Can Algal Biofuels Power the Mining Boom?

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A dissertation submitted in partial requirement for the degree of Master of Science in Renewable Energy
Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the University or other institute of higher learning, except where due acknowledgment has been made in the text.

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Acknowledgements

This thesis paper is the culmination of an interesting journey that has had me revisiting Murdoch University twenty years after initially qualifying in a different field. I have had the incredibly good fortune to be born in a developed country in this era, when we have enjoyed the planet’s bountiful resources without yet suffering the consequences of their consumption.

Provision for future generation’s needs, whilst safeguarding the needs of our small planet will require new ways of thinking.

I would like to thank Dr Trevor Pryor for his recommendation to study algal biofuels and his assistance over the recent years of my study. I would also like to pass on my heartfelt thanks to Dr Navid Moheimani of the Algae R&D Centre at Murdoch. His unbridled enthusiasm has been inspiring, his advice and his support, even on weekends, are greatly appreciated.

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‘Adapt or perish, now as ever, is Nature's inexorable imperative’
-HG Wells

“We're reaching the point where the Earth will have to end the burden we've placed on her, if we don’t lift the burden ourselves.”
— Steven M. Greer

Cover image; Botryococcus braunii.
http://newenergyandfuel.com/http/newenergyandfuel/com/2010/03/16/the-algae-that-makes-petroleum-story/
Abstract

An ever-increasing demand for the planet’s finite energy resources is leading us to a pivotal point. Firstly, we are faced with issue of resource depletion, leading to price volatility and energy security issues. Secondly and perhaps more importantly is anthropogenic climate change induced by the release of millions of years’ worth of bound carbon.

A nation such as Australia, with vast expanses of land and an energy intensive economy is particularly exposed to fluctuations in energy price and availability. The current mining boom, especially in Western Australia, highlights this problem, with a heavy reliance on transport fuels to extract, refine and transport minerals across the globe. Interestingly, in Western Australia, those mineral resource-rich regions also provide some of the best locations (climatic conditions) for establishing an algal biofuel industry. These third generation biofuels hold the potential to provide for transport needs into the future without further straining the world’s food supply and can actively reduce carbon dioxide by reducing fossil fuel consumption and binding carbon. However they have never been produced on a commercial scale. This paper reviews the current status of the algal biofuel industry in Western Australia. If the correct conditions are present, with a willing local market and an industry able to supply a reliable and sustainable fuel, can the transition from the laboratory to commercial success be made? An analysis of the current and future fuel demand from iron ore mining is undertaken and a number of locations identified as being suitable sites for development. It is reasoned that using current theoretical levels of productivity and overcoming issues of scale and economics, it would be possible to contribute a significant proportion of fuel demand from algal biofuels produced in the local environment.
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BOM- Bureau of Meteorology
BREE- Bureau of Resources and Energy Economics
CAPEX- Capital expenditure
CO$_2$- Carbon dioxide
CaCO$_3$- Calcium carbonate
CREST- The Centre for Research into Energy for Sustainable Transport
CSIRO- Commonwealth Scientific and Industrial Research Organisation
EFA’s- Essential Fatty Acids
EPA- Environment Protection Authority
FAMEs-Fatty Acid Methyl Esters
GHG’s- Greenhouse Gases
GIS- Geographic Information Systems
GTL- Gas to Liquids
H$_2$O- Water
HAP- Hamersley Agricultural Project
HRAP’s- High Rate Algal Ponds
IEA- International Energy Association
IPCC- Intergovernmental Panel on Climate Change
IPP- Import Parity Pricing
NER- Net Energy Ratio
NOAA- National Oceanic and Atmospheric Administration
NO$_x$- Nitrogen Oxides
OPEX- Operating Expense
PCE- Photosynthetic Conversion Efficiency
PUFA’s- Polyunsaturated Fatty Acids
SO$_x$- Sulphur Oxide
SPP- Species
SWIS- South West Interconnected System
TAG's- Triacylglycerols
UV- Ultraviolet
US- United States
WWTP- Waste Water Treatment Plant
Units of Measurement

cm- centimetre

G- Gram

Gj- Gigajoule (10^9 Joules)

GL- Gigalitre (10^9 litres)

Ha- Hectare (10000m^2)

kg- Kilogram (1000g)

kWh- Kilowatt Hour

MTPA- Mega Tonnes Per Annum (10^6 tonnes)

MWh- Megawatt Hour (10^6 Watt hours)

m^2- square meter

MJ- Megajoule (10^6 Joules)

Mt- Megatonne (10^6 tonnes)

p.a- per annum

p.p.m- Parts per Million

t.- tonne
Chapter 1  Introduction

1.1  Is it possible to supply the fuel needs of the Pilbara iron ore industry with algal biofuels and why do it?

The world is currently using fossil fuels at an unsustainable rate (Dukes 2003; Fronk B M et al 2010). Our past and current economies are based on a model of using abundant cheap fuels to provide energy and ignoring the consequences of releasing their by-products into the environment (Owen 2006). Increasing population numbers and rising living standards are necessitating change, such as the need to search for alternate ways to deliver the energy needs for the future. Realistically, the only sustainable way forward is to use energy resources at the same rate they are being produced. The Sun is the source of all of the Earth’s energy apart from nuclear energy and as a matter of fact, enough solar resource reaches the Earth per day to satisfy all of the world’s annual current energy requirements (Stephens, Ross et al. 2010). The issue, however, is how do we harvest that energy? Great advances have been made in the photovoltaic and wind energy industries (electrical energy), enabling a reduction in fossil fuel requirements for standing power generation. However, the production of alternate transport fuels (chemical energy), sustainably and at scale, has not been achieved apart from bioethanol production in Brazil and other countries including the USA and China (Stephens, Ross et al. 2010)

There are a number of reasons for this. Fossil fuels are relatively cheap and seemingly abundant and their production is often subsidised by governments (Koplow and John 2001). Current biofuel production relies on using existing agricultural lands and resources, providing direct competition with food production. Increasing output would result in further strain on these supplies.

Microalgal biofuels have been proposed as a means of producing the quantities necessary to reduce dependence on finite fossil fuel supplies whilst not pressuring existing agricultural industries. Despite over 60 years of research the algal biofuel industry is still in its infancy. Making the
transition to alternate fuels requires long-term investment in research and development to overcome a number of biological and engineering issues related to the stability of the growth medium and scale of production the would be required. Like any process of innovation there will be success and failure. Ultimately, if these obstacles can be overcome, the commercial rewards could be enormous with great benefits to the planet as a whole.

Western Australia could possibly be the best location in the world for an algal biofuel industry to develop (Borowitzka, Boruff et al. 2012). It has an economy largely based on mining (DMP 2008) and is heavily reliant on diesel fuel that is mainly imported (ACIL-Tasman 2008). There are wide stretches of sparsely populated land and coastline (Borowitzka, Boruff et al. 2012) and finally a world class solar resource (Geoscience Australia 2013).

The mining industry and in particular the iron ore industry are mainly located in regions which have been identified as being suitable for the development of an algal biofuels industry (WorleyParsons, Evans&Peck et al. 2012).

Using the Pilbara region and proposed Mid-West mining regions of Western Australia as case studies, an assessment of the potential contribution that algal biofuels can make to the diesel requirements of the local mining industry will be undertaken. The resource requirements and implications for the Western Australian environment of a large-scale algal biofuel industry will be assessed. Where the necessary resources aren’t present in sufficient quantities, the effects of limited availability upon final production will be considered.

To improve the economic and environmental viability of the industry a number of supplementary measures will be considered that would improve economic feasibility and may be suitable in the Western Australian environment.

1.2 Methodology

To assess the viability of the industry, this report will initially provide background information on current and future fossil fuel production and use.
Data gathered from government and industry will provide an indication of diesel requirements for current iron ore production. Future growth expectations for iron ore exports shall be used to estimate future fuel needs.

Using current theoretical and demonstrated productivity levels of algal biofuel production an estimate of the land requirements necessary to fulfil demand will be determined.

Research undertaken previously regarding siting an algal biofuel industry will be expanded upon: incorporating variations in solar radiation and resource availability at each location.

These include the report, “Identification of the Optimum Sites for Industrial scale Microalgae Biofuel Production in WA using a GIS Model.” Prepare for CREST (Borowitzka-Boruff 2012) and ‘Pilbara Algae Industry Study” a report issued by the Pilbara Cities office of Regional Development (WorleyParsons, Evans&Peck et al. 2012).

Three case studies will be discussed.

Case 1: Pilbara sites - using land area identified in siting reports, the production capacity will be estimated and this will be related to fuel demand.

Case 2: Geraldton/Mid-West - using proposed iron ore production data for the region, an estimation of fuel requirements will be made. The land area and resource requirements to produce this will then be calculated and any limiting factors discussed.

Case 3: Marandoo mine - using the iron ore production data from a mine located inland, fuel requirements will be determined and the resource requirements necessary to produce this fuel at the mine site will be determined. Resource limitations and synergies with the mining company will be discussed.

A sensitivity analysis will be undertaken to assess the impact of resource availability, including solar resource, water and CO₂ on production and land requirements.
Information sources will be restricted to peer reviewed articles and government documents. However in the absence of available information company reports will be used to provide background.

The work in this paper is intended to provide some background information regarding the production potential of an algal biofuel industry in Western Australia with specific focus on the Pilbara and Mid-West regions.

1.2.1 Scope

This paper will not consider issues associated with policy, land tenure, carbon tax and renewable energy subsidies and will only briefly discuss environmental, engineering and economic factors relating to an algal biofuel industry. Some of these background issues have been covered in the reports issued by CREST (Borowitzka-Boruff 2012) and Pilbara Cities Office (WorleyParsons, Evans&Peck et al. 2012).
Chapter 2  Background

2.1  Introduction

The development of alternate energy sources is occurring against a backdrop of resource availability issues, environmental concerns and economic challenges. To fully grasp the need to transition to a more sustainable energy future some consideration of the present world situation is necessary.

2.2  Fossil Fuels

The oil that we consume today was formed by millions of years of solar energy falling upon the planet. Organic material formed mainly by photosynthetic algae in lakes, swamps and coastal areas, accumulated in sedimentary rocks and was converted under heat and pressure to hydrocarbons (Broadhead 2004). This natural thermogenic process that has been occurring over the eons is still continuing today. However, when the rate that these hydrocarbons are being used exceeds their rate of production, they become a finite resource, ultimately leading to their depletion (Höök, Bardi et al. 2010).

2.3  Peak Oil

In the 1950’s Hubbert predicted that the supply of oil would peak in the US around 1965-1970 and then production, despite increasing market demand, would start to decline (Barry 2008). This theory was extrapolated in the 1970’s to estimate the peak of the world’s oil supply (Figure 1). Varying opinions subsequently have put this peak from 2010-2020 (ACIL-Tasman 2008; Ian Lowe 2008).
Figure 1 Hubbert's peak oil graph indicating predicted and actual US consumption from 1956-2000 (Deffeyes and Silverman 2004)

The concept of peak oil can be expanded to include other fuel resources including non-fossil fuels such as nuclear, demonstrating that the only sustainable source of energy long term is solar (Figure 2).

Figure 2 Peak fuels graph incorporating Projected Global Energy Production (Edwards John D 2001).

Figures 1 and 2 indicate that we are nearing the peak availability of oil. A switch to alternate fossil fuel sources, although beneficial in the short term, will also lead to a peak over the next 30-40 years. This process of depletion is
occurring whilst demand is increasing; the consequences of this increasing competition for resources could include price volatility and energy security issues.

The decline in supply would occur not purely because of a lack of resource, but the cost of recovering that resource becoming increasingly uneconomical (Höök, Bardi et al. 2010). Easily recoverable supplies are the first exhausted, leading to the need for increased technical requirements to obtain resources from deeper waters or more inaccessible terrains.

The advent of peak oil for Australia will not be seen as an immediate shortage of supply, as production levels have only peaked and will then decline over time. Rather, there will be an escalation in price as supply reduces (ACIL-Tasman 2008). This is because Australia sources oil from many locations around the world and indigenous supplies of fuel can be used in the short-term. Price increases particularly affect economies with a high-energy demand, such as Australia, usually resulting in increased efficiency of use or a move to alternate energy sources. Historically, moves to increase subsidies on fossil fuels to maintain the status quo can cause delays in innovation, distorting the market and countering government efforts to reduce greenhouse gas emissions (Koplow and John 2001; ACIL-Tasman 2008; Vine 2012).

### 2.4 Transport Fuels

The high energy content and ease of transport of liquid fuels derived from crude oil has led to their successful integration into all parts of modern society. Diesel fuel in particular is universally relied upon for heavy haulage in road and rail transport and in particular mining operations (Shastri SS, Kamper SF et al. 2012).

IEA statistics over the past 30 years show a huge increase in the consumption of oil worldwide, especially in the transport sector, which has increased from 45% in 1973 to 62% of the total consumption in 2009 (ACIL-Tasman 2008; IEA 2011). This increased demand was not matched by the industry and non-energy sectors, which remained constant or even reduced in size (Figure 3.).
IEA statistics below (Figure 4) show the dramatic increase in oil consumption from 1973-2010. The total increased from 2738 Mt to 3889 Mt during this period with an 8% increase in both China and Asia (Benemann 1997). High rates of economic growth in the developing countries has led to increased fossil fuel consumption, further straining supply.
Figure 4 1973-2010 Regional shares of current and projected refinery output (Benemann 1997)

2.5 Australian Fuel Production and Requirements

It was estimated in 2006 that Australia had a total reserve of 2.7 billion barrels of crude oil and condensate. This was considered to equal 12 years of capacity at 2006 rates of production (ACIL-Tasman 2008). Historically Australia has always been seen as a net exporter of energy in the form of coal, gas and uranium but is reliant upon imported liquid fuels (Vine 2012).

According to Bureau of Resources and Energy Economics, production rates for crude oil products have been largely stable over the past years. Diesel production however has reduced by comparison, from a peak of 117ML in 2002-03 to 3ML in 2009-2010 (Syed A and Penny K 2011). Figure 5 indicates this shortfall in dollar terms showing both an overall increasing quantity of fuel use and increased reliance on imported fuel. The shortfall in supply is being imported from many sources, but the majority is from Singapore. As such, prices are subject to change based on international market rates. In addition, the reduction in local refining capacity leaves the system with little reserve capacity and exposed to international price fluctuations (ACIL-Tasman 2008; Vine 2012).
2.6 Energy Security- Supply Disruption

The oil crisis of the 1970’s exposed the US economy’s overreliance on imported oil, with shortage of supply resulting in dramatic price increases. The concentration of oil reserves in locations that are often politically unstable, with transit routes through ‘choke points’ such as the Straits of Hormuz and Malacca Straits, often result in price spikes when conflict arises (Walsh and Mann 1995).

Australian society is also heavily reliant on imported oil for everyday life and the impact of supply restriction and price hikes would be considerable (ACL-Tasman 2008). World Bank data in Figure 6 demonstrates clearly the rapid increase in consumption towards the end of the last decade coinciding with the demands of the mining boom. This places an additional reliance on imports to satisfy demand (The World Bank 2013).
Figure 6 Diesel for transport use in Australia 2002-08 (The World Bank 2013)

The US National Algal Fuels Roadmap cites the issue of energy security as a driving factor in the development of sustainable biofuels (Ferrell and Sarisky-Reed 2010). The Energy Independence and Security Act (EIS) was introduced in the US in 2007, and aimed at increasing efficiency and diversifying fuel sources. A similar initiative was introduced in Australia to produce a proportion of the defence fuel requirements from biofuels to establish security of supply long-term (Rio Tinto Mining 2012).

2.7 Fuel Pricing

Import parity pricing (IPP) policies provide the benchmark price for fuels paid in Australia, reflecting the spot price paid in Singapore, plus the cost of shipping that fuel to Australia. Local prices correlate to international prices, and volatility can occur as a consequence of many factors beyond Australian borders, such as economic crises in addition to supply disruption problems.

Information from the Australian Institute of Petroleum clearly shows that over the past 7 years there has been a steady increase in diesel price of almost 40%, with volatility in the 2007-08 period (AIP 2012). This peak followed by a fall may have been due to the global financial crisis. Industry, with a heavy reliance on imported fuels, can be severely impacted by these rapid price fluctuations (Figure 7).
2.8 CO₂ Production and Global Warming

Since the advent of the industrial revolution in the 1750's there has been a continual rise in atmospheric CO₂ levels. This increase has exceeded normal levels of variability and is at its highest level in the last 650,000 years (IPCC 2007). The scientific consensus is that anthropogenic induced climate change is a reality (Oreskes 2004; IPCC 2007; Karoly, Tryjanowski et al. 2008). Data gathered over the past 50 years at the Mauna Loa Observatory by NOAA demonstrates this increase with CO₂ levels increasing from 318 in 1960 to over 390 p.p.m in 2010 (Figure 8).
Carbon dioxide emissions, in combination with other anthropogenic greenhouse gases, have risen by over 70% since preindustrial levels (Tans P and Keeling RK 2012). The effect of increasing GHG emissions and global warming are resulting surface temperature increases, sea level rises and snow cover changes can be seen in Figure 9 from the latest IPCC Synthesis Report.

Figure 9 Changes in Temperature, sea level and snow cover 1850-2007 (IPCC 2007)

Across the Australian continent, even if greenhouse gases (GHG) could be held at current levels, temperatures will continue to rise and rainfall become more variable. Changes observed thus far, and as published by the CSIRO, include an average temperature increase of 0.9°C, with significant variations seen in rainfall, from increases in North and Central Australia and reductions in the South West and Central East Coast. Sea levels have also risen by around 17cm since the beginning of the century (Preston and Jones 2006). These impacts will become worse as CO₂ levels rise, as shown in figure 10, indicating changes expected in 2030 and subsequently in 2070.
Figure 10 Predicted changes to temperature and rainfall across Australia 2030/2070 (Preston and Jones 2006)
2.9 Biofuels

The development of biofuels is seen as a way to maintain our current transport infrastructure whilst reducing fossil fuel use and carbon production. Secondary benefits may include the development of new industries, increased employment (especially in regional areas) and increased energy security (Mata, Martins et al. 2010).

The current biofuels industry is mature and widespread using a number of terrestrial crops, with countries such as Brazil producing biofuels for over 75 years (Luciano Lourenço, Pedro Antônio Arraes et al. 2007). In 2009 the IEA reported worldwide liquid biofuel production at 77 656 Mt. During the same period crude oil production was 3 518 456 Mt (IEA 2009). Thus liquid biofuel represents only 2.2% of total fuel production. Ramping up output of all current first generation biofuels (i.e. bioethanol from corn or biodiesel from oil seeds) would result in increased competition for arable land and a loss of biodiversity (Mata, Martins et al. 2010).

Maximising the production of second-generation biofuels may provide a further fuel source. These include dedicated lignocellulosic crops such as switchgrass, mallee, and sorghum. Waste products from agriculture and forestry industries and municipal solid waste are also used (DeBoer, Moheimani et al. 2012). Even with maximising the efficient use of these waste resources, satisfying demand will be impossible to achieve due to pressure on existing land use (Stephens, Ross et al. 2010).

Decoupling the production of biofuels from traditional land based sources is the only sustainable way forward (Revelle 1980). Removing the need to use valuable agricultural land and forests and using more marginal lands, allows greater integration with existing crop cultivation.

Australian government figures show that in 2010-11 biomass utilisation contributed by far the largest amount of energy to the total renewable resource. However, during the same period there was a 5% reduction in the output of biomass energy from traditional biomass sources including wood, bagasse etc. (Figure 11).
### Figure 11 Consumption of energy by fuel type and Growth - Australia 2010-11 (BREE 2012)

#### 2.10 Conclusion

The use of abundant and cheap fossil fuels has enabled a rapid increase in energy consumption worldwide. However, this dependency has also resulted in an unsustainable rate of energy resource use and rising atmospheric CO₂. The industrialisation of countries such as China and India will further increase pressure on finite reserves of fuel and could exacerbate anthropogenic climate change. Current biofuel production using terrestrial crops will unlikely be able to produce sufficient quantities of fuel to satisfy demand (Chisti 2007). Competing demands for land, water and nutrient supplies (for biofuel production) potentially could put pressure on existing food supplies and prices (Schenk, Thomas-Hall et al. 2008).
Chapter 3  Algal Biofuel Production

3.1 Introduction

Algae have been present for many millions of years growing naturally in a large range of diverse environments across the planet (Falkowski, Katz et al. 2004). Microalgae are the most primitive plant forms. Many present as simple cellular organisms with little support structures, enabling them to grow rapidly in aqueous solutions (Sheehan 1998).

They are ideal for cultivation as they have the following attributes:

1. Can be grown on marginal land
2. Some species don’t require fresh water
3. There is a possibility to pack more chlorophyll per square metre of surface area compared to plant, increasing the photosynthesis rate.
4. Can have a faster growth rate than terrestrial plants
5. Some species can accumulate a high oil content
6. Some species have a high temperature and salinity tolerance
7. Some species can produce some high value products such as poly unsaturated fatty acids and pigments (Darzins 2010; Borowitzka 2013).

Techniques for cultivating algae commercially for biofuel production have been developed over the past 65 years. Work undertaken by the Aquatic Species Program between 1978-1996 and subsequently followed by the Algal Fuels Roadmap, both funded by the US Department of Energy, have sought to provide a resource guide for the industry (Sheehan 1998; Sheehan, Dunahay et al. 2008; Ferrell and Sarisky-Reed 2010). A large amount of research has also been conducted in Australia by universities, government departments and companies; Figure 12 demonstrates some of those currently working in the field (Knoshaug and Darzins 2011; Li 2012).
Figure 12 Examples of major Australian centres, facilities and industry partners aiming to develop microalgal biofuel (Li, Moheimani et al. 2012)

Algal biofuels have had a high media profile in recent times, an example being the US Military Green Fleet Initiative looking at powering the US Navy fleet with biofuels (US Navy 2010). Another example is the Algal Biomass Organisation, based in the United States, which incorporates numerous aviation companies seeking to find a green sustainable fuel for the aviation industry (Algae Biomass Organisation 2013). Although these programs and initiatives can be beneficial in aiding progression of the technology, they may also provide unreal expectations for an industry very much in its infancy.

Currently algal farms mainly produce high value pharmaceuticals such as β-carotene, cosmetics and feed additives (Li, Horsman et al. 2008; Milledge 2011). These can be produced with low levels of productivity and remain commercially viable as they are high value. Whilst many of the techniques for producing algal products are well established, production of biofuels on a scale that is affordable, sustainable and scalable has not been demonstrated.

This process has its basis in any traditional agricultural system. It begins with the cultivation of preferably a monoculture of algal species. Minimising species variation generally will maximise production rates using the minimum of resources, although this is not always the case. Harvesting
(dewatering) the grown algae requires a lot of energy and therefore has high costs and presents a major challenge to commercial viability (Fon Sing, Isdepsky et al. 2011). Processing and refining of the dehydrated biomass then follows the method used depends upon the fuel required (Figure 13).

Success will be achieved by the selection of an optimal species of algae for the environmental conditions and the employment of a cultivation technology that is technically suitable and economically feasible.

![Cultivate → Harvest → Refine](image)

**Figure 13** Simplified microalgal biofuel production process

### 3.2 Cultivation

The basis of the process is the conversion of solar energy to chemical energy. Microalgae are sunlight driven cell factories converting carbon dioxide into protein, carbohydrate and lipid (Darzins 2010; Ferrell and Sarisky-Reed 2010).

Photosynthetic plants use the Calvin/Benson cycle: This process converts carbon dioxide and water into sugars in the chloroplast of the cell, the by-product being oxygen.

\[
6\text{CO}_2 + 6\text{H}_2\text{O} + \text{light} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2
\]

To operate this process optimally, a good solar energy source, adequate water and nutrients (mainly \text{CO}_2 and fertilisers) need to be present. The chemical reaction is affected by temperature with optimum temperatures increasing conversion rates. Algae are particularly well suited for cultivation as they have a high photosynthetic conversion efficiency (PCE) levels. This is basically the fraction of light energy that is converted to chemical energy enabling growth.

The theoretical efficiency of solar to chemical conversion in plants is approximately 27%. However plants can only utilise around 42% of the total
visible light spectrum (λ 400-700nm) resulting in a theoretical maximum PCE level of 11.3-12% (Brennan and Owende 2010). In reality most land plants have much lower PCE levels of perhaps 1-2% (Brennan and Owende 2010). Algae by comparison have a higher conversion rate as minimal energy is wasted on support structures such as bark, roots and leaves for growth, and as such have a higher density of chlorophyll than land based plants. Also being immersed in water they have higher rates of nutrient exchange than land-based species, enabling rapid growth rates (Dismukes, Carriéri et al. 2008). Biomass doubling rates have been quoted anywhere between 3.5 hours and 3-4 days, allowing oil productivity 10 times that of the best oilseed crop (Schenk, Thomas-Hall et al. 2008; Mata, Martins et al. 2010; Uday Bhan and Ahluwalia 2013).

During the growth phase of the cell the majority of lipid production is in the cell membranes. As the cells enter a more stationary phase accumulation of triacylglycerols (TAG’s) can eventually contribute 20-50% of dry weight in some microalgae (Tornabene, Holzer et al. 1983). In most cases, the accumulation of lipids results in decreased protein and carbohydrate synthesis resulting in a reduced overall growth rate (Day, Slocombe et al. 2012). Restriction of nitrogen at this point has been demonstrated to initiate this change in lipid productivity (Spoehr and Milner 1949; Smith, Sturm et al. 2010).

3.2.1 CO$_2$

Carbon dioxide is essential for photosynthesis and insufficient levels are a limiting factor in microalgae growth. Without supplemented CO$_2$ growth rates may be reduced by as much as 50% (Moheimani, Webb et al. 2012). The diffusion of CO$_2$ from air to seawater is low as atmospheric CO$_2$ levels are between 0.03-0.06% (Wang, Li et al. 2008). Water surface tension is also high, restricting diffusion (Van Den Hende, Vervaeren et al. 2012). The majority of dissolved carbon is in the form of H$_2$CO$_3$ with less than 1% being present as CO$_2$ (Moheimani 2005). Therefore, maximising growth requires the addition of CO$_2$. This can be added in the form of pure CO$_2$, usually in the form of waste flue gas from fossil fuel plants. CO$_2$ in industrial flue gases can be as high as 15%, providing a rich source of carbon for growth (Wang, Li et al. 2008).
There is marked species variation in rates of conversion of CO₂. The production of one tonne of algal biomass requires a minimum of 1.8t of CO₂ (Chisti 2007; Acien Fernandez, Gonzalez-Lopez et al. 2012). The production of commercial quantities of fuel would therefore require substantial inputs of CO₂ and locating farms within close proximity to a source of CO₂ is essential to maximise growth and minimise pipeline costs. Flue gas has other properties that need consideration, including the presence of SO₃ that may need to be removed due to their toxic effects on the culture. The gas may also need to be cooled prior to injection (Van Den Hende, Vervaeren et al. 2012).

Photosynthesis only occurs during daylight hours; hence CO₂ uptake from flue gases will only occur during this time. This limits both CO₂ sequestration potential and biofuel production if the source is insufficient for total requirements.

3.2.2 H₂O

In most cases, regions with high levels of solar irradiation also have high rates of evaporation (Ferrell and Sarisky-Reed 2010). Water requirements vary depending on the cultivation method and need to fill and replace evaporative losses during cultivation and processing. In a large-scale facility these inputs could be huge requiring replenishment from saline (sea) water sources. Ready access to the coast or an alternate water supply is necessary to provide this resource.

3.2.3 Light

Solar energy is the Earth’s main renewable energy input. Apart from nuclear and geothermal energy, every other source of energy is driven by solar radiation. Average local temperatures should be considered when selecting an algal species as tolerance to temperature varies. Cell stress and reduced productivity result if ambient temperature is not maintained (Fon-Sing 2010).

Light intensity also varies across the globe. Areas close to the equator have higher levels of light intensity, which are essential to maximise growth potential. Excessive light levels or high exposure to UV can damage the algal cells leading to photoinhibition. Necessary precautions must be made with
the system design to minimise these effects, as failure to do so leads to reduced productivity (Fon Sing, Isdepsky et al. 2011).

3.2.4 Nutrients

Nutrient requirements are important in the overall economics and long-term sustainability of algal farming. The two main nutrients required are nitrogen and phosphorus and quantities can be derived based on the overall mass balance using the following Redfield ratio. This is the ratio of carbon, nitrogen and phosphorus found in phytoplankton (Ketchum and Redfield 1949; Falkowski 2000).

\[ C_{106}H_{181}O_{45}N_{15}P \]

Theoretically for every tonne of dry algal biomass, if we assume 50% is carbon, the nitrogen requirement will be around 75kg and phosphorus 4.7kg (Pate, Klise et al. 2011). These are supplied in various forms including NaNO\textsubscript{3} and NaHPO\textsubscript{4}. Transporting large quantities of fertiliser can be logistically difficult and expensive, so recycling nutrients from harvested biomass and water has many benefits. These include a reduction in overall water use in addition to conserving nitrogen and especially phosphorus, which are finite resources essential for all farming. This ability to recycle nutrients from the culture solution provides a distinct advantage over other biofuel cropping.

Coupling wastewater treatment plants to algal bio farms has also been described as providing a potential source of nutrients (Park, Craggs et al. 2011). Creating a synergy between the two industrial processes can reduce overall costs for each one if a location can be identified with both in close proximity. Microalgae have been demonstrated to remove >96% of nutrients from wastewater within days, reducing processing costs. At the same time the wastewater provides essential nutrients for algal growth (Craggs 1994; Sharma, Singh et al. 2011). High rate algal ponds (HRAP's) in conjunction with wastewater treatment plants recycle effluent and produce biomass for use as fertiliser, reducing the need to mine phosphate. This reduction in phosphate mining is considered to reduce overall CO\textsubscript{2} levels by as much as the savings gained from using the algal biofuel itself (Craggs 1994).

Work by Beal et al (2012) demonstrated that combining the two processes reduces overall energy demand for both and reduces the nutrient demands
necessary for algal growth. The nutrient outputs from the WWTP serves as inputs for the algal biofarms. This reduces operating costs (OPEX) but increases initial capital outlay (CAPEX) because of extra infrastructure costs that are required to integrate both industries.

### 3.2.5 Species Selection

Approximately 35 000 to 40 000 species of algae have been scientifically identified but it is thought that there are a significant number of species still to be classified (Borowitzka 2013). Those species identified range in size from single celled microalgae to macroalgae like kelp that can be many metres in length (Wellinger 2009). Although 300 species have been used for research, only 10 or 20 are used economically (Wellinger 2009).

Microalgae have rapid growth rates and can be selected based on their biomass productivity, lipid profile, ability to grow in saline or freshwater, photosynthetic conversion efficiency and resistance to contaminants and pathogens (see Figure 14) (Georgianna and Mayfield 2012). Species can also be identified based on their methods of producing energy, such as the heterotrophs that convert sugars to bioethanol in the absence of light and the autotrophs that use photosynthesis to produce biodiesel (Brennan and Owende 2010).
This paper will only consider the autotrophic microalgae, as they don't require sugars produced by other forms of agriculture for fuel production, making them more sustainable and avoiding the fuel vs. food issues affecting existing biofuel crops.

The most common organisms used in biofuel production are green algae and diatoms (phytoplankton) (Sheehan 1998). The ideal species needs to be selected for the application required. Each species has its own particular qualities and requirements for cultivation and processing. Some examples being, *Nannochloris* and *Dunaliella* species cannot be grown in a freshwater environment and *B. braunii* secretes hydrocarbons from its cell surface, requiring different processing methods to extract biofuels than other algal species (Li, Horsman et al. 2008).

Research undertaken by Fon Sing (Fon-Sing 2010) has identified the salt tolerant (Halophytic) species *Tetraselmis* as being particularly well suited to growth in Western Australian conditions. *Tetraselmis* can tolerate high temperatures (20-25C) and high saline levels (<12%). They are also relatively resistant to contamination with other species. Fon Sing (Fon-Sing 2010) also indicated the possibility of improving lipid and biomass production through genetic modification. However, the use of genetically
modified crops in Australia is restricted (Calcutt 2012). Hence most species used have been obtained locally to reduce risk of contamination of surrounding lands.

Ultimately the species and strain selected must be tested under outdoor conditions and a complete annual cycle monitored to demonstrate suitability for the chosen environment (Borowitzka 2013).

3.2.6 Open Raceway Ponds and Closed Photobioreactors

Currently there are two main methods of cultivation. Both suspend the algae in a broth exposed to sunlight. There are distinct advantages and disadvantages to each method and selection is based on a number of factors including location, water availability and cost (Figure 17). Open cultivation is by far the most widely used around the world (Sheehan 1998; Borowitzka and Moheimani 2013).

Open raceway ponds

These have numerous forms but essentially consist of shallow ponds 30-50cm deep. They vary in size and shape but most commonly are an oval shape and contain a series of baffles and a paddle wheel to prevent settling and thermal stratification (Borowitzka and Moheimani 2013). The paddle wheel circulates the broth, which is then subsequently harvested prior to reaching the paddle again (Figure 15). The ponds themselves can either be lined with inert UV resistant plastics, increasing set up costs, or placed directly on the ground if soil substrate is suitable.

Open ponds have lower set up costs but are less efficient than closed systems, and have a number of other disadvantages. They lose a lot of water through evaporation, especially in hot desert environments, and they are at risk of contamination. Maintaining a pure culture of algal species can be difficult, and opportunistic contaminant species can, at best, reduce productivity, at worst they can be difficult to eradicate.
Figure 15 Open raceway pond (Wen and Johnson 2009).

Closed Photobioreactor Systems

A great deal of work has been carried out on developing closed systems. They offer a number of advantages over open ponds. These include potentially higher productivity rates (up to fivefold), reduced water losses and reduced land requirements. These systems can be of varying types but are generally horizontal panels, vertical panels or inclined tubes (Figure 16). These require a support structure and a pump or an airlift for mixing the culture (Knoshaug and Darzins 2011). Simple designs using plastic culture-filled bags, either suspended from racks or supported in the ocean, have also been used. These reduce the need for mechanical mixing and temperature fluctuation within the culture medium is moderated by immersion in the surrounding water.
If production costs could be reduced through economy of scale, the net energy ratio (NER) of both open ponds and flat plate reactors (a closed system) has been demonstrated to be positive (Jorquera, Kiperstok et al. 2010). Increasing the energy output compared to energy input improves the economic viability of the technology (Jorquera, Kiperstok et al. 2010). At this moment in time photobioreactor NER has not been sufficiently positive to warrant large scale production (Jacobi A and Posten C 2013).

<table>
<thead>
<tr>
<th>PBR’s have</th>
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</thead>
<tbody>
<tr>
<td>Higher algae concentration/ easier harvesting</td>
</tr>
<tr>
<td>Higher total biomass productivities (g. L⁻¹d⁻¹)</td>
</tr>
<tr>
<td>Better process control (t. CO₂, O₂ etc.)</td>
</tr>
<tr>
<td>Little or no evaporative water losses</td>
</tr>
<tr>
<td>More efficient use of CO₂, nutrients etc.</td>
</tr>
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<table>
<thead>
<tr>
<th>Ponds have</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easier to scale up, Larger unit scales (hectares vs. &lt;100 m²)</td>
</tr>
<tr>
<td>Lower capital (10-100 times lower) costs</td>
</tr>
<tr>
<td>Lower operating costs and energy consumption</td>
</tr>
<tr>
<td>Self-cooling (evaporative)</td>
</tr>
<tr>
<td>Pond gas exchanger (reduces O₂ level)</td>
</tr>
</tbody>
</table>

Figure 16 Tubular PBR (Chisti 2007)

Figure 17 Arguments for PBR’s vs. ponds (Moheimani 2013)
Currently it is considered that open raceway production of biofuels is the most likely to achieve success in the West Australian environment as the ponds are much cheaper to construct and operate at the scale required for fuel production (Fon Sing, Isdepsky et al. 2011). Closed photobioreactors also require a lot of fresh water for cooling in the high irradiation environments seen in the north of the State, which excludes their use (Jacobi A and Posten C 2013).

3.3 Harvesting and Processing

The conversion of algal biomass to fuel or other products is dependent on the process used, product required and the choice of algal species.

This stage of the production process requires the most energy and is critical to economic viability (Stephens, Ross et al. 2010). As much as 20-30% of the total costs of production can be attributed to this step (Brennan and Owende 2010).

At the point of harvesting, the algal suspension is of very low biomass concentration, somewhere between 0.1-4.0g.l\(^{-1}\) (<0.4%). To concentrate the biomass to the point of oil extraction, this needs to be increased to a minimum of 150g.l\(^{-1}\) (15%) (Brennan and Owende 2010). This can be achieved through the use of settling ponds, flocculation, flotation, homogenisation and centrifugation, all resulting in high-energy costs (Stephens, Ross et al. 2010).

The large quantities of water removed need to be recycled in order to harvest the nutrients present, thus reducing the overall demand for water and fertiliser, resulting in increased efficiency of resource use (Pate, Klise et al. 2011; Rösch, Skarka et al. 2012). Recycling the water also reduces waste discharge into the environment, which at scale would be substantial and require strict government controls. There are many methods of dewatering, the most common of which is flocculation, either by the addition of flocculants or by the selection of species that naturally self-flocculate (Pahl S, Lee AK et al. 2013). Further concentration by a process of flotation that is commonly used in wastewater treatment plants can then be employed and the biomass is skimmed off.
The resulting concentrated algal biomass can be processed by a number of methods to extract its embodied energy (Brennan and Owende 2010; De Boer, Moheimani et al. 2012). These involve either extraction of the lipids and then processing the remaining biomass, or processing the biomass as a whole (see Figure 18).

![Figure 18 Algal processing pathways (Wang, Li et al. 2008)](image)

The major processes can be broken down into: biochemical, thermo chemical, chemical conversion or direct combustion (Wang, Li et al. 2008). Most effort to date has been in the extraction and subsequent conversion of the lipids to biofuel using a chemical conversion process such as transesterification. Extracting the large amounts of water necessary to concentrate the biomass requires enormous inputs of energy. To increase the efficiency of this step alternative approaches have been investigated (see section 3.3.2) (De Boer, Moheimani et al. 2012).

### 3.3.1 Chemical Processes-Biodiesel

This dissertation is looking primarily into the production of biodiesel. This is because biodiesel is technically similar to petro-diesel and can be directly substituted in order to satisfy existing transport requirements (Knothe G 2013). By definition these are non-petroleum based fuels consisting of alkyl esters of long chain fatty acids (Elshahed 2010). The production of fatty acid methyl esters (FAMEs) requires the transesterification of oils or fats with alcohol to produce biodiesel. This process can yield up to 96% of the oil from
the lipid feedstock and occurs under relatively mild conditions of 60-65°C at ambient pressure, thus not requiring specialised equipment (Cartens, Grima et al. 1996).

**Direct Secretion** – research has been undertaken into the properties of *Botryococcus braunii*, a species that excretes long chain hydrocarbons that are easily converted to biofuels. However they have a very slow growth rate and poorly compete for nutrients with faster growing species. Genetic manipulation transferring an oil-producing gene from *B. braunii* into *E.coli* has been proposed, as it will combine the benefits of hydrocarbon production with rapid bacterial growth (Okada et al). Currently restriction of genetically modified organisms in agriculture limits their applicability in Western Australia and they will not be considered further in this paper (Huntley and Redalje 2007; Calcutt 2012).

**Lipid Extraction** - cell disruption, using a variety of methods ranging from mechanical, such as milling and autoclaving, to non-mechanical, such as osmotic shock and the use of solvents and enzymes, has been employed (Brennan and Owende 2010). Cell disruption increases access to oils within cell walls and reduces the need for high temperature/high-pressure extraction methods (Fon Sing, Isdepsky et al. 2011). Concentration, using similar processes to oilseed extraction in terrestrial plants, is followed by oil extraction. A combination of pressure, solvents such as hexane or supercritical fluid extraction can be used (Sharma, Singh et al. 2011). It is to be noted, that even with solvent recycling rates of up to 95%, these techniques can be expensive (Stephens, Ross et al. 2010).

The oils extracted can vary widely in quality due to differing ratios of polyunsaturated fatty acids (PUFA's), remnant glycerol co-products, alcohol and the presence of catalysts that were used in the process of extraction (Day, Slocombe et al. 2012). Stringent international biodiesel standards are employed to monitor quality including the *Fuel Quality Standards Act 2000* (Fon Sing, Isdepsky et al. 2011; SEWPaC 2013). Other considerations in the standards are oxidative stability, viscosity and cold flow properties (Knothe G 2013). However the latter two are unlikely to cause problems in the Australian environment, especially in the North West, as ambient temperature is high.
Following lipid extraction, the remaining solid biomass can be harvested for carbohydrate and protein products such as animal feed stocks and fertilisers, or it can be anaerobically digested to produce methane to power the plant (Knoshaug and Darzins 2011). The nutrient-rich residue is recycled for use as substrate in the cultivation process, reducing the requirement for additional fertilisers (Stephens, Ross et al. 2010; Knoshaug and Darzins 2011; Li 2012).

### 3.3.2 Whole biomass processing (biochemical and thermochemical)

Reduction of the water content to a level that allows lipid extraction by solvents requires a very large energy input. As a consequence, alternate methods of whole biomass processing have been investigated. These have been covered extensively in recent publications. De Boer, Moheimani et al (2012) demonstrated that conversion of the whole biomass using thermochemical methods provided the most positive energy balance.

Although these methods have not been demonstrated at scale at this stage, studies support the conclusion that thermochemical liquefaction and pyrolysis of the whole biomass provide the best energy return (Brennan and Owende 2010).

Another method demonstrated by Duan et al successfully upgraded bio-oil using a process of thermal liquefaction, followed by extraction using supercritical water. The fuel produced was low in acids and high in hydrocarbons, similar to typical fossil fuels (Duan and Savage 2011).

The resultant bio-oil would require further processing to upgrade it and render it suitable for use in internal combustion engines. A large amount of infrastructure would thus be necessary to achieve the scale required for industrial biofuel production. Centrally located catalytic cracking reactors, similar to a petrochemical refinery, could enable large scale processing of bio-oils. These types of projects may be possible in the future if the industry achieved a scale that would support the infrastructure investment.

Biofuels from algae are energy carriers and production is only justified if there is a positive energy balance. The more positive the energy balance the greater the chances of economic success.

### 3.4 Biofuel Standards
Internationally, biodiesel is either used as a transport fuel in its own right (B100) or is combined with regular diesel to form a blend such as B5 (5% biodiesel) or B20 (20% biodiesel). The Australian government has fuel standards for biodiesel covered by the *Fuel Quality Standards Act 2000* (SEWPaC 2013). Any algal biofuel produced will need to comply with these regulations. With this consideration in mind, blending the biofuel output as B5 or B20 would enable local biofuel to be produced and incorporated into regular fuel supplies with minimal adaptations (Li 2012).

### 3.5 Conclusion

Algal biofuels show great potential to fulfil future fuel requirements. They have been shown to have high rates of oil production per hectare compared to other biofuel crops, e.g. canola, soy bean or palm, whilst being produced on marginal land using saline water (Day, Slocombe et al. 2012). In addition they can utilise wastewater, aiding in its remediation, and bind CO₂ produced by fossil fuel power plants (Park, Craggs et al. 2011; Beal, Stillwell et al. 2012). The successful production of algal biofuels may provide a solution for many of the problems outlined in chapter 2; however, currently they have only been produced on a small scale, in laboratories in controlled conditions. To make the transition to a viable alternative option, a larger scale must be achieved, production costs reduced and long term sustainability demonstrated.
Chapter 4  Assessment of Potential to Satisfy Fuel Demand

4.1  Introduction

The successful development of a new industry requires a demand for its product, and for that product to be supplied reliably and cost effectively. For algal biofuel to be a viable alternate fuel for the mining industry, resources need to be available locally to minimise transportation costs and in sufficient quantities to allow high levels of production. Assessing the potential of this industry to satisfy demand requires the quantification of fuel needs and the investigation of local resources including solar, land, water, carbon dioxide and nutrient availability. Limitations in availability of any of these resources will reduce the amount of fuel that can be produced, unless an alternative resource can be found.

4.2  Western Australia - Background

The state of Western Australia occupies over 2.5 million km² or 33% of the Australian continental landmass (Landgate 2012). The state is rich in mineral and energy resources, has large areas of undeveloped land and a long coastline with access to the Indian Ocean. There is also a stable political and financial climate as well as developed industrial infrastructure (Evans&Peck 2011; WorleyParsons, Evans&Peck et al. 2012). The mining industry has a large requirement for diesel fuel, which is mainly imported.

The Pilbara region in particular is over 500 000 km² in area with a population of 65 000, just fewer than 25% of which are fly-in fly-out workers. This region accounts for over $60 billion annually in exports, mainly from the mining sector (Evans&Peck 2011).

The region surrounding and particularly to the south of Geraldton was also identified as an area with high production capability, mainly due to suitable land characteristics and proximity to the deep-water port plus an available labour force (Borowitzka, Boruff et al. 2012).
Growth conditions for algal farming are also ideal. Western Australia has high levels of solar exposure by comparison with other locations worldwide (Figure 19). The northern areas of the State receive over 22MJ.m$^{-2}$ daily (Figure 20).

Figure 19 Map of average solar radiation (watts per square meter) (Jacobson and Delucchi 2011)

Figure 20 Map of global solar exposure across Australia (BOM 2013)

The dry desert environments seen in the north have the added benefit of clear skies and on average 8-10 hours of sunshine daily. Diurnal temperature ranges for each location are approximately 10-15$^\circ$C with Port Hedland
maintaining an average minimum temperature during the winter months above 10°C. This is critical to productivity levels in algal farming as low culture temperatures have been shown to reduce output through cell stress (Sheehan, Dunahay et al. 2008) (Figure 21 and Figure 22). Rainfall rates are typically low and evaporative rates extremely high in these areas, necessitating proximity to a water source such as the ocean.

![Diurnal temperature variation at Port Hedland (BOM 2013)](image)

**Figure 21** Diurnal temperature variation at Port Hedland (BOM 2013)

![Diurnal temperature variation at Geraldton (BOM 2013)](image)

**Figure 22** Diurnal temperature variation at Geraldton (BOM 2013)

Bureau of Meteorology statistics in Table 1 support the basic requirements for microalgal farming; an ample radiation source, warm all year round temperatures and minimal overnight temperature variations.
### Table 1 Climate observations Port Hedland and Geraldton (BOM 2013)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Geraldton</th>
<th>Port Hedland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Daily Sunshine Hrs.</td>
<td>10.3</td>
<td>10</td>
</tr>
<tr>
<td>Average Rainfall (mm)</td>
<td>440</td>
<td>317.3</td>
</tr>
<tr>
<td>Average Evaporation Rate (mm)</td>
<td>2600</td>
<td>3200</td>
</tr>
<tr>
<td>Av. Solar Insolation (kWh. m⁻²)</td>
<td>5.85</td>
<td>6.16</td>
</tr>
<tr>
<td>(MJ. m⁻²)</td>
<td>20.5</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Considering the above factors in Table 1, the Mid-West and Pilbara regions of Western Australia would be ideal sites for an algal biofuel industry to develop.

#### 4.3 Pilbara Mining Industry Fuel Demand

The mining industry relies heavily on diesel fuel in its operations. The iron ore industry makes up 75% of total mining production, and contributed about $61 billion in 2011-12 to the Western Australian economy (Figure 23) (Department of Mines and Petroleum 2013).

![Figure 23 Mining commodity production 2010-2012 (Department of Mines and Petroleum 2013)](image)

Overall diesel consumption in Australia in 2010/11 was 20 054 ML (BREE 2011). This is the total used for road transport and power generation. Recent information gathered and published through the Energy Efficiency Opportunities Program (EEO) allows a more industry specific indication of fuel use in Western Australia. Data compiled by the 40 reporting companies
in the program indicated an overall consumption of 52.5PJ of diesel equivalent in the 2008-09 period (RET 2010). Reference levels for diesel fuel energy content is approximately 36.4 MJ.L⁻¹ (The Engineering-Toolbox 2012). This would equate to a consumption of 1440 ML.y⁻¹ or 3.95ML.d⁻¹. Assuming that one-barrel of oil is 159 litres, this equates to just over 9 million barrels of oil per day.

These calculations are supported in work undertaken by the engineering company GHD in 2010 for a proposed GTL (gas to liquids plant) to supply fuel to the Pilbara via alternate methods (Shastri SS, Kamper SF et al. 2012).

During the same period Australian iron ore exports totalled 393.9 Mt, with 97% of this being exported from Western Australia.

<table>
<thead>
<tr>
<th></th>
<th>Pilbara*</th>
<th>Geraldton/Mid-West**</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>2008/09</td>
<td>2012</td>
</tr>
<tr>
<td>Iron Ore Production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Mt.y⁻¹)</td>
<td>393.9</td>
<td>525</td>
</tr>
<tr>
<td>Fuel Demand (BL.y⁻¹)</td>
<td>1.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>

* Based on data from Energy Efficiency Opportunities Program** Based on data from Geraldton Iron Ore Alliance

Table 2 Current and projected fuel demand based on iron ore production in Pilbara and Geraldton regions (RET 2010; Oakajee Port and Rail Project 2012) (See Appendix A)

Iron ore production rose to 525 Mt in 2012 (BREE 2012). Extrapolating the fuel use from 2009 would result in diesel consumption of 12 million barrels (1.9 billion litres) per year.

It is projected that in 2018 iron ore output will increase by another 320 Mt, requiring a further 7.3 MB (3.1 billion litres) of diesel per year (Stephen Webster 2012). (Assuming a linear relationship between iron ore production and fuel requirements)

All of these figures are a simple interpolation of current iron ore production values and fuel requirements. They make no allowances for increased efficiency of fuel use or changes to extraction, shipping or processing of ore and are only an indication of future use. They also assume that the 40 companies represented in the EEO are responsible for the majority of iron ore production as it targets the top 250 companies by energy consumption.
4.4 **Algal Biodiesel Potential**

Producing billions of litres of renewable algal biofuels annually has never been achieved thus far. To determine what is theoretically achievable an understanding of the resource availability and the theoretical productivity of algal farms will be considered.

4.4.1 **Productivity Assumptions**

To determine the maximum theoretical productivity of a location it is necessary to look at the drivers of photosynthesis and the available solar resource. The photosynthetic conversion efficiency of algae is much higher per square meter than terrestrial plants (Schenk, Thomas-Hall et al. 2008; Kovacevic and Wesseler 2010; Acien Fernandez, Gonzalez-Lopez et al. 2012). Various authors have discussed a range of conversion efficiencies of anything up to 10%, however 2.5% has been seen as a maximum using today’s technologies (Brennan and Owende 2010; Day, Slocombe et al. 2012).

Productivity can then be calculated in g m$^{-2}$ d$^{-1}$ and is 10g(carbon) m$^{2}$.d$^{-1}$ or 19.4-24g of ash free dry weight.m$^{-2}$.d$^{-1}$ (Ritchie 2010).

Oil content can vary depending on species selection and growth conditions and is usually from 15-35% (Stephens, Ross et al. 2010). Whether this can be done at scale or long term is the critical factor. Demonstrated productivity rates of around 20 g m$^{2}$ d$^{-1}$ with 30% oil content equating to a PCE of approximately 2.1% (see Appendix C: ) shall be used in the analysis of potential locations (Stephens, Ross et al 2010). This equates to the base case scenario used by Stephens, Ross et al in the paper ‘An Economic and Technical Evaluation of Microalgal Biofuels’ (Stephens, Ross et al 2010)(See Appendix B for methodology).

4.5 **Theoretical Land Requirement for Algal Biofuel Production**

After estimating the fuel demand and making assumptions of productivity, the land area required to fulfil 100% of the fuel demand for the Pilbara mining industry can be determined (Table 3).
### Table 3 Land requirements to fulfil 100% fuel demand for 2012-2018

<table>
<thead>
<tr>
<th>Fuel Requirement</th>
<th>2012</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>L.10^6 y^-1</td>
<td>1908</td>
<td>3069</td>
</tr>
<tr>
<td>Land requirement km^2</td>
<td>1109</td>
<td>1784</td>
</tr>
</tbody>
</table>

*Using 20 g.m^-2.d^-1 and 30% oil content

This is clearly a large land requirement (Figure 24). However these regions have pastoral stations with vast holdings, for example De Grey Station located east of Port Hedland with an area of over 12 000 km^2 (Wikipedia 2013). By comparison Malaysia alone has over 49 000 km^2 of palm oil crops, so the total area necessary is certainly feasible (Shean M 2011).

![Map showing land area required to supply 100% diesel fuel requirements for the Pilbara mining industry](image)

**Figure 24 Land Area required to supply 100% of diesel fuel requirements for the Pilbara mining industry (Google Earth 2013)**

By comparison, the land area needed to supply these requirements using terrestrial plant based biofuels would be far greater with crops such as corn requiring over 100 times the land area (Figure 25).
Figure 25 Comparative land requirements to satisfy Pilbara iron ore industry 2012 diesel requirement. Based on Chisti (Chisti 2007)

Finding a suitable location to provide ALL of the necessary resources in sufficient quantities may be more difficult. Targeting specific locations based on the necessary resources required to maximise productivity with minimal costs requires an in depth analysis of regional and local factors.

4.6 Case Study 1: Pilbara sites

Two major studies undertaken concurrently in Western Australia have sought to provide information for developing an algal biofuels industry.

2. ‘Pilbara Algae Industry Study’ (Pilbara Cities Office of Department of Regional Development and Lands, Department of Fisheries and Department of State Development) (WorleyParsons, Evans&Peck et al. 2012).

The CREST report identified the optimal sites for location using GIS technology. This took into consideration factors such as topography, climate, relationship to water, CO₂ nutrient sources and infrastructure as well as heritage factors such as land rights (see Figure 26) (Borowitzka-Boruff 2012). This report considered the entire state and provided a broad targeted approach to regional siting.
Figure 26 Controlling factors for the location of algae biofuel production facilities (Borowitzka-Boruff 2012)

The Pilbara Algae Industry Study undertook to assess the industry requirements within the Pilbara region considering additional synergies with other industries and the common use of infrastructure. This report commissioned by government under its ‘Pilbara Cities Vision’ project is aimed at investigating the land planning considerations required for establishing an algae industry in the Pilbara region. The long-term vision is of a diversification of industry within the region and development of a more robust economy not wholly dependent upon mining, whilst utilising common infrastructure to reduce overall costs.
Figure 27 GIS modelling results indicating optimal areas for production of algal biofuels (Borowitzka, Boruff et al. 2012)

GIS mapping indicated that a number of sites along the coastline provided the most favourable conditions for biofuels production (Figure 27). These had accessible, affordable land, a warm sunny climate and proximity to labour, water, CO₂ and nutrients.

The major region identified is located in a strip extending from southwest of Karratha to northeast of Port Hedland (Figure 28). This region has proximity to the coast; workable land conditions i.e. soils and good access to mines and population.
The main constraints for this region are:

1. Cyclone risk was considered to be high and would need to be factored in to any development.
2. Accessible land that is suitable for development of large-scale ponds is already taken, limiting future availability.
3. Labour force is limited and there are high wage concerns due to competition with other industries.
4. Infrastructure costs are expensive (WorleyParsons, Evans&Peck et al. 2012).

![GIS modelling Pilbara coastline sites with highest capabilities](image)

Figure 28 GIS modelling Pilbara coastline sites with highest capabilities (*Borowitzka, Boruff et al. 2012*)

The Pilbara Algae Industry Study identified three specific locations for a future algae industry located at Port Hedland, Karratha and Onslow.

### 4.6.1 Port Hedland

The main port in the region has large-scale industrial development, with competing demands for any available land (Figure 29). A site of approximately 871Ha was identified as being suitable for locating a farm; it is currently zoned as rural and allocated to Dampier Salt operations, requiring rezoning and negotiation with other industries before use (*Borowitzka-Boruff 2012*).
This location, southeast of the port, is approximately 9.7km from the Alinta power plant, the main CO$_2$ source, and 11.8km from the wastewater treatment plant, a potential nutrient source.

### 4.6.2 Karratha

The area indicated in the centre of the map (Figure 30) is the current area allotted to Aurora Algae. The current algae farm occupies this 1000Ha site. An area of approximately 2483Ha is located to the east and is considered to be a site of future expansion. Maitland Estate to the west, if available, is over 5 800Ha in size. These sites combined, if fully used, would be approximately 9 400Ha. Both of these sites have been identified by WA Planning Commission as land suitable for development. The Karratha site is 12.5km from the Horizon power plant and 20km from the Burrup Fertiliser plant, two notable sources of CO$_2$. The wastewater treatment plant is 16.5km away. Development of these sites within close proximity to the existing Aurora Algae plant could provide the scale of production required to allow more centralised processing of fuel to occur in a future industry (WorleyParsons, Evans&Peck et al. 2012).
Figure 30 Karratha potential development site (not to scale) (WorleyParsons, Evans&Peck et al. 2012)

4.6.3 Onslow

Figure 31 Onslow potential development site (not to scale) (WorleyParsons, Evans&Peck et al. 2012)
In Onslow, located further to the south, there is 10 000Ha site identified as suitable (Figure 31). The soil type is of low permeability, possibly alleviating the requirement for pond liners, which would reduce overall costs. The Onslow site is approximately 23km from the proposed Wheatstone gas plant, a huge potential source of CO₂ that could be used in production. Table 4 summarises the attributes of the locations identified.

<table>
<thead>
<tr>
<th>Location</th>
<th>Pro's</th>
<th>Cons.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Hedland</td>
<td>Large workforce</td>
<td>Limited land</td>
</tr>
<tr>
<td></td>
<td>Developed harbour</td>
<td>Limited CO₂ supplies</td>
</tr>
<tr>
<td></td>
<td>Proximity to sea</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local biodiesel market</td>
<td></td>
</tr>
<tr>
<td>Karratha</td>
<td>Multiple CO₂ sources available including Burrup</td>
<td>Main CO₂ source 20km from site</td>
</tr>
<tr>
<td></td>
<td>Proximity to sea</td>
<td>Land availability limited by cultural, existing development and topography</td>
</tr>
<tr>
<td></td>
<td>Large workforce</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local biodiesel market</td>
<td></td>
</tr>
<tr>
<td>Onslow</td>
<td>Large area of land available.</td>
<td>Limited workforce</td>
</tr>
<tr>
<td></td>
<td>Large source of CO₂</td>
<td>Only one major CO₂ source</td>
</tr>
<tr>
<td></td>
<td>Local biodiesel market</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proximity to the sea</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 Main considerations for each proposed site (Borowitzka, Boruff et al. 2012; WorleyParsons, Evans&Peck et al. 2012)

For the purposes of assessing the production potential of the various sites suggested in the reports, some assumptions need to be made. Cultivation in open raceway ponds only will be considered, as they are the only economically feasible option and they shall occupy all available land. In reality a portion of land between 20-40%, would be required for infrastructure requirements and buffering zones from other industries (WorleyParsons, Evans&Peck et al. 2012). Productivity will be based on assumptions made previously and it is assumed there will be 100% downstream conversion efficiency of oil produced (see 4.4.1)

All locations have adequate access to seawater. There are no competing demands for input resources from other industries.
Using the photosynthetic conversion efficiency and the solar irradiation levels, it is possible to determine the theoretical productivity of the different Pilbara locations (Figure 32). Water, CO₂ and nutrient requirements are based on prerequisites for growth outlined in Chapter 3 and Fon Sing (2011)(Larger table available in Appendix E).

<table>
<thead>
<tr>
<th></th>
<th>Port Hedland</th>
<th>Karratha</th>
<th>Onslow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Available (Ha)</td>
<td>871</td>
<td>9406</td>
<td>10000</td>
</tr>
<tr>
<td>Production (ML.y⁻¹)*</td>
<td>12.3</td>
<td>162</td>
<td>172</td>
</tr>
<tr>
<td>CO₂ Requirement (Mt.CO₂.y⁻¹)</td>
<td>22.5</td>
<td>296</td>
<td>315</td>
</tr>
<tr>
<td>Water Requirement (bn L.y⁻¹)</td>
<td>3.9</td>
<td>51</td>
<td>54</td>
</tr>
<tr>
<td>Nitrogen (NaNO₃) (Mt.y⁻¹)</td>
<td>26.3</td>
<td>314</td>
<td>333.9</td>
</tr>
<tr>
<td>Phosphorus (NaHPO₄) (Mt.y⁻¹)</td>
<td>1.04</td>
<td>11.96</td>
<td>13.23</td>
</tr>
<tr>
<td>Total Oil Supply Capability (BL.y⁻¹)</td>
<td></td>
<td></td>
<td>346.16</td>
</tr>
<tr>
<td>Percentage of 2012 Fuel Requirement Supplied by Each Site</td>
<td>0.65%</td>
<td>9%</td>
<td>8.48%</td>
</tr>
</tbody>
</table>

* Productivity based on 2.1% PCE (20g.m².d⁻¹ and 30% Oil Content) (See calculations in appendices)

**Table 5 Potential supply possibilities and resource requirements from designated sites**

The Port Hedland site, being only 871 hectares, could theoretically supply approximately 16.6 megalitres per annum or 0.87% of fuel demands from mining if all resources necessary were available. There is a shortfall in CO₂ availability from the local power station (Alinta output 44978 T.y⁻¹/50% availability during hours of growth) would limit production to 12.3 megalitres or 0.65% of fuel demand for the region.

Onslow, having a much larger land area available to develop an industry, could feasibly supply over 191 megalitres per annum or 9% of demands. Karratha had the potential to supply 172 megalitres or almost 9% of total demand (Figure 32).
If all identified areas were to produce biodiesel, a total of 18% of total demand could be fulfilled. This is a total of 346 ML of fuel worth approximately $533 million at today's pump prices ($1.54/litre)

4.7 Case Study 2: Geraldton Region

The land to the south of Geraldton was also noted as a suitable location (Borowitzka-Boruff 2012). There is good land availability, low population density and access to a deep-water port and labour, although it was noted that future regional development might create land use pressure in the area.

Although not identified in the CREST report, the proposed Oakajee Port and Rail link to be located 24km North of Geraldton, with export potential of upwards of 45 million tonnes of iron ore annually, could provide a nexus for a developing algal biofuels industry (Oakajee Port and Rail Project 2012). Iron ore exports are proposed to be 60-90Mt.y\(^{-1}\) (Geraldton Iron Ore Alliance 2013).

Using similar assumptions to the scenario in Case 1 (above) fuel demand can be estimated based upon proposed mining exports. For further details for table 6 refer to appendices.
<table>
<thead>
<tr>
<th>Area Required to Produce Estimated Biodiesel Demand for Geraldton/Mid-West</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Requirement (Ha)</td>
</tr>
<tr>
<td>Fuel Requirement (M.L.y(^{-1}))</td>
</tr>
<tr>
<td>CO(_2) Requirement (Mt.y(^{-1}))</td>
</tr>
<tr>
<td>Water requirement (bn L.y(^{-1}))</td>
</tr>
<tr>
<td>Nitrogen (NaNO(_3)) (Mt.y(^{-1}))</td>
</tr>
<tr>
<td>Phosphorus (NaHPO(_4)) (Mt.y(^{-1}))</td>
</tr>
</tbody>
</table>

Table 6 Land and resources required to satisfy proposed biodiesel demand in Geraldton region

The proposed fuel requirement for Mid-West mining activities was estimated at 215 megalitres per year. To satisfy this demand completely would require over 12 500 hectares of available land. The major issue however is not land availability but a readily accessible source of carbon dioxide. There are a number of regional sources listed on the CARMA site documenting worldwide CO\(_2\) emissions, however they are widespread and could collectively provide only 13% of total requirements (CARMA 2012). Mungarra power station, the largest source in the area, is located 50km SE of Geraldton. Access to water supply would potentially be an issue that may exclude it as an option, as it is located 30km from the coast.

Figure 33 CO\(_2\) and nutrient sources of Geraldton region
Three Springs Gas fired Power Station located to the North of Yarra Yarra Lakes produces 2.1 Mt.y\(^{-1}\) of CO\(_2\) and could provide a suitable site for development (CARMA 2012). The Yarra Yarra Lakes are 119km\(^2\) of salt lakes. However they are situated 78km from the coast, the nearest reliable water supply as the lakes don't have permanent water.

Eneabba to the southeast of Geraldton is located 30km from a sparsely populated area of coastline. This is the location of the proposed Coolimba Power Project, a 450MW coal powered and 360MW gas fired power station. Although this project has approval to proceed it has been put on hold (Aviva Corporation Pty LTD 2011). Kwinana power station is an equivalent size to the proposed coal powered station and has an emissions level of 4.6 Mt.y\(^{-1}\), and Pinjarra Works uses gas turbines to produce approximately 290MW of power with emissions of 1.46 Mt.y-1 of CO\(_2\) (CARMA 2012). If it is assumed that emissions will be similar to these levels, available CO\(_2\) at Coolimba could be over 6 Mt.y\(^{-1}\).

If we assume that only 50% of the CO\(_2\) can be utilised and that in theory 1.83 tonnes of CO\(_2\) is required to produce 1KL of biofuel, theoretical production from this site could be 1640 Megalitres annually (Fon Sing, Isdepsky et al. 2011).

The Geraldton Verve power station produces approximately 9 700 tCO\(_2\) annually and is located close to the coast and the port. It is mainly used to meet peak summer demand and only operates during daylight hours. The limited CO\(_2\) available could realistically only supply around 1.25% of anticipated demand (Table 7).

<table>
<thead>
<tr>
<th>CO(_2) Resources Geraldton Region</th>
<th>t.CO(_2)y(^{-1})</th>
<th>Production Potential (ML.y(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geraldton Verve Power Station</td>
<td>9676</td>
<td>2.64</td>
</tr>
<tr>
<td>Dongara Lime</td>
<td>1310</td>
<td>0.36</td>
</tr>
<tr>
<td>Mungarra Power Station</td>
<td>41886</td>
<td>11.44</td>
</tr>
<tr>
<td>Total</td>
<td>52872</td>
<td>14.45</td>
</tr>
</tbody>
</table>

*Table 7 CO\(_2\) resources available Geraldton region (CARMA 2012)*
The necessary combination of all of the basic requirements for an algae industry are difficult to find in one location when it comes to increasing to the scale needed. The Geraldton region has good land, water and workforce availability. However it is connected to the SWIS and as a result local power generation is small and resulting CO₂ availability is low. A number of new gas fired generators are coming online, but they are often located inland with limited water supply availability. The region also has limited industrial development to provide access to other infrastructure requirements. Potentially the Oakajee development may provide some opportunities into the future.

4.8 Case Study 3: Marandoo mine

Mine sites are spread over a wide range of lands and at varying distances from the coast. Many employ large scale dewatering if the ore bodies are located below the water table. The water abstracted is used for all stages of operations, from exploration through to refining. Surplus water is often disposed of by reinjection into aquifers or by storage and discharge into creeks (Government of Western Australia Department of Water 2011).

The quantities of water extracted from mine sites can be immense. Rio Tinto in its recent report on water use in the Pilbara estimated that 80 Gigalitres per year were being managed by them alone (Rio Tinto Mining 2010). The company has identified this water as a resource that requires considered management. One use proffered was the development of agricultural land producing alfalfa. This surplus water could be used to produce biofuels from a mixture of fresh and saline species, depending on salinity of the water available. Mining sites in the Pilbara are generally extracting fresh water, as they are inland. Utilising the surplus water would address a requirement of the mining company to minimise waste and avoid the need to release it into local watercourses, potentially creating ecological problems. In addition, recycling of flue gases from diesel powered electricity generation into the ponds would alleviate some of the issues associated with carbon pollution, reducing costs and providing an essential resource for growth.

Rio Tinto operates an iron ore mine approximately 37km from Mount Tom Price in the Pilbara region (Figure 34, Figure 35). This mine has operated since 1994, with phase two operations looking to extend its lifespan a further
22 years. At its peak, dewatering is expected to yield 100 million litres of fresh water daily.

One of the proposed uses for this water is to pump it to the Hamersley Agricultural Project (HAP) (Rio Tinto Mining 2012). This is based on a proposal to use 1650 Ha of pastoral land owned by Rio Tinto, to produce 25 000 tonnes of hay annually (CMEWA 2010). This usage of the discharge water alleviates a potential issue connected with a threatened ecological environment downstream from the proposed water discharge flow (Rio Tinto Mining 2012).

The Marandoo mine has a capacity to produce 15 mega-tonnes of iron ore annually. Using the similar ratio of fuel intensity as the above cases the mine would be expected to consume 54ML of diesel annually.

Electricity for the mine comes from generation in Tom Price via a high voltage cable linkage. Carbon dioxide produced on site at Marandoo is through diesel combustion in heavy vehicles and thus cannot used in production of biofuel.

![Figure 34 Marandoo mine location- Pilbara (Rio Tinto Mining 2012)](image-url)
Production options could include situating a series of farms near Tom Price station or locating the farms in close proximity to the mine.

<table>
<thead>
<tr>
<th>Marandoo- mine information</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstracted Water Available (GL.y⁻¹)</td>
<td>36.5</td>
</tr>
<tr>
<td>Lifespan of mine (y)</td>
<td>22</td>
</tr>
<tr>
<td>Iron Ore Output (Mt.y⁻¹)</td>
<td>15</td>
</tr>
<tr>
<td>Fuel Demand Based On Mining Output (ML.y⁻¹)</td>
<td>54</td>
</tr>
<tr>
<td>Mt Tom Price Power Station Output (Kt.y⁻¹)</td>
<td>21.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biofuel Production Capability</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Output (ML.y⁻¹)</td>
<td>11.9</td>
</tr>
<tr>
<td>Percentage of Mines Fuel Requirement</td>
<td>22%</td>
</tr>
<tr>
<td>Land Requirement to Produce Fuel Needs (Ha)</td>
<td>545</td>
</tr>
<tr>
<td>Water Requirement to Produce Fuel Needs (GL)</td>
<td>3.35</td>
</tr>
</tbody>
</table>

Table 8 Marandoo mine-iron ore production, fuel requirements and biofuel potential (Environment Protection Authority 2010)

The power station at Tom Price had an annual output of 68 328 MWh in 2009 and produced 43 625 tCO₂, however as only 50% can be utilised due to photosynthesis only occurring during daylight hours (CARMA 2012). The production of 54 ML of biofuel as required annually would require 2470 Ha of ponds and consume 9.89 kilotons of CO₂. The shortfall of available CO₂ would limit production to 11.9 ML, or 22% of demand. Land requirement would thus be around 545 Ha and utilise 3.35GL of the available water (Table 8).

An alternative approach would be locating the farm at the mine site. This would enable use of water on site and reduce pipeline infrastructure requirements. Groundwater used to establish the ponds initially would be of pH between 6.5-8.5 (see Table 9) (Environment Protection Authority 2010). Freshwater algal species such as Chlorella, if initially cultured, would raise pH, allowing subsequent use of marine species including the Haptophytes such as Coccolithophorid algae and in particular Pleurochrysis carterae. This strain is of particular interest, as Pleurochrysis carterae deposit carbon as
CaCO$_3$ plates on the outside of the cell wall using a carbon concentrating mechanism. This process also releases CO$_2$, subsequently making it available for photosynthesis. Therefore there is a reduced requirement for CO$_2$ and the deposition of CaCO$_3$ remediates carbon from the carbon cycle. In addition, the algae produce high grade lipids (Fernández, Balch et al. 1994).

*Pleurochrysis carterae* has been demonstrated to grow well in culture, as it is efficient at binding HCO$_3$, resulting in a pH increase in the culture solution that effectively reduces the ability of competing species to grow. Using these species inland has not been demonstrated, and although freshwater Haptophytes have been identified they are few in number (Jordan and Chamberlain 1997).

Alternatively, filling the ponds with freshwater and allowing evaporation to increase pH could also provide the right environment for saline species to be cultivated. The availability of freshwater to ‘top up’ the ponds replacing evaporated or harvested water would maintain optimum growth conditions. The absence of an external CO$_2$ source at the mine site could potentially reduce biomass output dramatically, making a more desirable location (using current technology) nearer to the township of Tom Price. One main advantage of *Pleurochrysis carterae* over many other saline algae is the potential of its growth with no addition of external CO$_2$ (Moheimani, Webb et al. 2012).

Further investigations would include land availability, with respect to future growth in the town, land suitability, environmental impact and cultural considerations associated with native title.

The costs and technical requirements of downstream processing of biomass to produce biodiesel at this location and at this scale needs consideration. Subsequent anaerobic digestion of the remaining biomass to produce methane for electricity generation in the town could potentially improve the economics.
Figure 35 Marandoo mine topographical (Environment Protection Authority 2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>ADWG aesthetic guideline value*</th>
<th>Marandoo borefield</th>
<th>Southern Fortescue borefield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>Median</td>
<td>Range</td>
</tr>
<tr>
<td>Aluminium unfiltered</td>
<td>mg/L</td>
<td>NA</td>
<td>&lt; 0.02 – 0.1</td>
<td>&lt; 0.02 – 0.34</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg/L</td>
<td>250</td>
<td>78 - 160</td>
<td>100</td>
</tr>
<tr>
<td>Conductivity at 25°C</td>
<td>µS/m</td>
<td>na</td>
<td>592 – 1202</td>
<td>863.26</td>
</tr>
<tr>
<td>Copper</td>
<td>mg/L</td>
<td>1</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005 – 0.01</td>
</tr>
<tr>
<td>Hardness as CaCO₃</td>
<td>mg/L</td>
<td>200</td>
<td>330 – 440</td>
<td>361.2</td>
</tr>
<tr>
<td>Iron unfiltered</td>
<td>mg/L</td>
<td>0.3</td>
<td>&lt; 0.02 – 0.05</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Manganese unfiltered</td>
<td>mg/L</td>
<td>0.1</td>
<td>&lt; 0.005 – 0.05</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>pH</td>
<td>NOUNIT</td>
<td>6.5 - 8.5</td>
<td>6.19 – 7.92</td>
<td>7.15</td>
</tr>
<tr>
<td>Sodium</td>
<td>mg/L</td>
<td>180</td>
<td>32 – 51</td>
<td>40</td>
</tr>
<tr>
<td>Sulphate</td>
<td>mg/L</td>
<td>250</td>
<td>38 – 89</td>
<td>68.5</td>
</tr>
<tr>
<td>Zinc</td>
<td>mg/L</td>
<td>3</td>
<td>&lt; 0.01 – 0.05</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>

Table 9 Water composition Marandoo and Southern Fortescue borefields (Environment Protection Authority 2010)
4.9 Costs of Production

As production at scale has never been achieved, the costs of production are largely theoretical (Fon Sing, Isdepsky et al. 2011; Day, Slocombe et al. 2012). Estimations of costs in the various current studies vary widely due to ranging assumptions about production levels, capital cost and operating expenses. Economic modelling considering capital costs (CAPEX) and operating costs (OPEX) on an idealised plant size of 500 hectares have been produced by Stephens et al. Taking into account current algal biofuels technologies, an estimated cost of US$84 per barrel (53 cents per litre) was predicted (Stephens, Ross et al. 2010). Researchers quote a future target possibility of US$50bl (31 c per litre) (Huntley and Redalje 2007). Operational analysis in the Pilbara Algae Industry Study included factors for distance of pipelines for CO₂ and water, and although they assumed a higher level of productivity than in this report (oil content of 30g.m⁻².d⁻¹), quoted figures between US$184-309 per barrel ($1.16-1.96), (WorleyParsons, Evans&Peck et al. 2012). To produce the oil at a competitive rate compared to fossil fuels, production costs will need to reduce (diesel currently around $1.54. litre⁻¹ at the pump)
(AIP 2012). Crude oil is currently priced at US$92. Barrel\(^1\) (Oil-Price.net 2013).

The final cost per litre of biodiesel will reflect the capital expenditure and the operating costs. CAPEX is affected by choice of location, construction costs and cost of finance. OPEX is affected greatly by energy requirements, labour costs, nutrient and CO\(_2\) requirements and costs of downstream processing. The transportation of processed fuel to the consumer also needs consideration. In theory this should be similar to fossil fuel distribution.

The current mining and energy boom in the Pilbara region is placing huge demands on local infrastructure and labour supplies, resulting in elevated costs and delays in construction in the region. It is also causing reduced investment in other projects throughout the remainder of the State including the Mid-West (Chatfield Mark 2012). The costs of establishing and operating an algal biofuel industry in the Pilbara would be considerably higher than elsewhere in the State because of this situation.

4.10 Conclusion

The two case studies indicate that production potential for an area is based on a combination of suitable land, nutrients (fertiliser), water and CO\(_2\) availability. Finding the correct combination of all rarely occurs. Some of the Pilbara locations, in particular Onslow and Karratha appear to be suitable as they have large potential sites (almost 10 000Ha each) and a ready supply of CO\(_2\) within close proximity. Nutrients, either by way of wastewater from local plants or fertiliser factories, are also regionally available.

The Geraldton/Mid-West case study was more speculative. A future iron ore industry utilising a proposed port would be necessary to provide demand. Limited CO\(_2\) resources could potentially limit production unless a proposed source south of Geraldton at Coolimba is realised. Undeveloped land is available close to the coast for access to water. Costs in Geraldton could be lower than in the Pilbara region due to a lesser demand for infrastructure and labour.
Chapter 5  Increasing Economic Feasibility

5.1 Introduction

Currently the production of algal biofuels is uneconomical according to theoretical calculations. Costs need to be reduced and productivity increased. The challenge is to maximise the efficiency of conversion of sunlight to biomass and lipid, then extract the fuel required at the lowest energy and resource cost. All steps in the process need to be optimised for efficiency and integrated with other synergistic industries to maximise resource use whilst ensuring a local market for the product is available (Fon Sing, Isdepsky et al. 2011). To improve the economics in the short term, production of high value co-products may be employed whilst the overall efficiency of biofuel production is improved. Ways to achieve this are discussed below.

5.2 Theoretical efficiency

As mentioned earlier, to date the PCE achieved in long-term cultures has been between 1.5% and 2.5%. Maximal PCE has been suggested at between 8-12% (Melis 2009; Brennan and Owende 2010). If we consider a base case scenario of 2.1% and a potential future target conversion efficiency of 6.5% it is possible to determine the rate of biomass productivity for selected locations based on the amount of available land and sunlight (see Appendix C: , Figure 37)

An example of the calculations used in this section is demonstrated in the appendices.
Data for Whyalla in South Australia has also been included, as an algal biofuel industry is being developed there. Increasing the efficiency of conversion has a dramatic effect on biomass productivity. The difference in solar resource becomes more important as conversion efficiency increases, demonstrating that a small increase in efficiency can create a large return in productivity.

Productivity can be calculated using the formula: (Stephens, Ross et al. 2010)

\[
\text{Calorific Value (MJ.kg}^{-1} = (19.9 \times \text{oil }\%) + 18
\]

Algae produce biomass and oil. The oil-less biomass has assumed specific energy content (18 MJ.kg\(^{-1}\)) and the pure microalgal oil will also have a defined value (37.9 MJ.kg\(^{-1}\)). Biomass specific energy content in MJ.kg\(^{-1}\) can then be calculated depending on % of total content of the biomass (Table 10) (Stephens, Ross et al. 2010).

<table>
<thead>
<tr>
<th>Oil Content</th>
<th>Calorific Value (MJ kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>22.98</td>
</tr>
<tr>
<td>30%</td>
<td>23.97</td>
</tr>
<tr>
<td>50%</td>
<td>27.95</td>
</tr>
</tbody>
</table>

Table 10 Theoretical energy values as a product of oil content (Stephens, Ross et al. 2010)

Using this as a base it is possible to assess each location for theoretical productivity rates. If we assume a PCE of 6.5% and a lipid content of 30%, oil
production rates increased by 300% at all locations. As productivity is directly related to the ability of the algae to convert sunlight into energy and subsequently biomass, there is an increase at a corresponding rate (Table 11).

<table>
<thead>
<tr>
<th></th>
<th>Geraldton</th>
<th></th>
<th>Port Hedland</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biomass Energy</td>
<td>Oil</td>
<td>Biomass Energy</td>
<td>Oil</td>
</tr>
<tr>
<td>2.1%PCE</td>
<td>t. Ha(^{-1})y(^{-1})</td>
<td>m(^3).Ha(^{-1}).y(^{-1})</td>
<td>t. Ha(^{-1})y(^{-1})</td>
<td>m(^3).Ha(^{-1}).y(^{-1})</td>
</tr>
<tr>
<td>30%</td>
<td>59.27</td>
<td>15.47</td>
<td>65.92</td>
<td>17.20</td>
</tr>
<tr>
<td>6.5%PCE</td>
<td>183.45</td>
<td>48.00</td>
<td>204.00</td>
<td>53.20</td>
</tr>
</tbody>
</table>

Table 11 Biomass and oil productivity at varying PCE

Increasing productivity three-fold in theory increases the oil yield as well as culture concentration. This results in reduced dewatering costs as a secondary benefit. An increased supply of nutrient resources (fertiliser, wastewater) and CO\(_2\) supply would be required to supply the increased biomass output. Numerous approaches have been made to increase efficiency through providing optimal conditions for photosynthesis to occur. Increased rates of mixing to expose the algae to light through the use of pumps or inclined bioreactors is beneficial but increases energy costs (Fon Sing, Isdepsky et al. 2011). Optimal mixing also reduces cell death through photoinhibition due to excessive solar irradiance (Day, Slocombe et al. 2012). Daylight length is also an important factor. When the culture is in darkness respiration occurs, resulting in a loss of biomass. The small difference in day length between Geraldton and the Pilbara of 0.3 hours, over the course of a full year approximates to around 110 hours of extra growth time; this may be significant in a large farm. Finding methods of extending light exposure through the use of artificial lighting may increase productivity.

The Pilbara locations, which are resource adequate but land limited would benefit from the increase in PCE. Where resources are limiting, higher PCE levels would enable smaller farm size, reducing overall cost.

Appendix F provides an indication of the variation in land requirements with changes in PCE and oil content.

5.2.1 Sensitivity Analysis

The following sensitivity analysis indicates the effect of increasing PCE and oil content on the area of land required to satisfy fuel requirements in the
Pilbara case study. Increased productivity dramatically reduces land requirements necessary to produce the required amount of biofuel.

![Graph showing land area required vs PCE% for different lipid contents (25%, 30%, 50%)](image)

*Figure 38 Pilbara sensitivity analysis demonstrating land requirement to produce fuel with varying lipid content.*

### 5.3 Lipid Productivity

As biodiesel is the product being sought, increasing oil yields per hectare would make a significant change to productivity. This can be done by a number of methods:

- Manipulation of lipid synthesis pathways through the restriction of nitrogen, resulting in a higher proportion of useful TAG’s.

- Selection of optimal species for lipid content.

- Maximising oil extraction during processing.

These are all areas of research currently being investigated (Brennan and Owende 2010; Day, Slocombe et al. 2012). It is to be noted that there are several studies to find an alternative method for converting algae biomass to biofuel as discussed previously. Development of techniques to culture Botryococcus braunii and ‘milking’ lipids off the culture without destruction of the algae themselves is also an exciting prospect, as it could reduce times required for growth and the costs associated with dewatering (Moheimani, Cord-Ruwisch et al. 2013).
An estimation of land required for meeting fuel requirements for the Port Hedland and Geraldton if oil content was increased can be seen in Appendix D.

5.4 Decentralisation-Inland Opportunities and Synergies with Mining

Land availability close to population centres on the coast may be a limiting factor, restricting the scale of industry required into the future. Locating farms within close proximity to the fuel demand would allow greater flexibility and the possibility of shared equity. A number of factors need to be considered including the land available, the expertise required, resource availability and the quantity of fuel required by the customer. The estimated lifetime of the mine will also determine if the capital expenditure is justified. Access to locally produced biofuel could insulate the mining company from market price fluctuations and reduce overall greenhouse emissions through reduced fossil fuel use and biological carbon capture.

Work needs to be done to investigate specific locations suitable for this synergy.

5.5 CO₂ Sequestration

There are many methods being currently investigated to reduce the levels of CO₂ in the atmosphere, including carbon capture and storage and biofixation by photosynthetic plants (Moheimani, Webb et al. 2012). Microalgae in particular are considered to have good rates of fixation compared to land based plants due to high rates of areal fixation (Benemann 1997).

The important factor to consider is the period of time that carbon is removed from the carbon cycle. Binding in a biological form either as trees, soil or algal biomass is only relatively short term. Binding as calcium carbonate such as the Coccolithophorids is more permanent, with the added possibility of selling the bound calcium as a high value product for the biomedical industry (Walsh and Mann 1995; Oliveira, Grech et al. 2007). These are only possibilities as they have never been demonstrated on a large scale to this point and would require a significant improvement in productivity, and a
reduction in the costs of oil production, to be considered as a viable biomitigation option (Benemann 1997).

However the production of algal biofuels utilising CO₂ from industrial flue gases is short-term capture. Benefits of algal farming include offsetting fossil fuel combustion (which releases new sources of CO₂) and reducing CO₂ production from wastewater treatment. Replacement of fossil fuels with renewable sources can reduce carbon emissions by up to 80% (Acien Fernandez, Gonzalez-Lopez et al. 2012). With regards to net greenhouse gas emissions microalgal biofuels may avoid as much as 75g of CO₂ per MJ of energy produced (Li 2012).

The figures in Table 12 indicate potential CO₂ abatement by injecting flue gases in the algal culture. The Port Hedland and Marandoo sites indicate 50% total abatement, as all of the CO₂ produced is utilised during daylight hours (50% of day). Geraldton is not included as the CO₂ resource is disseminated. If one site was selected it would be assumed that 50% of total emissions would be abated.

<table>
<thead>
<tr>
<th>Potential CO₂ Abatement</th>
<th>CO₂ Available</th>
<th>Abated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Hedland</td>
<td>44978</td>
<td>50%</td>
</tr>
<tr>
<td>Karratha-Burrup</td>
<td>786309</td>
<td>37.6%</td>
</tr>
<tr>
<td>Onslow</td>
<td>15000000</td>
<td>2.1%</td>
</tr>
<tr>
<td>Marandoo</td>
<td>21.8</td>
<td>50%</td>
</tr>
</tbody>
</table>

*Table 12 Prospective CO₂ abatement at selected sites*

It assumes that the industrial flue gases are suitable for injecting and non-toxic to the culture (Van Den Hende, Vervaeren et al. 2012). Bio prospecting for strains that are tolerant of high temperatures as well as NOₓ and SOₓ may be necessary to ensure the culture thrives (Stephens, Ross et al. 2010). Unique methods for introducing the CO₂ into the reactor need to be addressed also, as simply bubbling it in could result in most of the gas being released into the atmosphere, neither beneficial to the culture nor atmospheric carbon levels (Acien Fernandez, Gonzalez-Lopez et al. 2012).

The potential abatement at each site and the economic value to both emitter and user will depend on the efficiency of uptake of the CO₂, the cost of harvesting, treating, transporting and utilising it and the carbon price. This
potential to convert CO₂ could attract investment through carbon credits, providing an alternate income stream for algae companies (Li 2012).

5.6 Co-Production of High Value Products

The production of biofuels is not currently feasible, and establishing an industry may rely upon the creation of concurrent high value products to cross subsidise lower value biofuels until economies of scale and technical developments can drive down cost. Within the areas described in the siting reports there are a number of potential applications for algal products.

![Diagram of algae biomass conversion](image)

Figure 39 Five pathway options available for recovery and use of co-products (Sheehan 1998)

Nutraceuticals and pharmaceuticals are high value products in comparison to the fuel industry. However their markets are relatively small and can easily be saturated if a flood of product is released onto the market (Subhadra and Edwards 2011).

Algae can produce a wide variety of valuable compounds in addition to bio-energy sources (Figure 39). Algal cultivation techniques and efficiencies have been improved through the production of compounds such as β–Carotene. The 250Ha Hutt Lagoon site north of Geraldton is such an example within the region (Borowitzka-Boruff 2012).
The biomass remaining after oil extraction contains many of these products, making it a valuable resource to utilise. An integrated approach to the processing of the algal biomass produced after extraction of oils is achievable (Naylor, Hua et al. 2009). However it would require a large scale operation and a centrally located refinery to be viable (Subhadra 2010). Thus far coexistence of the two industries has yet to be seen.

5.6.1 Aquaculture

Over-exploitation of worldwide fish stocks has led to reduced catch and has put pressure on the marine environment. Mariculture is seen as one potential method of providing a growing world population with a sustainable source of nutrition and protein whilst relieving pressure on existing marine and land based resources (Subhadra 2010). The West Australian coastline has a number of zones identified by the Department of Fisheries as potential aquaculture zones. One is located in the Kimberley region, the other in the Geraldton region close to suitable sites identified in the CREST report (Borowitzka-Boruff 2012). The Mid-West Aquaculture Region in particular is also located close to the Western Rock Lobster Fishery, a $2billion industry which is potentially a market for algal based feed (Fisheries Department of Western Australia 2013).
Companies such as Aurora Algae have proposed producing A₂Feed, a product of algal farming aimed at a developing aquaculture industry (Aurora Algae 2011). These products are still relatively expensive and used only for plant-eating fish. In particular intensive rearing of hatchlings for stocking farms can benefit from these products. The use of a high quality, treated algal biomass containing the correct balance of protein, oil and carbohydrate, reduces the risk of introduction of pathogens that is seen in wild grown algal cultures traditionally used as feedstock.

5.6.2 Animal Feed

Western Australia has a large live cattle export industry with a value of $190 million (LiveCorp 2013). Recent events in destination countries have reduced exports by one third; consequently the future of the industry is not entirely certain. Exporting ports such as Port Hedland and Broome require extensive
animal handling facilities and feedlots to maintain the animals during the shipment process. Provision of a quality feed to this industry and export to countries of destination is a potential market.

Algal feedstock has been playing an increasingly vital role in production of animal feed, from chickens to cattle, and algal biomass containing high levels of protein, carbohydrates and oils including EFA's can be tailored to suit the individual requirements of each species.

5.6.3 Pharmaceuticals

Astaxanthin is a naturally occurring pigment that gives salmon flesh its colour; it is also a potent antioxidant (Fujii, Imazato et al. 2006). Produced by Haematococcus pluvialis the global market for Astaxanthin has been estimated at over US$250 million. Unfortunately, low levels of productivity coupled with susceptibility to contamination and adverse weather conditions makes it technically difficult to grow at scale (Oilgae 2011).

5.6.4 Human Food

Spirulina has been cultivated successfully for many decades as a dietary supplement. The future production of Spirulina as a major protein source could be vital in addressing food shortages. The ability to use marginal land and brackish water for production makes it suited to the hot desert climates seen in Western Australia. The land area and water required to produce 1kg of Spirulina protein compared to the requirements of other sources of protein can be seen in Figure 41.

Feeding a global population approaching 7 billion will require innovative approaches to agriculture and the use of algae could potentially provide protein more effectively.
Figure 41 Resource requirements to produce 1kg of protein (Henrikson 2011)

5.6.5 Bioplastics

Many current bioplastics are starch based, relying on food crops as a resource. Potentially the bioplastics industry could be worth US$20 billion by 2020, resulting in increased pressure on starch supplies. Spent algal biomass has been identified as an alternate resource, with companies such as Cereplast hoping to produce up to 40% of its bioplastics from algae (International Conference on Information Systems 2009).

5.7 Conclusion

In addition to the bioenergy possibilities, microalgae can also produce many other high value co-products including pharmaceuticals, animal feeds and bioplastics. Additional revenue streams from CO₂ sequestration will become increasingly lucrative as the need for companies to offset carbon emissions costs becomes more important. Establishing synergies with mining companies that produce surplus abstracted water can turn this wasted resource into biofuels to be used in the mining operation.
Chapter 6  Issues with scaling up

6.1 *Introduction*

Until now all commercial production from algae has been of high value products that require low levels of productivity to be economically successful (i.e. Hutt lagoon *Dunaliella salina* plant for producing β-carotene). Biofuel production has only ever been achieved on a small laboratory or pilot plant scale, never on an industrial scale (Li 2012). There are a number of constraints on large-scale production that need to be considered. These involve biological and engineering issues affecting the health and productivity of the algal growth medium, and then there are the demand implications for the resources essential for large-scale production.

In the West Australian situation these are discussed below.

6.1.1 *Land requirements and availability*

Large areas of sparsely populated land are available in regions with abundant sunshine. The main land restrictions are related to accessibility of developed land proximal to towns to allow access population and infrastructure and cultural heritage restrictions. The Pilbara Cities vision identified a total of just over 20000 hectares of land that would be suitable for development. Further investigation of suitable land for development in other regions is necessary to identify suitable sites.

6.1.2 *Water*

The regions identified have very high evaporation rates, with Port Hedland typical of the Pilbara region having in excess of 3200mm per year. Large algal biofuel farms have substantial water requirements due to water lost during cultivation and processing. Recycling of water can reduce this demand. Periodic discharging of pond contents requires needs consideration due to potential negative environmental impacts and would require EPA approvals.

Estimations of water use in algal farming range between 500-3400 gallons of water per gallon of biofuel produced (Yang, Xu et al. 2011). The cases considered in this paper assume a level of approximately 315 litres of water
per litre of oil produced (approximately 1320 litres per gallon), however consumption will vary with productivity (Fon Sing, lsdepsky et al. 2011). Water requirements for each location are shown in Figure 42

![Water requirements at each location](image)

**Figure 42 Water requirements at each location**

### 6.1.3 Carbon Dioxide

Karratha and Onslow have large-scale industrial plants with the capability of supplying the required amount of CO₂ necessary for algal biofuel production. Large CO₂ sources are otherwise hard to locate in proximity to the proposed sites and will limit the development of an algae biofuel industry. Future production of algal biofuels in a fossil fuel constrained world may be further limited by a lack of flue gas generation. A sensitivity analysis of oil production vs. CO₂ availability in Figure 43 demonstrates the increasing requirement for CO₂ as production increases. Additional CO₂ resources would be required or the use of algal species capable of oil production without an external source of CO₂.
Figure 43 Sensitivity analysis for CO2 requirements vs. Oil production

6.1.4 Nutrients

Supplies of nutrients can contribute one of the largest production costs in biofuel production (Pate, Klise et al. 2011). More importantly is the long-term sustainability of using large quantities of nutrients especially phosphorus a non-renewable resource derived from phosphate rock. Supplies worldwide are already declining for this essential nutrient used in all forms of agriculture with estimates suggesting a peak at around 2030 (Cordell, Drangert et al. 2009). Australia has a total demonstrated resource of 1390Mt, which is approximately 1% of world resources (Geoscience Australia 2012). By far the largest worldwide sources of phosphate are Morocco and China, resulting in bottlenecks to supply and periodic dramatic price increases (Figure 44) (Geoscience Australia 2012)
Recycling the water and nutrients can reduce demand by up to 55% (Yang, Xu et al. 2011). Anaerobic digestion of remaining biomass post lipid extraction would enable nutrient recycling at the same time as generating energy from methane production (Knoshaug and Darzins 2011; Li 2012). Nitrogen is derived from natural gas a non-renewable fossil fuel resource also subject to price variation over time (Pate, Klise et al. 2011).

The quantities of nutrients required are large, with the Onslow site alone projected to require over 330 kilotonnes annually (Figure 45). Coastal locations with good port access would be a prerequisite to enable ease of transporting these large quantities. Long-term sustainability issues need consideration if we are to supply fuels on a large scale. Nutrient requirement calculations are shown in Appendix G.
Utilising wastewater from regional centres may be an option if infrastructure costs aren’t prohibitive. All areas identified apart from Tom Price and Marandoo minesite have WWTP’s.

<table>
<thead>
<tr>
<th>Wastewater Treatment Plants (ML.d⁻¹)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Hedland</td>
<td>10</td>
</tr>
<tr>
<td>Karratha</td>
<td>10</td>
</tr>
<tr>
<td>Geraldton</td>
<td>150</td>
</tr>
<tr>
<td>Onslow</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 13 WWTP resource (Water Corporation of Western Australia 2013)

6.3 Conclusion

The production of significant quantities of biofuel from algae to replace fossil fuels will require a dramatic increase in resources. Suitable land and access to water shouldn’t be a major restrictive factor in Australia given the wide stretches of coastline and sparsely populated land. Nutrient supply will be an important factor as these are finite resources and are also used by food crops. The efficient recycling of water, nitrogen and phosphorus during the cultivation and processing of algae is essential both for economic and sustainability reasons. Utilising nutrient rich wastewater and whole biomass processing are important techniques that have been assessed and will lead to a reduction in inputs required. Carbon dioxide availability is crucial to achieve a high level of productivity and has been shown to be a limiting resource in many of the locations studied.
Chapter 7 Conclusions and Recommendations

Increasing demand for the world's finite fuel supplies and future climate change impacts require the development of renewable alternate fuel supplies from sustainable sources. Biofuels from microalgae offer one the only means possible to supply the scale of future fuel requirements. The ability to use marginal land and salt water separates this potential fuel supply from competition with agricultural crops. Reducing pressure on agricultural land and resources will allow an algal biofuel industry to prosper whilst not putting upward pressure on food costs. Although a great deal of research has been undertaken over the past 50 years, currently the industry remains in its infancy, with the majority of commercial production targeting the pharmaceutical industry. Upgrading scale and output to produce biofuels will require further research and technical innovation to overcome the many issues facing the industry. These include reducing setup costs, selection of appropriate species for each location, maintaining health of the culture and minimising the energy used to harvest and refine the oil to name but a few. This study demonstrates that if these challenges are overcome, finding the correct combination of resources required for production are difficult to find at one specific location. Work undertaken previously has demonstrated areas within the state that have optimal resources for industry location. This dissertation has then used productivity values based on laboratory and fieldwork to model the potential for algal biofuel production in this state.

Three case studies were used for this modelling: The Pilbara coastal region, the location of the majority of iron ore production facilities. The Geraldton region, the hub of a potential future iron ore industry and Marandoo mine an inland mine site with fuel requirements and a huge surplus of unutilised groundwater. Each case study demonstrated the limitations placed on production by a restriction of a required resource.

The three locations identified in the Pilbara; Port Hedland, Karratha and Onslow, are constrained by suitable land availability but could feasibly
supply approximately 20% of current diesel requirements of the mining industry at 2012 levels of demand.

The region around Geraldton had good land availability and infrastructure but a lack of a large source of CO₂ at one location restricted potential production. Locating farms close to mining sites such as Marandoo enabled the company to utilise abstracted water and turn a waste into a valuable product but limited by CO₂ availability would reduce productivity.

If novel ways of supplying CO₂ or a reduction in the requirement for CO₂ can be found, then potential production will not be limited to areas close to CO₂ sources. This dependency on CO₂ would appear to be the main restriction on production in this study.

As current costs of production are high and fossil fuel prices are relatively cheap, the co-production of other high value products, if possible, would ensure efficient use of all of the biomass. This can provide an economic synergy with other industry to reduce overall costs and ensure future viability.

If the technical and economic challenges facing the algal biofuel industry can be overcome, there is the potential in Western Australia to supply some of the fuel requirements of the mining industry. Numerous ancillary benefits could also result, including CO₂ reduction, more cost effective wastewater treatment and the diversification of the regional economy with energy security an added bonus. Currently algal biofuels cannot power the mining boom, but Western Australia may have the potential in the near future.
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### Appendices

**Appendix A: Background information for table 3 section 4.3**

<table>
<thead>
<tr>
<th>Current and Projected Demand Based on Iron Ore Production</th>
<th><strong>Pilbara</strong>*</th>
<th><strong>Geraldton/Mid-West</strong>**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2008-09</td>
<td>2012</td>
</tr>
<tr>
<td>Iron Ore Prod (T 10^6)</td>
<td>393.9</td>
<td>525</td>
</tr>
<tr>
<td>Diesel Consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrels 10^6 y⁻¹</td>
<td>8.90</td>
<td>12.00</td>
</tr>
<tr>
<td>Barrels d⁻¹</td>
<td>24383.56</td>
<td>32876.71</td>
</tr>
<tr>
<td>L 10^6 d⁻¹</td>
<td>3.95</td>
<td>5.23</td>
</tr>
<tr>
<td>L 10^6 y⁻¹</td>
<td>1415.011</td>
<td>1907.88</td>
</tr>
</tbody>
</table>

* Based on data from EEO  
** Based on data from the Geraldton Iron Ore Alliance

**Appendix B: Background methodology for calculating PCE**

**Calculating photosynthetic conversion efficiency**

If demonstrated productivity rate = 20 g m⁻² d⁻¹

Pilbara- Light intensity (Average) = 22.8MJ.m⁻².d⁻¹

Over 12 month period total solar radiation = 83,220 GJ.Ha⁻¹.Y⁻¹

If we assume conversion of the total solar radiation into biomass then energy content of biomass is 1580 GJ.Ha⁻¹.y⁻¹ based on a PCE of 2.1%.

The energy is stored in the form of biomass and oil and will vary depending on oil content.

Using Stephens’s method (Stephens, Ross et al. 2010)it is possible to calculate the calorific value of the biomass per kg based on oil content.

If we assume an oil content of 30% then calorific content = 23.97MJ.kg⁻¹

As we have determined the energy content possible using the PCE and we know the calorific content per kg it is possible to determine the theoretical quantity of total biomass per hectare for each location.

For Port Hedland with a PCE of 2.1% and oil content of 30% productivity is estimated at 66 tonnes per hectare per year of biomass then producing 17.2 m³.Ha.y⁻¹
This figure is equal to approximately 18g.m\(^{-2}\).d\(^{-1}\) of biomass output.

Appendix C: Calculating productivity from photosynthetic conversion efficiency using Bureau of Meteorology data (BOM 2013)

### Solar Resource at Optimal Locations

<table>
<thead>
<tr>
<th></th>
<th>Geraldton</th>
<th>Pilbara</th>
<th>Whyalla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Intensity MJ m(^{2}).d(^{-1})</td>
<td>20.5</td>
<td>22.8</td>
<td>19</td>
</tr>
<tr>
<td>Solar Radiation GJ Ha(^{-1}).y(^{-1})</td>
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<td>75240.00</td>
<td>62700</td>
</tr>
</tbody>
</table>

### Solar to Biomass GJ Ha\(^{-1}\).y\(^{-1}\)

<table>
<thead>
<tr>
<th></th>
<th>2.10%</th>
<th>4.50%</th>
<th>8%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1420.65</td>
<td>1580.04</td>
<td>1316.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4397.25</td>
<td>4890.6</td>
<td>4075.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5412</td>
<td>6019.2</td>
<td>5016</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6765</td>
<td>7524</td>
<td>6270</td>
<td></td>
</tr>
</tbody>
</table>

Calculating theoretical energy content of algal biomass using Stephens formula (Stephens, Ross et al. 2010)

### Calculating Theoretical Energy Content of Algal Biomass (Inc. lipid)

Calorific Value (MJ kg\(^{-1}\)) = (19.9 x oil%) + 18

<table>
<thead>
<tr>
<th>Oil Content (MJ/kg)</th>
<th>25%</th>
<th>30%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>22.98</td>
<td>23.97</td>
<td>27.95</td>
</tr>
<tr>
<td>30%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Calculating theoretical biomass and oil productivity at selected locations

<table>
<thead>
<tr>
<th></th>
<th>Geraldton</th>
<th>Port Hedland</th>
<th>Whyalla</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biomass Energy t.Ha(^{-1}).y(^{-1})</td>
<td>Oil m(^{3}).Ha(^{-1}).y(^{-1})</td>
<td>Biomass Energy t.Ha(^{-1}).y(^{-1})</td>
</tr>
<tr>
<td>2.1%PCE 25%</td>
<td>61.83</td>
<td>13.45</td>
<td>68.77</td>
</tr>
<tr>
<td>30%</td>
<td>59.27</td>
<td>15.47</td>
<td>65.92</td>
</tr>
<tr>
<td>50%</td>
<td>50.83</td>
<td>22.11</td>
<td>56.53</td>
</tr>
<tr>
<td>6.5%PCE 25%</td>
<td>191.39</td>
<td>41.63</td>
<td>212.87</td>
</tr>
<tr>
<td>30%</td>
<td>183.45</td>
<td>47.88</td>
<td>204.03</td>
</tr>
<tr>
<td>50%</td>
<td>157.33</td>
<td>68.44</td>
<td>174.98</td>
</tr>
<tr>
<td>8%PCE 25%</td>
<td>235.56</td>
<td>51.23</td>
<td>261.99</td>
</tr>
<tr>
<td>30%</td>
<td>225.78</td>
<td>58.93</td>
<td>251.11</td>
</tr>
<tr>
<td>50%</td>
<td>242.04</td>
<td>105.29</td>
<td>215.36</td>
</tr>
<tr>
<td>10%PCE 25%</td>
<td>294.45</td>
<td>64.04</td>
<td>327.49</td>
</tr>
<tr>
<td>30%</td>
<td>282.23</td>
<td>73.66</td>
<td>313.89</td>
</tr>
<tr>
<td>50%</td>
<td>242.04</td>
<td>105.29</td>
<td>269.19</td>
</tr>
</tbody>
</table>
Appendix D: Land requirement to fulfil demand-varying oil content and 6.5% PCE compared to 2.5% PCE

**Area required to Produce 2012 Demand for Pilbara Biodiesel in Pilbara/Geraldton (km²)**
* Based on 100% conversion to biodiesel and satisfying 100% demand

<table>
<thead>
<tr>
<th>Land Requirement based on 6.5%PCE Scenario km²</th>
<th>Geraldton</th>
<th>Port Hedland</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>458.32</td>
<td>412.08</td>
</tr>
<tr>
<td>30%</td>
<td>398.47</td>
<td>358.27</td>
</tr>
<tr>
<td>50%</td>
<td>278.78</td>
<td>250.66</td>
</tr>
<tr>
<td>Base Case Scenario 2.1% PCE/30% O</td>
<td>1233.36</td>
<td>1108.95</td>
</tr>
</tbody>
</table>

Appendix E: Theoretical productivity from each location and resource requirements

<table>
<thead>
<tr>
<th>Pilbara Ha Available</th>
<th>Source</th>
<th>Potential Supply</th>
<th>2012 Fuel Req</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt Hedland</td>
<td>871.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production (ML.Y⁻¹)</td>
<td>12.39</td>
<td>12289.07</td>
<td>0.64%</td>
</tr>
<tr>
<td>CO₂ Req’t (Mt.CO₂_e Y⁻¹)</td>
<td>22.49</td>
<td>Alinta: 44978 t/Yr</td>
<td>22489.00</td>
</tr>
<tr>
<td>Water Requirement (GL.Y⁻¹)</td>
<td>3.90</td>
<td>Ocean</td>
<td></td>
</tr>
<tr>
<td>Nitrogen (NaNO₃) (Mt.Y⁻¹)</td>
<td>29.68</td>
<td>Proposed 5th Hedland WWTP 10ML/day *</td>
<td></td>
</tr>
<tr>
<td>Phosphorus (NaHPO₄) (ML.Y⁻¹)</td>
<td>1152.69</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Onslow Ha Available</th>
<th>Source</th>
<th>Production (ML.Y⁻¹)</th>
<th>CO₂ Req’t (Mt.CO₂_e Y⁻¹)</th>
<th>Water Requirement (GL.Y⁻¹)</th>
<th>Nitrogen (NaNO₃) (Mt.Y⁻¹)</th>
<th>Phosphorus (NaHPO₄) (ML.Y⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>10000.60</td>
<td>172.04</td>
<td>314.84</td>
<td>54.60</td>
<td>333.89</td>
<td>13.23</td>
</tr>
<tr>
<td>Wheatstone</td>
<td></td>
<td></td>
<td>15 MTPA CO₂</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Karratha Ha Available</th>
<th>Source</th>
<th>Production (ML.Y⁻¹)</th>
<th>CO₂ Req’t (T.CO₂_e Y⁻¹)</th>
<th>Water Requirement (GL.Y⁻¹)</th>
<th>Nitrogen (NaNO₃) (Mt.Y⁻¹)</th>
<th>Phosphorus (NaHPO₄) (T.Y⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9406.00</td>
<td></td>
<td>161.82</td>
<td>296.4</td>
<td>51.60</td>
<td>314.06</td>
<td>12.40</td>
</tr>
<tr>
<td>* Burrup</td>
<td></td>
<td></td>
<td>766,369 Metric tonnes CO2-e (2008)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proposed Karratha WWTP 10ML/day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Area Req to Produce Est. Biodiesel Demand for Geraldton/Mid-West from local Production (km²)**

<table>
<thead>
<tr>
<th>Fuel Required (ML.Y⁻¹)</th>
<th>215.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>km²</td>
<td>139.21</td>
</tr>
<tr>
<td><strong>Hectares</strong></td>
<td>13921.48</td>
</tr>
<tr>
<td>CO₂ Req’t (Mt.CO₂_e Y⁻¹)</td>
<td>394.095</td>
</tr>
<tr>
<td>Water Requirement (GL.Y⁻¹)</td>
<td>68</td>
</tr>
<tr>
<td>Nitrogen (NaNO₃) (Mt.Y⁻¹)</td>
<td>365.52133</td>
</tr>
<tr>
<td>Phosphorus (NaHPO₄) (ML.Y⁻¹)</td>
<td>14.48423</td>
</tr>
</tbody>
</table>

** based on 60Mt/yr 2.1% PCE and 30% Oil with 100% conversion to biodiesel and supplying 100% demand
Appendix F: Land Requirements to fulfil fuel demand at each location based on oil content and PCE

<table>
<thead>
<tr>
<th>Location</th>
<th>Fuel (L 10^3$/Y^{-1}$)</th>
<th>25%</th>
<th>30%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pilbara</strong></td>
<td>1908000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>127557.66</td>
<td>110901.60</td>
<td>77589.48</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>41210.94</td>
<td>35829.75</td>
<td>35829.75</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>33483.89</td>
<td>29111.67</td>
<td>20367.24</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>26787.11</td>
<td>23289.34</td>
<td>16293.79</td>
<td></td>
</tr>
<tr>
<td><strong>Geraldton/Mid-West</strong></td>
<td>215350</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>16012.31</td>
<td>13921.48</td>
<td>9739.81</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>5173.21</td>
<td>4497.71</td>
<td>3146.71</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>4203.23</td>
<td>3654.39</td>
<td>2045.36</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3362.59</td>
<td>2923.51</td>
<td>2045.36</td>
<td></td>
</tr>
<tr>
<td><strong>Marandoo</strong></td>
<td>54000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>3610.12</td>
<td>3138.72</td>
<td>2195.93</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>1166.35</td>
<td>1014.05</td>
<td>709.45</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>947.66</td>
<td>823.92</td>
<td>576.43</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>758.13</td>
<td>659.13</td>
<td>461.15</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix G: Nutrient requirements for each location based on 2.1% PCE and 30% oil

<table>
<thead>
<tr>
<th>Redfield ratio $C_{106}N_{16}P_1$</th>
<th>Port Hedland</th>
<th>Onslow</th>
<th>Karratha</th>
<th>Geraldton</th>
<th>Marandoo</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{NaNO}_3$ Required (T.10^{3}.Y^{-1})</td>
<td>26.29</td>
<td>301.87</td>
<td>283.94</td>
<td>420.25</td>
<td>41.83</td>
</tr>
<tr>
<td>$\text{NaHPO}_4$ Required (T.10^{3}.Y^{-1})</td>
<td>1.04</td>
<td>11.96</td>
<td>11.25</td>
<td>16.65</td>
<td>1.66</td>
</tr>
<tr>
<td>Nitrogen ($\text{NaNO}_3$) (T.Y^{-1})</td>
<td>4333.14</td>
<td>49748.98</td>
<td>46793.89</td>
<td>69257.93</td>
<td>6893.66</td>
</tr>
<tr>
<td>Phosphorus ($\text{NaHPO}_4$) (T.Y^{-1})</td>
<td>270.82</td>
<td>3109.31</td>
<td>2924.62</td>
<td>4328.62</td>
<td>430.85</td>
</tr>
<tr>
<td>Ratio of N:C</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio of P:C</td>
<td>0.01</td>
<td></td>
<td></td>
<td><strong>Assume 50% Carbon in Biomass</strong></td>
<td></td>
</tr>
</tbody>
</table>