Strategic path for the development of microalgal bio-diesel in China

Yao Fu-de and Robert Tulip[1]

Abstract: The use of liquid fossil fuel is limited by the declining petroleum reserves in the earth's crust and the need to reduce atmospheric carbon dioxide level. To supply energy for development in a low-emission economy, bio-energy is required. Guangxi Province can be a leader for China in biofuel. Guangxi already has the largest ethanol production plants in China, but substitution of biofuel for diesel is stalled. We propose that investment in microalgae should be the main energy focus, aiming at producing 500 million tons of bio-diesel per year to replace China’s current fossil fuel use for liquid energy supply. Algae biofuel is likely to be the best and only practical source for energy security and stability in many market segments. Algae biofuel also has spillover benefits for climate, environment, economic growth and food supply. The Government of China should support algae biodiesel research and development on industrial scale.

1. Diesel in China

Liquid fuel, especially diesel, is a main source of energy for heavy vehicles and machines, enabling efficient movement logistics for trade and transport. Diesel use is already double gasoline use in China, and demand for diesel is growing faster than for gasoline. A global shift to diesel instead of gasoline, including for passenger cars, is seeing a growing proportion of passenger cars in China also using diesel.

China does not have enough fossil fuel deposits to supply its future energy needs. China’s estimated crude oil reserve will allow current production rate until 2025. Oil fields face depletion, with China’s first oil field in Yumen now nearly abandoned. The ‘Hubbert Peak’, the point when half the petroleum reserve is drilled, has already occurred in China.

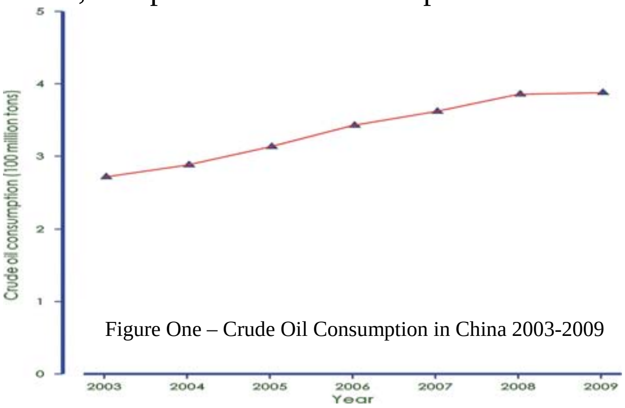


Figure One – Crude Oil Consumption in China 2003-2009

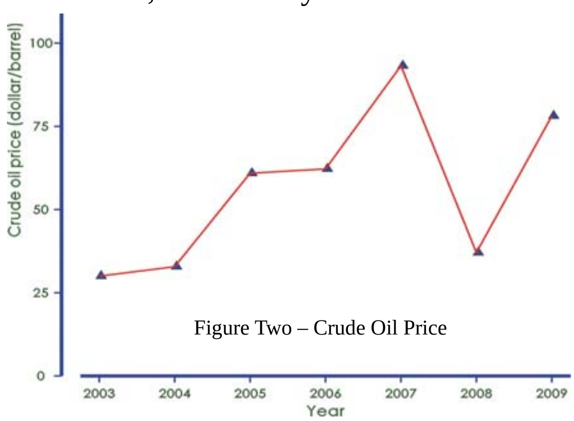


Figure Two – Crude Oil Price

From 2003-2009, crude oil consumption in China increased by more than 40% (Fig. 1), an average annual growth rate above 6%. Continued growth at this pace cannot be sustained using fossil fuel. Crude oil price is now about US$80 per barrel (Fig. 2), after peaking in 2008 at $147 per barrel. The peak price rose by 154% from 2003. The soaring crude oil price has

[1] Dr Yao Fu-de is a scientist at the Energy Crops Research Institute, Guangxi Academy of Agricultural Sciences, Nanning, Guangxi 530007, P.R. China. Mr Robert Tulip is a Policy Analyst at the Australian Agency for International Development, 255 London Circuit, Canberra ACT 2601, Australia. This paper is the personal opinion of the authors and does not seek to represent the views of their organizations. Comments to the authors may be provided here.

Strategic path for the development of microalgal bio-diesel in China © Yao Fu-de and Robert Tulip, August 2010

led to a tense fuel supply shortage in many places in China, where more than half of the crude oil consumption is imported.[2] In 2009, China used 8.32 million barrels of liquid fuels per day. Consumption is projected to rise by over 6% per year to 9.44 million barrels per day in 2011.[3]

2. Bio-diesel crops in China

Crops for producing bio-diesel are listed in Table 2. Popular crops such as oil palm and sunflower are primarily grown for food, so their use for bio-diesel is constrained. Oil palm is tropical, with only a small presence in Hainan Province. To develop biofuels that will not compete with land for food crops and will not cause environmental damage, high efficiency oil producing technologies must be developed. For China, the main choice is microalgae.

Table 2

Some typical biodiesel yields [4]

Crop	**Yield**	
	L/ha	**US gal/acre**
Algae[n 1]	~3,000, 15,000-30,000	~300, 1500-3000
Chinese tallow[n 2][n 3]	907	97
Palm oil[n 4]	4752	508
Coconut	2151	230
Rapeseed[n 4]	954	102
Soy (Indiana)[57]	550-900	60-100
Peanut[n 4]	842	90
Sunflower[n 4]	767	82
Hemp	242	26

2.1. *Why microalgae?*

We estimate that technical constraints can be overcome within five years to provide bulk fuel supply from microalgae if sufficient resources are applied. Big investment in algae biodiesel will secure China's future fuel supply and help to manage climate change.

Guangxi is the pioneer and mainstay of the biofuel industry in China, through cultivation of sugarcane and cassava, producing ethanol for bio-gasoline. Bio-diesel and bio-kerosene are not yet in wide production, but could quickly become a large industry. When fossil fuel can no longer meet the needs for liquid fuel in China, now around 500 million tons per year, this gap must be filled by bio-diesel. Alga is the only feasible source of biodiesel at the scale required. Guangxi is well placed to take a leading role in algae biofuel production.

Alga is superior to other feedstock crops. *Jatropha curcas* oilseed is one proposed option for oil feedstock, and is proposed for large area planting in Guangxi, although yields have not met claims.[5] Oilseed tree crops may alleviate a small fraction of the nation's diesel demand, but cannot provide the large amount needed. *Jatropha curcas* would need 500,000 square kilometers of land, almost two times the size of Guangxi Province, to produce 100 million

---

[2] http://www.eia.doe.gov/steo/#Global_Crude_Oil_And_Liquid_Fuels

[3] **U.S. Energy Information Administration / Short-Term Energy Outlook—July 2010**

[4] http://en.wikipedia.org/wiki/Biodiesel#Yield Notes: 1.**30,000 litre per hectare estimate for algae** is from the New York Times, "Colorado Company to Take Algae-Based Fuel to the Next Level," 11 Nov 2008, M.L. Wald. 2. **Information on Chinese Tallow is at** Klass, Donald, "Biomass for Renewable Energy, Fuels, and Chemicals", page 341. Academic Press, 1998. 3. Kitani, Osamu, "Volume V: Energy and Biomass Engineering, CIGR Handbook of Agricultural Engineering", Amer Society of Agricultural, 1999. 4. "Biofuels: some numbers". Grist.org. http://www.grist.org/article/biofuel-some-numbers. Retrieved 2010-03-15.

[5] Seeds of discontent: the 'miracle' crop that has failed to deliver: A new 'ethical' biofuel is damaging the impoverished people it was supposed to help. Jatropha was said to be resistant to drought and pests and able to grow on land that was unsuitable for food production. But researchers have found that it has increased poverty in countries including India and Tanzania.

http://www.independent.co.uk/environment/green-living/seeds-of-discontent-the-miracle-crop-that-has-failed-to-deliver-1899530.html tons of bio-diesel, 20% of China's liquid fuel demand. Oil seed cannot play a critical role in addressing China's shortage of bio-diesel, rather, it can only play a small scale role before the technology of microalgal bio-diesel becomes mature.

2.2 Microalgae

Microalgae are single-celled green plants, abundant in oceans and waterways. Algae form much of the biomass of the earth, supplying most of the natural conversion of CO_2 to oxygen through photosynthesis. Use of algae to replace fossil fuel is the subject of extensive international research. Alga grows much faster than any other oil crop and was the main natural source of fossil petroleum deposits. Algae can be a climate-friendly method to supply energy, but practical problems for algae biofuel production need to be solved to enable commercial production.

Bio-diesel from algae uses a process called transesterification, adding ethanol to convert algae oil into bio-diesel and glycerol. The Solar Energy Research Institute (SERI) at Golden, Colorado, USA conducted systematic research on microalgae oil production from 1978 to 1996, but found that microalgae bio-diesel was not competitive on price against crude oil. The situation has now changed. High oil price and looming shortage of oil supply will make algae biodiesel profitable once technical challenges for scaling up production are solved. So, algae biofuel has become a new hotspot with renewed efforts to revive it.

Natural crude oil is the remains of marine algae deposits from millions of years ago. Microalgae lipids can now be converted to crude oil in a matter of weeks, producing more than five times as much oil as oil seeds, without displacing food crops. Carbohydrate leftover can be used as feedstock for producing ethanol, and protein can provide animal and fish food. Algae biodiesel is a great invention with potential to solve energy and food shortages.

Inventors and start-up firms are finding many innovative uses for algae, including to generate electricity and hydrogen, and to make plastics, and are conducting intensive research on methods to convert algae to fuel. In 1993, researchers in the USA National Renewable Energy Laboratory used genetic engineering to improve lipid accumulation. Lipid oil content of over 60% was achieved in the laboratory, and over 40% in outdoor ponds, compared to below 20% in natural conditions.

Algae research in China is still in the fledging stage and can link to programs to industrialize algae in locations such as USA, Australia and India. China should take closer notice of firms working on construction and utilization of algae technology, they will surely inspire the bio-diesel industry. Capital investment for building algae production plants will require establishment of reliable low cost methods for supply of oil feedstock and conversion of algae to fuel, food and fertilizer. Funds for algae research and development will pay dividends in future security of energy, food supply and climate.

Molecular biology is assisting to develop high yielding strains of algae. The whole genome project of microalgae can help to solve problems in oil production. In order to better understand the algae genome *Chlorella prototheocoides*, the strain NC64A was whole genome sequenced by the Joint Genome Institute of the Department of Energy in the United States. [6]

Research in the breeding of elite algae species is addressing a range of problems. Saturated fatty acid content can be reduced to improve engine performance.[7] Algae oil can be

[6] In 1996, the baker's yeast genome, *Saccharomyces cerevisiae*, was sequenced, following the completion of the whole-genome sequencing project of the bacterium *Escherichia coli* K-12 in 1995.
[7] e.g. stearic acid, $C_{18:0}$ tends to accumulate carbon in an internal combustion engine because of incomplete combustion. It would be better if we can lower its content (it is about 5-7% naturally).

made more suitable for bio-diesel using additives.[8] Microalgae can grow in artesian or saline waters, bringing into production land and sea areas that are not suitable for irrigation in agriculture or forestry. Salt water can provide high yield if used for algae production with suitable species and methods. Plant husbandry and genetic engineering can deliver high yielding strains of algae that are robust and safe, with beneficial impacts on the surrounding natural environment. Centrifugation requires too much power, so alternative methods for separating water and algae are needed, such as “milking” by organic solvent, breeding fast flocculating strains, membrane systems or flocculating agent.

Laboratory testing can conduct *in silico* analysis to develop high yield strains. Analysis of the quorum sensing mechanism in algae can develop strains with denser and faster growth. The usual cell density that can be attained for microalgae is about one hundred million cells per milliliter of water (10^8/ml), producing dry matter of only 0.03% of water volume. The biggest obstacle to more rapid growth is the quorum sensing mechanism by which cells regulate their growth rate, preventing high cell density. Scientific research can produce varieties of algae with cells that can be grown to higher density while accumulating lipid oil for biodiesel. We also want the algae cell to flocculate at a certain speed, so enough cells precipitate but plenty of cells stay at the top portion for photosynthesis and growth. Flocculation can remove the need for energy-consuming centrifugation. We need to increase the photosynthetic rate and oil conversion rate. We can alter the fatty acid synthesis enzyme system to make lauryl acid to substitute kerosene. “Milking” technology can extract triacylglyceride (TAG) lipid oil from algae cells using organic solvent.

Bio-kerosene is an algae product that is rarely studied in China. Kerosene for aviation industry must guarantee not to be frozen at high altitude. Natural plant oil can rarely meet this requirement. Typical fatty acids produced by microalgae are listed in Table 3. Bio-kerosene requires the carbon chain to be shortened to about 12, such as lauryl acids ($C_{12:0}$). Some algae can produce short chain fatty acids (C_{12} or C_{14}), which can be methyl esterified to make bio-kerosene. Of the algae strains in Table 3, most fatty acids are too long to make kerosene. Under heterotrophic growth,[9] algae can turn glucose into oil. Using this feature, hexose and pentose from woody weeds (ligno-cellulose) can serve as substrates for producing bio-diesel or bio-kerosene, in addition to ethanol.

Table 3

Strain	**Nitrogen-sufficient cells**	**Nitrogen-deficient cells**
Ankistrodesmus	16:0, 16:4, **18:1, 18:3**	16:0, **18:1**, 18:3
Botryococcus braunii	**16:0, 18:1**, 18:2, **18:3**	16:0, **18:1, 18:3**, 20:5
Dunaliella bardawil	not determined	12:0, 14:0/14:1, **16:0, 18:1**, 18:2, 18:3
Dunaliella salina	14:0/14:1, **16:0**, 16:3, 16:4, 18:2, **18:3**	**16:0**, 16:3, 18:1, 18:2, **18:3**
Isochrysis sp.	14:0/14:1, 16:0, 16:1, **18:1**, 18:3, **18:4**, 22.6	**14:0/14:1, 18:1**, 18:2, 18:3, 18:4, 22:6
Nannochloris sp.	14:0/14:1, 16:0, 16:1, 16:2, 16:3, 20:5	not determined
Nitzschia sp.	14:0/14:1, 16:0, 16:1, 16:2, 16:3, 20:6	not determined

[8] Oil with high oleic and linoleic acids is quite suitable for bio-diesel. However, the double bond in them tends to be oxidized. This problem can be solved or retarded by adding 0.1% of rosemarin.
[9] Heterotrophic growth uses organic molecules as a primary source of nutrition.

Strategic path for the development of microalgal bio-diesel in China © Yao Fu-de and Robert Tulip, August 2010

The growth of microalgae relies on sunlight, water, carbon, macro-elements and micro-elements. Guangxi Province has rich resources of sunshine, water, natural resources including coastlines, and labor, so is very competitive for microalgae investment. It is foreseeable that Guangxi will play a vital role in using both land and sea microalgae farms. Growing algae in the shallow warm seas of Southern China replicates the environment where fossil fuels were produced by natural deposition of algae over millions of years, speeding up the process through industrial technology.

Carbon sequestration is another important application of microalgae. By converting the flue gas from coal-fired power stations and the CO_2 emissions from mining into bio-diesel and bio-kerosene, algae can sequester almost all the carbon dioxide emitted from these sources, cleaning the air. China can use algae to regulate the release of carbon dioxide from coal-fired power stations, reducing air pollution. To generate one kilowatt hour of electricity requires about 0.3 kilograms of coal, and produces three kilograms of carbon dioxide and fine particle pollution.[10] In 2009, China's power stations generated 3650 billion kilowatt hours of power, releasing more than eight billion tons of carbon dioxide. Microalgae absorb 1.7 kg of carbon dioxide per kg dry algae biomass. This high absorption can be managed at large scale to reduce CO_2 levels in the atmosphere through conversion of emissions into energy and food.

3. Microalgae farms

Microalgae are now cultured in open raceway ponds and photo-bioreactors. Light efficiency in raceway ponds is low and hard to control, limiting yield. Photo-bioreactor yield is higher but so is construction cost. Research is required to determine the most efficient production method. Cost of producing bio-diesel from algae will be low once production is scaled up to replace fossil fuels. Both land and marine micro-algal farms should be considered. At the upper annual yield estimates of 30,000 litres of fuel per hectare, to make 500 million tons of bio-diesel per year needs more than 160,000 square kilometres of sea or land area. Land-based algae production can use CO_2 sources such as power stations and mines. However, spare land is not available at the scale required, indicating need for research on algae farms at sea.

3.1 Terrestrial microalgae farms

Building large microalgae farms is challenging, whether by raceway ponds or photo-bioreactors. Cost is high, and good land has competing uses. At 30 tons per hectare oil yield and 5000 Yuan/ton, gross annual income per hectare will be 150,000 Yuan, about US$25,000. Locations should be near to CO_2 emission sources. Water demand is high. In Guangxi, rainfall must be collected during the rainy season from May to July. Biological stability of the system must be guaranteed. Good bio-film management should be adopted. The use of underground saline water and sea water should be considered.

3.2 Marine microalgae farms

Marine production offers promise to combine pond and reactor advantages. An estimated 160,000 square kilometres is needed to produce 500 million tons of algae biodiesel per year, assuming yield of 30 tons/ha. 160,000 square kilometres is 0.03%, of the planetary ocean surface of 500 million square kilometres. Controlled production of microalgae at sea on this scale would provide enough bio-diesel for China's current use, and would have environmental benefits including reduced CO_2 emissions, increased fish stocks, treatment of liquid waste and local cooling of ocean water. Ocean-based algae production will not compete for land with other uses such as industry, housing, forest, nature reserves and food crops. Marine algae

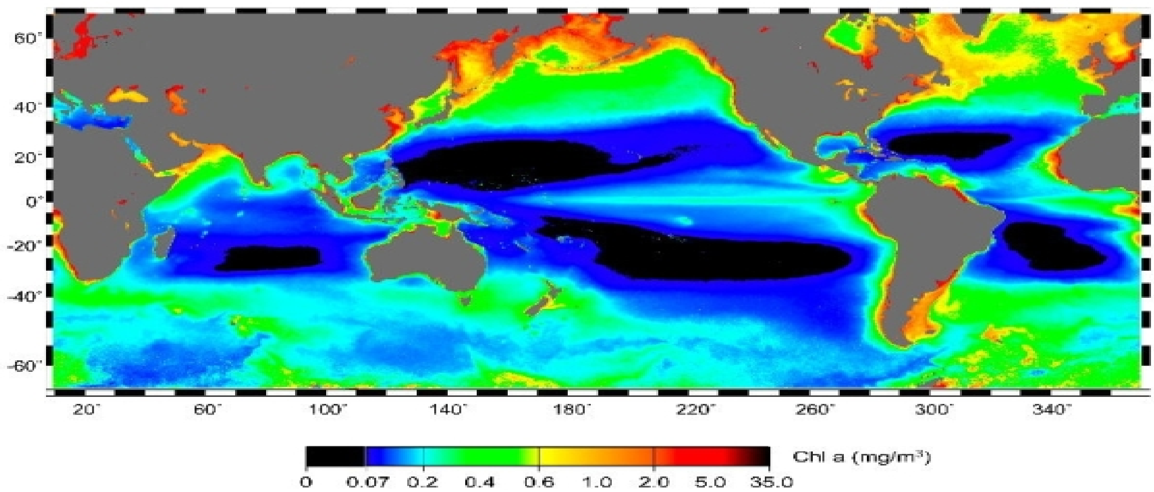
[10] http://en.wikipedia.org/wiki/Coal#Carbon_intensity

farming has potential for rapid scale up at low cost to produce diesel fuel, as well as solid fuel, fertilizer, fish food, plastics, compressed carbon blocks, and CO_2 sequestration.

China coastal waters can be used to test algae production. We propose the use of bags of fresh water to provide flotation, stability and energy supply for algae farms.[11] Polymer fabric bladders containing fresh water will float in the ocean, because fresh water is lighter than salt water. Waterbags can be used for fresh water transport and storage, and for waste water treatment.[12] Initial tests can study stability and design of floating bags of fresh water, including use for water supply and sanitation. Fresh water bladders can stabilise algae farms at sea, enclosing a surface production chamber. This new simple technology can use wave and tidal energy for pumping and propulsion, including to raise nutrient-rich water from the deep ocean. After mixing rich deep ocean water with CO_2 in a controlled algae production system at the ocean surface, a floating bag system can use wave and tidal power to transport and de-water the produced algae and to separate the oil for biodiesel feedstock. Algae slurry can be sunk in bags to the bottom of the ocean and raised again using wave energy, as a method to expel water and separate lipids by membrane pressure. Deep ocean separation of algae can also produce compressed carbon blocks and solid fuel.

Marine algae farms must identify cost-effective materials that can withstand the ocean environment and ensure safe operations. New technology can provide robust polymers that are suitable to make algae bioreactors at sea. Storms and shipping hazards are big problems. Protection from rough weather can be provided by temporarily sinking the production system to still depths below the ocean waves. An algae production system could be lowered under the sea surface during bad weather by expelling air from buoyancy chambers. Marine algae farms should be tested with small pilot projects in sheltered locations to examine proposed methods. This kind of farm may be operated all year round in south China coastal waters and in summer in north China.

Once production methods are established in coastal waters, it is possible to extend this kind of algae farm in the "desert" areas of the ocean which have very low chlorophyll content. This kind of "desert" is now 50 million square kilometers and expanding in size due to global warming. The black areas on this NASA map[13] of the world ocean are the 'desert' areas of



low algae growth due to lack of mixing of surface water with nutrient-rich deep ocean water. Algae farms in these areas of the world ocean could use ocean energy to bring nutrients from

[11] http://rtulip.net/ocean_based_algae_production_system_provisional_patent
[12] www.waterbag.com
[13] http://environmentalism.suite101.com/article.cfm/ocean_desert_areas_are_escalating

Strategic path for the development of microalgal bio-diesel in China © Yao Fu-de and Robert Tulip, August 2010

the deep to the surface. Algae farms in the open ocean could supply biofuel to address global energy shortages, while also providing fish food and other products and cooling the ocean temperature.

4. The key questions to be addressed

Subjects needing further study include: biomass yield; oil content; short chain fatty acid content for bio-kerosene; production systems, locations, content of saturated fatty acids; algae separation methods; concentration of carbon dioxide at night time; and the use of emissions from power stations and mines. Investors in algae biofuel research and development will share in ownership of the intellectual property for this large new energy industry.

5. Prospective

To sum up, algae biofuel has the following advantages:

(1) Yield is much higher than other biofuel crops for equal land area.

(2) Algae biomass has a wide range of commercial uses including for diesel fuel, bio-kerosene, food production, fertilizer, carbon blocks, solid fuel and plastics.

(3) Bio-fuel can sequester carbon dioxide from power stations and mines, providing rapid reduction of atmospheric carbon dioxide to stabilise global climate.

(4) All outputs can be recycled to maximize product value and improve environmental health.

(5) For molecular biology modifications the gene improvement cycle is short, the operation is simple compared with higher plants, and it is easier to apply.

(6) Marine and land based locations and production methods can be considered.

Economic progress for all countries in the world relies on steady supply of liquid fuel. In the near future, we may not be able to find the resources that we need for such supply. Bio-energy is the way to go, but remember, large area is needed for this purpose, and both terrestrial and marine farms may be needed. After the key problems have been solved, the supply of bio-diesel can be secured in the near future, but only if we invest soon. Using microalgae to produce bio-fuel should have a very bright future.

Acknowledgments

Yao Fu-de and Robert Tulip are sincerely thankful to Dr. Thomas G. Lessie, Ph.D. adviser, and Dr Tom Beer, CSIRO, for critical scrutiny of this manuscript.

References

[1] Department of Energy Aquatic Species Program, National Renewable Energy Laboratory. Bio-diesel Production from Algae. http://www.eere.energy.gov/biomass/pdfs/biodiesel_from_algae.pdf
[2] A2BE Carbon Capture, LLC. http://www.a2be.com/
[3] Robert Tulip. http://rtulip.net/ocean_based_algae_production_system_provisional_patent
[4] Joachim Heller, 1996. Physic nut *Jatropha curcus* L. IPGRI
[5] Joint Genome Institute, Department of Energy. http://genome.jgi-psf.org/ChlNC64A_1/
[6] National Statistical Bureau. http://www.stats.gov.cn/
[7] Trends in Biotechnology
[8] Algae biofuel website: www.oilgae.com

Tags
Algae, biofuel, Guangxi, China, energy, technology, climate, ocean

Strategic path for the development of microalgal bio-diesel in China © Yao Fu-de and Robert Tulip, August 2010