Carbon Dioxide Removal by Ocean Algae Production

DFAT Ideas Challenge - Technical Annex

Robert Tulip

Pitch

Large scale ocean based algae production can make a major contribution to global security interests in energy, food, commerce and climate. DFAT can support a technology research program in partnership with the energy industry and scientific experts to assess the most cost-effective ways to bring algae biofuel to market and to develop new negative emission technologies based on algae. The goal is to produce commodities that directly support the goals of shared prosperity and poverty reduction advanced by Australian Government foreign policy, in line with the Government's economic diplomacy goals of improved growth, investment, trade and business, and climate change goals of supporting least cost abatement. DFAT can convene a Public Private Partnership with the natural gas industry on ocean algae production as a practical way to deliver emission reduction. Carbon dioxide can be converted into commercial commodities using innovative technology, including potentially through new safe and simple systems suited for siting at sea. The goal is eventually to scale up to remove more carbon from the air than total emissions, using methods that directly involve major energy companies. My concept is that deep ocean processing of algae, using the resources and energy available from natural systems, presents a method able to eventually produce energy at a cost below the production cost of fossil fuels, in a way that also brings a range of economic, social and environmental co-benefits.

Introduction

Addressing climate change requires open dialogue about ambitious and innovative ideas. My interest in using simple biological methods for emission reduction was spurred in 2006 when I worked on the Australian Government Forest Carbon Initiative.[1] This program supported the claim[2] that emission reduction through forest protection could be an effective way to help stabilise the climate. Although forest protection is highly important for a wide range of reasons, my analysis led me to question its specific contribution to climate goals. A global climate policy needs to remove carbon from air and sea on a much larger scale than is possible through forestry. The world ocean is vastly bigger than available forest areas. The ocean could be used for industrial algae production, if suitable methods can be developed. Hence the importance of algae, which grows many times faster than trees, and can be funded through sale of produced commodities.

This proposal presents original research, building on scientific pilot studies, especially NASA's OMEGA algae project.[3] Some concepts in this proposal are new and untested, and are shared here to seek scientific, engineering and commercial assessment to determine their feasibility. My hope is that these ideas will enable the Australian government to catalyse a major new biofuel industry with global impact. After discussion of the context for ocean based algae production, I propose a specific technological research program in partnership with the Liquefied Natural Gas industry.

Climate Policy Context

The need for scalable methods to slow and reverse global warming requires ways to bring private industry and governments together as primary partners. The scientific community calls for rapid deep cuts to CO_2 emissions[4] as the only way to avert risk of global warming and ocean acidification.

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1 http://www.foreignminister.gov.au/releases/2007/fa047-budget10_07.html

2 http://en.wikipedia.org/wiki/Reducing_emissions_from_deforestation_and_forest_degradation

3 http://www.nasa.gov/centers/ames/research/OMEGA/#.VQ4JDo6Uc88

4 http://www.ipcc.ch/pdf/ar5/prpc_syr/11022014_syr_copenhagen.pdf

The energy industry is open to dialogue and data, but shares concerns, together with many governments, about potential adverse economic impact of some proposals for emission reduction such as carbon taxes.[5] Resolving the differences of view on how to address human-induced climate change requires workable methods that utilise the comparative advantages of governments and the private sector. Such methods will be most effective where they build upon existing resources and technologies to enhance economic growth and energy access, working in partnership with major energy companies.

Projections in the *BP Energy Outlook for 2035* help to show the problems of climate risk. BP predicts 32% growth in global fuel use over the next two decades, with renewables only 7% of the total and CO_2 emissions expected to rise to 25% above today's level.[6] This pace of increase offers little prospect for stabilisation of CO_2 levels as called for by climate science. However, the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change indicated a potential path to resolve this apparent impasse, through the development of new technology to remove carbon from the air at scale. In the words of the IPCC 2013 *Physical Science Summary for Policy Makers*: "A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible … except in the case of a large net removal of CO_2 from the atmosphere over a sustained period."[7]

This proposal suggests a method to achieve this "large net removal of CO_2 from the atmosphere" mentioned by the IPCC, through an innovative proposal with potential to form a workable solution with a big payoff for economic growth and climate stability.

Growth in energy supply has helped to lift a billion people out of poverty in recent decades, a trend that will only accelerate.[8] Strategies to slow global warming need to be placed within this real economic and political context of demand for power. Partnerships between governments, the energy industry, scientific experts and others are needed to find mutually beneficial solutions, creating synergy between climate security and economic security.

Human activity now adds about 32 billion tonnes of CO_2 to the air every year, mainly from burning coal, oil and gas.[9] This CO_2 contains about nine billion tonnes of carbon. This added carbon presents risks to climate stability, but is also a potentially valuable resource that can be re-used for energy, food and infrastructure, if viable economic methods can be invented to split the CO_2 molecule at scale and convert the contained carbon to useful commodities.

Suggestions for decarbonisation of the economy face political and economic obstacles, and will struggle to be delivered even if they are agreed as binding targets. European Union leaders agreed in 2014 to "a domestic 2030 greenhouse gas reduction target of at least 40% compared to 1990."[10] If agreed globally, this target would appear to require reduction of annual global emissions to just 12 gigatonnes of CO_2, less than one third of BP's 2030 projection of 40 gigatonnes. Such a global result is not possible with existing technology, given the failed precedent of the Kyoto Protocol which has essentially been abandoned[11] by major emitters.

The problem is how to remove carbon in ways that build upon the value of existing infrastructure and investment, and work in cooperation with the capitalist system rather than fighting against it. Against the economic dislocation in the unrealistic targets for emission reduction, my claim which this proposal seeks to test is that the same climate result could be achieved with broad economic and environmental co-benefits by building algae farms on one percent of the world ocean.

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5 http://cdn.exxonmobil.com/~/media/Files/Other/2014/Report%20-%20Energy%20and%20Carbon%20-%20Managing%20the%20Risks.pdf

6 http://www.bp.com/en/global/corporate/about-bp/energy-economics/energy-outlook/outlook-to-2035.html

7 http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5_SPM_brochure_en.pdf

8 http://www.minerals.org.au/file_upload/files/media_releases/Op_ed_08_04_2014_Coal_the_answer_to_energy_poverty.pdf

9 http://www.bp.com/content/dam/bp/pdf/Energy-economics/energy-outlook-2015/Energy_Outlook_2035_booklet.pdf p12, p82

10 http://ec.europa.eu/clima/policies/2030/index_en.htm

11 http://en.wikipedia.org/wiki/Kyoto_Protocol

Ocean Based Algae Production

Algae grows many times as fast as trees.[12] As Dr Jonathan Trent of the OMEGA project explains,[13] algae has oil yield up to one hundred times that of existing biofuels. The rationale for a focus on algae in addressing climate change is that to use plant matter as a carbon store, we should use the fastest growing plants. We should also identify locations where large scale industrial operation is possible with minimal disruption to existing land use, aiming to achieve beneficial effects. Controlled production of algae at sea as an RD&D focus can address these goals.

Can algae production make carbon capture and storage profitable? Yes it can. Fossil fuels were laid down over millions of years by capturing the sunlight embedded in plant materials, mostly marine algae. Technology could replicate this natural process at rapid speed and large scale. However, such technology does not yet exist, and algae is not yet commercially competitive as a biofuel. I propose here a research program to develop innovations which can radically reduce costs and increase algae yield, aiming for a commercially profitable and environmentally beneficial approach. The process I outline here aims to eventually be self-funding by producing commercial commodities, including food, fuel, feed, fish, fertilizer and fabric.

This proposal suggests that the gas industry can partner with governments and technical experts to remove CO_2 from the air and sea on a scale bigger than total anthropogenic emissions using ocean based algae production, through research, development and deployment of safe simple scalable systems suitable for siting at sea.

In studying climate science as an international development official with the Australian Government,[14] my analysis has led me to conclude that new thinking is needed on methods to stabilise the global climate. We should shift away from the focus on carbon taxes and towards direct action to remove carbon in partnership with the energy industry, in line with the goals of Australia's Emissions Reduction Fund.[15] As the Copenhagen Consensus Centre argues,[16] investment in Research, Development and Deployment (RD&D) for new energy technology has high benefit cost ratio and economic rate of return and should be the top focus of global climate response. My assessment is that ocean based algae biofuel production is the most promising RD&D path in the energy sector, as a practical and rapid way to stabilise the global climate, with a central positive role for the fossil fuel industry.

This proposed focus on new technology involves the rather startling corollary conclusion that instead of reducing the amount of CO_2 that human activity adds to the atmosphere, the focus of climate policy should instead be on mining carbon from the air and sea to convert CO_2 into useful products, aiming eventually to remove and recycle carbon at an even bigger scale than total emissions. This means that emission reduction should combine with the IPCC call for a large net removal of CO_2 to achieve a workable framework for response to climate change.

NASA's OMEGA Project

The American National Aeronautic and Space Administration (NASA) supported a scientific research program on Offshore Membrane Enclosures for Growing Algae.[17] The OMEGA system proposes the use of microalgae species with high growth rates and high yields of oil to convert domestic wastewater to produce biofuel, fertilizer and food. NASA's work has identified suitable materials and

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[12] http://www.marine.csiro.au/microalgae/methods/Growth%20rate.htm

[13] https://www.ted.com/talks/jonathan_trent_energy_from_floating_algae_pods?language=en

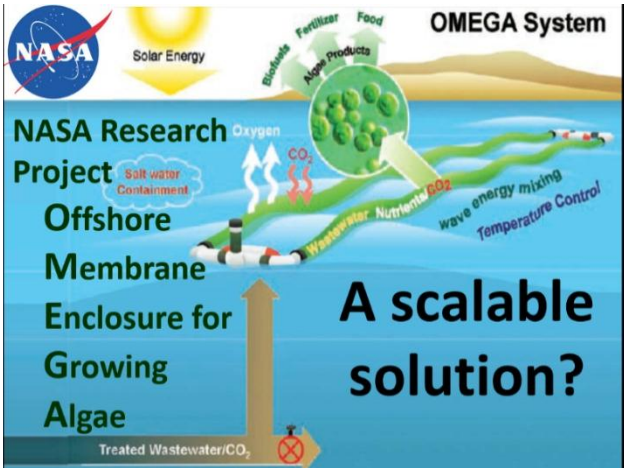
[14] I work in the Department of Foreign Affairs and Trade (DFAT) Trade Investment and Economic Diplomacy Division, in its resources and energy sector program, and worked for the Australian Agency for International Development (AusAID) from 1989. My work has involved managing aid programs in diverse fields, with a main focus on Papua New Guinea and sector policy.

[15] http://www.environment.gov.au/climate-change/emissions-reduction-fund

[16] http://www.copenhagenconsensus.com/sites/default/files/climate_change_one_pager_final_0.pdf

[17] Trent, Jonathan. (NASA Ames Research Center). 2012. *OMEGA (Offshore Membrane Enclosures for Growing Algae) - A Feasibility Study for Wastewater to Biofuels.* California Energy Commission. Publication number: CEC-500-2013-143.

initial methods, and answered common questions such as how structures built in the ocean can be made robust to cope with breakage and storms.[18]



The OMEGA system, using floating plastic bags at sea to grow algae, as depicted in this diagram, presents a basis for a more efficient biofuel production method than land based algae ponds or photo-bioreactors, due to its ability to tap into oceanic energy and resources. But the research to date has not established commercial viability. Additional key innovations are described in this paper to define a research agenda to bring the OMEGA methods to market at scale. The next steps require proof of concept through interdisciplinary expert peer review, aiming to validate safety and efficacy as a basis for laboratory and field tests. Testing these ideas has low risk, but could bring a big upside for governments, communities, investors and the biosphere.

This research can provide the foundation for a new global industry that could remove twenty billion tonnes of carbon from the air every year, double the amount of total emissions. The OMEGA system can be augmented by at least four important innovations which together promise a new technological paradigm that will be cost competitive. These new factors are:

- use of ocean tide, current and wave power to move CO_2, nutrient, algae and water;
- co-location with offshore gas projects to use their abundant low cost CO_2, capital and expertise, while developing methods suitable for deep ocean deployment;
- hydrothermal liquefaction
- use of produced algae to make more algae factories using bioplastic.

These methods offer potential to drive capital expenditure and operating costs down way below existing biofuel models in order to enable algae production to become competitive against fossil fuels when replicated and expanded to achieve efficiencies of scale.

Algae biofuel is not yet profitable, primarily because of space, energy and input costs for land-based photo-bioreactor and pond systems and processing methods. Shifting production to the ocean could solve those problems to deliver sustained high yield, especially by starting in locations with available waste CO_2 such as gas projects like Gorgon in Western Australia. Ocean based algae production can be tested and developed in sheltered bays using waste water as proposed in the OMEGA concept, in order to optimise methods and materials for scaling up. The eventual goal is to make the vast ocean deserts[19] productive, as a method to deliver negative emission technology[20] at a scale bigger than total anthropogenic carbon emissions.

The OMEGA Project has piloted methods that have potential to pay for themselves by sale of produced commodities to enable replication at scale, offering the prospect that emission reduction can actually become profitable, rather than a cost to business. NASA's pilot activities indicate that algae carbon dioxide removal at sea can become an attractive venture capital investment opportunity that energy companies, pension funds, aid donors and the military should support. Ocean based algae production can deliver energy security in a way that will enable diversification of supply locations and sustained protection of the stock price of fossil fuel companies against climate

[18] Bags can be sunk below the surface in rough weather, and in the event of breakage the contained algae will just be eaten by fish.
[19] http://www.noaanews.noaa.gov/stories2008/20080305_oceandesert.html
[20] http://en.wikipedia.org/wiki/Negative_carbon_dioxide_emission

related risks, agendas of strong strategic and economic interest. This environmentally sustainable energy production method also offers ethical and reputational benefits for the energy industry and social licence by providing positive externalities compared to some existing energy supply technologies.

Role of DFAT InnovationXchange

The concepts for algae production discussed in this proposal require assessment by an organisation with standing, capacity, resources and focus on the public good. The DFAT Ideas Challenge is ideally suited to investigate this proposal, and to broker relationships with the energy industry, partnering with companies such as Chevron, Shell and Exxon on the RD&D program. DFAT can also involve major multilateral agencies such as the World Bank Group and Australian Government agencies such as the Department of Industry and Science, the CSIRO and State Government authorities. These proposals are directly relevant to World Bank programs such as the Public Private Infrastructure Advisory Facility, the Energy Sector Management Advisory Program and the Global Gas Flaring Reduction Public-Private Partnership.

Ocean based algae farming can become a method for developing countries to increase economic growth and participate in trade, generating energy, food, revenue and jobs, in direct alignment with Australia's Economic Diplomacy Foreign Policy. Papua New Guinea and Indonesia have excellent physical locations for algae production at sea, which could provide a major new industry. Construction could be funded by revenues from mining, with strong potential for local management and employment in a new energy export industry. Improved fishery productivity from algae farming can also be a key deliverable to provide a path to long term stability and growth.

Industry partners are needed because public sectors alone cannot mobilise the capital, skills and resources needed to deliver such a large scale innovative profit driven project. Initial desk analysis should consider technical and commercial feasibility, environmental risks and institutional structures. The produced biofuel from algae aims to power existing transport and energy infrastructure, including as a direct substitute for diesel fuel in vehicles and for the coal and gas that are burnt in power stations and for heating. Algae biofuel is already the subject of major commercial research programs.[21] This proposal brings unique new intellectual property that has significant cost reduction promice, and seeks to build upon existing research through a research program suited to the InnovationXchange. When algae biofuel proves profitable it will draw in commercial investment, but the threshold feasibility analysis of innovative ideas such as my proposals for ocean based operations requires initial public investment and strong regulatory risk frameworks. Powers and rights relating to use of areas of ocean involve local and national authorities especially for regulation of impact on fishing, shipping and the natural environment.

Development of ocean based algae production needs multi-stakeholder engagement for a business plan that the InnovationXchange is uniquely well placed to convene and mobilise. If initial analysis proves positive, private industry can invest money, expertise and resources, while governments can bring regulatory systems, seed funding, expert analysis, community engagement and political will. DFAT can mobilise innovative partnerships with companies such as Chevron, Shell and Exxon-Mobil, and with interested energy users such as the US Navy Great Green Fleet,[22] with a view to rolling out algae biofuel production including in developing countries. The Small Island States of the Pacific have major potential to develop ocean based algae industries using the methods described here.

Scaling Up to Address Climate Change

The IPCC recognises that the primary destabilising factor for global climate is the human addition of carbon to the air, now about nine gigatonnes each year.[23] Algae farms at sea could in theory remove

[21] http://en.wikipedia.org/wiki/List_of_algal_fuel_producers

[22] http://greenfleet.dodlive.mil/energy/great-green-fleet/

[23] CO_2 contains 27% carbon and 73% oxygen. Current CO_2 emissions of 32 GT therefore contain 9 GT carbon.

one tonne of carbon per hectare per day, orders of magnitude above the rate possible from forests on land. And the unit yield of algae can be scaled up in size in ocean locations that do not compete with agriculture or ecological habitat but rather have positive environmental impact. At this unit yield, algae farms on 3 million square kilometres would hypothetically remove the same amount of carbon as added by all emissions. That is an immense scale. Before dismissing it as inconceivable, we should get an understanding of the potential scale of operation at sea. The world ocean is 361 million km^2 in surface area.[24] The target of removing an amount equal to all added carbon would involve algae farms on an estimated one percent of the world ocean, if yield projections can be achieved and all produced algae is stored. Even a tiny fraction of this scale would remove a lot of carbon as a low cost abatement method to deliver climate change goals. If half the produced algae is used as fuel, the area required for algae farms to sequester as much carbon as all global emissions would be about 2% of the world ocean. The scale of the oceans means there are enough suitable locations, especially considering the environmental co-benefits to endangered places such as coral reefs. If the ideas here are valid this scale up may be feasible.

Uses of Produced Algae

The eventual goal of this proposal is to mine more carbon from the air than we emit. Carbon from algae production is an economically useful product, whether used as food or fuel, stored in a strategic petroleum reserve, or even potentially sequestered in infrastructure such as roads and buildings in forms such as bioplastic and bitumen. Such storage of mined carbon would enable continued fossil emissions by providing a way to remove their added carbon from the air. By finding useful ways to store the bulk carbon produced through algae, the coal, oil and gas industries could continue to transfer carbon from the earth's crust to the air in a way compatible with efforts to manage global warming.

Bituminous products from algae oil[25] can be used in road works, as one potentially major sequestration opportunity. Bioplastic made from produced algae oil should be the main constituent of algae farm membranes and pipes. Algae can be a profitable product line for the energy, food, infrastructure and defence industries that will also deliver on climate change, closing the loop in the carbon cycle to remove and recycle the extra carbon added to the air and sea by fossil extraction.

Fixing the carbon cycle through industrial algae production offers promise to solve two major economic problems. The first is that much new energy technology does not utilise the sunk costs of existing transport and power infrastructure which will continue to use fossil fuels.[26] The second is that the stock price of energy companies is premised on shifting a dangerous amount of carbon from the earth to the air without any plan to remove it.[27] If ocean based algae biofuel can become a viable industry, existing methods and firms could adapt and evolve to an emerging stable climate economy, maintaining the social, economic and ecological sustainability of fossil fuel extraction. The important co-benefit alongside the economic value of algae is that such a shift would protect global and local ecology, enabling sustainable development. Algae farming can be a Negative Emission Technology, not just through biofuel, but through other large scale products such as infrastructure, biochar[28], fabric construction and fisheries.

Algae farms can provide environmental services through local insurance against climate change, severe weather events and pollution. Large scale algae farms would reflect sunlight back to space to help cool the sea and reduce storm intensity. Location near coral reefs and river mouths would reduce the heat and acid and nutrient loads that are now placing pressure on these ecosystems, as a

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[24] http://en.wikipedia.org/wiki/Ocean
[25] http://en.wikipedia.org/wiki/Asphalt#Occurrence
[26] http://newclimateeconomy.report/innovation/
[27] http://www.rollingstone.com/politics/news/global-warmings-terrifying-new-math-20120719
[28] http://en.wikipedia.org/wiki/Biochar

climate response with high benefit.[29] Australia's Great Barrier Reef and the Mississippi Delta in the Gulf of Mexico should be considered as primary potential locations to clean up damaged and potentially threatened environmental heritage.

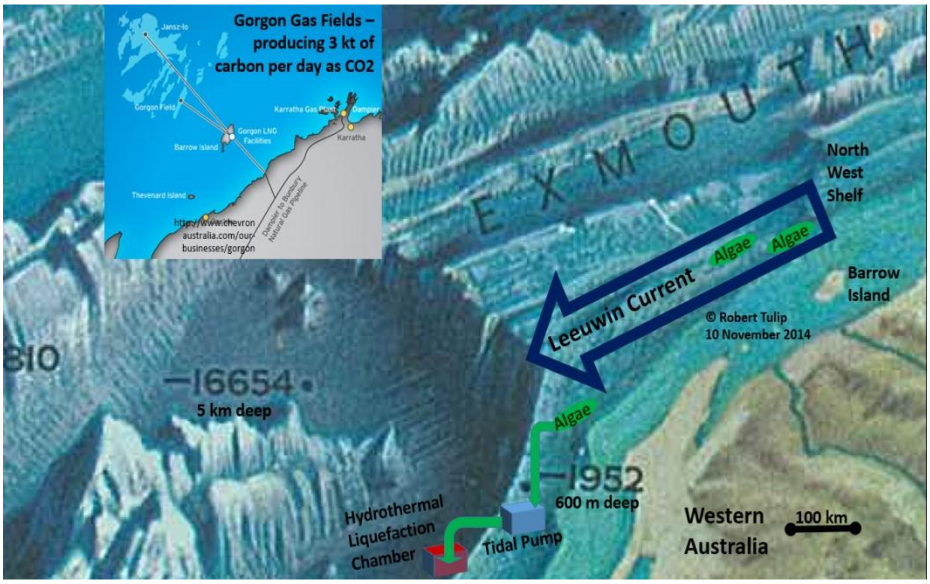
Technological Challenges

Key efficiency innovations for algae farming at sea to drive down unit costs can include: automation; use of natural ocean energy (sun, wave, wind, tide, current, ocean thermal, geothermal); low cost material inputs; development of high yielding algae varieties and production methods; use of deep ocean pressure and heat for hydrothermal liquefaction; use of produced algae oil to make plastic for pond liner construction at sea; and location in places with beneficial impact on large scale. These technological innovations can close the energy price gap between industrial algae systems and fossil fuels. Microalgae can become the best option for carbon dioxide removal as a method to stabilise the global climate if its technical cost problems can be solved. My claim is that marine processing offers promise to be an economical and technically simple approach with significant contribution to energy production and climate change mitigation.

The methods described in existing land-based algae proposals[30] are nowhere near cost effective as biofuel production systems able to compete with coal and oil without a carbon tax subsidy. But such subsidies face the unworkable problem that they must be global in order to work, and will be undermined where any large nations do not enforce them. A new technological paradigm is needed.

Proposed Gorgon LNG Project Algae Production System

One potential suitable pilot location for ocean based algae production is Barrow Island on the North West Shelf (Exmouth Plateau) in Australia. Chevron's Gorgon gas project, the biggest ever energy project in Australia, plans to geosequester four megatonnes per year of CO_2 under Barrow Island. The Government of Western Australia states "the Gorgon CO_2 Injection Project is expected to be the largest long term CO_2 storage project in the world, and plans to inject about 3.3 to 4 million tonnes of CO_2 per year into a geological layer known as the Dupuy Formation, about 2.5 km beneath Barrow Island."[31] 4 million tonnes of CO_2 per year equals 2986 tonnes of carbon per day. My proposal aims to turn this CO_2 from a cost line into a source of profit by processing it into fuel and other products via algae.



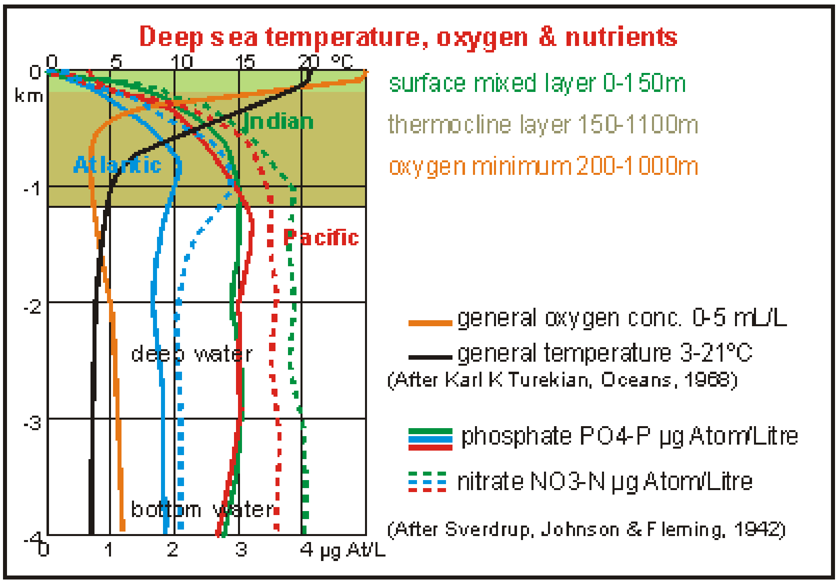
This diagram of a proposed pilot site off Western Australia provides a schematic explanation of how this system can work. Based at Barrow Island, CO_2 and algae are added to enclosed floating plastic bags of water, on the model of NASA's OMEGA

[29] http://www.copenhagenconsensus.com/post-2015-consensus/biodiversity

[30] Existing algae technology is analysed by Beal et al in their paper *Economically competitive algal biofuel production in a 100-ha facility: a comprehensive techno-economic analysis and life cycle assessment*. Beal et al have also written *Energy Return on Investment for Algal Biofuel Production Coupled with Wastewater Treatment*. Another typical paper on algae yield and energy return on investment is *Reduction of water and energy requirement of algae cultivation using an algae biofilm photobioreactor*.

[31] http://www.dmp.wa.gov.au/8514.aspx

project. The water is enriched by nutrients pumped up from deep water using tidal energy. These algae production bags float down the Leeuwin Current as shown, to create a contained algal bloom, converting sunlight into chlorophyll. The contained algae is then piped to the ocean floor using tidal pumping, described below, where a method called hydrothermal liquefaction converts the algae slurry into crude oil.

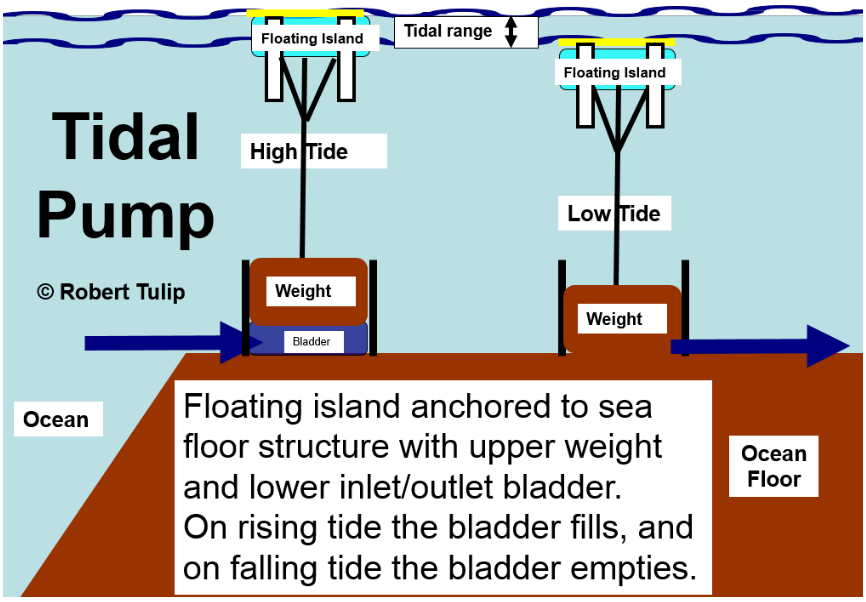


To illustrate the availability of nutrients in the deep ocean, below the warm/cold barrier called the thermocline, this diagram shows phosphate and nitrate are available at up to 3 parts per million at depth of 500 metres.[32] Using tidal pumping and algae to mine these nutrients offers potential to create access to abundant new economic resources.

Tidal pumping can bring these nutrients to the surface, to mimic the natural processes of the formation of fossil fuels from algae blooms caused by nutrient upwelling and geological formation, at vastly accelerated pace in a tightly managed and controlled industrial environment.

Tidal Pumping

My new ideas on tidal pumping are a key innovative cost efficiency to make this whole algae production system competitive. Below I show my original concept for tidal pumping. To date this concept is only proved at the level of informal expert peer review. My concept for this tidal pumping method has had no formal research validation, although my informal discussions with hydrologists indicate it is feasible. The Tidal Pump uses a floating island to cause a weight on the ocean floor to rise and fall with the tide. The weight is anchored above an inlet/outlet bag on the ocean floor. The weight is lifted on a rising tide by a neutral buoyancy anchor line from the rising surface vessel. The rising weight causes the connected bag below the weight to fill during the rising tide through an inlet valve and pipe to the surface or the deep ocean. The weight then slowly falls to the ocean floor with the



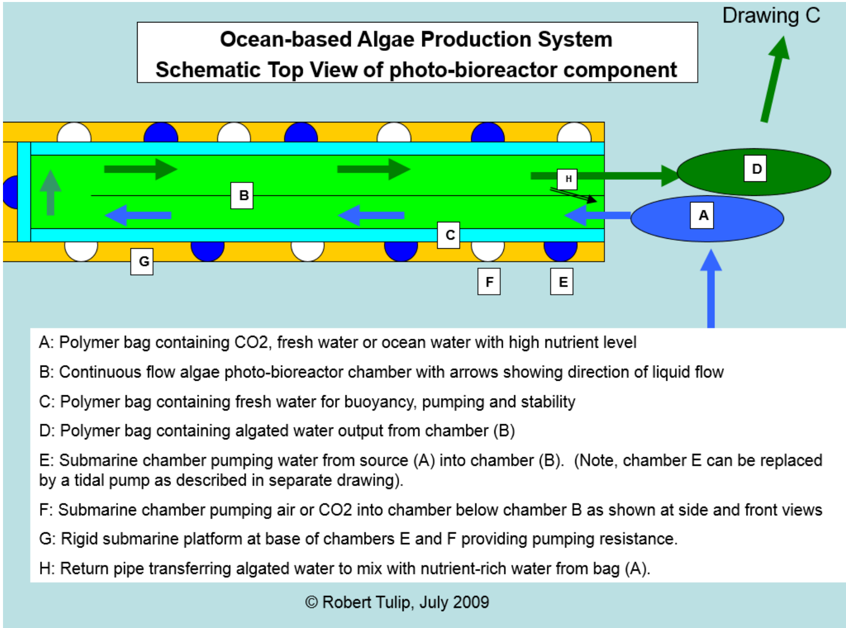
32 http://www.seafriends.org.nz/oceano/ocean49.gif From *The chemical composition of seawater* By Dr J Floor Anthoni (2000, 2006) www.seafriends.org.nz/oceano/seawater.htm

falling tide, placing pressure on the bag of liquid below the weight and causing the bag to empty through an outlet valve and pipe. This rising and falling tidal motion produces large scale pumping energy which requires no fossil fuel input to move large amounts of liquid, providing a large cost advantage for the volumes of water needed for algae production.

The Gorgon project would require systems big enough to raise and sink 500 megalitres of water per day by my rough calculation. My preliminary estimate is that two floating islands one square kilometre in size would be needed to move the quantity of water involved for the Gorgon carbon project. Such floating islands could be constructed of bladders of fresh water and submerged plastic air containers, with a surface providing a useful platform. Research is needed to determine the feasibility and possible environmental effects of this new tidal pumping concept.

Ocean Based Algae Farm Design

Algae blooms can optimise the growth environment in large enclosed floating plastic photo-bioreactors. Mixing high yield algae feedstock with nutrients and CO_2 in such an enclosed plastic floating container, enclosed by fresh water bladders[33] for buoyancy, stability and pumping, will develop a contained algae bloom. The whole system is designed to optimise yield through continuous selective improvement of strains and structure to ensure the most productive growth cycle, developing salt water algae strains that are adapted to the high CO_2 contained environment. For example with three parallel tracks, the highest yielding track can be fed back to the inlet to produce continued adaptation to desired traits, with different varieties of algae cultivated to produce lighter or heavier biocrude oils or other products such as fertilizer and food.



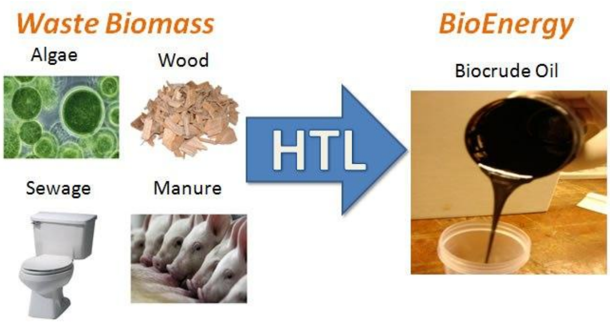
Hydrothermal Liquefaction

In the proposed Gorgon Algae Project, the produced algae will reach 1% concentration in the floating bag. This dilute slurry could be piped using a tidal pump down from the ocean surface at the edge of the continental shelf into a container on the adjacent abyssal plane, which is up to five kilometres deep. The reasons for operating at great depth, despite its challenges, are that this is the most efficient way to extract oil using a method called Hydrothermal Liquefaction (HTL), which has recently been identified[34] as the most cost-effective way to extract algae oil using pressure and heat. HTL needs to concentrate algae to about 30% by volume of water, which can be done using pressure and forward osmosis membranes to expel water. The HTL process then can use the pressure of the deep to enable oil extraction at scale.

[33] Based on work of www.waterbag.com

[34] See for example *Process development for hydrothermal liquefaction of algae feedstocks in a continuous-flow reactor,* Douglas C. Elliott et al, Algal Research Volume 2, Issue 4, October 2013, Pages 445–454,

The water pressure on the ocean floor can be used to separate the algae soup using HTL. This proposal offers major cost advantages for dewatering and fuel extraction at pressure, solving a major cost obstacle for algae biofuel, which until now has required expensive centrifuges, drying time and solvents.



Hydrothermal Liquefaction is described as follows by researchers at the University of Illinois: "High moisture biomass is subjected to elevated temperatures (250-350° deg C) and pressures (10-20 MPa) in order to break down and reform the chemical building blocks into a bio-crude oil. At these temperatures and pressures, water becomes a highly reactive medium promoting the breakdown and cleavage of chemical bonds, allowing for the reformation of biological molecules. The conversion mimics the natural geological processes which produced our current fossil fuel reserves and allows for the conversion of a wide range of feedstocks. Tested feedstocks include low lipid algae, swine manure, sawdust, garbage, and sewage sludge."[35]

The placement of this HTL algae method at sea involves major advantages which justify the challenges of marine operation. The required pressure of 10-20 megapascals is found at depths of one to two kilometres, removing the need to apply energy to create this pressure chamber at the surface. In the proposed pilot the CO_2 required for algae growth is available from the Gorgon project, which now plans to bury it at a cost of USD 2 billion over the life of the project. HTL processing of algae offers to turn this CO_2 cost line into a profit line for the Gorgon project, and for similar projects in countries such as Indonesia, Papua New Guinea and the small island states of the Pacific. Ocean depth provides pressure in a way not readily available at scale on the surface. Ocean currents, waves and tides can provide the energy required to transport and pump the vast quantities of water involved, based on innovative inventions derived from the floating waterbag concept.

Operating Scale at Gorgon

The co-produced CO_2 with the Gorgon LNG project has estimated volume of nearly 3000 tonnes of carbon per day. Converting this amount of CO_2 into algae would require an estimated water volume of about 500 megalitres per day. In a floating bag of one metre depth, the surface area of daily production for the entire CO_2 quantity would be five square kilometres. The Leeuwin Current flows at about 2 km/hour, so floating the bags along the 500 km from Barrow Island to the edge of the continental shelf would take about ten days. Overall scale to utilise the full amount of Gorgon CO_2 would therefore be about 50-100 square kilometres. This is big, and it is an order of operation that could only be gradually approached. This scale would cool the ocean water, and would be manageable within existing shipping and fisheries needs. Its environmental impacts include strong benefits, which need to be considered against detailed scientific analysis. Against the overall scale of the ocean, and the scale of global carbon emissions, this proposal is still only at pilot level. The overall size of the North West Shelf is more than 1.5 million square kilometres[36] so a 100 km^2 pilot would use less than 0.01% of its area.

This tiny ratio of area required helps to illustrate how we have barely begun to use the massive areas and resources available in the world oceans. At 71% of the planetary surface, the oceans are more than twice the size of all the planet's land masses combined. This method offers promise to help turn our oceans from a plundered commons into a managed stewardship, due to the ability of

[35] Source (including picture): http://algae.illinois.edu/projects/Hydrothermal.html University of Illinois at Urbana Champaign Department of Agricultural and Biological Engineering
[36] http://www.nwsda.com/download/Figures/Fig_1_NWSDA_Location.jpg

industrial algae to massively increase ocean fertility and fish stocks and reduce ocean heat, acidity and nutrient load, while also sequestering a large amount of carbon.

The initial goal here is to show that algae biofuel could be produced at sea for profit in ways that are ecologically beneficial. The methods described will face great technical challenges but aim to be fundamentally simple in concept. This proposal presents a way that DFAT can cooperate with the energy sector and other government agencies on a valuable climate energy project. It requires a low cost source of CO_2 such as Gorgon to start. The aim would be to prove that this method can also eventually be economic using CO_2 mined straight from the air, probably using wave and wind power at sea and other innovative technologies such as artificial trees.[37]

The scale needed to reduce atmospheric CO_2 is about ten thousand times the proposed Gorgon algae project, and would need to produce the annual equivalent of a cube of algae with edge about three kilometres in length. The world ocean is on average four kilometres deep, and 361 million square km in area. There is plenty of space to achieve that carbon production and storage goal, in a way that would provide abundant sustainable energy and related carbon products while protecting biodiversity and reducing water acidity and temperature, in order to stabilise the global climate.

The proposal is that an OMEGA system is field tested at Barrow Island, after proof of technology concept and risk assessment through desk analysis, development in laboratories and piloting in sheltered bays. This Gorgon Algae Project can be a precursor to eventual large scale deployment around the world, especially in waters of developing countries. Barrow Island is proposed for piloting due to the available technology, commercial interest, CO_2, capital and hydrology from the Gorgon Project and its nearby waters, in public private partnership involving the Chevron, Exxon and Shell Joint Venture and a range of government authorities.

Conclusion

In London in the 1850s, the sanitarians[38] solved the problem of cholera by pumping sewage out of the city into the Thames River downstream, where the tide took it out to sea. Global warming can be compared to a cholera epidemic for the twenty first century. Sanitation enables urban growth by managing and recycling waste to prevent water borne diseases. We need new sanitarians to work out how to pump carbon out of the air to solve the problems of rapid climate change. Funding that process can best be achieved by establishing economic and scalable methods to convert the harmful extra CO_2 into useful commodities. That means finding practical commercial uses for more than ten billion tonnes of carbon every year. The only way to do that, in my view, is to apply solar and ocean energy to grow algae on industrial scale at sea.

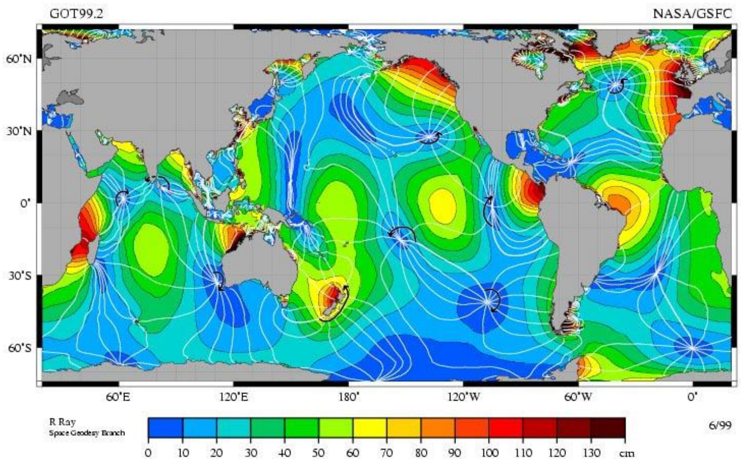
If CO_2 is split to make algae, and the algae is then held in a range of forms, from infrastructure on land and sea to oil in large fabric storage bags at the bottom of the sea, we have an enduring resource, a carbon bank. Keeping oil in bags at sea in this way could deliver local energy security through fuel stock holding as a strategic petroleum reserve. Perhaps the best way to store carbon produced from algae is to use it to build infrastructure. Algae farms would themselves be made of carbon, processed into plastic fabric, and would therefore be a carbon storage location. Other uses for carbon include road works and other construction materials such as for buildings. Compression of algae at the sea floor offers potential to invent strong light materials at low cost. By contrast, storing CO_2 through geo-sequestration[39] has little value and high cost, and this CO_2 can be put to much better use.

[37] http://en.wikipedia.org/wiki/Carbon_dioxide_removal#Artificial_trees

[38] http://www.medicine.mcgill.ca/epidemiology/hanley/temp/material/SnowCholera/EyleronWilliamFarrCholera.pdf

[39] http://en.wikipedia.org/wiki/Carbon_sink#Geological_sequestration

The ocean is a perpetual motion machine driven by earth's orbital dynamics. 1.3 billion cubic kilometres (teralitres) of water move the ocean surface up and down by about half a meter each tide on average, as shown in this diagram.[40] Tapping a tiny fraction of this tidal energy source for pumping should be a primary objective for an algae production and Carbon Dioxide Removal system. Such a system would enable a massive increase in the practical use of carbon. We can apply ingenuity and know-how to create innovative new methods to make good use of carbon stored as algae for infrastructure, energy and food. An industrial production system that is largely automated, and that uses oceanic energy to manufacture its own replication resources, can become profitable. Against this objective, ideas about prices on carbon and the strategic model of decarbonisation are secondary. We need a new integrated economic and ecological paradigm with eyes on the prize of mining more carbon than we emit.



The stock prices of energy majors can remain realistic only if their factored carbon reserves can be stabilised once they are burnt into the air. It is possible for DFAT to work in cooperation with the fossil fuel industry to stabilise the global climate, turning their commercial interests, resources and skills to advantage for new sustainable technology. Climate solutions must be based on cooperation and trust. Carbon Dioxide Removal through ocean algae production presents a great opportunity to save ecosystems while also supporting growing economic abundance and shared prosperity.

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[40] The M_2 tidal constituent. Amplitude is indicated by color, and the white lines are cotidal differing by 1 hour. The curved arcs around the amphidromic points show the direction of the tides, each indicating a synchronized 6-hour period. Tidal ranges generally increase with increasing distance from amphidromic points. The colors indicate where tides are most extreme (highest highs, lowest lows), with blues being least extreme. (Wikipedia, Tide)