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ANNEX: Algae concepts in practice

In recent years, many ideas for the deployment of algae-based technologies have evolved into practical projects. This chapter provides a collation of relevant case studies that illustrates the multiple applications and status of development of different concepts which make use of algae as a feedstock. Also some specific and simple technologies more suitable for the developing world are presented.

These are just a few examples of the many projects and ideas currently under development worldwide.

The information contained in this chapter has been provided by the project developers themselves and hasn't been proved by the FAO.

Algae Food & Fuel, The Netherlands

The project aims to grow algae on the waste streams of a biogas installation which powers a combined heat and power generator. The biogas system provides green electricity for LED illumination, heat, nutrients from digestate and CO_2 from the flue gas for algae cultivation. The algal biomass is primarily used for the extraction of algal oils for food and fuel applications, and utilisation of the non-oil biomass is anticipated.

Algae Food & Fuel is an initiative from BioSoil, Tendris and Solarix. These companies have a background in biological soil remediation, lighting innovations and biodiesel production. Combined, they provide a wide scope and diverse solutions. The first project is an algae production plant in Hallum, Fryslân, The Netherlands. Kelstein, a dairy farm and biogas company, owns the biogas installation which powers a combined heat and power generator that supplies. The results so far are successfully growing algae on the excess heat and flue gas. Current experiments use the digestate (after it passes a reverse osmosis step) as a nutrient source.

The 3 year, 3 million euro project is financed privately by the four partners above, except for 20% public funding by the Dutch Ministries of economic affairs and of agriculture.

The algal biomass contains approximately:

- 30 % raw Fat's (expected; 20 % PPO)

- 20 % proteins

- 30 % cell wall materials (sugar, cellulose based)

- 20 % ash, vitamins and minerals

Besides algal oil production, co-production of (refined) algae materials as feed for animal and fish industries, fine chemicals for chemical industry are considered. Some components can be interesting for health, cosmetic's or pharmaceutical purposes. A preliminary estimation of the income of the algal products is 60% derived from algal oil, 40% from other products.

The pilot facility at the dairy farm in Hallum Friesland consists of four 20 m3 photobioreactors. The unique combination of submerged LED illumination in conventional horticultural water basins creates a very efficient algae production system with low areal footprint in relation to productivity.

The pilot plant runs currently four reactors in chemostat or turbidostat mode for continuous production and to fullfill some criteria for convenience of research. The reactors have a volume of 20 m^3, and a depth of 2 m, and are connected to spargers with gas supply and horticultural pumps for dosing nutrients and trace elements, compressors for CO_2, pumps to mix and transport, centrifuges for harvesting biomass and a drying system for harvested biomass. In the pilot project an anaerobic digester with biogas driven combined heat/power generator supplies the CO_2, 2^{nd} best would be a (municipal) water treatment system with anaerobic digester to treat sludge and get energy from the sludge. The goal is a closed carbon cycle for a dairy farm with an acceptable energy balance and economical viability. The system can be adapted to sweet water, brackish water or seawater, depending on the algae species, wild algae can be selected for any type of water. The nutrient source will be digestate treated to retain high nutrient concentration and transparent for light all optimised to sustain fast growth of algae. Future goals are to set up a productive algae biomass production system that can be run at farmsites, find and commit the market partners for algae biomass. Planned expansion of operation to four 200 m^3 scale systems on the drawing board for 2010. Currently several other algae based projects are in development but operational status is lower compared to the pilot plant.

The level of technological skills required to operate algae farms of significant scale could be a barrier to implementation of the concept in developing countries. Other, internationally present, barriers are that the rules considering the production of raw material, downstream processing and application field are a complication to market penetration.

Algae to Biofuel, United States

The Center of Excellence for Hazardous Materials Management (CEHMM)[24] has been cultivating and harvesting a (proprietary) marine alga from outdoor raceway ponds in south-eastern New Mexico in the United States. The minimum annual operating budget is approximately two million dollars.

Experimentation with a variety of algae species has been underway since June 2006 with construction of the first one-eighth acre outdoor raceway pond in 2007. Currently CEHMM has three outdoor raceways with approximately 416,395 litres maximum capacity. The New Mexico Environment Department has granted permission to construct additional twenty one-quarter acre ponds proximal to the current three. They collaborate with U.S. national laboratories and a variety of universities both within and outside New Mexico. The experimental extraction unit is provided by Solution Recovery Services (SRS, Inc.) out of Dexter, Michigan. They affirm to have the first vertically integrated pilot plant to grow and harvest algae and extract oil all in one location, with the aim of using this paradigm to build a commercial facility.

A suite of nutrients are provided at propitious times. The timing of nutrient delivery has been honed over the course of nearly three years of experimentation. The carbon dioxide source is atmospheric and any required supplemental carbon comes through other (proprietary) sources.

Several harvesting techniques have been attempted with effluent water recycled to source ponds. Currently centrifugation is the technique of choice, but additional experimentation continues with flocculants. During the summer, CEHMM harvests every day from nearly all the ponds. During the winter months, the rate of harvest decreases due to inclement weather and cold temperatures. CEHMM algae has been successfully grown and harvested year-round.

The intended co-products include human and livestock food products, neutraceuticals, and an array of chemical compounds used in such industries as cosmetics. Our extraction process is wet so there is no energy expended to dry algal biomass. De-lipified biomass is solar dried for use as food products, such as animal (livestock) feed. The estimated market value for chemical co-products include USD8.87 for 25,000 international units or 1500 micrograms for beta carotene, USD40.00/pound for essential amino acids (EAA), USD367/pound for eicosapentaenoic acid (EPA), which is part of omega 3, USD45,450/pound of decosahexaenoic acid (DHA), also a part of omega 3 and omega 3 itself for an estimated USD3,272/pound.

Currently CEHMM's focus is on conversion of algae oil to transportation fuel but plans exist to examine other fuel profiles and co-products (e.g., bioplastics) as well.

An environment with ample sunshine, generally warm temperatures, an area of little topographic relief and access to both fresh and saline waters is ideal. The desert southwest, including all of southern New Mexico and West Texas in particular, is a particularly hot, dry region with large tracts of land that are non- arable. The fact that algae do not compete with commercial agriculture and produce high quantities of lipid which in turn can be extracted and converted into transportation fuels and high value products makes this renewable energy source ideal. The application of the CEHMM model can be translated to alternate sites such as tropical climates.

To date, a significant part of private, state and federal investments has focused on companies that experiment predominantly in research laboratories working to develop genetically modified organisms (GMOs). There is considerable controversy about the use of GMOs in an open environment. CEHMM has chosen to use a wild strain which is safe to grow in open ponds and poses no threat to the peripheral environment.

CEHMM is planning to build a large facility. Much of the electricity requirements for a commercial facility will be provided through either solar or wind energy. A techno-economic model has been developed that suggests the approach could be successful at a commercial scale.

First oil from algae at the CEHMM Artesia algae plant and a quarter-acre pond with extraction facilities in the background

AlgaFuel, Portugal

AlgaFuel´s Secil project is an advanced prototype study which uses microalgae to capture the combustion gases from a Cement Plant. The project consists of the development and implementation of a Prototype Unit for CO_2 mitigation.

Tubular photobioreactors (left) and green wall panels (right)

The main differentiation and innovation of the AlgaFuel Prototype Unit consists of the development and selection of a technology for CO_2 fixation adapted to the specific conditions of the cement plant. The implementation of the Prototype Unit in a Cement Plant was preceded by a period of 12 months to develop several studies, fieldwork and laboratory activities, aiming to characterize the local conditions, namely a phycological study for characterization of the local microalgae, physico-chemical evaluation of the plant's water supply and flue gas analysis, and preliminary testing for flue gas use as microalgae carbon source. The results were crucial for the selection of the appropriate species to produce at this particular site.

The cultivation system implemented in the Prototype Unit operates in a semi-continuous and semi-automatic way and uses two distinct technologies: Tubular photobioreactors and Green Wall panels. The Prototype Unit established at the Secil cement company occupies an area of 1500 m^2.

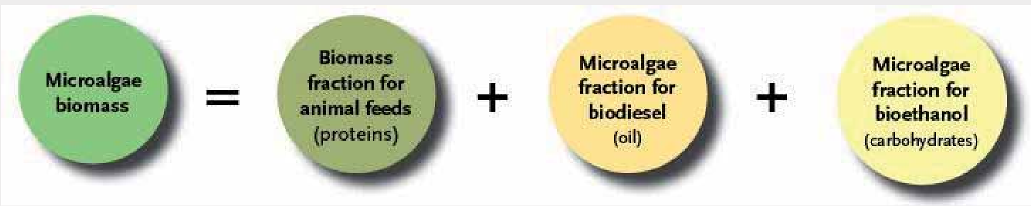
The cost of a Microalgae Production Unit Prototype can change significantly depending on the local conditions and the amount and type of experimental assays to be conducted in a Prototype Unit. As an estimate the investment required for such a Unit is approximately 0.7 M€. The annual operating and maintenance costs are around 0.5 M€.

The cement industry is currently responsible for 7% of global CO_2 emissions. The establishment of Microalgae Production Units in high-emitting industries could be an efficient alternative for the reduction of greenhouse gases emissions to the atmosphere. Several companies are emerging with the objective of large-scale production of microalgae as an energy source, AlgaFuel´s Prototype being the largest in operation with flue gas from a cement company.

A4F - AlgaFuel, S.A. is a bioengineering company aiming the development of projects for the industrial production of microalgae. It is a spin-out from Necton S.A., with an extensive R&D curriculum and the experience of large-scale production of microalgae using raceways and photobioreactors continuously in the last 12 years for the aquaculture and cosmetic markets. The Prototype Unit technology is in the market since March 2009 and is already operational at the Secil Cement Company’s plant in Pataias, Portugal. The present results are very promising and the next scale-up for a pilot plant is already being considered.

The technology applied in the Microalgae Production Unit allows the fixation of greenhouse gases, namely CO_2. Furthermore, this process allows the continuous and reliable production of high amounts of biomass with a potential use as sustainable biofuels. The fixed CO_2 can be commercialized in the CO_2 license exchange market.

The microalgae biomass may be marketed for several purposes in a biorefinery-type approach: from the direct use of whole cells as sustainable biofuel raw material, to the applications of each biomass component: protein for feed, lipids for biodiesel, pigments and polysaccharides for pharmaceutical applications.



The break-through of this project is the combination of scale and the use of CO_2 flue gas from a Cement company as nutrient for microalgae. The AlgaFuel prototype is the world's first assemblage of systems using tubular photobioreactors, integrated in an emitting industry. This prototype combines all the steps from inoculum production in laboratory scale to the final biomass achievement.This technology can be used for other industries with CO_2 emission.

There aren’t specific barriers in the developing countries where the climatic conditions are more often closer to optimum. Constrains in developing countries are the same as elsewhere: water and CO2 availability for almost free, solar radiation, and knowledge.

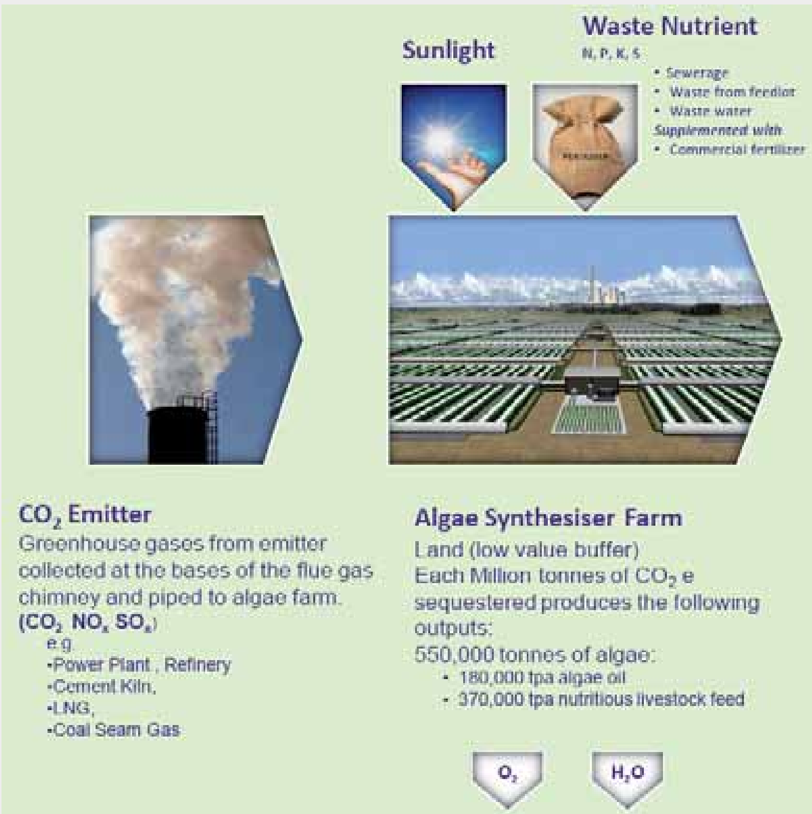
Bio CCS Algal Synthesiser Project, Australia

Established in 1997 and owned by the Queensland Government, Tarong Energy Corporation Limited (Tarong Energy) has the capacity to produce one quarter of Queensland's electricity needs. The Corporation owns a mix of generating and mining assets and employs more than 450 people in electrical and mechanical trades, engineering, and a wide variety of professional and support roles at its generating sites and in its Brisbane corporate office.

Tarong Energy reached a joint development agreement with MBD Energy in 2009 to develop a Bio CCS Algal Synthesiser plant at Tarong Power Station. The project is managed by a joint steering committee comprising representatives of both parties with MBD Energy responsible for personnel to design, construct, operate and maintain the display plant beginning in 2010; and Tarong Energy responsible for the supply and preparation of the trial site and the supply and maintenance of flue-gas, water and electricity to the Bio CCS Algal Synthesiser.

The initial facility will occupy a one hectare site adjacent to Tarong Power Station and, depending on the success of the trial and pending all appropriate approvals, Tarong Energy and MBD Energy may decide to design and construct a larger (nominally 80 hectares) Bio CCS Algal Synthesiser at Tarong Power Station.

MBD Energy and its partner team at JCU have developed a technology that allows this natural carbon cycle to be replicated under process controlled conditions for the bio-sequestration of industrial greenhouse gases over as short a timeframe as a single day.



Called Algal Synthesis, the process involves the injection of captured flue-gases into a waste water growth medium contained in large, elongated plastic membranes to produce rapid expansion approximating up to a doubling of oil-rich algal biomass every 24 hours. This algal biomass, grown from locally selected strains of microalgae in order to protect local biodiversity, may be harvested daily to produce algal meal suitable for nutritious, lower-methane animal feed, human nutritional supplements, and oils suited to the production of plastics and transport fuels including large quantities of bio-diesel.

Current production forecasts indicate that the sale of these commodities can be expected to readily offset the expenditure of building and operating such a greenhouse gas emissions reduction technology, thus progressively helping deliver cleaner electricity production at the lowest possible cost to consumers, whilst significantly reducing net CO2 emissions.

The Bio CCS Algal Synthesiser project at Tarong Power Station aims to determine whether Algal Synthesis can be scaled to achieve the desired CO2 emissions reductions. The project will also determine if the captured waste can be converted into supply chain input commodities for food production, plastics production and transport energy.

Planning and design of the display plant began in January 2010. The plant is anticipated to capture 800 tons per annum of greenhouse gases, produce over 400 tons per annum of algal biomass, 120 tons per annum of algal oil and 280 tons per annum of algal meal in 2011. Once proven and optimised at 1ha the project will then be scaled up in 2012/13 to 80ha, abating 70,000 tons of CO_2 producing 11.8 million litres algae oil and 25,000 tons of stock feed.

Cape Carotene, South Africa

Cape Carotene is a South African start-up biotechnology company that is developing a production process for the manufacture and marketing of natural products derived from micro-algae. The objective of its current project is to produce natural astaxanthin from microalgae for the local and international markets using closed system cultivation technology for better process control.

Astaxanthin is a valuable carotenoid pigment used in the aquaculture and animal feed industry and is gaining increasing status a human nutritional supplement because of its antioxidant properties. The major market for astaxanthin is the aquaculture industry which formulates feed for salmon (80%), trout (15%) and shrimp (3%). Other markets include the food and nutraceutical/ over the counter (OTC) market segments. Together these markets constitute about 2% of the global market value. Astaxanthin for the feed industry sales for between $2000-$3000 per kg, but is considerably more for the OTC markets as this requires further processing of the crude product. Worldwide consumption of astaxanthin is about 170 tons per annum in 2008. Major consumers of astaxanthin include Europe (65%), Latin America (25%) and Asia (10). Natural astaxanthin for the OTC or nutraceutical market is sold at a premium due to its associated health benefits. Ongoing research has proved that natural astaxanthin is effective against a number of health problems including cancer and blindness.

The main current focus is aquaculture; pen-reared salmonid fish cannot synthesise the carotenoids that cause their characteristic pinkish colour. Hence salmonid fish require feed where astaxanthin is added as a supplement.

Astaxanthin accounts for a large percentage of production cost (about 20%) of aquaculture feeds. Carotenoids, including astaxanthin, are largely produced synthetically via chemical processes; however, there is a trend towards deriving carotenoids naturally.

Cape Carotene currently uses facilities in Upington in the Northern Cape region of South Africa for its manufacturing and piloting studies where the climatic conditions are favourable to algal growth. The facility uses both municipal and fresh river water in ponds cultivation system where nitrogen and carbon nutrients are added. The carbon source is carbon dioxide and nitrogen source are nitrates. The waste water is recycled to recover nutrients and for reuse.

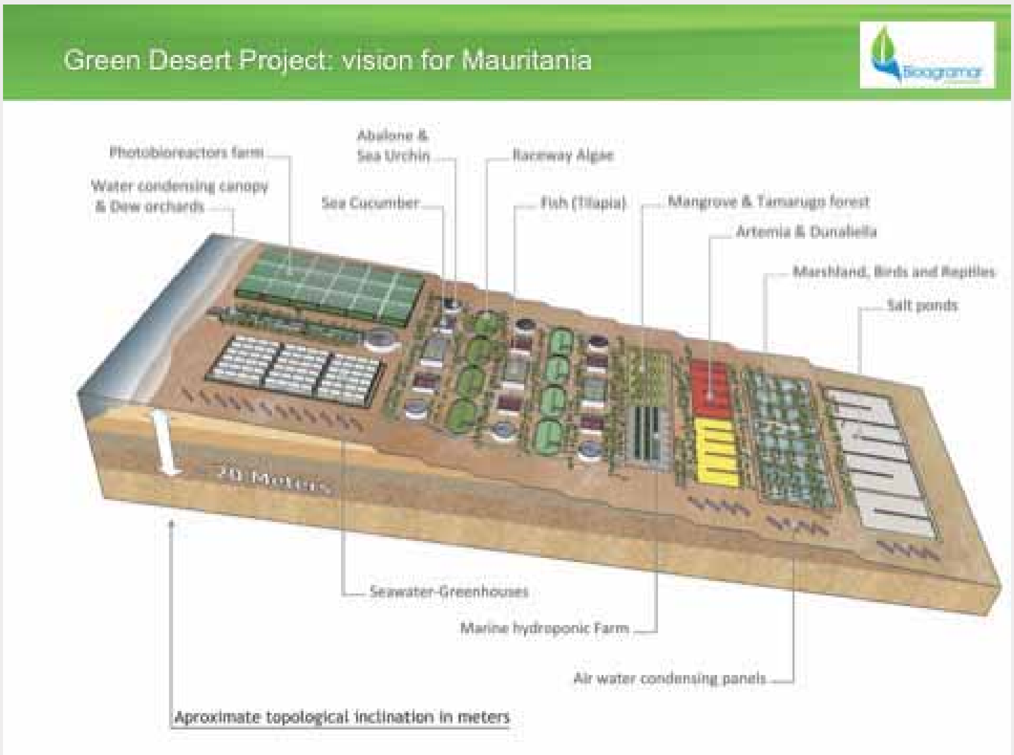
There is a plan for setting up an algal technologies platform at the pilot plant facilities in Upington where nascent algal companies can be accommodated. In this way commercialisation can be centrally stimulated and coordinated, benefitting companies such as Cape Carotene. The market depends very much on the type of product e.g. astaxanthin market in South Africa is miniscule, hence most of the product will be for export. In this regard companies such as Cape Carotene will act as primary algal products producers with onward distribution to established formulation global companies such as Nutreco in Europe, Fuji Chemicals in Asia or to the established players in the global carotenoids market, i.e DSM and BASF.

Cape Carotene was incorporated in March 2006 after receiving funding (~USD600,000) from Cape Biotech Trust, an independent trust under the auspices of the South African Department of Science and Technology. The astaxanthin project uses technology developed at the University of Cape Town. The company also has access to beta-carotene technology.

Cape Carotene is in a three year development phase from 2006 to 2009. After this phase a full scale plant capable of producing up to 2 tons of 100% astaxanthin will be established. Cape Carotene is now seeking a second round of funding to progress to full scale production.The natural astaxanthin is produced using the green micro-alga Haematococcus pluvialis. The final biomass yield on the test plant is between 0.5 to 1.0 g/l. Each test pond is has an area of 100 m^2 and volume of 10 m^3. The content of astaxanthin in the biomass is 2% of the dry weight.

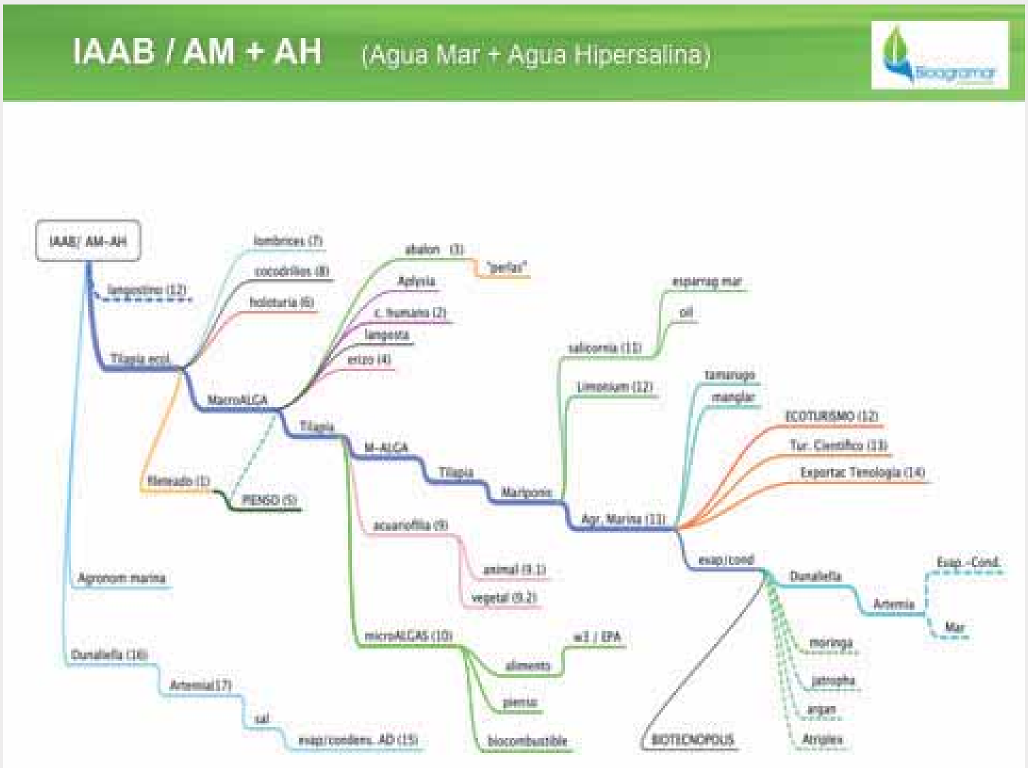
Green Desert Project (GDP)

The Green Desert Project (GDP) is a concept for re-greening the Sahara through integrated marine polycultures, including microalgae, macroalgae and halophytes (plants grown with salt water). These are key links in the multitrophic biomass chain of on-land cultures. The concept has been developed by the Bioagramar Foundation, a private non-profit R&D foundation, based in Spain but with a global scope, who aims to realize this concept under a frame of joint-ventures with companies and international institutions.



Biomass (even for biofuels) from the IAAB-microalgae farms are planned in a new, simple, cheap and recyclable semi-closed photobiorector design, that might allow production costs lower than 765 €/ton (dw).

The first steps to develop a Technological Center at Gran Canaria (Canary Islands, Spain) as the 10 hectare pilot-plant polyculture farm have been made. The next step is to export the system to the Sahara, to the coasts of Mauritania (3.800 km^2, below sea level, but without hydroelectric seawater power). Eventually desert area of 20.000 km^2, below sea level, bordering the coast of Mauritania, Western Sahara, Morocco, Algeria, Tunisia and Libya might be put in production for marine and algae biomass for food, feed and biofuels.



The "basic GDP" contains 17 subsystems that co-produce fish, seaweed, molluscs, algae, crustaceans, salt, biofuels, quality food, feed, water, mangroves, trees, and amphibians. At the same time the concept brings quality of life and sustainable wealth in the Sahara desert. This new bio-industrial ecosystem polyculture co-production concept is called Integrated Aqua Agro-Biotechologies (IAAB). 90% of the technologies needed to form the IAAB are already applied at a commercial scale, but not integrated.

Other opportunities and benefits include as a side effect, the concept will reduce the rise in sea level through the hydration of the desert, an impact on food markets and global climate (not just Africa) and with potential to generate third-generation biofuels (energy balance positive), reuse of effluents from fish farming and shellfish production for cultivation of algae and halophytes, strategic location at the Scientific-Technological Park of the University of Las Palmas, Gran Canaria, off the coast of north-west Africa, with access to knowledge, experience and scientific and technological infrastructure in biotechnology of microalgae, seaweeds farming, cultivation of plants with sea water, one of the best collections of marine microalgae and extremophiles (many are native of NW Africa).

Stepwise development of the Green Desert Project for the implementation of Saharan Biotecnopolis

Improving Algal Oil Synthesis for Biodiesel, South Africa

The main aim of this project, implemented by the University of the Witwatersrand, is to produce lipids which are chemically suitable for the production of biodiesel.

The percentage of lipid composition on a dry mass basis in the microalgae species used in this research laboratory ranges from 20 to 65% depending on species and culture conditions. Co-products would be lipid or oils not suitable for biodiesel production. Some of the co-productions in the form of heavy oils could be used as fuels for steam generation for electricity generation. Other possible lipid co-products are certain essential oils. A major key co-product in algal biodiesel production would be glycerol. Glycerol could be used as feedstock in dark fermentation for the production of ethanol and methane. It could also be used as a carbon feedstock for heterotrophic algae production.

At this stage the market value or size for the possible products and co-products is not clear. However, a number of mining companies have already expressed an interest in algal biodiesel or algal heavy oils for electricity generation. This would reduce their dependency of state utilities for electricity supply and may reduce the cost of mining operations.

While biodiesel production being the main goal, heavy oils, waxes and essential oils would be an additional consideration for co-production. In addition algae biomass as a by-product of biodiesel can be used as a feedstock for anaerobic fermentation for methane production. This project is currently still at the R&D phase and therefore unable supply any reliable information on income flows from algal products at this stage.

The project work is based on a surface of 0.5 m^2 and uses the *Isochrysis galbana* alga.

The patented projected algal lipid production facility will have a volumetric capacity of 8000 m^3/ha in the form of plastic airlift tubular photobioreactors. In lab scale photobioreactors the lipid production ranges from 20 to 60 mg/L/d with an average of 38 mg/L/d. If this value is scaled up for the production facility above, an annual dry biomass production of up 110 tons per ha can be calculated.

The project is based at the University of the Witwatersrand and has a budget of over € 150.000.

The South Africa Government's Department of Science and Technology through its company South Africa National Research Institute (Saneri) (Pty) Ltd has provided the funding. The runtime is 3 years starting from October 2008. The Project is now in its second year. Saneri and The University of the Witwatersrand are the major partners. Sufficient Intellectual Property has been generated to provide a satisfactory foundation for commercialization.

Low cost raceway ponds and tubular photobioreactors can be constructed from plastic materials. Only brackish or seawater would be required. Nitrate and phosphate would be main nutrients. CO_2 is the main carbon source. However algal production system could be operated as a mixotrophic system using fermentation products such as volatile fatty acids. An algal oil refinery would generate waste algal biomass and glycerol which could be used as a feedstock for methane production via dark anaerobic fermentation or even as a feedstock for mixotrophic algal production. A combination of agricultural fertilizer and biomass recycling would be the source of N and P.

Oil and biomass production from microalgae could be one of the most appropriate means for energy farming in developing countries. Algal energy farming can be carried out on extremely marginal agricultural land resources and could contribute to the energy self-sufficiency of developing countries. In order to avoid possible barriers, to algae-based energy farming, socioeconomic stability is needed in areas such as the enforcing of national laws, protection of property rights, robust public institutions and civil society organizations, political and economic freedom. The investment would not be less than € 10.000/ha and the production process would be labour intensive as there would 100.000 photobioreactors per ha that would have be maintained. It would be a form of farming – roughly similar to green house crop production.

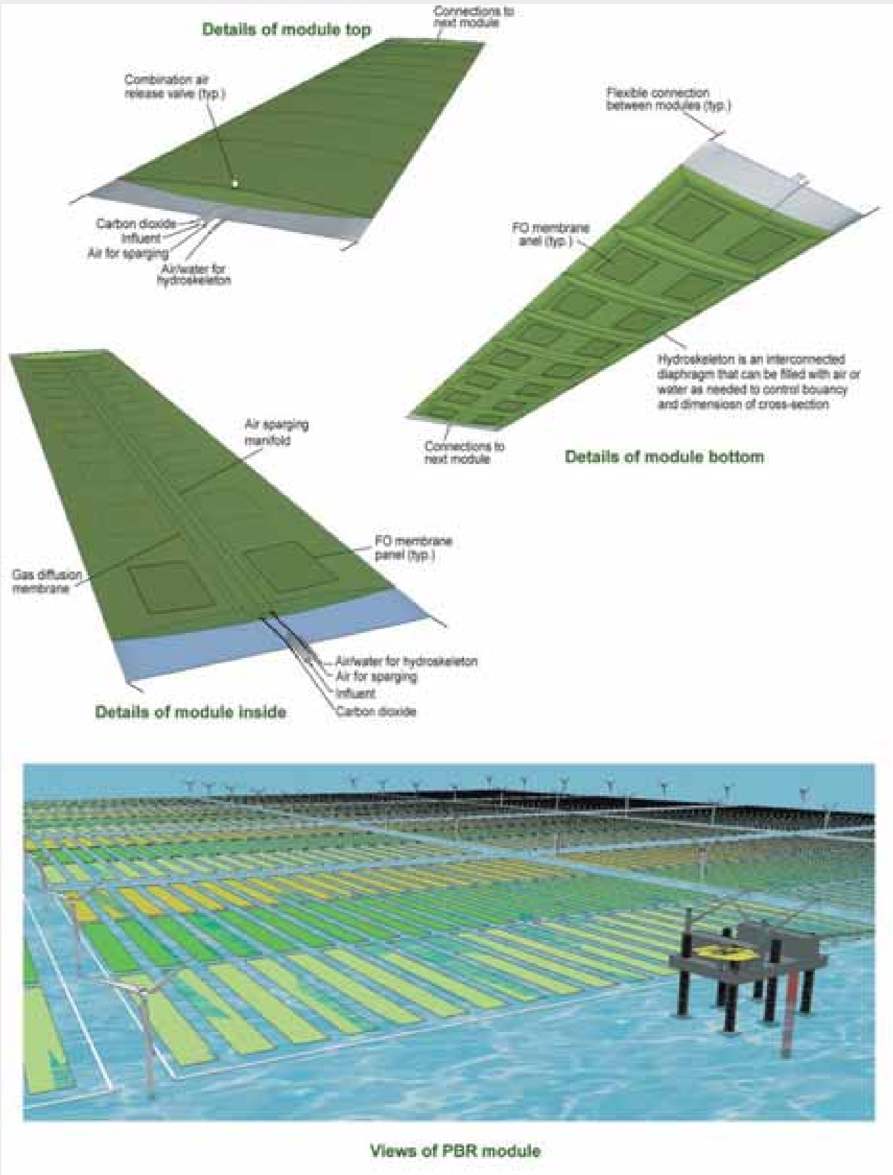
Offshore Membrane Enclosures for Growing Algae (OMEGA)

The Offshore Membrane Enclosures for Growing Algae (OMEGA) is a proposed system of floating photobioreactors for growing freshwater algae on municipal wastewater in marine environments. The algae grow within the enclosures and the surrounding seawater provides physical support, temperature regulation, wave energy for mixing, and a salt gradient for containment (freshwater algae die in saltwater) as well as forward osmosis (the flow of water molecules across a semi-permeable membrane in the direction of the highest salt concentration. Algae, nutrients and pollutants cannot pass the membrane. Forward osmosis membranes concentrate nutrients in the wastewater, dewater the algae in preparation for harvesting, and clean the water released into the surrounding seawater. OMEGA generates products from algae including sustainable carbon-neutral biofuels, as well as food, fertilizer, and nutraceuticals. OMEGA also provides services, including advanced wastewater treatment, environmental remediation, and carbon sequestration. It provides these products and services without competing with agriculture for land (it is offshore), or for fertilizer or freshwater (it uses nutrient-rich municipal wastewater currently discharged into the ocean).

The goal of the NASA OMEGA project is to demonstrate the feasibility and scalability of the OMEGA system with respect to the associated biology, engineering, economics, and environmental impact. The system represents an "ecology of technologies" in which "wastes" become resources, local energy sources are utilized, and compatibility with the environment is an essential part of the system.

On the one hand, the NASA OMEGA project is focused on the challenge of growing sufficient quantities of algae to substitute for fossil fuels and on the other, it is an ecology of technology that seeks to eliminate waste. As a biofuels system, OMEGA focuses on growing algae species with high lipid content for making jet fuels, and rapid growth rates for producing biomass. As a demonstration of technology ecology, OMEGA focuses on using all aspects of its products and processes; the non-oil biomass can be used for fertilizer, animal feed, and specialty algal products. The OMEGA system can grow any desired strain, species, or community of freshwater algae that can utilize wastewater, cope with local ocean temperatures, but that cannot thrive in saltwater. Hence, within these constraints, the OMEGA system can be used for any product or co-product associated with algae farming, in addition to the environmental services mentioned above. The value of OMEGA products and services will depend on local conditions and needs, and a host of down-stream considerations, such as processing requirements, transportation, market considerations and what can be considered secondary consequences: for example, the impact of wastewater treatment on fisheries or health or tourism.

There are no general barriers to installing OMEGA systems in developing countries, provided there is access to saltwater, wastewater, sunshine, and the large quantities of relatively inexpensive materials needed for OMEGA construction (such as plastic, pipes, valves, and moorings). The relevant engineering and fabrication skills are borrowed from the fields of marine engineering, plastics, aquaculture, wastewater treatment, and oil refining. The OMEGA system uses wastewater effluent for the nutrients required for algal growth, which is enhanced by the addition of CO_2. Therefore, if a country has a wastewater discharge into the ocean and a neighboring CO_2 source, such as a near-shore power plant, the OMEGA system can provide advanced wastewater treatment and quantitative capture of CO_2, in addition to the algae products described above. Barriers to OMEGA in developed countries include restricted access to coastal zones and long permitting processes, which may not be problems in developing countries. Furthermore, the wastewater effluent may be higher in nutrients in some developing countries, which increases algal growth rates.



One of many hypothetical offshore photobioreactor designs being evaluated by the NASA OMEGA team

The OMEGA system consists of flexible plastic enclosures with reinforced plastic on the underside and clear plastic on the upper sunny-side. An internal gas-permeable membrane provides a constant supply of CO_2 and regions of forward osmosis membranes concentrate nutrients to stimulate growth and dewater the algae to facilitate harvesting. The OMEGA modules are floating photobioreactors (PBRs), used in either batch or continuous flow modes with inputs of non-saline wastewater and CO_2 along with an inoculum of oleaginous algae. The mature, concentrated algae suspension is pumped back to shore, thickened, dewatered, while the lipids are extracted and converted to fuels. The OMEGA system is focused on wastewater treatment, which includes removing nutrients that contribute to the creation and growth of dead zones as well as heavy metals and other potential toxins adsorbed or degraded by microbes included in the OMEGA biological consortium.

• *Project location:* OMEGA research on the laboratory scale is conducted at NASA Ames Research Center, Moffett Field, CA and at the California Department of Fish and Game in Santa Cruz, CA. The pilot scale testing will be conducted in the San Francisco Bay area, with plans for a site north of Treasure Island, CA.

• *Project budget:* USD10 million from NASA ARMD and USD800,000 from the California Energy Commission

• *Project funding source:* Two separate aspects of OMEGA are funded, one by NASA ARMD (Federal) and the other by the California Energy Commission (State).

• *Runtime/age*: The OMEGA concept originated in 2008, but the currently funded projects began in January 2010 and will be completed by December 2011.

•*Commercialization status:* A "business plan" was developed for Phase I and a "technology transfer strategy" with a commercialization objective is a component of Phase II.

• *Annual biomass yield per hectare:* Estimated 50 to 120 Mg/ha/yr (14 to 33 dry $g/m^2/d$, 365 d/yr).

• *Current/projected surface size:* Experiments with OMEGA modules range from laboratory sizes to a pilot deployment of 1000 m^2. The full-scale system will cover several km^2.

• *Species used:* Initially, *Chlorella vulgaris,* along with the natural community of microbes in wastewater, will be the basis for algae cultivation studies. The OMEGA system has the potential to use any other strains, species, and freshwater algal communities that are appropriate for a given location.

The OMEGA team consists of scientists and engineers from a variety of public and private organization. The team is using an "open source" model to meet their goals and welcomes contributions from colleagues and collaborators with interests in marine biology, ecology, engineering, environmental studies, economics, and public policy. The current project partners are: NASA Ames Research Center, URS Corp, SETI, USRA, Dynamac, the University Affiliated Research Center (UARC), Jacobs Technology, Inc. University of California (UC) Santa Cruz, California Polytechnic San Luis Obispo, Drexel University, California Department of Fish and Game, Hydration Technology Innovations, with consultants and advisors from Scripps Institution of Oceanography and the National Renewable Energy Lab.

ProviAPT: a scalable, light-efficient and robust photobioreactor

The ProviAPT is a flat panel photobioreactor with an efficient use of solar light. The panels are enclosed in a water-filled, outer bag that levels out the daily temperature cycles, thus being suitable for use in a wide range of climatic situations. It is produced from recyclable thin-layer polypropylene and does not require additional support structures. Scaling-up within the capacity limits of the service module is therefore straight-forward, and a production site can be built up very fast and requires little engineering or site preparation. It can be used for cultivating multiple algal species and multiple products. The polypropylene film is the only material in contact with the culture and the reactor can therefore be used with sea water as well as fresh water

The ProviAPT photobioreactor system is being developed by a Belgian chemical company, Proviron in collaboration with Wageningen University, the Netherlands and the Belgian custom-made machinery maker, Matthys nv. The project group is currently being extended with additional industrial and academic partners. The project development privately funded by the industrial partners and supported by the Belgian government through a research and development grant from IWT (*Agentschap voor Innovatie door Wetenschap en Technologie* of Flanders).

The project started in January 2008. Proof of concept has been completed. Proof of principle, including validation from a 500 m^2 pilot reactor plant, operated Belgium, is ongoing and will be completed in 2011. At present, there are no specific plans about the localization of future production sites.

Intended products are both unrefined algal biomass for aquaculture and feed purposes and refined products, such as specialty oils. Proviron is an established supplier of chemicals for the feed market. Oils and delipidized biomass for feed use are main anticipated products from algal biomass.

A number of food, feed and energy applications have been considered with the system. Multiple future products are anticipated, both by production of several species and by developing several refined products from the same biomass (biorefinery).

Laboratory trials have suggested that a photosynthetic efficiency of 5% (sunlight) is achievable with the system, which, at Belgian light conditions, is equivalent to an annual production of 125 ton dry weight/ha.

The water in the surrounding bag is not renewed. Water for the algal cultivation depends on species, currently sea water is used. Membrane technology based water recirculation is being investigated in a new research project.

Nutrients used are currently chemical fertilizers and compressed CO_2, but the use of flue gas carbon dioxide and waste ammonium is being investigated in a new research project.

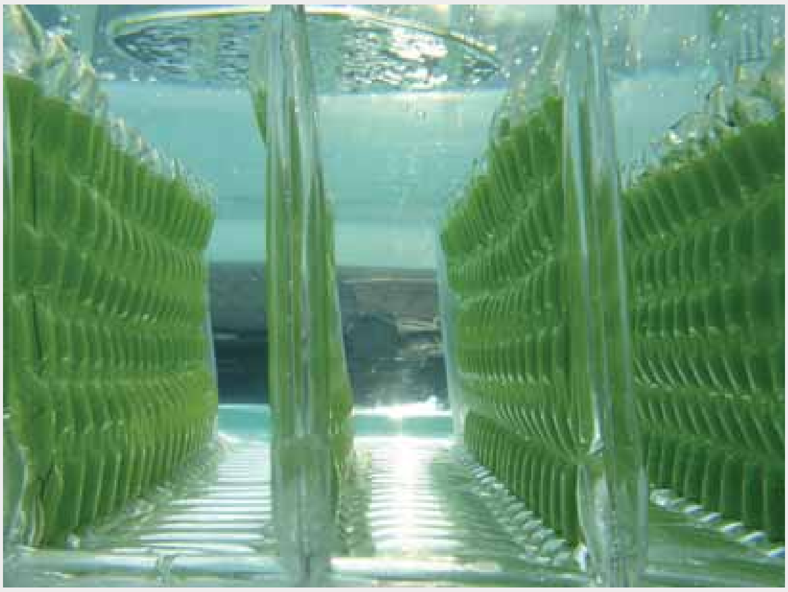
A custom designed polypropylene based film that can be recycled is currently used for the construction of panels and bags. A life time of 3-5 years is expected.

The system is a closely-spaced, flat panel system, keeping light intensities at the surface of the panels at low levels through mutual shading and reflection between the panels which is the basis for obtaining high photosynthetic efficiency values (5% solar). The panels are enclosed in a water filled outer bag, which serves as a heat reservoir, leveling the daily temperature cycles in the reactor (see photos below). The bags are currently being produced on a semi-automated machine in panel widths of 1.5 m. Feeding and harvesting channels are integrated in the bottom of the bag. Feeding and harvesting is carried out by a support unit in a semi-continuous way. One support unit (built in a container) currently serves 500 m^2 of reactor surface. This ratio may be increased 2-10 times. Keeping the aeration costs low is achieved by recirculating the maximum possible air because a lower pressure drop for recirculating air as opposed to freshly aspired air is required. Also, the height of the panels is kept low (< 0.5 m) to obtain low pressure drop on the aeration air. System oxygen and carbon dioxide is measured by the support unit, but no additional data collection is required from the reactors.

The system has been tested with the strains *Nannochloropsis oculata, CCAP 849/1* and *Phaeodactylum tricornutum, Utex 640* and un-interrupted production cycles of 6+ months have been experienced with these strains. Winter production with both species was tested. *Phaeodactylum* thrives at temperatures about 0 °C, whereas *Nannochloropsis* requires heating when ambient temperatures are below 15 °C.

It is the experience so-far that the algal production in the ProviAPT module has been robust once the culture has been established in the reactor and in principle the system would be well suited for implementation in developing countries where high solar irradiation is found alongside with scarcity of water.

The system is at present time not ready for routine production and a period of 3-4 years before it is sufficiently well tested for implementation elsewhere, including remote developing countries, is expected. The system requires a relatively flat surface area. For establishing the system in developing countries, a special concern is the recycling of the plastic material.



Experimental module of ProviAPT reactor, Algal species: Nannochloropsis

Seaweed cultivation, Peru

Brown seaweed (also known as kelp) has a long history of use in Peru, but only based harvesting natural sources. Over-exploitation of natural beds in recent years has led to a reduced seaweed population. This project is the first to cultivate brown seaweeds cultivation project in Peru. The project is coordinated and executed by Peruvian Seaweeds SRL, a company specialized in biotechnology, added value generation and commercialization of seaweeds products in Peru. The main goal of the project is to implement the culture technology for brown seaweeds considering the specific local natural conditions and to contribute to the sustainability of Macrocystis spp supply as raw material, mainly for the production of an organic agglutinate, attractant and bio-stimulant used by aquaculture feed industry.

The main motivation for developing this project was to assure in the mid long term the availability of raw material from this species without depending on the natural biomass offer. Starting in 2006, a massive overexploitation of natural beds occurred, due to the lack of control, management, regulations and ecological knowledge on seaweeds exploitation. As a consequence, a massive arrival of foreign companies in the alginate industry generated important social, environmental and ecosystem damages.

The primary target products with the cultured biomass obtained are nutritional supplements for the aquaculture feed industry, secondary options are the production of different seaweeds extracts, biogas or bioethanol. Besides, the culture itself could be used as a biofilter in coastal marine areas contaminated by mining or wastewater effluents.

The Macrocystis spp. or giant kelp culture is developed in two main stages. The first stage is carried out under controlled conditions (see figure below), where rope-attached zoospores grow until the sporophyte stage.

Hatchery under controlled conditions

Subsequently the ropes with the juvenile sporophytes are transferred to natural conditions.

Once the ropes are attached in a suspended long line system, they stay at this pre-stage nursery for 1 or 2 months depending on the season, until they reach an average of 10 cm size. For the second stage, the seaweed is transferred to the final culture ropes until harvest (Fig. 2).

Growing Macrocystis on a long line system

The expected production is 300 - 400 wet tons/ha/year. The project is funded by the Science and Technology Program of the Presidency of Ministries Cabinet, the Inter-American Development Bank (IADB) and Peruvian Seaweeds SRL. The total budget is USD 150.000.00. This funding covers the experimental and pilot culture (1 Ha). Kelp culture project is developed by Peruvian Seaweeds SRL with the collaboration of the Agronomic University La Molina. The runtime of the project is two years started in October 2008.

The only barrier for the kelp culture would be the resource geographical distribution and appropriate natural conditions for the species. To develop this project in a different region, coastal zones research with specific characteristics should de carried out first.

SunCHem: hydrothermal biomethane production, Switzerland

The SunCHem project aims at developing an innovative process for the production of bio-synthetic natural gas (BIO-SNG) via hydrothermal processing of algal biomass. As depicted in the simplified scheme below, the SunCHem process consists of two parts. The first part is concerned with the production of biomass using microalgae. Microalgae growing in photobioreactors or raceway ponds fix CO_2 and transform it into biomass through photosynthesis. Next, the biomass slurry is dewatered to about 20% dry matter and the nutrient-rich water is recycled back into the process. The biomass is then fed into the second stage of the process where it is gasified to methane (BIO-SNG) through hydrothermal treatment. Other types of biomass, such as manure, sewage sludge, seaweeds can also be process as long as they are pumpable. Hydrothermal treatment is performed at temperatures between 300 and 450°C and pressures between 20 and 30 MPa using water as the reaction medium. The nutrients contained in the biomass are separated and recovered in the hydrothermal step. Together with the CO_2 produced, they are recycled back into the algal production process. Alternatively, the CO_2 can relatively easily be sequestered to underground storage as the CO_2 stream after the hydrothermal treatment is at a pressure of 30 MPa and pure. 55-70 % of the energy content of the feedstock is recovered in the final product gas (based on the lower heating value of the biomass and the product gas). This value takes in account the energy required to provide the process heat as well as the energy to pump the biomass slurry up to 300 bars. Gas composition depends on the biomass composition but is usually in between 50-60% CH_4 and 40-50% CO_2 in the raw product gas. The coupled co-production of fine chemicals can be a value-adding option.

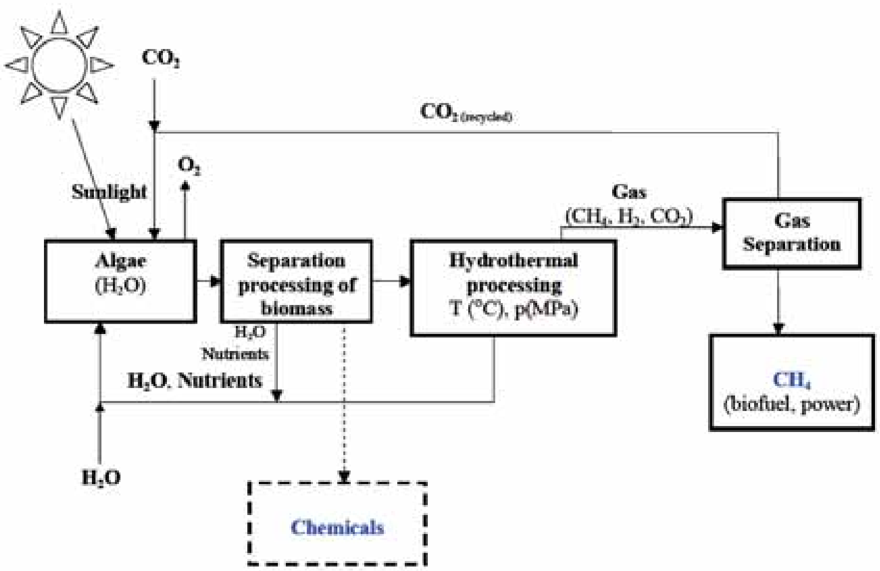


Figure 1. Simplified scheme of the SUNCHEM process for the production of methane (and fine chemicals) using microalgae.

The main advantages of the SunCHem process are:

- No drying of algal biomass is required. Dewatering up to 20 wt. % TS is sufficient. The dewatering technology is not yet fixed, but a combination of filtration with centrifugation is expected (depends on the algal species used in the process).

- Full conversion of algal biomass during the hydrothermal gasification process.

- Residence times during algal biomass conversion in the order of minutes.

- No use of solvents or other chemicals in the downstream processing (biofuel production).

- Clean energy carrier: Nitrogen and sulphur in the biomass stays in the water phase. There is no production of NO_x and SO_x during the fuel burning process.

- Limited resources such as phosphor and water are recovered and reused in the microalgae production process and not lost or evaporated during the production process of the fuel. SunCHem is a closed loop process.

Bio-synthetic natural gas (BIO-SNG) can be used for transport, heating and power production. The widely available natural gas grid infrastructure can be used for BIO-SNG distribution and storage. Possible co-products are high-value algae-based chemicals and a concentrated CO_2 stream. The focus lies on BIO-SNG production. The current calculated cost is anticipated to be around 0.66 €/kWhBIO-SNG. Presently natural gas is sold at around 0.06 €/kWhTH in Switzerland. In the future an SNG price of 0.14 €/kWhBIO-SNG may be achieved with open/raceway ponds if algal productivity and harvesting increases very significantly. In countries with lower labour costs than Western Europe, lower production prices may be achieved. The price to process one energy unit of microalgae through hydrothermal gasification amounts to around 0.0225 €(kWhTH) The remaining costs are due to biomass production, dewatering, labour, overheads…etc.

An inherent feature of gaseous fuels is that the distribution systems and technology with high efficiency and low impact on the environment are available, or in development: Gas combined cycle power stations approaching 60 % of electric efficiency, gas engines, fuel cell systems for decentralized combined heat and power production with electric efficiency well above 40 %, advanced concepts for gas engines for CNG (compressed natural gas) vehicles all share high efficiency coupled with very low emissions of atmospheric pollutants.

As an example, current results show that using the SunCHem process, a land area of 1 m^2 in Jerez (Spain) could produce an average of 1.89 kg SNG per year. This represents a potential range of 35.5 km with an average CNG (compressed natural gas) car. To meet the mobility requirements for the entire car fleet in Switzerland, assuming that it is only composed of average SNG (synthetic natural gas) cars and the climatic conditions are constant, a plant with a surface of 2080 km^2 with 1540 km^2 covered by ponds would be required. Compared to the size of Spain, i.e. 505.000 km^2, this would represent 0.41% of its total surface.

In developing countries, the substitution of wood by algae derived BIO-SNG as a cooking fuel, avoids deforestation and reduces significantly the emission of fine particle and other cancer-causing products during the cooking process in rural areas, but skilled engineers and operators are necessary to run the installation.

The intended water sources for the SunChem process are ideally brackish water and "the possible" make up nutrients should come from nutrient rich flows (such as wastewater).

Hydrothermal gasification is not dependent on the microalgae species. The requirements are solely focused on the areal productivity and carbon fixing efficiency of the organisms. High carbohydrate fraction may be an advantage.

The 2-part SunCHem project is located in Switzerland, 1st part running from 2007-2010 and with a budget of 500.000€, the 2nd part running between 2010 and 2013 on 3.000.000€, funded from both private and public sources. The project partners involved are: Paul Scherrer Insitute (PSI), Swiss Federal Institute of Technology at Lausanne (EPFL), Zürich School of Applied Sciences (ZHAW), Swiss Institute for Materials Science and Technology (EMPA), Subitec (GmbH).

Sustainable Fuels from Marine Biomass (BIOMARA), UK and Ireland

Co-ordinated at SAMS, Scotland, the Sustainable Fuels from Marine Biomass project, BIOMARA, is a 6 million Euro UK and Irish joint project aiming to demonstrate the feasibility and viability of producing third generation biofuels from marine biomass. This case study outlines the macroalgae and anaerobic digestion part of the BIOMARA project only. BIOMARA also has a microalgae and biodiesel research strand. Large brown macroalgae (kelps) can be cultured and naturally grow very fast in easily accessible coastal locations. They can potentially be used as biofuel. The most obvious route for the conversion of macroalgae to fuel is via anaerobic digestion (AD) to produce methane. They can also be fermented to produce ethanol. With no lignin and little cellulose, they provide better material than land plants for complete biological degradation via AD to methane, figures from the literature indicate methane yields of $0.27 m^3 kg^{-1}$ of volatile solids. AD systems are now in place at SAMS and the methane yield from seaweeds grown locally is being quantified. Seaweed cultivation is well established at SAMS in Scotland. Spores are germinated in laboratory conditions to form tiny plants, which are transferred to sea and then harvested 6-8 months later, thus generating the biomass for anaerobic digestion or fermentation to produce ethanol.

The primary aim of this part of the BIOMARA project is to further develop our knowledge and understanding of how the selected species of macroalgae perform in modern AD systems. The primary product is therefore biomass for AD to methane or biogas. However, other research projects are planned to run in tandem with the culture effort and examine high-value end products from the seaweeds including fucans, fatty acids and vitamin E. Methane yield from the residual biomass pre- and post extraction of these more valuable products will be compared. The resulting digestate will be used as organic fertiliser, an increasingly valuable commodity given the high price of chemical fertilisers. There are no specific barriers for developing countries other than the availability of suitable macroalgal species that can be grown in bulk; i.e. the species they are concentrating on are the temperate-water large brown kelps.

The cultivation system used to grow the seaweeds is similar to that for commercial mussel culture in Scotland: a horizontal long-line system from which strings bearing the culture plants are vertically suspended. This is similar to the system used in China for the culture of *Laminaria japonica*, the world's largest aquaculture crop by volume. Presently our seeded ropes are suspended vertically from depths of 2–8 m in inshore waters to allow easy access. In future, if cultured kelps is to make a significant contribution to energy then large farms further offshore are envisaged. The cultures require fully salinity and high water exchange (a tidal stream as opposed to breaking waves). The nutrients come from the surrounding seawater; they have cultured seaweeds alongside salmon cages to examine the bioremediation potential and to examine whether the seaweeds benefit from the extra available nutrients. The answer is yes, if / when background nutrients are limiting. As the cultures are small scale at present, they are harvested by hand. In the larger scale cultures (1 ha) planned, harvesting will be mechanised using a mussel farm harvest barge.

Germinating macroalgae (approx 2mm) on the strings ready for outplanting

The previous culture data suggests that production from research scale can be scaled up (1 ton max) to 200 tons wet weight per ha. The species in use are *Saccharina latissima*, *Sacchoriza polyschides* and *Alaria esculenta*. SAMS are developing a proposal for a pilot scale (1-5 ha) macroalgal farm near Oban.

Cultures of Saccharina latissima, Scotland

The project is co-ordinated by SAMS, Argyll Scotland, with partners in the Republic of Ireland and Northern Ireland; The Centre for Renewable Energy at Dundalk Institute of Technology (CREDIT), Ireland; University of Strathclyde, Glasgow, Scotland; Centre for Sustainable Technologies, University of Ulster, N. Ireland; Institute of Technology, Sligo, N. Ireland; The Questor Centre, The Queen's University Belfast, Northern Ireland.

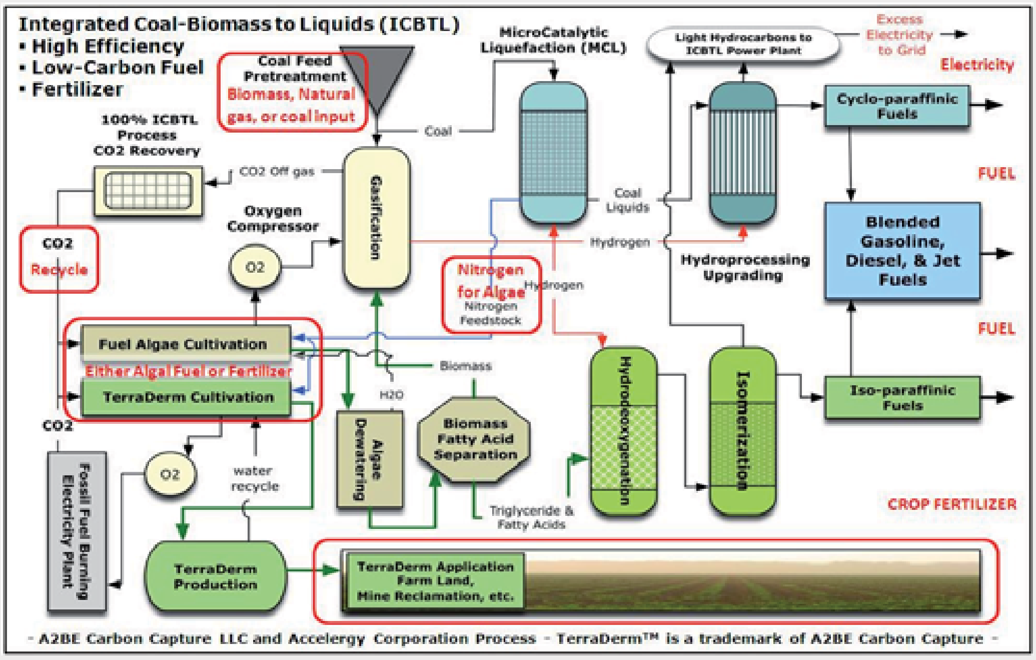
The total project budget for all partners and both research strands (macro- and micro- is 6 million Euro), the funding comes from the European ERDF fund Interreg programme, with additional funding from Scottish Government, Highlands and Islands Enterprise and The Crown Estate. This four year project started in 2009.

TerraDerm: algae based CO_2 recycle for fuel and fertilizers

A2BE Carbon Capture LLC of Boulder, Colorado and its partners are developing a sustainable low-carbon transportation fuel process that can further offset the fuel's CO_2 emissions via co-production of a unique living fertilizer. This algae-based fertilizer "TerraDerm" is produced using the CO_2 emissions of the biofuel production process. When applied, TerraDerm draws CO_2 directly from the atmosphere while improving soils. This technology is scalable and will allow countries with native access to biomass, coal or natural gas feedstock to become independent producers of transportation fuels and natural agricultural fertilizers while dramatically limiting their total CO_2 emissions and potentially earning significant CO_2 credits.

The process converts almost any carbon containing material to high quality fuel including Jet-Fuel using an ultra-high efficiency, Exxon developed, non-Fischer-Tropsch process that is exclusively licensed to Accelergy Corporation. Accelergy thereon has an exclusive relationship with A2BE Carbon Capture to recycle the remaining CO_2 process emissions using A2BE's algal cultivation technology that features scalable, low-water consumption, passively cooled, high productivity closed photobioreactors.

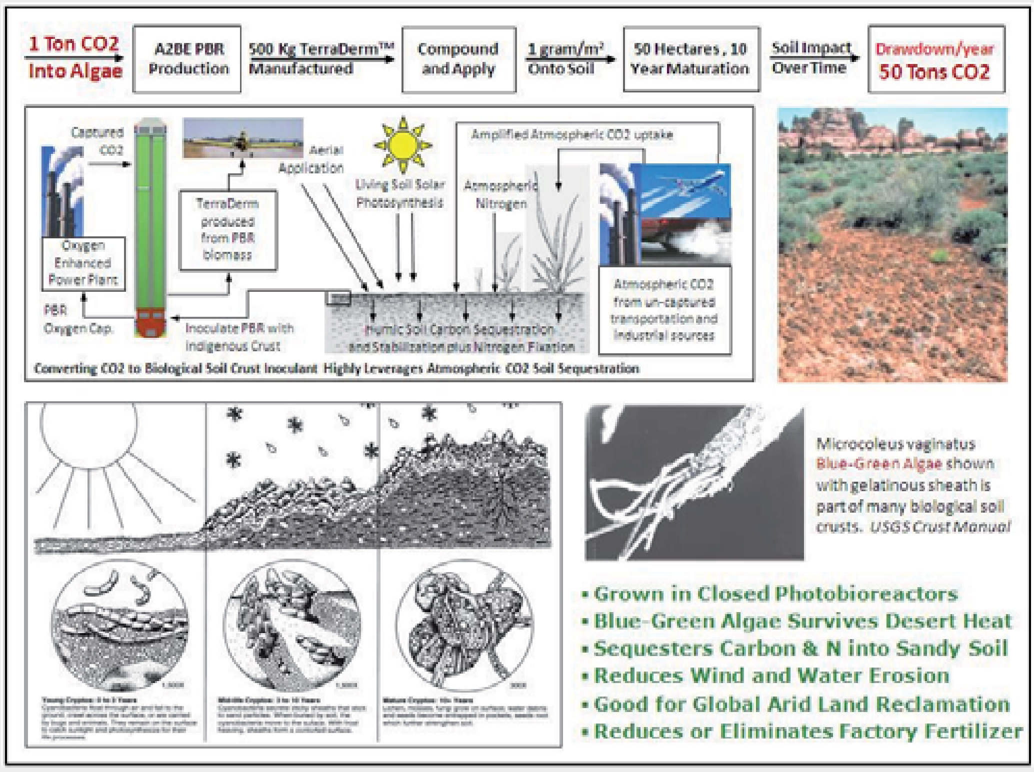
The combined process has not yet been installed at an operational site nor has all the technology been completely proven. However, significant US public and private funding is being focused on completing development of this specific combination of technology. The State of Pennsylvania is currently commissioning a study of the application of this technology in their state.



This diagram illustrates the combination of the best-in-class carbon-to-liquids technology with what is expected to be the best-in-class industrial algal cultivation technology being developed by A2BE. The resulting fuel will have a 20% lower carbon lifecycle emission that fossil oil based fuels allowing large scale ICBTL production globally. Even greater lifecycle CO_2 emission reductions result from TerraDerm.

Process CO_2 can be used to produce TerraDerm, a living soil fertilizer that not only sequesters CO_2 into the soil as in bio-char but that goes vastly beyond biochar as TerraDerm restores natural photosynthetic soil crust colonies that draw CO_2 and nitrogen directly from the atmosphere via photosynthesis. When tilled or damaged arid soils are treated with photobioreactor grown TerraDerm, then soil fertility and erosion stability are improved and the requirement for factory fertilizers can be eliminated or reduced.

The process shown below is in the development phase but significant partners such as Battelle Labs, Raytheon Corporation, and the Colorado School of Mines are joining A2BE in moving to demonstrate the fundamental technology. As shown in the diagram below, converting 1 ton of CO_2 into TerraDerm and applying it to damaged land is expected to induce a resurgence of restored natural biotic soil health over a period of years that can result in 50 tons of CO_2 being naturally drawn into the soil each year via restored natural process alone.



While biochar involves tilling approximately 1 kg of biologically inactive carbon into each square meter of soil, TerraDerm is a living indigenous-sourced cyanobacterial based re-inoculant sprinkled onto the soil surface by aircraft at the rate of only 1 gram per square meter. Even infrequent desert rains should be sufficient to re-propagate these naturally adapted soil microorganism consortia that use photosynthesis to continuously feed nitrogen and carbon based nutrition to the subsurface soil biota. The photosynthetic cyanobacteria surface layer feeding of these crypto-biotic sub-surface microorganisms is essential for overall soil health and the eventual establishment of vascular plants like grasses and shrubs that can then take over the sub-surface feeding by nourishing nitrogen fixing diazotroph species of soil bacteria. The results of this experimental soil crust re-inoculation approach may vary in different soils and climatic conditions. However, the CO_2 and nitrogen drawdown from the atmosphere is expected to be a continuous process over many decades leading to permanent improvement of the "soil net primary productivity" as long as the soil is not re-damaged by subsequent unsustainable land use such as overgrazing. Roughly 1 billion hectares or 1/7th of global landmass may be a candidate for this type of soil restoration. TerraDerm application as a replacement for factory fertilizer is being aggressively studied as well as how to qualify its carbon drawdown capability for carbon credits.

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ENVIRONMENT – CLIMATE CHANGE – BIOENERGY – MONITORING AND ASSESSMENT

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The possible competition for land makes it impossible to produce enough first generation biofuel to offset a large percentage of the total fuel consumption for transportation. As opposed to land-based biofuels produced from agricultural feedstocks, cultivation of algae for biofuel does not necessarily use agricultural land and requires only negligible amounts of freshwater, and therefore competes less with agriculture than first generation biofuels. Combined with the promise of high productivity, direct combustion gas utilization, potential wastewater treatment, year-round production, the biochemical pathways and cellular composition of algae can be influenced by changing cultivation conditions and therefore tailored on local needs. On the other hand, microalgae, as opposed to most plants, lack heavy supporting structures and anchorage organs which pose some technical limitations to their harvesting.

The reasons for investigating algae as a biofuel feedstock are strong but these reasons also apply to other products that can be produced from algae. There are many products in the agricultural, chemical or food industry that could be produced using more sustainable inputs and which can be produced locally with a lower impact on natural resources. Co-producing some of these products together with biofuels, can make the process economically viable, less dependent from imports and fossil fuels, locally self sufficient and expected to generate new jobs, with a positive effect on the overall sustainability.

This document provides an overview of practical options available for co-production from algae and their viability and suitability for developing countries.




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