alberta pipeline system, which is connected to the BC gas grid. Table 4 shows the theoretical amounts of algae needed to replace realistic percentages of these markets[17]. While the export market is the largest, due to the volumes required,

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[15] Despite this, there are several factors which increase the uncertainty with respect to the above estimates and these are further explained in Appendix A.

[16] The BC market for biodiesel in 2012 is estimated to be in excess of 183ML. The BC mandate require non-road use to be included, more than doubling the transportation –only volumes.

[17] As it is unrealistic to assume that all conventional natural gas will be replaced by algae.

it is more feasible that algae could displace imported natural gas from two planned terminals in BC[18] (103; 199).

Table 4 Theoretical Markets for Methane from Algae in BC

Natural Gas Market	Total Market Size	Estimated Market Potential	Estimated Market for Algae (dry tonnes)
Current BC Market	6 billion $m^3.yr^{-1}$	2%	600,000
LNG Imports to BC	13 million $m^3.yr^{-1}$	100%	65,000
Alberta demand	179 billion $m^3.yr^{-1}$	10%	90 million
Sumas pipeline to US (capacity)	13.5 billion $m^3.yr^{-1}$	10%	7 million

Additional energy markets for algae may be found in decentralized applications. For example, remote communities that are able to cultivate algae might be able to generate biogas to produce heat and electricity for local needs, displacing diesel fuel and heating oil.

1.3 Other Market Options

1.1.6. Tertiary municipal wastewater treatment (nutrient removal)

Algae can be used to reduce the phosphate content in treated municipal wastewater in controlled environments, thus addressing the problem of eutrophication in watersheds (123; 151), while simultaneously reducing costs by producing bioenergy from harvested algae[19].

1.1.7. Protein

Protein concentrations ranging from 15 to 71% have been reported in algae (13; 88; 169). Protein from residues of biodiesel and ethanol feedstocks are already being used for livestock feed and by aquaculturists. However, this market is limited and may soon be saturated by by-products from agricultural biofuel production (59; 166). Protein rich algae residues could also be used as human food items or supplements. However, appearance, digestibility, marketability and taste may be impediments to customer acceptance (13). Clearly, the market for these products would have to be created while a large-scale algae plant is starting up.

1.1.8. Health Foods, Vitamins, Food Colouring & Fine Chemicals

Food additives to preserve colour, pigments, fibers, enzymes, sugar, fats, amino acids, vitamins, antioxidants, cosmetic products, calcium, specialty oils etc. are being discussed as potential high-value products from algae. Such high-value co-products could boost the economics of using algae as

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[18] Two LNG terminals are being proposed for BC, one on Texada Island and the other at Kitimat. These facilities would receive up to 6 million m^3 (199) and 7 million m^3 (103), of LNG respectively per year, starting in 2010.

[19] A discussion of the potential of algae culture in wastewater treatment is beyond the scope of this study and readers are referred to studies conducted by van Harmelen and Oonk (189) and Hoffman (90).

a bioenergy feedstock[20]. However, it is impossible to determine if there is significant potential from these by-products without further intensive research[21].

Poly-hydroxyalkanoates (PHAs) are a family of water-insoluble, stereo specific polyesters of different hydoxyalkalinic acids with properties similar to those of conventional plastics that can also be produced by several organisms including cyanobacteria (170; 191; 192). While the size of this potential market still needs to be determined, PHAs are already being used on a commercial scale in disposable razors, trays and utensils in Japan, biodegradable bottles in Europe, and absorbable sutures, pins and staples for medical purposes [22] (191).

1.1.9. *Emission Reduction Credits*

Carbon credits can be created when CO_2 is sequestered. However, because the algae products (biofuels or feeds) are usually consumed and hence oxidized within a short time period, the sequestered CO_2 is returned to the atmosphere and the product is ineligible for CO_2 credits.

Credits can also be earned when a CO_2 neutral fuel displaces a fossil fuel. If CO_2 from a fossil fuel is used to grow algae, two possible scenarios may apply:

In the first scenario, if the liability for the CO_2 emissions remain with the original source (i.e., a power plant, cement plant, etc.) then, from a carbon credit context, the bioenergy made from this CO_2 will displace a fossil fuel and can earn credits. However, under government biofuel mandates, only non-mandated activities are considered “additional” and therefore eligible for credits. Thus, only biofuel quantities exceeding the mandated levels would qualify for credits. However, the legal problems of attributing such credits to one specific biofuel producer will be difficult, if not impossible. It is therefore currently unknown if credits will come from such biofuels, although there is a higher market value and tax credits for a carbon neutral fuel.

In the second scenario, if the original emitter wants to claim credits because of an algae operation using the CO_2 in its flue gas before it is released to the atmosphere, then, from a carbon credit context, the bioenergy made from this CO_2 will become a fossil fuel and will not earn credits. In addition, algae cannot use all of the CO_2 in flue gases (see Section 5.3), and only a percentage of the algae biomass is oil or carbohydrate which is used for bioenergy production, i.e. only a fraction of the CO_2 sequestered from the emitter would eventually displace a fossil fuel and be eligible for credit. While this could be considered in contractual agreements, due to the CO_2 liability, the bioenergy could not be sold as CO_2-neutral[23].

While CO_2 credits can be generated from electricity produced from algae, in BC these will accrue to BC Hydro whenever power is sold to the utility (as mandated in power purchasing agreements). Credits can, however, be created where biogas is purified to biomethane and used to displace natural gas. Algae can also be used for hydrogen production, butanol and synthetic gasoline, pyrolysis products and compost. These are discussed in more detail in Appendix B.

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[20] However, differences in the composition of microalgae must be considered as species suitable for the production of high-value products may be less suitable for biofuels production than others and vice versa.

[21] Comprehensive overviews of products made from algae are provided by Pulz and Gross (148) and Spolaore et al. (169)

[22] A wider market has been suggested for these products (23; 189), which needs to be verified. Moreover, cyanobacteria which produce PHAs are not known to exhibit high levels of lipids.

[23] The bioenergy could be sold as a biologically produced “grey” fuel with a CO_2 footprint. Whether such a fuel could be used under current biofuels mandates remains uncertain.

1.4 Technologies and Plant Setup Options

Currently, several options exist for turning algae biomass into bioenergy. Appendix E summarizes the approaches chosen by a number of companies and research teams today[24]. What follows is a brief discussion of each technology, the main elements and criteria necessary for algae as a feedstock for the three main bioenergies: biodiesel, ethanol and biogas[25].

1.1.10. Biodiesel

> ***"A commercial-scale algae-to-biodiesel process is at least eight to ten years away from hitting the market."***
>
> ***John Hemmings, Process Director of Studies and Technology, SNC Lavalin, Canada***

To obtain algae oil, the algae are first concentrated and the oil extracted, usually using an organic solvent, which recovers about 90% of the oil in algae biomass (134), or using a filter press (about 75% oil recovery). Supercritical fluid extraction with cooled CO_2 is another possibility which can recover close to 100% of the oil (4). The residue, which contains starch and protein, can be further processed to make ethanol, animal feed, or used as a feedstock in an anaerobic fermenter.

Biodiesel production is a transesterification process during which oils with a high viscosity are transformed into alkyl esters with lower viscosity, similar to normal diesel fuel, and glycerin. The transesterification process is caused by the addition of methanol to the oil in the presence of a catalyst. The addition of 10% methanol and 90% oil will produce 90% biodiesel and 10% glycerin as a by-product.

While oils for biodiesel production can be made from a variety of sources, including animal fats, virgin oils and used vegetable oils, the value of the oil will depend upon its composition(104). For example, oils with high water content or free fatty acids, such as waste vegetable oils, lead to soap formation during transesterification, increasing cleanup costs and hence reducing their value.

Some algae produce oils rich in highly unsaturated and polyunsaturated fatty acids (see Appendix C). These are more prone to oxidation, and biodiesel made from these oils are not likely to meet the iodine value of 120-130g per 100g biodiesel required in international standards (46). Despite this, biodiesel produced from these oils has a lower melting point and thus excellent cold flow properties compared to biodiesel from saturated fats (which tends to gel at ambient temperatures (91; 164)). To meet the biodiesel fuel quality standards (EN14214 and ASTM D6751), the extent of unsaturation in algal oils can be reduced by partial catalytic hydrogenation (46; 57).

Based on this information, it is difficult to predict the value of algae oil as a biodiesel feedstock. Although it appears to be very similar to alternative oils, the exact composition of the algae oil can be influenced by the selection of species used and the process parameters (88).

1.1.11. Ethanol

The starch content of algae is reported to be between 9 and 69% (68), with the higher values being comparable to corn, wheat and other conventional ethanol feedstocks (160).

Once the algae are concentrated and the oil extracted as described above, the enzyme alpha-amylase is mixed with the residue and passed through heated cookers, where the starch is liquefied. By

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[24] While biodiesel and the use of flue gas is the main approach chosen so far, there is still no clear direction concerning the choice of open ponds, raceways, or PBRs (discussed further in section 2.1 and Appendix F).

[25] More detailed descriptions and diagrams can be found in the literature, such as Envint Consulting (66)

adding a secondary enzyme (gluco-amylase), the liquefied starch is converted to fermentable sugars. Yeast is then added to the mash to ferment the sugars to ethanol and carbon dioxide. Using a continuous process, the fermenting mash is allowed to flow through several fermenters, until the mash leaving the final tank is fully fermented. The fermented mash contains about 11-15% ethanol by volume as well as the non-fermentable solids from the algae and the yeast cells. Ethanol is distilled off the mash at 96% strength, while the residual stillage can be recovered from the base of the column and dried to obtain dried distiller's grain.

1.1.12. Biogas

Algae can be digested by bacteria in anaerobic digesters. While digesters are distinguished based on their operating temperature, operating mode, and design, the exact layout and technology used will be subject to an assessment of feedstock composition and volume.

To optimize biogas yields from anaerobic digestion, the carbon-nitrogen (C/N) balance in the feedstock should be in a range of 25-30 (since the bacterial carbon demand is much higher than nitrogen demand). Algae, however, have a low C/N balance (202) and may require the addition of carbon to the digestion process (e.g. waste paper). The removal of oil or starch may exacerbate this problem as these compounds contain carbon, further distorting the optimal C/N balance.

The biogas produced by the digester consists of roughly 60% methane and 40% carbon dioxide, plus trace gases, and can be used to produce heat and/or electricity. Purified biogas, known as biomethane, can be used in natural gas vehicles or introduced into the natural gas pipeline. However, to do so it must first meet the TransCanada pipeline standards (Appendix D).

1.1.13. Integration with Existing Distribution Infrastructure

If algae plants produce only the feedstock and not the final biofuel, location will be determined by availability of suitable land, access to water, sources of CO_2 and climate, and not by proximity to the distribution network. This is because the delivery of the algal oil to the refineries or feedstock to the digester can easily be accomplished using truck or rail companies[26].

Furthermore, even if the facility were to produce both the feedstock and the biofuel, because both diesel and ethanol are currently used as an additive, rather than stand-alone fuels, they are not compatible with current distribution pipelines and must be blended into existing fuels, close to, or at the end user. This again limits the transportation of biodiesel and ethanol to rail or truck delivery.

If the algae were used to produce biogas for heat and /or electricity production, the digester would need to be near a large commercial heat sink (due to the high costs of heat transfer pipes) or a three phase power line. Projects that choose to upgrade the biogas to biomethane would need to be close to an intermediate pressure gas pipeline. Projects that are not close to the existing gas network will likely have difficulty financing and building an access pipe, while the alternative - to pressurize and bottle the biomethane and then transport via rail or truck – will also be cost-prohibitive. The technical feasibility of anaerobic digestion will also depend on the size of the operation (a minimum of around 150 dry tonnes of biomass per year is required to feed a very small digester), and possibly the availability of additional high-carbon feedstocks, such as waste paper[27].

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[26] Companies like CN rail which already have existing infrastructure in place to move liquid biofuels through the North American rail network. In addition to accessing biodiesel and ethanol blending facilities on their rail network, they also offer rail-to-truck and rail-to-storage facilities to those not on their rail network.

[27] Agricultural digesters in BC producing heat and electricity were shown to not be economically feasible without a higher electricity tariff (9), whereas the cost of biomethane production was found to be close to current natural gas market prices only if a gate fee can be charged for the biomass to be processed (11).

2 Current Algae Cultivation Methods

1.2.Introduction

Successfully cultivating algae requires that they be provided with specific environmental conditions, which vary between species. These include requirements for light (intensities, wavelengths), temperature ranges, CO_2 concentration, nutrient composition, salinities and mixing conditions. The following highlights the most important of these requirements for algae cultivation (see Appendix F for a more detailed discussion).

1.2.1. Light

Being the base source of energy for phototrophic algae, the availability and intensity of light is one of the key parameters affecting the success or failure of algae cultures.

At very low light intensities, the net growth of the algae culture is zero (the compensation point) (113). As the light intensities increases, photosynthesis increases until a point is reached where the growth rate is the maximum attainable (the light saturation point) (77; 108; 154). Increasing the light intensity beyond this point does not increase the growth rate and can lead to photo oxidation, damaging the light receptors of the algae and decreasing the photosynthetic rate and productivity (photoinhibition).

Being adapted for low light levels in the wild, the light harvesting antennae of algae cells are so efficient they absorb all the light that hits them even though it cannot all be used for photosynthesis. Thus, at high algal cell concentrations, almost all the available light is absorbed by a thin top layer of cells, leaving the rest in the dark (mutual shading). However, most algae get light saturated at about 20% of solar light intensities (77; 126; 147; 183; 185), hence, while the cells below the surface of the culture may be light limited, the cells in the top layer may face the opposite problems of light saturation and inhibition.

Overcoming these issues involves reducing the light path length of algae culture system (to increase light penetration), and increasing cell densities to a point at which mutual shading minimizes the exposure of each cell (or the majority of cells) to light. This is also facilitated by proper mixing which ensures that individual cells are not stationed exclusively in the dark or light zones of the culture[28] as well as increasing mass transfer (80; 81; 195).

1.2.2. Temperature

In general, algae growth increases exponentially with rising temperatures until an optimum level is reached, after which growth declines. This is of particular importance for outdoor cultures, where the ability to control temperatures is often limited (especially in open systems) and is determined by atmospheric temperature, solar irradiance and humidity. Fluctuations in ambient temperatures can result in diurnal temperatures differences of as much as 20°C in algae cultures (36; 138; 153), which can affect the productivity in the following ways:

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[28] The "flashing light effect" whereby high frequencies (>10Hz) of brief flashes of high intensity light followed by a longer dark period were shown not to reduce productivity compared to continuously illuminated cultures (105; 136) has not yet been replicated in commercial situations.

1). Because large water bodies have long response times to air temperatures, even when the air temperature is optimal, the algae culture temperature can be 10-15°C below optimal(36). Therefore, optimal culture temperatures are only achieved for part of the day (153; 156).

2). While optimal culture temperatures may not be achieved until after mid-day, solar light intensity increases very rapidly in the morning (99; 168; 193). This causes a lack of synchronization between these environmental factors, affecting photosynthesis and creating a situation under which photo inhibition may occur during low levels of light intensity and sub-optimal temperatures (121; 193).

While temperatures below the optimal range will generally not kill algae (except for freezing conditions) sustained temperatures above the optimal range will. Furthermore, higher temperatures during dark periods have been shown to increase biomass losses (195). Thus, it is important for the culture to reach optimal temperatures quickly in the morning and to rapidly decrease temperatures after darkness, thereby maintaining high productivity during the day and minimizing biomass loss at night.

1.2.3. Mixing

As discussed above, at high algae concentrations, almost all the available light is absorbed by a thin top layer of cells. As such, mixing must be sufficient to keep the algae cells in suspension, and to provide all the cells with a uniform, average exposure to light. Mixing also decreases the boundary layer around cells, facilitating the increased uptake and exudation of metabolic products (see Appendix F for a more detailed discussion).

1.2.4. Gas Exchange (CO_2 Addition and O_2 Removal)

As roughly 45-50% of algal biomass is made of carbon (12; 44; 63; 162), the low percentage of CO_2 in the air (0.033%) will quickly limit growth if supplementary carbon is not supplied. This CO_2 is generally blended in with air in aerated cultures or injected into the algae cultures via gas exchange vessels in PBRs or sumps in open raceways. Several methods have been used to reduce the losses of expensive CO_2 in open algae cultures, including bubbling through air stones, using plastic dome exchangers with perforated PVC pipes, injection into deep sumps, trapping the CO_2 under floating gas exchangers and maintaining high alkalinities in the culture water[29].

If oxygen (O_2) concentrations exceeding saturation occurs in algae cultures, photo-oxidative damage occurs to the chlorophyll reaction centers, inhibiting photosynthesis and reducing productivity(132; 147; 161; 186). Where there is an interface between the culture and the atmosphere in agitated cultures, this is not usually a problem as the O_2 concentrations will remain similar to that of ambient air. However, in systems without an interface, such as closed PBRs, additional facilities such as gas exchange chambers are required. (see Appendix F for a more detailed discussion).

1.2.5. Nutrients

Nutrients added to algal cultures must provide the inorganic elements that make up the algal cell and include macronutrients, vitamins and trace elements. While there is very little published work on the optimal levels of nutrients required for mass algal cultures, the macronutrients required are generally considered to be nitrogen, phosphorus and silicon[30] (86) at a ratio of 16N: 1P (39). In practice, however, to avoid nutrient limitation, nutrients are usually added to excess (3; 70; 161) and

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[29] Addition of CO_2 can also be used to control fluctuating pH levels which may occur as the algae consume nitrates. Excessively high or low pH disrupts many cellular processes and reduces the productivity of algae.

[30] Silicon is only required for diatoms, silicoflagellates and some chrysophyes.

widely different ratios are used, even when culturing the same alga (152; 157). Typical trace metals used include chelated salts of iron, zinc, cobalt, manganese, selenium and nickel.

2.1 Culture Techniques

1.2.6. Open Pond Culture:

The large-scale cultivation of algae and cyanobacteria in outdoor open pond systems is well established (12; 27; 36). Ponds can be excavated and used unlined or lined with impermeable materials, or they can be built up with walls. Open ponds are only suitable for a small number of algal species that can tolerate extreme environmental conditions to the exclusion of most other species (Table 5). These species include fast growers, such as *Chlorella,* and species that require highly selective environments, such as *Spirulina* and *Dunaliella*, which thrive in highly alkaline or saline environments.

Currently, there are four main types of open ponds:

Unmixed open ponds: Generally used for the culture of *Dunaliella salina*, these ponds have low productivities (<1 g.m^{-2}.d^{-1}) (27) and are unsuitable for the culture of most algal species (36; 38).

Raceway ponds: Widely used for the commercial cultivation of *Spirulina*, *Haematococcus* and *Dunaliella* (27; 36), these ponds utilize paddle wheels for culture agitation and mixing. Reported productivities have ranged from 14 g.m^{-2}.d^{-1} (0.07 g.L^{-1}.d^{-1}) to 50 g.m^{-2}.d^{-1} (0.42 g.L^{-1}.d^{-1}) (106; 107; 166; 196).

Circular ponds: Used mainly in Asia for the production of *Chlorella*, these ponds are mixed by a centrally located rotating arm (similar to those used in wastewater treatment). Productivities achieved by commercial plants range from 8.5 g.m^{-2}.d^{-1} to 21 g.m^{-1}.d^{-1} (27), with the higher productivities attributed in part to mixotrophic growth (as organic carbon is added (113)).

Thin layer, inclined ponds: These consist of slightly inclined shallow trays, over which a very thin layer of algae flows to the bottom where the culture is collected and returned to the top. High productivities of up to 3.1 g.L^{-1}.d^{-1} (31 g.m^{-2}.d^{-1}) have been reported (62).

1.2.7. Photobioreactors (PBRs)

Closed (or mostly closed) photobioreactors (PBRs) were developed to overcome the problems associated with open pond systems. These include contamination, uncontrollable environments, evaporation, limited species suitability, low volumetric productivities and the need for large land areas (Table 5). They can be located indoors and provided with artificial light or natural light via light collection and distribution systems or outdoors to use sunlight directly. The former option currently involves complex and costly light collection and distribution systems or the use of artificial light and are not feasible for the production of algae for commercial bioenergy applications, hence, only the latter options are discussed here (see Appendix F for more detailed discussions on natural and artificial illumination).

Due to its high cost, algae production for biofuels is not feasible with artificial lighting.

Tubular PBRs: Several serpentine, vertical, horizontal and inclined tubular PBRs have been designed and built in the last few decades (3; 111; 115; 132; 138; 144; 155; 188). These systems include glass or plastic tubes with gas exchange vessels for the addition of CO_2 and the out-gassing of O_2, and a recirculation pump (using air or water) for mixing. Maximum reported productivities for horizontal systems growing *Phaedactylum tricornutum* are: 34 g.m^{-2} (land area).d^{-1} and 2.2 g.L^{-1}.d^{-1} (161), while for inclined systems growing *Chlorella sorokiniana*, productivities of 20.89 $g.m^{-2}.d^{-1}$ (0.67 $g.L^{-1}.d^{-1}$) have been reported(187). Sustained average productivities of 13 $g.m^{-2}$ (occupied land area).d^{-1} (0.05 $g.L^{-1}.d^{-1}$) have been reported for commercial-scale cultivation of *Haematococcus pluvialis* in 25,000 L horizontal PBRs (138) (see Table 4 of Appendix F for a comparison of productivities obtained in different culture systems).

Vertical bubble columns and airlift reactors: These cylindrical PBRs have gas bubbles introduced at the bottom of the columns and may be simple bubble columns, split cylinder airlifts or draft tube airlifts. An areal productivity of 93 $g.m^{-2}.d^{-1}$ (corresponding to a volumetric productivity of 0.64 $g.L^{-1}.d^{-1}$) was reported for *P. tricornutum* grown in a bubble column PBR (161). This is a higher areal productivity than obtained in a comparable tubular PBR, which, while exhibiting a higher volumetric productivity (2.2 $g.L^{-1}.d^{-1}$), exhibited an areal productivity of only 34 $g.m^{-2}.d^{-1}$.

Combined bubble column and inclined tubular PBR: A patent application submitted by Berzin (29) is for a right angled triangular PBR which combines the principle of a bubble column with mixing by built-in static mixers in an inclined "down comer". The system also has a counter current of gas to increase mass transfer. Gas exchange occurs at a gas exchange vessel located at the apex of the triangle.

Helical PBRs: Helical PBRs are composed of parallel sets of flexible translucent tubes coiled helically around a cylindrical mesh frame. Gas exchange is accomplished via an incorporated gas exchange system at the top of the unit and a heat exchange system may be included for temperature control. High productivities of up to 113.7 $g.m^{-2}.d^{-1}$ (0.9 $g.L^{-1}.d^{-1}$) have been reported (185).

Flat Plate PBRs: Flat plate PBRs are made of thin rectangular translucent boxes, which are open at one end and may have ribs (alveolae) running vertically from bottom to top. Aeration and mixing are provided via a perforated tube running along the entire bottom of the FPR (184). (92). Productivities of 1.09 $g.L^{-1}.d^{-1}$ (15.3 $g.m^{-2}$) have been reported with *Spirulina platensis* (185).

1.2.8. Fermenters

Heterotrophic culture: While most algae grow phototrophically, some are capable of heterotrophic growth using organic substrates as the sole carbon and energy sources[31]. This mode of algal cultivation is well established (7; 15) and has several advantages over phototrophic modes of growth (Table 5). These include the large, existing fermentation technology knowledge base, the high degree of process control for consistent, reproducible production, the elimination of light requirements, the independence from weather and climatic conditions, and lower harvesting costs (7; 43; 45). Sufficient oxygen is required for the catabolism of the organic substrates in heterotrophic cultivation of algae, hence, O_2 supply is often the single most limiting factor preventing high cell concentration and high growth rate (51; 133).

Generally, heterotrophic cultivation has been found to increase the total lipid content in algae compared to phototrophically grown cells (117; 129; 177; 197). In a comparison done by Miao and Wu (129), heterotrophically grown *Chlorella* cells accumulated lipids to 55.2% of the cellular dry weight as opposed to 14.6% in phototrophically grown cells. Furthermore, heterotrophic cultivation of algae usually (but not always) results in higher yields[32] (14; 67; 197; 203).

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[31] To date, the most widely used source of organic carbon has been glucose. However, other organic substrates such as acetate, fructose, citrate and ethanol have also been used.

[32] This highlights the need for optimization of the heterotrophic culture of individual strains prior to mass heterotrophic culture.

Table 5: Comparison of Raceways, Photobioreactors and Fermenters (see Appendices F & G for more details)

Factor	Raceway	Photobioreactor	Fermenter
Cell density in culture	Low	Medium	High
Limiting factor for growth	Light	Light	Oxygen
Culture volume necessary to harvest a unit weight of cells	High	Medium	Low
Surface area-to-volume ratio	High	Very high	Not applicable
Control over parameters	Low	Medium	Very high
Commercial availability	Readily available	Usually custom built	Readily available
Construction costs per unit volume produced	Medium	High	Low
Operating costs	Medium	High	Low
Technology base	Readily available	Under development	Readily available
Risk of contamination	High	Medium	Low
Evaporative water losses	High	High[33]	Low
Weather dependence	High	Medium	Low
Maintenance	Easy to maintain	Difficult to maintain	Requires specialized maintenance
Susceptibility to overheating	Low	High	N/A
Susceptibility to excessive O_2 levels	Low	High[34]	N/A
Ease of cleaning	Very easy	Difficult	Difficult (must be sterilized)
Ease of Scale-up	High	Variable[35]	High
Land requirement	High	Variable	Low
Applicability to different species	Low	High	Low

Mixotrophic culture: Mixotrophic culture is a nutritional mode in which photo assimilation of CO_2 and the oxidative catabolism of organic carbon sources proceed simultaneously, thereby offering the potential of greatly increased productivities. For species that can utilize both light energy and chemical substrates, this mode of cultivation offers a superior alternative to phototrophic and heterotrophic growth as both biomass and productivity increases have been reported[36] (43; 49; 55; 67; 197; 203). Productivities as high as 127 $g.m^{-2}.d^{-1}$ (daytime), and 79 $g.m^{-2}.d^{-1}$, (night time), have been

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[33] Water losses may be high in PBRs if water sprays are used for cooling.

[34] In enclosed PBRs without aeration.

[35] With the exception of vertical bubble column and some tubular PBRs, it is difficult to scale up PBRs and still maintain optimum light, temperature and mixing properties. See Appendix F for a full discussion.

[36] As with heterotrophic systems, mixotrophic systems offer a high degree of process control, higher volumetric productivities and a large fermentation technology knowledge base. However, and as with heterotrophic systems, not all algae species are able to use organic substrates.

reported for mixotrophic cultures of *Chlorella*[37]. This compares to 35.8 – 41.4 $g.m^{-1}.d^{-1}$ obtained in photosynthetic cultures (112).

As with heterotrophic growth, several authors have reported changes in the biochemical composition of the alga depending upon the culture system. For instance, when *N. laevis* was grown phototrophically, heterotrophically and mixotrophically, the percentages of unsaturated fatty acids declined as light levels declined (thus the values of the parameters followed the sequence phototrophic > mixotrophic > heterotrophic). However, the total fatty acids were higher in the mixotrophic and heterotrophically grown algae than in the photoautotrophically grown algae.

1.2.9. Harvesting

The costs of harvesting can be a significant proportion of the total algal production costs, ranging from 3.3% (135) to 30% (83). This is because obtaining the algae biomass from the relatively dilute culture broths requires processing large volumes of water. To conserve energy and reduce costs, algae are often harvested in a two step process. In the first step, the algae are concentrated, often by flocculation, which concentrates the dilute cultures to about 1-5% solids. In the second step, the cells are further concentrated by centrifugation, filtration or micro straining to get a solids concentration of 15-25%. (see Appendix H for more detail).

Flocculation: Algae carry negative cell surface charges (78; 167), which, when neutralized, leads to the agglomeration of the algae into large clumps or "flocs". These flocs can then be more readily separated from the culture. Flocculation can be induced in various ways:

Chemical flocculation (inorganic chemicals): Algae may be induced to flocculate by the addition of inorganic chemicals, such as aluminum sulfate ($Al_2(SO_4)_3$) (alum), ferric sulfate $Fe_2(SO_4)_3$, ferric chloride $FeCl_3$ or lime ($Ca(OH)_2$) (78; 87; 166), which neutralize or reduce the negative surface charge of the cells, causing the formation of flocs. The requirement for large doses of these chemicals led the Aquatic Species program (ASP) to conclude that chemical flocculation was too expensive for the production of biofuels (166). The incorporation of the metal salts in the harvested biomass also limits its use for human and livestock feeds and creates disposal problems (27; 130).

Chemical flocculation (polyelectrolytes): Polymeric organic flocculants[38] (polyelectrolytes) are highly charged organic macromolecules or aggregates formed in aqueous solution by dissociation of charged units of these macromolecules. In addition to neutralizing the negative charges on algae cells, they also physically link the algae cells to each other (181), thus producing more stable flocs. Lower levels of polyelectrolytes are required for flocculation compared to inorganic chemicals and this, together with their reported lack of toxicity[39], has made them a more attractive flocculation option. The costs of using organic polyelectrolytes has been estimated to range between $5 to $50 per ton (8; 165).

Bioflocculation: Some algae will naturally flocculate after transfer to settling ponds when left quiescent for some time (116; 135; 166; 195). This occurrence has been attributed to environmental stimuli, some of which have been identified, including nitrogen limitation, pH and dissolved oxygen level (27; 32; 109; 195). Benemann and Oswald (27) reported on an effort to establish operating conditions under which *Microactinum sp.* cultures could be induced to bioflocculate in 0.1 ha ponds. However,

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[37] This highlights another advantage of mixotrophic cultures (albeit one shared with heterotrophic cultures): the elimination of night time biomass losses.

[38] Only cationic polyelectrolytes have been found to be useful flocculants (27; 166; 167; 181).

[39] This has been called into question as Heasman et al.(87) reported increased mortality when Sidney rock oysters were fed chitosan flocculated algae.

relatively little was learned, and although they obtained high removal efficiencies, the authors concluded that the processes were still unreliable.

Electroflocculation: This is a coagulation/flocculation process which is based on the movement of electrically charged particles in an electric field in which active coagulant species are produced by oxidation of a metal anode. It involves the application of an electric current to a sacrificial anode (usually aluminum or iron), which then goes into solution generating metal ions which act as coagulating agents and releasing hydrogen gas at the cathode (see Appendix H for details). The metal ions coagulate with the algae cells and the bubbles produced at the cathode rise to the surface taking the flocs with them. Electroflocculation works irrespective of the size or morphology of the algae (145; 178) and a separation efficiency of over 96% has been reported with an energy consumption of 0.3 $kWh.m^{-3}$ (145).

Dissolved air floatation: After flocculation, the flocs may be left to settle before recovery by pumping off the surface liquid layer (sedimentation), or the flocs may be removed by dissolved air floatation (27; 34; 116). This involves pressurizing some of the liquid to dissolve additional air. When the pressurized liquid is mixed with the algae culture at atmospheric pressure, the air comes out of solution as bubbles that attach to the flocs, making them float. .

Centrifugation: This is a well-established industrial process that uses gravitational force to achieve separation. The morphology and sizes of the cells being harvested affect the recovery (and costs) as filamentous cells and large colonial cells will settle more readily than single smaller cells (135). Centrifugation is energy intensive, with estimates of the energy consumption required for various types of centrifuges estimated to range from 0.3 to 8 $kWh.m^3$ (130). The high capital and running costs associated with centrifuges limit their use to second-stage filtration in the processing of microalgae for biofuels.

Filtration: The principle of filtration is introducing the particles onto a screen of given aperture sizes. The particles either pass through or are retained on the screen according to their size. Filtration can be performed under pressure or vacuum with energy requirement estimates ranging from 0.2 to 0.88 $kWh.m^3$ and 0.1 to 5.9$kWh.m^3$ respectively (130; 167). Filtration can also be carried out by microstrainers which consist of a rotating drum covered by a straining fabric. A backwash spray collects the particles into an axial trough. Low power requirements of between 0.02 to 0.2 $kWh.m^3$ have been reported (22; 167). Although the costs associated with filtration are low, screen clogging and membrane fouling limits its suitability to larger species of algae.

1.2.10. Strain Selection

As explained in section 1.4, several different renewable fuels can be produced from algae, with the desired end product being the primary factor influencing the choice of species. Other factors that should be considered during species selection include growth rate and optimal temperature range as these affect the performance and productivity of the algae in the proposed culture system (see Table 10 in Appendix I).

Under normal conditions, the lipid production of most oleaginous algae from various taxa is about 25% of the dry cell weight (21; 91). Under conditions of stress, such as nutrient deprivation however, cell division stops while the cells continue accumulating storage products at about the same rate (27; 166). This results in the accumulation of neutral lipids (including hydrocarbons) and increasing the percentage of lipids to around 35 – 45%.

The responses of different algae (in terms of their storage product) to nutrient deprivation are variable (140), enabling this method to be adapted towards the generation of whatever storage product is required. For instance, while *Botryococcus braunii* increased its lipid content from 46 to 54% under nitrogen starvation stress, *Dunaliella salina* **decreased** its lipid content from 25 to 9%

and instead increased carbohydrates from 16 to 56% (21). This of course, requires prior screening to identify and select strains producing and accumulating the desired product.

While nutrient starvation may increase the lipid (or carbohydrate) content of algae, it is also correlated with a decrease in total cell and lipid productivity of the culture, and thus there appears to be little benefit obtained by nutrient starvation. Benemann and Oswald (27) suggested a phased approach whereby the algae are grown under non-limiting conditions in a first phase, followed by culture under nitrogen-limiting (not starvation) conditions in the second phase. In effect, this imposes a growth rate limit on the algae and enables the algae to accumulate nutrients without the resultant decrease in biomass that nitrogen-deficient cultures will face.

3 Potential Issues and Benefits of Large-Scale Culture of Algae for Biofuels

Currently there is little published information on the environmental and public health impacts of algae cultivation. As such, for the purposes of this report, where information is unavailable, relevant issues arising from aquaculture operations have been used.

3.1 Physical Effects of Algae Cultivation

Space: The main impact of algae cultivation will be the amount of space required for large-scale facilities. This may become seriously restrictive in areas of BC where competition for coastal and near-shore resources intensifies. Significant issues are not expected for facilities located on unfertile or marginally productive lands, or lands undesirable for residential accommodation.

Ecosystem damage: Site preparation for pipelines and production facilities involves the removal of rocks, earth, trees and vegetation. This may result in damage to coastal and terrestrial ecosystems.

Aesthetic impacts: The potential aesthetic impact has dominated many discussions around aquaculture development (142), and to avoid conflicts with other users, planners have had to ensure that potential aesthetic changes are considered during the development of new ventures (58).

3.2 Ecological Aspects of Algae Cultivation

Potential for eutrophication: The presence of residual nutrients in effluent waters can cause net increases in nutrient levels in waters receiving effluent. While the wider environmental effects are not yet known, eutrophication caused by fertilizer runoff from agriculture has been implicated in the development of harmful algal blooms (6; 40; 74; 75; 97) and fish kills (73). Therefore, it is likely that algae cultivation effluents will have to be treated before being released to the ocean or a waterway.

Chemical pollution: In large-scale algae culture, chemicals and disinfectants are used for the prevention and control of disease, water treatment, removal of predators and cleaning and disinfection of the culture equipment. In some cases, concerns have arisen over the potential impacts of such chemicals on the environment and the health of farm workers and consumers

Potential for introducing non-native species: Of potentially over 100,000 species of algae (166), only a handful have been well studied and described and adopted for widespread cultivation in aquaculture and the health food industry. This has resulted in the movement of algae species beyond their native ranges for the purposes of research and production. This movement carries the risk for potential adverse effect on wild species, either through introduction of new diseases or competition with native species. There is no evidence that diseases have been transferred as a result of algae cultivation, and the ecological implications of such introductions are difficult to assess. Despite this, the potential risks warrant a careful assessment of potential impacts prior to the introduction of new species.

Public health impacts: If chemicals or flocculants are used to harvest the algae, concerns are that these may remain in the residual by-products, thus negatively impacting the health of livestock consuming it[40]. There are also concerns about the possibility of changing microclimates[41], the

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[40] If the by-product is used to make ethanol, such impacts can be ruled out.

[41] For example, the formation of fog and haze over large areas containing clusters of algae ponds,(or PBRs, if water is used to cool them). There may also be glare, from light reflecting off PBRs.

danger to wildlife (which may fall into open ponds and drown), and the public health risks if the water is not turbulent enough to prevent the laying and hatching of mosquito eggs and larvae.

3.3 Benefits of Algae Cultivation

Does not compete with food or feed crops: Unlike first generation biofuels, the cultivation of algae needs not compete with food crops for land or water as (a) land-based cultivation does not depend on soil fertility and can be conducted on barren land and (b) both marine and freshwater algae can be cultivated, so either source of water can be used. Despite this, it should be noted that large-scale cultivation will require significant amounts of fertilizer, and this could impact the production of food and feed crops.

Benefits to small-scale farmers: Biofuels can benefit small-scale farm holders by generating employment and increasing rural electrification and incomes. However, the scale of these benefits is likely to remain limited with current technologies as algae production requires large economics of scale and vertical integration to be economically feasible (see Section 4.2).

Energy security: Algae production for biofuels shares some benefits with first generation biofuels, such as the potential to increase energy security by reducing reliance on imported fuels.

Mitigation of climate change: Algae are theoretically carbon neutral in that they recycle CO_2 otherwise released to the atmosphere, rather than adding CO_2 to it (as occurs when fossil fuels are burned). However, this potential needs to be evaluated on a case-by-case basis, as it will depend on the GHG emissions associated with the mode of cultivation chosen (see Table 18).

3.4 Public Perception of Algae Cultivation

As in other forms of aquaculture, the establishment and continued development of a viable algae biomass industry in BC will depend upon access to, and the sustainable use of, shared water and terrestrial resources. The lack of credible information about health and safety issues and environmental sustainability have been cited as key factors in the loss of confidence by communities in the aquaculture industry (118; 128; 146; 146). Therefore, public perception of the algae industry as an environmentally responsible steward will help facilitate its establishment and development. This can be achieved by undertaking proper communication and activities to demonstrate the industry's transparency and concern for the environment.

4 Economic analysis

4.1 Algae Growth Potential in BC

Two phototrophic algae production technologies, the open raceway and the closed PBR, were modeled to determine the maximum yields achievable in BC. Both systems are fed with CO_2 from flue gas and are modeled with and without supplementary heating.

1.2.11. Available Solar Energy

The intensity of available solar energy varies with latitude, longitude, time of year and various geographical factors. While the solar radiation from the sun is constant at 1,370 $kW.m^{-2}$, because this is averaged over the earth's surface, the maximum theoretical solar radiation that falls on the earth's surface is 342.5 $kW.m^{-2}$[42]. Actual solar radiation is measured at various weather stations[43] (see Figure 45 in Appendix J, for an example of solar radiation and temperatures at Prince George, BC, over a three-year period). As the productivity of algae is determined by the available solar radiation, an understanding of the solar radiation levels in BC is important in determining the potential of algae growth in BC. Figure 2 shows a yearly global radiation map and Figure 3 shows the available yearly solar radiation in Canada.

1.2.12. Maximum Productivity Model

For a realistic estimation of maximum theoretical algae production possible in BC, an immaturity algae growth model (AlgaeG) was developed based on modifications of the basic theories described by Livansky (119). This is a daily growth model that calculates the maximum productivities expected in BC using the following assumptions:

- Ponds are very shallow, thus the water temperature approximates the air temperature. This model does not consider conditions of frozen water
- CO_2, nutrients, mixing and all other factors (except for temperature and solar radiation) are optimal for algae growth
- There is no contamination or crashes of the algae cultures
- Radiation and temperature are the only environmental conditions affecting or determining algae growth, and
- Not all of the incoming photosynthetically active radiation (PAR) is intercepted by the algae, and the intercepted *PAR* (corresponding to PAR_m) is completely used for algae growth and metabolism.

The model also includes management sub-routines to determine harvest dates for maximum biomass productivity (avoiding net respiratory losses) as well as pre-defined harvesting scenarios The detailed formulae used in the model are presented in Appendix J.

The model was run using *Chlorella sp.* as a test organism at two different geographic locations in BC:

- Prince George: middle interior BC: Latitude: 53° 53.4'N; Longitude: 122° 40.8'W), and

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[42] This can be reduced by reflection of solar energy back into space, by clouds blocking the radiation, and by atmospheric dust and air.

[43] This information is available in detailed minutely and hourly databases in electronic format from Environment Canada and on-line at www.climate.weatheroffice.ec.gc.ca/climate_normals/stnselect_e.html.

- Nanaimo: south BC: Latitude: 49° 3.000’N; Longitude: 123° 52.200’N).

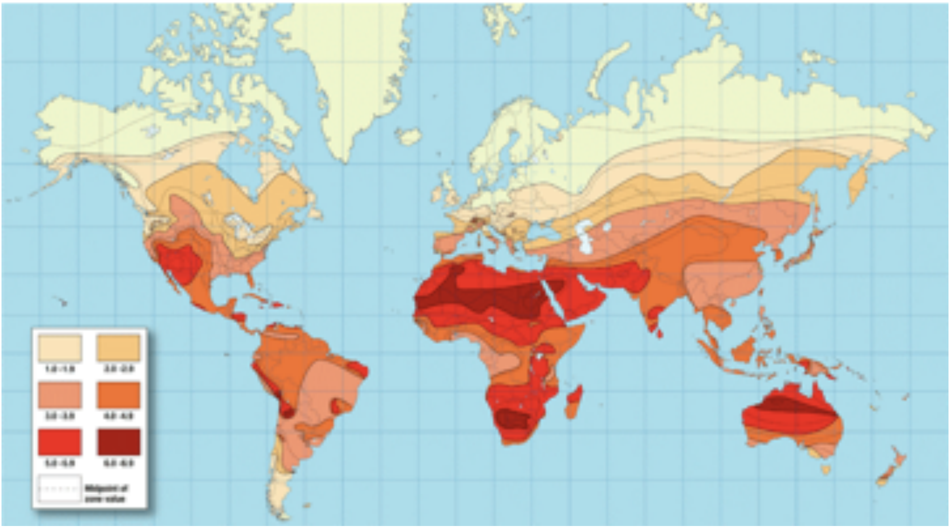

Figure 2: Solar Radiation Around the World (Kwhr.M^{-2}.Day^{-1}) (OKSolar [137])

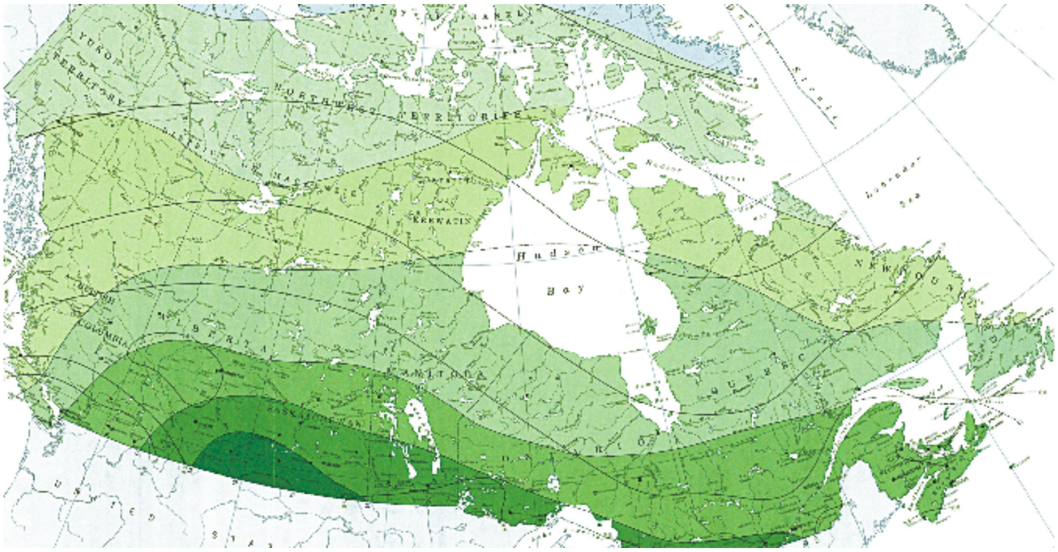

Figure 3: Average Yearly Solar Energy in Canada (in MJ.m^{-2}) (NRCAN)

For each of the sites, the following technologies were modeled under the following scenarios:

Scenario 1: Open raceways: 15 cm deep, with 94% of the incident light penetrating the culture and three circumstances:

1. Run year round with no supplementary heat,
2. Run year round with supplementary heat,[44] and

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[44] Note that this option was found not to be feasible in BC due to the low winter temperatures (see Figure 47 and Table 11 in Appendix K).

3. Run only six months a year (mid April – mid September) with no supplementary heating.

Scenario 2: PBR: Assumed the use of 5 cm path length PBRs, with 90% of the incident light penetrating the culture. The PBR scenario was run year round assuming optimal temperatures.

Biochemical composition: Open raceways only allow certain species to be grown successfully. There is therefore great uncertainty with respect to the composition of the algae that can be grown in open raceways in BC. Such cultures will almost certainly be overrun by native species and this may mean that only those species can be grown in the long run, with obvious impacts on productivities and oil yields. If this is the case, the biomass yields and oil content may be less than desirable for commercial algae production. A lipid concentration of 15% was retained for algae grown in the raceway model[45]. In contrast, the closed (or mostly closed) nature of PBRs reduces their susceptibility to contamination such that selected algal species that may not succeed in open raceways may be successfully cultivated in PBRs. This enables the cultivation of species with the required biochemical composition. A lipid concentration of 25% was retained for the algae grown in PBRs in this model. The assumptions of the composition of algae grown in raceways and PBRs are shown in Table 8.

Table 6: Predicted Average Daily Algae Production from BC Using AlgaeG Model and 15% Lipid[46] Content for Raceway production and 25% Lipid Content for PBR production.

Algae culture system	**Production period**	**Maximum algae biomass yield (g.m^{-2}.d^{-1} dry weight)**		**Maximum algae oil yield (g.m^{-2}.d^{-1} dry weight)**	
Location		Prince George	Nanaimo	Prince George	Nanaimo
Open raceway (unheated)	12 months	9.38	11.40	1.41	1.71
Open raceway (heated)	12 months	15.47	16.00	2.32	2.40
Open raceway	6 months (April-September)	21.60	22.89	3.24	3.43
PBR (25% lipids)	12 months	15.30	15.30	3.83	3.83

Algae culture system	**Production period**	**Maximum yield of biodiesel from algae (ml.m^{-2}.d^{-1})**		**Land area required for 1 million liters of biodiesel per year (Km^{2})**	
Location		Prince George	Nanaimo	Prince George	Nanaimo
Open raceway (unheated)	12 months	1.66	2.01	1.66	1.36
Open raceway (heated)	12 months	2.73	2.82	1.00	0.97
Open raceway	6 month (April-September)	3.81	4.04	1.44	1.36
PBR (25% lipids)	12 months	4.50	4.50	0.61	0.61

As can be seen in Table 6, operating an unheated pond year round in PG and Nanaimo gives average daily productivity values of 9.38 and 11.40 g.m^{-2}.d^{-1}, respectively. At an assumed lipid concentration of 15%, the corresponding oil yields are 1.41 and 1.71 g.m^{-2}.d^{-1} respectively. If the ponds were

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[45] In the search for oleaginous algae undertaken during the ASP, lipid content of the algae collected ranged from 5.3% of the dry weight to 31% depending upon species) (24; 159; 174; 180; 182).

[46] Lipid content used for the two technologies were: 15% for the raceway and 25% for the PBR.

heated and operated year round, the average daily productivity in PG and Nanaimo increases to 15.47 and 16.00 $g.m^{-2}.d^{-1}$ with oil yields of 2.32 and 2.40$g.m^{-2}.d^{-1}$, respectively. Very similar results are found for average daily PBR productivity in both PG and Nanaimo, although oil yields, at 3.83$g.m^{-2}.d^{-1}$, are about 60 to 65% higher due to the higher lipid concentration in the algae used (Table 6). The highest average daily productivities are obtained when the ponds are only operated for six months of the year[47]. Under this scenario, average daily productivity levels in Prince George and Nanaimo were 21.60 and 22.89 $g.m^{-2}.d^{-1}$, respectively. However, at 3.24 and 3.43 $ml.m^{-2}.d^{-1}$ respectively, oil yields were lower than obtained in the PBR due to lower lipid concentrations in the algae strains used. The difference between average daily productivity obtained in the open raceways during the six month period compared to that obtained in heated raceways can be attributed to reduced temperatures and solar radiation during the winter months which reduces growth[48].

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[47] Run from April to September when temperatures and solar insolation are highest.

[48] Methods that could be used to heat the raceway are considered and described in Appendix J.

4.2 Algae Production Cost

1.2.13. Introduction

The economic analysis conducted here includes the two phototrophic technologies modeled in Section 4.1.2, as well as the aerobic fermenter. While it is often difficult to derive accurate cost parameters from existing literature[49], where possible, this information was used. Where actual cost information was unavailable, data from laboratory-scale facilities, previous modeling exercises and commercial facilities cultivating algae for non-energy purposes was used. Care was taken to update older data to 2008 dollars with a 2% annual inflation rate and to correctly transfer data based on specific productivities and proximate composition (i.e. literature cost data can rarely be transferred as it is given in the original source). The cost parameters used are essentially agnostic of the algae species to be used, but certain design assumptions may exclude some strains[50].

> Although large-scale microalgal culture has now been undertaken for over 40 years, our experience is still limited to a few species, and even for these, our understanding of their biology and ecology is still very incomplete.
>
> (Borowitzka (37))

The concepts pursued by different groups today are varied and stress different factors, such as yield, final product (ethanol, biodiesel, biogas, etc.) and plant design (open pond, PBR, fermenter, or mixed concepts). Therefore, to determine the cost of algae cultivation and bioenergy products, generic plant concepts were developed for each of the three technologies. These were then used to determine the influence of cost parameters, such as biomass yield, lipid content, operational costs, energy use and other factors.

1.2.14. Open Raceways

Land costs: Recent listings on the MLS website show that in the BC interior, agricultural land can be purchased for as little as $500 per ha, with property taxes as low as $1,000 per year (31). In the Lower Mainland, agricultural land prices range from $40,000 to $120,000 per ha, while in the Okanagan valley prices range from $37,000 to $94,000 per ha(124). These higher land prices are unsuitable for large-scale algae production. A cost of $2,000 per ha was used for the base case model, which assumes a large algae production plant with 400 ha of ponds[51].

Raceway design: Many sites, especially in the BC Interior, feature till or sandy ground. They are therefore unsuitable for unlined raceways and as such, construction costs for lined raceways were used[52] (37). It is important to note that these landscaping costs assume flat terrain, as a slope of 1% requires earth works and thus significantly increases costs (by over $5,000 per ha (26)).

Capital costs: Several studies and companies have developed detailed cost data for the production of algal biomass in open ponds. Benemann et al. (28) calculated production costs of about $100 t^{-1} of

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[49] Algae cost data can vary by orders of magnitude, ranging from $0.20(27) to several hundred dollars per kg (35).

[50] For example, *Isochrysis galbana* cannot be grown in open cultures for extended periods of time (27), while other species may require design features different from the ones used in the generic layout.

[51] Additional land will be necessary for harvesting facilities, oil extraction, ancillary buildings and infrastructure. However, because land prices are not a major factor in the base case, this is insignificant.

[52] In addition to clay, Ben Amotz (20) has suggested that ponds could be lined with salt. Note however, that the use of salt limits one to cultivating only algae that can tolerate high salt levels.

dry biomass for very simple unlined ponds situated nearby a flue gas source with covered lagoons to digest waste material. In Israel, algae producer NBT Ltd. gives production costs of $340 per tonne (excluding capital cost and overheads) for their open ponds with a concrete basin, in which the biomass is harvested through auto-flocculation and the CO_2 is derived from the flue gas of a nearby coal plant (19). Borowitzka (37) reports detailed costs, amortized over twelve years for cultivation equipment and six years for harvesting equipment, of US\$8.88.kg^{-1} ($8,880 per tonne) for raceways with harvesting by flocculation and centrifugation.

Table 7 compares the data for a 400 ha raceway system developed in Benemann and Oswald (27) to the generic model in this study. To reflect the lower input costs for the lower algae productivity of 9.38 g.m^{-2}.d^{-1} in the base case, costs were reduced by 60% for parameters sensitive to yields (CO_2 use, centrifugation, nutrients and waste treatment). Where assumptions were replaced, the data source is listed in the last column. Backup generators were added, assuming a cost of \$1.W^{-1} and a need of 18 kW per ha.

Table 7: Capital Cost Parameters for a 400 ha Raceway Algae Production Plant

Parameter	Benemann et al (28)	This study	Source
$ per ha (400 ha algae culture facility)			
Site preparation, grading, compacting	2,500	3,171	
Pond levees, geotextiles	3,500	150,000 (lined)	Borowitzka (37)
Paddle wheels	5,000		
CO_2 supply and diffusers	10,000	12,682	
Settling ponds	7,000	8,878	
Flocculation, centrifugation, oil extraction	14,500	18,390	
Water & nutrients	5,200	6,595	
Waste treatment	1,000	1,268	
Buildings, road, drainage	2,000	2,536	
Electricity infrastructure	2,000	2,536	
Backup generators	-	18,000	See text
Instrumentation, machinery	500	634	
Land	2,000	2,000	
Sub-total	55,200	226,690	
Engineering & contingency (15%)	8,280	34,004	
TOTAL	**63,480**	**260,694**	
Annual capital cost	9,522 (15%)	36,497 (14%)	Tampier et al.(175)

Inoculum costs: Producing inoculum to initiate and restart algae pond cultures can be a major cost factor, with estimates of up to 10% of total production costs (27). However, whether or not inoculum is necessary depends on the type of algae. For example, *Spirulina* is generally cultivated without producing inoculum, while *Dunaliella* requires inoculum that can be produced in open ponds and *Chlorella* requires inoculum produced in PBRs. For this study, it is assumed that the algae species used does not requires separate on-site production of inoculum.

Algae species: As explained in Section 4.1.2, only certain algal species can be grown in open ponds, and engineered or otherwise selected species may not succeed. The base case composition of algae is given in Table 8. A sensitivity analysis is conducted at the end of this chapter to examine the impact of algae with different biochemical compositions.

Yields: In their study, Benemann and Oswald (27) assume a yield of 30 $g.m^{-2}.d^{-1}$. This has been corrected to 9.38 $g.m^{-2}.d^{-1}$ for this study, based on the BC model. These lower yields will have an impact on several other parameters, such as frequency of harvesting and fertilizer use.

Harvesting costs: At $1,000 to $1,500 per dry tonne produced, centrifugation is clearly too costly as a primary harvesting method for algae biofuel production. However, it could be used as a secondary step to increase solids content to 20% - estimated to cost $15 to $20 per tonne (27).

Table 8: Assumptions on the Composition of Algae Grown in Raceways, Bioreactors and Heterotrophic Fermenters

Parameter	Percentage of Dry Matter		
	RACEWAY	BIOREACTOR	FERMENTER
Oil	15	25	50
Protein	25	25	10
Starch	40	30	20
Nitrogen	5.5	5.5	5.5
Phosphorous	1.1	1.1	1.1

Oil extraction costs: Benemann and Oswald (27) proposed that, instead of drying the algae, oil extraction be combined with the concentration step through centrifugation. Similar to existing technology used for extracting beta-carotene, the algae mass is introduced into hot oil, and is then separated by centrifuge into water, oil and algae cake.

Wastewater Treatment costs: There is little published information on wastewater discharged from algae plants. However, it is likely that some pre-treatment will be required[53]. An indication of potential costs per liter is developed in the section on heterotrophic fermentation below. Previous research has demonstrated that a reduction in nutrient requirement of 16% and water savings of 63% can be achieved by recycling the medium after each algae harvest (120). If the culture medium is re-used several times without pre-treatment, yields may decrease due to accumulation of inhibiting substances and dissolved organic material from previous batches. Therefore, a complete replacement of the medium may be necessary at least periodically. Pretreatment of the used medium (using for example activated carbon or expanded clay) may alleviate this problem. However it is unclear whether the costs will be counterbalanced by the savings in fertilizer and water use.

Fertilizer costs: Agricultural fertilizer costs have increased rapidly over the past two years. Di- and mono ammonium phosphate prices increased from $272 per tonne in 2007 to $1,230 per tonne in April 2008 (85), while urea costs $400 per tonne. Assuming cell N content of 5.5% and P content of 1.1% of dry weight (37), fertilizer costs will be just over $2,500 per ha, per year[54]. This is increased to $3,000 to allow for additional inputs of micronutrients such as iron and vitamins. While there are claims that NOx in flue gas can act as a nitrogen source (19; 20), this could not be conclusively proven (204) and is not included in the analysis. No recycling of the algae biomass is assumed as the algae cake will be sold (see below).

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[53] Large-scale algae plants may be in settings without access to sewage systems, or the amounts discharged may be too great for the local treatment plant. This aspect, however, was not investigated as treatment costs are a smaller component than other costs, such as labour.

[54] Based on a long-term stabilized price of $1,000 per tonne of fertilizer and an assumed yield of 9.38 $g.m^{-2}.d^{-1}$.

Carbon costs: Only 2.5 tonnes of algal biomass per ha, per year, can be produced when using atmospheric CO_2 as the carbon source (26), while for saltwater, 43 tonnes per ha, per year can be grown due to its alkalinity and pH[55]. For this reason, a continuous supply of free[56] CO_2 is assumed to be supplied from flue gas. In addition, a small amount of organic carbon will be supplied from recycled medium or digester effluent.

Power costs: Benemann and Oswald (27) calculated total power demand of 44,154 $kWh.ha^{-1}.yr^{-1}$ or 1,472 MWh per month (equivalent to 2,000 kVA) for a 400 ha plant. In BC, tariffs for large industrial users are as low as 2.5 cents per kWh (up to 90% of base demand with the remaining 10% charged at $\$0.074.kWh^{-1}$), plus a demand charge of $\$5.kVA^{-1}$ of billing demand. This would correspond to a \$10,000 monthly load charge ($\$300.ha^{-1}.yr^{-1}$), plus \$1,324 in annual power costs per ha[57].

Labour costs: The assumptions of labour costs in the source paper were modified based on the NBT case, where eight workers are required for a 10-hectare raceway plant (0.8 employees per ha)[58] (19; 20). One company that provided data for this study reported employing 1.2 workers per ha of raceways, or 0.67 per hectare of footprint (about 1 worker per ha of footprint using the same relation as used in Benemann and Oswald (27)). Assuming some economies of scale for a system with 400 ha of ponds, 0.5 workers per ha are used in the base case (see Appendix M for a more detailed description of tasks in an algae plant). The cost of \$40,000 per worker, per year used, is assumed to also cover basic overhead costs, such as administrative personnel, but not R&D.

Operational cost parameters derived for this study are compared to the estimates of Benemann and Oswald (27) in Table 9. Cost parameters dependent on yields have been reduced proportionately from the estimates made in Benemann and Oswald (27), which were based on a yield of 30 grams per square meter, per day, after correcting the cost to 2008 dollars. This was applied to flocculants, nutrients and waste disposal.

Algae cake revenue: The market values of distillers' grain in Iowa (56) were used to estimate corresponding values for selling algae cake as a protein source (as animal feed) (Table 10), instead of digesting it[59]. Pricing for distillers' grain is given in US dollars per short ton, whereas the value of algae cake is given in dollars per metric tonne. While these values would be reduced if transportation is required, for this analysis, it is assumed that the algae cake can be used locally.

As shown in Table 11, the algae cake may also be sold for its starch content – for instance, to an ethanol producer. Corn prices in Canada were around \$200 per tonne in 2008 (1). Based on starch content, the value of algae cake for ethanol production may be slightly higher than its value for animal food. However, actual pricing will depend both on the specific moisture content and protein content[60].

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[55] The water would, however, have to be replaced each day as the carbon is depleted.

[56] Apart from costs associated with distribution and pumping.

[57] The authors left out the power consumption required for harvesting for the case using flue gas, which seems inconsistent and was therefore corrected here.

[58] This compares to 0.5 employees per ha in aquaculture (100) and 9 employees per ha in BC's greenhouse sector (not including packing (124)).

[59] Distillers' grain from corn contains almost no starch (which is used for ethanol production) and some oil, whereas algae cake (from which oil has been extracted) contains little oil and some starch.

[60] If algae is grown in saltwater, this may impact its value. Washing the cake to remove the salt and then passing it through a filter press or centrifuge a second time appears to be cost prohibitive. Salt may also reduce the algae's digestibility. However, the question of whether salt is compatible with animal husbandry or ethanol production was beyond the scope of this study and was not examined further.

Table 9: Annual Operational Cost Parameters for a 400 ha Raceway Algae Production Plant

Parameter	Benemann et al. (27)	This study	Source
Yield	30 $g.m^{-2}.d^{-1}$	9.38 $g.m^{-2}.d^{-1}$	
$ per ha per year (400 ha algae culture facility)			
Power, mixing	700	1,600	BC Hydro (10)
Power, harvesting, processing	500		
Power, water supply	570		
Power, flue gas supply	1,000		
Power, other	100		
Nutrients (N,P,Fe)	900	3,000	See text
CO_2	7,400	0	Flue gas
Flocculant	1,000	396	
Labour, overhead	3,000	20,000	Staple (171)
Waste disposal	1,000	423	
Maintenance, tax, insurance (5% capital cost)	3,170	13,035	
TOTAL operational cost	**19,340**	**38,454**	

Table 10: Distillers Grain and Assumptions on Algae Cake Value

	Distillers Grain (wet)	Distillers Grain (dried)	Algae cake, (wet)	Algae cake, (dried)
Value per ton	$40	$132	$15*	$115*
Protein	15%	30%	6%	26%
Starch	~0%	~0%	10%	41%
Oil	6%	11%	0.50%	2%
Moisture	60%	10%	80%	10%

* conservatively estimated based on protein content

Table 11: Corn Pricing and Assumptions on Algae Cake Value

	Corn	Starch	Algae cake (wet)	Algae cake (dried)
Value per ton	$200	$760	$30*	$130*
Protein	7.70%	0.10%	6%	26%
Starch	62%	88%	10%	41%
Oil	3.30%	0%	0.50%	2%
Moisture	15%	12%	80%	10%

* conservatively estimated based on starch content

1.2.15. Photobioreactors

Capital costs: Benemann (25) reports costs of over $1 million per ha ($100.m^{-2}) for PBRs in Spain, Germany and Israel, (as opposed to costs of around $100,000.ha^{-1} ($10.m^{-2}) for open ponds). The Dutch company Algae Link, sells a tubular PBR pilot plant (48 m^{2}) for €69,000, or $2,100.m^{-2} (4) – a number that can serve as an upper limit, but which is clearly unrealistic for a large-scale algae farm. Dmitrov (60) estimated the minimum costs for a GreenFuels type PBR at $190.m^{-2}$, while GreenFuels themselves estimated capital costs at $125-$150.m^{-2} (59). Although considered optimistically low by some industry experts, this higher estimate of $150.m^2 is used for the generic base case PBR[61].

Inoculum costs: Similar to the case developed for the open raceways above, it is assumed that the algae species used does not require separate, on-site production of inoculum.

Algae species: As described in Section 4.1.2, as a consequence of the closed (or mostly closed) nature, selected species can be grown in PBRs enabling the cultivation of species with the required biochemical composition. For the generic base case PBR plant considered in this study, the algae composition assumed is shown in Table 8. A sensitivity analysis is conducted at the end of this chapter to examine the impact of algae with different biochemical compositions.

Yields: A yield of 15.3 $g.m^{-2}.d^{-1}$ has been assumed based on the results from the algae productivity model developed for this study. These lower yields will have an impact on several other parameters, such as frequency of harvesting and fertilizer use.

Harvesting and extraction costs: Recovery of a unit weight of biomass from PBRs costs less than in raceways due to their higher volumetric concentrations. As such, harvesting costs are assumed to be similar to that of the second stage used for open raceways as described in the previous section i.e. $500 per ha for electricity for centrifugation[62], and no extra cost for flocculants. Actual harvesting costs do, however, depend on strain morphology and harvesting efficiencies by centrifugation can vary by orders of magnitude (see Appendix H for a more detailed discussion).

Wastewater treatment costs: As discussed above, wastewater treatment may be required for the algae plant. There are more restrictions on waste water re-use in a PBR compared to open raceways because of the need to avoid contamination. Hence pre-treatment of the wastewater prior to re-use is essential. An indication of potential costs per liter is developed in the section on heterotrophic fermentation below.

Carbon costs: Similar to the case developed for the open raceway, a continuous supply of free[63] CO_2 is assumed to be supplied from flue gas.

Power costs: Considerable energy is required to push the thick media (caused by higher cell densities) against the friction obtained in the narrow channels of most PBRs[64]. Currently, mixing energy equivalent to about 10-30% of the incoming solar energy is said to be required in some cases, which is much more than the algae would actually produce from sunlight. One percent is currently deemed feasible only in thin layer PBRs (164). With an average insolation of 3 kWh per square meter per day in BC, this 1% corresponds to 0.03 kWh per day or 109.5 MWh per ha, per (365-day) year [65]. Keeping all other power inputs equal as for the raceway system, overall power consumption increases to 143 MWh per ha, per year (equivalent to 6,514 kVA per month for a 400 ha plant). Counting 2.5 cents per kWh (up to 90% of base demand, remaining 10% charged at $0.074.kWh^{-1}$), plus a demand charge of $5 per kVA of billing demand, monthly load charge costs amount to $32,648.40 ($977.$h^{-1}y^{-1}$), plus $4,280.00 in annual power costs per ha.

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[61] For comparison, the BC greenhouse industry lists capital costs of $250.m^{-2} (124).

[62] Capital costs for the centrifuge are assumed to already be included in the total capital costs estimated above.

[63] Apart from costs associated with distribution and pumping.

[64] PBRs are generally narrow panels or tubes to maximize the surface area-to-volume ratios.

[65] This contrasts with a mixing energy of 11 MWh per hectare assumed above for paddle wheels (based on Benemann and Oswald (27)).

Cooling costs: Cooling, which will likely be required during the warm summer period, can be achieved with water or through air-conditioning and will increase capital cost and electricity consumption. For this analysis, it is assumed that these costs are sufficiently covered in the cost parameters used. However, the need for cooling even in temperate climates (65; 122) underlines the fact that the cost parameters used here are fairly optimistic.

Cleaning: Over time, light penetration into PBRs is reduced due to adherence of algae cells to the internal surfaces. Hence, periodical cleaning is required. Replacing the cultures from time to time is also necessary in order to maintain optimum yields, or due to 'crashes' caused by exhaustion of culture nutrients, invasion of bacteria or other contaminants. Cleaning, which is expected to occur 5 – 6 times a year (65), can be difficult in many PBRs[66] and could lead to interruptions of up to two days each time.

Table 12: Capital and Operational Cost Parameters for a 400 ha Bioreactor Algae Production Plant in BC

Parameter	Value	Source
Yield	15.3 $g.m^{-2}.d^{-1}$	This study
$ per ha, year (400 ha system)		
Capital cost	1.5 million	Dmitrov (60)
Annual capital cost (14%)	210,000	Tampier et al (175)
Power, mixing	5,257	Power costs increased (see text)
Power, harvesting, processing		
Power, water supply		
Power, flue gas supply		
Power, other		
Nutrients (N,P,Fe)	5,106	Proportionate to yield
CO_2	0	Flue gas
Flocculant	0	not required
Labour, overhead	40,000	Labour increased (see text)
Waste disposal	846	2 x raceway
Maintenance, tax, insurance (5% capital cost)	75,000	
TOTAL annual operational cost	**126,209**	
TOTAL annual costs	**336,209**	

Labour costs: Dmitrov (60) estimated labour costs of \$1.33.m^2 (\$13,300.ha^{-1}) for a GreenFuels PBR plant. Considering the increased complexities of PBRs, salaries may even be higher for a PBR plant than for an open raceway plant. Molina Grima et al. (130) lists labour costs for a 26 tonne per year PBR as 1.2 full-time positions, at a cost of \$70,000. Assuming proportionality based on annual production, the present case (56 tonnes per ha, per year) would then require about 2.4 full-time people per ha [67]. Assuming that significant economies of scale will be derived from the larger size of the modeled plant (400 ha), labour requirements were set at 1 person per ha, at a cost of \$40,000 per position. Again, this can be considered a very optimistic scenario and actual labour costs may be much higher.

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[66] Due to the narrow openings in short path length PBRs.

[67] This compares favourably with existing PBRs producing biomass for food or cosmetic products, which can employ up to 17 workers per ha (65).

1.2.16. Fermenters

Capital costs: In 1995, Martek Biosciences acquired a fermentation plant in Winchester, KY with a capacity of 1.2 million liters of oil from algae for US$10 million (33) ($13 million in 2008 dollars). Assuming the fermenters are used at 80% of capacity and that cultivation of one batch takes seven days (50 weeks per year), with an algae biomass concentration of 50 g.L^{-1} and an oil content of 50%, about 1.4 million liters of oil can be produced per year (a commercial facility may produce 200 million liters or more).

> "Although good design and construction practices do much to avoid an unnecessary inflation of costs, a plant designed for sterile fermentation is significantly and unavoidably more expensive than non-sterile designs, such as used in ethanol distilleries."
>
> Grapes (79)

Capital costs may also be estimated from those of an ethanol facility. While costs per annual liter produced in a typical ethanol plant is about $0.70 (82), the more sophisticated lignocellulosic Iogen process is expected to have capital costs of $2 per liter. Given that a sterile fermenter is more complex and costly than conventional ethanol production, the cost per liter of oil produced is assumed to equal that of a lignocellulosic plant. This would be equivalent to $2.8 million for the Martek fermenter discussed here.

Yield: In contrast to raceways and PBRs, the yield from fermenters is better expressed as grams per liter, per day. Algae cell densities of up to 51g.L.d^{-1} have been obtained in seven-day cultures (117; 201), and up to 116 g.L.d^{-1} have been reported by other groups. While even higher cell concentrations of 302 g.L.d^{-1} have been achieved by Theriault (179) in mixotrophic cultures, for the base case fermentation scenario discussed here, a yield of 50 g.L.d^{-1} is conservatively assumed (also confirmed in (7; 14) for Martek operations). This is because illumination may not be used to save power costs and different algae strains with different growth rates may be used. In addition, antibiotics, vitamins, plant hormones etc. may have to be added to achieve the highest yields. A balance between increasing yields and reducing the cost of process inputs must therefore be found.

Lipid content: As described in section 2.2.3, heterotrophically grown algae generally exhibit higher lipid yields compared to phototrophic cultures. A lipid content of 50% is assumed for a realistic base case (Table 8).

Harvesting and extraction costs: for ease of comparison, it is assumed that the same process as for the raceway and PBR processes is used to extract the oil, i.e. hot oil extraction from an algae cake by centrifuge. The oil is then sold to a separate biodiesel production facility.

Wastewater treatment costs: A fermenter must replace the growth medium after each batch to maintain sterility. It can be assumed that the algae will only use about 95% of the carbon in the growth medium, leaving some BOD to be treated in the wastewater. 1.07 grams of oxygen is required to transform one gram of glucose to water and carbon dioxide (stoichiometric calculation). Assuming that 5 grams per liter of glucose remain unoxidized in rejected medium, this would be equivalent to 5.35 grams of oxygen demand. This is roughly ten times the amount usually tolerated for sewer systems, i.e. an additional fee applies. The City of Prince George charges $0.5756 per kilogram of BOD above 500 ppm (0.5 grams per liter). The plant is supposed to produce 50 batches of 960,000 liters per year, or 232,800 kg of BOD above the 500 ppm limit. The wastewater treatment cost would thus be $134,000 per year, or $0.10 per liter of oil. Note that semi-continuous operations may only discharge some of the spent medium, i.e. this estimate should represent the upper limit of wastewater treatment costs.

Organic carbon source costs: Behrens (14) presented substrate costs at $0.67per kg, and Li et al (117) used substrate costs of $0.55 per kg ($1.09 per liter of algal oil produced). These authors further suggested that costs can be reduced by 40% when using starch and cellulose-hydrolyzed solution or 60-70% by using cellulose solution only. Therefore, in the base case, it is assumed that costs can be cut by at least 50%, this results in a cost of $0.55 per liter for oil. Costs could be reduced further if a no-cost carbon source can be used, such as sugary waste from soft drink production. Theoretically, the cost of the carbon source could even become negative, i.e. the algae operation could obtain revenue from treating the wastewater. Since the algae will, however, not use up all carbon in the medium, it is likely that wastewater treatment costs are only reduced, not eliminated. No revenue is therefore assumed for using organic waste streams for the algae operation[68].

Power costs: The cost of electricity used provided in the source paper (117) was not broken down into its energy units, hence, a correction could not be made for what that same amount of electricity would cost in BC[69].

Labour costs: Grapes (79) assumes a minimum of ten staff (two administrators plus four shifts of two people) for a 4,500 tonnes per year butanol production facility. This assumption can be used as the maximum for the algae fermenter with a much lower production. At $40,000 per worker, labour cost equals $0.29 per liter.

1.2.17. Anaerobic Digestion

Several options are available to integrate anaerobic digestion into an algae biomass plant:

- Growing and harvesting algae biomass to feed a digester that produces electricity or biomethane: this option is not feasible in BC as electricity production from agricultural digesters is uneconomic at current power prices (9) and biomethane production would barely break even, even with a gate fee of $20 to $30 per tonne of feedstocks (11). Using algae in a digester may also require the addition of another material, such as waste paper, to achieve an optimal C-N balance in the substrate. Since algae cannot be grown for free, this option is currently unfeasible.
- Instead of selling the algae cake, it could be digested: Again, electricity production would generate negative returns, and producing biomethane would at best break even. Furthermore, savings on fertilizer cost through nutrient recycling are somewhat lower than the value of the cake (Table 14), and as such, this option is also ruled out for economic reasons (since selling the cake is the more attractive option).
- Benemann and Oswald (27) suggested digestion of the residual biomass after oil extraction, with the digester effluent then being reintroduced into the algae ponds to reduce fertilizer requirements (estimated to be by 75% for N and 50% for P)[70]. One kg of urea (46% N) is assumed to cost $0.40 and one kg of di-ammonium phosphate (52% P) $1[71]. Table 14 clearly

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[68] The organic carbon from the waste stream would also have to be concentrated before use and the costs of concentration and transportation would likely negate any revenue that may be obtained from reducing the organic loading in the waste stream.

[69] Electricity costs in BC are expected to be lower than reported by the source given the lower costs of electricity from BC Hydro.

[70] However, recycling of algae biomass can lead to bacteria taking over the cultures, as excess organic nutrients from the digester or the accumulation of by-products may inhibit cell growth (120) in the ponds after some time.

[71] The value of nitrogen contained in phosphate fertilizer was deducted from the phosphate fertilizer cost in the table below.

shows that the value is lower than that for dried algae biomass cake estimated above. Similarly, the nutrients in the effluent created by the centrifuges or in the harvesting ponds may be recycled. However, the accumulation of inhibitory substances and bacteria caused by organic material from the digester will require the exchange of the medium from time to time. Therefore, overall savings are unlikely to warrant the construction of a digester.

Table 13: Capital and Operational Cost Parameters for Algae Production through Heterotrophic Fermentation (1,200 m^3 fermenter)

Parameter	Value	Source
Oil yield	50%	See text
Cell concentration at harvest	50 $g.L^{-1}$	See text
Capital cost	$2.8 million	See text
$ per liter of oil		
Power	0.73	Li et al. (117)
Steam	0.34	Li et al. (117)
Aseptic air	0.16	Li et al. (117)
Inorganic chemicals (potassium)	0.08	Li et al. (117)
Carbon source	0.55	Li et al. (117)
Flocculant	0	Not required
Labour, overhead	0.29	See text
Wastewater treatment	0.1	See text
Maintenance, tax, insurance (5% capital cost)	0.1	
TOTAL annual operational cost	**2.35**	
Revenue from selling algae cake	-0.05	
Annual capital cost (14% of capital cost)	0.28	Tampier et al.(175)
TOTAL annual costs	**2.58**	

Table 14: Fertilizer Cost and Assumptions on Algae Cake Value

	Fertilizer cost	Algae cake (dry weight)	Nutrient Recycling
N	$870 per tonne	6.5%*	75%
P	$1,740 per tonne	1.3%*	50%
Value		$79 per tonne	$54 per tonne

* after oil extraction, assuming oil mainly contains carbon and hydrogen

1.2.18. Discussion

Cost data reported in the existing literature vary by orders of magnitude, and can range from $0.20 per kg (27) of algae to several hundred dollars (35), depending on climate, species, growing systems and other conditions [72].

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[72] As such, this data does not answer the question 'is algae production feasible in BC?' But rather 'under what circumstances will algae production be economically feasible in BC, and can these circumstances can be created'? This has been achieved by identifying the main cost parameters and minimum performance criteria required to make algae production economically feasible in BC.

shows the cost parameters for the three algae cultivation technologies[73]. None of the three base cases can currently compete with fossil diesel prices. With a raw biomass cost of $2.66 kg^{-1}, the raceway estimate (based on a yield of 9.38 $g.m^{2}.d^{-1}$), while lower than some and higher than other estimates (Table 16), is far too high to produce biodiesel since the resulting oil price (at 15% oil content) is $14.44 per liter. The biomass production costs are also much higher than for corn ($0.20 per kg) and woody biomass ($0.10 per kg when harvested from the forest; less when residues) in BC.

Table 15: Comparison of Base Case Capital and Production Costs for Three Algae Production Technologies

	Raceway		Photobioreactor		Fermenter	
Initial Investment ($.$L^{-1}$)	52		111		2	
Production Cost	($ per liter of oil produced)					
Labour cost	$4.03	26.69%	$2.96	11. 90%	$0.29	10.88%
Other production cost	$3.71	24.59%	$6.37	25.59%	$2.06	78.45%
Capital cost	$7.35	48.71%	$15.56	62.50%	$0.28	10.66%
Total Cost	$15.09		$24.89		$2.63	
Credit from the sale of algae cake*	$0.65		$0.29		$0.05	
Net total cost	**$14.44**		**$24.60**		**$2.58**	
Lipid content	15%		25%		50%	
Cost per kg of algae	$2.66		$7.32		$1.54	

* Assumes that the algae cake is sold to an ethanol producer for its carbohydrate content

Despite the higher oil content of 25%, the cost of producing algae biomass ($7.32 kg^{-1}) and oil ($24.60 per litre) are even higher when they are produced in the PBR. This result is independently confirmed in the literature (41; 150; 172). Of the three technologies, heterotrophic fermentation appears to be the most promising technology with the price of the resulting algae oil being closest to current fossil fuel costs at $2.58 per litre of algae oil[74] (with a raw biomass cost of $1.54 kg^{-1}). This result is very much in line with other sources citing a cost of $2.01 per litre (14) and $1 per kg of biomass (150) for heteotrophically produced algae and algae oil. Furthermore, heterotrophic fermentation is also independent of climatic conditions, because it is carried out in closed vessels, and may be realized at a smaller scale than raceways or PBRs.

Table 16: Biomass Cost Comparisons

Source	**Cost**	**Comments**
	Actual experience	
Lee (114)	$8-15.$kg^{-1}$	Commercial raceway facilities
Benemann et al. (28)	$5.$kg^{-1}$	Small scale, incl. drying (Earthrise Farms)
Ben Amotz (19)	$17.$kg^{-1}$	Open raceways in Israel, saltwater, pure CO_2
Behrens (14)	$2.01.$kg^{-1}$	Heterotrophic culture

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[73] These results should be seen as estimates, as exact costs will depend heavily on each parameter.

[74] Even if the carbon source is more expensive than in the base case, there is still room for improvement in terms of higher growth rates and possibly even higher oil content.

Source	Cost	Comments
Theoretical scenarios		
Gladue and Maxey[75] (71)	$12.kg^{-1}$	Heterotrophic culture, N. alba
Sheehan et al. (166)	$0.37-1.16.L^{-1}$	Open raceways in southwestern U.S.; 1995 dollars
Benemann and Oswald (27)	$0.2.kg^{-1}$	Large unlined raceway ponds (400 ha), 30 $g.m^{-2}.d^{-1}$
Benemann (28)	$0.1.kg^{-1}$	Large natural pond; no drying; water and nutrients, CO_2 considered free; high productivity (33 $g.m^{-2}.d^{-1}$)
Molina Grima et al. (130)	$32.kg^{-1}$	Tubular bioreactors; pure CO_2
Chisti (46)	$0.47.kg^{-1}$	Photobioreactors. Assumes CO_2 is available for free, 10,000 tons of biomass per year
	$0.60.kg^{-1}$	Raceway ponds (10,000 tons per yr)
Li et al. (117)	$2.40.L^{-1}$	Vegetable oil extracted from heterotrophically cultured algae, 50% lipid content in dry matter
Dmitrov (60)	$5.36.L^{-1}$	Cost of biodiesel, using GreenFuel Technologies design
Barclay et al. (8)	$1.63.kg^{-1}$	Open raceways in Vacaville, California, 4 ha pond with productivity of 370 tons per yr. Harvesting by flocculation and centrifugation.
	$2.37.kg^{-1}$	Open raceways in Vacaville, California, 4 ha pond with productivity of 220 tons per yr. Harvesting by flocculation and centrifugation
Ben Amotz (19)	$0.34.kg^{-1}$	Open raceways in Israel, saltwater, flue gas (capital costs not included)
Radmer and Parker (150)	<$1.00.kg^{-1}$	Biomass from heterotrophically grown algae
This study	$2.66.kg^{-1}$ $14.5.L^{-1}$	Large lined raceway ponds (400 ha), 9.38 $g.m^2.d^{-1}$

Individually, the most important cost, contributing almost half of total costs for the raceway and two-thirds for the PBR, is capital cost[76]. However, for fermentation, these costs were the lowest of all three at only one-tenth of total costs. At 27% of the total costs, labour is a much more important factor in raceway operation than identified in previous studies[77]. While increased automation may help reduce labour expenditures, the daily requirements for pond evaluation, determination of residual nutrient levels, mixing, measurements and augmentation of nutrients, adjustment of flow rates, cleaning, maintenance and harvesting make the reduction potential likely to be insignificant. For PBRs and fermenters, the labour costs were similar and much lower than for raceways, at 12% and 11%, respectively.

At about 25% of total costs, the other production costs obtained in both raceways and PBRs in BC (without labour and capital costs) are still too high for phototrophic algae production to achieve price parity with conventional diesel. As such, these options can be ruled out as economically non-feasible, even with generous assumptions about future cost reductions[78], These other production

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[75] The authors do not provide a cost calculation but instead refer to textbooks as their cost information source.

[76] While significant when compared to other studies, the raceway capital cost estimate is backed up by other sources, and was corrected upwards in order to allow for lined ponds.

[77] Algae production is a labour intensive activity, and the assumptions of requiring at least one full-time worker per two ha for growing and harvesting was derived from the Israeli company NBT and a second (anonymous) company.

[78] This is also reflected in the very high investment cost per (annual) liter produced, which is a measure often used by the biofuels industry.

costs form the bulk of the costs associated with heterotrophic production, at over 78% of the costs. However, given the higher productivity and oil yields obtained with fermentatively grown algae, total production costs were still lower than obtained when the algae were grown in raceways or PBRs.

1.2.19. Sensitivity Analysis and Minimum Performance Levels

Whereas there is uncertainty around some of the parameters used above, some (such as labor costs, fertilizer costs and capital costs) are unlikely to change substantially, even with increased knowledge, and thus general conclusions can be drawn from this analysis.

The parameters used for the different scenarios in Table 17, are based on the maximum possible yields expected from phototrophic cultivation of algae in BC (shown in Table 6). Using these scenarios, Figure 4 compares economic performance of various technologies in different scenarios and with different oil content.

Base cases: As described in Section 4.1.2, the yield predictions in Table 6 are the maximum yields that can be expected in raceways and PBRs in BC when every parameter is optimal (other than solar insolation and temperatures). For the raceway, a mix of wild algae species that occur in BC is expected to be grown[79] and it is not heated, therefore yielding very little biomass during the winter. The PBR is heated during the winter (ideally, using hot flue gas) and it is assumed that a high oil yielding algae species is isolated and grown in the PBR. The fermenter is reasonably expected to yield 50 g.L^{-1} after one week, with an oil content of 50%. As was already shown in Table 15, none of the technologies is able to produce a biofuel in BC that can compete with current fossil fuel prices.

Table 17: Parameters Used for Different Scenarios

Technology	Base Case	Scenario 2	Scenario 3	Scenario 4
Raceway	Unheated raceway (run year round)	Heated raceway (run year round)	Unheated raceway (run April to September)	Unheated raceway (run April to September with half the capital costs of Scenario 3)
	Location: Prince George	Location: Prince George	Location: Vancouver Island	Location: Vancouver Island
	9.38 g.m^{-2}yr^{-1}	15.47 g.m^{-2}yr^{-1}	22.89 g.m^{-2}yr^{-1}	22.89 g.m^{-2}.yr^{-1}
	15% oil	15% oil	15% oil	30% oil
PBR	15.3 g.m^{-2}yr^{-1} 25% oil	15.3 g.m^{-2}yr^{-1}; 35% oil	6,000 gal.ac^{-1}yr^{-1} Ethanol secretion	n/a
Fermenter	50 g.L^{-1};	100 g.L^{-1};	n/a	n/a
	50% oil	60% oil		

Raceway: Operating a raceway during winter months, when temperatures and solar insolation are too low, makes little sense as yields drop to zero. Therefore, Scenario 2 reflects a heated raceway in Prince George that maintains optimal temperatures throughout the year. As such, yields are similar to the PBR, although algae oil content remains lower, and the cost of the algae oil production is still too high to compete with fossil fuels (Figure 4). In an attempt to improve on this situation, Scenario 3 assumes a seasonal operation on Vancouver Island, from April to October, when yields are highest. Under this scenario, average yields are much higher than the year round heated option, but while the operating costs are lower, oil production costs are still too high to compete with fossil fuels. The last scenario, Scenario 4, assumes that it is possible to grow a specific algae species that yields twice

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[79] As a consequence of its open nature.

the oil (30%), and that capital costs can be halved by leaving out the liner[80]. However, once again, even with this optimistic scenario, the production costs are still too high, at $2.65 per liter (Figure 4), to compete with fossil fuels.[81]

PBR: While the base case assumes that an algae species with 25% oil content is grown, Scenario 2 represents a PBR growing a species with an oil content of 35%, achieved through species selection[82] or nutrient limitation. Under this scenario, production costs are still dominated by capital costs and the higher oil yields are still insufficient to reduce costs enough to compete with fossil fuels. Scenario 3 assumes the production of 6,000 gallons of ethanol per acre, per year[83] in a more southern region[84]. In this example, it is not known how the ethanol, which is excreted by blue-green algae, is separated from the medium, and assuming energy-intensive distillation, production costs would increase well over base case assumptions. The capital costs were assumed to be the same as for other PBRs, and the resulting cost per liter of ethanol (even without distillation costs) is still prohibitively high at $5.87 per liter (Figure 4)[85].

Fermenter: Despite having the lowest costs of all three base cases, fermentation production costs are still too high to compete with fossil fuels. However, because algae oil content can be higher than 50% (up to 70% has been reported in the literature), a 60% oil content was assumed for Scenario 2. Moreover, the growth rate could be increased and yields of more than 100 g L^{-1} have been achieved in laboratories (200). Using these parameters for this scenario, the cost of oil is reduced to $1.54 per liter (Figure 4.). While this is still more expensive than for example canola oil[86], this comes much closer to what is needed to compete with fossil fuels.

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[80] I.e. the raceway would have to be on clay or use clay or salt as the liner, which is sometimes suggested in the literature.

[81] In regions with higher insolation and lower labour cost than BC, it may be possible to reduce production costs further if all other uncertainties with open raceways can be controlled.

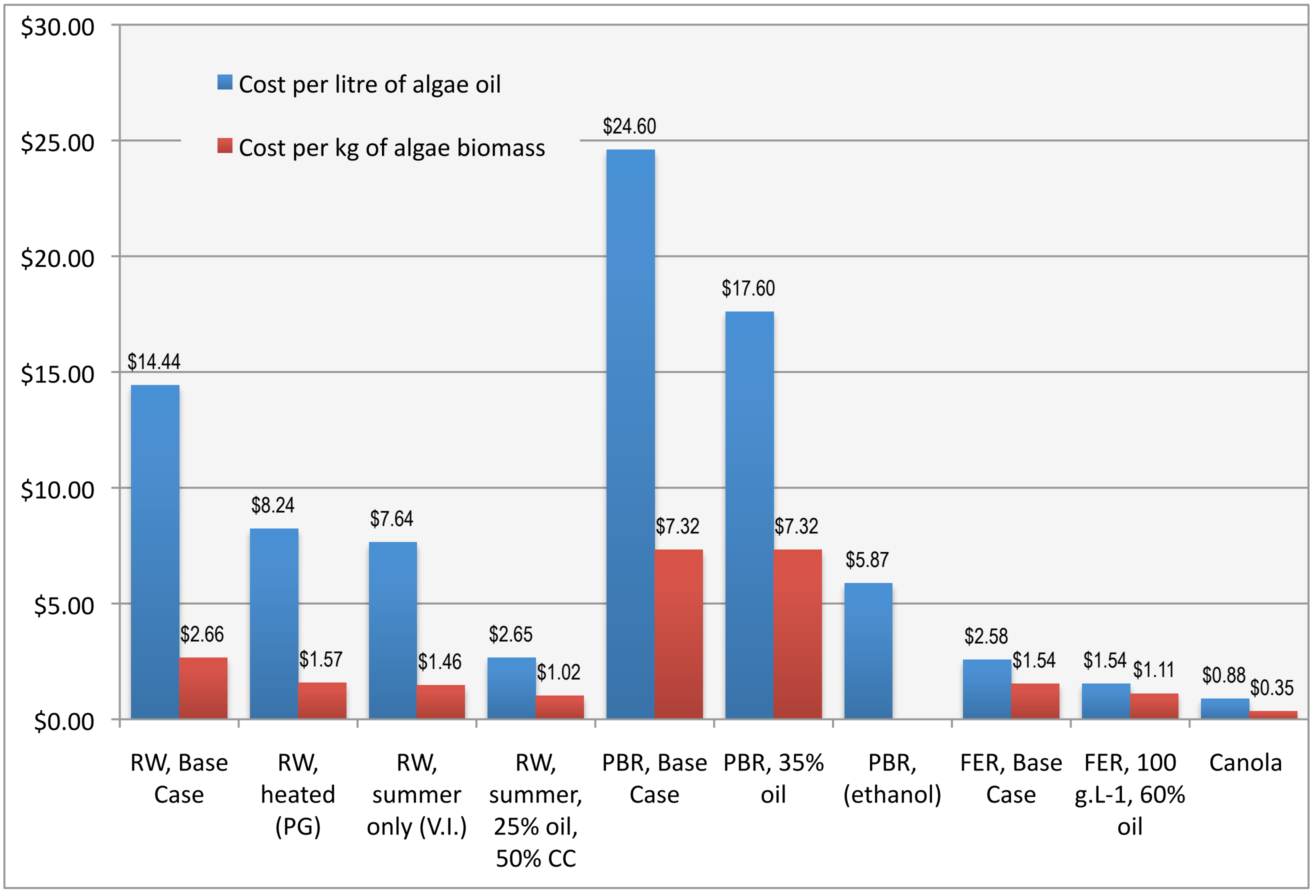
[82] While values of up to and exceeding 50% have been suggested in the literature, these are considered unrealistic. This is because they are either based on species being subjected to nutrient starvation where, as described earlier, the increased oil production occurs at the expense of productivity (thereby making no difference in final oil yield), or slow growing species.

[83] According to the Algenol website, for their Direct to Ethanol™ process (5).

[84] This provides an idea of production costs, based on industry yield data, for a process that does not focus on biodiesel or biocrude production.

[85] Increasing the yield to 10,000 gallons per ha, per year, a potential indicated by the producer(5), does not remedy this situation.

[86] Included for comparison in Figure 4.



RW: Raceway; PBR: Photobioreactor; FER: Fermenter

Figure 4: Cost per kg of Algal Biomass and per Litre of Oil/Ethanol Produced Using Different Systems and Different Scenarios.

1.2.20. Conclusions

From the above economic and sensitivity analysis, the following conclusions can be drawn:

- Raceways cannot currently produce oil at competitive costs in BC. Even when assuming a yield of 20 $g.m^{-2}.yr^{-1}$ and an overly optimistic oil content of 50%, production costs are still around $2 per liter. However, raceways may be able to produce oil at competitive costs in areas with higher insolation and lower labour costs.
- PBRs are unable to produce oil at competitive costs; this is mainly due to the very high capital costs[87]. Even if these costs are reduced from 15% to 8% (fully financed by a bank loan), this will not reduce costs enough to achieve parity with fossil fuels. Based on this finding, PBRs are unsuitable for the production of low-cost products from algae. Instead, they will remain restricted to the production of higher-value cosmetic, food, or health products.

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[87] Assuming a cost of $1.5 million per ha (a cost deemed low by many), capital costs alone are between $3 and $5 per liter of oil produced.

- Fermenters appear to be the most promising option for producing algae oil. However, before algae fermentation can become commercial, more R&D is required. This must address issues related to optimization of oil content and biomass yields, and the possibility of substituting cheaper carbon sources for those often used currently, such as glucose.

- Algae cultivation is by no means a simple process, and a sample of questions that needs to be successfully answered is given in Appendix L.

5 Energy and GHG Balance

5.1 Comparison of Results for BC

Table 18 shows the energy and GHG balances of the three base cases. This assessment is not an accurate life-cycle analysis, but it does provide a general picture of the energy and GHG performance of each process. For each liter of biodiesel consumed in place of fossil diesel, emissions of 3.3 kg of CO_2 are avoided.

For the fermenter, a power price of 6 ¢ per kWh is assumed. The natural gas requirement for fermentation was approximated by converting the cost estimations from the economic analysis in Chapter 4 directly into natural gas use, assuming a price of $8 per GJ. This is converted to GHG by assuming emissions of 50 kg per GJ of natural gas. Grid emissions from electricity consumption in BC are calculated as 50 kg CO_2 per MWh (190).

Fertilizer energy was estimated as 22.3 MJ per kg of urea and 13.2 MJ per kg of diammonium phosphate (DAP) (89), assuming a minimum use of 109 grams of urea and 48 grams phosphate per kg of dry algae biomass – a low estimate, since this is based on cell N and P content and assumes that 100% of the fertilizer input is actually used by the algae. No nutrient recycling is assumed. GHG emissions were calculated as 732 grams of CO_2 per kg of urea (55 grams N in one kg of algae) and 894 grams of CO_2 per kg of DAP (11 grams of P in one kg of algae). The energy balance assumes an energy content of 37 MJ per liter of algae oil. The carbon source for the fermenter is assumed to be carbon neutral. No energy consumption was attributed to this feedstock, although this would have to be done if it is not a waste stream. The analysis is split into a GHG balance and an energy balance. For the GHG balance:

Assumptions used for the GHG balance estimates:

- Emissions are calculated based on assumptions for electricity and natural gas use (first line) and indirect emissions from fertilizer use (second line).
- A GHG credit is assumed for the agricultural inputs for corn cultivation, which is displaced by the algae cake used in ethanol production. This credit is based on the inputs to grow corn with equivalent starch content[88] (1.9 MJ or 190 grams of CO_2 for one kg of corn with 60% starch) (176).
- The starch contained in algae cake after oil extraction is assumed to be used for the production of ethanol as described in Chapter 4, and the energy gained and GHG emissions reduced are therefore credited to the algae oil produced. For the ethanol credit, a yield of 400 liters of ethanol per 600 kg of starch is assumed, at an ethanol energy content of 29.7 MJ per kg(176). The energy required to produce ethanol from starch is subtracted from the result, based on GHGenius data.
- Grams of CO_2 displaced represents the fossil diesel fuel that is replaced by biodiesel from algae, and the last line shows the net GHG displacement after all process emissions are deducted and credits are added.

The energy balance is structured in the same way as the GHG balance, except that the energy ratio represents the value obtained when the energy in the oil and any energy displaced from other processes are divided by the energy consumed when producing algae oil.

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[88] These inputs are avoided as no corn production is necessary if starch from algae is used for ethanol production.

The results show that in BC, all three algae production technologies reduce GHG emissions and have a positive energy balance. In comparison, corn ethanol and biodiesel from canola oil have an energy ratio of around 2[89], and ethanol from switchgrass delivers an energy gain of around 10-20% (176), which can be improved upon through technical innovation[90]. The energy balance base case for algae production through heterotrophic fermentation is similar to that of canola and is therefore comparable with existing biofuel options.

Table 18: Energy and GHG (CO_2) Balance per Liter of Oil Produced

	Raceway	**Bioreactor**	**Fermenter**
Daily Biomass yield (dry)	9.38 $g.m^{-2}$	15.3 $g.m^{-2}$	50 $g.L^{-1}$
Oil content	15%	25%	50%
Starch content	40%	30%	20%
Electricity ($kWh.L^{-1}$ / $MJ.L^{-1}$)	8.9/32.0	10.6/38.0	2.4/8.8
Natural Gas ($MJ.L^{-1}$)	0	0	8.5
Fertilizer ($MJ.L^{-1}$)	20.4	12.3	6.1
CO_2 Balance (Grams per liter)			
Grams of CO_2 emitted	-444.6	-528.3	-547
Fertilizer CO_2 losses	-818	-491	-245
Corn CO_2 credit	844	380	127
Ethanol CO_2 credit	3,215	1,447	482
Grams of CO_2 displaced	3,300	3,300	3,300
CO_2 Balance ($g.L^{-1}$)	6,097	4,108	3,117
Energy Balance (MJ per liter)			
Total energy consumed	-52.4	-50.3	-23.4
Corn energy credit	8.4	3.8	1.3
Ethanol energy credit	46.7	21	7
Energy displaced	37	37	37
Energy balance ($MJ.L^{-1}$)	39.7	11.5	21.9
Energy ratio	1.76	1.23	1.93

When the corn energy credit[91] is compared to the energy used to grow the algae, it becomes clear that the relatively low energy ratio for phototrophically grown algae in raceways despite the higher yield per surface area compared to field crops, is a consequence of the much greater energy input required for algae cultivation[92]. This however, is only valid for the low areal yields estimated to be achievable in BC. Increasing the yield to 20 grams per square meter for raceways increases the energy ratio to about 2, similar to algae fermentation or the conventional corn-to-ethanol process. If higher oil content is assumed for the phototrophically grown algae (25% for raceways and 35% for photobioreactors), the energy balance is not significantly increased for the PBR, and actually

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[89] I.e. for one unit of energy input, two units are gained.

[90] Such as replacing distillation with membrane separation.

[91] Which reflects the (avoided) agricultural inputs for corn that would have been used in ethanol production.

[92] Currently, the energy needs for continuous mixing, pumping, harvesting, and CO_2 insertion in algae cultures are high.

decreases for the raceway and the GHG balance for both systems is deceased, because the ethanol yield would be reduced. This result (not shown) illustrates the importance of this by-product in the overall process.

The carbon content of dry algae biomass and of starch is approximately 50%, thus about 1.7 kg of corn (60% starch) would have to be used to grow 1 kg of algae in fermenters when using starch as a carbon source. Including the corn production energy used in the energy balance for heterotrophic fermentation (i.e. the carbon source is no longer assumed to be a waste stream, which is more likely for large-scale operations), reduces the energy balance by about 5.5 MJ.L^{-1}, that is, it is still strongly positive

Looking at the energy balance another way, fermentation using corn starch (as a theoretical example) can be compared to using corn starch directly to make ethanol. Table 19 compares these processes in terms of fuel yields and energy balance using the fuel yield parameters for each process in the upper half of the table. The lower half compares the net energy yield for conventional corn ethanol production and the algae fermentation base and enhanced cases described in the previous chapter. The functional unit is the energy obtained in the fuel product obtained for each kg of starch feedstock.

The base case scenario shows no advantage of algae-to-oil over corn-to-ethanol, but the enhanced case, which assumes twice the yield (100 g.L^{-1}) per batch and a 60% oil content, has an almost fourfold energy yield compared to corn ethanol. A large-scale plant may also produce its own starch from algae cake, such that less corn is required as a substrate. The total areal footprint of such an operation would thus be larger than phototrophic algae production, but smaller than producing ethanol from corn. Note that this simple calculation does not include respiratory losses, i.e. the higher yield scenario is definitely required to obtain an advantage over first generation biofuels[93]

Table 19: Theoretical Energy Comparison Between Corn Ethanol and Heterotrophically Produced Algae Oil

		Fuel Yield	
Starch ethanol yield		0.67 liters per kg starch	
Starch oil yield, fermentation base case		1.18 liters per kg starch	
Starch oil yield, 60% oil in algae		1.41 liters per kg starch	
Energy, MJ per kg starch	**In Product**	**Production Loss**	**Net Energy Gain**
Corn ethanol	20	10	10
Fermentation base case	44	36	8
Fermentation, enhanced	52	14	38

Algae oil production can be compared to the production of oil from canola, using a scenario previously analyzed based on GHGenius data for the Prairies. This information is relevant to canola production in the climate in northeastern BC, which is the most likely location to grow agricultural energy crops. An oil yield of around 470 liters can be expected for one tonne of canola oilseed harvested, and 1.3 tonnes of oilseed is harvested from each hectare of land (176). This corresponds to an areal oil yield of only 0.11 g.m^{-2}d^{-1}, but yields an energy ratio of 2.3.

More importantly, for all three processes, the GHG balance assumes the use of BC-Hydro generated electricity, which is almost entirely produced with low-emission hydropower. Indirect emissions

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[93] Relevant because if algae is to be used as an energy feedstock, the energy ratio must be at least as good as conventional biofuel feedstocks.

from electricity use would be a multiple of what is used above in many other jurisdictions[94]. For example, a grid emission factor of 500 kg CO_2.MWh^{-1} (ten times higher than the one used for BC, reflecting a high share of coal-based power generation) would reduce GHG benefits. Also, the primary energy consumption would increase because power generation based on fossil fuels is only 40-50% efficient. For the energy balance above, a kWh was converted to MJ at the nominal factor of 3.6 MJ per kWh, which does not account for the way electricity is generated. If the electricity used is made from coal at 40% conversion efficiency, the energy balance becomes negative for the two phototrophic processes and drops to 8.7 MJ.L^{-1} for fermentation. Electricity could be produced from algae cake, instead of using it to make ethanol; however, even if 100% of the electricity needs could be met, the energy balance is less favourable than when the cake is used to make ethanol from its starch content.

Comparing the energy production by algae farming to coal-to-liquid technology, which can produce about two barrels (318 liters) of Fischer-Tropsch diesel per tonne of coal, provides an illustration of an alternative process that can use coal to directly create a liquid fuel. A tonne of black coal (at 20 MJ.kg^{-1}) produces up to two MWh of power, which would yield about 200 liters of algae oil in a raceway (at 10 g.m^{-2}d^{-1}), plus 190 liters of ethanol[95], less the approximately 500 kWh energy needed to produce fertilizer, - approximately 25% of the fuel yield. Taking the energy value of algae cake into account, it appears to be a slightly better option to produce liquid fuels than coal-to-liquid, at least from an energetic perspective, and especially so for regions with higher areal yields than BC.

For PBRs and raceways, the low algae production yields expected in BC dictate that the energy balance is only slightly positive and there is no substantial energy gain from the process. The energy balance therefore shows that phototrophic algae production is preferably situated in more southern areas with higher insolation.

5.2 Comparison of BC Analysis with other GHG and Energy Balance Estimates

Chisti (47) calculated the energy ratio of algae oil grown in raceways in the tropics to be 2.8. He assumed an oil content of 20%, a biomass concentration of 1% (1 kg.m^{-3}) and a productivity of 25g.m^{-2}. He further assumed that harvesting is by a combination of sedimentation and continuous vacuum belt filtration (instead of energy-consuming centrifugation), and that 500 m^3 of biogas per dry tonne is generated through anaerobic digestion. The assumed biogas yield may be correct, but considering that the oil, (which contributes significantly to the biogas yield) has been extracted, a more realistic extrapolation would be around 250 m^3 (2). Refining biogas to pipeline standards, currently the only near-commercial option in BC, would require about 0.3 kWh of electricity per cubic meter of biogas (11), resulting in a methane gas with 36 MJ heat content per cubic meter. The energy content of biogas varies with methane content, which may be up to 65%; however, assuming 50% methane, the estimated energy value is 18 MJ.m^{-3}, not the 25 MJ used by Chisti. Table 20 illustrates a revised energy balance, based on the assumption of 20% oil content and a daily productivity of 10 and 25 g. m^{-2} for BC and tropical environments, respectively. Values for the Tropics have been modified from Chisti (47) as described above. Construction and energy embodied in equipment (included by Chisti) is left out of the energy balance.

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[94] If electricity were generated using fossil fuel sources.

[95] Net, after discounting the energy lost to produce the ethanol.

Table 20: Revised Energy Balance for Raceway Cultivation of Algae in BC and the Tropics Using Alternative Energy Parameters

Parameter	**Tropics**	**BC**
Daily yield	25 $g.m^{-2}$	10 $g.m^{-2}$
Oil content	20%	20%
Energy Balance (MJ per kg of oil)		
Cultivation energy	-8.77	-21.9
Harvesting energy	-0.3	-0.3
Fertilizer energy	-14.12	-14.12
Oil recovery	-3.17	-3.17
Energy for biogas production	-0.88	-0.88
Energy for biogas purification	-1.08 to -2.16	-1.08 to -2.16
Energy in algae oil	37.8	
Energy in biogas	18 to 36	
	(based on 4 kg of dry biomass per kg of oil)	
Energy balance	27.48 to 44.4	14.35 to 30.27
Energy ratio	2.03 to 2.51	1.35 to 1.74

Chisti uses a harvesting and cultivation energy requirement of only about 12 MJ per kg of oil (about 10.3 $MJ.L^{-1}$). Given that testing with paddle wheels resulted in a power requirement of 100 kWh per hectare, per day (at 30 $cm.s^{-1}$)[96], a minimum of 36,000 kWh (130 GJ) is required. Based on a yield of 18 tonnes of oil per hectare (25 $g.m^2$, 20% oil), this is 7 MJ per kg. Energy for CO_2 supplies, harvesting and oil extraction has to be added. The energy to operate the paddle wheel increases exponentially with speed, i.e. it is only 10% at 15 $cm.s^1$. This essentially leaves a lot of room for uncertainties around this parameter, since a small reduction can yield substantial energy savings. The general assumption of 30 $cm.s^1$ for raceways to keep the algae suspended is used.

Chisti's assumptions on energy use requires half of the energy use for cultivation and harvesting in BC, showing the uncertainty around this parameter. The results for BC remain fairly low (maximum 74% energy gain if an oil content of 20% can be achieved) and do not differ much from the results obtained in Table 18. In contrast to the BC situation, there is potential to at least double the energy return in regions with higher insolation.

Benemann et al. (26) calculated energy use based on primary energy consumption (2,150 $kcal.kWh^{-1}$) and arrived at 1,335 kcal per gram of biomass (assuming a biomass productivity of 22.5 $g.m^{-2}d^{-1}$, and that carbon is supplied by flue gas). At an oil content of 15%, this corresponds to energy use of 37 MJ per liter of oil i.e. as much as is contained in the oil produced. These authors' analysis assumed a high degree of nutrient recycling. Note that at lower productivities, energy consumption per liter of oil increases as the same degree of mixing is still needed. Benemann and Oswald (27) found a positive GHG balance (2,800 $g.L^{-1}$ of oil) even with the use of coal generated electricity (grid emission factor: 880 $g.kWh^{-1}$), but they assume a high yield of 30 $g.m^{-2}d^{-1}$ and assume that the digester will produce enough electricity to export the excess to the grid. The basis of this estimate is a 50% lipid content of algae cells and a high electricity yield[97].

From the little analysis that can be found in the literature so far, there does not appear to be any indication that the data determined for BC in Table 18 are unreasonable. Specific processes will,

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[96] – See Sheehan et al. p.157 (166).

[97] A conversion efficiency of 25% yields around 30% less electricity than claimed in their study.

however, differ in the details and technology promoters will certainly come up with their own energy balances as they approach market readiness.

Based on the preceding analysis, the following observations can be made:

- Phototrophic algae production in raceways requires a high yield (15 $g.m^{-2}d^{-1}$ or more) to reach an energy ratio of 2 until biomass oil content exceeds 15%.
- Producing ethanol from algae cake yields more energy and GHG reductions than conversion to biogas.
- Assuming a conversion efficiency from biogas to electricity of 20%, it may be possible to use the residual biomass to generate enough power to operate the plant (Table 20), but a high biogas yield of around 500 m^3 per tonne of cake would be required.
- All three algae-to-biofuel processes yield GHG benefits. However the current assumption that the GHG benefits arise from both algal oil and from the conversion of algal starch to ethanol means that higher oil content does not necessarily increase overall GHG benefits since correspondingly less ethanol will be produced from the algae cake.
- Algae production in areas with high solar insolation, appears to be a more efficient option for liquid fuel production than coal-to-liquid technology. However, this would also have to compete on a cost basis (coal-to-liquid technology is generally quoted as costing $50 per barrel).
- The energy balance for a fermentation system is superior to the two phototrophic options in the BC context, even when the carbon source is not a waste stream.

5.3 Carbon Capture Potential

Use of atmospheric or fossil fuel derived CO_2 has the advantage of reducing the input costs of microalgae cultivation and it opens the door for algal biomass production for carbon capture and sequestration as part of a GHG reduction strategy. Algae culture has the potential for simultaneously capturing atmospheric or fossil fuel derived CO_2 and producing a useful product, decreasing carbon capture costs. The high growth rate coupled with the ability of algae to directly utilize CO_2 from flue gases (19; 29; 44; 63; 98; 141) has led to algae being considered for biofixation of CO_2 followed by either long-term storage in soils or oceans (sequestration) or for low carbon fuel production (23). While this approach has promise, the uptake of CO_2 by such cultured microalgae will not be constant as CO_2 uptake varies diurnally and seasonally in phototrophic systems: uptake occurs only during the day and more CO_2 will be fixed during active growth in summer compared to winter.

Currently, the cost of existing CO_2 capture technologies ranges from around $40 per ton of carbon for burial in saline aquifers (IPCC) to about $150 per ton of carbon using amine absorbers and cryogenic coolers, which is much too high for carbon emissions applications (61). When existing coal plants are retrofitted with carbon capture and storage capability the estimated increase in power generation costs is between 2.5 and 4 cents per kWh.

In view of the interest and potential utility of algae culture for carbon capture, a preliminary calculation of the costs was conducted using our base model scenario, running for 6 months[98]. As seen in Table 21 the current cost of producing algae for carbon sequestration in BC is $793 per tonne of CO_2. Note that this calculation only considers the carbon fixed in the algae biomass; full life-cycle carbon losses due to electricity and fertilizer use, etc. and other costs such as transportation

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[98] A detailed analysis of carbon capture and sequestration is beyond the scope of this study. Interested readers are directed to an excellent overview by Benemann and Pedroni (22).

and deep burial would have to be included, which will increase the cost per tonne. This cost is prohibitively high, about twenty times higher than the estimated cost of burying CO_2 underground, and at least one order of magnitude higher than the cost of the fuel, indicating that at this point carbon capture using algae is not cost-effective in BC.

Table 21: Estimated Costs For CO_2 Sequestration using Algae Grown for Six Months per Year In BC (excludes costs of transportation and deep burial)

CO_2 Sequestration (excludes burial)	
Algae cost	$60,302.ha^{-1}
Production (6 months)	41,202 Kg.ha^{-1}
CO_2	76 tonnes of CO_2
Cost of sequestration	$793.t^{-1} of CO_2

5.4 Potential to Meet Mandated Biodiesel Levels in Diesel Blends in BC

In fulfillment of commitments made to renewable fuels in the BC Energy Plan, released on April 17, 2008, the BC legislature passed Bill 16 - 2008 Greenhouse Gas Reduction (renewable and low carbon fuel requirements) Act which mandates the inclusion of five percent renewable fuels in all diesel and gasoline sold in BC by 2010. For diesel, this equates to an approximate demand for 183 million liters of biodiesel in BC.

Using the maximum productivity model described in Table 6, raising algae with 15% lipid content and a productivity of 22.89 $g.m^{-2}.d^{-1}$ (4 ml $oil.m^{-2}.d^{-1}$), in raceways for six months of the year requires 1.36 km^2 of pond area to produce 1 million liters on Vancouver Island (Table 6). Therefore, a raceway system operating for 6 months of the year would require approximately (1.36)(183) = 249 km^2 (24,900 ha) to produce the mandated 183 million liters of biodiesel. If PBRs were used, the areal requirement would be (0.61)(183) = 112 km^2 (11,200 ha), to produce the mandated 183 million liters of biodiesel.

In section 1.2.16, a fermentation plant with a capacity of 1.2 million liters was calculated to be capable of producing 1.4 million liters of oil annually. Meeting the BC mandated 183 million liters of biodiesel would therefore require plants with a total fermentation capacity of 157 million liters of algae culture annually.

As algae culture does not require fertile soils, it is not restricted to the limited arable land in BC. With a total land area of 929,730 km^{-2} (92,973,000 ha), the siting of algae plants would be more dependent on topography. About 203,000 km^2 (20,300,000 ha) of this is not available, being composed of rock, alpine barren ice fields, or glaciers, leaving 726,730 km^2 (72,673,000 ha) that could be potentially available for algae culture.

Satisfying all of BC's mandated requirement of 183 million liters of biodiesel by 2010 from microalgae oil grown in BC would require the cultivation of 249 km^2 of open raceway ponds operating for six months a year at a cost of $1.5 billion annually or 112km^2 of PBRs operating year round, at a cost of $3.8 billion annually. If the algae are grown heterotrophically, an annual fermentation capacity of 157 million liters will be required at a cost of $481.3 million annually.

6 Production of Biofuels with High Value Co-Products

6.1 Initial Economic Analysis

The production of algae for biofuels may become more economically feasible if a high value by-product is also created. Below is a preliminary evaluation of one such high value product; Eicosapentaenoic acid (EPA)[99].

EPA value: While a determination of the size of the EPA market was beyond the scope of this study, a preliminary analysis identified two distinct markets for purified EPA. The first is for highly purified (99%) analytical grade EPA esters that retails for $2,154 per kg (Sigma Chemicals). However, this market is very small, and was therefore not considered further for this analysis. A second, larger market is for bulk purified (50-75% pure) EPA esters derived from fish oils, which are currently sold around $185 per kg of 70% pure EPA ester.

Algae species: Several microalgae synthesize EPA, with the richest algal sources identified as *Phaedactylum tricornutum*, *Nannochloropsis oculata* and *Monodus subterraneus* (52). A comparison of the ease of extraction and yield of EPA from *M. subterraneus* and *P. tricornutum* was carried out by Belarbi et al. (16). These authors reported that obtaining 1 kg of esterified EPA oil would require 56.3 kg, 70.0 kg and 15.2 kg of *P. tricornutum*, *M. subterraneus* and fish oil, respectively, with the purity of the esterified EPA obtained being 96.5%, 91.9% and 82.7%, respectively. The ease of extraction-transesterification of oils from P. *tricornutum* over *M. subterraneus* made it the superior microalgal source of EPA. These two algae species are modeled for this study.

Algae composition: The biochemical composition of the algal strain used is not only a key factor for oil production but is even more critical in evaluating the potential co-products. The analysis detailed below uses specific biorefinery options that are possible for these two species. The biochemical composition used for *P. tricornutum* was 9.5% carbohydrates, 50% protein and 10% lipids (16; 130; 162), the residual algae oil (after extraction of EPA[100]), is valued similarly to soybean oil used as biodiesel feedstock at $0.5 per L (54; 149). Algae cake left after removal of the lipids from *P. tricornutum* contained 10.5% carbohydrate and 55.6% of protein, and was assumed to be sold as animal feed at $246 per ton[101]. The biochemical composition of *M. subterraneus* used was 38.5% carbohydrates, 7% protein and 42% lipids (122), and the algae cake left after removal of the lipids[102] from *M. subterraneus* contained 66% carbohydrate and 12.1% protein, and was assumed to be sold for ethanol production or as animal feed at $200 per ton[103].

Processing: No cost data for the commercial production of purified EPA esters were found. Hence, the following analysis determined the maximum cost at which algae biomass could be obtained and still produce purified EPA to be competitive with EPA derived from fish oil.

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[99] A poly-unsaturated fatty acid that is essential for the development of marine organisms and important in the human diet (173).

[100] *Phaedactylum tricornutum* has a total EPA content of 2.6-3.1% (162) and recoverable EPA of 1.8% EPA (16).

[101] Calculated from Table 9, assuming proportionality of pricing if distiller's dried grain with 30% protein costs $132 per ton.

[102] M. *subterraneus* has a total EPA content of 2.3-3.2% (122), and recoverable EPA of 1.4% (16).

[103] Calculated from Table 10, assuming proportionality of pricing if corn with 62% protein costs $200 per ton.

For this preliminary analysis, quotes were obtained for bulk cod liver oil of $4.50 per kg. At this price, $68.4 worth of fish oil is required to produce 1 kg of purified EPA ester[104]. At the market price of $185 per kg of 70% pure EPA ester, the difference between the cost of biomass and sales price of purified EPA ester, $116.60, can be reasonably assumed to include the cost of processing and a profit margin. If it is assumed that the cost of processing algae oil to obtain purified EPA will be similar to that for fish oil if similar processes are used (16), and that the downstream processing into EPA ester is also similar, then to be competitive with fish oil derived EPA esters, the microalgae must have a raw biomass production cost of no more than $1.21 per kg and $0.98 per kg for *P. tricornutum* and *M. subterraneus,* respectively.

However, the fatty acid composition of algae is simpler than that of fish oil (16; 158), making the recovery of EPA from algae easier than from fish oil. This is reflected in differences in the volumes of solvents required, the purity of the final product, and the cheaper costs of downstream processing of EPA from algae compared to fish oil. Consequently, algae biomass may actually be produced at higher costs than calculated above and still be used to produce esterified EPA priced competitively with fish oil derived EPA ester.

The recovery of 1kg of EPA was calculated to require 9,400 L, 15,000 L and 37,500 L of solvent for *P. tricornutum*, *M. subterraneus* and fish oil, respectively (16), with the associated solvent recycle costs being in the ratio of 1:1.6:4 for *P. tricornutum*, *M. subterraneus* and fish oil, respectively[105]. If the algal biomass required to produce 1 kg of EPA ester can be produced for the same price as the fish oil required for this, and it is assumed that the processing costs for fish oil ($116.60) is the total cost of processing into EPA ester, then the cost of processing microalgal EPA can be obtained by multiplying the processing costs for the fish oil ($116.6), by a factor to account for the reduced solvents (and costs) used. These factors are 0.25 and 0.4 for *P. tricornutum* and *M. subterraneus,* respectively, from the solvent recycle volumes given earlier (16). For algae derived EPA esters, this results in processing costs of $29.15 and $46.64 for *P. tricornutum* and *M. subterraneus* required to produce 1kg of EPA ester respectively.

Table 22 and Table 23 show the results obtained when the estimated EPA ester processing costs were used with the price calculations and model productivities obtained in Table 15 and Table 17 respectively. For these tables, it is assumed that the $29.15 and the $46.64 processing costs to produce 1kg of EPA ester represent the entire cost of processing to obtain the algal EPA esters from *P. tricornutum* and *M. subterraneus* biomass respectively, and that, to be comparable with fish oil derived EPA, the concentration of the EPA esters obtained from algae is diluted to 70%.

The two scenarios tested (base case and enhanced case scenarios), were based on the productivities (but not the oil contents) as stated in Table 18[106], as specific monocultures of *P. tricornutum* and *M. subterraneus* with the pre-defined biochemical compositions given above were used in this model. Hence, for the raceways, the base case scenarios included a productivity of 9.38 $g.m^{-2}.d^{-1}$, run year round, and for the enhanced case, the algae had a productivity of 22.89$g.m^{-2}.d^{-1}$, run for six months of the year. For the fermenters, the productivity of the algae was 50$g.L^{-1}$ and 100 $g.L^{-1}$ in the base and enhanced cases respectively. Only the base case was modeled for the PBR as the enhanced case only included an increase in oil content (not biomass productivity).

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[104] Since 15.2kg of fish oil is required to produce 1kg of EPA ester.

[105] If assumed to be directly proportional to the amount of solvent that needs to be recycled.

[106] Note that only the productivities from Table 18 were used. The oil content of the algae from Table 18 were not used as specific monocultures of microalgae with predefined biochemical compositions were being used in this case.

Table 22: Annual Costs and Returns from the Co-Production of EPA Ester with Algae Oil and Algae Cake (Protein) using *P. tricornutum* grown in Raceways, PBRs and Fermenters

Scenario	**Factor**	**Technology**		
Base case		**Raceway**	**PBR**	**Fermenter**
	*Annual Yield	28,140kg.ha^{-1}	45,900kg.ha^{-1}	1,190,000 kg
	Oil yield (10%)	2,814kg	4,590kg	119,000kg
	EPA yield (at 96.5%)	500kg	815kg	21,137kg
	EPA yield (diluted to 70%)	689kg	1,124kg	29,139kg
	EPA value (at 70%)	$127,473	$207,924	$5,390,631
	EPA processing costs	$14,570	$23,765	$616,137
	Value of algae oil	$1,157	$1,887	$48,933
	Value of algae cake	$6,230	$10,162	$263,466
	Total Revenue	**$134,860**	**$219,974**	**$5,703,029**
	Total cost of Production	$89,495	$359,761	$4,298,137
	Net Revenue	$45,356	-$139,787	$1,404,892
Enhanced case		**Raceway**	**PBR**	**Fermenter**
	*Annual Yield	41,202kg.ha^{-1}	N/A	2,856,000 kg
	Oil yield (10%)	4,120kg	N/A	285,600kg
	EPA yield (at 96.5%)	731.83kg	N/A	50,728.24kg
	EPA yield (diluted to 70%)	1,008.88kg	N/A	69,932.50kg
	EPA value (at 70%)	$186,643	N/A	$12,937,513
	EPA processing costs	$21,333	N/A	$1,478,728
	Value of algae oil	$1,694	N/A	$117,439
	Value of algae cake	$9,122	N/A	$632,318
	Total Revenue	**$197,459**	**N/A**	**$13,687,270**
	Total cost of Production	$81,638	N/A	$5,160,728
	Net Revenue	$115,821		$8,526,542

* Annual yield is expressed in kg per ha for the raceway and the PBR, but is given in kg per 1,200m^3 reactor for the fermenter.

6.2 *Discussion of Eicosapentaenoic Acid as a Co-Product*

In the base case scenario for both algae species, the combined revenue from the sale of EPA ester, algae oil and algae cake exceeded the costs of production using both the raceway and fermenter technologies. When *M. subterraneus* was grown, total revenues slightly exceeded the total costs of production in the base scenarios for both technologies. The profits were wider in the enhanced scenarios, which can be attributed to the higher yields of algae biomass in the enhanced scenarios. can be attributed to the low recovery of EPA from the microalgae biomass. Despite having a higher oil content of 42%, compared to 10% for the *P. tricornutum*, the lower recovery of EPA from *M. subterraneus* (1.4% vs. 1.8% in the *P. tricornutum*) meant that net revenue from *P. tricornutum* was higher in both the base and enhanced scenarios. Even the greater volume of the resulting algae oil for biodiesel feedstock, valued at $192,000 higher than for algae oil from *P. tricornutum*, was not enough to make up the difference.

The high unit biomass production costs of algae in PBRs, is reflected in the contribution of the secondary (EPA) processing costs to total costs. In the base cases for both algae species tested, this was16.28%, 6.61% and 14.33% when *P. tricornutum* was grown in raceways, PBRs and fermenters respectively, and 20.02%, 8.34% and 17.72% respectively when *M. subterraneus* was the test algae species. As a percentage of total revenue in the base cases, total costs were 66.36%, 163.55% and 75.37% when *P. tricornutum* was modeled in raceways, PBRs and fermenters respectively and 87.86%, 210.80% and 99.25% respectively when the algae species was *M. subterraneus*. This high production cost resulted in PBRs being uneconomical even when high value products were produced. No enhanced cases were modeled for the PBR because, as explained above, the enhanced case model for the PBR assumes increased oil yields (not increased biomass productivities)., which was not relevant as this model was conducted using monocultures of algae with specific oil contents.

Although the raceway model also appears to be economically viable in the scenarios presented here, it was only included for theoretical comparison as, with the exception of extremophile species, open systems are unable to support the monocultures required for the production of such high value products at this time.

This analysis highlights the importance of knowing the final product being targeted by the algae production plant. If the planned co-production of a high value product is to improve the economics of producing algae oil for energy, then it leads intuitively to the choice of an alga like *M. subterraneus* which produces more algae oil for energy. However, the reduced volume of the high value EPA co-product results in virtually no net profit [107] (Table 23). If the above analysis included transportation or other additional sales costs, or factored in the effect of a drop in prices of the high value product as a result of mass production, then this approach would not be considered to be economically viable. The other option of producing the high value product as the main product and the algae oil as a by-product would result in less oil for bioenergy, but it would be more profitable (see Table 24). Co-production could be further justified if strains with high oil content are found that also have high quantities of easily extractable high value products like EPA.

In the enhanced cases, the economics are better for both cases. Note, however, that fairly optimistic assumptions underlie these enhanced cases.

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[107] In the base case scenario.

Table 23: Annual costs and Returns from the Co-Production of EPA Ester with Algae Oil and Algae Cake (Carbohydrate) using *M. subterraneus*[108] grown in Raceways, PBRs and Fermenters

Scenario	**Factor**	**Technology**		
Base case		**Raceway**	**PBR**	**Fermenter**
	*Annual Yield	28,140kg.ha^{-1}	45,900kg.ha^{-1}	1,190,000 kg*
	Oil yield (42%)	11,819kg	19,278kg	499,800kg
	EPA yield (at 91.9%)	402.00kg	655.71kg	17,000.00kg
	EPA yield (diluted to 70%)	527.77kg	860.86kg	22,318.57kg
	EPA value	$97,637	$159,259	$4,128,936
	EPA processing costs	$18,749	$30,583	$792,880
	Value of algae oil	$5,712	$9,318	$241,570
	Value of algae cake	$3,264	$5,324	$138,040
	Total Revenue	**$106,614**	**$173,901**	**$4,508,546**
	Total cost of Production	$93,674	$366,579	$4,474,880
	Net Revenue	$12,940	-$192,678	$33, 666
Enhanced case		**Raceway**	**PBR**	**Fermenter**
	*Annual Yield	41,202kg,ha^{-1}	N/A	2,856,000 kg
	Oil yield (42%)	17,305kg	N/A	1,199,520kg
	EPA yield (at 91.9%)	588.60kg	N/A	40,800.00kg
	EPA yield (diluted to 70%)	772.75kg	N/A	53,564.57kg
	EPA value	$142,958	N/A	$9,909,446
	EPA processing costs	$27,452	N/A	$1,902,912
	Value of algae oil	$8,364	N/A	$579,768
	Value of algae cake	$4,779	N/A	$331,296
	Total Revenue	**$156,102**	**N/A**	**$10,820,510**
	Total cost of Production	$87,757	N/A	$5,584,912
	Net Revenue	$68,345	N/A	$5,235,598

* Annual yield is expressed in kg per ha for the raceway and the PBR, but is given in kg per 1,200m^3 reactor for the fermenter.

Table 24: Relative Contribution of Algae Oil and the High Value Co-Product, EPA Ester, to Revenues from the Production of *P. tricornutum* and *M.subterraneus* Grown in Raceways Under the Base Case Scenario.

Factor	***P. tricornutum***		***M. subterraneus***	
	Algae oil yield	**EPA ester yield**	**Algae oil yield**	**EPA ester yield**
Weight (Kg)	2,314kg	500kg	11,416.8kg	402kg
Value	$1,157	$127,473	$5,712	$97,637
Grand total value	**$128,630**		**$103,349**	

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[108] Biochemical composition of *M. subterraneus* used was lipid 42%, carbohydrate: 38.5% and protein 7%. Obtained from Lu et al. (122).

6.3 Minimum By-Product Value Required

In the economic analysis section, values for algae cake of around $200 per tonne were established, either as animal feed or as an ethanol feedstock. Another possibility is to use algae as a human protein source, similar to tofu, as a medium value co-product. A quick Internet search showed tofu retail pricing of around $4,000 per tonne in Japan. Without a more detailed analysis, a substitution of algae cake values in the economic analysis model shows that an open raceway in BC operated for six months per year could produce oil at $1 per litre if the cake were sold for at least $1,300 per tonne. Compared to tofu, this price could be realistic if a market for algae cake exists or can be created. This would require that all oil extraction and other processing steps are compatible with food-grade standards. This may be a challenge when working with open ponds. It also does not account for any further processing of the cake, which is unrealistic.

The economic model shows that at an algae cake value of $1,300 per tonne, oil costs for the fermenter base case are reduced to about $2 per litre, but for the PBR they are still at over $21 per litre. The required value for alternative by-products can be extrapolated from this analysis by considering that only a given percentage of the cake can be used and then multiplying the required minimum value per kg accordingly.

Clearly, by-product values must be several hundreds, or even thousands of dollars per kg if they are to have a major impact on the economics of algae production for biofuels in BC.

7 Rules and Regulations

The following table is intended to act as a guide to rules and regulations that a project proponent may face in BC when building and operating an algae production and / or biofuel processing facility. For more detail on each of these see Appendix N.

7.1 Federal Rules and Regulations

Rule/Regulation Title	Brief Description
Fisheries Act	Management and regulation of fisheries including access, control over conditions of harvesting, enforcing regulations, protecting fish and fish habitat.
Fisheries Act - Harmful Alteration of Fish Habitat	Prohibits work resulting in the Harmful Alteration, Disruption or Destruction of fisheries habitat (HADD) unless authorized to do so.
Fisheries Act - Deleterious Substances	Prohibits introduction of a 'deleterious substance' into any type of fish-bearing waters without authorization.
Fisheries Act - Petroleum Refinery Liquid Effluent Regulation	Regulates average deposit levels for various deleterious substances, including oils, grease, sulphide and other substances harmful to fish.
Navigable Waters Protection Act	Protects public right of navigation and regulates structures that interfere with navigation.
Canadian Environmental Assessment (EA) Act	Establishes a process for conducting EA of projects involving federal government decisions.
Canadian Environmental Protection Act (CEPA)	Provides federal government with wide ranging powers to protect and maintain the health of the environment.
CEPA New Substances Notification Regulations (Organisms)	Ensures no new substances are introduced into the Canadian marketplace without a potential toxicity assessment and that all appropriate or required control measures have been taken.
Species at Risk Act	Prevents wildlife species from extinction or extirpation in the wild, and helps species at risk because of human activities.

7.2 *Provincial Rules and Regulations*

Rule/Regulation Title	Brief Description
Land Act	Main legislation prescribing conditions for the occupancy of crown land.
Land Title Act	Regulates how the rights to land are bought and sold in the province.
Notice regarding pollution	Alert buyers and others that serious pollution exists on a property.
Subdivision	Approval must be given for land subdivision.
Farm Practices Protection Act	Protects farmers from lawsuits involving odour, noise, dust and other disturbance.
Waste Management Act	Regulates introduction of waste into the environment.
Environmental Management Act	Prohibits introduction of waste into the environment in the course of conducting a prescribed industry, trade or activity without a valid authorization, permit or approval.
Environmental Management Act and Health Act	Provides exemption from the requirement for a waste management permit for operations conducted in accordance with the Code of Agricultural Practice for Waste Management.
Fisheries Act	Prohibits the release of aquatic plants or fish from an aquaculture facility unless authorized to do so.
Fish Protection Act	Provides authority for water managers to consider impacts on fish and fish habitat before approving new licenses, amendments to licenses or issuing approvals for work in or near streams.
Water Act	Provides right to use, store or divert water in natural watercourse (i.e. rivers, streams, lakes, swamps, etc).
Drainage, Ditch and Dyke Act	Establishes a system for the regulation and authorization of ditches, watercourses, drainages and dykes.
Agricultural Land Commission Act	Preserves and encourages farming and agricultural practices on agricultural land.
Environmental Assessment Act	Requires an environmental assessment to be done before certain projects are built.
Wildlife Act	Protects wildlife, endangered species and wildlife habitat.

7.3 Municipal Rules and Regulations

Rule/Regulation Title	Brief Description
Subdivision	Approval must be given for land subdivision.
Zoning Bylaws	Regulates the form and character of development.
Official Community Plans	Guides decisions on planning and land use management.

8 Funding Opportunities

8.1 General

As the technologies for commercial algae culture are not readily available at present, the following funding sources focuses on early-stage financing for technology demonstration purposes. It also focuses on capital investment, rather than production or tax incentives. The latter are, however, considered in the economic analysis in this study where appropriate. The reader is cautioned that this section should be regarded as only a "snapshot" since funding programs are created, terminated and modified constantly.

8.2 Funding Available to the Private Sector

For a demonstration project, banks will generally only provide a maximum of 50% of the required investment. The remainder must come from other sources. Very often, high-risk technologies require public funding to reduce the risk for private investors.

ecoAGRICULTURE Biofuels Capital Initiative (ecoABC) – This initiative, delivered by Agriculture and Agri-Food Canada, is a federal $200 million four-year program ending on March 31, 2011 that provides repayable contributions for the construction or expansion of transportation biofuel production facilities. Funding is conditional upon agricultural producer investment in the biofuel projects, and the use of agricultural feedstock to produce the biofuel. For more information, visit www.ecoaction.gc.ca/ecoagriculture/biofuels-biocarburants-eng.cfm

Advancing Canadian Agriculture and Agri-Food (ACAAF) program – This program is a five-year, $240 million program ending in March 2009, aimed at positioning Canada's agriculture and agri-food sector at the leading edge to seize new opportunities. Funding is available for eligible projects identified and carried out by the agriculture and agri-food sector. For more information, visit www4.agr.gc.ca/AAFC-AAC/displayafficher.do?id=1182366508375&lang=e

Sustainable Development Technology Canada (SDTC) – This program provides grants for pre-commercial technology projects. SDTC requires that applicants join with partners to form a consortium (consult the SDTC website for more information). SDTC funds up to one-third of the capital cost of demonstration projects, including the cost of feasibility studies. Specifically, SDTC's $500-million NextGen Biofuels Fund™ supports the establishment of first-of-kind large demonstration-scale facilities for the production of next-generation renewable fuels. For more information, visit www.sdtc.ca

Technology Early Action Measures (TEAM) – This is a federal program supporting technologies that tackle the problem of climate change. TEAM requires that (private or community) project proponents team up financially with the provincial governments, municipalities or each other. TEAM will only fund part of a project, and additional funds should come from a different federal program. Funding is provided as equity investment, but repayment can be negotiated in certain cases. TEAM funds new technologies that are to be demonstrated. For more information, visit www.team.gc.ca

The Canadian Biomass Innovation Network (CBIN) – This funds research and development of biomass technologies. It fills the space between basic research and demonstration/ pre-commercialization. All projects must have a Federal Government lead and partners (industry, academia, provincial or municipal governments, NGOs, etc.). Eligible projects will have to have an important research component. For more information, visit www.cbin.gc.ca

Natural Resources Canada's ecoENERGY Technology Initiative – This initiative provides funding for biomass energy projects at the demonstration stage. Calls for proposals are issued by government with specific themes, i.e. it is not possible to submit proposals unless a suitable call has been issued. For more information, visit www2.nrcan.gc.ca/ES/OERD/English/View.asp?x=1603

Western Economic Diversification (WD) – WD provides funding for economic development in Western Canada, including energy projects. For more information, visit www.wd.gc.ca

BC Innovative Clean Energy Fund – This is a $25 million fund to support pre-commercial alternative energy sources, including bioenergy. For more information, visit www.gov.bc.ca/empr/popt/innovative_clean_energy_fund.html

The BC Bioenergy Network Fund – This $25 million fund is for bioenergy development projects, particularly at the demonstration stage. However, the first round of expressions for interest indicates this fund will be oversubscribed. For more information, visit www.bcbioenergy.ca/

Genome BC – This research organization invests in and manages large-scale genomics and proteomics research projects and science and technology platforms focused on areas of strategic importance such as human health, forestry, fisheries, ethics, agriculture, and the environment. It could assist in algae research, such as optimizing fermenter technology and identifying suitable strains. For more information, visit www.genomebc.ca

The Encana Environmental Innovation Fund – This fund invests in new energy technologies. For more information, visit www.encana.com/responsibility/eif/index.htm

8.3 Funding for Municipalities and First Nations

Algae companies will need to team up with municipalities and/ or First Nations communities to access these funding sources. Usually, there are specific conditions for using these funding sources, such as evidence for local benefits, job creation, and environmental benefits created through the project. Additional sources of funding are almost always required.

Moving on Sustainable Transportation (MOST) – This government program may apply to biofuels projects in BC. Funding is only provided up to a limit of $100,000, which may be insufficient for algae demonstration projects. For more information, visit www.tc.gc.ca/programs/environment/most/applyingtomost.htm

ecoENERGY for Aboriginal and Northern Communities – This program, which began on April 1, 2007, will provide $15 million in new funding over four years to support Aboriginal and Northern communities working on clean energy projects, including the approximately 130 remote communities that rely on diesel power generation. Goals include: catalyzing renewable energy projects, improving energy efficiency and adopting alternative energy sources to reduce dependence on diesel fuel. For more information, visit www.ecoaction.gc.ca/ecoenergy-ecoenergie/aborignorth-autochnord-eng.cfm

Northern Development Initiative Trust – This funding is available for local governments, not-for-profit societies, and First Nations. For more information, visit www.nditrust.ca

BC's Municipal Rural Infrastructure Fund – This is specifically geared towards local governments of communities under 250,000 inhabitants. Renewable energy projects qualify for grants to cover part of the capital costs. For more information, visit www.canadabcmrif.ca/en/guide.htm. Infrastructure projects of First Nations communities are funded separately and administered by Indian and Northern Affairs Canada (INAC). For more information, visit www.ainc-inac.gc.ca/

Innovations Fund & Strategic Priorities Fund – This provides grants for community energy projects and planning (up to 100% of project costs). Local governments can apply through the Union of BC Municipalities. For more information, visit www.civicnet.bc.ca/siteengine/ActivePage.asp?PageID=294#gas%20tax

Green Municipal Funds – This is administered by the Canadian Federation of Municipalities. Grants for 50% of the cost of energy planning and feasibility studies are available, as well as low-interest loans towards the capital cost of energy projects (15-25% of total cost). Only municipalities are eligible. For more information, visit www.sustainablecommunities.fcm.ca/GMF/

Municipal Finance Authority of BC – This provides low-interest loans (under 5% annual interest rate) to BC municipalities, Regional Districts and Hospital Districts. Applications are approved at meetings during spring and fall each year. For more information, visit www.mfa.bc.ca

Towns for Tomorrow – This is a BC government program that can cover 80% of energy project costs, to a maximum of $400,000. Only governments of small communities (under 5,000 people) are eligible. For more information, visit www.townsfortomorrow.gov.bc.ca

Remote Community Electrification Program (RCE) – This was created to help provide electricity to remote communities by extending the power grid or with alternative energy in order to replace diesel generation. For more information, visit www.bchydro.com/

The Northern Development Initiative Trust – This is an economic development funding corporation for central and northern BC . It provides the funding and ability for local government and First Nations to identify and pursue new opportunities for stimulating economic growth and job creation. The trust offers both grants and loans. It will assist with up to 28% of the capital cost of projects and covers approximately 70% of the Province. For more information, visit www.nditrust.ca. Also see the Southern Interior Development Initiative Trust (www.sidit-bc.ca) and Island Coastal Economic Trust (www.islandcoastaltrust.ca) for the remaining areas.

Suncor Energy Foundation – This provides grants for communities in Northeastern BC (only not-for-profit entities are eligible). Funding covers community projects and environmental initiatives. For more information, visit www.suncor.com/default.aspx?ID=2729

First Nations communities should also consider the **New Relationship Trust** (www.newrelationshiptrust.ca). Other grant programs applicable to local government can be found at Civic Info BC (www.civicinfo.bc.ca/18.asp). Financing options for municipalities are also explained in the Funding Your Community Energy Initiatives guide of the BC Community Energy Association (www.communityenergy.bc.ca/sites/default/files/CEA%20Funding%20Guide.2008-Apr.pdf).

9 Scope for Improvement and Recommendations

9.1 Scope For Improvement

Further R&D efforts are required to achieve improvements in algae productivities and reduce production costs. To give an idea of the scale of technological advances required, it took twenty-seven years to achieve a productivity increase of 50% in canola production (42). While it is possible that productivity improvements may occur over a shorter time frame compared to canola[109], significantly higher breakthroughs in productivity are required for algae-to-biofuels to become a commercial reality in BC (a 50% improvement in productivity, keeping costs the same will still result in a price of $4.89 per liter of algae oil if algae are grown in raceways for 6 months a year). Clearly, the phototrophic culture of algae for biofuels is not a near-term enterprise and should not be regarded as such.

Improvements in productivity can be achieved through technical and biological approaches:

- The selection of algae species with desirable characteristics of high growth rates, high oil content (or the content of the product of interest) and the manipulation of algae species to tolerate high light intensities (either by genetic improvement or acclimation) are obvious areas where improvements could be made and R&D efforts are already being directed.
- Other areas include improvements in system design for better light utilization and improved mixing, and a significant reduction in the input energy requirements.

The cost of PBRs is the single most important constraint against the commercial reality of microalgae for biofuels using this technology. However, PBRs are necessary if genetically modified algae or selected strains are to be grown phototrophically. If PBRs are ever to become feasible in the production of biofuels from microalgae, a significant reduction in the costs of PBRs is essential. Since the main components of PBRs are basic materials like glass and plastic, it will be difficult to achieve this.

The limitation imposed by the available amount of solar insolation in BC (and Canada) is a major constraint that cannot be overlooked. As this cannot be increased, it means that even if all the factors necessary for improving the productivity of phototrophic microalgae production are achieved, the major benefits would accrue to countries with higher solar insolation, rather than BC or Canada. BC can remain relevant in this aspect by supporting or undertaking research aimed at developing intellectual property, which can be used under license by such foreign countries. However, all these are still medium to long-term goals. As described above, the commercial culture of microalgae for biofuels is not a near-term enterprise and strategic planning should reflect this.

One avenue proposed for improving the poor economics of phototrophic algae production is the co-production of high-value products. Initial analysis within the context of this report, indicates that very high values must be achieved, but the markets for such products may be very limited, or would have to be created. Any large-scale deployment of algae production would therefore require some detailed market analysis in order to confirm the market for, and value of any co-products meant to provide a large part of the operation's revenue.

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[109] Such as the development of high throughput methods for screening for beneficial characteristics in algae strains, which will be facilitated by the short generation times of the microalgae compared to land -based plants (see Table 10 in Appendix I).

9.2 Recommendations

Given the results in terms of achievable productivities, economic performance and energy balance, current knowledge strongly suggests that phototrophic options can be ruled out for BC at the present time. Despite some data uncertainties, the results obtained from the analysis in this report are resilient enough to rule out photobioreactors as an option to produce biofuels in general, and also rule out raceways at least currently, as an option in BC. Technology proponents should provide convincing evidence that they have found a way to improve economics (e.g., a large enough market for by-products exists, and a way to prevent contamination if specific algae are to be grown) and the energy balance enough before public funds are invested in raceway research and technology.

If research on raceways is undertaken or supported, it should be conducted with a view to developing IP for eventual use in areas with high solar insolation and lower labour costs. If such research is undertaken, the approach most likely to contribute to immediate improvements is to identify design and culture parameters which would remedy the light saturation and photoinhibition effect and increase the light utilization efficiency of algae strains. Other areas of potential improvements include the design of cost effective systems to introduce light to greater depths in ponds, improved mixing using efficient mixers and culture methods to prevent the contamination by undesirable species in open systems. In parallel, ways to reduce capital and operating costs, such as increased automation, would have to be found[110].

Algae production by fermentation was shown to currently be the most promising avenue towards biofuel production in BC. Although it is likely to rely, at least initially, on agricultural carbon sources such as sugar or starch, it may be able to use other feedstocks, such as lignocellulosic residues, in the future. It may also have advantages over current starch-to-ethanol pathways if algae oil can be produced with consistently high biomass productivity and oil yields. However, it is still not competitive with fossil fuels, even using the 'enhanced' scenario discussed in section 0.

Before investing in heterotrophically grown algae, more research needs to be carried out to identify and isolate strains capable of heterotrophic growth and optimization of the rearing protocols to achieve very high yields and oil content. Biofuels from algae are therefore not a commercial technology. If fuelling transport is the goal of setting up an alternative energy structure, solar photovoltaics should also be compared to algae, since a quick analysis (see Appendix O) found that due to the much higher light conversion efficiency, powering electric or hybrid cars with PV panels can be a better option than raceways producing fuels for internal combustion engines.

Options to bring algae fermentation technology to market-readiness include:

- Launching a RFP for algae fermentation companies to build a pilot plant in BC.
- Supporting research on heterotrophic algae cultivation in BC.
- Verify the energy and cost balances developed in this report with more reliable data as it becomes available.
- Evaluate and test algae fermentation compared to the use of yeast or bacteria in fermenters to make biofuels.
- Network with research facilities outside BC to research detailed problems linked to heterotrophic algae cultivation, such as increasing yields and oil content, as well as the use of different carbon sources.

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[110] Note that automation of some tasks, such as chromatographic monitoring of raceways, is currently not technically feasible and would require breakthroughs in remote monitoring technology.

- There is no immediate need to enact policy measures with respect to algae-based biofuels. Once the process has been proven and can produce oil at prices close to those of fossil fuels, the government may elect to create a regulatory obligation to mix in algae biofuel with conventional diesel fuel. Similar policies are in place worldwide with respect to electricity from renewable resources, as well as biofuels mandates in Canada and the US. Creating a tier for algae biofuel within these mandates can help finance early ventures, until the technology is fully mature.

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11 Appendices