Asia-Pacific
Economic Cooperation

Resource Potential of Algae for Sustainable Biodiesel Production in the APEC Economies

APEC Energy Working Group
Biofuels Task Force

December 2011

This report was prepared for the APEC Energy Working Group under EWG 18/2009 by:

David F. Batten, Ph.D.
The Temaplan Group and CSIRO Energy Transformed Flagship
Private Bag 1, Aspendale, Victoria 3195, AUSTRALIA
Telephone: +61 3 9239 4420 or +61 3 9592 0720
Mobile: 0457 564 837
Email: david.batten@csiro.au

Peter K. Campbell
The Temaplan Group
Hobart, Tasmania, AUSTRALIA

Greg Threlfall
CSIRO Material Science and Engineering
Highett, Victoria, AUSTRALIA

APEC#211-RE-01.9

ACKNOWLEDGMENTS

The authors would like to acknowledge and thank the project overseer, Jeffrey Skeer (Department of Energy, USA and Chair of the APEC Biofuels Task Force), for his support, review, and guidance throughout this project. They are grateful to Tom Beer (CSIRO) for his initiation of the project, his helpful comments during its execution and his constructive review of this report. Other scientists to have provided helpful comments during the writing of this report include John Benemann, Eric Jarvis, Anelia Milbrandt, Ron Pate, John Raison, Jesse Roach, Michael Wang and Jian Xu.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

APEC	Asia-Pacific Economic Cooperation
ASEAN	Association of Southeast Asian Nations
BAT	Biomass Assessment Tool
C	Carbon
CO_2	Carbon dioxide
DHA	Docosahexaenoic acid
DW	Dry weight
E10	10% of ethanol mixed with 90% of gasoline
Fe	Iron
GHG	Greenhouse gas
GIS	Geographic information system
HRAP	High rate algal pond
K	Potassium
N	Nitrogen
NREL	National Renewable Energy Laboratory (U.S. Department of Energy)
P	Phosphorus
PNNL	Pacific Northwest National Laboratory (U.S. Department of Energy)
PONCH	Phosphorus, Oxygen, Nitrogen, Carbon, Hydrogen
RS	Remote sensing
Sandia	Sandia National Laboratories (U.S. Department of Energy)
TNO	Netherlands Organisation for Applied Scientific Research
WWTP	Wastewater treatment plant

UNITS

g	gram
ha	hectare
kg	kilogram
kL	kilolitre
km^2	square kilometres
kt	kilotonne
ML	megalitre
Mt	megatonne
MW	Megawatt
m^2	square meters
t	tonne (metric)

EXECUTIVE SUMMARY

Using algal biomass to produce biofuels has received increased attention recently. Some compelling arguments for the growing interest are that algae grow rapidly, yield more biofuel per hectare than terrestrial plants, contain little or no toxic substances, are biodegradable, can be used in ways that generate relatively low GHG emissions and, in most instances, do not compete directly with food production on agricultural land. Thus algae could add significantly to the potential for biofuels to displace fossil fuels.

However, major challenges lie ahead. Although the scientific literature indicates very high potential productivity for algae, it is unlikely that such laboratory values can be achieved in practical industrial applications. Furthermore, it is not clear how much land is available and affordable in locations such as coastal areas, where the climate, water and nutrients may be sufficient to support the commercial cultivation of algae.

The goal of this study is to assess the potential amount and location of algal biomass that could be made available for the sustainable production of biodiesel in the APEC economies. To achieve this, the study discusses three methods of assessment. Method 1 is based on the TNO authors, van Harmelen and Oonk (2006), who claimed that the most suitable resources for the application of microalgae mass cultures to renewable energy production in the near-term are human, animal and some industrial wastes containing sufficient nutrients (principally nitrogen and phosphorus) for algal growth. This approach suggests that about 52 million tonnes of algal biomass could be grown in the APEC economies over the next 10-15 years, if the TNO approach is applied without any modifications. However, if the method is adjusted to allow for the fact that not all wastewaters from human and animal sources in the APEC economies are collected for treatment, then the total algal potential within the APEC economies is only about 21 million tonnes. This corresponds to the production of just over 8 GL of algal biodiesel, hardly enough to replace 2% of current fossil diesel usage.

Method 2 assumes that the key nutrients – CO_2, N and P – will be provided by the same sources of human and animal wastes, with the limiting factor being the amount of carbon available. Facilities are assumed to have water, N and P available that can be used in the ponds to produce the algal biomass. After the oil is extracted, it is processed into biodiesel. Nutrients are recycled in the water and the residual biomass is used to produce biogas via anaerobic digestion, which is then combusted to provide additional electric power and CO_2 on-site. If temperature variations and incident solar radiation are not taken into account, this approach estimates that about 211 million tonnes of algal biomass could be grown in the APEC economies in the foreseeable future. This corresponds to a maximum APEC-wide production of about 71 GL of algal biodiesel, enough to replace 12% of current fossil diesel usage. If temperature variations and solar radiation are considered, then these figures drop by about 50%.

The largest potential producers of algal biodiesel among the APEC group are China and the United States. Both economies have large populations located in cities and towns throughout their land areas, providing a broader and more flexible distribution of wastewater, nutrients and CO_2 sources to feed algal ponds. In the short-term, China has the greatest potential because of its larger populations of people, pigs and other animals which are currently generating huge wastewater streams that could be used to

produce about 9 GL of algal biodiesel. Although this amounts to less than 10% of their current diesel usage, they could develop the capacity to almost triple this amount in the long-term, thereby increasing their replacement of fossil diesel substantially.

Indonesia and Thailand possess the potential capacity to replace about 2 GL of their fossil diesel use with algal biodiesel in the future. However, uncertainty prevails with respect to the amount of wastewater that is collected and treated in both economies, as well as in Malaysia, Mexico, Papua New Guinea, The Philippines and Viet Nam. Since several of these economies also possess the capacity to replace up to 10% of their fossil diesel by algal biodiesel, there is an urgent need to increase the amounts of wastewater collected and treated in these countries instead of allowing it to remain uncollected and untreated. This urgency also exists on the basis of improving overall sanitary conditions and lowering the risks of disease.

Economies with the potential to replace 15% or more of their current fossil diesel usage with algal biodiesel are Indonesia, Peru, Russia, Thailand, the United States and Viet Nam. In Australia, Brunei Darussalam, Canada, Chile, Japan, Malaysia, Mexico, Singapore and the Phillipines, the extent of the replacement potential is about 10%.

As it focuses on marginal coastal land and the potential use of saline water, the third method discussed herein requires further survey work that is beyond the scope of this report. However, it is clear from earlier work that Australia, Chile, Indonesia, Mexico, Russia and the United States possess greater potential in terms of marginal coastal land than the other APEC economies. More reliable estimates of the amounts of marginal coastal land in each economy need to be collected and then combined with information on the locations of sources of CO_2. Only then will additional biomass potential be identified. Method 3 should be viewed as a "coastal land plus CO_2" approach that treats the algal biomass potential as being limited by local availability of CO_2 and marginal coastal land. It can provide an upper-bound assessment of additional possibilities in the long term.

Further research is needed to locate all the sources of nutrients and water that exist in each economy and assess how close they are to the available land and sources of CO_2. Geographical proximity assessment is best done with the assistance of GIS-based tools such as Sandia's PONCH model. For example, a more sophisticated version of this model could be developed to determine the optimal coastal locations for algal biomass production in terms of the transportation costs of moving the nutrients and energy needed to maintain HRAPs. The PONCH model has been applied successfully to two APEC economies (Canada and Australia), so it would be a natural choice for an APEC-wide study of this kind. However, further research is needed to quantify more precisely the effects of temperature variations and incident solar radiation on algae growth potential at various locations in each APEC economy.

INTRODUCTION

The objective of this report is to assess the potential amount and location of algal biomass that could be made available for the sustainable production of biodiesel in the APEC economies. Potentially, algal biomass could be a sustainable, relatively low GHG emissions feedstock that is widely available, grows rapidly, yields more biofuel per hectare than terrestrial plants, contains little/no toxic substances, is biodegradable, and in most instances does not compete directly with food production on agricultural land. For these reasons, algae could contribute significantly to the resource potential of biofuels to displace fossil fuels.

The scientific literature indicates very high potential productivity for algae. However, it is still unclear whether such laboratory values for biodiesel production from algae can be achieved in practical industrial applications. Furthermore, it is not clear how much land is available in suitable locations (such as coastal areas) where the climate and availability of water and nutrients are sufficient to support the cultivation of algae in some of the APEC economies. Through an initial assessment of these key factors, and the range of yields that might be achieved for biodiesel production from algae using sustainable technology and industrial methods, this report will provide a rough set of estimates of the amount of biodiesel that might potentially be produced sustainably from microalgae in the APEC economies, and thus the amount of conventional oil that biodiesel from algae could potentially displace.

The findings of this report should assist agricultural, economic, energy and land ministries in developed and developing APEC economies. Some typical questions it may help to answer are: To what extent could waste streams – such as human and animal wastes near towns and cities – become a sustainable source of algal biofuels? Should waste locations be surveyed to have a fuller understanding of their potential? Can marginal land in coastal areas be used for biodiesel production?   Do limits exist on the scaling-up of biodiesel from algae owing to competition for key nutrients? Which ways of displacing fossil diesel for transport are the most sustainable? This report should enhance the capacity of officials and experts to address these and other related issues. By identifying locations that have the key resources available to make them potentially suitable for the cultivation of microalgae as biodiesel feedstock, and assessing their overall resource potential, the report may encourage algae cultivation as a means of displacing oil consumption in transport.

Before discussing potential methodologies, we need to clarify what the term “algae” signifies in this report. Eukaryotic algae are generally divided into unicellular “microalgae” and multicellular “macroalgae” (e.g. seaweed). Three ways of making oils like biodiesel from these algae have been proposed in the literature:

[1] Microalgae may be cultivated photosynthetically – i.e. with sunlight. Benemann (2010) estimates that annual world commercial production of the microalgal biomass grown in this way is about 10,000 tonnes. The main algae currently cultivated photosynthetically are Spirulina, Chlorella, Dunaliella and Haematococcus. About half of this production is of Spirulina, mostly in China, with Japan and Taiwan being the main producers of Chlorella, and other major producers in Australia, the U.S. and India. Thus some APEC economies are important production areas for photosynthetic algae, but a negligible proportion of this current production is used to make biofuels.

[2] Microalgae may be grown heterotrophically – i.e. by dark fermentations using a source of carbon like sugar or starch. Benemann (2010) suggests that another 10,000 tonnes are produced annually via this technology, mainly in the Far East for Chlorella (used as a nutritional supplement) and in the U.S. and Germany, for oil (triglycerides) high in the omega-3 fatty acid DHA, used mainly as an infant formula ingredient. Once again, a negligible amount is currently used to make biofuels. This is done in small pilot plants only.

[3] Some macroalgae might be used to produce biofuels, but work on the conversion of seaweed into biofuels is in its infancy.

This report focuses exclusively on planktonic microalgae grown photosynthetically, meaning that the algae are suspended in a liquid growth medium (water). As almost all commercial algal biomass is currently produced in open raceway ponds containing water, this will be the only technology assumed for this project.

To accomplish its objective, the report adopts three methods of assessing the resource potential of algae for production of biodiesel fuel in APEC economies. Method 1 is based on the TNO authors, van Harmelen and Oonk (2006), who suggested that the most suitable resources for the application of microalgae mass cultures to renewable energy production in the near-term are human, animal and some industrial wastes containing sufficient nutrients (principally nitrogen and phosphorus) for algal growth. The TNO estimates for waste potential must be adjusted downwards because they assumed that all wastewater would be collected and treated. This is not the case for most APEC economies. Being limited by nitrogen production, Method 1 provides an approximate estimate of the algal biodiesel potential among the APEC economies in the near-term — possibly over the next 10-15 years.

Another set of estimates, optimistic in the short term but plausible and definitely more sustainable in the longer term, result from assuming that the key nutrients (N and P) will come from human and animal wastes (e.g. cattle lots and piggeries). In this case, the limiting factor will be the amount of carbon available. Such facilities are assumed to have water that can be used in HRAPs to produce algal biomass. The biomass will have its oil extracted and processed into biodiesel. The nutrients will be recycled in the water and the residual biomass will be converted into biogas (methane; CH_4) via anaerobic digestion, which is then combusted to provide additional electric power and CO_2 on-site. This technology we label Method 2.

Our anaerobic digestion pathway is not new, being founded on Oswald and Golueke (1960), Regan and Gartside (1983), Benemann and Oswald (1996) and Campbell, Beer and Batten (2009), among others. It is nutrient-efficient, energy-efficient and displays a good carbon footprint. Although it assumes an alga that is amenable to flocculation and oil extraction using hexane, there are new technologies appearing that may be able to dewater the algae cheaply and extract the oil with minimal energy, using methods observed in nature (e.g. using membranes to cause a capillary action in combination with cohesion, adhesion, absorption and transpiration). These do not require dangerous chemicals; as such the algae could also be further processed for food products and pharmaceuticals.

The third proposed method (Method 3) requires estimates of the amount of marginal land available on coastlines in close proximity with sources of CO_2 (e.g. derived from the CARMA database and other sources). This may be viewed as a "coastal land plus CO_2" approach. It treats algal biomass potential as being limited by local availability of CO_2 and marginal coastal land, ignoring the availability of other nutrients such as N and P. Method 3 should be regarded as an upper-bound assessment of additional possibilities in the long term. Since such estimates cannot be realized unless locally sustainable sources of nutrients can be identified or ways of recycling nutrients developed, this method is too approximate to be relied upon without further detailed assessment with the assistance of GIS-based tools such as Sandia's PONCH model or PNNL's Biomass Assessment Tool (BAT). These models will be discussed in a later section.

MAKING BIODIESEL FROM MICROALGAE

Finding suitable locations for large-scale cultivation and processing of microalgae for conversion into biodiesel is a challenging task. In addition to the selection of robust species and strains of algae, other key resources required to grow it successfully are:

(1) warm sunlight and good insolation – preferably all year round;
(2) a sustainable source of nutrients (N, P) – preferably recyclable;
(3) a sustainable water supply – preferably recyclable;
(4) a sustainable source of CO_2 – preferably nearby; and
(5) reasonably flat land – preferably at least 400 hectares.

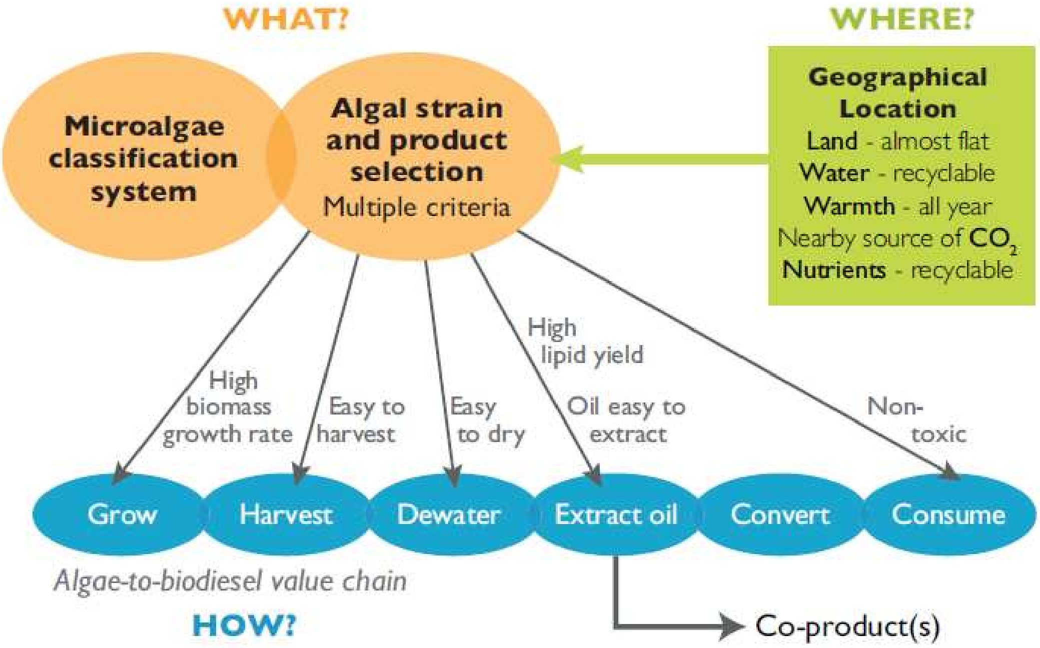


Figure 1: The What, Where and How of Algal Biodiesel (Source: Batten et al, 2011)

To answer the key WHAT and WHERE questions implied in Figure 1, a potential maker of biodiesel must consider two sets of questions simultaneously: (1) what is known about the suitability of different algal strains in certain locations and (2) what is known about the products that can be produced from those strains in the preferred locations. This is no easy task. A major challenge is that not all strains that grow well in a laboratory are suitable for large-scale culturing in the field (Sheehan, 1998). For example, certain non-laboratory strains may be better for biodiesel production. Thus strain, product and site selection are intimately interrelated. Although this kind of co-selection is a significant challenge, it will not be discussed further here.

All the subsequent processing steps in the algae-to-biodiesel supply chain – from algal growth to final combustion – comprise the HOW questions in Figure 1. These kinds of processing steps are required to make biodiesel from algae. However, many microalgae harvesting studies have ignored the main subjects of the investigation – the microalgae – when choosing their harvesting and dewatering technologies (see

Benemann and Oswald, 1996). More often than not, the microalgae are treated as homogeneous, uniform and unvarying colloidal particles, when in reality they are complex and highly variable, not just between species but within the same strain exhibiting different surface charges (a major determinant in harvesting responses), depending on culture condition. Development of universal harvesting technologies applicable to all microalgae is unrealistic economically, because they consist of crude and expensive methods such as centrifugation and chemical flocculation. Secondly, therefore, a biodiesel maker must match the algal strain to the harvesting, dewatering and oil extraction technologies.

This report will attempt to answer some WHERE questions for the APEC economies as a whole. In reality, it is important to keep the biology and whole supply chain in view, since location decisions about the algal growth medium will depend on the strain selected which, in turn, will affect the choice of downstream processes – such as suitable methods of harvesting, dewatering and oil extraction. Many choices must be made when arranging the complete supply chain, from algal selection and growth to final combustion in the vehicle.

METHOD 1: THE ADJUSTED TNO APPROACH

Introduction

Given limited data, a pragmatic way to tackle biomass resource assessment is to start by estimating the theoretical possibilities and then introduce a set of constraints that gradually whittle these theoretical resources down to a more realistic set of achievable possibilities. This sequential constraints method corresponds to the approach adopted by two Dutch authors at the TNO (van Harmelen and Oonk, 2006) for algal biomass and by Farine et al (2011) and others for terrestrial biomass. A brief summary of the TNO approach adopted by van Harmelen and Oonk follows, including indications of some flaws in their original approach and ways of overcoming them.

Climatic Resources

The first constraint limiting algal production is climate, defined by temperature, sunlight and moderate seasonality. Van Harmelen and Oonk (2006) decreed that those locations within the blue rectangle shown in Figure 2, enjoying annual average temperatures of 15°C or more, were suitable for microalgae production on wastes. As we shall see shortly, such an arbitrary and simplistic approach would exclude several APEC economies where algae can be grown (albeit more slowly) from our list of prospects. In future assessments, constraints arising from incident solar radiation, minimum winter and night-time temperatures should be adopted, because these are much closer to the actual limiting factors.

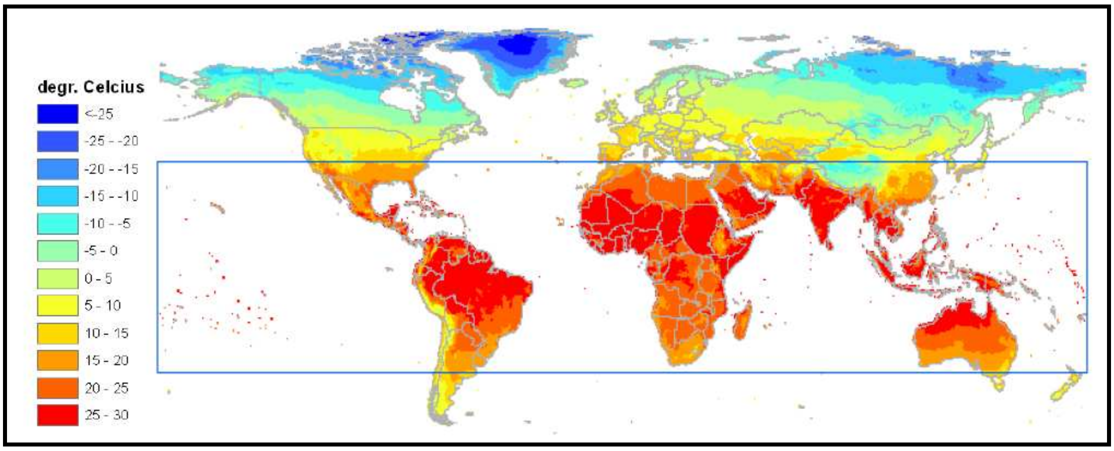


Figure 2: Temperature zones declared suitable for algae biofuel feedstock production (Source: van Harmelen and Oonk, 2006)

Water Resources

A sustainable supply of water in sizeable amounts is an essential resource for the algal ponds. Potential sources include fresh water, bore water, seawater, brackish water, wastewater and other aquifers, marshes, lakes and estuaries. Given that most ASEAN economies need fresh water and bore water for other purposes, they will be ruled out for this study. Also, they should be ruled out on sustainability grounds. Brackish water and other specific water bodies will be ruled out because they require individual assessment to confirm their location and suitability. This task is well beyond the scope of this study. Thus we are left with only two possibilities as key resource candidates – seawater at coastal locations or wastewater.

In many APEC economies, coastal land is highly prized and highly priced because it is in great demand for various purposes. This makes it difficult to use seawater at coastal locations unless the location is remote from cities and towns or it is piped significant distances inland from the coast to the algal pond. Thus seawater could be an expensive option which, when combined with the cost of transporting or piping sufficient nutrients and CO_2 to the same facility, is likely to drive up the overall costs of coastal facilities to uneconomic levels. For this reason, a few Asian economies (Japan in particular) farm algae at sea. Coastal land is unavailable or is prohibitively expensive in these economies. However, other APEC economies have the potential to develop algal facilities on marginal land in coastal locations. This coastal resource potential is discussed in the chapter entitled METHOD 3: A COASTAL LAND PLUS CO_2 APPROACH.

Thus we are left with wastewater as the best, near-term option for new algal ponds. Another reason why wastewaters containing human and animal wastes are attractive as media for microalgal growth is that a growing number of wastewater facilities have several levels of treatment (primary, secondary and tertiary), resulting in ponds and lagoons with water of different qualities. In those existing ponds, one can find all the nutrients (in different proportions) needed to sustain new algae growth in separate, high-rate algal ponds. By overcoming the need to rely upon external sources of water and nutrients, the overall cost and sustainability of such facilities for algae growth and oil extraction improve markedly.

Our spreadsheet assessment of algal oil production for Melbourne Water showed that wastewater treatment plants can outperform other systems in cost-benefit terms and also display an excellent carbon footprint (Batten et al, 2011). More importantly, if wastewater systems are chosen as the medium to initiate algal biodiesel production, as this technology is perfected it can be expanded by recycling available nutrients and waters and digesting the residual biomass to produce biogas as a self-sufficient source of power and CO_2. This strategy can increase the viability of producing biofuels (Benemann, 2010). For these and other reasons, wastewater treatment would seem to be the best short-term business model for algae-to-biodiesel production. Therefore, Method 1 (this chapter) and Method 2 (next chapter) will focus on algal oil production with the help of wastewater treatment of human and animal wastes.

Waste Nutrient Resources

We are not the first to conclude that the resources considered most suitable for the near-term application of microalgae cultures for renewable energy production and GHG abatement are human, animal and some industrial wastes (see e.g. Benemann, 2003; 2010; van Harmelen and Oonk, 2006). A recent report from the University of California at Berkeley goes even further by projecting an unfavourable outcome for large-scale production of biofuels from microalgae unless wastewater treatment is the primary goal (Lundquist et al, 2010). As mentioned above, further confirmation of the importance of the wastewater treatment path came from recent spreadsheet modelling of two treatment plants in Melbourne (Batten et al, 2011). The scenario of growing microalgae near existing treatment lagoons, extracting the algal oil and feeding the remaining biomass through an anaerobic digester to produce biogas for the renewable production of electricity in on-site generators, resulted in algal oil being producible at a cost of less than US$1 per litre. Although this promising result was possible because of the availability of all the key resource inputs at little or no cost, it suggests that wastewater warrants more in-depth consideration than it has received to date. If the additional income associated with the wastewater treatment is taken into account, then Lundquist et al (2010) have shown that algal oil could be produced for as little as 20 cents per litre.

Part of the attraction of the wastewater path emanates from an important change in emphasis in wastewater treatment technology – from oxidizing the organic matter in the waste (i.e. removing the biological oxygen demand) to removing, recovering or recycling the key nutrients – N and P. This growing need for nutrient removal, recovery and recycling improves the economic potential of using new algal ponds in wastewater treatment, since microalgae are particularly efficient in capturing and removing such nutrients (Woertz et al, 2009). Thus the third constraint on where to grow algae is the location of waste nutrient sources – people, pigs and dairy cows – in the climatically suitable areas. Without a sufficient, sustainable density of N-rich and P-rich resources, algae cultivation at commercial scale will not be viable.

One way of estimating the nitrogen and phosphorus needed for algae production is to use the Redfield ratio (Redfield, 1934), which provides a coarse elemental molar ratio of 106:16:1 for C:N:P for all marine phytoplankton. Using the atomic weights of 12, 14, and 31 for C, N and P respectively, the relative mass ratio becomes 1272:224:31. For dry algae biomass consisting of 50% carbon, this gives the relative percentages of C, N and P on a mass basis as 50, 8.8, and 1.2 percent, respectively. The percentages of N and P are often rounded to 9% and 1% respectively.

In this report, we assume that these elemental content percentages can be generally applied as an approximate average for microalgae. If we also assume that the nutrient uptake efficiencies for each are of the order of 75% – being comparable to that reported for nitrogen in terrestrial crops like corn – it follows that the nutrients needed to produce 1000 kg of dry weight microalgae are estimated to be nominally 117 kg of nitrogen and 16 kg of phosphorus (Pate, Klise and Wu, 2011). In other words, 1 kg of N translates to a potential of 8.5 kg of algal biomass. Although the nutrient use projections calculated here are only rough estimates subject to uncertainty, the ratio of 1 to 8.5 is of the same order as the 1 to 10 ratio assumed by van Harmelen and Oonk (2006) to calculate their global theoretical algae resource production potentials. For consistency with the TNO method, we have adopted the higher ratio of 1 kg of N producing 10 kg of algae biomass to estimate the lower-bound production potential of each APEC economy by the year 2020 (see Table 1).

APEC's Theoretical Resource Production Potential

After assessing availabilities of suitable climatic conditions, wastewater and nutrient resources, the TNO analysis summed the theoretical regional resource potential of municipal wastewaters, piggeries and dairy cow feedlots in climatically suitable areas of the world. It used spatially differentiated grid data from the Edgar GHG emission database to calculate and display spatial resource potentials for the year 2020 in a map form, as shown in the TNO report (see van Harmelen and Oonk, 2006, page 26).

Their estimated global theoretical resource potential in 2020 is 366 million tonnes of algal biomass production (up from 200 in 1990), based on the assumed nutrient content of the human, dairy cow and pig wastes in the climatically suitable areas. In comparison, our estimate of the APEC economies' theoretical resource potential in 2020 is about 204 million tonnes of algae biomass production (Table 1). This is just under 60% of the global theoretical resource potential, the bulk of the difference being attributable to the algae production potential of India, Africa and South America. From this and earlier analyses, it is clear that Asia has the largest theoretical potential – especially China (an APEC economy) and India (outside the APEC region).

Table 1: Theoretical algae resource production potential by APEC economy in 2020 (based on total waste N nutrient located within 15C area in Figure 2)

APEC ECONOMIC ZONE	MUNICIPAL WASTE (t)	ANIMAL WASTE (t)	TOTAL WASTE (t)	ALGAE (Mt)
Australia	217,000	572,400	789,400	7.89
Brunei Darussalam	0	0	0	0
Canada (See Note 1)	0	0	0	0
Chile	7,000	0	7,000	0.07
Peoples Republic of China	**5,257,750**	**5,281,600**	**10,539,350**	**105.39**
Hong Kong, China	0	0	0	0
Indonesia	977,500	216,000	1,193,500	11.94
Japan	20,000	11,000	31,000	0.31
Republic of Korea	0	0	0	0
Malaysia	111,000	64,800	175,800	1.76
Mexico	**619,500**	**3,060,700**	**3,680,200**	**36.80**
New Zealand	0	0	0	0
Papua New Guinea	22,000	400	22,400	0.22
Peru	119,750	58,800	178,550	1.79
The Philippines	111,750	99,100	210,850	2.11
Russia (Note 1)	0	0	0	0
Singapore	0	0	0	0
Chinese Taipei	25,000	30,000	55,000	0.55
Thailand	428,250	299,800	728,050	7.28
United States of America	**848,500**	**1,033,500**	**1,882,000**	**18.82**
Viet Nam	430,500	468,600	898,600	8.99
TOTAL	**9,195,500**	**11,196,200**	**20,391,700**	**203.92**

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone

Adjusting the TNO Approach to Constrained Estimation

Next, constraints were introduced on the availability of flat land, the availability of low cost land and the availability of CO_2 supply, energy and other infrastructure. The first constraint was approximated by land located at or below 500 metre altitudes, whereas the second and third constraints were related purely to population densities. Locations that fulfilled all three constraints, in addition to climatic conditions, were deemed to have the best economic potential. This brought the global resource potential down from a theoretical maximum of 366 million tonnes to a pragmatic possibility of 90 million tonnes of algal biomass production per annum. In other words, municipal and animal wastewater potentials are limited to about 25% of their theoretical potential by the combined constraints of lack of populated areas and the availability of suitable land (flat and cheap).

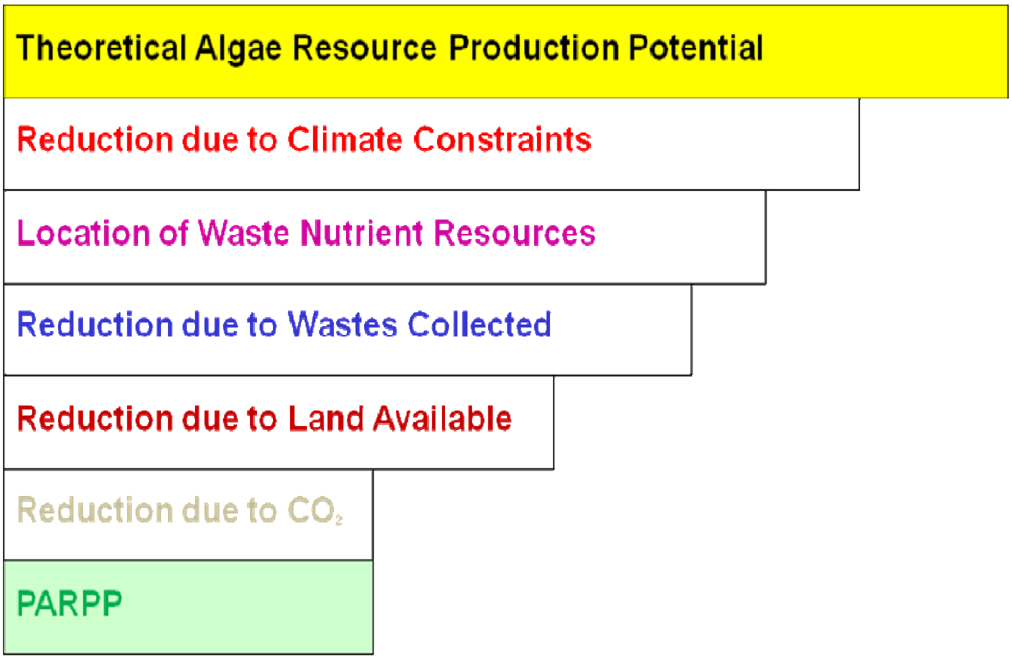


Figure 3: Adjusting the TNO Approach down from a Theoretical to a Practical Potential (PARPP = Practical Algae Resource Production Potential)

Our Method 1 estimates for the practical resource potential of the APEC economies are derived from the maps of global technical potentials provided in van Harmelen and Oonk (2006, Figure 4.7, page 32). Originally, we hoped to receive sufficient responses to our questionnaire – which was sent out last year to all APEC economies – to obtain improved estimates of the algal resource potentials in each economy (see Appendix A). Because the response level to our survey was low, however, we have adopted the TNO approach for our lower-bound estimates. The resulting estimates are given in Table 2. In this table, it has been assumed that 1 tonne of microalgae can produce 333 litres of biodiesel.

After constraints were introduced on the availability of flat low-cost land, CO_2 supply, energy and treatment infrastructure (as discussed earlier), the resource potential of the APEC economies came down from a theoretical maximum of 204 million tonnes per annum to a pragmatic likelihood of just over 58 million tonnes of algal biomass production per annum (see Table 2). In other words, municipal and animal wastewater potentials are limited to less than 30% of their theoretical potential by the combined constraints of the lack of populated areas and the scarcity of flat, low-cost land. Of note is the fact that China, the USA and Indonesia seem to offer the best prospects for making algal biodiesel in the near future. In terms of replacing fossil diesel (in % terms), Indonesia offers the greatest potential with the opportunity to replace almost one quarter of its current diesel use. When their practical potential is viewed as a percentage of their theoretical potential, the two leading APEC economies for algae production from wastes are Japan and the USA. These two economies stand out because they have a relatively large number of highly-populated urban settlements. However, Japan has very little real potential because of its lack of available land, while the United States has significant algae production potential in the near-term. In absolute terms, however, China has the potential to become the leading waste-to-algae producer in the APEC bloc.

Table 2: Practical algae resource production potential by APEC economy in 2020 (adjusted for various constraints)

APEC ECONOMIC ZONE	USABLE NITROGEN (t)	ALGAE (Mt)	BIODIESEL (ML)	AS A % OF DIESEL USE
Australia	32,750	0.33	110	1.1%
Brunei Darussalam	1,750	0.02	7	3.5%
Canada (See Note 1)	0	0	0	0
Chile	3,000	0.03	10	0.25%
Peoples Republic of China	**2,749,500**	**27.5**	**9,165**	**11.4%**
Hong Kong, China	0	0	0	0
Indonesia	**709,750**	**7.1**	**2,366**	**23.5%**
Japan	14,000	0.14	47	0.15%
Republic of Korea	4,800	0.05	17	0.1%
Malaysia	121,250	1.21	404	7.1%
Mexico	402,750	4.03	1,343	8.1%
New Zealand	7,500	0.07	25	1.1%
Papua New Guinea	0	0	0	0
Peru	7,000	0.07	23	0.8%
The Philippines	176,750	1.77	589	9.5%
Russia (Note 1)	0	0	0	0
Singapore	0	0	0	0
Chinese Taipei	0	0	0	0
Thailand	579,000	5.79	1,930	14%
United States of America	**776,650**	**7.77**	**2,589**	**1.6%**
Viet Nam	228,750	2.29	762	16%
TOTAL	**5,817,000**	**58.17**	**20,185**	**4.9%**

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone.

Unfortunately, there are weaknesses in the assumptions adopted in van Harmelen and Oonk (2006) to generate practical potentials from the theoretical potentials discussed above. In the APEC economies, not all wastewater from human and animal wastes is collected. Even less is treated. This means that the estimates in Table 2 need to be adjusted downwards in accordance with the extent to which each economy’s wastewater is collected and treated. Furthermore, only a small percentage of cattle are raised in feedlots where wastewater can be made available for algae production. The percentages of pigs raised in piggeries with wastewater ponds are higher (see Table 3). But in both cases, the assumed wastewater available from animal waste sources that could be used for algae growth will be less than the amount assumed in Table 2.

Table 3: Practical algae resource production potential by APEC economy in 2020 (adjusted for % of sewage collected, cattle in feedlots and pigs in piggeries)

APEC ECONOMIC ZONE	**% of Sewage Collected**	**% of Cattle in Feedlots**	**% of Pigs in medium-size Piggeries**	**ALGAE (Mt)**
Australia	87%	5.4%	54%	0.30
Brunei Darussalam	40%	1%	20%	0
Canada (See Note 1)	74%	20%	40%	0
Chile	96%	1%	20%	0
Peoples Republic of China	**46%**	**10%**	**24%**	**8.78**
Hong Kong, China	93%	1%	20%	0
Indonesia	25%	1%	20%	1.78
Japan	67%	1%	20%	0
Republic of Korea	50%	1%	20%	0
Malaysia	40%	1%	20%	0.42
Mexico	20%	5.7%	40%	0.65
New Zealand	80%	1%	20%	0
Papua New Guinea	30%	1%	20%	0
Peru	81%	1%	20%	0.05
The Philippines	7%	1%	20%	0.27
Russia (See Note 1)	55%	1%	20%	0
Singapore	100%	1%	20%	0
Chinese Taipei	85%	1%	20%	0
Thailand	**40%**	**0**	**80%**	**3.18**
United States of America	**71%**	**80%**	**45%**	**5.44**
Viet Nam	5%	1%	5%	0.11
TOTAL				**20.98**

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone.

We have estimated the amounts of human sewage collected in each APEC economy in 2005 and the proportion we expect will be collected and treated by the year 2020. We have repeated this estimation for the percentage of dairy cows in feedlots and the percentage of pigs in large or medium-sized piggeries. Table 3 contains the results. The reduced quantities of wastewater available for algae culturing in each APEC economy have led to a reduction in the total algal biomass capacity of the APEC region from 58 Mt to about 21 Mt.

METHOD 2: A SUSTAINABLE INPUTS APPROACH

Introduction

Making substantial reductions in CO_2 emissions from large, coal-based (or gas-fired) power plants using algae – the major argument put forward for algal biofuels by many proponents – is most unlikely. Grobbelaar et al (2000) calculated that biofixation of CO_2 from a 300 MW thermo-electric coal-fired power station would require an algal culture area of about 100 km^2. They concluded that conventional mass cultures of microalgae are economically infeasible to absorb substantial amounts of CO_2 emitted from point sources. This scale-up challenge has been confirmed in other studies (e.g. Campbell, Beer and Batten, 2009). The extra costs associated with providing more land and infrastructure (capital costs) and electricity for pumping over much longer distances (operating costs) make the production of biodiesel alone economically unattractive under these conditions.

The expected economies of scale found in other industries do not apply for current algal raceway pond designs. Furthermore, using microalgae in this way postpones the replacement of unacceptably dirty industries by cleaner, renewable ones. Therefore, smaller, renewable and distributed CO_2 sources – such as abattoirs, piggeries, cement plants, cheese factories, ammonia plants and wastewater treatment plants – are more suitable. It may be erroneous to assume that algal biodiesel can replace fossil diesel to a significant extent, just as ethanol is unlikely to replace petrol. At current E10 levels, ethanol is a fossil fuel extender (Batten, 2008). In colder climates especially, algal biodiesel may not blend properly with fossil diesel if their respective properties differ before blending.

The Basics of Method 2

A more sustainable and scalable strategy for the production of algal oils and biodiesel is to recycle the water, carbon and key nutrients (N and P). For example, the residual biomass after oil extraction could be converted to biogas via anaerobic digestion, with digester residues (containing nutrients and carbon) being recycled to the ponds. This would not only facilitate additional on-site power generation and thus CO_2 for the algae, but also ensure that nutrient supplies do not become a bottleneck if and when the ponds increase in size and/or number. As Benemann (2010) noted, this approach can cover most process ("parasitic") energy needs, and perhaps even generate surplus power to enable fossil energy to be replaced by bioenergy. Self-sufficient approaches based on recycling of key inputs will be necessary to ensure that algal biofuels are carbon-neutral or carbon-negative in a life cycle assessment.

As mentioned in the Introduction, the oil extraction plus anaerobic digestion pathway is not new. Oswald and Golueke (1960) suggested it. Other authors to have confirmed its credentials include Regan and Gartside (1983), Benemann and Oswald (1996) and Campbell, Beer and Batten (2009), among others. In a recent Australian biomass resource assessment (Farine et al, 2011), it was found that Australian wastewater treatment plants provide about 33.8 kg of dissolved carbon per person. This figure provides a means of estimating the maximum theoretical amount of carbon produced via wastewater treatment each year, which can then be converted into a CO_2 estimate for each APEC economy. In a similar manner, the number of pigs in piggeries and cattle in feedlots can be used to estimate the maximum theoretical amount of CO_2 that could be collected from these animal wastes in each economy. The total CO_2 from human and animal wastes can then be calculated and converted into potential algal biomass – to form part of our Method 2 estimate.

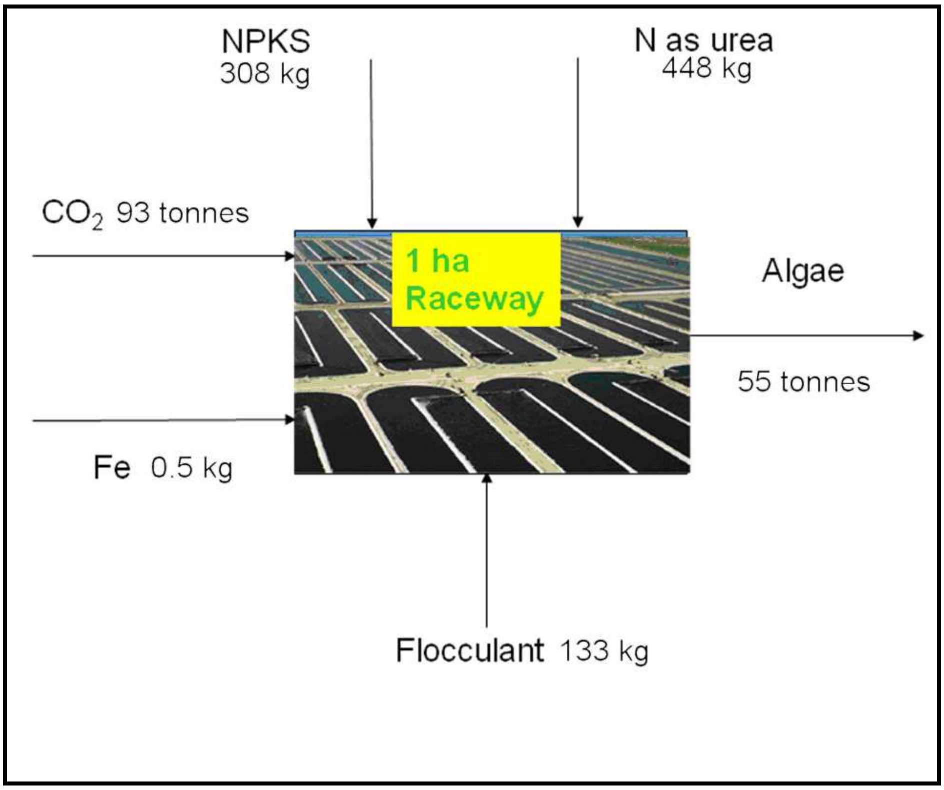


Figure 4: Our assumed annual materials inputs and outputs for Method 2 (adapted from Campbell, Beer and Batten, 2009)

Although many production systems of this kind have been proposed for growing algae and extracting oil, in this report we shall adopt the one discussed in Campbell, Beer and Batten (2009), which is displayed in Figure 4. With CO_2 supplementation, an annual algal growth rate of 15 g/m^2/day or 55 tonnes per ha dry weight is a reasonable expectation. In turn, about 16.5 kL/ha of biodiesel could be produced per annum. Although this figure may appear to be conservative, at the present time it is unrealistic to adopt higher growth rates that correspond to ideal conditions – such as a biodiesel production rate of 33 kL/ha. Such ideal conditions are rarely if ever experienced in the field, so a conservative figure is more appropriate at this point in time.

The need for CO_2 supplementation is due to the fact that municipal wastewaters are deficient in C, in relation to their N and P (Benemann and Oswald, 1996). Without CO_2 supplementation, only about 5-10 tonnes/ha of dry-weight algal biomass is likely. Regan and Gartside (1983) estimated 6 tonnes/ha annually for common algae strains. At a growth rate of 15 g/m^2/day, the annual nutrient requirements are approximately 310 kg/ha of nitrogen and 31 kg/ha of phosphorus (and possibly some potassium), all of which can be obtained from the organic waste. A similar deficiency in C applies for wastewaters containing animal wastes, since they are of a similar composition. In Method 2, therefore, the limiting factor will be the supplementary carbon dioxide.

According to Campbell, Beer and Batten (2009), 93 tonnes of CO_2 supplementation will result in 55 tonnes of dry weight algae per hectare per year. If we assume that 6 tonnes per hectare per year results from atmospheric absorption (Regan and Gartside, 1983), we can calculate the amount of supplementary CO_2. At a growth rate of 15 g/m^2/day, a minimum of 87 tonnes of supplementary CO_2 per hectare will be required each year – equivalent to 23.8 tonnes/ha of carbon.

Using this approach (Method 2), we can roughly estimate the potential algal biomass production of an APEC economy based on the amount of carbon in its organic waste that reaches large processing plants. Based on the above calculations we shall assume that on average each tonne of carbon results in 2.3 tonnes of dry-weight algae, which in turn produces 0.76 kilolitres of biodiesel and requires 0.042 ha of land for ponds. The actual land area needed will be about 0.053 ha in total, with the extra land being taken up by roads, buildings, processing equipment, piping and other equipment.

Table 4: Practical algae resource production potential by APEC economy (using Method 2)

ECONOMIC ZONE	ALGAE (Mt) *ºC adjusted*	ALGAE (Mt) *ºC unadjusted*	BIODIESEL (ML)		AS % OF DIESEL	
			ºC adj	*ºC unadj*	*ºC adj*	*ºC unadj*
Australia	3.28	3.28	1,092	1,092	9.6%	9.6%
Brunei Darussalam	0.05	0.05	15	15	7.4%	7.4%
Canada (See Note 1)	0	4.77	0	1,550	0	8.0%
Chile	0.75	1.50	244	488	5.0%	10.0%
Peoples Republic of China	**36.70**	**73.40**	11,927	23,855	9.5%	24.8%
Hong Kong, China	0.57	0.57	185	185	12.4%	12.4%
Indonesia	**5.73**	5.73	2,366	2,366	19.5%	19.5%
Japan	3.57	**7.14**	1,160	2,320	3.1%	6.2%
Republic of Korea	2.19	2.19	712	712	3.3%	3.3%
Malaysia	1.12	1.12	404	404	5.9%	5.9%
Mexico	4.02	4.02	1,343	1,343	6.7%	6.7%
New Zealand	0.04	0.39	13	127	0.5%	4.5%
Papua New Guinea	0.21	0.21	68	68	70.0%	70.0%
Peru	2.23	2.23	725	725	20.3%	20.3%
The Philippines	0.92	0.92	589	589	7.9%	7.9%
Russia (See Note 1)	0	6.70	0	2,178	0	11.7%
Singapore	0.51	0.51	166	166	7.8%	7.8%
Chinese Taipei	1.75	1.75	569	569	1.0%	1.0%
Thailand	2.71	2.71	1,930	1,930	11.7%	11.7%
United States of America	**45.80**	**91.50**	14,869	29,738	7.3%	14.5%
Viet Nam	0.58	0.58	189	189	13.2%	13.2%
TOTAL	**112.73**	**211.27**	**37,968**	**71,156**	**6.9%**	**12.9%**

Note 1: Wholly located outside of the 15 degrees ºC optimal algal growth zone.

The Effects of Variable Temperatures, Solar Radiation and Time

In Table 4, we have included several different estimates of the amount of algae and biodiesel that could be produced by each APEC economy under the abovementioned assumptions for Method 2. The column labeled *ºC adjusted* (or *ºC adj*) reduces the maximum resource potential shown in the column labeled *ºC unadjusted* (or *ºC unadj*) whenever (1) the night-time average temperatures or temperature variations between summer and winter are below the levels needed to achieve the assumed growth rate of algae and/or (2) the levels of incident solar radiation are below the levels needed to achieve the assumed growth rate. The levels of incident solar radiation assumed for each APEC economy in this assessment are shown in Figure 5.

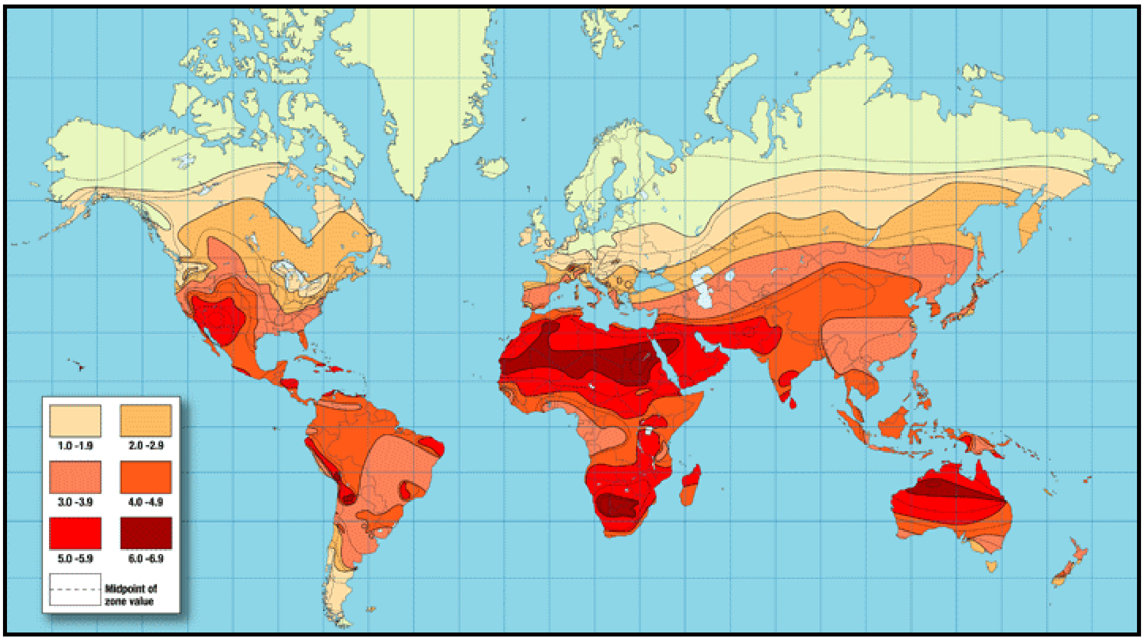


Figure 5: World Daily Incident Solar Radiation Map
(Source: OKSolar – www.oksolar.com/abctech/solar-radiation.htm)

The pertinent adjustment factors are shown in Table 5. The top three APEC economies in terms of the potential amount of algae that could be produced under the different assumptions are highlighted in yellow in Table 4. Two of these economies have an adjustment factor of 0.5 (China and the USA). Together with Chile, they have been assigned this value because roughly half their land is located in areas that are regarded as less suitable for the growth of algae because of levels of incident solar radiation, night-time temperatures or temperature variations between summer and winter. New Zealand has an adjustment factor of 0.1 because only about 10% of its land area is located in areas deemed suitable for growth of algae at the assumed rate.

One should bear in mind that these estimates do not rule out the growth of algae in the economies that have been adjusted downwards. Growth may be slower and may need more research to identify the species and strains of algae that are suited to the cooler temperatures, their variations and the levels of incident solar radiation observed.

Table 5: Adjustment Factors for APEC Economies

APEC ECONOMIC ZONE	Adjustment Factor for Temperature Variations and Solar Radiation
Australia	1.0
Brunei Darussalam	1.0
Canada (See Note 1)	0.0
Chile	0.5
Peoples Republic of China	0.5
Hong Kong, China	1.0
Indonesia	1.0
Japan	1.0
Republic of Korea	1.0
Malaysia	1.0
Mexico	1.0
New Zealand	0.1
Papua New Guinea	1.0
Peru	1.0
The Philippines	1.0
Russia (See Note 1)	0.0
Singapore	1.0
Chinese Taipei	1.0
Thailand	1.0
United States of America	0.5
Viet Nam	1.0

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone.

These adjustment factors are crude, first approximations and further research will be needed for each APEC economy to quantify more precisely the effects of temperature variations and incident solar radiation on algae growth potential.

METHOD 3: A COASTAL LAND PLUS CO_2 APPROACH

Introduction

Although algal ponds are best located close to smaller sources of CO_2 and nutrients (such as wastewater treatment plants, piggeries, feedlots, abattoirs, landfills, ammonia plants and distributed power plants), there may be further opportunities for algal ponds in those APEC economies that have significant areas of vacant land in coastal locations. The economics of coastal locations rests heavily on the price of land and the distances involved, since CO_2 and other nutrients must be transported from their sources to the algal ponds. These piping or transport costs can be expensive, as has been confirmed in several studies (e.g. Campbell, Beer and Batten, 2009; Griffin and Batten; Stephens et al, 2010).

How much land in coastal areas could be used for production of biofuels? For ethanol, several multi-economy assessments of bioenergy potential in the literature are based on assumptions about availability of “marginal”, “idle” or “waste” land (e.g. Hoogwijk et al., 2005; Milbrandt and Overend, 2009; Milbrandt and Jarvis, 2010). These studies suggest that significant opportunities exist for growing terrestrial biomass suitable for the production of ethanol. One assessment suggests that some APEC economies could replace a substantial share of their current gasoline and crude oil imports with ethanol from marginal lands (Milbrandt and Overend, 2009) – including Australia (537%), Chile (357%), New Zealand (78%), Peru (1,666%) and Vietnam (79%).

The situation is vastly different for algal biodiesel. Finding sufficient flat land suitable for growing algae in hundreds of large, open ponds is a major challenge. Although coastal areas provide limited opportunities for algae in most APEC economies, the concept of growing algae in coastal deserts should not be dismissed. It is an old idea (Regan, 1980; Wagener, 1981) that was piloted in the coastal areas of Calabria and blossomed commercially in South America's Atacama Desert (the driest desert in the world) in 1991, when Solarium began to produce about three tonnes of Spirulina per annum. According to Milbrandt and Overend (2009), several of the APEC economies – Australia, Chile, Mexico, Peru and the United States – have large areas of dry, flat, low-lying land along or near their coastline. The viability of desert areas for algal biodiesel will need to be explored individually for each APEC economy in the future.

Other biomass assessments have not considered land to be marginal, idle or waste. Instead they have adopted location-specific assumptions for land areas to be devoted to new production systems, like co-location by land-sharing (O’Connell et al., 2009; Farine et al., 2011). In many ASEAN nations, most cleared land is used for activities akin to light agriculture – e.g. grazing or light cropping. Giving up light agricultural uses in favour of algal facilities would involve some degree of trade-off between food production and energy production capacity. Co-location near existing sources of nutrients, CO_2 and water appears to be the best solution for algal ponds.

Once we look beyond wastewater sources, finding suitable areas of land to grow algae at a commercial scale is much more challenging than finding land to grow terrestrial biomass for ethanol. The difficulty with algae is that five additional input factors must be considered and co-located simultaneously with land (as mentioned earlier) – warm sunlight, a sustainable water supply, and sustainable sources of N, P and CO_2. Several studies examining the economics of algal biofuels have suggested or calculated that the breakeven size for a viable algal biodiesel facility consisting of open raceway ponds is about 400 hectares (Benemann and Oswald, 1996; Campbell, Beer and Batten, 2009; 2011; Stephens et al., 2010). Beyond this size, diseconomies of scale (such as piping, pumping and general transport costs) may offset the scale economies (see Figure 6). Considerably larger land areas have been recommended for algal facilities based upon photobioreactors (Darzins et al, 2010), but this technology will not be investigated in this report.

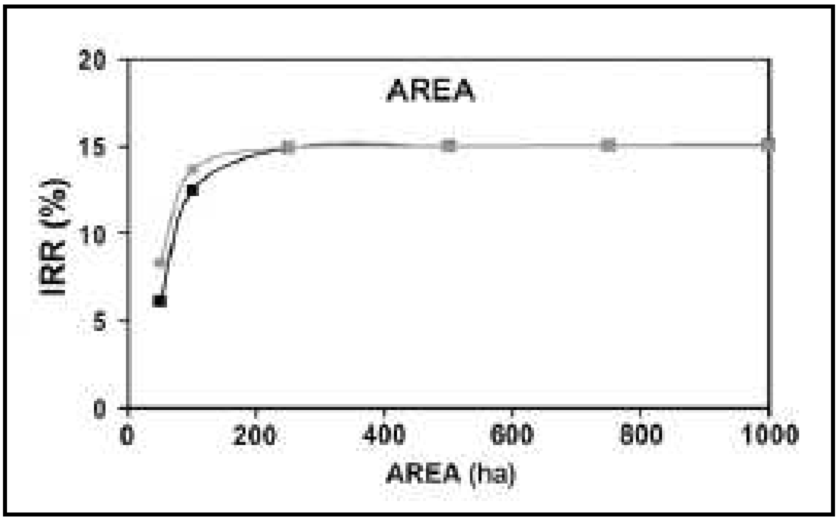


Figure 6: Sensitivity of Internal Rate of Return to Total Land Area of Algal Ponds (Source: Stephens et al, 2010)

Access to affordable land may still be a constraint for municipal wastewater facilities, and is unreliably represented by the simple population density constraints imposed in the TNO analysis. On the other hand, municipal wastewater treatment systems are generally government functions and land is sometimes reserved for these facilities to a greater extent than for private activities. Governments can accord them future priority by reserving larger areas of land for wastewater facilities associated with algae. As more detailed surveys of land ownership, availability and cost will be needed before a better understanding of land availability can be gained, we shall not dwell any further on the issue here. The availability of land at the level of an individual site, local government area or township is beyond the scope of this report.

Estimating the Amount of Marginal Coastal Land

If a distance limit from the coastline is assumed – Regan and Gartside (1983) chose 3 km – the amount of marginal land that is coastal could be estimated with the help of earlier estimates of the areas of marginal land available in each APEC economy (see Milbrandt and Overend, 2009; Figures 7 and 8; and Table 7). Although it is unclear if these earlier estimates are still reliable today, it is clear that Australia, Chile, Mexico, Russia and the United States possess greater potential in terms of marginal coastal land than other APEC economies.

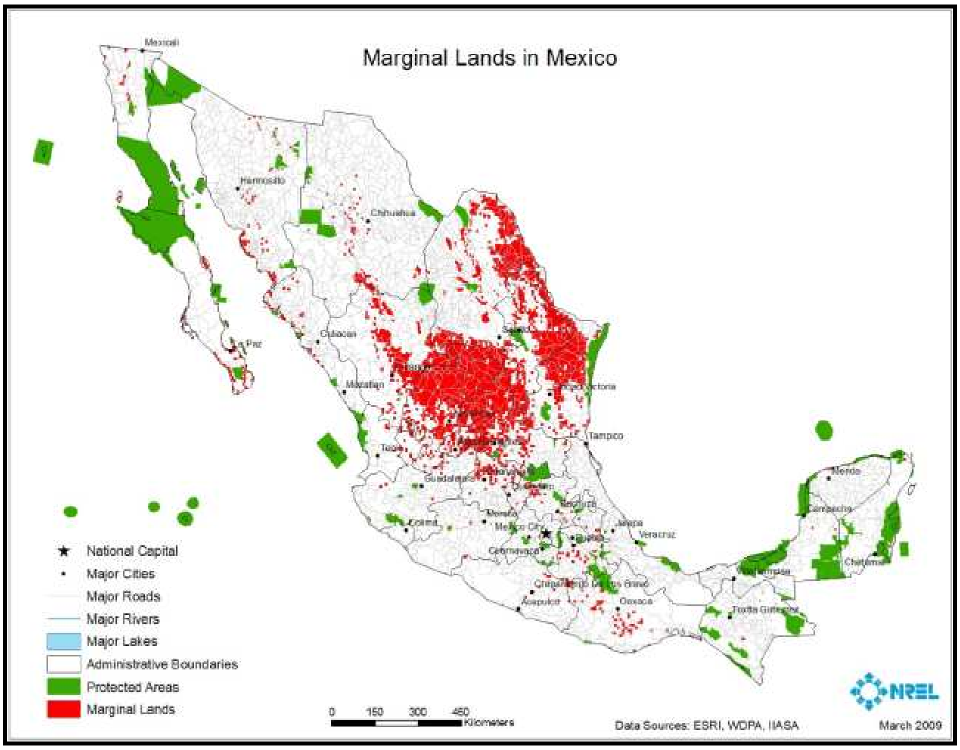


Figure 7: Marginal Lands in Mexico
(Source: Milbrandt and Overend, 2009)

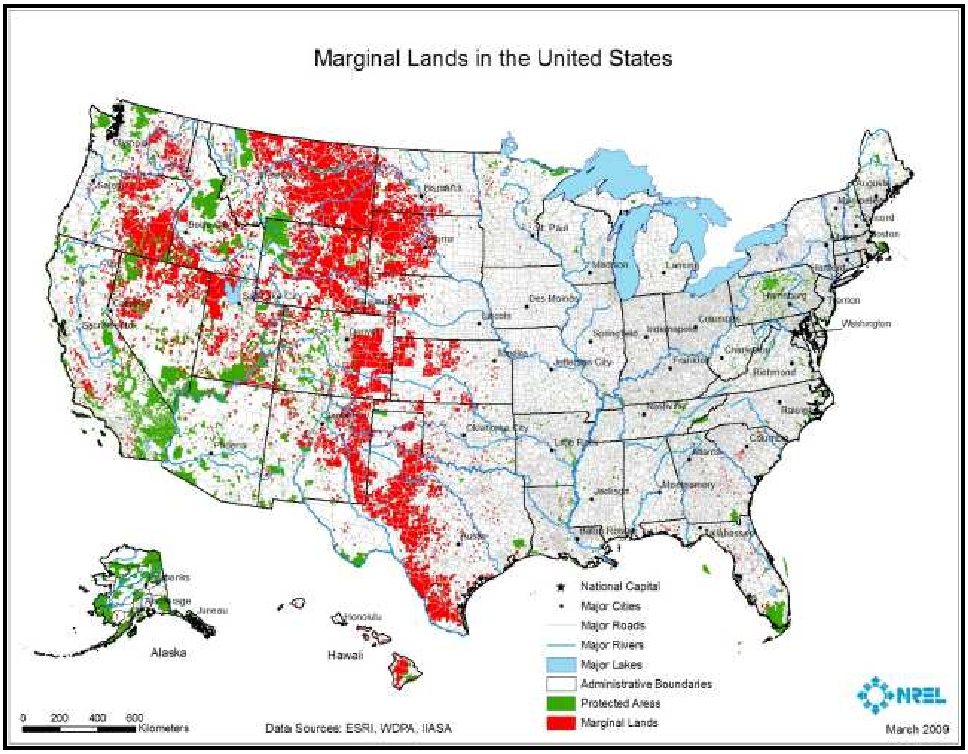


Figure 8: Marginal Lands in the United States
(Source: Milbrandt and Overend, 2009)

In most cases, the others possess tiny quantities of marginal land at coastal locations. We ruled out Canada and Russia earlier because of their cooler climates, although this would not prevent them from growing algae /more slowly or in the dark.

Based on the amounts of marginal land reported in Milbrandt and Overend (2009) and displayed in Table 6, we have roughly estimated the amount of marginal coastal land in each APEC economy. As these rough estimates were done by visually inspecting the spatial maps and assessing the proportion of marginal land that was within 3 km of the nearest coastline, they should be regarded only as a crude first approximation. To improve their accuracy, a series of GIS-based measurements of the areas available at various distances from the coastlines will be required at a later date.

Table 6: Marginal Coastal Land in the APEC Economies
(Adapted from Milbrandt and Overend, 2009)

APEC ECONOMIC ZONE	Land area (ha)	Marginal land	Rough estimate of amount of marginal coastal land (ha)
Australia	**769 million**	**13.50%**	**Less than 1 million**
Brunei Darussalam	0.6 million	1.40%	A few thousand
Canada	983 million	3.80%	Less than 50,000
Chile	72 million	13.00%	About 0.25 million
People's Republic of China	940 million	5.40%	Less than 50,000
Indonesia	185 million	2.00%	Less than 50,000
Japan	37 million	1.30%	About 5,000
Korea	9.5 million	1.70%	About 25,000
Malaysia	33 million	1.00%	About 50,000
Mexico	**195 million**	**13.00%**	**Less than 0.5 million**
New Zealand	27 million	6.50%	About 50,000
Papua New Guinea	46 million	1.60%	Less than 100,000
Peru	130 million	4.40%	About 25,000
Philippines	28 million	2.30%	Less than 80,000
Russia	**1,690 million**	**2.20%**	**Less than 0.5 million**
Chinese Taipei	3.6 million	2.20%	About 10,000
Thailand	52 million	3.30%	About 100,000
United States of America	**943 million**	**13.00%**	**About 0.25 million**
Viet Nam	32 million	6.50%	Less than 25,000

As mentioned earlier, the price of land in coastal locations close to metropolitan areas is often high because it is highly valued for other purposes – such as for residences or for recreational activities. Thus the viability of coastal land must be assessed for its likely price and availability before a reliable assessment of the amounts that might be available for algal ponds can be carried out.

Locating Sources of CO_2

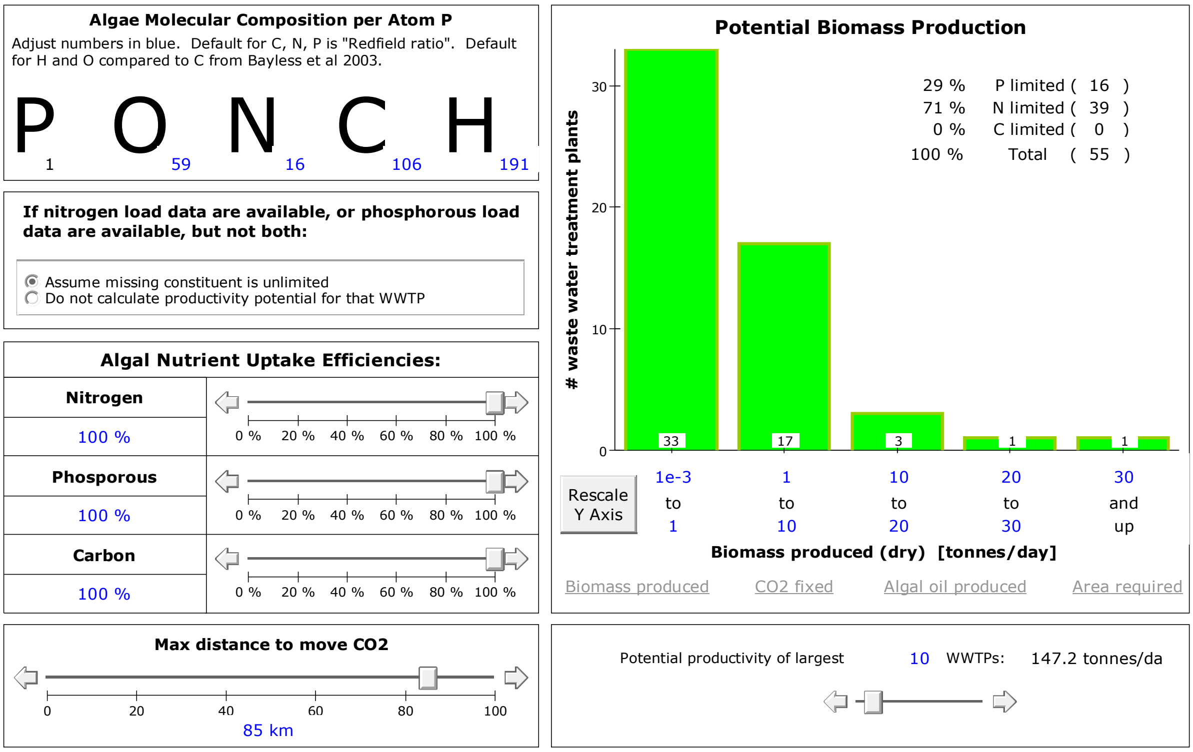
Potential sources of CO_2 include grid-connected power stations, independent power stations, mining sites, wastewater treatment plants, piggeries, cattle feedlots, abattoirs, landfills and ammonia plants, to name a few. We used the CARMA.com website as a source of data about the amounts of CO_2 potentially available from the larger, grid-connected power stations in each APEC economy. The problem with relying on the

CARMA.com website is that it includes only the larger power stations. In reality, algal ponds are best located close to smaller sources of CO_2 and nutrients. These other sources that could be drawn upon in the future will need to be identified by analysts in each of the APEC economies.

Selecting Suitable Sites

Sandia National Laboratories, the Canadian National Research Council and CSIRO in Australia are working together to develop and apply a model that evaluates potential possibilities for algal biomass production in varying geographic locations. This effort assesses existing geospatial data to define the geographic relationships between variables of interest such as solar radiation, CO_2 sources and available land, and link them to locations of potential production near wastewater treatment plants (WWTPs). Another version of this model could be used in the future to help determine optimal coastal locations for algal biomass production in terms of the transportation distances for nutrients and the energy requirements for maintaining a hybrid pond system. Model output includes a suitability ranking of potential algal production sites based on the input described above as well as estimates of the amount of algal biomass that could be produced at these locations.

The geospatial data collected for analysis includes CO_2 sources, wastewater locations with nutrient (N, P) concentrations, land cover and slope and solar resources. In the future, it is intended to include air temperatures, transportation networks and waste heat (from the power plants). All data is used in Sandia's dynamic decision-support model (known as PONCH) to determine the best locations for more detailed research. Preferred sites are likely to be where the limiting nutrients are co-located.



Algae Molecular Composition per Atom P

Adjust numbers in blue. Default for C, N, P is "Redfield ratio". Default for H and O compared to C from Bayless et al 2003.

P	O	N	C	H
1	59	16	106	191

If nitrogen load data are available, or phosphorous load data are available, but not both:

● Assume missing constituent is unlimited
○ Do not calculate productivity potential for that WWTP

Algal Nutrient Uptake Efficiencies:

Nitrogen	100 %
Phosporous	100 %
Carbon	100 %

Max distance to move CO2

85 km

Potential Biomass Production

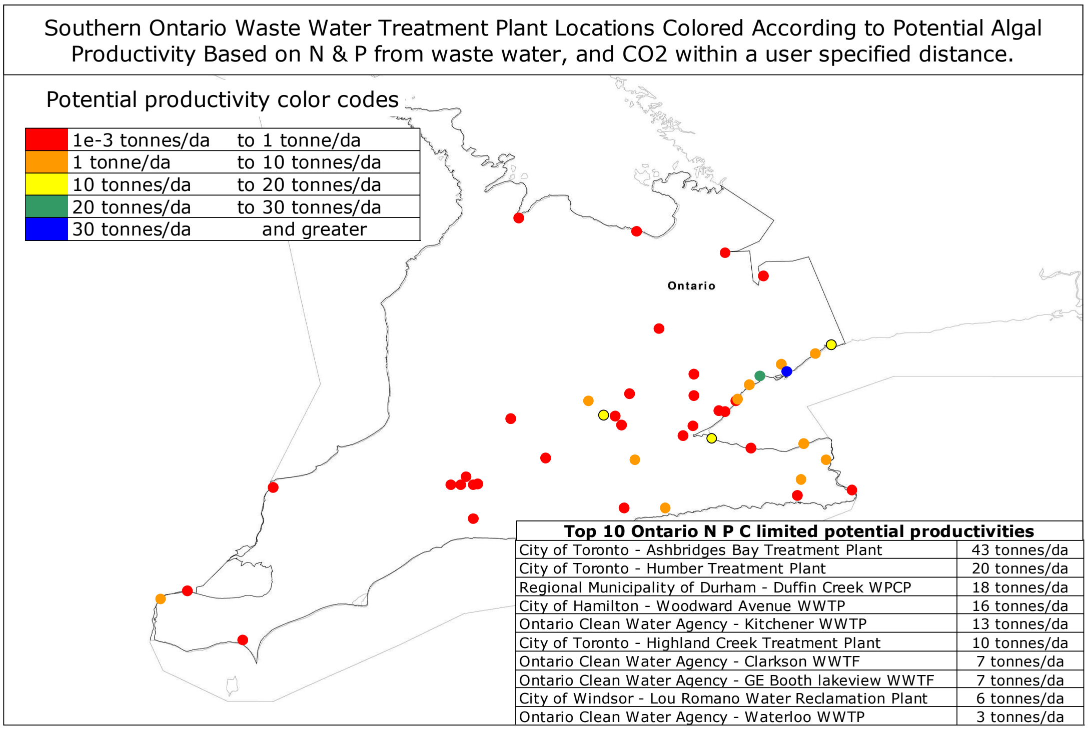
29 %	P limited	(16)
71 %	N limited	(39)
0 %	C limited	(0)
100 %	Total	(55)

Potential productivity of largest 10 WWTPs: 147.2 tonnes/da

Figure 9: The Basic Worksheet of the PONCH Model
(Source: Klise et al, 2010)

The main worksheet of the PONCH model is shown in Figure 9. Users can change nutrient uptake efficiencies or elemental composition if more information is known about a particular algae species. The search radius the model uses to determine the amount of CO_2 available within a specific distance from the WWTPs can also be changed. Based on the nutrient load and the CO_2 available, the theoretical maximum productivity can be calculated and interactively displayed on a map. Being an interactive model, a change can be made easily and scenarios can be compared.

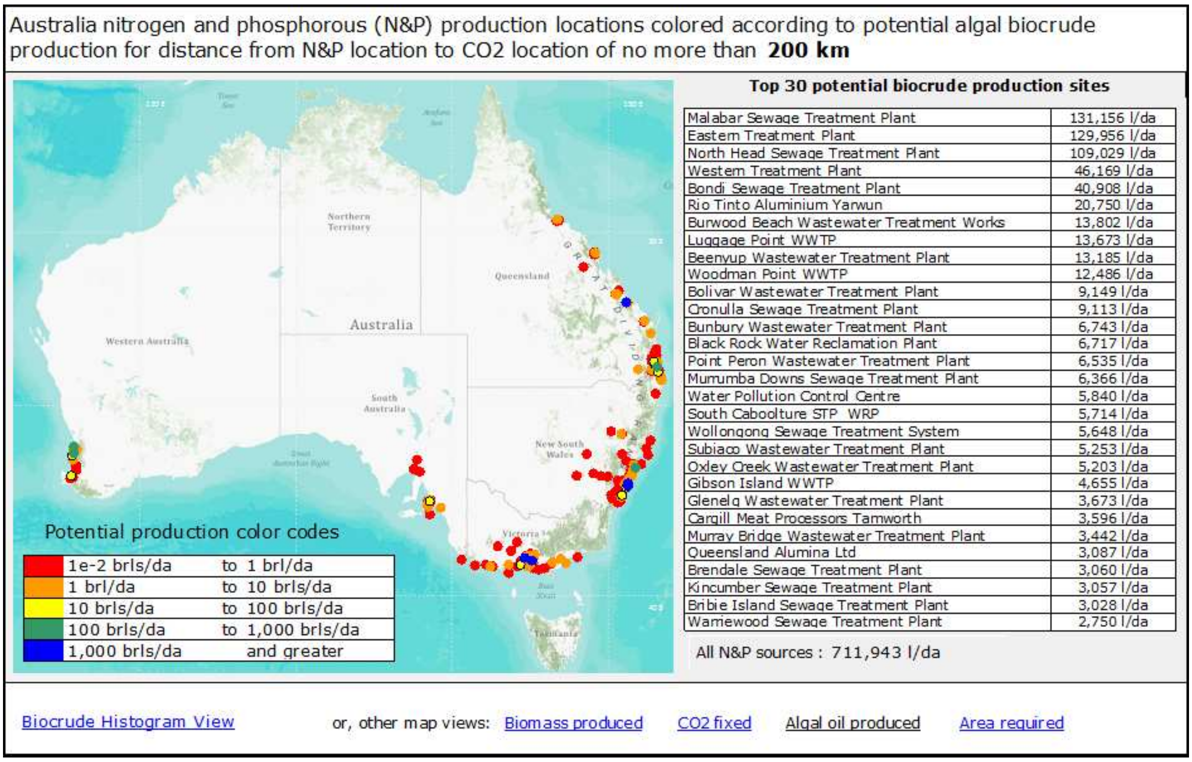
If saline water from a coastal location or wastewater from a WWTP is to be used as a water source and algae-based fuels will be produced and refined on-site in a type of hybrid pond system, an assessment of additional land requirements will be necessary before selecting and ranking the feasibility of various alternative locations for large-scale production. In other words, the PONCH model can only provide an initial, coarse ranking of potential sites based on the locations of resource inputs that are included in the data set supplied. The reliability of the sites selected depends heavily on the comprehensiveness and accuracy of the data set provided. To complement this macro perspective, a more fine-grained assessment of each site and the available land nearby needs to be undertaken on a site-by-site basis.



Top 10 Ontario N P C limited potential productivities	
City of Toronto - Ashbridges Bay Treatment Plant	43 tonnes/da
City of Toronto - Humber Treatment Plant	20 tonnes/da
Regional Municipality of Durham - Duffin Creek WPCP	18 tonnes/da
City of Hamilton - Woodward Avenue WWTP	16 tonnes/da
Ontario Clean Water Agency - Kitchener WWTP	13 tonnes/da
City of Toronto - Highland Creek Treatment Plant	10 tonnes/da
Ontario Clean Water Agency - Clarkson WWTF	7 tonnes/da
Ontario Clean Water Agency - GE Booth lakeview WWTF	7 tonnes/da
City of Windsor - Lou Romano Water Reclamation Plant	6 tonnes/da
Ontario Clean Water Agency - Waterloo WWTP	3 tonnes/da

Figure 10: Southern Ontario's Potential Algal Productivity using CO_2 Sources within 85 km (Source: Klise et al, 2010)

The PONCH model has been applied to two APEC economies (Canada and Australia) and some results of these applications are displayed in Figure 10 and Figure 11. Because the province of Ontario has no external coastline, instead featuring a very large number of lakes (internally and on its borders), some of the preferred sites are near lakes while others are distant from any natural water body. By way of contrast, most of the preferred sites in Australia are on its coastline, because about 90% of its population lives in coastline cities. Cities are where potential water sources – larger WWTPs and saline water – can be found. More importantly, there are several areas of inexpensive, marginal land near the coastline in northern Western Australia, Northern Territory and Queensland that could be good for growing algae.



Australia nitrogen and phosphorous (N&P) production locations colored according to potential algal biocrude production for distance from N&P location to CO2 location of no more than **200 km**

Top 30 potential biocrude production sites

Malabar Sewage Treatment Plant	131,156 l/da
Eastern Treatment Plant	129,956 l/da
North Head Sewage Treatment Plant	109,029 l/da
Western Treatment Plant	46,169 l/da
Bondi Sewage Treatment Plant	40,908 l/da
Rio Tinto Aluminium Yarwun	20,750 l/da
Burwood Beach Wastewater Treatment Works	13,802 l/da
Luggage Point WWTP	13,673 l/da
Beenyup Wastewater Treatment Plant	13,185 l/da
Woodman Point WWTP	12,486 l/da
Bolivar Wastewater Treatment Plant	9,149 l/da
Cronulla Sewage Treatment Plant	9,113 l/da
Bunbury Wastewater Treatment Plant	6,743 l/da
Black Rock Water Reclamation Plant	6,717 l/da
Point Peron Wastewater Treatment Plant	6,535 l/da
Murrumba Downs Sewage Treatment Plant	6,366 l/da
Water Pollution Control Centre	5,840 l/da
South Caboolture STP WRP	5,714 l/da
Wollongong Sewage Treatment System	5,648 l/da
Subiaco Wastewater Treatment Plant	5,253 l/da
Oxley Creek Wastewater Treatment Plant	5,203 l/da
Gibson Island WWTP	4,655 l/da
Glenelg Wastewater Treatment Plant	3,673 l/da
Cargill Meat Processors Tamworth	3,596 l/da
Murray Bridge Wastewater Treatment Plant	3,442 l/da
Queensland Alumina Ltd	3,087 l/da
Brendale Sewage Treatment Plant	3,060 l/da
Kincumber Sewage Treatment Plant	3,057 l/da
Bribie Island Sewage Treatment Plant	3,028 l/da
Warriewood Sewage Treatment Plant	2,750 l/da

All N&P sources : 711,943 l/da

Potential production color codes

🟥	1e-2 brls/da	to 1 brl/da
🟧	1 brl/da	to 10 brls/da
🟨	10 brls/da	to 100 brls/da
🟩	100 brls/da	to 1,000 brls/da
🟦	1,000 brls/da	and greater

Figure 11: Preferred Sites in Australia Selected Using the PONCH Model
(Source: Roach, 2011)

Sandia's PONCH model is not the only GIS-based, algae site selection model that has been developed. Remote sensing (RS) and GIS have been used previously to develop resource availability models for several crops including algae. For example, suitability analysis approaches have been used to select sites for bioethanol processing centres (Koikai, 2008) and microalgae facilities (Maxwell et al, 1985; Pate, 2008). More recently, GIS methods were employed for an analysis of algae resource availability in California (Lundquist et al, 2010). Available resource data were collected from a variety of sources and used to identify optimal locations. Given the high cost of water (e.g. groundwater) in California, wastewater sources were targeted. Like in Sandia's model, the point locations of all (Californian) WWTPs were mapped within the GIS. Only areas located within a 3 mile radius of the WWTP were evaluated, since beyond 3 miles, the capital costs for piping and the power costs for pumping in California become too expensive.

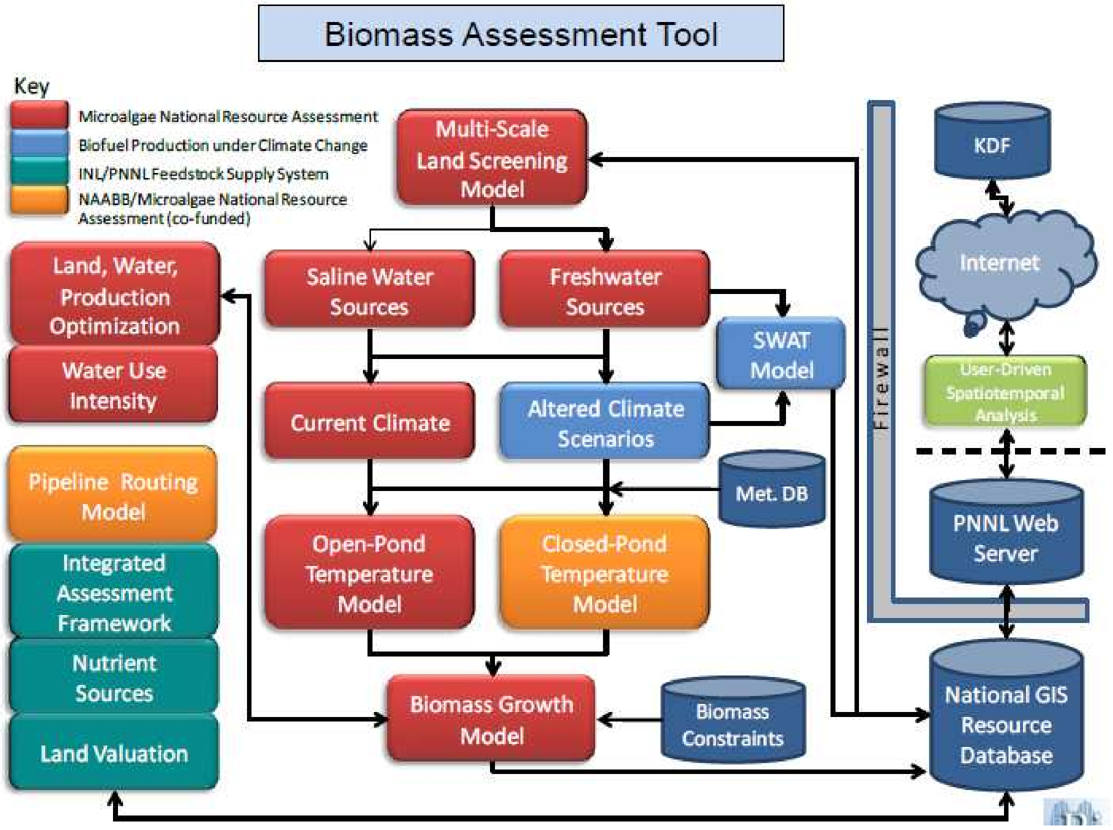


Figure 12: PNNL's Biomass Assessment Tool
(Source: PNNL website)

Pacific Northwest National Laboratory has been developing an adaptive, GIS-based Biomass Assessment Tool (BAT) for optimal site locations, production rates, and resource demands (see Figure 12). This tool may be more comprehensive than the PONCH model, but it is unlikely to be able to drill down to the fine-grained micro-level required to assess the variety of issues that are the final hurdles in identifying viable sites for commercial-scale algae facilities.

CONCLUSIONS AND FURTHER RESEARCH

Preliminary Conclusions

The three methods described in this report can provide lower and upper bound estimates of the amounts of algal biomass, oil and biodiesel that may be produced in the APEC economies in the near and longer terms. Method 1 provides lower bound estimates by the year 2020 which, although modest, may still turn out to be optimistic within such a short time-frame. Method 2 provides very optimistic estimates of the algal biomass that could be produced sustainably by 2020, given the extent of the requirements for nutrient recycling. Both the unadjusted and the adjusted estimates discussed earlier are shown in Table 7.

Table 7: Practical algae resource production potential by 2020
(using Method 1 and Method 2)

APEC ECONOMIC ZONE	METHOD 1: Adjusted for wastewater collected ALGAE (Mt)	METHOD 1: Unadjusted for wastewater collected ALGAE (Mt)	METHOD 2: Adjusted for temperatures and radiation ALGAE (Mt)	METHOD 2: Unadjusted for temperatures and radiation ALGAE (Mt)
Australia	0.30	0.33	3.28	3.28
Brunei Darussalam	0	0.02	0.05	0.05
Canada (See Note 1)	0	0	0	4.77
Chile	0	0.03	0.75	1.50
Peoples Republic of China	**8.78**	**27.50**	**36.70**	**73.40**
Hong Kong, China	0	0	0.57	0.57
Indonesia	1.78	**7.10**	**5.73**	5.73
Japan	0	0.14	3.57	**7.14**
Republic of Korea	0	0.05	2.19	2.19
Malaysia	0.42	1.21	1.12	1.12
Mexico	0.65	4.03	4.02	4.02
New Zealand	0	0.07	0.04	0.39
Papua New Guinea	0	0	0.21	0.21
Peru	0.05	0.07	2.23	2.23
The Philippines	0.27	1.77	0.92	0.92
Russia (See Note 1)	0	0	0	6.70
Singapore	0	0	0.51	0.51
Chinese Taipei	0	0	1.75	1.75
Thailand	3.18	5.79	2.71	2.71
United States of America	**5.44**	**7.76**	**45.80**	**91.50**
Viet Nam	0.11	2.29	0.58	0.58
TOTAL	**20.98**	**58.17**	**112.73**	**211.27**

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone.

No firm estimates using Method 3 have been provided in this report. However, once the necessary research has been undertaken (see below), it can provide estimates of the additional algal biomass that could be produced in the long run (say by 2050 and beyond). All these estimates should be regarded as very approximate, optimistic and heavily conditional upon the assumptions invoked being realized over the time frames mentioned. Except for the adjusted estimates calculated using Method 1 (the figures in the first column of Table 7), realization of any of the larger estimates will require a significant amount of technical progress, so as to achieve the necessary improvements in productivity and lipid yields and the required reductions in capital and operating costs that are needed to make commercial volumes of algal biodiesel.

The unadjusted total amount of algal biomass calculated using Method 2 – about 211 million tonnes for the total APEC economy – is almost the same as the theoretical maximum of 204 million tonnes estimated using the TNO method (see Table 1). Given the significantly different assumptions in these methods, one may conclude that about 200 million tonnes of algal biomass is a consistent, upper-bound estimate to the amount of algae theoretically producible by all APEC economies in the very long run.

Table 8: Potential Replacement of fossil diesel by algal biodiesel in the APEC economy
(In the near-term and long-term)

APEC ECONOMIC ZONE	METHOD 1: Adjusted for wastewater collected BIODIESEL (ML)	METHOD 1: Adjusted for wastewater collected AS A % OF DIESEL USE	METHOD 2: Unadjusted for temperatures and radiation BIODIESEL (ML)	METHOD 2: Unadjusted for temperatures and radiation AS A % OF DIESEL USE
Australia	114	1.0%	1,092	9.6%
Brunei Darussalam	0	0	15	7.4%
Canada (See Note 1)	0	0	1,550	8.0%
Chile	0	0	488	10.0%
Peoples Republic of China	**3,463**	**3.6%**	**23,855**	**24.8%**
Hong Kong, China	0	0	185	12.4%
Indonesia	**716**	**5.9%**	**2,366**	**19.5%**
Japan	0	0	2,320	6.2%
Republic of Korea	0	0	712	3.3%
Malaysia	171	2.5%	404	5.9%
Mexico	220	1.1%	1,343	6.7%
New Zealand	0	0	127	4.5%
Papua New Guinea	0	0	68	70.0%
Peru	21	0.6%	725	20.3%
The Philippines	112	1.5%	589	7.9%
Russia (See Note 1)	0	0	2,178	11.7%
Singapore	0	0	166	7.8%
Chinese Taipei	0	0	569	1.0%
Thailand	**1,270**	**7.7%**	**1,930**	**11.7%**
United States of America	**2,256**	**1.1%**	**29,738**	**14.5%**
Viet Nam	12	0.8%	189	13.2%
TOTAL	**8,355**	**1.8%**	**71,156**	**12.9%**

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone.

In terms of the amount of algal biodiesel that could be produced in each APEC economy, and how much fossil diesel it could replace, our results are summarized in Table 8. China and the United States are the two APEC economies that have the greatest potential to produce algal biodiesel via the sustainable pathways discussed in this report (Method 2). They both have large populations located in many cities and towns, providing a broader and more flexible distribution of wastewater, nutrients and CO_2 sources to feed their algal ponds. In the short-term, however, China has the greatest potential because of its huge populations of people, pigs and other animals which are already generating large wastewater streams that could be used to produce about 9 GL of algal biodiesel. Although this amounts to less than 10% of their current diesel usage, they possess the capacity to almost triple this amount in the long-term, thereby increasing their replacement of fossil diesel substantially.

Indonesia and Thailand possess the capacity to replace about 2 GL of their current fossil diesel use with algal biodiesel in the future. However, right now there is a high degree of uncertainty with respect to the amount of wastewater that is collected and treated in both economies, thereby ensuring a sustainable supply of wastewater for the algal ponds. This is also true of several other APEC economies, such as Malaysia, Mexico, Papua New Guinea, The Philippines and Viet Nam. Since several of these economies also possess the capacity to replace up to 10% of their fossil diesel by algal biodiesel, there is an urgent need to increase the amounts of wastewater collected and treated in these countries instead of allowing it to remain uncollected and untreated. This urgency already exists on the basis of improving overall sanitary conditions and lowering the risks of disease.

Economies with the long-term potential to replace 5-10% of their current fossil diesel usage with algal biodiesel are Australia, Brunei Darussalam, Canada, Chile, Japan, Malaysia, Mexico, the Phillipines and Singapore. Replacement potential in Russia, the United States and Viet Nam may be higher – closer to 15%.

As we mentioned at the start of this section, all the various estimates provided in this report may be turn out to be optimistic within the time frames suggested. In particular, estimates provided by the Sustainable Inputs Approach (Method 2) are undoubtedly optimistic unless and until governments in each APEC economy energetically develop sustainable policies that set aside suitable land for HRAPs close to nutrient sources. Municipal WWTPs, piggeries and cattle lots must include HRAPs in the construction and reconstruction of their facilities in the future. Sustainable approaches to the production of algal biofuels and bioenergy are in their infancy. It requires government leadership and support (partly via subsidies and incentives) to ensure the emergence of multi-purpose plants that can recycle water, nutrients and biomass in a sustainable manner.

Future Research Needs

In terms of further research needs in the area of algae resource assessment, there are many. Nevertheless, we shall concentrate on key research requirements that follow on naturally from the findings discussed in this report.

As mentioned earlier, further survey work is required before reasonable estimates of the amount of marginal land that might be available on coastlines or at other locations can be assessed accurately. Based on the amounts of marginal land reported in Milbrandt and Overend (2009), we produced very crude estimates of the amount of marginal coastal land in each APEC economy within a distance of 3km from the coastline. Since these estimates were done by visually inspecting spatial maps, they are nothing more than a first approximation. The viability of coastal and other land must be assessed for its likely price and availability before a reliable assessment of the amounts that might be available for algal ponds can be assessed. We would suggest that the governments of each APEC economy engage in measurement of the amounts of coastal and other land likely to be available for HRAPs at an affordable price.

This fine-grained, land availability information can be combined with information on the locations of sources of CO_2. One source of international data on CO_2 is the CARMA database. However, CARMA provides emissions data for the larger power stations in each APEC economy only. In reality, algal ponds are best located close to smaller sources of CO_2 and nutrients. Thus, the many smaller CO_2 sources will need to be identified by analysts in each of the APEC economies.

The next research step is to locate the sources of nutrients and water that exist in each economy and assess how close these are to the available land and sources of CO_2. Geographical proximity assessment is best done with the assistance of GIS-based tools like Sandia's PONCH model. A more sophisticated version of this model could be developed to determine the optimal coastal locations for algal biomass production in terms of the transportation distances for nutrients and the energy requirements for maintaining a HRAP system. Versions of this model have been applied successfully to two APEC economies (Canada and Australia), so it would be a natural choice for an APEC-wide study of this kind.

The PONCH model requires data on levels of incident solar radiation. However, solar radiation data will need to be enhanced with monthly and seasonal data on variations between daytime and night-time temperatures. These temperature variations, together with solar energy inputs, are important for successful growth of algae. The reduction factors that have attempted to take these multiple effects into account in this report (see Table 5) are unacceptably crude approximations. Further research will be needed to quantify more precisely the effects of temperature variations and incident solar radiation on algae growth potential in each APEC economy.

Finally, there are several other pathways that could be used to produce biofuels from algae that were overlooked in this study. For example, microalgae can be grown in photobioreactors or in dark fermenters. It may be possible to produce biofuels from macroalgae (seaweed). The potential for growing algae in coastal deserts should not be dismissed. However, the economic viability of each of the above for algal biodiesel will need to be explored individually for each APEC economy in the future.

REFERENCES

Anda, J. de and Shear, H. (2008): Challenges facing municipal wastewater treatment in Mexico, Public Works Management and Policy, 12: 590-598.

Batten, D.F. (2008): Biofuels need flexi-fuel vehicles to achieve sustainable mobility, in A. Subic, M. Leary and J. Wellnitz (eds.), Meeting the Challenges to Sustainable Mobility, Melbourne: RMIT University, pp. 219-230.

Batten, D., Beer, T., Freischmidt, G., Grant, T., Paterson, D. and Priestley, T., (2011): Using wastewater to produce microalgae for nutrient removal and bioenergy production, Proceedings of the 19th European Biomass Conference, Berlin, June.

Benemann, J. (2003): Biofixation of CO_2 and greenhouse gas abatement with microalgae – technology roadmap, Report to the U.S. Department of Energy: National Energy Technology Laboratory, January.

Benemann, J. (2010): Microalgae biofuels and animal feeds: an introduction, mimeo.

Benemann, J. and Oswald, W. (1996): Systems and Economic Analysis of Microalgae Ponds for Conversion of CO_2 to Biomass, Report to the U.S. Department of Energy: Pittsburgh Energy Technology Center.

Campbell, P., Beer, T. and Batten, D.F. (2009): Greenhouse gas sequestration by algae: energy and greenhouse gas life cycle studies, Proceedings of the 6th Australian Conference on Life Cycle Assessment, Melbourne, Australia.

Campbell, P., Beer, T. and Batten, D.F. (2011): Life cycle assessment of biodiesel production from microalgae in ponds, Bioresource Technology, 102: 50-56.

Darzins, A., Pienkos, P. and L. Edye (2010): Current Status and Potential for Algal Biofuels Production, Report T39-T2 prepared for IEA Bioenergy Task 39, National Renewable Energy Laboratory and BioIndustry Partners, Golden, Colorado.

Farine, D. et al. (2011): An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia, Global Change Biology – Bioenergy (in press).

Griffin and Batten (2009): The economics of producing biodiesel from microalgae in Australia, Proceedings of the Bioenergy Australia conference, Gold Coast, Queensland (on CD).

Harmelen, T. van and H. Oonk (2006): Microalgae Biofixation Processes: Some Applications and Potential Contributions to Greenhouse Gas Mitigation Options. Report prepared for the International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae, TNO, Apeldoorn, 45p.

Heubeck, S. and R. Craggs (2007): Resource Assessment of Algae Biomass for Potential Bioenergy Production in New Zealand, NIWA Client Report number HAM2007-157 prepared for New Zealand Forest Research Institute (Scion), National Institute of Water & Atmospheric Research, Hamilton, New Zealand.

Hoogwijk, M., Faaij, A., Eickhout, B., de Vries, B. and W. Turkenburg (2005): Potential of biomass energy out to 2100 – for four IPCC SRES land-use scenarios, Biomass and Bioenergy, 29: 225-257.

Klise, G., Roach, J, Moreland, B., Passell, H., O'Leary, S., McGinn, P., Bhatti, S. and J. Whalen (2010): Resource assessment and analysis for algal biofuel production in selected regions in Canada, Poster presented at the Algae Biomass Summit, September.

Koikai, J.S. (2008): Using GIS-based suitability modelling to assess the physical potential of bioethanol processing plants in Western Kenya, mimeo.

Lundquist, T., Woertz, I., Quinn, N. and J. Benemann (2010): A Realistic Technology and Engineering Assessment of Algae Biofuel Production. Report to the Energy Biosciences Institute, University of California, Berkeley, California.

Maxwell, E.L., Folger, A.G. and S.E. Hogg (1985): Resource Evaluation and Site Selection for Microalgae Production Systems, Solar Energy Research Institute.

Milbrandt, A. and R. Overend (2009): Assessment of Biomass Resources from Marginal Lands in APEC Economies, Asia-Pacific Economic Cooperation, Energy Working Group, Colorado, USA.

Milbrandt, A. and E. Jarvis (2010): Resource Evaluation and Site Selection for Microalgae Production in India, Report no. TP-6A2-48380, National Renewable Energy Laboratory: Golden, Colerado, 78p.

O'Connell, D., Braid, A., Raison, J., Handberg, K., Cowie, A., Rodriguez, L. and B. George (2009): Sustainable Production of Bioenergy: A review of global bioenergy sustainability frameworks and assessment systems. Publication number 09/167, Rural Industries Research and Development Corporation.

Oswald, J.W. and Golueke, C.G. (1960): Biological transformation of solar energy, Advanced Applied Microbiology, 2, 223-261.

Pate, R. (2008): Algal biofuels techno-economic modelling and assessment, Sandia National Laboratories, December.

Pate, R., Klise, G. and B. Wu (2011): Resource demand implications for U.S. algae biofuels production scale-up, Applied Energy, 88: 3377-3388.

Regan, D.L. (1980): Marine biotechnology and the use of arid zones, Search, 11: 377-381.

Regan, D. L. and Gartside, G. (1983): Liquid Fuels from Microalgae in Australia, CSIRO: Melbourne, 55p.

Roach, J. (2011): personal communication.

Royal Danish Embassy (2009): Indonesian water and wastewater sector

Sheehan, J., et al. (1998): Close Out Report, Aquatic Species Program, NREL/TP380-24190.

Stephens, E., Ross, I.L., King, Z., Mussnug, J.H., Kruse, O., Posten, C., Borowitzka, M. and B. Hankamer (2010): An economic and technical evaluation of microalgal biofuels, Nature Biotechnology, 28: 126-128.

U.S. Department of Commerce (2005): Water supply and wastewater treatment market in China.

U.S. Department of Energy, (2010): National Algal Biofuels Technology Roadmap. U.S. DOE: Office of Energy Efficiency & Renewable Energy, Biomass Program.

Van Harmelen, T., and Oonk, H. (2006): Microalgae biofixation processes: applications and potential contributions to greenhouse gas mitigation options. International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae.

Wagener, K. (1981): Mariculture on land – a system for biofuel farming in coastal deserts, Biomass, 1: 145-158.

Woertz, I., Fulton, L. and Lundquist, T. (2009): Nutrient removal and greenhouse gas abatement with CO_2 supplemented algal high rate ponds, Proceedings of the WEFTEC Annual Conference, Water Environment Federation, Orlando, Florida, October, 7924-7936.

APPENDIX A:
QUESTIONNAIRE SENT TO THE APEC ECONOMIES

Dear APEC member,

Diesel fuel produced from large-scale algae cultivation provides a potential substitute for fossil fuels, and can reduce dependence on fossil fuels and reduce the release of greenhouse gases to the Earth’s atmosphere. CSIRO is working on behalf of the APEC Biofuels Task Force to produce estimates and a report on the resource potential of algae for biodiesel production in APEC economies. All information provided to us will be used to create special Geographical Information System (GIS) maps which will be available to all participating APEC economies at the conclusion of the project.

The potential for large scale algal growth will depend on the co-location of suitable land, usually flat and otherwise of little economic value, with a large source of nutrients (especially nitrogen) from sources like sewage treatment plants and large scale animal farms, as well CO_2 from industry or fossil-fuel fired electricity generation stations.

To help us complete the report for APEC we seek information from all APEC economies (see Appendix for our preliminary estimates). To do this, we seek quantitative information as follows:

1. Diesel fuel
Please provide the total annual consumption of diesel fuel for your economy (in tonnes), based on the latest available data.

2. Waste water treatment
a. Please provide a current list with geographical coordinate pairs of your municipal waste treatment plants serving populations above 1 million people.
b. For each plant, state its annual turnover of waste (tonnes/annually).
c. For each plant, state its annual nutrient concentration (tonnes of Nitrogen).
d. For each plant, state its total annual discharge of wastewater.

3. Livestock (cattle, dairy, pigs, chickens) intensive farming or feed lots.
a. Please provide a list of your largest livestock farms with geographical coordinate pairs.
b. For each livestock farm, state its annual output of livestock waste/manure (tonnes).
c. For each livestock farm, state its annual output in terms of nutrient concentration (tonnes of Nitrogen).
d. For each livestock farm, state its annual output in wastewater.

4. Land
a. Please provide raster or polygon maps characterizing land use, particularly those areas close to livestock farms (cattle, dairy, pig, chicken) as well as power stations; or
b. Please provide coordinate pairs for flat uneconomic land adjacent to power stations, and/or large-scale livestock (cattle, dairy, pigs, chicken) farms that may be suitable for the construction of an algae facility.

We thank you for your cooperation.