ON FARM BIO-CNG: DESIGN AND FEASIBILITY

The Systematic Design of Sustainable Bio-Compressed Natural Gas Energy Systems for use within the Wheat Farming Industry

By Michael Lange

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Submitted: 13\textsuperscript{th} November 2015
Declaration

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..............................................................
Michael Lange
Abstract

Demand for energy for transport and electricity has increased dramatically throughout the world and represents a significant financial and environmental burden to rural businesses in Australia. Currently, there are no viable replacements for diesel fuel in the form of conventional biofuels and with the substantial rise in oil price since 2002 the investigation of alternative fuel sources is high on both national and international agendas. Third generation ‘advanced’ biofuels derived from microalgae have the potential to sustainably replace fossil fuels by utilising non-arable land allowing it to co-exist with terrestrial food crops.

This document details the design and feasibility assessment of two different sustainable energy systems, which are then applied to a sample case representing a typical wheat farm in Western Australia. The objectives of such a system are to firstly, provide a sustainable energy solution, and secondly, reduce the delivery cost when compared to conventional diesel fuels. An exhaustive review of available technologies is conducted to determine the system that has the highest potential for viability based on the available resources.

The current annual energy consumption requirements are 286,957 kWh, which is satisfied using diesel fuel at an annual energy cost of $63,130. The calculated energy costs to deliver the two options from an operational level were $331,196 and $228,014 respectively. While it was determined that the biogas system was possible, it does not meet the second objective and is therefore not a practical alternative to diesel fuels in the current economic climate.

Several situations are considered under which this assessment may change in the future, such as an increase in the price or reduction in availability of diesel fuel, or improvements in the way biogas is produced.
Acknowledgements

I would like to thank my academic supervisors, Professor Parisa Bahri and Dr Karne de Boer for providing me with the opportunity to conduct this thesis project. I am greatly appreciative of the guidance and advance they afforded me throughout the completion of this project.

My sincerest thanks go out to my family and friends and in particular my partner Jordon Scale. This project marks the end point of a four-year journey, which without their support and encouragement would not have been possible.
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<th>Abbreviation</th>
<th>Full Form</th>
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</thead>
<tbody>
<tr>
<td>AD</td>
<td>Anaerobic Digestion</td>
</tr>
<tr>
<td>ARENA</td>
<td>Australian Renewable Energy Association</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CSTR</td>
<td>Continuously Stirred Tank Reactor</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gases</td>
</tr>
<tr>
<td>PPMV</td>
<td>Parts Per Million by Volume</td>
</tr>
</tbody>
</table>
1.0 Introduction

Demand for energy for transport and electricity has increased dramatically throughout the world and represents a significant financial and environmental burden to rural businesses in Australia (Department of Industry, 14). Currently, there are no viable replacements for diesel fuel in the form of conventional biofuels and with the substantial rise in oil price since 2002 (CSIRO, 13), the investigation of alternative fuel sources is high on both national and international agendas.

This project will investigate a new source of unconventional biofuel derived from microalgae and determine its feasibility for use as the primary source of energy in grain farming. Microalgae can be grown and harvested directly on these farms in saline water (Nuffield Bioethics), thereby providing functionality to salt affected patches of land which are unsuitable for growing crops and can then be combined with farm waste products such as excess straw, chaff and waste grains to produce biogas (Nuffield Bioethics, 15). Biogas, unlike diesel, is a renewable and sustainable energy source, which imposes a much smaller carbon footprint (CSIRO, 13).

The first purpose of the project presented in this report is to determine whether a renewable energy system based upon biogas derived from microalgae could suitably replace or supplement existing energy systems, typically based upon diesel, in rural businesses in Western Australia with particular respect to the Wheat Farming Industry. A suitable sustainable energy system is defined as one, which has the ability to replenish or retain key characteristics, resources or inputs over time (Cutcher-Gershenfeld, 2004) with negligible detriment to environmental and economic impact. This section of the report will consider both the feasibility and practicality of the sustainable energy system including the amount of energy that can be generated and the cost at which this energy is generated and will determine whether the expected return warrants further consideration of the concept with pilot plant testing.
The second purpose of the project is to consider the implications that the implementation of such a system would have, including the impact on fuel security, benefits to climate change and the reduction of carbon emissions, as well as land, water and health benefits.

The aim of this project is to ultimately determine feasibility and practicality of the concept, or consider the circumstances under which it would be viable.

Three main sections comprise the report. Firstly, the report will look at existing technologies that are available for the conversion of microalgae to usable fuel in the form of biogas, and existing examples from around the world of progress in this field. Secondly, the report will examine how a sustainable energy system may be implemented to a typical rural business in Western Australia, concerned with fuel consumption, required technologies and the implications of such systems. Lastly, the report will analyse the applied methodology, providing recommendations and speculating on possible changes and key influencers to the viability of renewable energy systems in Western Australia.
2.1 Background
In 2008, the annual world primary energy consumption was estimated to be 11,295 million tonnes of oil equivalent according to the BP Energy Statistics Review (BP, 2015), with fossil fuels accounting for over 88% of all primary energy consumption (Oil – 35%, Coal – 29%, Natural Gas – 24%), and nuclear energy and hydroelectricity accounting for just 5% and 6% respectively. Existing energy systems remain the clear preference due to affordability however there are growing concerns over their continued use and the potential threat of global climate change as a result of the greenhouse gas emissions that they cause (CSIRO, 13).

Fossil fuels are the most significant contributor of greenhouse gasses, with total greenhouse gas emissions of 29 gigatonnes coming as a direct result of fossil fuel consumption in 2006. Further to this, it is estimated that an approximate 12 gigatonnes is removed from the biosphere through natural processes each year, resulting in a significant burden to our atmosphere, and several strategies are required in order to neutralise the excess CO$_2$ (Brennan & Owende, 2009).

These strategies include but are not limited to, decreasing the amount of energy required per unit of product or process, increasing the use of clean fossil energy such as blends and fossil fuels coupled with CO$_2$ separation from fuel gases and injection into underground reservoir for gradual release, increasing the use of renewable energies, and the development of CO$_2$-neutral energy resources (Parson and Keith, 1998).

2.2 Development of Biofuels
In order to achieve these goals of mitigating GHG emissions and improving fuel security, the use of liquid biofuels has seen rapid growth in the transport sector in recent years (Schenk, et al., 2008). First generation biofuels, which are defined as being made from the sugars and vegetable oils found
in arable crops such as corn, wheat and sugarcane (Gokianluy, A.;, 2014) have shown to be commercially viable using conventional technology, but are limited in their ability to meet total energy demands due to competition with food and fibre production in their use of arable land, high water and fertiliser requirements and a need for conservation of bio-diversity (Brennan & Owende, 2009).

Currently, around 14 million hectares or 1% of total worldwide arable land is used for the growth of first generation biofuels and accounts for just 1% of the global transport fuels consumption with the U.S. already appropriating 30% of its corn supply to offset approximately 6% of its gasoline consumption (Drevense, 2011), meaning that any increase in this share to sustainable levels would have significant ramifications to the world’s food supply (CSIRO, 13).

Second-generation biofuels otherwise referred to as advanced biofuels, are fuels that can be manufactured from various types of waste biomass products such as woody crops, agricultural residues and wastes. The advantage of second-generation biofuels compared with first-generation biofuels is that they utilise residual non-food parts of existing crops (e.g. stems, leaves and husks) or non-food crops (e.g. grass and flowers), or industry waste (e.g. woodchips, skins and pulp) from fruit processing (Gokianluy, 2014), meaning that there is no competition for the use of arable land and essentially zero feedstock cost.

The disadvantage of second-generation biofuels is that the processes required to extract usable biomass are much more difficult and expensive by comparison and have been shown to be not commercially viable using current technologies. Further to this, the liquid products that are produced fall short of typical fuel and biofuel standards and require one or more chemical processes to improve their fuel properties to usable levels (Gokianluy, A.; 2014).
2.3 Development of Microalgae as a Feed Stock for Advanced Biofuels

In recent years, the role of microalgae as a feedstock for a third-generation of biofuels has been of great interest in the pursuit of sustainability. Algae are organisms that grow in aquatic environments and combine light with carbon dioxide to produce biomass. There are two different classifications of algae: macroalgae and microalgae. Microalgae refers to all unicellular and simple multi-cellular microorganisms, including prokaryotic microalgae such as cyanobacteria (Chloroxybacteria) and eukaryotic microalgae such as typical green and red algae (Chlorophyta and Rhodophyta) and is typically measured in micrometres.

Algal-biofuel research originated in 1979 through an initiative by the United States Department of Energy called the Aquatic Species Program. Running through to 1995 before closing due to budget reduction, the 16-year project pursued research in three main areas.

The first area involved the study of the biological aspect of microalgae. Algal species were collected and screened to determine their potential for high oil production, with further investigation of their potential for use of molecular-biology techniques and genetic engineering to enhance oil yield.

The second area involved the development of mass production systems. While initial laboratory scale tests proved promising, there were significant challenges in replicating the same levels of algal-oil production reliably in full-scale outdoor systems.

The third area involved the analysis of resource availability, such as land, water and carbon dioxide. The research concluded that there availability was more than sufficient to pursue microalgae as an
alternative to classic fuel sources, but concluded that production at the time was too expensive, citing three limiting factors toward commercialization: difficulty of maintaining desirable species in the culture system, low yield of algal oil and the high cost of harvesting the algal biomass.

The potential use of microalgae as a source of biomass for third-generation biofuels has a number of advantages when compared to first and second-generation biomass sources. These advantages, in addition to a number of other benefits are detailed below:

1. Microalgae are capable of year round production, making them extremely reliable and significantly increasing amount of biofuel that can be produced per hectare of land (biofuel yield rate), even when compared to the best oilseed crops. For example, microalgae are capable of producing upwards of 12,000 litres of biodiesel per hectare per year, compared with rapeseed, which yields just 1200 litres of biodiesel per hectare per year (Chisti, 2007).

2. Microalgae are grown in aqueous media but require less water than typical crops, reducing load on freshwater resources when compared with first and second-generation biofuels (Chisti, 2007).

3. Microalgae can be cultivated in saline-water on non-arable land, minimising competition with food crops and associated environmental impacts (Brennan & Owende, 2009). Non-arable land, including land which lacks sufficient fresh water for irrigation, has poor drainage or is excessively saline makes up over 59% of all pasture and non-forested rangeland in the United States in 2013 (NRCS, 2013) providing significant expansion potential for current world wide biofuel efforts. Microalgae have a rapid and exponential growth rate, doubling their biomass in periods as short as 3.5 hours during peak growth periods with an oil content in the range of 20-50% dry weight of biomass (Brennan & Owende, 2009). Typical microalgae cultures have a harvesting cycle of 5-15 days and can produce as much as 18 tonnes (See in Table 1) (Brennan and Owende, 2009) of algal biomass per hectare per year (Schenk, et al., 2008). By comparison, terrestrial crops take a season to grow and contain a mere maximum of approximately 5% of dry weight of oil (Chisti, 2007).
Table 1: Oil yields based on crop type (Chisti, 2007)

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Oil Yield (L/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>34.84</td>
</tr>
<tr>
<td>Soybeans</td>
<td>92.90</td>
</tr>
<tr>
<td>Canola</td>
<td>245.80</td>
</tr>
<tr>
<td>Jatropha</td>
<td>390.95</td>
</tr>
<tr>
<td>Coconut</td>
<td>555.46</td>
</tr>
<tr>
<td>Palm Oil</td>
<td>1230.91</td>
</tr>
<tr>
<td>Microalgae*</td>
<td>39180.62-97951.55</td>
</tr>
</tbody>
</table>

*Based on lipid content range from 20% to 50%.

4. Microalgae are capable of passively removing approximately 1.83kg of waste CO2 from the atmosphere for every 1kg of dry algal biomass equivalent, improving air quality (Brennan & Owende, 2009).

5. The nutrients which are required for the growth of microalgae, particularly nitrogen and phosphorus can be obtained directly from wastewater, serving the dual purpose of providing the growth medium and treatment of organic effluent from the agri-food industry (Brennan & Owende, 2009).

6. Microalgal polycultures are very hardy and capable of protecting themselves from illness and disease, eliminating the need for pesticide and herbicide application (Brennan & Owende, 2009).

7. Microalgae oil extraction has the added benefit of producing a number of bi-products including proteins and excess biomass which may be used as feed or fertilizer for crops, or fermented to produce other forms of biofuels such as bioethanol and biomethane (Brennan & Owende, 2009).

8. The biochemical composition is sensitive to growth conditions, allowing for significant enhancement of oil yield according to environment modulation (Brennan & Owende, 2009).

9. Microalgae are capable of photobiological production of biohydrogen, which can be used as transport fuel in liquid-hydrogen combustion engines.
Despite the detailed benefit to biofuel production and other associated benefits, significant challenges still stand in the path to development of algal biofuel technology and commercial viability that would allow for sustainable production and utilisation. These challenges include but are not limited to:

1. The potential for negative energy balance after consideration of requirements for water pumping, CO2 transfer, harvesting and extraction.

2. Low photosynthetic conversion values meaning that to achieve sufficient lipid yield rates, polycultures or expensive heterotrophic strains of microalgae must be used.

3. Significant lack of data available for large-scale production due to cost limitations and reliance upon cheap diesel fuels.
2.4 Microalgal Biofuel Production
The production of biofuels such as biogas and biodiesel from microalgae occurs in three main stages: cultivation and harvesting, conversion and consumption.

2.3.1 Cultivation and Harvesting
Cultivation and harvesting involves the selection of a suitable microalgal culture, growth and collection of the microalgae.

Most microalgae are photoautotrophic organisms, meaning they are capable of synthesising their own food from inorganic substances using light as an energy source. More specifically, most microalgae, as green plants can anabolically convert carbon dioxide into organic material by utilising the process of photosynthesis (Brennan & Owende, 2009). This type of microalgal culture depend on constant and reliable supply of light, which can be supplied at no cost directly by the sun, however can be a limiting factor in locations where solar radiation is high (NRCS, 2013).

Where sufficient light energy is not available, the limitation of natural growth conditions can be addressed by supplementing sunlight with artificial means with fluorescent lamps. Artificial lighting allows for continuous uninterrupted production, but requires a significantly greater energy contribution, which is typically be supplied by electrical power derived from fossil fuels, thereby being both counterproductive to efforts to provide sustainable energy and reducing price competitiveness.

Microalgae under normal growth conditions obtain their carbon primarily from carbon dioxide in the atmosphere, but are also capable of drawing from discharge gasses from industry waste streams and from soluble carbonates (Brennan & Owende, 2009) if and where available. Air typically contains 360
ppmv (parts per million by volume) CO2, however most microalgae are capable of utilising substantially higher levels of CO2, and up to 150,000 ppmv, and therefore carbon dioxide will typically fed to the growth media from external sources such as power plants or soluble carbonate such as Na2CO3 (Sodium Carbonate) and NaHCO3 (Sodium Bicarbonate).

In addition to light for energy and carbon dioxide for carbon, microalgae require other inorganic nutrients for production, including nitrogen and phosphorous and in the case of certain species of microalgal diatoms, silicon. While certain species are able to obtain small amounts of nitrogen from nitrous oxide in the atmosphere, the majority of the nitrogen and phosphorus required can be obtained from wastewater fed directly to the growth media.

Certain cultures of microalgae known as heterotrophs are capable of growing in darkness by using organic carbons such as glucose and acetate as energy and carbon sources. This method of growth, termed heterotrophic, requires the addition of organic matter and is independent of light energy, allowing for simpler systems, albeit at a financial cost. Heterotrophic microalgae strains have typically higher cell densities, allowing for more compact systems and can produce as much as four times the lipid content of autotrophic strains under similar conditions (Miao X, 2005).

A third type of microalgae culture, known as mixotrophs are capable of using either metabolic process (autotrophic or heterotrophic) for growth meaning they are able to both carry out photosynthesis and ingest organic matter. These types of microalgae have the obvious benefit in that they are able to source their energy from sunlight at no cost but are not limited by it. Examples of mixotrophic microalgae include Chlamydomonas and the well-known Spirulina platensis (Brennan & Owende, 2009). Cell densities of mixotrophic microalgae are similar to that of photosynthetic microalgae, but considerably lower than that of heterotrophic microalgae.
**Microalgae Cultivation Systems**

There are two different methods commonly used for the cultivation of microalgae, open ponds and closed photobioreactors.

Open ponds are the simplest system for the mass cultivation of microalgae and have been used readily since the 1950’s. In this system, microalgae are grown in a shallow pond approximately 0.2 to 0.5m deep and cultures under conditions, which closely mimic that of their natural environment. Ponds are typically designed in a ‘raceway’ configuration, shown below in Figure 1, in which a paddle wheel circulates the algal cells and nutrients within the growth media in order to stabilise algal growth and productivity, and prevent sedimentation.

![Figure 1: Algae Raceway Pond Design](image)

The open ponds are usually made from poured concrete or in its simplest form, can simply be dug in to the ground and lined with plastic sheeting (Chisti, 2007). Baffles in the channel assist with circulation by guiding the flow around bends in order to minimise area. Open ponds are generally operated in a continuous mode, with fresh feed (nitrogen and phosphorous) introduced to the
growth media in after the paddle wheel, and wet algal biomass harvested from behind the paddle wheel after it has circulated through the loop.

The greatest advantage of open pond systems is that they can be constructed in areas with a low crop potential and therefore do not compete with terrestrial crops. In addition, they are the cheapest method for large-scale biomass production as a result of cheap capital setup costs and ease of maintenance and cleaning reducing operational expenses.

Although open ponds are simple in design and have a lower capital and operational cost than closed photobioreactors, this cultivation system has a number of disadvantages. As open ponds are, as the name suggests, open-air systems they lose a lot of water due to evaporation, limiting the ability of the microalgae to use carbon dioxide as efficiently and reducing the rate of biomass production (Chisti, 2007). In addition, being an open-air systems also allow for contamination with unwanted algal species as well as organisms which feed on algae. Lastly, optimum culture conditions can be difficult to maintain and recovering the biomass from such a dilute culture can be an expensive exercise (Chisti, 2007).

Enclosed photobioreactors were developed to combat the issue of contamination and evaporation experienced in open pond systems (Molina Grima, Belarby, Acien Fernandez, Robles Medina, & Chisti, 2002). They are made of transparent materials and designed to maximise surface area to volume ratio in order to absorb the greatest amount of light.
The most commonly used photobioreactor design is the tubular photobioreactor, which has a series of transparent tubes that are characteristically between 5 and 10 centimetres in diameter and aligned in order to maximise sunlight penetration as shown below, Figure 2.

![Figure 2: Tubular Photobioreactor (Wikipedia Commons)](image)

The media is circulated by a pump through the reactor tubes where it is exposed to light for photosynthesis, and returned to a mixing tank where nutrients such as carbon dioxide, nitrogen and phosphorous are introduced. A percentage of the biomass is extracted from each cycle allowing for continuous operation.

Two other commonly used photobioreactor designs are the flat plate and column photobioreactor designs that operate under similar principles as the tubular photobioreactor with a few notable differences:

1. Tubular photobioreactors are deemed to be the most suitable design for outdoor cultures as they expose a larger surface area to sunlight but have design limitations, which determine total length of the tubes as a product of oxygen accumulation and carbon dioxide depletion.
2. Flat Plate photobioreactors have the greatest surface area to volume ratio and are capable of producing the highest density of photoautotrophic cells per litre.

3. Column photobioreactors are the most controllable growth conditions as a result of efficient mixing conditions and highest mass transfer rates (Brennan & Owende, 2009).

By comparison, although enclosed photobioreactors will remedy many the challenges of open-air systems such as contamination and evaporation they have their own set of limitations. Principally, enclosed photobioreactors are very difficult to scale up in production size, attachment of microalgae cells to the tube walls can prevent light penetration, reducing productivity, fouling can occur and they can be substantially more expensive to implement.

A summary of the advantages and limitations for each cultivation system is outlined below, Table 2.

<table>
<thead>
<tr>
<th>Production System</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Pond</td>
<td>Relatively cheap</td>
<td>Poor biomass productivity</td>
</tr>
<tr>
<td></td>
<td>Easy to clean</td>
<td>Large Area of land required</td>
</tr>
<tr>
<td></td>
<td>Utilised non-arable land</td>
<td>Limited to certain strains of algae</td>
</tr>
<tr>
<td></td>
<td>Low energy requirements</td>
<td>Poor mixing, light and CO2 utilisation</td>
</tr>
<tr>
<td></td>
<td>Easy maintenance</td>
<td>Contamination of cultures</td>
</tr>
<tr>
<td>Tubular Photobioreactor</td>
<td>Large illumination surface area</td>
<td>Wall Growth</td>
</tr>
<tr>
<td></td>
<td>Suitable for outdoor cultures</td>
<td>Fouling</td>
</tr>
<tr>
<td></td>
<td>Relatively cheap</td>
<td>Requires large amount of land</td>
</tr>
<tr>
<td></td>
<td>Good biomass productivity</td>
<td>Dissolved oxygen and CO2 along tubes</td>
</tr>
<tr>
<td>Flat Plate Photobioreactor</td>
<td>High biomass productivity</td>
<td>Difficult to scale-up</td>
</tr>
<tr>
<td></td>
<td>Easy to sterilise</td>
<td>Difficult to control temperature</td>
</tr>
<tr>
<td></td>
<td>Low oxygen build-up</td>
<td>Small degree of hydrodynamic stress</td>
</tr>
<tr>
<td></td>
<td>Readily tempered</td>
<td>Wall Growth</td>
</tr>
<tr>
<td></td>
<td>Good light path</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large illumination surface area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suitable for outdoor cultures</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Advantages and Limitations of Algae Cultivation Systems. Adapted from Brennan and Owende et al.
**Column Photobioreactor**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Very compact</td>
<td></td>
</tr>
<tr>
<td>High mass transfer</td>
<td></td>
</tr>
<tr>
<td>Low energy consumption</td>
<td></td>
</tr>
<tr>
<td>Good mixing with low shear stress</td>
<td></td>
</tr>
<tr>
<td>Easy to sterilise</td>
<td></td>
</tr>
<tr>
<td>Reduced photoinhibition and photo-oxidation</td>
<td></td>
</tr>
<tr>
<td>Small illumination area</td>
<td></td>
</tr>
<tr>
<td>Very expensive</td>
<td></td>
</tr>
<tr>
<td>Shear stress</td>
<td></td>
</tr>
<tr>
<td>Sophisticated construction</td>
<td></td>
</tr>
</tbody>
</table>

**Microalgae Recovery Methods**

Recovery involves the extraction of raw algal biomass from the open-pond or photobioreactor. Choice of recovery technique depends on both the cultivation method and also the characteristics of the algae, such as size and density. Recovery of algal biomass occurs in two stages: bulk harvesting and thickening and dehydration.

Bulk harvesting aims to separate the biomass from the suspension to concentration levels around 2-7%. The most commonly used harvesting method is through gravity or centrifugal sedimentation. The method of gravity and centrifugal sedimentation is based upon Stokes’ Law (Shelef, Sukenik, & Green, 1984), whereby the rate at which a very small particle, such as that of microalgae, sinks through the viscous growth media is proportional to that of the difference between cell and medium density. Centrifugation is estimated to cost approximately $2.40/kg, requiring an additional energy input of 3 kJ m⁻² day⁻¹.

Where $F_d$ is the frictional force, known as Stokes’ drag, acting on the interface between the fluid and the particle, $\mu$ is the dynamic viscosity, $R$ is the radius of the spherical object and $V$ is the flow velocity relative to the object.
Other harvesting methods include flotation and filtration.

Flotation involves the collection of microalgae from the surface of the growth media. This method of recovery requires that the strain of algae is capable of floating naturally or will demand the assistance of chemicals to facilitate the process.

Filtration involves the recovery of microalgae cells using a membrane and pressure or suction. This method of separation is most suitable for larger strains of microalgae such as Coelastrum and Spirulina, which are larger than 70 micrometres, and cannot be used for algae strains that are smaller than 30 micrometres in size. Filtration is the most effective method for the concentration of microalgae, and has been demonstrated to produce sludge with 27% solids (Schenk, et al., 2008).

Flocculation is a method that can be used to improve the efficiency of all three recovery methods. Flocculation refers to the chemical process by which very small particles are caused to clump together to form a ‘floc’, thereby increasing the aggregate size of the microalgae particles and increasing effectiveness of other harvesting methods such as flotation, where the floc rises to the surface of the media, sedimentation where the floc settles on the bottom of the media, or simply assisting with filtration from the media. As microalgae cells carry a negative charge, natural aggregation of cells cannot occur without the addition of a flocculating agent such as multivalent cations and cationic polymers to neutralise the negative charge. Classic agents include metallic salts such as ferric chloride, ferric sulphate and aluminium sulphate (Chisti, 2007). Harvesting by flocculation requires an additional 0.5kJ m$^{-2}$ day$^{-1}$ and costs roughly $1.95 per kg algal biomass, although the flocculating agent provides the majority of this expense.
Selection of harvesting technique is an important factor to consider with respect to economic viability as certain algae species are much easier to harvest such as Spirulina, which has a long spiral shape, which can easily be extracted by way of micro-harvesting screen. An estimate of 20-30% of the total cost of production can be attributed to recovery, with the processes involved being highly energy intensive and the difficulty of extracting low cell densities and cells in the size range of as low as 2 micrometres.

Once recovered, the biomass slurry will have a concentration anywhere between 5% and 25% depending on the culture and recovery method and will need to be processed immediately. As microalgae is perishable, it is typically dried using a method such as spray drying or freeze drying to extend the period of viability.

The most common form of dehydration is sun drying as it does not incur any further energy expense, however requires a large surface area in order to dehydrate the algae in a sufficient time frame. Spray drying is an alternative that is used for the extraction of high value strains, but is comparatively expensive and can result in significant deterioration of some algal pigments (Brennan & Owende, 2009). Similarly, freeze-drying is also expensive, with costs increasing exponentially as the scale of operation increases but assists with the extraction of oils from the biomass.

### 2.3.2 Conversion Technologies
A wide range of viable technologies exist for the conversion of raw biomass to functional biofuel and energy. From thermochemical conversion methods such as gasification, pyrolysis and direct combustion to biochemical conversion methods such as anaerobic digestion and alcoholic fermentation, the choice of conversion process will depend on factors including but not limited to:
type and quantity of biomass and the desired form of energy, as well as project specific considerations such as availability and cost.

As the emphasis of this project is the generation of Biogas derived from methane, this section will focus on the three main conversion methods used: anaerobic digestion, pyrolysis and gasification.

**Anaerobic Digestion**

Anaerobic Digestion involves the conversion of organic wastes into a biogas comprised primarily of methane (CH4, 60-70%) and carbon dioxide (CO2, 30-40%) (Brennan & Owende, 2009) with traces of nitrogen, hydrogen, ammonia and oxygen also present. The anaerobic digestion process is most appropriate for organic wastes with a high moisture content (80-90% moisture), making it ideal for use with wet algal biomass. It is widely considered to be the most straightforward method of biochemical conversion for producing biogas from microalgae.

Methane is the main combustible constituent of biogas and can be readily burned with air or oxygen to produce water, carbon dioxide and energy as shown in the equation below, from (Cheng, 2010):

\[ CH_4 + 2O_2 \rightarrow 2H_2O + 803 \text{ kJ/mol} \]

Since the biogas is principally methane, it can be used in much the same way as conventional natural gas for use in cooking, electricity and heat generation and even in transport fuels.
The most typical form of commercially available reactors are Continuously Stirred Tank Reactors (CSTR) such as those found in wastewater treatment plants in combination with up-flow anaerobic sludge blanket (UASB) digesters. UASB’s are a sealed reactor vessel in which biomass enters through the bottom as an approximately 5% solids suspension which is percolated through granulated solids to produce biogas that is removed from the top.

Anaerobic digestion occurs in three stages: hydrolysis, fermentation and methanogenesis, shown below in Figure 3. In hydrolysis, the large complex compounds of organic matter including carbohydrates, proteins and lipids are ‘hydrolysed’ by anaerobic bacteria into smaller molecules such as soluble sugars, fatty acids, amino acids and peptides as well as trace levels of acetic acid, hydrogen and carbon dioxide (Orosz & Forney, 2008).

Fermentation is comprised by two sub-stages: acidogenesis and acetogenesis. Acidogenesis involves the fermentation of sugars, fatty acids, amino acids by anaerobic bacteria into volatile fatty acids (propionate, butyrate, etc.) (Chisti, 2007). During acidogenesis, small amounts of gasses containing hydrogen and carbon dioxide are also produced. In the second sub-stage, acetogenesis, the volatile fatty acids are then converted to acetic acid, hydrogen and carbon dioxide.
In the final stage of anaerobic digestion, methanogenesis involves the conversion of acetic acid and hydrogen to methane. The reaction of hydrogen with carbon dioxide results in the production of methane and water as shown in the first equation below, while the degradation of acetic acid leads to the production of methane and carbon dioxide as shown in the second equation below.

\[ 4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \]
\[ CH_4COOH \rightarrow CH_4CO_2 \]

The overall energy efficiency of anaerobic digestion of algae is approximately 60%, producing about 0.35kg of methane (CH4) per kilogram of biomass (Orosz & Forney, 2008). The cost of Anaerobic Digestion of algae varies greatly depending on feedstock, but typical yields are $2.66 per gigajoule or $0.42 per kilogram of biomass digested (Orosz & Forney, 2008). As microalgae typically has a low carbon-to-nitrogen ratio, yield rates can be improved with the addition of organic products with high carbon-to-nitrogen ratios to the digestion process such as waste paper, excess straw and chaff, thereby reducing this cost (Brennan & Owende, 2009).

**Gasification**

Gasification refers to the thermochemical process shown below, figure 4, and by which dehydrated biomass is partially oxidated to form a gas which is combustable at high temperatures (800-1000°C) (Orosz & Forney, 2008). The biomass is reacted with oxygen and water (steam) to generate ‘Syngas’ or Synthesis Gas (SNG), a fuel mixture containing hydrogen and carbon monoxide.
At equilibrium the efficiency of this reaction is ~91% due to the loss of some energy in the partial oxidation to CO. The equation for this reaction is shown in the equation below. It is estimated that algae biomass gasification is capable of producing a theoretical yield of 0.64g methanol from 1g of biomass.

\[ C_5H_8O_2 + 3H_2O \rightarrow 5CO + 7H_2 + 377.6 \text{kJ/mol} \]

Lastly, methane formation is necessary to distillate the methane concentration to high enough levels for use as biomethane.

**Pyrolysis**

The process of pyrolysis is similar to gasification with the exception that pyrolysis is performed in the absence of oxygen at lower temperatures (350-700°C) to produce bio-oil, Syngas and a combustible non aqueous phase liquid (NAPL), mainly pyrene. Pyrolysis has a theoretical equilibrium efficiency of 98%, with significantly lower energy consumption in processing than gasification, with the equation shown below, with typical yields of 60% CH4.
2.3.3 Biofuel Storage Requirements

Biogas will typically be stored for one of three reasons: for later use, when applications require variable power or when production is greater than consumption. The simplest and most cost-effective methods for the storage of biogas for on-farm, intermediate applications are low-pressure systems. Low-pressure systems are only suitable for the short-term storage of biogas, with capital costs varying considerably with respect to the duration for which the gas must be stored.

Short and intermediate storage options operate over a pressure range of 0-0.42 kPa and are typically suitable for storage of gasses for no longer than 1-2 days. Longer-term options include steel cylinders and tanks, which operate at pressures above 1,000 kPa. The per-kWh cost of storage is approximated as being between $0.030 and $0.069 (average $0.049) per day of storage.
2.4 Case Studies and Examples

As mentioned in section 1.0 Introduction and 2.0 Background, research into the viability of third generation advanced biofuels is high on national and international agendas with all parties involved very keen to achieve the collective goal of sustainability.

The Australian Renewable Energy Agency (ARENA) is a commercially oriented agency established on 1 July 2012 with the aim of improving competitiveness of renewable energy technologies, and increasing the supply of renewable energy in Australia. ARENA supports activities along the innovation chain from laboratory research to large-scale pre-commercial deployment activities by providing government legislated funding. Outlined below are three projects which have received funding in the past three years from ARENA.

2.4.1 Muradel Pty Ltd, Whyalla, SA, Australia

Muradel established a pilot plant in 2011 to produce algae for biofuel which had promising results. In their aim to advancing marine microalgae biofuel to commercialisation, they have been provided $4,398,000 in funding toward a total project value of $10,738,000 to advance their pilot plant to design and trial technology at demonstration scale.

In partnership with SQC Pty Ltd, Murdoch University and Adelaide Research and Innovation Pty Ltd, Murdael has evaluated an elite microalgae species that is high productive, tolerant to a wide salinity range which can be successfully propagated in outdoor environments such as low-cost raceway ponds. If successful, this project has wide reaching implications by delivering a viable solution that can be applied at commercial scale by offering a renewable fuel which is both energy efficient and economically attractive.
2.4.2 Licella Pty Ltd, Somersby, NSW, Australia

Licella Pty Ltd, in partnership with University of Sydney and Ignite Energy Resources Ltd, received $2,288,000 of a total project value of $3,038,000 to assist them with the design, construction and successful operation of a commercial demonstration facility for the conversion of inedible plant material into a bio-crude oil with similar characteristics to traditional crude oil from fossil fuels.

Commencing in December of 2009 and completing in June 2012, the project involved the testing of biomass such as radiate pine, banna grass and microalgae with their Catalytic Hydrothermal Reactor (Cat-HTR) process to produce bio-crude oil which can be blended with fossil crude oil and processed
through traditional refineries to deliver sustainable transportation fuels whilst using existing distribution infrastructure. The project was considered to be a success, paving the way for the next stage of commercialization.
3.1 Application to Western Australia
In order to achieve the primary objective of this report by determining the feasibility of implementing a sustainable energy system to a rural business in Western Australia with particular respect to the wheat farming industry, three key factors have been considered: the operation of the wheat farm, the method for determining suitability of a sustainable energy system, and the effect that a sustainable energy system will have on the wheat farm and it’s immediate area.

3.2 Wheat Production Cycle
The wheat production cycle refers to the annual process of growing wheat and is comprised by two main stages: Sowing and Harvesting. Intermediary stages such as irrigation and insecticide consume comparatively negligible levels of energy and are outside the scope of this report. Understanding the wheat harvesting process is essential to being able to model energy consumption requirements by identifying fuel usage per hectare of wheat and seasonal fluctuations in total energy demand.

3.2.1 Sowing
Sowing involves the preparation of land and sowing of seeds using a commercial tiller and planter, and typically occurs between late April and mid-June, depending on the presence of sufficient moisture. This process uses approximately 4.25 litres of diesel fuel (41.9 kWh) per hectare, based upon the operation of a ‘CaseIH Rowtrac 450’ planter working at a speed of 8.5km/h (Špokas & Steponavičius, 2009).

3.2.2 Harvesting
Harvesting involves the collection of fully-grown wheat and typically commences early to mid-October in Western Australia, with lower rainfall farms generally starting earlier than higher rainfall farms, however in a typical year most farms will be at peak harvest in mid to late November. Wheat is harvested and collected using a combine harvested such as the ‘Claas Lexicon 540C’ which uses approximately 20 litres of diesel fuel per hectare under standard operating conditions, but can be up to as much as 25 litres of diesel fuel per hectare when weather is poor according to the Department of Agricultural Machinery of Lithuanian University of Agriculture (Špokas and Steponavičius 2009).
3.2 Proposed Methodology

The proposed methodology has been designed with a focus on sustainability and based upon the four principles of sustainable energy as outlined by Kreith and Kreider (2011).

The first principle is to identify the fundamental desired outcome of the sustainable energy system. The primary purpose of any sustainable energy system is understandably to be capable of fulfilling the requirements of a given system in a sustainable manner. The term sustainable is multi-faceted and refers not only to the commonly discussed environmental sustainability issues such as greenhouse gas emissions, climate control and the use of renewable energy sources, but also engineering (technological), environmental and ethical sustainability. The ultimate goal of a sustainable energy system is to mimic the processes of nature whereby the system is capable of providing continuous supply of energy over many years without negative ethical, environmental or economic impact.

The second principle is to investigate the energy requirements of the system. The types of questions asked as part of this investigation include the amount of energy required, what the energy will be used for, and what opportunities exist to optimise energy consumption and efficiency processes. For existing energy systems, information can be readily obtained by way of energy audit that seeks to provide a detailed breakdown of key load requirements, total consumption of the system, seasonal trends and to identify the major consumers within the system. This process helps to identify the minimum specification for the sustainable energy system such as peak and average power output, and the corresponding resources, which will be required to carry it out.

The third principle involves an assessment of the available energy resources of the system. The assessment serves to determine what constraints and limitations the system will be subjected to by
factors including but not limited to climate, land availability and renewable resource goals. This principle is essentially an assessment of the feasibility of a given solution and seeks to eliminate systems identified as part of the first two processes which are impractical or prohibitive.

Lastly, the fourth principle involves the review of energy technologies that may be employed to utilise the energy resources identified in the previous assessment. A comparison of the many dynamics of a renewable system including but not limited to the type of energy used, the processes by which the energy is obtained and the way in which the energy is used by factors such as cost, technical requirements, security and availability. By utilising these four principles in combination, a final list of viable solutions allows for the identification of the most suitable strategy to achieve sustainability.
3.3 Implications of Biofuel Technologies

In addition to the overarching goal of achieving sustainable energy consumption, there are a number of co-benefits to the implementation of biofuel technologies in Australia.

1. Reduced greenhouse gas emissions from fossil fuels, reducing air pollution and preventing further climate change.

2. Diversification of energy supply and reduction of dependence on imported fuels.

3. Creation of local jobs in manufacturing, installation and other technical expect positions.
4.1 Application and Case Study Analysis

In order to address the project aim of determining the feasibility and practicality of a sustainable energy system based upon microalgae in Western Australia, the methodology outlined in section 3.2 can be applied to a sample case, which has been created, based upon statistical information for a typical wheat farm. In order to satisfy a project definition level of 10-15% to achieve the requirement for a study of concept or feasibility, the scope of the study case has been restricted to the contributing factors that have the greatest impact on the system.

4.2 Design Considerations

The principal outcome objective of designing a biogas system for the wheat farming industry in Western Australia is to both reduce energy costs, thereby improving profits and to also reduce the amount of greenhouse gas emissions produced.

The investigation of energy requirements of the system is based upon the principles of the wheat production cycle outlined in section 3.1 above. The wheat production cycle is comprised by two main processes, sowing and harvesting, which account for the majority of total annual fuel consumption. Intermediary steps including irrigation and insecticide treatment are negligible by comparison and beyond the scope of this report.

The farms location has been selected to fall in close proximity to the majority of Western Australian wheat farms in the ‘Wheat Belt’ in the South-West of Australia which is responsible for the growth of more than two-thirds of the states wheat production. The region has a total area of 154,862 square kilometres and is typically known for mild temperatures and relatively high rainfall highly suited to agriculture.
According to the Australian Bureau of Statistics (Australian Bureau of Statistics, 2012), the total annual wheat production of a standard wheat farm in Western Australia is 1,884 tonnes producing a profit of $156,637. Annual energy consumption for a typical farm, sowing and harvesting 1200 hectares of wheat is 286,957 kWh, with amounts of 50,291 kWh and 236,666 kWh utilised in late May and mid-November respectively. The current primary energy source for wheat farms is diesel fuel, which costs approximately $0.22 per kWh (Orosz & Forney, 2008) resulting in a total fuel cost of more than $63,000 per year. The dominant use of this energy is for use as a transport fuel in agricultural vehicles such as tractors.

Total percentage of non-arable land attributed to excessive saline levels is estimated as being 22.95% (Price Waterhouse Coopers, 2011), resulting in an additional 357 hectares of vacant land that does not compete with growth of wheat and is available to be utilised for energy production.
4.3 Energy System Analysis
Utilising the information contained within section 4.1 Design Considerations along with the proposed methodology outlined in section 3.2, a suitable energy system is designed to meet the requirements of the sample case. As the focus of this report is on the feasibility of a sustainable energy system based upon biogas, the scheme has been structured to support this.

Microalgae Species
The most suitable microalgae species for use in this energy system is a mixotrophic species, capable of processing both organic and inorganic carbons. This is due to the abundance of both forms of carbons and nutrients from wastewater and highly saline environment. Mixotrophic species of microalgae produce much higher lipid content biomass than phototrophic alternatives, without carrying the cost of heterotrophic microalgae, which are only able to process organic carbons and not absorb carbon dioxide straight from the atmosphere. Narrowing the selection down further, the species of Spirulina platensis is favoured for hardiness, ability to adapt to high alkaline environments and ease of collection as a result of being one of the larger kinds of microalgae. The addition of sugars to the growth media will increase the yield of mixotrophic microalgae.

Cultivation Method
The most suitable method of cultivation for use in this energy system is the open pond system. The open pond system requires very little by way of inputs is simple to operate and requires very little energy to be added. The location of the farm means that natural light conditions will allow for microalgae yields to exceed demand without expensive costs installing large photobioreactors.
**Recovery Method**
The most suitable method of recovery for use in this energy system is unassisted filtration. As a result of the selection of Spirulina platensis, one of the larger species of microalgae filtration becomes a cheap and effective option for bulk harvesting biomass.

**Conversion Method**
The proposed method for conversion of raw algal biomass to usable biogas is Anaerobic Digestion. This is the most suitable method as it does not require any additional treatment of algae such as dehydration, and can utilise excess farm streams such as straw, chaff and other wastes to boost production levels.

**Storage Analysis**
Storage represents a significant financial burden to sustainable energy systems, and so two different scenarios are considered in an attempt to reduce operating costs. The first solution involves the design of an energy system which uses the minimum specification required to produce the biofuel over the course of a year. Excess biogas will be stored between sowing and harvesting period, thereby minimising fixed capital costs.

The second solution involves the design of an energy system to minimise operational costs at the expense of increased fixed capital costs. This is a cost mitigation opportunity, whereby excess biofuel may be sold to other businesses, or converted to electricity for on-grid storage. The transport costs of biogas are estimated to be $0.55/kWh (Orosz & Forney, 2008).

The breakdown of the first solution and operating expenditure breakdown is shown below in Table 3 and Table 4.
Table 3: Resource Breakdown Solution 1

<table>
<thead>
<tr>
<th>Proposed Solution 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Land Usage</strong></td>
<td></td>
</tr>
<tr>
<td>Total Area ha</td>
<td>1,557</td>
</tr>
<tr>
<td>Total Area km²</td>
<td>15.57</td>
</tr>
<tr>
<td>Salinity %</td>
<td>22.95</td>
</tr>
<tr>
<td>Wheat km²</td>
<td>12.00</td>
</tr>
<tr>
<td>Microalgae Ponds km²</td>
<td>0.946</td>
</tr>
<tr>
<td>Unused Land km²</td>
<td>2.624</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Yield</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat t/year</td>
<td>1,884</td>
</tr>
<tr>
<td>Microalgae t/year</td>
<td>1,601</td>
</tr>
<tr>
<td>Algal Biofuel kWh</td>
<td>289,254</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Energy Consumption</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Algal Biofuel L/year</td>
<td>116,400</td>
</tr>
<tr>
<td>Algal Biofuel kWh</td>
<td>289,254</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Costs</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivation $</td>
<td>31,818.00</td>
</tr>
<tr>
<td>Recovery $</td>
<td>57,851.00</td>
</tr>
<tr>
<td>Anaerobic Digestion $</td>
<td>99,793.00</td>
</tr>
<tr>
<td>Storage $</td>
<td>141,734.00</td>
</tr>
</tbody>
</table>

Table 4: Annual Cash Flows Solution 1

<table>
<thead>
<tr>
<th>Operating Expenditure</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual Cash Flows</strong></td>
<td></td>
</tr>
<tr>
<td>Wheat $/year</td>
<td>220,273</td>
</tr>
<tr>
<td>Algal Biofuel $/year</td>
<td>-331,196</td>
</tr>
<tr>
<td>Total $/year</td>
<td>-110,923</td>
</tr>
</tbody>
</table>

As is shown in Table 3, 0.946 km² of the 3.57 km² available land is utilised for the growth of mixotrophic microalgae, utilising open pond systems minimal energy input cost, harvested by filtration and converted using anaerobic digestion. The total fuel cost of this solution is $331,196 and results in a total cash flow of -$110,923.
The breakdown of the second solution is shown in Table 5 and Table 6.

Table 5: Resource Breakdown Solution 2

<table>
<thead>
<tr>
<th></th>
<th>Proposed Solution 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Land Usage</strong></td>
<td></td>
</tr>
<tr>
<td>Total Area</td>
<td>ha 1,557</td>
</tr>
<tr>
<td>Total Area</td>
<td>km(^2) 15.57</td>
</tr>
<tr>
<td>Salinity</td>
<td>% 22.95</td>
</tr>
<tr>
<td>Wheat</td>
<td>km(^2) 12.00</td>
</tr>
<tr>
<td>Microalgae Ponds</td>
<td>km(^2) 3.570</td>
</tr>
<tr>
<td>Unused Land</td>
<td>km(^2) 0.000</td>
</tr>
<tr>
<td><strong>Yield</strong></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>t/year 1,884</td>
</tr>
<tr>
<td>Microalgae</td>
<td>t/year 6,426</td>
</tr>
<tr>
<td>Algal Biofuel</td>
<td>kWh 1,091,190</td>
</tr>
<tr>
<td><strong>Energy Consumption</strong></td>
<td></td>
</tr>
<tr>
<td>Algal Biofuel</td>
<td>L/year 116,400</td>
</tr>
<tr>
<td>Algal Biofuel</td>
<td>kWh 289,254</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td></td>
</tr>
<tr>
<td>Cultivation</td>
<td>$ 31,818.00</td>
</tr>
<tr>
<td>Recovery</td>
<td>$ 57,851.00</td>
</tr>
<tr>
<td>Anaerobic Digestion</td>
<td>$ 99,793.00</td>
</tr>
<tr>
<td>Storage</td>
<td>$ 38,552.00</td>
</tr>
</tbody>
</table>

Table 6: Annual Cash Flows Solution 2

<table>
<thead>
<tr>
<th>Operating Expenditure</th>
<th>Annual Cash Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>$/year 220,273</td>
</tr>
<tr>
<td>Algal Biofuel</td>
<td>$/year -228,014</td>
</tr>
<tr>
<td>Total</td>
<td>$/year -7,741</td>
</tr>
</tbody>
</table>

As shown in Table 6, similarly to Option 1 there exists a negative cash flow of $7,741 despite significant mitigation measures to storage requirements which served to reduce total cost by $103,182.
As both solutions fail to provide a positive cash flow, capital costs are not considered as payback period is infinite, and return on investment is negative.
4.4 Recommendations
As can be seen in Table 7, each of the two proposed situations result in a significantly greater cost than that of diesel fuel with Option 1 having a Fuel Cost of $331,196 or 524.6% of that of diesel fuel and Option 2 with a Fuel Cost of $228,014 or 361.2% of that of diesel fuel.

Table 7: Annual Cash Flow Comparison

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>220,273</td>
<td>220,273</td>
<td>220,273</td>
</tr>
<tr>
<td>Diesel Fuel</td>
<td>-63,636</td>
<td>-331,196</td>
<td>-228,014</td>
</tr>
<tr>
<td>Total</td>
<td>156,637</td>
<td>-110,923</td>
<td>-7,741</td>
</tr>
</tbody>
</table>

With respect to feasibility, it is the determination of this report that both Option 1 and Option 2 are capable of providing sufficient growth potential for biogas to operate a typical wheat farm in Western Australia; however with respect to practicality it is the determination of this report that in the current economic climate neither solution provides a suitable alternative that is economically viable. Further cost mitigation strategies may be possible such as implementing a gas pipeline to supplement in Option 1, reducing storage cost requirements and the ability to sell excess biogas in Option 2, recovering some of the cost of production.

The final cost of producing biogas, where all infrastructures are readily available for each of the solutions is $1.14/kWh and $0.79/kWh respectively. The cost per kWh of diesel fuel is $0.22/kWh and it is therefore the recommendation of this report that further consideration of capital expenditure is not required.
5.1 Conclusion

The preceding report has considered in detail the design and analysis of a sustainable energy system for use in Western Australia. A complete literature review was undertaken which served to provide a background into the development of first and second generation biofuels and the emergence of advanced biofuels created from microalgae.

Using the principles outlined by Kreith and Kreider (2011) in Principles of Sustainable Energy an assessment of the typical energy requirements and available resources was conducted for a sample case Wheat Farm located in the Western Australian wheat belt region. An exhaustive review of technologies allowed for the most suitable and cost effective system to be designed, utilising freely available resources such as sunlight and carbon dioxide to grow microalgae in an open pond system due to reduced energy requirements compared to enclosed photobioreactors.

The harvesting method utilised was by filtration for large microalgae species and centrifugation for smaller microalgae species, which was then converted to usable biogas using anaerobic digestion. Anaerobic digestion is ideal for use on a wheat farm due to the abundance of excess straw, chaff and other wastes as co-reactants which serve to significantly enhance the yield rate of biofuel per algal biomass.

An analysis of the operational cash flows for two separate solutions were considered based upon a system aimed at minimising fixed capital costs, and a system aimed at minimising operational costs, however both failed to provide a fuel cost less than that of the current method of diesel fuel. Considering that any overhaul to a farms energy system would result in significant capital costs to not only implement new infrastructure, but also to convert existing infrastructure to allow it to
accept the new fuel type it was determined that while the project may be feasible, it is not economically viable in the current financial climate.

In closing, the report considers the following future changes which would have the potential of improving the prospects of the energy systems outlined in this report:

1. Increasing the amount of lipid content and therefore energy potential of existing microalgae strains, or the development of new microalgae strains with higher oil content.

2. Improvements to the way in which algae is grown such as reduction in cost, or increases to growth rate.

3. Development of more robust algal-growing systems designed to mitigate the limitations of current systems.

4. Development of processes which use a greater percentage of the biomass product rather than just oil.

5. Improvements to the efficiency of oil extraction processes.

In addition, changes to the availability or cost of using diesel fuels due to security or shortage concerns will also serve to improve the overall viability.
6.0 References


http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/1301.0~2012~Main%20Features~Agricultural%20production~260


Chalmers, S. (12, 6 19). *Realistic Estimation*. Retrieved 8 1, 15, from The Institute of Engineers Australia:


