UNIVERSITY OF CALGARY / UNIVERSIDAD SAN FRANCISCO DE QUITO

# *A Prefeasibility Study of a 100 MW Ocean Thermal Energy Conversion (OTEC) Hybrid Cycle Plant in South East Queensland, Australia.*

By

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CERTIFICATE OF COMPLETION OF INDIVIDUAL PROJECT

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, the Individual Project Report entitled "A Prefeasibility Study of a 100 MW Ocean Thermal Energy Conversion (OTEC) Hybrid Cycle Plant in South East Queensland, Australia" submitted by **Paul Martin** in partial fulfilment of the requirements for the degree of Master of Science in Sustainable Energy Development.

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## Abstract

In tropical areas there exists a constant temperature gradient of about 20°C between warm surface seawater and cold deep water. This temperature difference can be utilised in a heat engine to generate electricity; a process the subject of considerable research known as Ocean Thermal Energy Conversion (OTEC).

This paper investigates the feasibility of a hybrid cycle OTEC plant which produces electricity, fresh water and has the potential to sequester Carbon Dioxide ($CO_2$) using algae, in the context of South East Queensland (SEQ), Australia. Included is an assessment of the limitations and capacity of the technology, the possible environmental impacts, and the economic parameters that make the project viable. It was found that based on current estimates of costs, the proposed 100 MW plant would be viable as a fresh water producer alone. This assumes intake pipes can be constructed, which are of a larger scale than is currently available. The potential for algae to sequester $CO_2$ and produce biofuel was shown to be substantial, although too expensive based on current production rates and costs.

## Preface

According to Lloyd & Subbarao (2009), mankind's desire for more and more has created an exponential consumption of energy since the start of the industrial revolution. This energy has been provided (predominantly) by fossil fuels. The unsustainable usage of these non-renewable resources has continued unabated until now, where we find ourselves at the limits of the demand and supply equilibrium. Either by reaching conventional production capacity limits, or (hopefully) through precautionary government intervention; the use of scarce resources to provide the bulk of our energy needs will have to end. This poses a number of challenges to our current way of life, which span every aspect of our modern society; transport, electricity production, food production, water supply, our lifestyle and the environment. In addition to these issues, we are in the midst of the undefined and unquantifiable threat of climate change - be it anthropogenic or naturally caused. These issues are forcing an alternative paradigm with regards to the use of our energy and water resources. As such, mankind is in need of innovations such as Ocean Thermal Energy Conversion (OTEC) which offer a more sustainable future.

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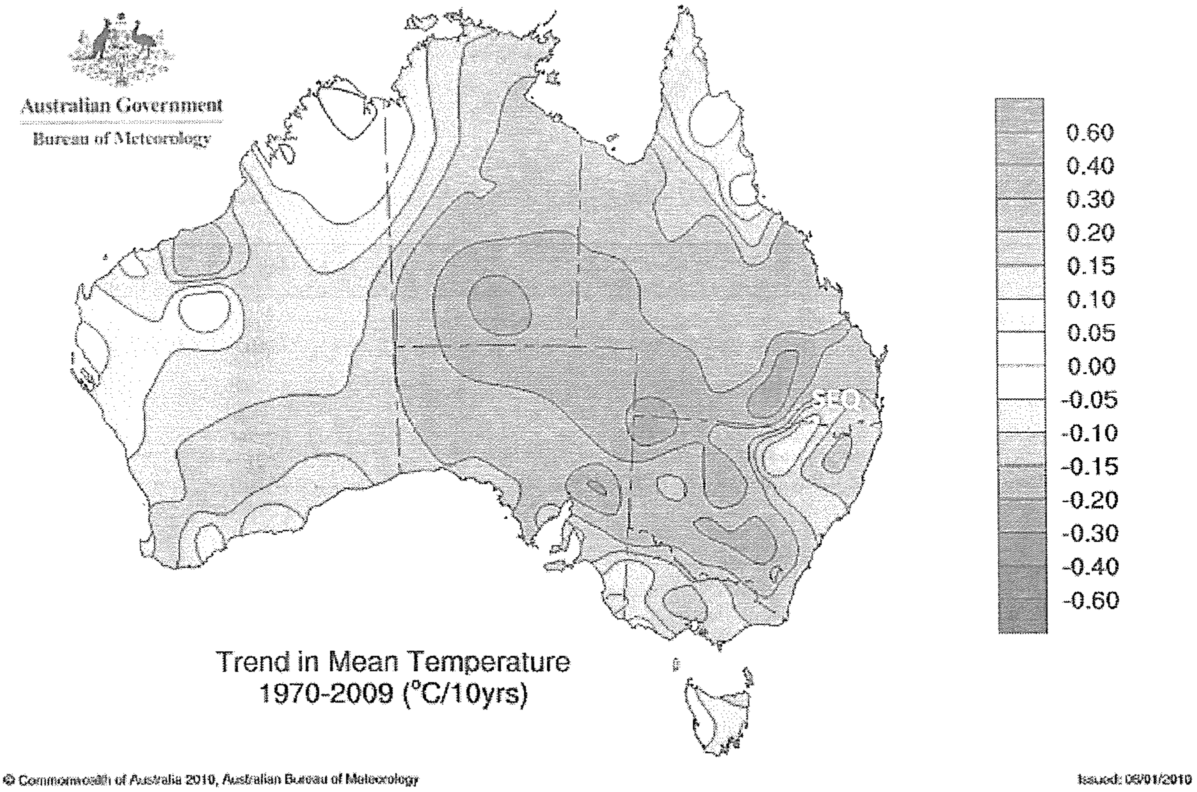
# 1 CHAPTER ONE: INTRODUCTION

## 1.1 Australian Context

### 1.1.1 Australia's Changing Weather and Climate

The delicate relationship between weather, climate and Greenhouse Gas (GHG) emissions can be illustrated by Australia over the last ten years. Australia is one of the driest continents in the world. Since the year 2000, due to La Nina weather patterns, it has experienced one of the worst droughts on record (Colvin, 2006). This extended period of dry weather, known as the 'Millennium Drought', has had sweeping consequences at both state and federal level. As Figure 1 shows, Australia's temperature and rainfall patterns are subject to changing climatic conditions as well as variable weather effects.

Figure 1: Trend in Mean Temperature from 1970 - 2009 (°C /10yrs) (Australian Government Bureau of Meteorology, 2010).



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As Colvin (2006) reported, during 2006, South East Queensland (SEQ) experienced its worst water shortage in over one hundred years. SEQ encompasses the local government areas of Brisbane, Gold Coast, Ipswich, Lockyer Valley, Logan, Moreton Bay, Redland, Scenic Rim, Somerset and Sunshine Coast – refer to Appendix A for a map of the area. Lack of rain, political mismanagement and personal misuse resulted in 60% of SEQ being placed under drought declarations. In response, on August 8, 2006, the Queensland Premier, Peter Beattie, received the Governor's approval to declare a 'water emergency'. Subsequently, in a partnership between the Queensland Government and the Council of Mayors of SEQ, The South East Queensland Regional Water Supply Strategy (SEQRWSS) was created. The aim of SEQRWSS is to formulate regional strategies for managing the future water supply needs of SEQ. In particular, the strategy outlines an approach to the management and maintenance of a safe water supply for the residents of South-East Queensland. Its key objectives are to:

- Assess future needs for a safe and reliable supply of water in SEQ;
- Assess the processes and mechanisms required to meet those needs; and
- Obtain agreement for an implementation framework for the strategy that achieves optimum social, environmental and economic terms.

As McGuirk (2007) reported, by mid 2007, combined dam levels had fallen to 17%, even with the implementation of severe water restrictions, and adoption of water use efficiency initiatives. Premier Beattie conceded; "we're not getting rain; we've got no choice", and was forced to rush the approval of plans to introduce recycled water into the state's supply chain. He abandoned public consultation out of necessity, despite widespread objection, and construction began mid 2007. New initiatives in demand management and source substitution were implemented concurrently, such as, requiring all new homes to be equipped with 5,000 L rainwater tanks and imposing irrigation restrictions for instance.

The drastic measures, however, were not limited to Queensland. In fact, most of South East Australia (including the most populous states; New South Wales and Victoria) were experiencing rolling water restrictions. John Howard, the Prime Minister at the time, declared the Murray-Darling basin to be at risk and subsequently took over the management of the entire river system from individual states. The Murray-Darling basin is an area the size of France and Spain and accounts for more than 70% of Australia's irrigated crop lands and pastures. It is home to almost two million people and extends from Queensland to South Australia. Mr Howard "a long-time sceptic about the effects of global warming, acknowledged that Australia's climate was getting hotter and that the southerly weather systems that brought rains to Australia were failing" (Lagan, 2007). He subsequently announced AU$10.5 billion to replace old pipes and irrigation channels, help farmers reduce water wastage and a complete review of water resources.

In fact, the water shortage across eastern Australia got so severe that it began to affect power supplies. Coal and hydro power generation require huge amounts of water, and are responsible for 86% of the generation capacity of the eastern states. For example, the three coal-fired power stations, Loy Yang A, Loy Yang B and Yallourn W, supplying the state of Victoria receive an annual water entitlement equal to approximately 20% of Melbourne's annual water use. This prompted Paul Holper, the head of Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) climate change science program, to concede to the extent of Australia's water / energy nexus: "You've got to find a supply of water to set aside for power generation, but there is already a shortage of water for agriculture. So this is going to become more of a problem" (SMH, with AAP, 2007).

More recently, the unpredictable and inconsistent nature of Australia's weather has been demonstrated by mass flooding. The rains that never reached SEQ inundated the north, causing mass flash flooding and property damage in 2008. The floods experienced by New South Wales in 2010 have transformed dusty, parched areas of the Murray-Darling basin into a reservoir, expected to last for up to two years (Gray, 2010). The areas now covered with water were the source of a giant dust storm that covered Sydney in a carpet of red-orange dust in 2009. Indeed, in almost ironic fashion, Sydney's new AU$2 billion desalination plant came online in May 2010, as the area experienced the wettest May in seven years. The plant which was commissioned in mid 2007, at maximum capacity will consistently supply 15% of Sydney's needs, despite high reservoir levels (Robins, 2010).

### 1.1.2 Australia's Energy / Environment Nexus

Tim Flannery, a renowned environmental and global warming activist, and Australian of the Year in 2007, confessed that "[Australian's] are, on a per capita basis, the worst greenhouse polluters in the world" (Lagan, 2007). This is not surprising given Australia's dependence on coal and natural gas, both for domestic consumption and export. In 2009, 80% of Australia's electricity was produced by burning coal, making it one of the largest coal burning countries in the world (ESAA, 2009). Table 1 is a breakdown of Australia's primary energy consumption and forecast to 2020. It shows that on current trends, non renewable fuels are set to provide the vast majority (93.7%) of Australia's energy for the next ten years.

Wind energy is the only renewable source to show any solid growth over this period, however; at only 11 PJ (0.10% of consumption) by 2020 it remains almost inconsequential as an energy provider.

Table 1: Australia's Primary Energy Consumption & Projection, by fuel, in petajoules (Becker, 2002).

| | 1998-9 PJ | 2019-20 PJ | 1998-9 % | 2019-20 % | Annual growth % |
|---|---|---|---|---|---|
| Black coal | 1,366.20 | 1,841.20 | 28.20 | 24.80 | 1.40 |
| Brown coal | 6,368.60 | 701.00 | 13.20 | 9.40 | 0.40 |
| Oil | 1,687.70 | 2,644.50 | 34.80 | 35.60 | 2.20 |
| Natural gas | 871.30 | 1,773.70 | 18.00 | 23.90 | 3.40 |
| Renewables | 288.60 | 469.20 | 5.90 | 6.30 | 2.30 |
| - Biomass | 217.10 | 357.60 | 4.50 | 4.80 | 2.40 |
| - Biogas | 8.90 | 25.50 | 0.20 | 0.30 | 5.10 |
| - Hydro | 58.70 | 68.80 | 1.20 | 0.90 | 0.80 |
| - Solar | 3.80 | 6.10 | 0.10 | 0.10 | 2.30 |
| - Wind | 0.10 | 11.10 | - | 0.10 | 25.20 |
| **Total** | 4,852.40 | 7,429.60 | 100.00 | 100.00 | 2.00 |

The coal and natural gas industries are substantial exporters and provide the government with considerable revenue. Hence, federal energy policies continue to support these industries through subsidies for fossil fuel use and production (Diesendorf, 2003). This has severe implications given the growing drive towards global carbon emissions reductions and the potential increase in the cost of polluting carbon. A carbon tax or cap will have detrimental impacts on current energy production in Australia, given its dependence on fossil fuels. Hence, energy alternatives are likely to become a focus of state and federal government in the near future, to reduce this dependency and vulnerability to carbon prices.

## 1.2 Problem / Issue

Given the environmental and political context outlined above, the problem that SEQ faces, as a result of changing climatic conditions and growing energy demand, is threefold:

- Firstly, the need to be weaned off non-renewable energy sources;
- Secondly, to manage $CO_2$ emissions to avoid catastrophic runaway climate change; and
- Thirdly, as weather becomes increasingly variable, to secure increasing quantities of fresh water.

## 1.3 Objective

The primary objective of this paper is to assess the feasibility of a 100 MW OTEC project ("Project") in SEQ, Australia, with the view to addressing the threefold problem mentioned above. The underlying primary goal of this paper is to determine the economic parameters that make a 100 MW OTEC plant viable. Specifically, this entails the assessment of potable water and biofuel volumes produced, electricity produced and carbon credits generated, against the costs of production, and capital investment. A secondary objective is to identify the key environmental issues surrounding an OTEC plant operating in QLD.

## 1.4 Strategy / Method

The methodology of this research project consists primarily of literary review. The technology has been well researched; accordingly this paper aims to apply this research to the proposed Australian application. To achieve this, the paper will focus on the following:

- Technology review – Specifically the hybrid cycle OTEC system, its components, costs, capacity and limitations. An overview of the history of OTEC is also included to illustrate the technological advancements made over the last one hundred years and identify the key players and projects. The proposed energy production will be assessed with regards to Australia's and specifically Queensland's energy system and requirements.

- Water production – An analysis of the desalination potential of the Project with regards to SEQs water issues and current and proposed state projects.
- $CO_2$ emissions control – the potential for reducing Australia's $CO_2$ emissions will be outlined through utilising the DOW effluent for growing microalgae for biodiesel production.
- Environmental impacts – a project wide assessment of potential environmental impacts will be discussed, including during construction and operation.
- Economics assessment – combining findings from the above sections, including; cost of the plant, revenues from energy production, water production and $CO_2$ sequestration. A simple financial analysis will conclude if the project is viable.

# 2 CHAPTER TWO: TECHNOLOGY ANALYSIS

## 2.1 OTEC Definition and Principle

Lennard (2004) defines Ocean Thermal Energy Conversion (OTEC) as the extraction of solar energy derived from the temperature difference existing between warm surface water and the cold Deep Ocean Water (DOW) of the oceans. The surfaces of the oceans capture huge amounts of solar energy—some thousands of times more than the energy consumed by our current civilization— with most of this being stored in the form of thermal energy in the surface layers of the oceans. The surface layers do not mix freely or easily with the deeper waters, which are much colder. This temperature separation enables the application of a standard heat engine, but where the temperature difference is much less than that in the case of a steam engine or an internal combustion engine.

Is it possible to make steam with such a small temperature difference? We normally think of water boiling at 100°C, but this only occurs when the atmospheric pressure is exactly 1 atm (at sea level). For example, in the city of Quito, Ecuador where pressure is only 72 kPa at an elevation of 2,800 m, water boils at only 90.4°C. Therefore, water can boil and turn to steam at say 25°C, if the ambient pressure is sufficiently low (Takahashi, 2000). This steam can then be used to drive turbine to generate electricity in the same fashion as any coal or nuclear fired power plant.

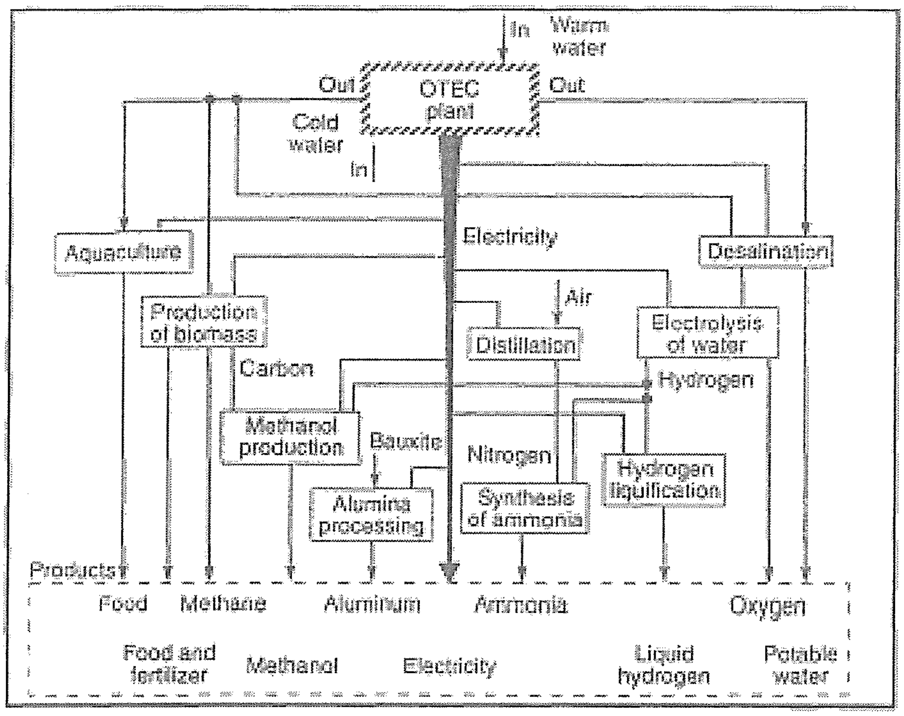
In order to create a large enough temperature difference from the warm surface flow, water must be pumped up from a depth of some 600 m to 1000 m, depending on the topography, where the water temperature is a consistent 4°C or 5°C throughout the oceans (Damy & Marvaldi, 1987). Even though the net efficiency of capturing the vast amount of energy available is low, estimates suggest that there is roughly 10 tera watts ($10^{13}$ W) of continuous electrical output that could be extracted through OTEC without significantly changing the thermal structure of the oceans (Daniel, 1999).

### 2.1.1 OTEC Byproducts

Despite the obvious benefits of base load (constant output), renewable energy production; there are a wide range of alternative applications of OTEC. As shown by Figure 2, these alternatives have considerable benefits which reduce the limitations of OTECs energy production capabilities. The by-products discussed in more detail are:

- Desalinated water - a direct by-product of the open and hybrid cycles; it occurs when warm seawater is evaporated and then condensed.
- Deep Ocean Water (DOW) - The first OTEC experiments utilised DOW purely as an element essential or the energy system. Now, through various applications of the DOW, it plays a key role in improving the economic viability of the complete OTEC system, by providing pathogen free, nutrient rich water for a range of DOW applications (Cavrot, 1993).

Figure 2: Potential Products of a Commercial OTEC Plant (Avery & Wu, 1994, cited in Wright, 1996).



## 2.2 OTEC history

OTEC has existed for almost one hundred and thirty years. In 1881 the Frenchman Arse`ne d'Arsonval was the first to suggest that one could generate electricity from utilizing the temperature difference of warm and cold seawater to drive a heat engine (Takahashi, 2000). Dr. d'Arsonval proposed what would later be called the Closed Cycle System (CCS), and postulated the use of high vapour density liquids, such as ammonia or propane, rather then seawater (Takahashi, 2000).

Another Frenchman, G. Claude, who along with P. Boucherat, were the first to actually experiment with Dr. d'Arsonval's ideas in 1926, some fourty years later. They successfully demonstrated electricity production from a small thermal difference, using an Open Cycle System (OCS).

Professor Claude went on to experiment with the technology extensively over the next thirty years, funded largely of his own accord. First, he investgated land based Cold Water Pipe (CWP) possibilities in Matazans Bay, Cuba in 1929. His attempts to lay a durable CWP largely failed during several years of attempts, however; he did manage to pump suficient water to generate 22 kW for ten days, utilising a temperature difference of 14°C . This small achievement was enough for Claude to announce that mankind would never be hindered by a lack of energy (Takahashi, 2000).

Later, in 1933, Claude began investigating the potential of floating OTEC plants. He converted a 10,000 t cargo ship 'Tanisie' into an 800 kW OTEC generator and sailed the seas off Rio de Janeiro. Unfortuntely, again after problems with the CWP, the ship sank (Takahashi, 2000).

In 1940 he endevoured again, this time on the French West African nation of Côte d'Ivoire, off the capital Abidjan. Cold water was to be pumped up from 430 m through a 4 km long pipe at a rate of 14 t/s, along with 42 t/s of 30°C surface water, in order to produce a projected 15 MW. Of this, it was expected that 5 MW would be needed for pumping and gas extraction, netting 10 MW of electricity. The project gained the support of the French government in 1948, however; by 1955 after large amounts of cheap oil became available, the project was abandoned (Takahashi, 2000). Sadly, Claude passed away in 1960 at the age of 90, having never seen his lifes work come to fruition.

France did, however; continue to develop two more open cycle plants in the 1950s for their overseas territories; Ivory Coast and Guadeloupe (Lennard, 1995).

Dr. J. H. Anderson picked up where Claude left off. He felt that the problems associated with Claude's OCS were insurmountable, and so he developed a submerged CCS. Anderson was able to determine that electricity could be produced at $166 /kW, the first time an estimate of costs per production unit had been made (Takahashi, 2000).

More recent developments in the technology have been driven predominantly by Japan, USA and Taiwan. Japan became active in OTEC research and development in the 1970s, and accelerated their developments following the 1973 oil shock. The Institute for Comprehensive Electronic Technology completed a CCS model using fluorine as the working fluid in 1975 and successfully generated 100 W of electricity by circulating 50 t/h of temperature controlled warm and cold water. Saga University also experimented with several CCS models, and produced 1 to 1.2 kW. In 1980 the University completed 'Imari No. 2'; a demonstration plant on the coast of Imari City, which is capable of producing 50 kW. Later, the Tokyo Electric Power Company susccessully built and deployed a 100 kW, CCS on the pacific island of Nauru. The plant, which became operational in 1981, produced 120 kW of gross electricity and provided 30 kW net power to the local community; the first instance of an OTEC system providing power to a grid (Takahashi, 2000).

The USA became involved in OTEC research in 1974. The Natural Energy Laboratory of Hawaii Authority successfully demonstrated the potential of OTEC with a 100 kW gross, 18 kW net power output on a morred barge at Keahole Point off the coast of Hawaii in 1979 (Lennard, 1995). Then later in the 1990s, with the help of the Pacific International Center for High Technological Research, they built and operated a land based 255 kW gross, OCS plant that contributed net power to Hawaii (Lennard, 1995).

Taiwan's geographic position, topography and growing energy demand has driven much of the interest into OTEC technology. The temperature difference between surface water and DOW off eastern Taiwan is around 20°C year round, and the sea floor drops off rapidly reducing the length of CWP required for efficient energy production. The Taiwanese have been developing ideas for OTEC for thirty years, and have plans for a 5 MW plant at a number of sites. In the mid 1990s, a twenty year Master OTEC Plan was developed that hoped to see the completion of a 100 MW demonstration plant, and set an ambitious target of 3,200 MW of OTEC capacity envisaged over the following twenty years (Lennard D. E., 2004).

Since 2000, India has piloted the development of a 1 MW floating OTEC plant near Tamil Nadu, assisted by Saga University (Lennard D. E., 2004). Its government continues to sponsor research in developing floating OTEC facilities.

More recently, research from offshore oil and gas activities has provided key insights into heat exchangers, DOW pipes and mooring techniques. However, many technological improvements must be made in order to make demonstration and eventually commercial scale operations feasible, as discussed herein.

## 2.3 Systems / Technologies

The application of OTEC has several variations; floating, land based or shelf mounted, open, closed or hybrid cycle, and for solely electricity generation or combinations of electricity, desalination and aquaculture (Lennard, 1995). This section provides a brief description of each, as follows:

### *Closed Cycle System*

A Closed Cycle System (CCS) is one which utilises a low-boiling-point fluid to turn the turbo-generator. The 'working fluid' is pumped to the evaporator, where through the use of heat exchangers; the fluid absorbs the energy from the warm sea water. Once at a similar temperature to the surface water, the working fluid changes to a gaseous phase with a considerable increase in volume and pressure. The gas then passes through a turbine connected to an electrical generator which utilises some of the increased energy contained in the gas. It is then recycled on through the condenser, where again through the use of heat exchangers; the excess energy of the gas is absorbed by the heat sink (i.e. the DOW). Once cooled and condensed, the working fluid is able to be pumped through the system again. The working fluid is any liquid that has sufficient vapour pressure to drive the

**Figure 4: Diagram of the Closed Cycle OTEC System (Lennard, 2004).**

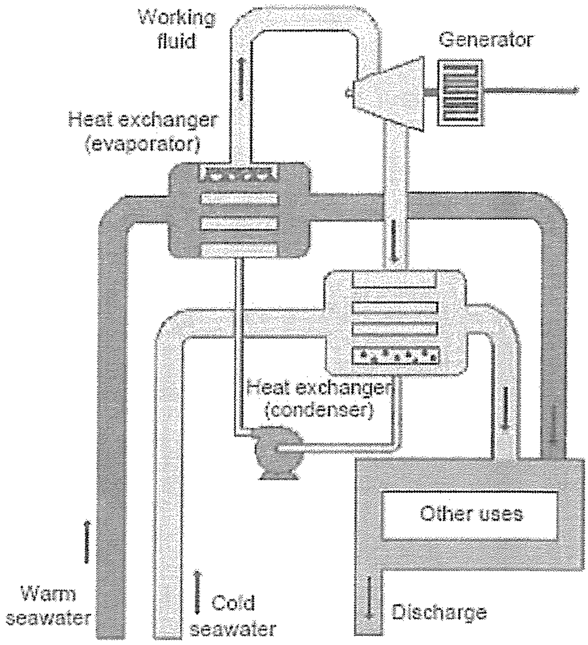
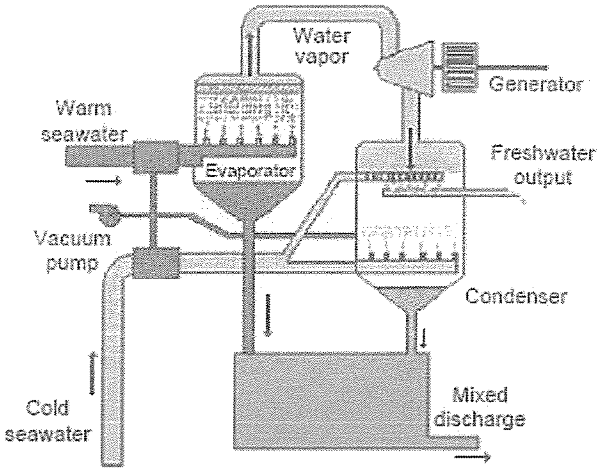


**Figure 3: Diagram of the Open Cycle OTEC System (Lennard, 2004).**



turbine at a temperature close to that of tropical surface seawater, such as Ammonia, Propane, Butane, or Freon. The main point of difference with the CCS is that the working fluid is circulated through the OTEC system without mixing with either the heat source or the sink (Lennard D. E., 2004).

### *Open Cycle System*

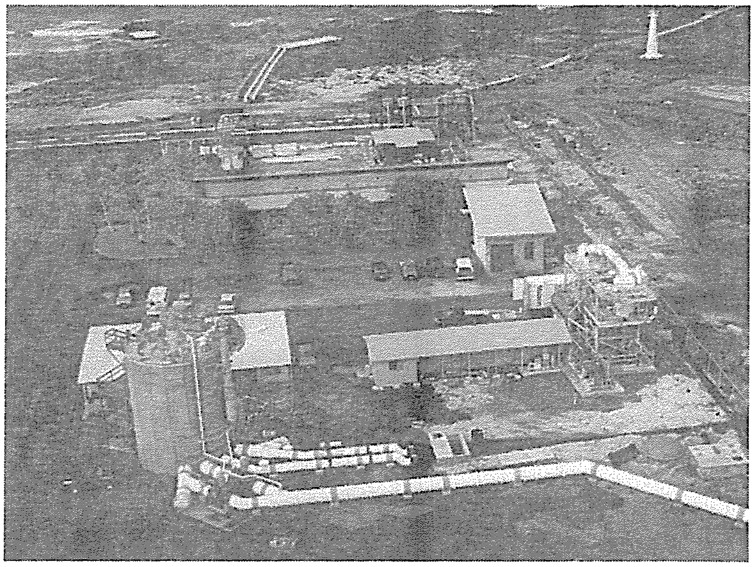
The Open Cycle System (OCS) is where the 'working fluid' is warm seawater itself. To achieve the vapour pressure required of the warm sea water, the evaporator must maintain very low pressure. Vega (1992) calculated that the vacuum chamber pressures required for OCS are approximately 3% atmospheric. Reducing the pressure of the evaporator requires pumping, which requires energy. Hence, the OCS is less efficient then the CCS. One benefit of the OCS however, is that the water vapour, once condensed, is distilled fresh water – a valuable resource in most some circumstances.

### *Hybrid System*

A Hybrid System (HS) combines the best features of both the closed and open cycle systems. An HS is divided into two stages. In the first stage, the warm seawater drives a CCS to produce electricity. Then in a second stage, the temperature difference available from seawater effluents from stage one (i.e. approximately 12$^{o}$C) are used to produce desalinated water via a flash evaporator and a surface condenser. That is, an OCS without the turbine generator.

### *Land Based Plant*

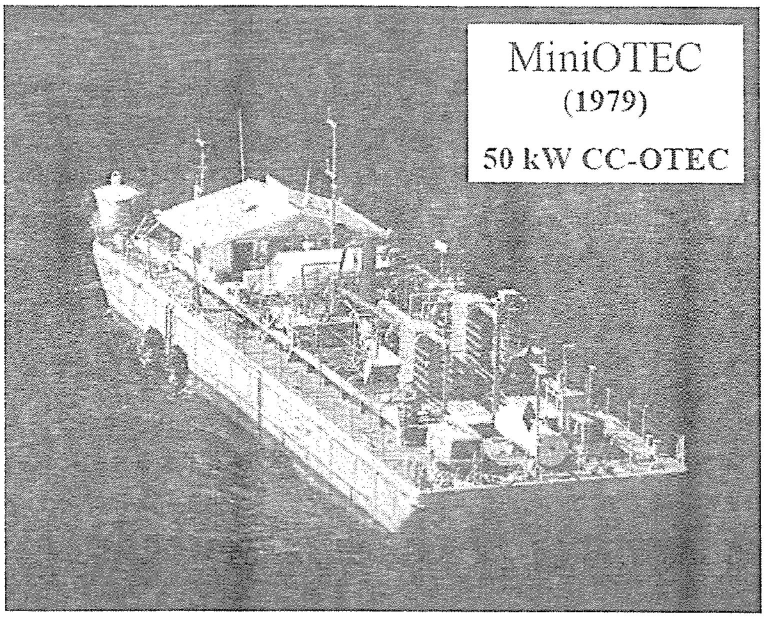
**Figure 5: Land based 210 kW OCS Experimental Plant (1993-1998), Keehole, Hawaii (Vega L. A., 1999).**



A land based plant benefits from being closer to existing infrastructure, but relies on longer pipes to feed it with warm and cold water. Also, the saline discharge stream (for open and hybrid systems) poses additional obstacles, as further piping may be required. The engineering and operation of the plant is somewhat less complicated, and there are no physical restrictions on size, making scaled up commercial projects more viable. However, coastal land is often much more expensive, which may deteriorate the plant's cost effectiveness.

### *Floating Plant*

Figure 6: Floating CCS, 'Mini OTEC' off Keahole Point, Hawaii (Vega, 1999)



Experimental floating plants have traditionally been converted barges. They benefit from shorter water input pipes and are not limited to the geographical restrictions of land based plants. However, there are additional factors to consider; extreme weather conditions, mooring lines and how to transfer the produce (fresh water and/or electricity) to the shore. One option being explored is combining floating OTEC applications with Hydrogen production, or some other electricity intensive process. That way the electricity produced is converted into a medium which is easier to transport. They are also limited in capacity to the size of the barge. All plants thus far have been relatively small demonstrations, but commercial projects would require much larger hulls to house the bulky equipment.

## 2.4 OTEC Limitations

According to Takahashi (2003) the three most critical components needing breakthroughs are the input pipes (specifically the CWP), the closed and hybrid cycle heat exchanger, and the open cycle turbine. These major pieces of equipment are the most expensive, and are currenty limiting the boundaries of OTEC application, as discussed futher below. The magnitude of the equipment needed is the major constraint to commercial application of OTEC, such as the Project. However, given SEQ does not require new water supply infrastructure until late 2030s (discussed in Chapter 3), there is sufficient time for more detailed research to occur.

### 2.4.1 Pipes and Pumps

It is widely agreed (Damy & Marvaldi, 1987; Takahashi, 2003) that the main dimensioning parameter is the diameter of the CWP, which determines the available cold flow. Pumping DOW from greater depth creates greater costs through not only the greater engineering required, but also because of the higher pumping head requirements due to frictional losses. Furthermore, pumping through multiple pipes in order to increase production capacity can only be economically viable up to two or three pipes in parallel (Lavi, 1979). The length of the pipe also affects the magnitude of the temperature difference, as some heat transfer can be expected as the DOW passes through warmer.

Despite some variation amongst researchers, as to the actual requirements of a commercial scale plant; several studies (Rey & Lauro, 1981; Vega, 1999) estimate that approximately 4 $m^3$/s of warm seawater and 2 $m^3$/s of cold seawater (i.e. a ratio of 2:1), at a temperature difference of 20°C, are required per MW of net electricity. Where, net power is gross power less in-house usage. This huge quantity of warm and cold seawater has to be pumped to the plant. This results in the consumption of 20% – 30% of the power generated by the system. The power required to pump the DOW has to account for the pipe-fluid fictional losses and for the density head, i.e. the gravitational energy acting on the denser / heavier, cold water as it travels up the inside of the pipe compared to the surrounding water column (Vega, 1999). To keep the pumping losses at this level, the seawater flowing through the input pipes must be kept to an average speed of less than 2 $m^3/s$. Therefore, a 100 MW plant would use 400 $m^3/s$ of 24°C water flowing through a 16 m inside diameter pipe extending to a depth of 20 m; and 200 $m^3/s$ of 4°C water flowing through an 11 m diameter pipe extending to depths of 1,000 m. Current technology requires costly reinforced concrete pipe or fiberglass reinforced plastic materials for pipelines of these diameters. The design of CWPs and their mooring systems must consider extreme environmental phenomena, as well as fatigue induced failure through extended operations (Vega L. A., n.d.). Pipelines of the dimensions outlined above are not currently commercially available. In fact, the largest deep water pipe in operation at the Natural Energy Laboratory of Hawaii Authority (NELHA) is only 1.4 m in diameter. Thus, this paper recommends substantial research into engineering a more cost effective and logistically effective solution, before commercial scale plants are able to be implemented.

### 2.4.2 Heat Exchangers

CCSs require very large surface areas of heat exchangers. Current technology limits the construction of OTEC plants no greater than 100 MW (Lennard, 2004). Lavi & Lavi (1979) calculated that an OTEC system requires 8 $m^2/kW$ of heat transfer surface. This equates to some 800,000 $m^2$ for a 100 MW plant. They also suggested that this would cost approximately $113 /kW (1979 US$), which equates to $273 million in inflation adjusted terms for a 100 MW capacity (The Federal Reserve Bank of Minneapolis, 2010). However, this figure is dated, and does not reflect current materials or prices.

### 2.4.3 Turbines

Another major technical difficulty for commercial scale OTEC and OCS in particular, are the large turbines required. Vega (1999) stipulated that due to the low vapour pressure of the steam, the OCS turbine is currently limited to sizes of no more than 2.5 MW. However, current technology suggests that commercial scale CCSs can be achieved up to 100 MW in size. The Project is a Hybrid System, with a CCS 100 MW turbine, which is within the relm of current technology. As discussed above, the main limiting parameter to the proposed project is the CWP and the heat exchange system. However, SEQ has the luxury of time in terms of requirements to implement electricity and water production (ignoring GHG emissions target or the cost of emitting $CO_2$), therefore; there is the possibility of developing more cost effective equipment before the project is implemented.

### 2.4.4 Warm Water

Although the temperature of DOW is relatively constant, surface temperature can vary to some extent over short and seasonal time intervals. An OTEC plant's design and economic viability are heavily dependent on the availability, consistency and predictability of the thermal resource contained in the surface sea water (Lavi G. H., 1979). Hence, the positioning of fixed warm water intake pipes, and consequently the OTEC plant itself, is extremely limiting. As a result, much interest is being focused on floating systems, which have the advantage of being able to seek out optimal thermal conditions. As will be discussed in section 2.6, the proposed SEQ plant has consistent warm water inflow of 24°C. The possibility of a moored offshore shelf mounted or floating plant should be explored due to the deep water trench that exists 10 km offshore.

## 2.5 OTEC Capacity

### 2.5.1 Energy Harvesting

As previously mentioned, the basis behind the OTEC system is a heat engine driving a Rankine cycle. A heat engine is a physical device that converts thermal energy to mechanical output via the thermodynamic process. In other words, heat is transferred from the source, through the engine, to the sink, and in this process some of the heat is converted into work. A Rankine cycle is simply a heat engine that converts the working fluid from a liquid to a gas to provide the mechanical work. This model of heat engine is commonly used power generation plants. In general terms, the larger the difference in temperature between the hot source and the cold sink, the larger is the potential thermal efficiency of the cycle. This relationship has limited efficiency, as outlined by Carnot's theorem as follows:

> *No engine operating between two heat reservoirs can be more efficient than a Carnot engine operating between the same reservoirs (Editors of McGraw-Hill, 2010).*

This maximum efficiency $\eta$ is defined as:

$$\eta = \frac{W}{Q_H} = 1 - \frac{T_C}{T_H} \qquad \text{(Eq. 2.1)}$$

Where:

W = the work done by the system (energy exiting the system as work);

$Q_H$ = the heat put into the system (heat energy entering the system);

$T_C$ = the absolute temperature of the cold reservoir; and

$T_H$ = the absolute temperature of the hot reservoir.

Hence, for a warm water source at 25°C (298K) and cold water source at 5°C (278K) the maximum theoretical efficiency can be derived as follows:

$$\eta = 1 - \frac{T_C}{T_H} = 1 - \frac{278}{298} = 0.0671 = 6.71\%$$

Practical experience dictates that actual maximum efficiency is roughly 50% of the theoretical maximum. Therefore, the actual maximum energy conversion efficiency of a 20°C temperature difference is **3.36%.** Cavrot (1993) estimated that a temperature difference of 20°C is likely to provide an overall operating efficiency of 2.5%, taking into account system losses. Furthermore, a 2°C increase in temperature difference can increase the efficiency by over 20%.

OTEC plants have often been labelled as inefficient when compared to other technologies based on first law (or Carnot) efficiency. First law efficiency is defined as the "fraction of the energy from the source which may be converted to work; and is an irrelevant measure of performance or economics when the energy is essentially free" (Johnson, 1983, p. 928). A more applicable measure of efficiency between different energy conversion plants would be the second-law efficiency, which is "the ratio of the actual work output of the plant to the exergy of the energy source" (Johnson, 1983, p. 927). Despite the enormous amounts of thermal energy contained in the oceans, only a minute fraction of this energy can be considered exergy. Exergy is defined as the maximum amount of energy that can be extracted from a source when the remaining energy is exhausted to the dead state (Johnson, 1983). Left over energy after work has been extracted is said to be in the dead state. It is the role of the heat sink to absorb this 'dead state' energy. In an OTEC system, the sink is the cold DOW.

The ratio and quantities of warm and cold water required to generate electricity have been given above by Rey & Lauro (1981) and Vega (1999); that is 4 $m^3$/s and 2 $m^3$/s per megawatt of net power produced (at a 20°C temperature difference). Thus, with a rudimentary heat capacity calculation the exergy of a 1 MW OTEC system can be shown as follows:

ASSUMING:

- The salinity of the seawater off the coast of Queensland = 35.7 g/kg (Pearce, 1981);
- Therefore, the Specific Heat of SEQs seawater (at 24°C & 1 atm) = 4,001.45 J/kgK (Sharqawya et al., 2010);
- The Density of SEQs seawater (at 24°C & 1 atm) = 1,023.46 kg/m$^3$ (Sharqawya et al., 2010);
- SEQs Surface Temperature = 299K (26°C )
- The temperature of the water leaving the evaporator is 295.5K (22.5°C ). That is, the working fluid extracted 3.5°C, available for producing work.

**Total Incoming energy** $= 4{,}001.45\frac{J}{kgK} \times 4\frac{m^3}{s} \times 1{,}023.46\frac{kg}{m^3} \times 299K$

$$= 4{,}898{,}007{,}524\frac{J}{s}$$

$$= 4{,}898\frac{MJ}{s}$$

**Total Exergy** – i.e. the energy extracted:

$$= 4{,}898\frac{MJ}{s} - \left(4{,}001.45\frac{J}{kgK} \times 4\frac{m^3}{s} \times 1{,}023.46\frac{kg}{m^3} \times 295.5K\right)$$

$$= 57\frac{MJ}{s} = 57MW$$

Which, at operational efficiency of 2.5% (Cavrot, 1993), provides a gross output of:

$$= 0.025 \times 57MW$$

$$= 1.4MW$$

Therefore when considering the power consumption of the OTEC system to run pumps, at approximately 20 – 30% of gross output, net output is calculated as follows:

**Net Power Output** $= (1 - 0.30) \times 1.4MW$

$$= 1MW$$

### 2.5.2 DOW Required

Research has determined that as a general rule, a ratio of 2:1 of warm to cold water is needed for efficient OTEC (Vega, 1992; Rey & Lauro, 1981). As stated previously, this equates to a flow rate of 200 m$^3$/s of DOW for a 100 MW application. For the purposes of this paper it is assumed that 100% of the DOW (17,300 m$^3$/d) is utilised for DOW applications, as will be discussed in Chapter 5. Normal OTEC practice is to pipe the DOW back down to a suitable depth after it has been utilised in the energy production process. To minimize the environmental impact, a discharge depth of 20 m - 60 m is considered sufficient, however; this may be unnecessary for the proposed application as the temperature and nutrient content of the DOW following aquaculture applications should be similar to surface conditions.

### 2.5.3 Fresh Water Production

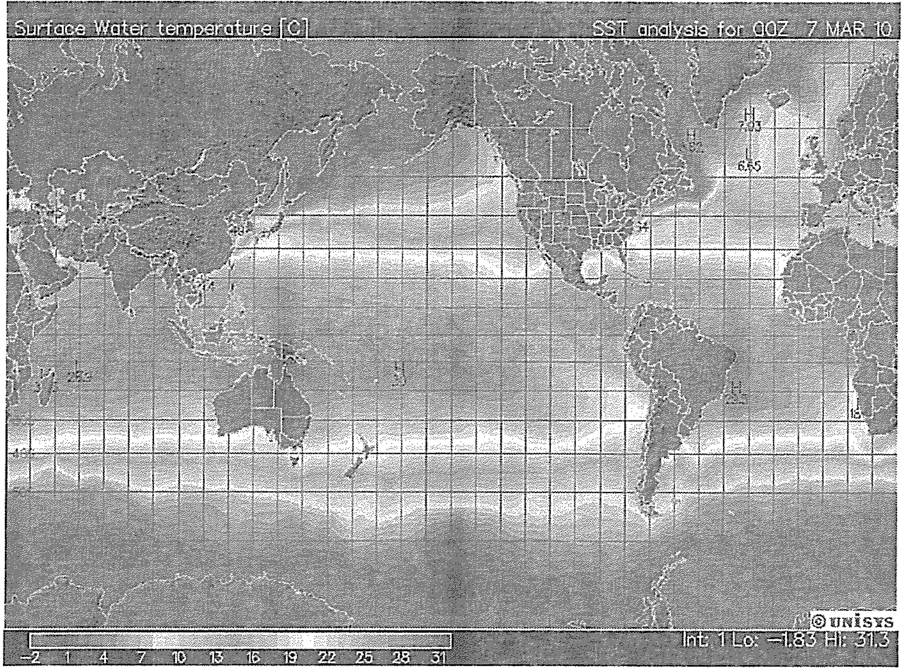
The fresh water is a product of the warm water inflow, which as per above, is determined by the 2:1 ratio of DOW per MW. Therefore, the Project's warm water flow would be 400 m$^3$/s. This equates to 34.5x10$^6$ m$^3$/d. Literature is fairly inconsistent with estimations of commercial scale fresh water production. Rey & Lauro (1981) estimate the rate of distillate to be 1,500 $m^3$/d/MW of power generated; Vega (1992) suggests 1,240 $m^3$/d/MW; whereas Takahashi (2003) ventures that a 1 MW plant can produce up to 3,500 $m^3$/d. Takahashi has 12 years experience based at Hawaii's research station at Keahole leading research and development into OTEC for the USA, hence; for the purposes of this paper, a distillate rate of 2,000$m^3$/d/MW is assumed to be conservative. This equates to a theoretical distillate flow of 200,000 $m^3$/d or 200 ML/d for the 100 MW Project, which is roughly 0.60% of the warm water flow.

## 2.6 SEQ Application

There are many other factors to be considered when deciding on a location that is suitable for an OTEC installation. These include distance from shore to the thermal resource, depth and topography of the ocean bed, depth of the DOW resource, replenishment capability for both warm and cold water, typical weather conditions and potential for hurricanes or cyclones, sea bed conditions for anchoring & power cables of floating plants, the present installed power distribution network, local power demand and water consumption, present cost per unit (including any subsidy), local oil, gas, and/or coal production, scope for aquaculture potential, and environmental impact (Lennard, 2004). This section will assess the physical attributes of a potential site in SEQ.

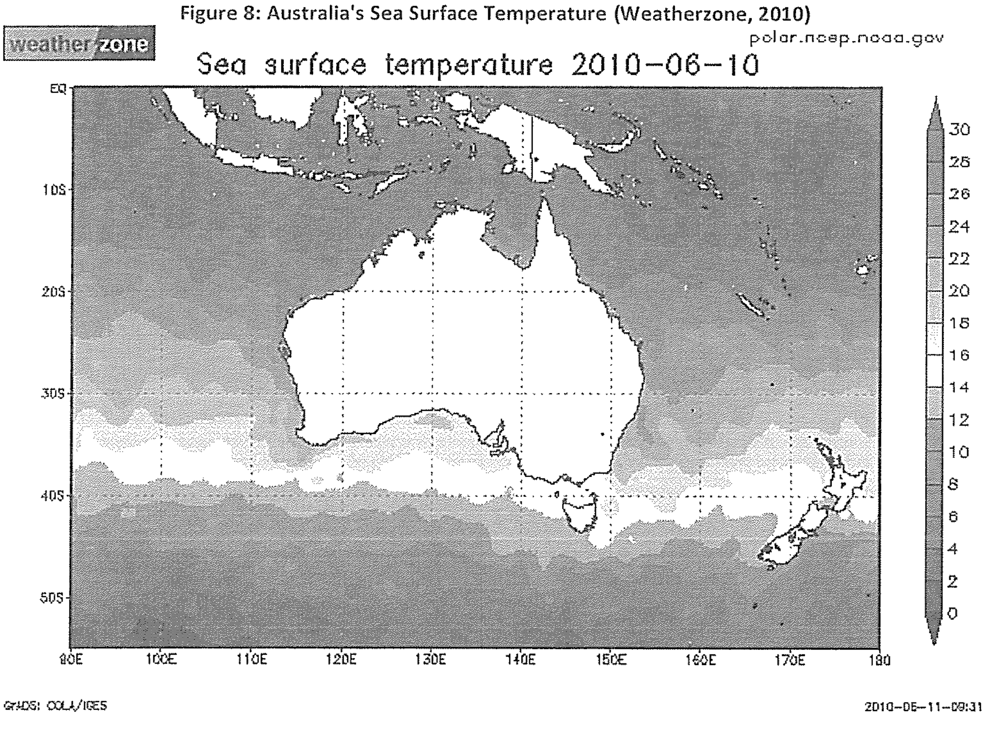
Given that the minimum required temperature difference between the warm and cold water is about 18°C - 20°C in the OTEC system, the application of OTEC is generally limited to the tropics, as depicted by the orange and red areas in Figure 7.

Figure 7: Sea Surface Temperatures (Unisys, 2010)



More specifically in Australia, areas with sufficient surface temperatures are limited to; Queensland, Northern Territory and parts of Western Australia, as seen in Figure 8 below:

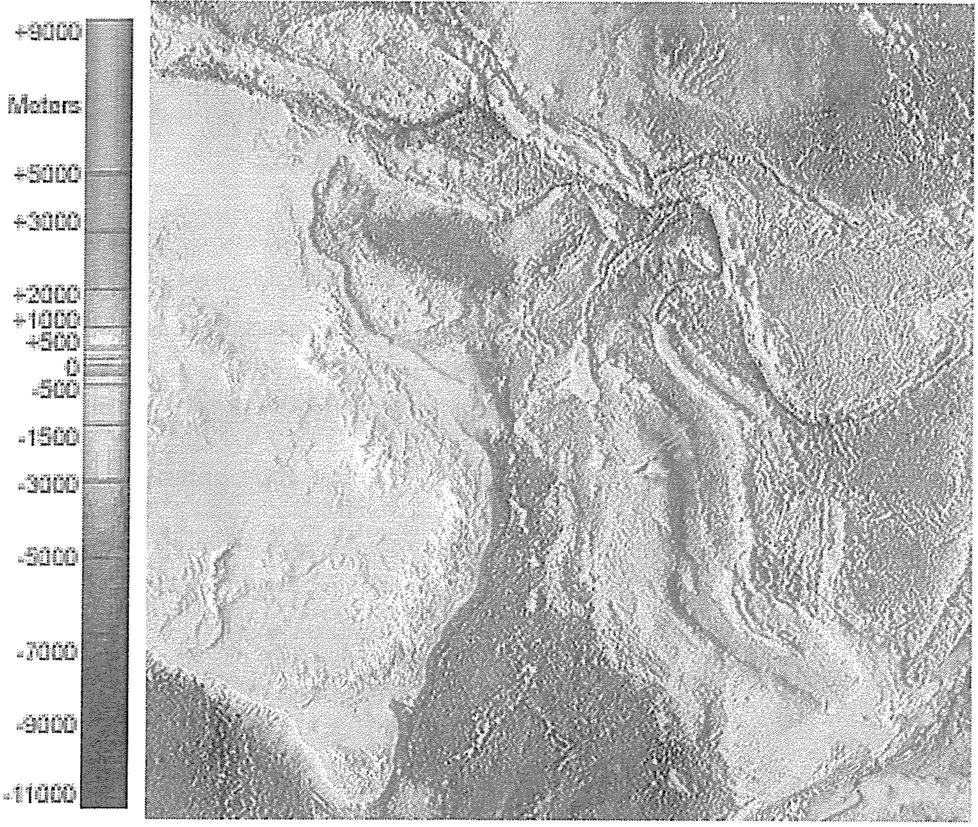
Figure 8: Australia's Sea Surface Temperature (Weatherzone, 2010)



Despite DOW being relatively constant (4°C - 5°C) at sufficient depth (1,000 m) throughout the oceans, access to sufficiently cold water imposes further constraints to viable sites. It is obviously beneficial to minimise the length of CWP required to reach the DOW to reduce cost and pumping requirements. In the case of land based plants, the cold water intake head, at a depth of 600 m – 1,000m, should not be located at more than 5 km from the shoreline. Otherwise it may be more economical to set the plant in 20 m – 30m of water on a small platform and deliver the power and water through small diameter pipes to shore (Damy & Marvaldi, 1987).

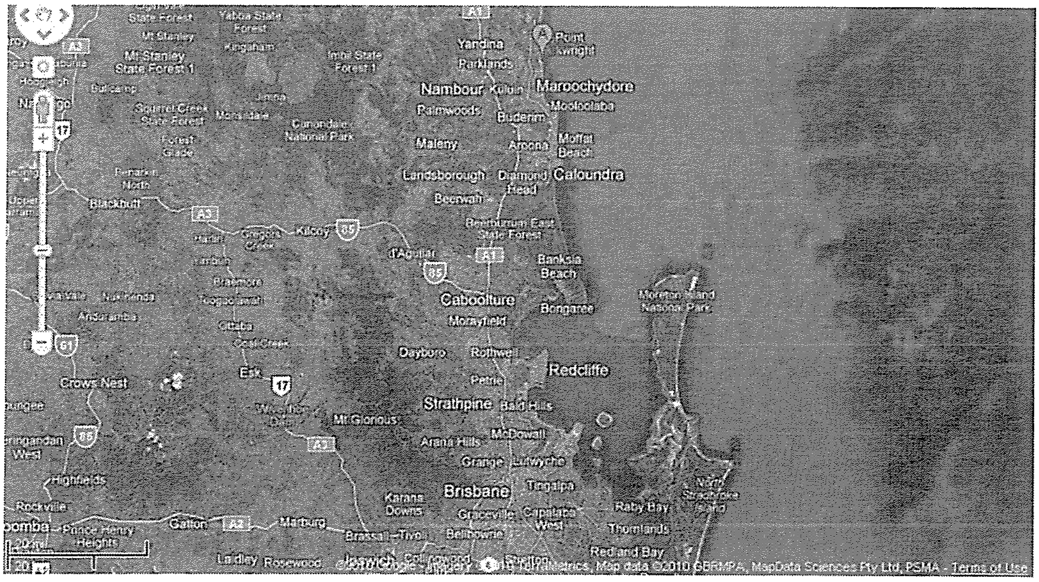
SEQ's surface water ranges around 24°C – 26°C making it at the bottom of the viable range. As shown by Figure 9, the eastern coast of Australia up to SEQ is on the verge of a steep drop off into the Tasmanian Sea.

Figure 9: Oceanic Topography (NOAA, n.d.).



However, this natural drop off is some 80 km – 100km off the coast of SEQ, as shown by the dark blue colouring in Figure 10.

Figure 10: Topographical Map of SEQ (Google Maps, 2010). (A = Marcoola, the proposed site).

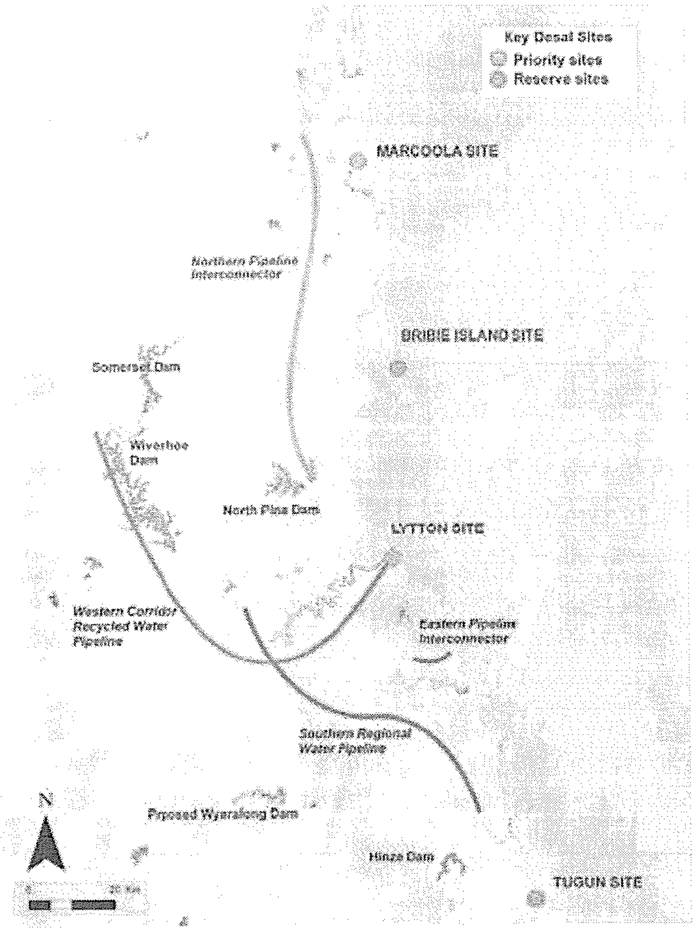


For the purposes of this paper, it is assumed that DOW source of 4°C can be found at 1,000 m within 2 km from the shore line. This provides a SEQ plant with an 18°C – 20°C thermal difference; the minimum required to run an OTEC system.

### 2.6.1 SEQ Site Analysis

As part of the SEQRWSS, several potential future desalination sites have already been earmarked within SEQ. These potential sites were selected after a preliminary review of engineering and environmental considerations. The top four potential sites are shown in Figure 11 below:

Figure 11: Potential Future Desalination Sites (Queensland Water Commission, 2009)



Detailed engineering assessments have already been conducted to confirm the practical suitability of the identified sites. These assessments included consideration of the ease of construction on the site and construction of the intake and outfall pipes (for a desalination plant), and the impacts of the brine concentrate dispersion, using hydrodynamic modeling

(Queensland Water Commission, 2009).

Of these potential sites, Marcoola offers the most benefits to an OTEC application for the following reasons (Queensland Water Commission, 2009):

- Consistency of feed water quality (low level of suspended solids), and access to an environmentally acceptable method of disposing of the waste concentrate stream (open ocean discharge);
- The close proximity to the ocean (within 1.5 km) and existing infrastructure connections (i.e. distribution network for produce water and power);
- The large site (53 hectares), enables the proposed biofuels DOW application discussed herein;
- Natural buffers exist to residential and recreational areas and it's not visible from the coastal strip;
- The site is currently agricultural land adjacent to commercial land (the Sunshine Coast Airport); and
- The site is already owned by the Sunshine Coast Regional Council.

Figure 12: Potential OTEC Site at Marcoola (outlined in red) (Queensland Water Commission, 2009).

The next steps for site analysis would be (Queensland Water Commission, 2009):

- Collecting detailed environmental information about the sites and outlet areas;
- Confirming the routes for connecting pipelines;
- Master planning for the site and adjourning area with councils;
- Geotechnical testing to confirm ground conditions of off-shore areas to determine the optimal way to return the concentrated seawater from the process;
- Engineering studies to determine the best design options preparing preliminary designs; and
- Preparing an environmental impact statement.

# 3 CHAPTER THREE: FRESH WATER POTENTIAL

> *"The world is facing increasing problems in providing water services, particularly in developing countries. There are several reasons for this, which are not necessarily linked to climate change. A lack of available water, a higher and more uneven water demand resulting from population growth in concentrated areas, an increase in urbanisation, more intense use of water to improve general well-being, and the challenge to improve water governance, are variables that already pose a tremendous challenge to providing satisfactory water services" (Bates et al., 2008).*

## 3.1 SEQ Context

### 3.1.1 SEQs Demand and Supply Predicament

Currently, 95% of SEQs water supply is dependent on dams and weirs, which are susceptible to weather and climate events, such as the Millennium Drought and climate change (Queensland Water Commission, 2009). SEQs climate is naturally highly variable, which when combined with increasing uncertainty regarding global climate change, may adversely affect rainfall and dam storage levels. This creates significant risks to SEQs water supply.

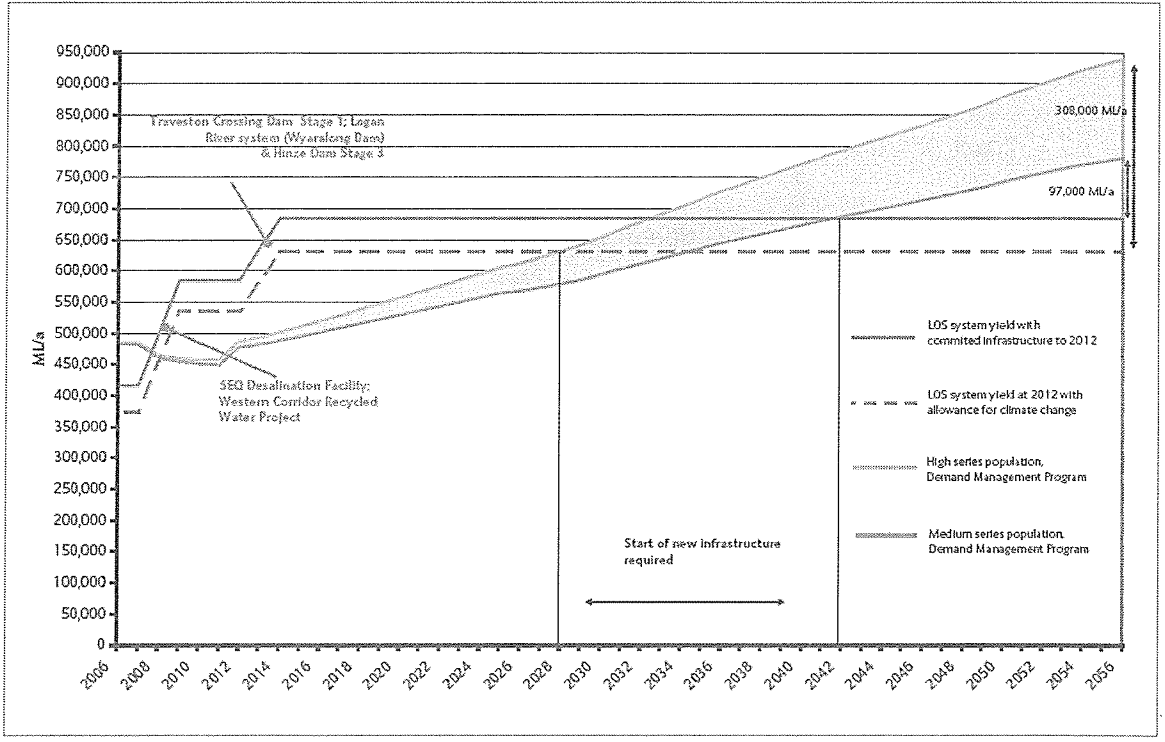
Moreover, SEQ continues to experience the fastest growth rate of any urban region in Australia. Currently, almost three million people live in SEQ and this figure could increase to more than six million by 2056 (Queensland Water Commission, 2009). Even with significant new efficiency measures to reduce water consumption, this sustained level of population growth is substantially increasing the region's demand for water. As a result, regional demand (based on pre-drought unrestricted demands) is expected to increase to 1,200 GL per annum by 2056. However, following the implementation of the demand management program and potable water substitution projects described in the SEQRWSS, projected potable water demand is expected to be about 900 GL per annum. This is based on a 'Permanent Water Conservation Measure' (PWCM) of 230 litres of consumption per person per day, which is a significant reduction compared to pre-drought consumption of over 300 litres per person per day (Gardner, Yeates, & Shaw, 2008).

### 3.1.2 SEQs 'Supply Gap'

Taken overall, the anticipated future demand of 750 GL - 900 GL per annum cannot be met by the likely long term supply of 416 GL per annum from existing dams (Gardner, Yeates, & Shaw, 2008). Hence, even with the PWCM target of 230 litres of consumption per person per day in place, the Queensland Water Commission estimates between 97 GL and 308 GL per annum of additional water will be needed by 2056, of which 69 GL - 203 GL per annum will need to come from 'climate resilient' sources (Queensland Water Commission, 2008). Climate resilient water sources include; wastewater recycling for power station supply, industrial reuse and to augment drinking water supplies by replenishing dams, sea water desalination for potable uses, and the extensive pipeline network of the SEQ Water Grid connecting existing and new water sources (Gardner, Yeates, & Shaw, 2008).

The SEQRWSS is forecast to reduce the supply gap (that is, the demand for additional supplies over and above supply provided by existing and committed infrastructure) by approximately half by 2056. Two projects anticipated to provide the bulk of this target, are; the Western Corridor Recycled Water Scheme for replenishing dams and power station supply, and the Gold Coast Desalination Plant. These projects are expected to supply up to 128 GL per annum, which is 63% of the climate resilient target. However, there still remains a shortfall of supply of 100 GL – 300 GL per annum by 2056, over and above all existing and future planned infrastructure to 2056, as shown by Figure 13 below (ARUP, 2009). The Queensland Water Commission (QWC) (p.137, 2008) suggests that "the supply gap would increase significantly with climate change or high series population growth. Under a worst case scenario, the supply gap is forecast at 597 GL per annum."

**Figure 13: SEQ Supply Gap in Normal Operating Mode (Queensland Water Commission, 2008)**



## 3.1.3 SEQs Political Framework for Future Water Supply

To address the water supply challenges SEQ faced, the Queensland Government developed a long term strategy, the SEQRWSS, which assessed the long-term supply options for the area, demand forecasts and levels of service required. From this, strategies were developed for regional, urban, industrial and rural water supply and distribution to meet future needs of SEQ (Queensland Water Commission, 2009). To realize these strategies the Queensland Government implemented the Water Regulation 2002 as an amendment to the Water Act 2000. Within this regulation, a number of emergency water supply projects were outlined, at a total cost of AU$9 billion. The projects are a coordinated set of actions to be undertaken by a number of State and Local Government entities and include (Government of Queensland, 2002):

- The construction of an inter-connected water pipeline, throughout the south east;
- The construction of the 'Western Corridor Recycled Water Scheme' and the Gold Coast Desalination Plant;
- The upgrading or construction of several dams, weirs, bores and reservoirs;
- The upgrading of the Enoggera Water Treatment Plant; and
- Implementing water efficiency measures to reduce urban water demand.

The Regional Water Security Program sets out these actions and facilitates the achievement of the desired levels of service objectives for SEQ (Queensland Water Commission, 2010). The program was introduced in November 2006 under section 1141 of the Water Act 2000. Key outcomes of the program include:

- Developing a System Operating Plan; and
- Ensuring key actions and responsibilities are complied with.

The South East Queensland System Operating Plan outlines the rules for operating the Water Grid, including the desired levels of service objectives for the region.

## 3.2 OTEC Application

As calculated above, the volume of fresh water produced is assumed to be 200,000 $m^3$/d or 200 ML/d for the Project. This equates to 63 GL per annum, which is roughly 63% of the 'supply gap' existing in SEQ to 2056, on medium demand growth forecast. This would also account for 31% of the climate resilient target of 203 GL/a. In summary, based on the conservative distillate to warm water ratio of 0.60%, the proposed OTEC 100 MW plant would provide 63% of SEQs needed fresh water to 2056. What's more, this supply would be climate resilient.

Given that the SEQRWSS has earmarked desalination plants to cover the supply gap, it is worth while assessing the costs of the supply alternatives for comparison. Taking the existing Gold Coast Desalination Plant as a model for future SEQ desalination plants, we can make the following assumptions:

- Plants will have a similar capacity of 133 ML/d, which equates to 49 GL per annum (Water Secure). Thus we can assume that in order to meet the 100 GL per annum supply gap, an additional two desalination plants will be built in SEQ by 2056. The capital costs of constructing these plants should be factored when assessing a cost benefit analysis, compared to the proposed OTEC plant.
- The plants will consume about 3.2 megawatt hours (MWh) of energy per ML produced. So at full production, each plant consumes about 412.3 MWh of energy per day (Water Secure). This equates to 301 GWh per year consumed to produce the 100 GL required. The cost of this energy consumption will be assessed as above in Chapter Six.

# 4 CHAPTER FOUR: THE $CO_2$ SEQUESTRATION POTENTIAL OF DOW

In this section, Australia's GHG emissions will be framed within the context of the federal Government's commitments and goals for reducing the country's carbon footprint. Then, utilising the DOW once it has been through the OTEC system, the potential of algae cultivation will be assessed, with the view that the algae can be refined to produce biodiesel. The biodiesel provides a renewable substitute for the transportation sector, and will reduce Australia's emissions inventory. The value of this biodiesel and carbon credits obtainable will be assessed in the Chapter Six.

## 4.1 Australia GHG Context

### 4.1.1 Australia's Framework for Reducing GHGs

According to the Stern report (2006), Australia is one of the country's most at risk from climate change. As such, the Australian Government has set several long term targets in an effort to achieve a more sustainable future. The first is reducing Australia's GHG emissions by 60% below 2000 levels by 2050. To do this they committed to implementing a national emissions trading scheme by 2010. However, on 4 May 2009 the scheduled commencement date of the precursory Carbon Pollution Reduction Scheme (CPRS) was delayed by twelve months to 1 July 2011 in response to the global recession. In addition, a one-year fixed price period was established, setting the price of carbon permits at AU$10 per tonne of carbon in 2011-12 with the transition to full market trading to take place from 1 July 2012 (ESAA, 2009).

The second target of the federal government is to produce 20% of Australia's electricity from renewable sources by 2020. To achieve this goal, an additional 45,000 GWh's will need to be generated from renewable sources by 2020. The government established a transitional scheme, known as the expanded Renewable Energy Target (RET), which expanded the Mandatory Renewable Energy Target scheme targets set for 2010. The RET will be phased out between 2020 and 2030, after which the national emissions trading scheme is expected to be the main policy mechanism to drive reductions in greenhouse gas emissions (ESAA, 2009). On 20 August 2009, the federal government passed legislation which governs the RET; the Renewable Energy (Electricity) Amendment Bill 2009 and the Renewable Energy (Electricity) (Charge) Amendment Bill 2009. The Office of the Renewable Energy Regulator oversees the implementation of the existing Mandatory Renewable Energy Target scheme and will also administer the national RET scheme once it comes into operation.

The Australian Greenhouse Office was also set up to manage programs designed to reduce GHG emissions. It implemented the Mandatory Renewable Energy Target scheme in 2001 and administers specific programs, such as; the Renewable Remote Power Generation Program, the Photovoltaic Rebate Program, the Renewable Energy Industry Development Program, the Renewable Energy Equity Fund, and the Alternative Fuels Program (Becker, 2002).

### 4.1.2 Australia's Emissions Inventory

As shown by Table 2, Australia's national inventory was an estimated 537 Mt $CO_2e$ (million tonnes of carbon dioxide equivalent), over the four quarters to the December quarter of 2009.

Table 2: Australia's National Inventory: for the four quarters to December quarter 2009 (Department of Climate Change and Energy Efficiency, 2010).

| [illegible] | [illegible] | [illegible] | [illegible] |
|---|---|---|---|
| **National Inventory – Annex A sectors** | | | |
| Energy – Electricity | 207 | 202 | -2.0% |
| Energy – Stationary energy excluding electricity | 93 | 89 | -4.2% |
| Energy – Transport | 80 | 79 | -0.7% |
| Energy – Fugitive emissions | 39 | 41 | 3.1% |
| Industrial processes | 31 | 27 | -10.6% |
| Waste | 15 | 15 | 1.5% |
| Agriculture | 86 | 84 | -2.8% |
| **National Inventory total[(b)]** | **550** | **537** | **-2.4%** |

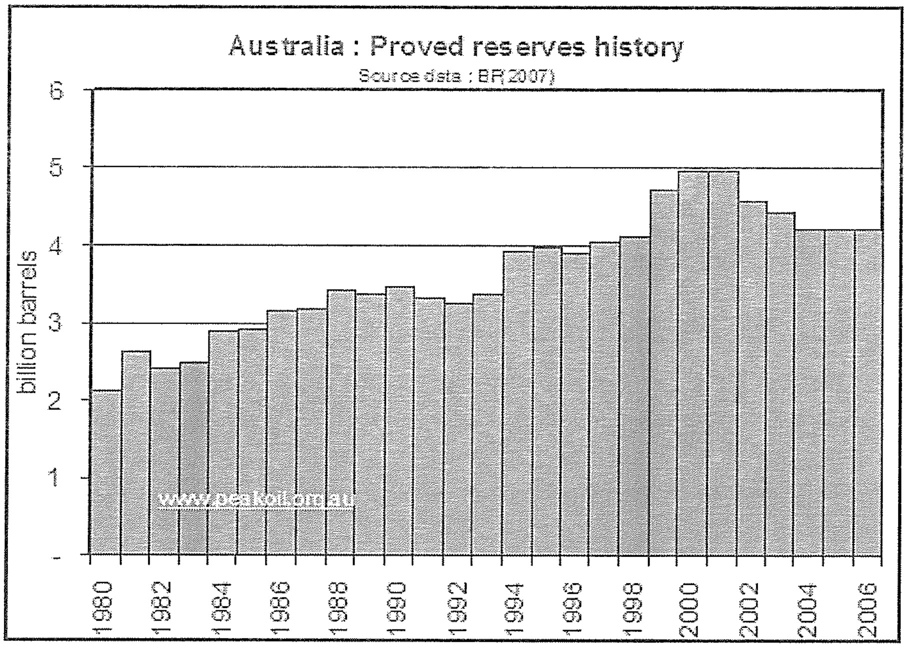
Source: Department of Climate Change and Energy Efficiency preliminary estimates.
Notes: (a) Carbon dioxide equivalent, $CO_2$-e; this concept enables the aggregation of individual greenhouse gases through the use of Global Warming Potentials (GWPs).
(b) The national inventory total does not include estimates of net credits from article 3.3 Land Use, Land Use Change and Forestry activities, which are estimated on an annual basis only.
(c) Values are estimates of annual emissions through to the end of the December quarter.
(d) The percentage change is the year on year grow h rate for the December quarter (ie the increase in emissions for the four quarters to the December quarter over the corresponding period of the previous year).

According to the Department of Climate Change and Energy Efficiency (p.8, 2010), "in 2008 Transport contributed 80.2 Mt $CO_2$ -e or 14.6% of Australia's national inventory emissions. Transport emissions are one of the strongest sources of emissions growth in Australia. Emissions from this sector were 29.2% higher in 2008 than in 1990, and have increased by about 1.4% annually on average. Between 2007 and 2008, Transport emissions increased by 0.7%. Preliminary estimates for 2009 indicate that Transport emissions have decreased by 1.5% (1.2 Mt). Road transport was the main source of transport emissions and accounted for 86.3% (69.2 Mt) of 2008 transport emissions. Road transport emissions increased by 27.5% (14.9 Mt) between 1990 and 2008."

The vast majority of this Transport $CO_2$ is provided by oil. Australia consumes roughly 950,000 bbl/d (in 2008), of which 40% is imported (CIA, 2010). It's worth noting also, that

Australia's oil production peaked around 2000 – 2001, hence it will become more and more reliant on imported oil to meet domestic transportation needs.

**Table 3: Australia's Proved Reserves, 1980 - 2006 (PeakOil.org, 2007).**



## 4.2 Carbon Dioxide Sequestration & Carbon Credits

Life on Earth is carbon based, meaning humans rely on plants to photosynthesize (fix) atmospheric carbon dioxide into biological material (biomass), which is used for energy. In fact, even the fossil fuels that are consumed today were mostly produced by algal photosynthesis (Packer, 2009). It makes intuitive sense to use the same process to sequester the carbon dioxide that was released when these fossil fuels were burned. In fact, the oceans have already absorbed nearly half of the anthropogenic $CO_2$ generated since the industrial revolution, which has caused a measurable effect on the acidity of the water, effecting marine life, corals and carbonate containing microalgae (Riebesell et al., 2007 cited in Packer, 2009).

Carbon sequestration is the process of long-term storage of carbon dioxide or other forms of carbon to mitigate global warming. Another way of saying this is to remove $CO_2$ from the active carbon cycle. The key point to note here is that the process is one directional; once the carbon has been stored, it can no longer be used. This is an important distinction to make, as it implies that true 'sequestration' techniques are completely reliant on the value of the captured $CO_2$ to make it viable. In other words, the value of the carbon stored (as determined by the value of the carbon credits obtained) must be greater than the cost of sequestering it by a reasonable profit in order to make it attractive to investors.

Contrast this to a $CO_2$ neutral process, whereby the $CO_2$ is in fact 'trapped' within a closed carbon loop, such as the biofuels process. Here, every tonne of $CO_2$ emitted due to the combustion of the biofuels, is inherently absorbed by the next biofuels crop. Ergo, you can assume that no $CO_2$ is emitted from the operation, no matter what the scale of operations. Not only is this attractive from an environmental point of view, but this also makes more economic sense utilizing carbon credits as above. The only difference being the $CO_2$ emissions avoided (i.e. the carbon credits obtained) are perpetual. That is, every tonne of $CO_2$ emitted from burning biofuels is a tonne of $CO_2$ not emitted from fossil fuels. Since every tonne of biofuels $CO_2$ emitted is inherently reabsorbed, it represents a tonne of $CO_2$ avoided, therefore eligible for the same value of carbon credits. It is important to note however, that the production of biofuels from algae does not reduce atmospheric $CO_2$, because any $CO_2$ taken out of the atmosphere by the algae is returned when the biofuels are burned. Biofuels do eliminate the introduction of new $CO_2$ emissions by displacing fossil hydrocarbon fuels. Notwithstanding the above, the carbon captured by algae could be diverted to true sequestration pathways if the value of carbon makes it economically viable (Packer, 2009).

## 4.3 Biofuel Potential of Microalgae

A biofuel is simply any fuel (solid, liquid or gas) that is derived via chemical, physical or biological process from biomass. Biomass is organic matter derived from living organisms, namely plants. Plants are able to convert $CO_2$ to biomass, utilizing the energy from the sun via photosynthesis. Because this $CO_2$ is converted into chemical energy it can then be converted into fuels, thereby creating a carbon neutral fuel source (Demirba, 2004).

Algae are eukaryotic organisms (those with cells displaying a high degree of internal organization, including a membrane bound nucleus and several other internal parts that are also surrounded by membranes). Algae can be either fresh water or marine, although some grow optimally at intermediate saline levels and some in hyper saline conditions (Packer, 2009). They are photoautotroph organisms which perform oxygenetic photosynthesis, and can be thought of as either; seaweeds or microalgae.

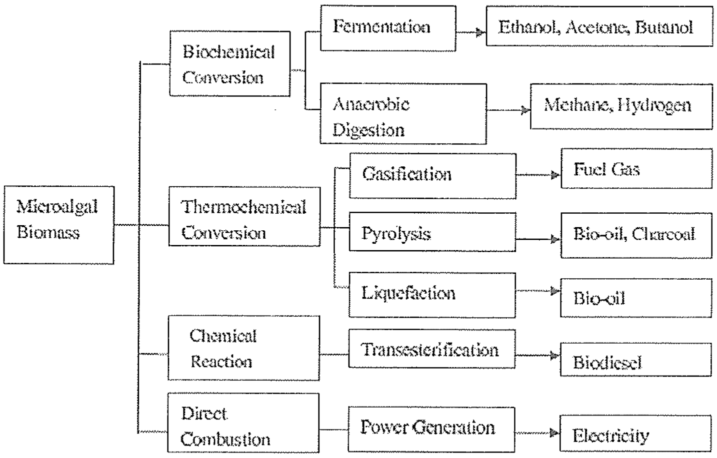
Microalgae are, as the name suggests, microscopic algae. Many are unicellular and can be motile or non-motile depending on the presence of flagella. Where multi-cellular conglomerations exist, very little specialization of cell types occurs, distinguishing them from seaweeds. There are a huge range of different types of microalgae including (non- exclusively) dinoflagellates, the green algae (Chlorophyceae), the golden algae (Chryosophyceae) and diatoms (Bacillario- phyceae) (Packer, 2009). Packer (2009) provides a brief synopsis of Green Algae and Diatoms and their usefulness as biofuel feedstock as follows:

- Green algae include about 8,000 species, covering both marine and fresh water environments and contain complex long-chain sugars (polysaccharides) in their cell walls. These carbohydrate cell walls account for a large proportion of the carbon contained in these organisms, though many species contain quite high levels of various lipids (circa 20%) and for some species under certain situations this has been quoted as up to 80% oil by wet weight.
- Diatoms are a group including approximately 100,000 organisms which dominate marine phytoplankton. They have silicate cell walls and have been of considerable interest in the area because they can accumulate very high levels of lipid. Lipids are 'natural' fats and oils. That is, they are produced by biochemical processes rather than fossilization, as petroleum oils are. Diatoms, like many other organisms, use the tri-acylglycerol lipid molecules (TAGs) as energy storage molecules that can be easily transesterified to biodiesel. Transesterification is the process of reacting triglycerides with an alcohol (usually methanol), using either sodium or potassium hydroxide as a catalyst (Potter & McCaffery, 2006). The process involves displacing the glycerol molecule from the triglyceride (fatty acid molecule) with a methanol molecule. This produces methyl esters (biodiesel) and the co-product glycerin.

Microalgae are able to grow and fix $CO_2$ at much higher rate than conventional forestry, agriculture and aquatic plants. In fact, they have the ability to fix $CO_2$, utilizing solar energy, at an efficiency of ten to fifty times greater than that of terrestrial plants (Li et al., 2008). As a tool for sequestering carbon, Stewart and Hessami (2005) found that a 4,000 $m^3$ pond under natural daily light exposure cycles could sequester up to 2.2 kt of $CO_2$ per year.

As the microalgae grow they produce biomass which can be converted into usable energy via; Biochemical Conversion, Thermochemical Conversion, Chemical Reaction or Direct Combustion, as shown in Figure 14:

**Figure 14: Energy production via different processes (Wang, Li, Wu, & Lan, 2008).**



Not only is the algal biomass produced more efficiently, it also contains high levels of lipids. Assuming an average oil content of 42%, Packer (2009) confirmed, from recent studies and current commercial production in the USA, that algae are generally thirty times more productive with regards to oil production then the leading terrestrial oilseed crops (i.e. the sum of soy, rapeseed, sunflower and palm). Some species of micro algae, however; contain up to 80% lipids, as shown in Table 4, and production rates of algae in open ponds can currently reach up to 300 t/ha/y of dry weight. Current methods for extracting these lipids are extremely efficient too; up to 95% of the total oil present in the algae can be removed using solvent extraction methods.

Table 4: Microalgal lipid content % dry weight Becker (1994) & Moheimani and Borowitzka (2005) cited in Packer (2009).

| Species | Lipid % dry weight |
|---|---|
| *Botyococcus braunii* | 80 |
| *Chlorella protothecoides* | 57.9 |
| *Nannochloris sp.* | 30–50 |
| *Pleurochrysis carterae* | 30–50 |
| *Chlorella pyrenoidosa* | 46.7 |
| *Scenedesmus dimorphus* | 16–40 |
| *Prymnesium parvum* | 22–38 |
| *Dunaliella tertiolecta* | 35.6 |
| *Hormidium Sp.* | 38 |
| *Chlorella vulgaris* | 14–22 |
| *Tetraselmis sueica* | 20 |
| *Euglena gracilis* | 14–20 |
| *Scenedesmus obliquus* | 12–14 |

This means cultivating algae requires much less land area than other biodiesel feedstock's of agricultural origin, therefore; the competition for arable soil with other crops, in particular for human consumption, is greatly reduced (Mata et al., 2010). As the Table 5 shows, the land area required for microalgae cultivation is far less then equivalent biodiesel sources:

**Table 5: Comparison of microalgae with other biodiesel feedstocks (Mata, Martins, & Caetano, 2010).**

| Plant source | Seed oil content (% oil by wt in biomass) | Oil yield (L oil/ha year) | Land use ($m^2$ year/kg biodiesel) | Biodiesel productivity (kg biodiesel/ha year) |
|---|---|---|---|---|
| Corn/Maize (*Zea mays* L.) | 44 | 172 | 66 | 152 |
| Hemp (*Cannabis sativa* L.) | 33 | 363 | 31 | 321 |
| Soybean (*Glycine max* L.) | 18 | 636 | 18 | 562 |
| Jatropha (*Jatropha curcas* L.) | 28 | 741 | 15 | 656 |
| Camelina (*Camelina sativa* L.) | 42 | 915 | 12 | 809 |
| Canola/Rapeseed (*Brassica napus* L.) | 41 | 974 | 12 | 862 |
| Sunflower (*Helianthus annuus* L.) | 40 | 1070 | 11 | 946 |
| Castor (*Ricinus communis*) | 48 | 1307 | 9 | 1156 |
| Palm oil (*Elaeis guineensis*) | 36 | 5366 | 2 | 4747 |
| Microalgae (low oil content) | 30 | 58,700 | 0.2 | 51,927 |
| Microalgae (medium oil content) | 50 | 97,800 | 0.1 | 86,515 |
| Microalgae (high oil content) | 70 | 136,900 | 0.1 | 121,104 |

These substantial benefits to microalgae as a feedstock are largely due to its less complex structure, fast growth rate, and high oil content. Packer (2009) does mention, however; the trade off that seems to exist between biomass production rates and oil yield. That is, species with faster growth rates tend to produce relatively less lipid content. He also notes that the remaining biomass, after the biodiesel production process, has the potential to cause problems on large scale applications. Already there is an oversupply of glycerol on the world market, which is a by product of the transesterification of TAGs, due to the biodiesel production from terrestrial crops. However, this waste could be utilised for plastic production, anaerobic digestion for methane production, or as fertilizers.

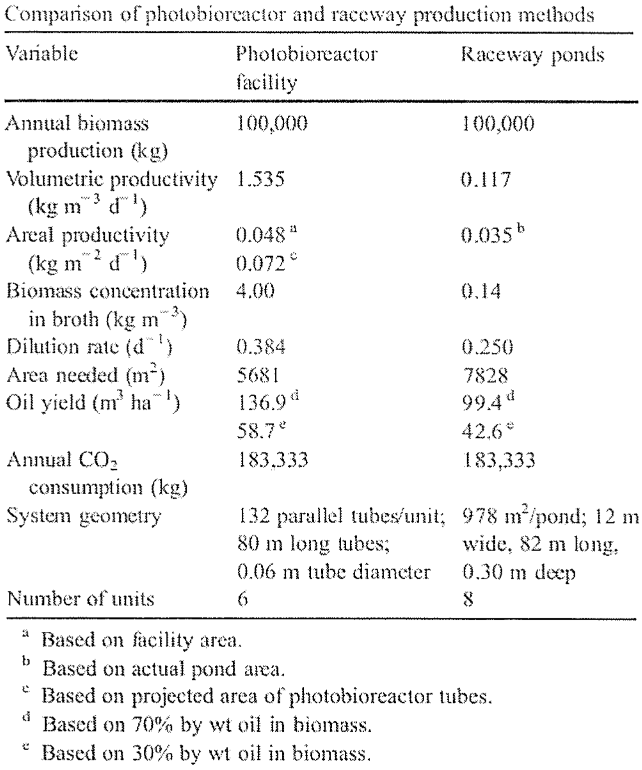
Much research has been done as to the specific strain of algae is most appropriate for various applications. Wang et al. (2008) suggest the Botryococcus braunii shows promise as a candidate for a combined $CO_2$ mitigation and biofuels producer, as it contains high levels of hydrocarbons. However, it is not the purpose of this paper to make recommendations as to specific strains of algae to be used. For demonstration purposes, however; production rates for some common algae strains are shown below.

**Table 6: Biomass productivity figures for open pond production systems (Brennan & Owende, 2010).**

| Algae species | $X_{max}$ (g l$^{-1}$) | $P_{aerial}$ (g m$^{-2}$ day$^{-1}$) | $P_{volume}$ (g l$^{-1}$ day$^{-1}$) |
|---|---|---|---|
| *Chlorella* sp. | 10 | 25 | – |
| N/A | 0.14 | 35 | 0.117 |
| *Spirulina platensis* | – | – | 0.18 |
| *Spirulina platensis* | 0.47 | 14 | 0.05 |
| *Haematococcus pluvialis* | 0.202 | 15.1 | – |
| *Spirulina* | 1.24 | 69.16 | – |
| Various | – | 19 | – |
| *Spirulina platensis* | 0.9 | 12.2 | 0.15 |
| *Spirulina platensis* | 1.6 | 19.4 | 0.32 |
| *Anabaena* sp. | 0.23 | 23.5 | 0.24 |
| *Chlorella* sp. | 40 | 23.5 | – |
| *Chlorella* sp. | 40 | 11.1 | – |
| *Chlorella* sp. | 40 | 32.2 | – |
| *Chlorella* sp. | 40 | 18.1 | – |

Nor is it the objective of this paper to recommend a particular end fuel type or production process, however; for the purposes of economic assessment it is assumed that all biomass produced will be utilised in biodiesel production. It is worth mentioning that algae biodiesel contains no sulphur and performs as well as petroleum diesel, while reducing emissions of particulate matter, CO, hydrocarbons, and SOx (Mata et al., 2010). Ogbonna & Tanaka (1997) note that most commercial algae production use open cultivation ponds as no efficient large-scale photobioreactors are yet available. However, it is difficult to obtain high productivity in open ponds because light intensity varies throughout the day and year. In addition, open ponds require a large surface area, and problems with contamination arise. For the purposes of this paper, both open 'raceway' ponds and closed photobioreactor systems will be assessed to calculate the potential biodiesel production rates. Chisti (2007) summarises the parameters needed to produce 100,000 kg/y of biomass for each production system in Table 7. Note, the algae production rate used in the open 'raceway' system (0.117 kg/m$^3$/d) is roughly the average of Brennan & Owende's production rates above (i.e. kg/m$^3$/d = g/L/d).

**Table 7: Comparison of photobioreactor and raceway production methods (Chisti, 2007).**



Comparison of photobioreactor and raceway production methods

| Variable | Photobioreactor facility | Raceway ponds |
|---|---|---|
| Annual biomass production (kg) | 100,000 | 100,000 |
| Volumetric productivity (kg m$^{-3}$ d$^{-1}$) | 1.535 | 0.117 |
| Areal productivity (kg m$^{-2}$ d$^{-1}$) | 0.048 [a]<br>0.072 [c] | 0.035 [b] |
| Biomass concentration in broth (kg m$^{-3}$) | 4.00 | 0.14 |
| Dilution rate (d$^{-1}$) | 0.384 | 0.250 |
| Area needed (m$^2$) | 5681 | 7828 |
| Oil yield (m$^3$ ha$^{-1}$) | 136.9 [d]<br>58.7 [e] | 99.4 [d]<br>42.6 [e] |
| Annual $CO_2$ consumption (kg) | 183,333 | 183,333 |
| System geometry | 132 parallel tubes/unit; 80 m long tubes; 0.06 m tube diameter | 978 m$^2$/pond; 12 m wide, 82 m long, 0.30 m deep |
| Number of units | 6 | 8 |

[a] Based on facility area.
[b] Based on actual pond area.
[c] Based on projected area of photobioreactor tubes.
[d] Based on 70% by wt oil in biomass.
[e] Based on 30% by wt oil in biomass.

Using these parameters, and assuming 100% utilisation of the DOW effluent, the theoretical maximum algal production was calculated as follows (refer Appendix B):

Table 8: Algae production via photobioreactor and raceway methods

| | BIOMASS of Algae Produced (kg/y) | BIODIESEL Produced (kg/y) |
|---|---|---|
| **PHOTOBIOREACTOR PRODUCTION** | | |
| 30% Oil Yield or Algae (wt in BIOMASS) | 9,681,552,000 | 2,323,572,480 |
| 70% Oil Yield or Algae (wt in BIOMASS) | 9,681,552,000 | 5,421,669,120 |
| **'RACEWAY' PRODUCTION** | | |
| 30% Oil Yield or Algae (wt in BIOMASS) | 737,942,400 | 177,106,176 |
| 70% Oil Yield or Algae (wt in BIOMASS) | 737,942,400 | 413,247,744 |

### 4.3.1 Potential of DOW for other Aquaculture

As mentioned previously, one of the most important components of an OTEC system is the continuous supply of DOW pumped up from depths. This 'heat sink' once expelled from the OTEC condenser, can be of further use as a valuable resource for aquaculturists. Wright (1996) explained that the DOW not only has a low temperature, but it is also rich in nutrients. Compared to warm surface water, inorganic nitrate-nitrite, phosphate and silicate values in DOW are 190 times, 15 times and 25 times higher respectively, which could be utilised for growing a mix of aquatic animals and plants. Other benefits stemming from the OTEC effluent streams is their ability to provide flexible, accurate and consistent temperature control, high volume flow rates, and sea water that is relatively free of biological and chemical contaminants.

## 4.4 Australian application of DOW for Biofuel

Cultivation of algae is not new to Australia. There are several ponds (in the order of 50 ha total area) for the mass culture of Spirulina existing already (Packer, 2009). Australia also has an active, albeit relatively small biodiesel industry, as shown in Table 9.

Table 9: Current Biodiesel production in Australia (Biofuels Association of Australia, 2010).

| Biodiesel plant | Location | Owner (* BAA Member) | Capacity (ML) (at 01.01.09) | Feedstock | Status (at 01.01.09) |
|---|---|---|---|---|---|
| Eco Tech Biodiesel Plant | Narangba, Qld | Gull Group * | 30 | Tallow; used cooking oil | Not in production |
| BIA Biodiesel Plant | Maitland, NSW | Biodiesel Industries Australia * | 20 | Used cooking oil; vegetable oil | In production |
| BPL Biodiesel Plant | Wodonga, Vic | Biodiesel Producers Limited * | 60 | Tallow; used cooking oil | In production |
| Laverton Biomax Plant | Melbourne, Vic | Smorgon Fuels Pty Ltd * | 15 | Tallow; used cooking oil; vegetable oil | In production |
| Moama Biodiesel Plant | NSW/Vic border | Future Fuels | 30 | Tallow; used cooking oil | Not in production |
| ARF Largs Plant | Adelaide, SA | Australian Renewable Fuels Limited * | 45 | Tallow | In production |
| ARF Picton Plant | S-WA | Australian Renewable Fuels Limited * | 45 | Tallow | In production |
| National Biofuels Plant | Port Kembla, | National Biofuels | 300 | Soya | Not yet constructed |
| TOTAL CAPACITY (ML) | | | 245 | | |

The main difference between existing production and the DOW application proposed herein, however; is the volume of water involved. Some 200 m/s of DOW is available from the OTEC system. This is a huge flow of water, capable of filling an Olympic sized swimming pool in 12.5 seconds. Current literature and commercial algal cultivation technology focuses on production rates per m$^2$ of land area, as this represents the amount of sunlight available – the limiting factor of growth. The flow rate through the system is minimal in an effort to control the inputs to the system. For example, if pathogens are introduced, they could destroy the entire culture. Substantial amounts of nitrogen and phosphorus (in the form of ammonia, urea and superphosphate fertilisers) and small amounts of iron (iron sulphate fertiliser) need to be added regularly to the algae ponds, in addition to the carbon dioxide to stimulate growth (Campbell et al., 2009). Although, as mentioned previously, DOW is rich in these minerals and pathogen free, therefore; the DOW flow replaces the need for additional inputs. Furthermore, given the magnitude of the DOW resource, this paper will focus on maximum algae production based on theoretical optimization to demonstrate the potential of DOW.

## 4.5 Other benefits of Microalgae

Aside from its high growth rate, Mata et al (2010) outline several other benefits of cultivating algae for biofuel production:

- It is easy to cultivate and to obtain nutrients for;
- It can grow with little or even no attention; and
- It can use water unsuitable for human consumption (i.e. it can be grown in wastewater).

In short, microalgae can grow almost anywhere, requiring only sunlight and some simple nutrients, although the growth rates can be accelerated by the addition of specific nutrients and sufficient aeration.

These benefits create several other opportunities for the cultivation of algae that are not directly related to the production of biofuel. As such, they will not be discussed in much detail herein, however; it is worth mentioning a few of these possibilities as they may indeed be able to be incorporated into the proposed project, further enhancing the value of the DOW.

### *Wastewater treatment*

A promising added application to microalgal growth stems from its capacity to biologically clean. The extra nutrition available in some industrial wastewaters stimulates growth of microalgae which utilise the organic compounds (nitrogen and phosphorous). Mallick (2002, cited in Chisti, 2007) found that microalgae are efficient at removing nitrogen, phosphorus and iron from wastewater. In fact, Aslan and Kapdan (2006, cited in Mata et al., 2010) used C. vulgaris for nitrogen and phosphorus removal from wastewater with an average removal efficiency of 72% for nitrogen and 28% for phosphorus. Additionally, Mata et al. (2010) found that microalgae can mitigate the effects of sewage effluent and industrial sources of nitrogenous waste such as those originating from water treatment or fish aquaculture and at the same time contributing to biodiversity. Moreover, removing nitrogen and carbon from water, microalgae can help reduce the eutrophication in the aquatic environment. Thus, utilising wastewater streams will potentially reduce the need for treatment plants, while significantly enhancing the environmental benefits of preserving freshwater reservoirs, and may also lead to cost savings by minimising the use of chemicals such as sodium nitrate and potassium phosphate as nutrients.

### *Flue gas treatment*

Algae can also be used to capture the $CO_2$ in flue gases. Sources of carbon rich exhaust include manufacturing facilities and electricity generation plants, especially those which burn coal. Flue gases from conventional power plants are responsible for more than 7% of the total world $CO_2$ emissions (Wang et al., 2008). Thermal power plant flue gases contain between 3% and 15% $CO_2$ depending on the fuel source and design of the plant; coal-fired plants generally having higher $CO_2$ emissions. As already discussed, this is an important nutrient for any photosynthetic organism, and when delivered to algal cultures in a variety of different ways most studies indicate that $CO_2$ addition to algal cultures stimulates growth (Packer, 2009). This approach not only provides the raw materials for the system; it changes those wastes into resources (Mata et al., 2010). Furthermore, Packer (2009) found that NOx levels present in flues gases pose no problem for algal growth. He found that the main impact is SOx where the pH of the culture, through the formation of sulphuric acid, can become a problem for some species if the flue gas concentration of SOx is above 400 ppm (Matsumoto et al. cited in Packer, 2009). He cites a variety of studies that look at different algal species, power plant and fuel-types including coal, some scrubbed for SOx (many of the 'dirtier' plant emissions are already scrubbed using existing but expensive technology to below this level for other reasons such as acid rain prevention), heavy fuel oil, or natural gas and use different methods of application (pulsed or continuous). He found the data to be consistent over different scales and growth systems, from enclosed research and pilot-scale through to large-scale open raceways and some of the studies extend for long periods.

Some commercial interests into large scale algal-cultivation systems are looking to tie in to existing infrastructures, such as coal power plants or sewage treatment facilities. These can easily be retrofitted to existing plants; all that is required is the redirection of flue output. If smokestack emissions are diverted to an algae bioreactor, carbon dioxide and other pollutants are almost completely absorbed and utilized by the algae reducing carbon emissions and improving air quality. This certainly has potential in the Australian context, as it is heavily reliant on coal fired power plants.

### *Toxic remediation*

Packer (2009) found no data to suggest that mercury (Hg) has any detrimental effects on algal growth and in fact it has been demonstrated that some algae may bio-convert Hg between forms representing a possible route to toxic remediation (Kelly et al. cited in Packer, 2009). However, he notes that bioaccumulation of metals may be important if high-value nutritional oils are the goal (for food production), especially from coal-fired plants.

### *Other Uses*

Algae can also be utilized as a food source. At present, about 5,000 t of food and feed-grade microalgae biomass is produced annually in large open pond systems (Herzog & Golomb, 2004). In Japan, for instance, Chlorella and Spirulina biomass is grown commercially to produce health foods (Ogbonna & Tanaka, 1997). Packer (2009) points out that many algae contain high proportions of long chain fatty acids with a high degree of unsaturation. These very long chain polyunsaturated fatty acids have nutritional and 'nutraceutical' applications for humans.

Mata et al. (2010) also note that depending on the microalgae species, various high-value chemical compounds may be extracted such as; pigments, antioxidants, b-carotenes, polysaccharides, triglycerides, fatty acids, and vitamins, which are largely used as bulk commodities in different industrial sectors (e.g. pharmaceuticals, cosmetics, nutraceuticals, functional foods). Because of this variety of high-value biological derivatives, with many possible commercial applications, microalgae can potentially revolutionize a large number of biotechnology areas including; cosmetics, pharmaceuticals, nutrition and food additives. However, so far microalgae cultures have been more successful as a food source and feed additive in the commercial rearing of aquatic animals. As at 2004, the microalgae industry was producing 7,000 t of dry matter per annum for a variety of uses, as shown in Table 10.

Table 10: Microalgal production in 2004 (Brennan & Owende, 2010).

| Microalgae | Annual production | Producer country | Application and product | Price (€) |
|---|---|---|---|---|
| *Spirulina* | 3000 tonnes dry weight | China, India, USA, Myanmar, Japan | Human nutrition | 36 kg$^{-1}$ |
| | | | Animal nutrition | |
| | | | Cosmetics | |
| | | | Phycobiliproteins | 11 mg$^{-1}$ |
| *Chlorella* | 2000 tonnes dry weight | Taiwan, Germany, Japan | Human nutrition | 36 kg$^{-1}$ |
| | | | Cosmetics | |
| | | | Aquaculture | 50 l$^{-1}$ |
| *Dunaliella salina* | 1200 tonnes dry weight | Australia, Israel, USA, Japan | Human nutrition | |
| | | | Cosmetics | |
| | | | B-carotene | 215–2150 kg$^{-1}$ |
| *Aphanizomenon flos-aquae* | 500 tonnes dry weight | USA | Human nutrition | |
| *Haematococcus pluvialis* | 300 tonnes dry weight | USA, India, Israel | Aquaculture | 50 l$^{-1}$ |
| | | | Astaxanthin | 7150 kg$^{-1}$ |
| *Crypthecodinium cohnii* | 240 tonnes DHA oil | USA | DHA oil | 43 g$^{-1}$ |
| *Shizochytrium* | 10 tonnes DHA oil | USA | DHA oil | 43 g$^{-1}$ |

## 4.6 Other uses for DOW

There are many applications for utilizing the richness of deep ocean water, collectively known as Deep Ocean Water Applications (DOWAs). This paper has focussed on utilising the DOW strictly for algae cultivation with the view to produce biofuels from the biomass. However, there are several other DOWAs that may be incorporated into the Project, or as a substitute. Whilst they are not discussed in much detail herein, it is worth mentioning them to demonstrate the value of this resource.

### *Aquaculture*

The term 'aquaculture' simply refers to farming or cultivating marine organisms. DOW possesses three main characteristics that make it attractive for aquaculture:

1. It's cold. The temperature not only allows the culture of many valuable marine organisms that would not normally grow in the tropics, but it also provides cost effective temperature control of large volumes of seawater, for optimal growth conditions of a wide variety of organisms.

2. It's enriched with nutrients. DOW contains many times more nitrogen, phosphorous and silicate then surface sea water (Tanner, 1995; Takahashi, 2003; Wright, 1996). These elements feed the building blocks of life in the ocean.
3. It's clean. DOW is free of pathogens which hinder aquaculture activities.

In fact, the potential of DOW is already widely known and exploited by fishermen; more than 40% of all fish caught comes from 0.1% of the ocean where natural upwelling exists, where DOW is brought to the surface by the topography of the ocean floor and currents (Takahashi, 2003). Phytoplankton converts the nutrient organic materials into feed, which shellfish, seaweed and fish consume and grow at greatly enhanced rates.

Other organisms such as salmon, trout, abalone, oyster, lobster, giant sea clam, sea urchin, seaweed and microalgae have been successfully grown in the OTEC cold water system. However, as Write (1996) explains; the economics of OTEC-based aquaculture is site-dependent. "Commercial viability of an aquaculture operation relies in good measure on local market needs, social customs, consumer acceptance and economic returns. In essence, there is still too little experience in OTEC-based aquaculture to predict with confidence its future success" (p.130). That is not to say there isn't immense value to be extracted from DOW via aquaculture, just that more work on larger scales needs to be done. The Project offers such an opportunity.

### *Pharmaceuticals & Mining*

DOW is also rich in minerals, making it a valuable resource for pharmaceutical activities and mineral extraction (Tanner, 1995). As Post (1983) points out, the ocean is a virtual minerals producer; as dissolved minerals are replenished faster than humans can consume them. Each cubic mile of sea water contains about 165 million tons of dissolved minerals, totalling 50 quadrillion (50 $\times 10^{12}$) tons. Salt, bromine and magnesium are currently being extracted from offshore seawater, however; commercial exploitation of other minerals such as uranium, platinum and gold depends on technological developments, and cost competitiveness of terrestrial sources.

### *Soil irrigation & climate control*

Exploiting the remaining heat sink potential of the DOW is another application. The DOW, still cool after passing through the condenser, could be utilised as cost effective air conditioning, or assistance to refrigeration and freezing systems or for agricultural purposes (Tanner, 1995).

Using piping and or heat exchangers, the DOW could help reduce the temperature of offices buildings or warehouses to close to 6°C. In other words, it could save the money expended in extracting the energy contained in the ambient air, which in SEQ is typically 25°C to 30°C.

Alternatively, the cool water could be passed through pipes buried in the soil, thereby enabling products of temperate climates, such as vegetables and tomatoes, to be grown in tropical zones—an application already occurring. This achieves two beneficial outcomes in terms of agriculture:

- The temperature difference between the roots and leaves of the plant induce a 'perpetual springtime. Thus many temperate plants could be grown in arid, sub-tropic climates where they would not normally grow; and
- The cold soil would also induce significant condensation from the humid atmosphere, providing a large fraction of the irrigation needed for the crops.

### 4.6.1 Other industrial applications of OTEC

Lennard (2004) suggests several other industrial applications of OTEC that make use of the electrical power produced in situ for energy-intensive products. For example, hydrogen may be produced by electrolyzing water, and that version of OTEC power can then be stored and transported to market—usually to industrialized nations outside the OTEC zones—as liquid hydrogen.

Alternatively again, hydrogen may be produced as an intermediate product, being used in turn to produce ammonia. Currently, the use of ammonia fertilizers is determined in part by production capacity from natural gas. The use of such fertilizers in the developing world, much of it in the tropical and subtropical zones where OTEC processes are available, could make a major contribution to world food production.

Finally, mention should be made of the production of some metals that requires considerable power input; for example, aluminium from bauxite. The location of an OTEC plant onshore by the bauxite deposits, or transportation of the deposits to an offshore plant with refined metal being shipped back on the return journey, are other, probably longer term options for application of OTEC power.

# 5 CHAPTER FIVE: ENVIRONMENTAL IMPACTS

OTEC appears to be environmentally benign; there are no combustion products or hazardous wastes created with its operation, as is the case with most other conventional energy production. However, there are some potential problems that need to be resolved before any large scale project can be implemented (Lavi & Lavi, 1979). Vega (1999) outlines some of the most pertinent environment impacts as follows.

## 5.1 Construction

There are significant environmental concerns during the construction phase of an OTEC plant, however; most are similar to those associated with the construction of any power plant or offshore platform. The most environmentally concerning aspects unique to OTEC applications is the construction of the CWP. Ocean Engineering and Energy Systems Inc. (OCEES) is an engineering consulting corporation which has been involved in OTEC development since 1988. They identify the fabrication and installation of deep-water pipelines as the single most expensive portion of any OTEC plant and the highest risk during construction. Furthermore, "because of these associated costs and risks, it is the least demonstrated major component of a large OTEC plant" (OCEES, 2002). Due to the threat of currents and waves, a buried or trenched method offers the most cost effective approach for protecting the pipeline from environmental loads. However, digging and blasting the trench can be environmentally damaging to reefs and the near shore region; therefore should only be pursued if other, more environmentally attractive means of traversing the near shore region prove unrealistic. The Natural Energy Laboratory of Hawaii Authority (NELHA) has developed less environmentally damaging alternatives to trenching, such as the gravity anchor mode, pendant mode or the long, inverted catenary mode. These designs are currently only conceptual for OTEC pipelines up to three metres in diameter, making use of segmented, fiber-reinforced plastic, deployed with the same controlled submergence techniques that have already been implemented in Hawaii. OCESS notes that tunnelling is the least environmentally intrusive pipeline scenario, albeit the most expensive. They outline two techniques and the benefits of tunnelling as follows:

> *"Tunnelling consists of two differing techniques for accomplishing the same effect — slant drilling and micro tunnelling. Slant drilling uses oil drilling techniques with a drill oil rig onshore pressing a drill bit and drill pipe through the soil at a fairly shallow angle to the approximately 60 foot depth. In the micro tunnelling approach, a large dry jacking pit is constructed onshore reaching well below sea level. A micro tunnelling machine with a drill bit equal in size to the outer diameter of the desired tunnel is pushed through the vertical wall of this onshore pit and continues to drill by adding drill pipe sections until reaching the offshore regions of 60 — 80 foot depths. Under each of these tunnelling configurations, the shoreline and seafloor regions are relatively undisturbed and prove the best protection for the near shore pipeline as well as the most environmentally favourable means of traversing the fragile shallow water region to a shore mounted OTEC facility" (OCEES, 2002).*

Given the cost savings of the proposed project, relative to other desalination alternatives to SEQ, as discussed in Chapter Six, this paper recommends further research into the feasibility of a tunnelled CWP. It may well be plausible that the most environmentally benign option is still cost competitive.

## 5.2 Operational

### *Water volumes*

The sheer volumes of warm and cold water required to run the proposed system is staggering. Some 200 $m^3$ of DOW and 400 $m^3$ of surface water needs to be pumped to the plant each second. This equates to 34.5 million $m^3$ and over 17 million $m^3$ per day or 12.6 billion $m^3$ and 6.3 billion $m^3$ per year of surface and deep water respectively. To put this into perspective, approved oil sands mining companies are licensed to divert 359 million m$^3$ per year from the Athabasca River (Griffiths, Taylor, & Woynillowicz, 2006). In other words, the proposed OTEC plant would require some 53 times the amount of water that the entire Alberta oil sands industry diverts from the Athabasca. This is more than 100 times the volume of water that is used by the City of Calgary each year.

These figures seem astronomical until one considers the vastness of the resource from which the water is being extracted. The oceans are enormous. Vega (1999) points out that the discharge from a 100 MW plant is equivalent to the nominal flow of the Colorado River into the Pacific Ocean. In other terms, this equates to 1/10th of the Danube, 1/30th of the Mississippi or 1/5th of the Nile in to the Atlantic. That's not to say that the accumulative effects of a global OTEC fleet should be ignored. The amount of total world power that could be provided by OTEC needs to be balanced with the impact to the marine environment. The discharge flow from 60,000 MW (1% of current electricity production (IEA, 2009)) or OTEC plants would be equivalent to the combined discharge from all rivers flowing into the Atlantic and Pacific Oceans (361,000 m$^3$/s). While he reiterates that river runoff is significantly different in composition to OTEC discharge, providing a significant portion of world electricity demand would have an impact on the environment below the oceanic mixed layer. This would inevitably lead to long-term effects in the marine environment.

### *Biostimulation / Eutrophication*

As mentioned previously, the DOW is rich with nutrients and carbon. If released, it has the ability to: at best improve local fishing, or at worst induce algal blooms and eutrophic conditions. This effect can be managed well by the integration of closed aquaculture applications, as discussed herein.

### *Antifouling*

Biofouling occurs on any surface exposed to the surface seawater. To have effective heat transfer, it is important to keep the surface materials of the heat exchangers clean and protected from unwanted growth. Chlorine ($Cl_2$) has been proposed along with several mechanical means to achieve this (Vega, 1999). To protect marine life, the Environmental Protection Agency (EPA) in the USA allows a maximum $Cl_2$ discharge of 0.5 mg/L and an average of 0.1 mg/L. A hybrid or open system would only need to use 20% of these limits, and a CCS less than 10%, as only the evaporators need to be anti-fouled (Vega, 1999).

### *Working Fluids*

With a CCS or Hybrid system, it is inevitable that small amounts of working fluid will be released during operation. If prudent occupational health and safety standards are met, working fluid of biocide (most probably anhydrous ammonia and chlorine) emissions from a plant should be too low to detect outside the plant site. A major release of working fluid of biocide would be hazardous to plant workers, and surrounding areas. Both ammonia and chlorine can damage eyes, skin and mucous membranes and can inhibit respiration. The risks of an accident occurring resulting in the release of large quantities of working fluid or biocide are similar to those in other industrial applications involving these chemicals e.g. fertilizer production or wastewater treatment (Vega, 1999). Additionally, metallic surfaces (heat exchangers, pumps and piping) exposed to sea water may be corroded or eroded, adding trace elements to the effluent. It is uncertain if these traces will prove toxic to local biota; however, due to the large volumes passing through the plant, trace metals will be quickly diluted (Vega, 1999).

### *Entrainment*

Organisms which become entrained in the OTEC water flows are likely to be impinged on screens protecting the intakes. This is likely to be fatal to the organism. If small enough, the organism may be drawn through the filters and pass through the plant. Entrained organisms may then be exposed to biocides, working fluid, oil and grease, and temperature and pressure shock. Although experiments suggest that mortality rates for phytoplankton and zoo plankton entrained by the warm water intake may be less the 100%, prudence suggests that for the purposes of assessment, 100% mortality is appropriate (Vega, 1999).

### *Salinity*

The discharge of brine concentrate produced from a desalination process can present a potential environmental risk for the receiving waters (Queensland Water Commission, 2008). In the case of SEQ, Moreton Bay is known to have poor flushing characteristics and is considered a sensitive environment.

However, as shown in section 3.2, the quantity of fresh water extracted during flash evaporation of the OTEC system represents only 0.60% of the surface water flow. This increase in salinity (of 0.60%) is negligible in comparison to the brine discharge of existing reverse osmosis plants. In any case, the effect of brine discharge has been extensively researched in the area by the QWC (2009), as part of the preliminary site selection process for future desalination plants. A detailed numerical hydrodynamic transport and water quality model was developed for the bay and surrounding open oceanic areas. The model was used to quantify the impacts of brine discharge by presenting the flushing time, the extent of the plume and the maximum concentration contour at the point of discharge. The model showed that dispersion through multiple diffuses along the sea floor can achieve safe mixing of effluent that has 66% increased salt concentration, which is typical for a 40% efficient reverse osmosis plant.

### *Temperature*

According to Lavi (1979), potential thermo-atmospheric modification outside the immediate OTEC vicinity is the single most important environmental issue facing OTEC. A sustained flow of cold DOW released at sea level could cause temperature anomalies if resident times in the mixed layer are long enough. OTEC effluent discharge experiments have found that mixed seawater returned at depths of 60 m results in dilution of one part OTEC effluent to three parts ambient seawater, and equilibrium depth below the mixed layer (Vega, 1999). This water return depth also provides the vertical separating from the warm water intake to avoid re-ingestion into the plant. It follows that the effects to marine life at the surface would be minimally affected, and that persistent surface temperature anomalies should not be induced (Vega, 1999).

The Project assumes that 100% of the DOW is utilized through the DOWA discussed above. The temperature of the DOW being discarded after the algal cultivation suggested herein is assumed to be similar to ambient surface temperatures. As such, the environmental impacts due to effluent temperature are expected to be minimal.

### *Dissolved Carbon*

Komiyama & Yamada (1995) found that in addition to the temperature difference, the chemical composition of the DOW differs significantly from surface water. This is mainly due to the vertical cycle of materials in the ocean. The 'plankton cycle', initiated by photosynthesis, creates the concentration gradients of organic and inorganic carbons, and fertilizing elements. The concentration of total organic carbon decreases with depth, since organic material produced by photosynthesis sinks and is oxidised and converted to inorganic carbon (i.e. $CO_2$, $HCO^{3-}$ and $CO_3^{2-}$).

When this is brought to the surface, at much lower pressure and higher temperature, much of the $CO_2$ is released. As mentioned previously, the project proposed herein assumes that 100% of the DOW is to be utilised by algae cultivation. Benemann et al. (1987) showed that up to 99% of $CO_2$ in solution is utilized by algae in large-scale open-pond systems. Under the assumption that the bulk of the dissolved $CO_2$ remains in solution by the time it reaches the cultivation ponds, then one can presume that this $CO_2$ will be sequestered by the algae. Furthermore, if the photobioreactors are used to grow the algae, the system is closed, therefore; very little $CO_2$ losses can be expected. In any case, Lavi & Lavi (1979) and Vega (1999) suggest that the release of $CO_2$ would be negligible due to the short transit time of the DOW through the CWP and condenser compared to the diffusion rate of dissolved $CO_2$. Any resulting $CO_2$ released during the operation of an OCS is less than 1% of the approximately 700 g/kWh released by fuel oil plants, and even lower in the case of CCS. For the purposes of this paper it is assumed that all dissolved $CO_2$ is absorbed by algae, contributing to the carbon credits obtained by the Project.

# 6 CHAPTER SIX: ECONOMIC ANALYSIS

As purely an electricity generating technology, OTEC is competing with a host of other renewable and non-renewable energy sources. As it stands today, in an economic sense, the environmental externalities of these other substitutes are not fully taken into account when selecting an energy producing system. Hence, the relative environmentally benign nature of OTEC is yet to play a significant role in its economic feasibility (Tanner, 1995). Furthermore, due to the low efficiency of the system (stemming from the small temperature difference), a large quantity of seawater has to be moved to obtain large amounts of thermal energy. This requires large equipment which is inherently more expensive. As a result the capital investment is relatively much higher than a conventional power system operating with a temperature difference of several hundred degrees (Rey & Lauro, 1981). However, as outlined in previous chapters there are many other benefits to this technology that offset the high capital cost.

This section, therefore, aims to assess the relative high cost of producing electricity with OTEC ($/kWh), offset by the desalinated water production, carbon credits and biofuel obtained through algae cultivation, and then equate this true cost to conventional power production in SEQ (Vega L. A., 1992). Then, the scenarios (i.e., fuel cost, cost of fresh water production, electricity prices and cost of carbon) under which OTEC is competitive can be obtained. As Vega (1992) points out, inherent to this approach is the assumption that operation and maintenance costs are proportionally the same for OTEC and conventional plants of the same power capacity. No attempt is made in this study to speculate about the future cost of oil or coal. The goal is simply to outline scenarios in which OTEC would be competitive.

## 6.1 Electricity Production

There is a large amount of inconsistency of estimates of OTECs capital costs by American and English researchers (Cavrot, 1993). The estimates used in this chapter are adjusted for inflation from Vega's (1992) study called "Economics of Ocean Thermal Energy Conversion (OTEC)". Vega investigated the feasibility of a range OTEC plants; 1 MW floating to 50 MW land based. The figures closet resembling the project proposed herein were of a 50 MW net hybrid ammonia power cycle plant with secondary stage water production, as seen in Table 12.

**Table 11: Capital Cost Estimates ($/kW-net) for 50 MW Land-Based Plants in 1990 US Dollars (Vega L. A., 1992).**

| | | |
|---|---|---|
| **PLANT NOMINAL SIZE:** | 50 MW; CC-OTEC | 50 MW; Hybrid Ammonia Power Cycle with 2nd-Stage Water Production |
| **PRODUCTION:** | | |
| **Electricity** | $336 \times 10^6$ kWh | $280 \times 10^6$ kWh |
| **Water** | n/a | 16.4 MGD (62,000 $m^3$/day) |
| **CAPITAL COST:** | 6,000 \$/kW | 9,4000 \$/kW |

For the purposes of this paper, it is assumed that these figures are a function of net output. That is, the proposed 100 MW net output plant would cost two times (100 MW / 50 MW) as much as a 50 MW net output plant – refer Table 12. Obviously this ignores any economies of scale and synergistic effects that larger infrastructure of a 100 MW plant may have. Essentially this budget accounts for two individual 50 MW plants built independently, side by side, including separate pipe systems. Whilst this may seem an absurd assumption to make, given the physical limitations of pipe dimensions that currently exist, there are no accurate estimates of larger scale OTEC output equipment because it has not yet been developed.

Table 12: Capital Cost Estimate for 100 MW Land-Based Hybrid in 1990 Dollars, based on Vega (1992).

| **Vega (1992) Capital Investment Estimate:** | 50 MW | Proposed 100 MW |
|---|---|---|
| Net Power Production (kW) | 50,000 | 100,000 |
| Net Energy Produced (kWh) | 180,000,000 | 360,000,000 |
| Internal Energy Consumption | 36% | 36% |
| Gross Energy Produced (kWh) | 280,000,000 | 560,000,000 |
| Water Produced (m3/d) | 62,000 | 124,000 |
| Capital Cost ($/kW) | $9,400 | $9,400 |
| Capital Cost ($) | $470,000,000 | **$940,000,000** |

As shown, this results in a capital estimate of a 100 MW net output Hybrid plant of $940 million, which equates to **$1.580 billion** in 2010 dollars (The Federal Reserve Bank of Minneapolis, 2010). Compared to the capital cost of a similar sized coal fired power plant, at around $247 million ($2,470 /kW) (POWER-GEN WORLDWIDE, 2010), the OTEC plant is 6.4 times more expensive.

As the capital investment and operating expense varies considerably between different technologies, it is useful to compare the levelised costs of power production. The levelised cost "represent the present value of the total cost of building and operating a generating plant over its financial life, converted to equal annual payments and amortized over expected annual generation from an assumed duty cycle (EIA, 2009)."

The levelised cost of OTEC power production is shown in Appendix C, as based on Vega's methodology (1992). The results are shown below, in comparison to conventional coal. The levelised cost of conventional coal power production is taken from the 2009 EIA report '2016 Levelised Cost of New Generation Resources from the Annual Energy Outlook 2010' which looks at plants coming into commission in 2016.

**Table 13: Levelised cost comparison between 100 MW Coal Fired and OTEC Power Plants.**

| | Coal Powered Plant | OTEC Plant | Cost Multiple |
|---|---|---|---|
| Levelised cost ($/kWh) | $0.10* | $0.33 | 3.3 |

*Assuming a cost of $CO_2$ emissions of $15/t & ignoring financing costs.

Thus it can be seen that the levelised costs of an OTEC plant far outweigh coal fired power production costs. In fact, an OTEC Plant would cost more than three times the cost of an equivalent output coal power plant over the plants' lifetime, if OTEC is assessed purely on an electricity production basis. This cost assessment, however, does not include the desalinated water production. Hence, for accurate comparison purposes the cost to produce this water must be assessed.

## 6.2 Desalinated Water Production

As calculated in section 2.5.3, the proposed OTEC Hybrid plant would produce some 200,000 $m^3$/d or 200 ML/d of fresh water, as a byproduct of electricity production. The capital investment to produce this flow is included in the $1.580 billion assessed above, therefore; given SEQs need for future desalination plants: How much capital investment is avoided by the construction of an OTEC plant?

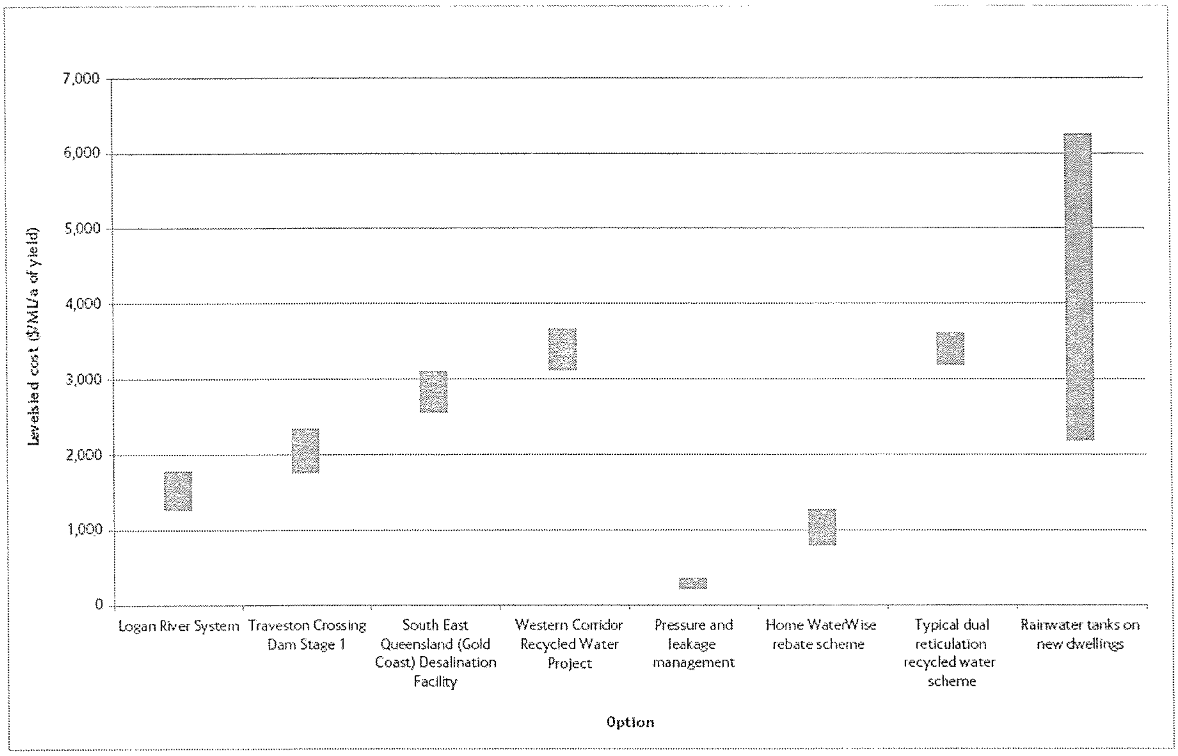
In section 3.2 it was established that SEQs potable water demand to 2056 would require the construction of at least two 133 ML/d reverse osmosis plants, similar to the Gold Coast Desalination Plant. The Queensland Water Commission undertook preliminary financial assessments of each of the potential future desalination sites in their report entitled 'South East Queensland Desalination Study' (2009). Therein they assessed a 100 ML/d desalination plant at the Marcoola site, the recommended site for the proposed OTEC plant, costing $1.887 billion (in 2008 AUD). When adjusted for exchange rate (1.15658AUD/USD, Friday, June 25, 2010 (x-rates.com, 2010)) and inflation, this equates to $1.666 billion (in 2010 USD). Therefore, without an OTEC plant, SEQ will likely have to invest $3.332 billion in reverse osmosis plants by 2056 to produce an equivalent volume of desalinated water. This assumes two 100 ML/d plants were constructed, whereas it is likely that one 400 ML/d plant is built for circa $ 5.234 billion. To incorporate some economies of scale, this paper assumes that a 200 ML/d desalination plant at Marcoola would cost $2.95 billion (average of $2.6 and $3.3 billion).

For the purposes of this paper, the additional infrastructure required to connect any fresh water production to the SEQ water grid has been ignored. This is appropriate for two reasons; firstly, this connection cost would apply to both plants (OTEC or Desalination Plant) so is irrelevant for the purposes of comparison, and secondly, following the planned infrastructure outlined by SEQRWSS discussed in section 3.1.3 the additional investment required would be negligible.

Focusing on production costs, the main benefit of OTEC is the essentially free ongoing production of fresh water. As outlined in section 3.1.2 the government of SEQ has committed to providing between 69 GL to 203 GL per annum of new 'climate resistant' sources of fresh water by 2056. To achieve this, several new reverse osmosis desalination plants are planned in conjunction with the Western Corridor Recycled Water Project and the existing Gold Coast desalination plant. Vega (1992) notes the cost of producing fresh water from conventional desalination plants is approximately $1 /m$^3$ for plants larger than 40,000 m$^3$/d. This equates to roughly $200,000 /d in operating costs avoided by the proposed OTEC application. The cost to produce water via from alternative means is heavily energy dependent, with recycled water and reverse osmosis consuming 1 and 3.2 megawatt hours (MWh) of energy per ML produced respectively (Water Secure & Queensland Water Commission, 2009). Thus, these methods are more vulnerable to energy prices, and more specifically coal prices in the future.

Again, given the differing cost schedules of each technology, it helps to assess the levelised cost over the lifetime of water production for comparison purposes. A basic levelised cost analysis of OTEC, purely as a producer of fresh water, is shown in Appendix D. Using a discount rate of 10% and taking inflation at 3%, a levelised cost of $922 /ML/annum of yield is achievable from OTEC. This is considerably below almost all of the levelised cost estimates of other fresh water initiatives currently underway in SEQ, as shown by Figure 15. Most notably, the levelised cost of reverse osmosis desalination is between $2,500 to $3,100 /ML/annum yield. This is around three times as expensive as OTEC produced desalinated water.

Figure 15: Levelised costs for major initiatives currently underway (Queensland Water Commission, 2008)



It is worthwhile noting that in 2007 the Australian Government announced an AU$1 billion National Urban Water and Desalination Plan. The fund offers grants of up to AU$100 million for up-front capital costs to approved major desalination, water recycling, and major storm water capture projects across Australia. The only requirement is that the project sources 100% of its energy requirements from renewable sources or fully offsets the carbon impact of its operations (Queensland Water Commission, 2008). The OTEC project certainly meets these requirements; hence, financing of the proposed project would include an AU$100 million contribution from the federal government.

## 6.3 DOW Utilisation for Biofuel Production

It has been proposed herein; that the DOW effluent from the OTEC plant could be fully utilised to grow algae which could then be used to produce biodiesel. This would serve several purposes; to produce a valuable fuel which would reducing Australia's dependence on imported oil, sequester carbon dioxide and thereby reduce Australia's carbon footprint, and reduce the environmental impacts of releasing the DOW back into the ocean.

Quirke et al. (2008) indicate capital costs of biodiesel production facilities at around AU$0.44 per annual litre. This is based on two proposed plants in Western Australia which are expected to cost AU$16.38 million and AU$18 million for 35 ML and 44 ML per year capacities, respectively. Furthermore, they estimate labour costs of approximately AU$0.012 – AU$0.088 per litre of biodiesel. Using these economic parameters and algae production figures from literature, a theoretical feasibility study was conducted utilising 100% of the DOW effluent – refer Appendix B. Table 14 below summarises the findings:

**Table 14: Algal Biodiesel from DOW production scenarios.**

|  | BIODIESEL Produced (kg/y) | Scenario 1: Current Production Costs Net Value ($mill/y) | Scenario 2: Breakeven Production Costs Net Value ($mill/y) |
|---|---|---|---|
| **PHOTOBIOREACTOR PRODUCTION** |  | *Biomass Production Cost = $2.95 /kg* | *Biomass Production Cost = $0.34 /kg* |
| 30% Oil Yield or Algae (wt in BIOMASS) | 2,323,572,480 | **-$25,246** | **$0** |
| 70% Oil Yield or Algae (wt in BIOMASS) | 5,421,669,120 | **-$21,557** | **$3,690** |
| **'RACEWAY' PRODUCTION** |  | *Biomass Production Cost = $3.80 /kg* | *Biomass Production Cost = $0.34 /kg* |
| 30% Oil Yield or Algae (wt in BIOMASS) | 177,106,176 | **-$2,552** | **$0** |
| 70% Oil Yield or Algae (wt in BIOMASS) | 413,247,744 | **-$2,270** | **$281** |

As can be seen, under Scenario 1, the current production costs are far too high to make algal biodiesel a competitive alternative to fossil fuel diesel. Using existing commercial technology for the culture, extraction and transesterification of algae to biodiesel, complete utilisation of the projects DOW flow would result in a net loss of more than $2 billion for raceway applications, and more than \$20 billion for photobioreactor applications. This is largely due to the production costs of \$2.95 and \$3.80 /kg of algal biomass for photobioreactor's and raceway's respectively. There are several other variables that will influence the feasibility of algal biodiesel production, such as:

- Rate of BIOMASS production;
- Value of CO2 equivalent offsets;
- BIOMASS to BIODIESEL Efficiency;
- Cost of BIODIESEL production; and
- Value of BIODIESEL.

Innovation into each of these represents an opportunity for reducing the cost per litre of biodiesel, however; the most significant advancement towards algal biodiesel feasibility is through reducing the production cost of algal biomass.

Scenario 2 demonstrates the breakeven point of 30% lipid content algae biomass production costs. As shown, the production of biodiesel will begin to become feasible when the costs of producing algal biomass is under \$0.34 /kg, holding all other variables ceteris paribus. It is worth noting that at this level of biomass production costs, higher lipid content algae would produce significant net value.

If the algal biodiesel was to become financially feasible, the benefits would be considerable. Table 15 below summarises the biodiesel production and $CO_2$ sequestration potential from 100% utilisation of the proposed project DOW flow.

Table 15: Biodiesel production and $CO_2$ Sequestration from 100% DOW utilisation.

| | Biomass of Algae Produced (t/y) | BIODIESEL Produced (ML/y) | $CO_2e$ Sequestered (Mt/y) | Value of $CO_2e$ Sequestered ($mill/y)* |
|---|---|---|---|---|
| **PHOTOBIOREACTOR PRODUCTION** | | | | |
| 30% Oil Yield or Algae (wt in BIOMASS) | 9,681,552 | 2,640 | 18.2 | $547 |
| 70% Oil Yield or Algae (wt in BIOMASS) | 9,681,552 | 6,161 | 18.2 | $547 |
| **'RACEWAY' PRODUCTION** | | | | |
| 30% Oil Yield or Algae (wt in BIOMASS) | 737,942 | 201 | 1.4 | $42 |
| 70% Oil Yield or Algae (wt in BIOMASS) | 737,942 | 470 | 1.4 | $42 |

*At $CO_2e$ of $30 /t.

As can be seen, using photobioreactor technology, almost ten million tons of algal biomass could be produced, which would result in 2.6 to 6.2 billion litres of biodiesel. This equates to 17 to 39 million barrels of biodiesel per year, which would save Australia AU$3 to AU$7 billion per annum in diesel imports (AIP, 2010). This quantity of algal biomass would also sequester over 18 million tons of $CO_2$, which equates to a value of over AU$500 million, based on AU$30 /t of $CO_2e$. At more than 3% of Australia's annual $CO_2e$ emissions in 2009, this would go a long way to help meet the federal government's long-term goal of reducing emissions by 60% below 2000 levels by 2050.

Obviously the above analysis makes a large assumption: that the cost of algal biomass production can be reduced by a factor of ten. Essentially the algae industry would require a technological breakthrough to achieve such efficiencies. As such, the production figures discussed above are unachievable using current cultivation and harvesting techniques. To illustrate this point, assuming a two day detention time (the period of time taken for DOW to pass through the system), which is an average time for algae to complete one growth cycle, it would take some 1.3 million, $27m^3$ (3 m x 3 m x 3 m) photobioreactors, or 115 $km^2$ of raceway pond area to manage 100% of the DOW flow from the proposed OTEC plant.

## 6.4 Risk Assessment

The proposed Project is subject to a raft of risks that would impact on its feasibility. Cavrot (1993) provides a comprehensive assessment of the risks or threats to a commercial scale OTEC project are set out below.

### *Finance Risk*

Traditional financial institutions seldom support 'new' technology, i.e. technology that has not already been proven on an equivalent scale, especially one as capital intensive as this proposal. Unfortunately to date, there are no OTEC plants with an operating record, as all have been experimental. The size of experimental plants (circa 0.3 MW) are about two orders of magnitude less than the size required for commercial applications, and data extrapolation of this order is not acceptable to developers of banks (Takahashi P. , 2003).

### *Contingency Risk*

Tropical cyclones and adverse weather conditions are relatively high risk elements. They have the potential to damage the intake pipes and the plant itself for a floating system. The risk of in-operation needs to be considered in this instance, as any commercial scale plant will be relied upon to supply base load electricity.

### *Construction Risk*

There are still many unknowns from the assembly perspective for a plant of this magnitude, as it would be the first of its kind. Assembly of the CWP is of special concern, as this is a fairly unique component of OTEC. Certainly, a pipe of the dimensions required for the proposed project (11m diameter and 3 km long) is beyond commercially available practices. Consequently, considerable time, money and risk must be taken for a commercial scale project to be realized, with regards to the CWP especially.

### *Equipment Risk*

The large scale turbines required, due to the inefficiency of the heat engine, adds considerable complexity to the development of the proposed plant. As such, within the confines of current technology, a commercial scale plant would have to be modular, running turbines of a similar scale to those in demonstration stage.

### *Operating Risk*

As mentioned previously, it must be expected that certain extreme weather conditions will cause interruptions to operations. Further to this, is the added complexity of a multi-faceted system, such as the one proposed. In this case multiple downstream applications are reliant on the warm and cold water that OTEC provides, as inputs. Consequently, any stoppages may prove very costly. For example, in the case of algae cultivation; if the supply of DOW is interrupted, an entire crop may die. This would not only cause the destruction of one crop, but the system would need time to regenerate to production capacity, from a seed.

### *Safety Risk*

The safety issues associated with the OTEC power system is synonymous with other steam electric power generation plants: electrical hazards, rotating machinery, compressed gases, heavy equipment, and maintenance hazards. However, because the OTEC plant operates a low temperature, low pressure Rankine cycle, it poses fewer hazards to operating personal and the local population than conventional fossil fuel plants (Vega, 1999).

### *Market Risk*

Fluctuations of the market prices of products (electricity, fresh water and carbon credits) need to be considered in conjunction with price volatility of competing energy sources, namely coal for electricity production and oil for transport. Some price stability will be achieved if there is some kind of fixed price agreement for sequestered carbon in Australia. This, however; remains to be seen. As the economics section explains, the economic viability depends on the prices of those products mentioned.

# 7 CHAPTER SEVEN: CONCLUSIONS

As a result of changing climatic conditions and thriving migration; SEQ, Australia is in the midst of growing energy demand, $CO_2$ emissions and an increasingly vulnerable water supply. To combat these challenges there needs to be a shift towards renewable energy sources to reduce dependency on coal fired power, which is the main source of Australia's $CO_2$ emissions. Concurrently, investment into secure fresh water supplies must be made to meet forecasted demand.

This paper has proposed a 100 MW, land based, hybrid OTEC system in SEQ to address these problems. OTEC is a promising technology that seeks to tap the vast quantities of energy stored in the surface layers of the oceans. The proposed hybrid system extracts energy from the surface water via a low temperature closed Rankine cycle, and then flash evaporates a portion to produce fresh water. The DOW which acts as the heat sink in the OTEC system is then utilised in the production of algae, to sequester $CO_2$ and produce biodiesel. Despite the obvious benefits of a renewable energy source (surface seawater) with several valuable by-products, OTEC faces a number of hurdles to be overcome before the technology is commercially viable.

In Chapter Two, the technological limitations and capacities of OTEC were assessed. It was determined that sufficient exergy could be extracted from the Tasman Sea off SEQ to meet the requirements of a 100 MW OTEC plant. This would entail the circulation of some 400 $m^3/s$ and 200 $m^3/s$ of warm and cold water respectively – massive quantities of seawater. Subsequently, the main limiting factor to the implementation of an OTEC plant of this magnitude is the scale of intake pipes required. This flow rate would require a surface pipe of 16 m diameter and a

CWP of 11 m diameter to a depth of 1,000 m along the sea floor. Piping of this scale is currently well beyond commercial availability. Clearly, this project will require a breakthrough in piping and pipe laying technology before it can become a reality. Alternatively, the possibilities of tunnelling and pipe bundling should be explored. Despite this obstacle to commercial OTEC development, researchers surveyed reiterated the temporary nature of this barrier. It seems all those involved in OTEC research and development foresee plants of this scale being achievable, following sustained investment into the technology and a series of incrementally scaled-up experimental plants.

Putting current physical limitations aside, the financial feasibility of the plant was assessed in Chapter Six. Here it was found that the potential for OTEC is enormous, although not solely as a method for producing electricity. It was shown that OTECs levelised cost of producing electricity is currently $0.33 /kWh. The major difficulty being the capital-intensive heat exchangers and pipes compared to, Australia's main electricity provider – coal. Thus it seems coal fired power production would not be under threat from OTEC until $CO_2$ emissions are priced correctly and several technological breakthroughs are achieved. This in itself should not prohibit developments toward commercial scale plants. Indeed, commercial applications of OTEC can become viable when considered as a package of by-products; the most important being fresh water.

Another obstacle to OTECs implementation is the lack of long term planning by government. Most national energy plans do not extend beyond twenty years, and from a private investment point of view, pay back periods within the energy industry are generally required to be less than twenty years (Tanner, 1995). SEQ poses a rather unique opportunity in this regard. Whilst energy security has not caused such long term planning, the 'Millennium Drought' provided the impetus to develop urgent and pragmatic solutions to the region's water security crisis. As a result the SEQRWSS outlines a strategy to provide 69 GL - 203 GL per annum of new 'climate resistant' sources of fresh water by 2056. OTEC certainly deserves some attention in this regard, as it was shown in section 2.5.3 that the proposed hybrid plant would produce some 200 ML of fresh water per day, in addition to 100 MW of net power output. This fresh water flow is substantial. When considered in the context of SEQ, this is also extremely valuable. Two additional reverse osmosis desalination plants of the capacity of the existing Gold Coast plant would need to be constructed, at a cost of almost $3 billion. Therefore, as purely a desalination technology, it seems that the current capital estimate of the proposed OTEC plant at $1.58 billion is too good to be true. At almost half the investment of the desalination plants planned in the SEQRWSS, the potential of an OTEC application in SEQ should be of great interest to the Queensland Government who have an infrastructure budget of AU$9 billion to meet projected water demand to 2056. Unfortunately, as Takahashi (2003) points out, the size of existing experimental plants (circa 0.3 MW) are about two orders of magnitude less then the size of the proposed project. Data extrapolation of this order is not accurate, thus; it seems that OTEC development will be limited to 1 to 10 MW incremental demonstrations and niche applications, until more accurate predictions regarding performance can be made.

The potential of the DOW effluent to reduce Australia's GHG emissions was also reviewed. As outlined in Chapter Four, DOW has long been known to aquaculturists as a valuable resource due to high nutrient levels and the absence of pathogens. The potential to utilise this resource for algae cultivation for the purposes of biodiesel production was explored based on current algae production costs. Disappointingly, the costs of production of algal biomass seems prohibitively expensive, with full DOW utilisation costing a total of $2 billion to $25 billion to produce 0.2 GL to 6 GL of biodiesel. As Packer (2009) points out, despite the real promise in algal technology for carbon sequestration and biofuel production there is more research to be done before commercial scale applications can be deployed. Producing algal biodiesel requires large-scale cultivation and harvesting systems, with the challenging of reducing the cost per unit area (Mata et al., 2010). There are many opportunities to improve the economic & environmental success of an algae production facility by coupling it with other industrial processes like wastewater treatment, flue gases, utilising waste heat, and the extraction of high value compounds for application in other process industries. Current limitations to the OTEC application concern the optimization of cost effective light distribution and microalgae harvesting, given the relatively limitless resource of DOW available. The benefits to an OTEC feed algae system is the ample nutrients available, the temperature control afforded by varying the warm and cold water, the dissolved $CO_2$ present in the DOW and the high turnover rate at the systems disposal.

Packer (2009) reiterates that the capture of $CO_2$ to produce biofuels represents carbon recycling, not sequestration. However, this will lead to more efficient uses of the remaining fossil fuels we have, and will go some way to mitigating the potential of further anthropogenic climate change. Given the right economic parameters, it is possible that algal capture of $CO_2$ might one day lead to technology that is able to return carbon to the large oceanic carbon sinks, thus re-linking anthropogenic use to the carbon cycle.

Finally, the environmental impacts of a commercial scale OTEC plant was investigated in Chapter Five. Whilst is appears that OTEC is environmentally benign, there are several potential impacts that are specific to OTEC applications that require addressing. The most notable being the construction of the CWP. As previously mentioned this is one area in particular where further research is required. As far as operating environmental impacts, there are risks associated with; the water volumes and temperatures involved, biostimulation and eutrophication from the DOW effluent, antifouling and working fluid contamination, entrainment, salinity of desalination effluent, and release of dissolved $CO_2$. These potential environmental impacts, however; do not appear insurmountable if OTEC design incorporates mitigation methods discussed herein. Although, as the proposed plant is of a scale beyond current experimentation, OTEC as a significant provider of power for the world cannot be assessed beyond the experimental plant stage, until some operational and environmental impact data is made available through the construction and operation of the pre-commercial plant (Vega L. A., 1999).

In summary, OTEC has been shown to work at research scales, which has demonstrated the potential for electricity, fresh water and algae production. Unfortunately there are several limiting factors to commercialisation of the technology. If breakthroughs in piping or tunnelling and algae production and harvesting can be made, the proposed Project may be possible.

## 7.1 Recommendations

Based on the findings above, and SEQs energy / water nexus described herein, the following action plan for OTEC development in SEQ is proposed:

*Objective*

**To achieve commercial scale deployment of OTEC in SEQ by 2056.**

To accomplish this objective, an emergent or 'learning school' strategy should be employed. Such a strategy should incorporate several incremental goals as outlined below:

*1 – 5 years (by 2015)*

- Establish OTEC Research Centre, at the likely commercial site at Marcoola. The site which is already owned by the Sunshine Coast Regional Council, is currently agricultural land adjacent to commercial land (the Sunshine Coast Airport). It is in close proximity to the ocean (within 1.5 km) and existing infrastructure connections (i.e. distribution network for produce water and power), and is a large site (53 hectares). A preliminary CWP of existing commercial dimensions would need to be installed to feed DOW to the research centre. This would provide opportunity for private and state funded research into potential DOW applications.
- The initial objective of state funded research would be to: Establish the technical ability to implement a demonstration scale (10 MW) plant.

*5 – 15 years (by 2025)*

- Construct a 10 MW demonstration plant using innovations established above.
- Construct a world class industrial park, utilising air-conditioning savings and other innovations established above from the demonstration plant DOW flow. Private, industrial DOW application research would be given priority, as well as the establishment of an 'OTEC University'.

*15– 25years (by 2035)*

- Develop system efficiency improvements through experimentation. The 'OTEC University' will provide further innovation towards improving efficiency through heat exchanger and turbine materials, and utilising concentrated solar for example.
- A second objective of state funded research would be to: Establish the cost effective best practise of 100 MW – 500 MW scale CWP applications (be it advancements in piping or tunnelling technology).

*25– 35 years (by 2045)*

- Expansion of the DOW industrial park, encouraging the most promising applications refined over the last 25 years. This could perhaps be a collaborative alignment between private and public interests to provide sufficient scale to operations to cope with the vast water flows.
- Construct a large scale piping network (i.e. 100 MW – 500 MW capacity warm and cold water flows). This increased water flow would provide the commercial scale DOW applications above.

*35- 45 years (by 2055)*

- Construction of a 100 MW – 500 MW capacity hybrid cycle OTEC plant. This could potentially provide SEQ with the remaining 'climate resilient' fresh water supply quota, as outlined by the SEQRWSS, as well as establish and power an entire DOW application industry based on the Sunshine Coast.

- Development of offshore and/or floating OTEC applications, utilising technology advancements achieved over the last 35 years. A secondary SEQ plant could also be investigated for the Gold Coast for water and electricity export to neighbouring New South Wales.

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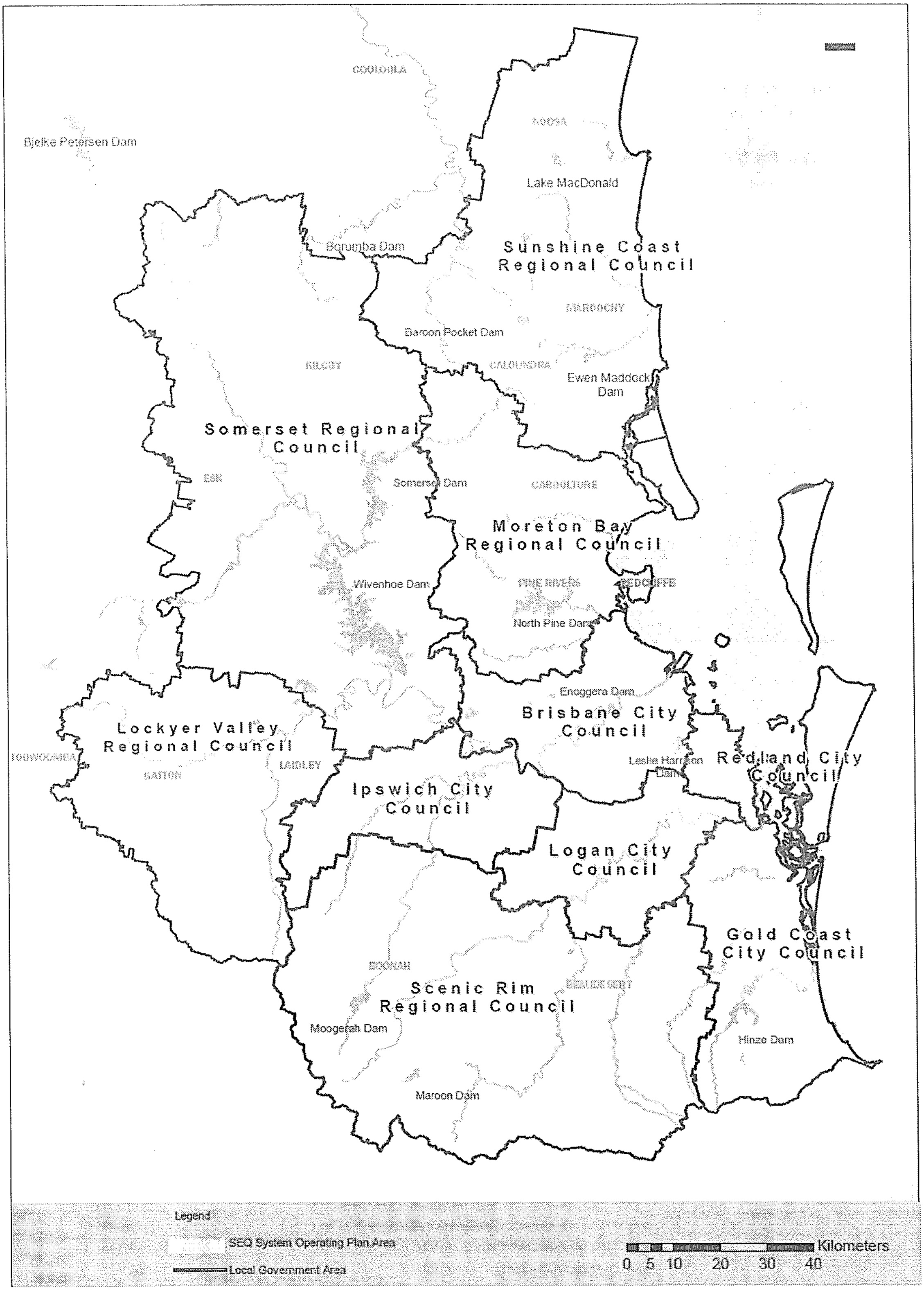
## APPENDIX A: Map of the SEQ System Operating Plan area.



# APPENDIX B: Biodiesel Production and Cost Estimates

## Scenario 1: Based on variables outlined by literature.

| **VARIABLES:** | |
|---|---|
| DOW Flow Rate (m3/s): | 200 |
| Percentage of DOW utilised for algae cultivation | 100% |
| Volume of DOW utilised (m3/d) | 17,280,000 |
| PHOTOBIOREACTOR BIOMASS Rate of production (kg/m3/d) | 1.535[*] |
| RACEWAY BIOMASS Rate of production (kg/m3/d) | 0.117[*] |
| Value of $CO_2$ e ($/t) | $30.00 |
| Cost of PHOTOBIOREACTOR BIOMASS ($/kg) | $2.95[*] |
| Cost of RACEWAY BIOMASS ($/kg) | $3.80[*] |
| BIOMASS to BIODIESEL Efficiency (by wt) | 80%[§] |
| BIODIESEL density (kg/m3) | 880[¥] |
| Cost of BIODIESEL production ($/L) | $0.45[α] |
| Value of BIODIESEL ($/L) | $1.50[β] |

**[*] (Chisti, 2007)**

**[§] (Packer, 2009)**

**[¥] (Biodiesel Industries Australia Pty Ltd, 2003)**

**[α] (Quirke, Steenblik, & Warner, 2008)**

**[β] Based on current diesel prices in Australia 0f $1.32 /L.**

| | Biomass of Algae Produced (kg/y) | BIODIESEL Produced (kg/y) | Cost of BIOMASS Production ($mill/y) | Cost of BIODIESEL Production ($mill/y) | Value of BIODIESEL ($mill/y) | Value of $CO_2$ e [ε] ($mill/y) | Net Value ($mill/y) |
|---|---|---|---|---|---|---|---|
| **PHOTOBIOREACTOR PRODUCTION** | | | | | | | |
| 30% Oil Yield or Algae (wt in BIOMASS) | 9,681,552,000 | 2,323,572,480 | $28,561 | $1,193 | $3,961 | $547 | **-$25,246** |
| 70% Oil Yield or Algae (wt in BIOMASS) | 9,681,552,000 | 5,421,669,120 | $28,561 | $2,785 | $9,241 | $547 | **-$21,557** |
| **'RACEWAY' PRODUCTION** | | | | | | | |
| 30% Oil Yield or Algae (wt in BIOMASS) | 737,942,400 | 177,106,176 | $2,804 | $91 | $302 | $42 | **-$2,552** |
| 70% Oil Yield or Algae (wt in BIOMASS) | 737,942,400 | 413,247,744 | $2,804 | $212 | $704 | $42 | **-$2,270** |

**[ε] Biomass is assumed to have the molecular formula: $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ (Chisti, 2007).**

## Scenario 2: Based on the breakeven cost of biomass production, for 30% oil yield algae.

| VARIABLES: | |
|---|---|
| DOW Flow Rate (m3/s): | 200 |
| Percentage of DOW utilised for algae cultivation | 100% |
| Volume of DOW utilised (m3/d) | 17,280,000 |
| PHOTOBIOREACTOR BIOMASS Rate of production (kg/m3/d) | 1.535 |
| RACEWAY BIOMASS Rate of production (kg/m3/d) | 0.117 |
| Value of $CO_2$e ($/t) | $30.00 |
| Cost of PHOTOBIOREACTOR BIOMASS ($/kg) | $0.34 |
| Cost of RACEWAY BIOMASS ($/kg) | $0.34 |
| BIOMASS to BIODIESEL Efficiency (by wt) | 80% |
| BIODIESEL density (kg/m3) | 880 |
| Cost of BIODIESEL production ($/L) | $0.45 |
| Value of BIODIESEL ($/L) | $1.50 |

| | Biomass of Algae Produced (kg/y) | BIODIESEL Produced (kg/y) | Cost of BIOMASS Production ($mill/y) | Cost of BIODIESEL Production ($mill/y) | Value of BIODIESEL ($mill/y) | Value of $CO_2$e ($mill/y) | Net Value ($mill/y) |
|---|---|---|---|---|---|---|---|
| **PHOTOBIOREACTOR PRODUCTION** | | | | | | | |
| 30% Oil Yield or Algae (wt in BIOMASS) | 9,681,552,000 | 2,323,572,480 | $3,314 | $1,193 | $3,961 | 547 | **$0** |
| 70% Oil Yield or Algae (wt in BIOMASS) | 9,681,552,000 | 5,421,669,120 | $3,314 | $2,785 | $9,241 | 547 | **$3,690** |
| **'RACEWAY' PRODUCTION** | | | | | | | |
| 30% Oil Yield or Algae (wt in BIOMASS) | 737,942,400 | 177,106,176 | $253 | $91 | $302 | 42 | **$0** |
| 70% Oil Yield or Algae (wt in BIOMASS) | 737,942,400 | 413,247,744 | $253 | $212 | $704 | 42 | **$281** |

## APPENDIX C: Levelised Cost of OTEC Power Production

Table 16: Levelised costs of OTEC Power Production, as outlined by Vega (1992).

| **Production cost of electricity levelised over the assumed life for the OTEC plant:** | |
|---|---|
| Interest Rate* | 8% |
| Plant lifetime (y) | 30 |
| FC : annual fixed charge | 10% |
| CC : plant overall investment capital cost ($) | $1,580,000,000.00 |
| OM : operation and maintenance expense (@ 3%) ($/y) | $ 47,400,000.00 |
| G : present worth factor (y) | 20 |
| CR : capital recovery factor | 8.88% |
| NP : net power production (kW) | 100,000 |
| CF : production capacity factor | 85% |
| 8760 : number of hours in one year | 8,760 |
| | |
| p ($/kWh) = [(FC x CC) + (OM x G x CR)] / (NP x CF x 8760) | |
| **p ($/kWh) =** | **$0.33** |

*Note: Interest rate considered conservative, given current 90 day Bill Yield in Australia is 4.87% (RBA, 2010).

## APPENDIX D: Levelised Costs Estimate of a 200 ML/d OTEC Plant in SEQ.

| | | | | | |
|---|---|---|---|---|---|
| **Levelised Cost of OTEC:** | | | **922** | **($/ML/y of yield)** | |
| Discount Rate | | | 10% | | |
| Inflation Rate | | | 3% | | |
| Year: | | | | | |
| | 1 | $ | 1,627,400,000 | $ | 1,479,454,545 |
| | 2 | $ | 48,822,000 | $ | 40,348,760 |
| | 3 | $ | 50,286,660 | $ | 37,781,112 |
| | 4 | $ | 51,795,260 | $ | 35,376,859 |
| | 5 | $ | 53,349,118 | $ | 33,125,605 |
| | 6 | $ | 54,949,591 | $ | 31,017,612 |
| | 7 | $ | 56,598,079 | $ | 29,043,764 |
| | 8 | $ | 58,296,021 | $ | 27,195,524 |
| | 9 | $ | 60,044,902 | $ | 25,464,900 |
| | 10 | $ | 61,846,249 | $ | 23,844,406 |
| | 11 | $ | 63,701,636 | $ | 22,327,035 |
| | 12 | $ | 65,612,685 | $ | 20,906,224 |
| | 13 | $ | 67,581,066 | $ | 19,575,828 |
| | 14 | $ | 69,608,498 | $ | 18,330,093 |
| | 15 | $ | 71,696,753 | $ | 17,163,633 |
| | 16 | $ | 73,847,656 | $ | 16,071,401 |
| | 17 | $ | 76,063,085 | $ | 15,048,676 |
| | 18 | $ | 78,344,978 | $ | 14,091,033 |
| | 19 | $ | 80,695,327 | $ | 13,194,331 |
| | 20 | $ | 83,116,187 | $ | 12,354,692 |
| | 21 | $ | 85,609,673 | $ | 11,568,484 |
| | 22 | $ | 88,177,963 | $ | 10,832,308 |
| | 23 | $ | 90,823,302 | $ | 10,142,979 |
| | 24 | $ | 93,548,001 | $ | 9,497,517 |
| | 25 | $ | 96,354,441 | $ | 8,893,129 |
| | 26 | $ | 99,245,074 | $ | 8,327,203 |
| | 27 | $ | 102,222,426 | $ | 7,797,290 |
| | 28 | $ | 105,289,099 | $ | 7,301,099 |
| | 29 | $ | 108,447,772 | $ | 6,836,483 |
| | 30 | $ | 111,701,205 | $ | 6,401,434 |
| | | | | **$** | **2,019,313,958** |

## GLOSSARY OF TERMS AND ABBREVIATIONS

CCS – Closed Cycle System

CO2 - Carbon Dioxide

CO2e - Carbon Dioxide equivalent

CPRS - Carbon Pollution Reduction Scheme

CSIRO - Commonwealth Scientific and Industrial Research Organisation

DOW – Deep Ocean Water

DOWA - Deep Ocean Water Applications

GHG - Greenhouse Gas

Heat exchanger – Devise used to transfer energy between two mediums.

HS - Hybrid System

MW – Mega Watt. A unit of power (1,000,000 Watts or J/s)

OCS – Open Cycle System

OTEC - Ocean Thermal Energy Conversion

PWCM - Permanent Water Conservation Measure

RET - Renewable Energy Target

SEQ - South East Queensland

SEQRWSS - South East Queensland Regional Water Supply Strategy

Working Fluid - The pressurized liquid that actuates the electricity generation by driving the turbine.