Energy From Algae

PRESENT & FUTURE

BioPlat

SPANISH BIOMASS TECHNOLOGY PLATFORM

UNION EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL

GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA E INNOVACIÓN

Thank you

This document has been created by the initiative and work of a group of entities, and great experts who constitute them, which have made possible its existence. It's a singular document for both, its contents: Algae for energy production, the roadmap needed to reach its efficient development in Spain and the first inventory of the Spanish projects, and for being the first document created under the consensus among all the members of this incipient bioenergy sector that has been published in our country.

The link of the concepts: Algae and strategic, came spontaneously from the Spanish Ministry of Science and Innovation, from where was boosted the creation of a sub-working group within the structure of BIOPLAT, with the objective of bringing together the agents of the science-technology-enterprise system, which sets a new force due to the crescent number of agents and to their projected initiatives. The valuable collaboration of IDAE (Spanish Ministry of Industry, Tourism and Commerce) since the launching of the sub-working group has implied an important support to fulfill the initially proposed objectives. Thank you both entities.

It has been decisive for the correct development of the work in the BIOPLAT's Algae sub-working group, the election by the own members of the sub-working group of its Coordinator, Jorge Sánchez Almaraz (AURANTIA), who has the ability to lead it with enthusiasm, good sense and perseverance, hallmarks of his great career. Thank you so much Jorge, and also thanks to the self named "editor team" of this document Gabriel Acien (University of Almería) and Miguel de la Parra (ACCIONA ENERGÍA), for working with such a dedication and good criteria all over the document, giving shape to the important contributions made by the expert members of the BIOPLAT's Algae sub-working group, without their support and constant participation it wouldn't have been possible to make real this document. In addition highlight the dedication of Alfonso Calvillo, Advisor of the Secretariat of BIOPLAT. Many thanks to all of you.

And a special acknowledgment to Guillermo García-Blairsy Reina (Las Palmas University), Spanish scientific pioneer in the algae sector, who kindly gave to BIOPLAT his exceptional knowledge of the algae, as well as a bit of his soul, that can be found in these lines.

MARGARITA DE GREGORIO.

MANAGER - BIOPLAT SECRETARIAT

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Executive Summary

This document is a guide to help steer and facilitate technical discussions on a R&D&i strategy for the production of biomass as an energy source through the cultivation of algae. Such a strategy would need to meet a series of basic requirements in terms of sustainability, economic factors and scale.

Biomass is a source of renewable energy that will play a key role in meeting the energy targets set for both Europe and Spain. European Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources sets the following medium-term goals (to be achieved by 2020):

- Reduce greenhouse gas emissions by 20% by 2020 (compared with 1990 levels).
- Increase energy efficiency by 20%.
- Use renewable energies to source 20% of Europe's total energy production.
- 10% of energy used by the transport sector to be from renewable energy sources.

Achieving these targets will lead to energy diversification and decreased dependence on energy imports, as well as energy savings and reduction in greenhouse gas emissions. Algae could play a very important role in achieving these goals, albeit in the long term, as research and technological development tasks still need to be carried out before the technologies will be ready for large-scale commercial development.

Algae are a very diverse group of photosynthetic organisms that have colonised a wide range of different water and land ecosystems thanks to their high plasticity and metabolic diversity. A lot of work needs to be done to explore the hugely diverse nature of algae species, as 90% of the estimated 100,000 or so different species that exist still need to be studied. This new sector offers a series of potential benefits (high photosynthetic efficiency, ability to cultivate algae in seawater and wastewater, use of excess CO_2 produced by industrial activities, etc...), which are not offered by conventional biomass production

Cyanobacteria and microalgae cultures enriched in laboratory in different culture mediums.
Photography courtesy of Marine Biotechnology Centre, University of Las Palmas de Gran Canaria - National Algae Bank.

cultivation techniques and technologies. Above all, algae fuel could make it possible to meet the targets set and still achieve a positive energy balance.

In order to produce algae for fuel successfully and sustainably, Spain needs to develop a national R&D&i plan and commit to funding that plan in the long term. The plan must focus on achieving three key aims: a positive energy balance, a positive ecological balance, and economic competitiveness with conventional fossil fuels. By meeting these targets, the plan could receive a similar level of support for development as that given to other renewable technologies.

As such, research and development must be promoted through collaborative work by scientists and technologists from different fields as well as companies involved in the sector. It is only through integrated research connecting the laboratory scale to the industrial scale, and with contributions from research groups and companies, that any decisive step forward will be made in the road towards obtaining biofuels from algal biomass. Whatever the design of the collaborative model drawn up, it would be advisable to set up a technology coordination centre for R&D&i in algal biomass where the majority of the work could be carried out.

IN ORDER TO PRODUCE ALGAE FOR FUEL SUCCESSFULLY AND SUSTAINABLY, SPAIN NEEDS TO DEVELOP A NATIONAL R&D&I PLAN AND COMMIT TO FUNDING THAT PLAN IN THE LONG TERM. THE PLAN MUST FOCUS ON ACHIEVING THREE KEY AIMS: A POSITIVE ENERGY BALANCE, A POSITIVE ECOLOGICAL BALANCE, AND ECONOMIC COMPETITIVENESS WITH CONVENTIONAL FOSSIL FUELS. BY MEETING THESE TARGETS, THE PLAN COULD RECEIVE A SIMILAR LEVEL OF SUPPORT FOR DEVELOPMENT AS THAT GIVEN TO OTHER RENEWABLE TECHNOLOGIES.

Developing these programmes could lead to the emergence of a new bioindustrial sector linked to the production of foodstuffs for human consumption, animal feeds, aquaculture, pigments, dermocosmetics, nutraceuticals, biomedicine, treatment of pollutant gases and water, the climate change industry, etc… In fact, it is more than likely that these new bioindustries will need to be developed to make the production of algal biofuels cost-effective. As such, applying the biorefinery concept will be essential if these processes are going to become economically viable.

It is clear that producing algal biomass as an energy source is a scientific reality of great potential and that further research and development needs to be carried out in order to turn it into an industrial reality. Below is a list of proposed aims that should be met so that the cultivation of algae for fuel can fulfil its potential:

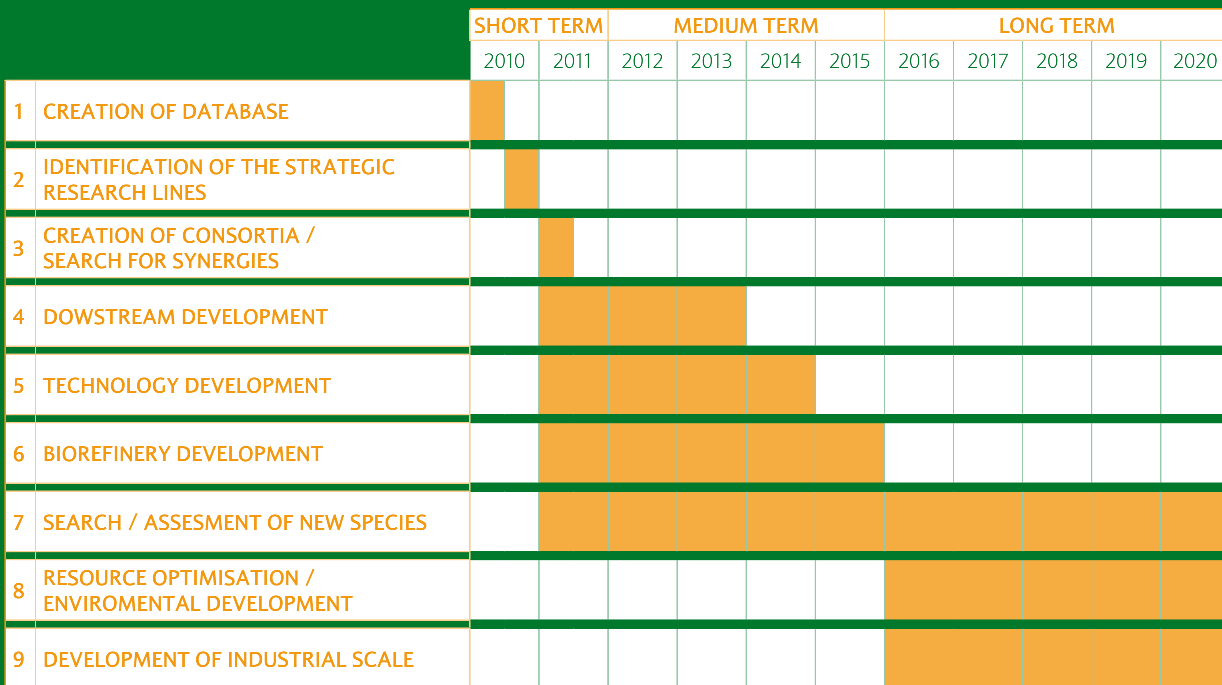
- Creation of a database of projects already underway. The appendix to this document contains a preliminary list of national projects, drawn up by BioPlat.

- Report on technologies under development and existing facilities.

- Identification of technological barriers. This process should include the following phases:
  - Obtaining the best species of algae.
  - Developing cultivation technologies: striving for increased production, energy efficiency and improved materials.
  - Developing downstream processes (harvesting and processing): preconcentration, dehydration, drying and oil extraction processes and complete biomass recovery.

- Identification of the areas that require the most work (both technologically and economically speaking), in order to reduce costs and adapt most effectively to conditions in Spain.
- Scalable demonstration with large-scale vision.
- Study of environmental synergies.
- Inclusion of algae energy in the national renewable energy policy framework.

A fixed timescale for the plan's execution should be set out. A proposed timescale is outlined below:



1

Introduction

Biomass is a key source of renewable energy for the fulfilment of the energy objectives set in both Europe and in Spain. These objectives focus on the diversification and the reduction of the dependence on external energy sources, and on energy saving and the reduction of greenhouse gas emissions.

In Spain, biomass contributes significantly to the total renewable energy targets. According to the Spanish Renewable Energy Plan (PER) 2005-2010, bioenergy should constitute almost 60% of the global renewable energy contribution of 12.1% of the consumption of primary energy by the end of 2010.

In the medium term (by 2020) the new European Renewable Energy Directive 2009/28/EC proposes the following targets:

- 20% reduction in the emission of greenhouse gases by 2020 (compared with 1990 levels).
- 20% increase in energy efficiency.
- 20% of total European energy production to come from renewable sources.
- 10% of total energy consumed by the transport sector to come from renewable energy sources.

Technical development, enhanced energy efficiency, the reduction in production costs of biomass products, the development and implementation of sustainability criteria and the efficient application of measures to foster the use of biomass, will be decisive in the development of this energy source.

This document aims to serve as a guide to broach and facilitate technical debate on a R&D&i strategy devoted to the production of biomass for energy purposes through the cultivation of algae, meeting the basic requirements of sustainability, economy and scale.

The role that algae could play in the fulfilment of the objectives set for the production of renewable energy is very important, although its participation will be long term. This is currently a sector with great potential, but is at the stage of research and technological development prior to large-scale commercial exploitation.

Algae constitute a very diverse group of photosynthetic organisms, which have colonised a wide variety of aquatic and terrestrial ecosystems thanks to their high plasticity and metabolic diversity. Algae can be classified by size into:

- Microalgae: all kinds of prokaryotic and eukaryotic unicellular or filamentous photosynthetic organisms measuring less than 0.02 cm.
- Mesoalgae: prokaryotic and eukaryotic unicellular, filamentous or colonial, unialgal or plurialgal photosynthetic organisms ranging between 0.02 and 3 cm. The significant differences in terms of technologies and harvest costs make the introduction of this new term advisable.
- Macroalgae: pluricellular algae of various shapes and sizes, ranging from a few centimetres to several metres in length.

It is estimated that there are from 30,000 the 100,000 species of microalgae including both eukaryotic and prokaryotic representatives (cyanobacteria or blue-green algae). Moreover, it is estimated that there are around 15,800 species of macroalgae divided into red macroalgae (6,000 species), brown (1,800 species) and green (8,000 species of which 1,000 are marine species and the rest freshwater).

Algae have been eaten by people in Eastern countries for thousands of years, and only in the last century has intense research been carried out leading to a diversification in the use of algal biomass, for example:

- Phycocolloids: agar (agaroses) carrageenans, alginates, species of *Ulva*.
- Animal food.
- Bio-fertilisers.
- Bioremediation agents.
- Secondary metabolites (biomedicine).
- Simple molecules with high energy content: ammonia, methane, hydrogen and alcohols.
- Essential fatty acids (long-chain PUFAs).
- Exopolysaccharides.
- Antioxidants.
- Pigments.

All these advances have been made in the sphere of phycotechnology, considered a branch of biotechnology that takes sea vegetables as its main object of interest and which integrates phycology and technology (including the latest advances in cellular and molecular biology, chemical engineering, mariculture and other related disciplines) with specific commercial ends[1]. The phycotechnology concept includes a considerable number of large-scale bioprocesses, which range from open systems with natural light to heterotrophic crops in closed fermenters.

The production of microalgae for human consumption began about 30 years ago, with a worldwide production of around 500 tonnes at the end of the eighties. The current world production – for both human and animal consumption – is around 10,000 tonnes per annum (*Spirulina, Chlorella, Dunaliella* and *Haematococcus*). In terms of biomass for biofuels, the current production of microalgae in very small, although in the light of the above example, the potential is enormous. The production of macroalgae is exponentially greater, due above all to the importance of the phycocolloid and food-grade algae industries. In contrast to other types of biomass, energy production is not the main purpose; it is the minority use of algae (larger quantities are used to produce food, cosmetics, etc.).

According to various references, the current of production costs of microalgae vary between 10 €/kg (raceway) and 35 €/kg (closed photobioreactor). It is estimated that the production of macroalgal biomass oscillates between 0.05 €/kg (near the coast) and 0.40 €/kg (in open seas), indexed to weights of dry biomass.

Until recently, phycotechnology (phycology applied to marine agronomy in general) was limited to small groups of scientific researchers. However, during recent years announcements of projects related to algal biotechnology have grown exponentially. The cause of this change is to be found in the advantages (still potential) of this new sector in comparison with conventional crops and technologies for biomass production and, above all, in the possibility of achieving these objectives with a positive energy balance. The proof of the expectations this new technology is awakening is that major international companies and departments of defence, energy and the environment of leading countries are making significant investments in applied phycology and are beginning to form joint ventures[2].

Irrespective of whether the final objective -to produce competitive biofuel- is achieved or not, the development of these programmes will boost the emergence of a new bio-industrial sector related to the following: the production of food for human consumption, animal fodder, aquaculture, pigments, dermo-cosmetics, nutraceutics, biomedicine, treatment of pollutant waters and gases and the climate change industry, etc. It is more than probable that these new bio-industries will have to be developed as an indispensable complement in order to attain profitability in the production of biofuel from algae. In other words, they are a prerequisite and not a case of "collateral profits".

AT PRESENT WE ARE CONSUMING FINITE FOSSIL FUELS, WHICH CAN ONLY BE REGENERATED OR REPLACED IN VERY SMALL QUANTITIES.
THE DEPLETION OF THESE FOSSIL FUELS, WHICH ARE PRODUCTS DERIVED FROM THE REMAINS OF MASSIVE BLOOMS OF MARINE ALGAE THAT LIVED MILLIONS OF YEARS AGO WHEN THE PLANET WAS GOING THROUGH A WARM PERIOD, HAS CREATED THE NEED TO GENERATE NEW ALGAE BLOOMS IN A CONTROLLED MANNER AS A SOLUTION TO THE GLOBAL WARMING GENERATED BY THE USE OF THESE FUELS.

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1 Nonomura´s definition, 1988.

2 In the case of macroalgae, an enormous number of projects are currently arising with energy-related objectives. A few of these are the OCEAN SUNRISE PROJECT (Japan), MACROALGAE FOR CO_2 SEQUESTRATION AND RENEWABLE ENERGY (USA) BIOMARA (Scotland) BIO-OFFSHORE (Holland).

The application of the biorefinery[3] concept is considered essential to ensure the future economic viability of processes based on algae for the production of biofuels. Along these lines, significant efforts in research and development will be necessary in the stages following the harvest of the biomass, and the development of assessment strategies of the same.

In this diagram of a biorefinery proposed by the Energy Research Centre of the Netherlands (ECN), the concept of the process can be clearly seen.

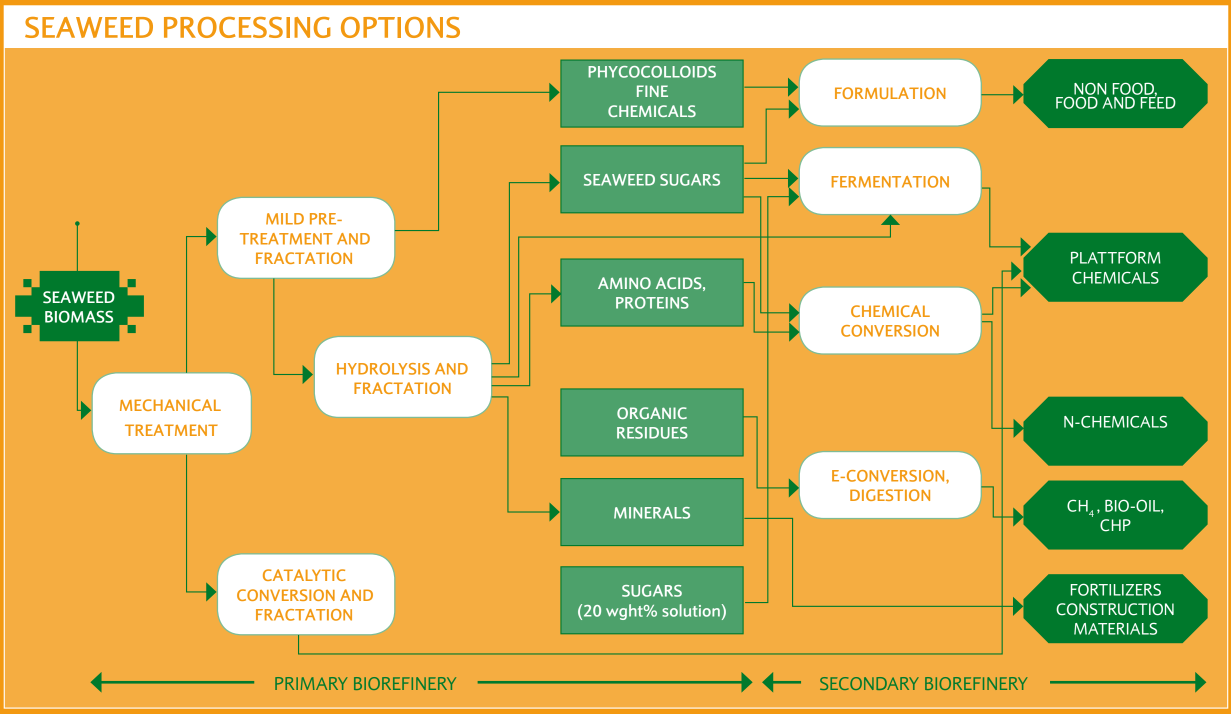
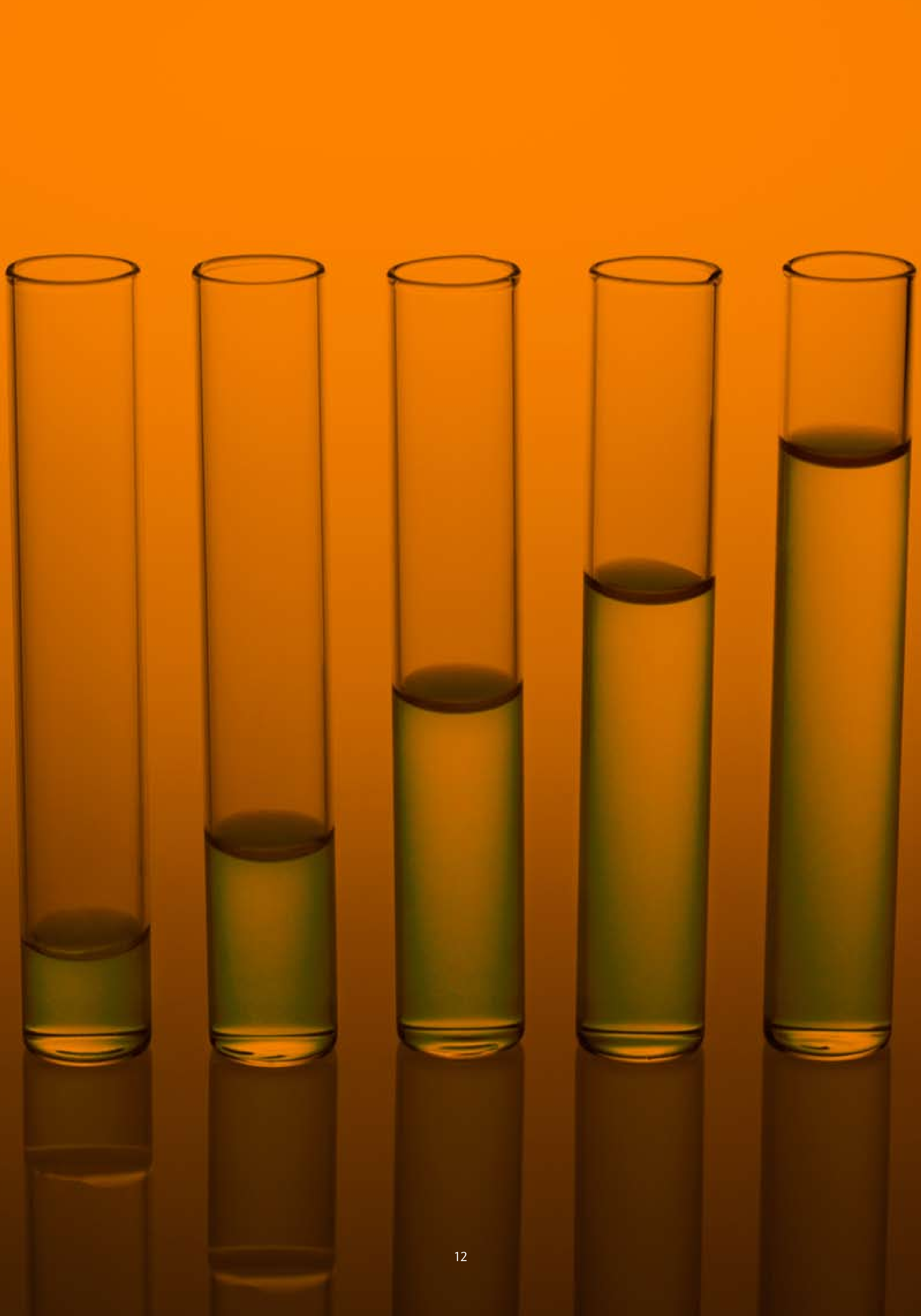


Figure 1, Biorefinery diagram ECN.

Experts in applied phycology are currently focusing on intensifying the establishment of algae production plants to supply these energy needs.

Before looking at the advantages and problems of algal biomass for the production of biofuel, a preliminary strategy proposal should be drafted.

[3] Definition of biorefinery: "Biorefinery is the sustainable processing of biomass into a spectrum of marketable products and energy" International Energy Agency – IEA – Bioenergy Task 42: Biorefineries: Co-production of Fuels, Chemicals, Power and Materials from Biomass.



2

Preliminary Strategy Proposal

Throughout this document the most important conditions and factors to be taken into account in the production of algae are established. In addition, previous experiences carried out worldwide are reviewed in order to obtain lessons learned in order to avoid repeating the same mistakes.

In order to make a significant impact on energy demand on a national or global scale (achieving 1% of current fossil fuel consumption would be a relevant figure), the new algal biomass production systems for biofuel will have to have the following two basic features:

- They must be environmentally sustainable systems: avoiding using fertile land; achieving a positive energy balance (with a balance of greenhouse gas emission carried out using life cycle analysis -LCA- techniques, which permit significant reductions compared to fossil fuels); which do not pollute the environment; with minimum use of fertilisers and minimum water consumption, not using water suitable for human consumption.

- They must be profitable at competitive production costs, at least in the medium and long terms. This implies having a suitable scalable production process, monitoring efficiency within adequate space and time margins (hyper-intensive systems) and ensuring the commercial exploitation of both the process and the product.

Good agricultural practices must also be applied with regards the use of fertilisers due to their energy cost and availability. The use of the so-called integrated systems is an efficient solution: this consists of the use of nutrient-rich effluents as an alternative culture medium, which not only cheapens the production of algal biomass, but also performs an environmental service (wastewater treatment).

2.1. CONCLUSIONS TO PRELIMINARY REQUIREMENTS

Once these preliminary ecological and energy neutral or positive balance requisites have been established, the following options are presented:

- Photosynthetic processes[4].
- In the specific case of microalgae, a selection of suitable areas that combine a high sunshine index and moderate temperature range (preferably average temperatures of between 20 and 35 °C) is necessary, bringing together all the environmental conditions that optimise production.
- Multi-integrated systems using nutrient and CO_2 rich effluents as a culture medium.
- Development of a new agronomy based on species found in marine environments (brackish or hypersaline).

[4] Biomass production technologies based on the (heterotrophic) cultivation of genetically modified bacteria (eg.: *E.coli* generated by the company LS9 (USA) need very specific industrial wastewaters and are only viable on a local scale (in Brazil).

- Utilisation of freshwater, which is unsuitable for human consumption or agriculture. Brackish waters in some aquifers are of this type, as well as waters proceeding from secondary wastewater treatment, water polluted with nitrates and phosphates from agricultural use and even more or less polluted aqueous industrial effluents.

As photosynthetic organisms, the algae fix CO_2, and the massive production of algae requires a supply of CO_2 or of CO_2-enriched air (both as a source of carbon and for the regulation of the pH of the culture medium). The current cost of CO_2 is high, but could be reduced by using alternative CO_2 sources, taking advantage of emission centres of the gas (e.g., energy industry) or the content of effluents from the respiratory activity of bacteria, fish-farms, etc. At all events, the use of algae for the abatement and sequestration of greenhouse gases[5] (CO_2, NO_x) and other residues proceeding from industrial combustion systems are not included in this report.

RECENTLY A LOT OF EXPECTATION HAS BEEN AROUSED WITH REGARD TO ALGAE AS A SOURCE OF BIOFUEL. THE FACT THAT THE AMBITIOUS OBJECTIVES SET FOR PROJECTS IN PROGRESS ARE NOT ATTAINED, SHOULD NOT BE ALLOWED TO SLOW ADVANCES IN THE SECTOR, WHICH IS CURRENTLY IN A PHASE OF RAPID TECHNICAL DEVELOPMENT.

Although the absorption of CO_2[6] is inherent in the production of biomass for energy purposes, apart from the production of hydrogen[7] the process cannot be considered photosynthetic sequestration since the fuel obtained from this biomass will be burned once more (in spite of this, recently there have been cases in which those companies that harness the CO_2 they emit for the cultivation of algae are benefiting from the facility of discounting this harnessing from the declared total of their CO_2 emissions).

[5] There are currently 4 greenhouse gas abatement/sequestration technologies/strategies with micro and mesoalgae:

1. Photosynthetic sequestration.
2. By the induction of oceanic phytoplankton blooms. Although some US companies are developing this line of business (PLANTOS, CLIMOS), lately the effectiveness of the process has been discredited (2009, *Global Biogeochemical Cycles*).
3. By the induction of specific blooms of coocolithophorads (haptophytae, or microalgae with $CaCO_3$ exoskeleton).
4. By catalytic bioprecipitation induced in a liner-pipe (partner patent pending).

[6] As a maximum, 50% of algal biomass (in AFDW = ash free dry weight) is composed of carbon, so that (at an efficiency of 10%) 2.1 kg of CO_2 AFDW of algal biomass would be necessary.

[7] Experiments have been carried out recently, aimed at using macroalgae for the renewable production of H_2, an energy source that does not produce CO_2 as a by-product: Park et al, 2009, *Biotechnology and Bioprocess Engineering* Vol. 14, tried this with *Ulva, Laminaria, Undaria and Porphyra*. The best results were obtained with *Laminaria*.

2.2. PRELIMINARY LEGAL ASPECTS

- The fact that algae can be cultivated both using sea water and residual effluents is one of the main advantages of these organisms. Other advantages that they may possess should be assessed in order to create a strategy to help with research and development. Such support, at least in the initial phases of technological development (the current phase of the algae sector), would ensure greater advances in the field. Possible aid would not constitute the only prerequisite to overcoming the current difficulties, since several scientific and technological obstacles still need to be solved.

- The bases need to be defined for the calculation of energy efficiency and of CO_2 emissions with regards algal biomass production.

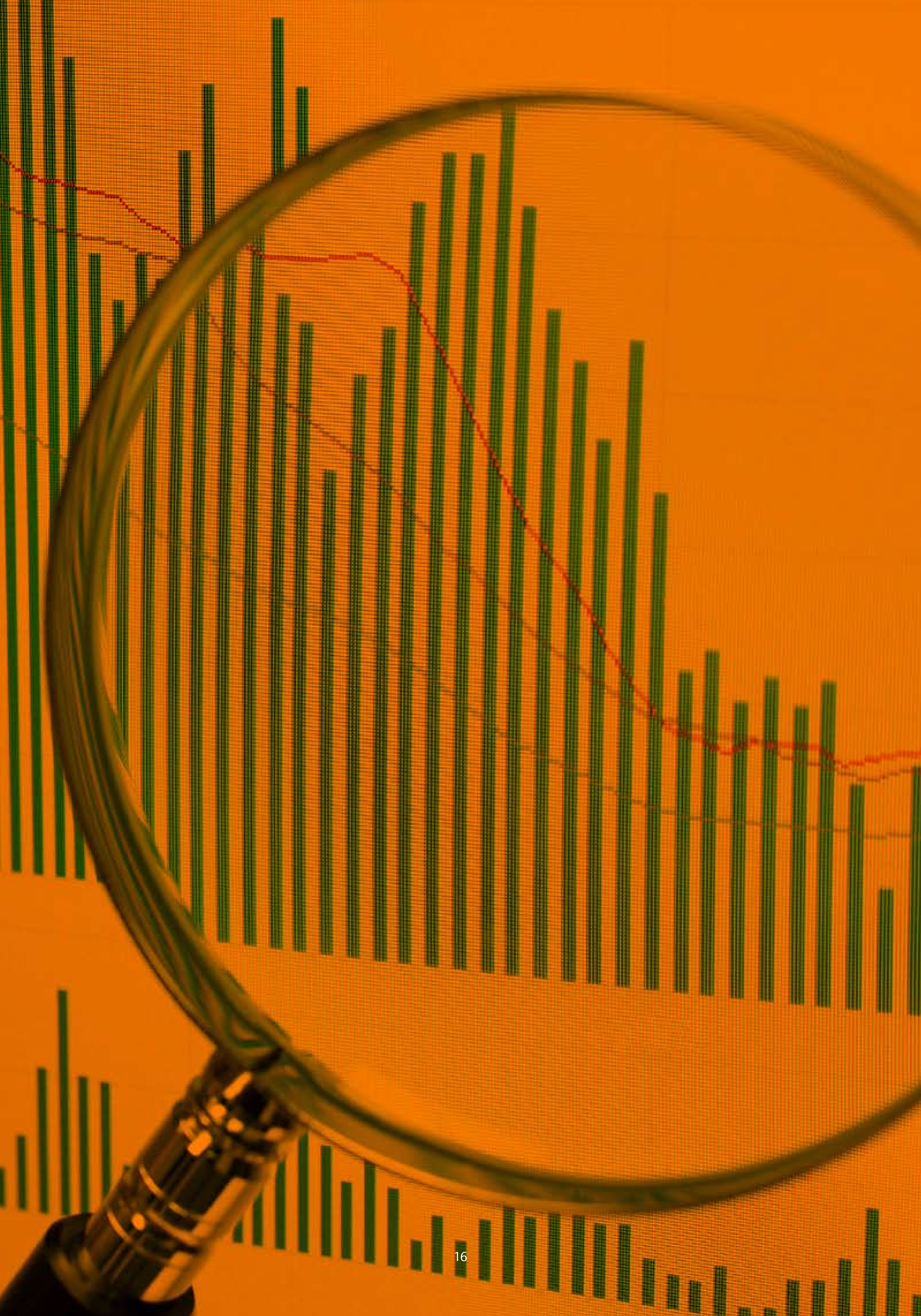
    - Present algae production plants (raceways) absorb between 20% and 50% of the CO_2 injected into the crop, generating an equivalent amount of oxygen.
    - It is vital to ensure a real energy balance (and a balance of CO_2 emissions) during the harvesting, extraction, processing stages, etc.
    - It is very important to analyse the full life cycle of systems based on the production of algae in order to establish their viability and sustainability. In this respect, the recommendations of the Algal Biomass Organization (ABO[8]) may be helpful in the drafting of an analysis of the life cycle of such systems.

- Genetic engineering for algal biomass production is another possible line of research9. However, it will require the establishment of a preliminary legal framework in order to be developed. In parallel with the advances in genetic engineering, the fact that the high functional diversity of algae is still to be explored must be taken into account. Thus, research should not be limited to the investigation of a single exploration route. Nevertheless, advances in molecular biology and, in particular, the complete sequence of the genetic map of various species of algae, opens up new perspectives for biotechnology, such as the obtaining of strains with higher triglyceride or carbohydrate content for energy purposes.

THE FACT THAT ALGAE CAN BE CULTIVATED BOTH USING SEA WATER AND RESIDUAL EFFLUENTS IS ONE OF THE MAIN ADVANTAGES OF THESE ORGANISMS. OTHER ADVANTAGES THAT THEY MAY POSSESS SHOULD BE ASSESSED IN ORDER TO CREATE A STRATEGY TO HELP WITH RESEARCH AND DEVELOPMENT.

[8] More information on the following website: http://www.algalbiomass.org/documents/ABOLCABrief.pdf

[9] One example of the interest in this field is the EXXON –SYNTHETIC GENOMICS alliance to create an oleaginous microalga through genetic synthesis.



3

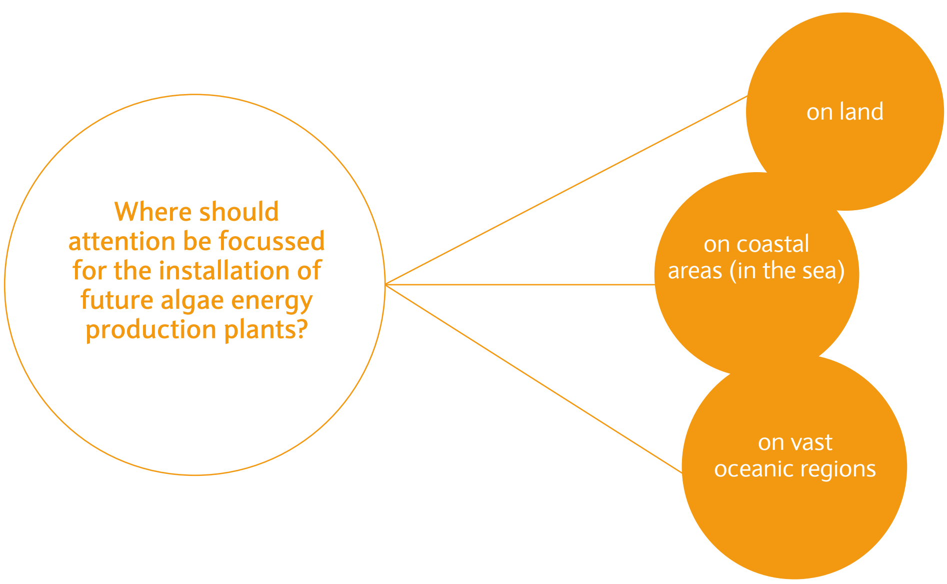
Technical Aspects

3.1. IMPORTANT FACTORS FOR LOCATING ALGAE PRODUCTION PLANTS FOR ENERGY PURPOSES

The efficiency of cultivation systems of different strains of algae depends on each geographic location, so that it is always recommendable to begin with local varieties. This fact once again demonstrates the importance of defining, a priori, where the potential zones for the future establishment of energy-producing algae production plants may be located.

The starting point for defining the perfect location is to establish, for this new algae biofuel sector, what may be considered to constitute an economy of scale. This concept is the end result of the interaction between multiple technological variables, many yet to be clarified, which condition algae production. Environmental variables to be taken into account include the following:

3.1.1 PHYSICAL SUPPORT: LAND VERSUS SEA



MACROALGAE

The first proposals for the production of biofuel, in the decade of the 70s, were based on US oceanic marine macroalgae cultivation projects (kelp, large cold-water fucoid algae) on floating platforms -petroleum-type platforms- which generated *upwelling*[10], using harvest ships[11]. It was demonstrated that this was biologically possible (J.H. Ryther and colleagues) but storms destroyed the pilot farms and the price of petrol fell. The American Gas Association -AGA- then carried out several trials. The concept was a biorefinery on the platform itself, which served as the axis of a radial microalgae farm, but it was finally abandoned. Norway revived the project decades later (the petroleum company NORSK-HYDRO), but also abandoned it.

A project is currently being carried out in Asia to produce algae belts around the coast of Korea, but more as a CO_2 sink than as a biomass generator.

Macroalgae grown on ropes around a floating salmon cage are being used in Chile to reduce the load of nutrients in the water and thus the eutrophication of coastal areas. The biomass produced is in turn used by the food industry, but could also be employed for energy production[12].

MICROALGAE

In 2009, a group of Silicon Valley researchers led by Dr Jonathon Trent presented the OMEGA project in collaboration with NASA, which aims to cultivate microalgae in special plastic bags with semi-permeable membranes floating in coastal waters. They propose the use of urban residual water and simplified harvests due to the reverse osmosis made possible by the properties of the plastic, developed to recycle urine in space vehicles. For various reasons (logistic, legal, biological, security, maintenance costs, performance, the state of the art, etc.) it can be concluded that this line of approach is not a R&D priority in Spain.

In conclusion, at present it would appear that the most reasonable microalgae production systems are those located on land, although other possibilities should not be ruled out.

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[10] Surfacing of deep, cold, nutrition-rich water containing plankton.

[11] Similar to those of the Californian company KELCO (the so-called WILCOX project).

[12] Buschmann, A., Hernández-González, M. Varela D. (2008) *Seaweed Future Cultivation in Chile: Perspectives and Challenges.* International Journal of Environment and Pollution 33: 432-456.

3.1.2 DAILY SOLAR RADIATION RATE AND TEMPERATURE

Two important limiting factors for the production of biomass for energy purposes, at least as far as the ecosystem is concerned, are sunlight and, in particular the daily photosynthetically active radiation (PAR) rate, and the temperature. In other words, a suitable location would be one that allows the maximum production of the selected strain to be maintained all year round (g $m^{-2}day^{-1}$). Ideally, production farms should not stop at all due to insufficient light or temperature excess or deficit. It is important to bear in mind that to keep biomass production costs competitive, the system must operate constantly at optimum density, production and monospecificity.

SHOULD THE LOCATION FORCE THE PRODUCTION TO STOP DUE TO LACK OF LIGHT OR TO LOW TEMPERATURES DURING THE MONTH OF JANUARY, FOR EXAMPLE, THIS WOULD MEAN THAT THREE MONTHS' PRODUCTION WOULD BE LOST (THE TIME NEEDED TO REACTIVATE THE ENTIRE SYSTEM), AND THAT DURING THE OTHER HALF OF THE PRODUCTIVE MONTHS, PERFORMANCE WOULD BE HALF OF THAT OBTAINED DURING THE "GOOD" MONTHS.

Some examples may be mentioned:

- On the island of Gran Canaria, theoretically located in the ideal production zone (below the 30th parallel), *Spirulina* cultivation systems in raceways double their production during the summer half year (Centro de Biotecnología Marina de la Universidad de Las Palmas de Gran Canaria - Las Palmas de Gran Canaria University Marine Biotechnology Centre). Four degrees of latitude further south, in the Sahara, a commercial farm cultivating the same strain of *Spirulina* obtains sustained production figures that double those obtained on Gran Canaria during the summer, in spite of using a greenhouse which attenuates 30% of the PAR due to condensation of the desert dust. The difference in the annual solar radiation rate between two sites separated by no more than 10 km may be highly significant, so that to define the general limit as 30° of latitude would be somewhat inexact. This evidently emphasises the need for the prior selection of zones where PAR rates make the production of algae for energy purposes profitable.

• In Almería (36.5° North) microalgae production (cultivated in horizontal tubular photobioreactors) during the 6 coldest months of the years is less than half of what is obtained in June, and, during the 5 hardest moths of winter, production falls by a third compared to June (University of Almería, Department of Chemical Engineering).

• *Spirulina* farms in Imperial Valley (California, USA) close production in raceways for 4-5 months a year (October-March) due to plant stress (low productivity, pollution, etc.) caused by low temperatures, not solar radiation, in the southernmost latitudes of the Californian Desert (latitude 32ºN).

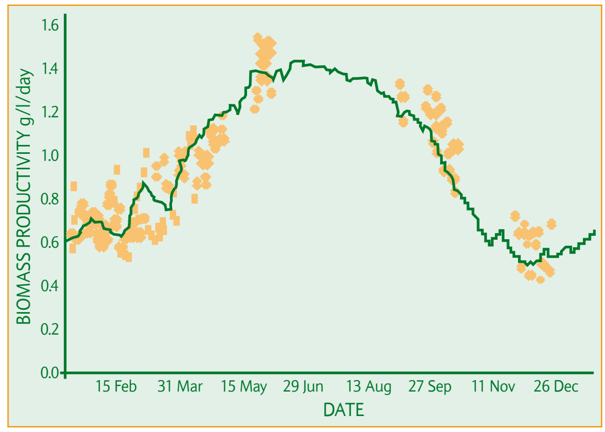


Figure 2, Biomass productivity.

The following map indicates the potential (yellow) and clearly favourable (red) zones on the planet in terms of the annual solar radiation rate.

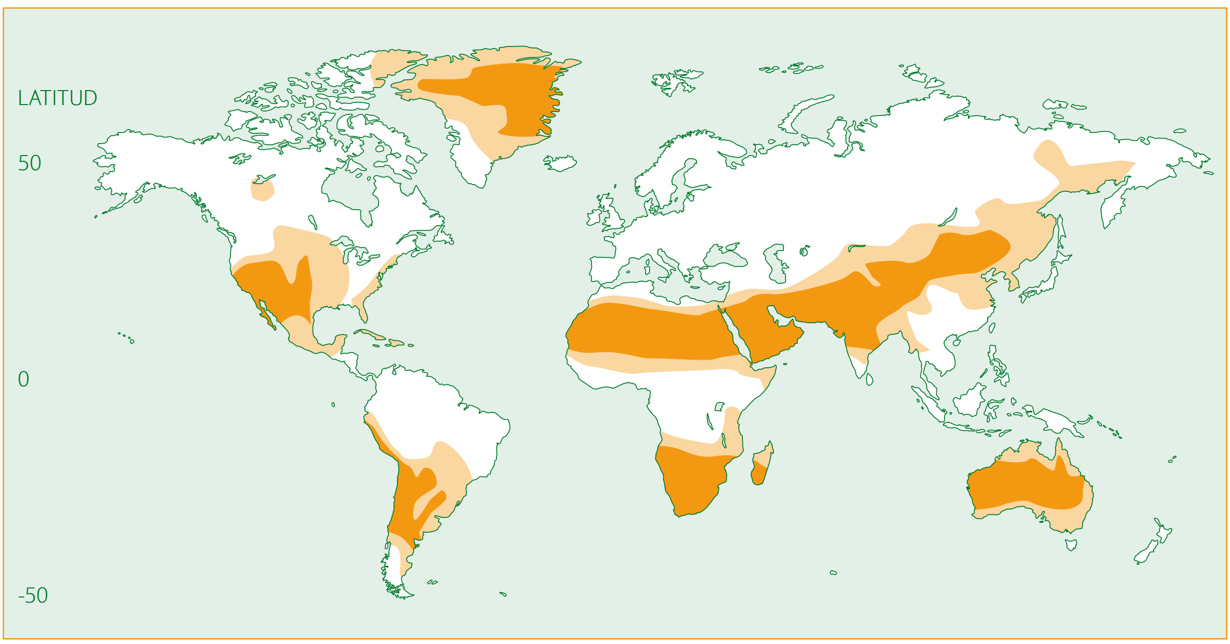


Figure 3, Solar radiation map.

According to the authors[13], this map indicates the most suitable regions for the cultivation of algae. The zones in red and yellow are the ideal locations for this purpose. The red area receives direct radiation of 2,500 - 3,000 kWh/m^2 per year and the yellow area 2,000 to 2,500 kW/m^2.

[13] *Comprehensive Oilgae Report: Energy from Algae: Products, Market, Processes & Strategies* September 2009, pages 37-38. More information at: www.oligae.com.

In the following map even the theoretical limits of maximum production of microalgae in photobioreactors are indicated, taking the most optimistic of the variables into account. This map by Prof. Mario Tredici was presented in the meeting of the Algal Biomass Organization -ABO- in San Diego (USA) in October 2009.

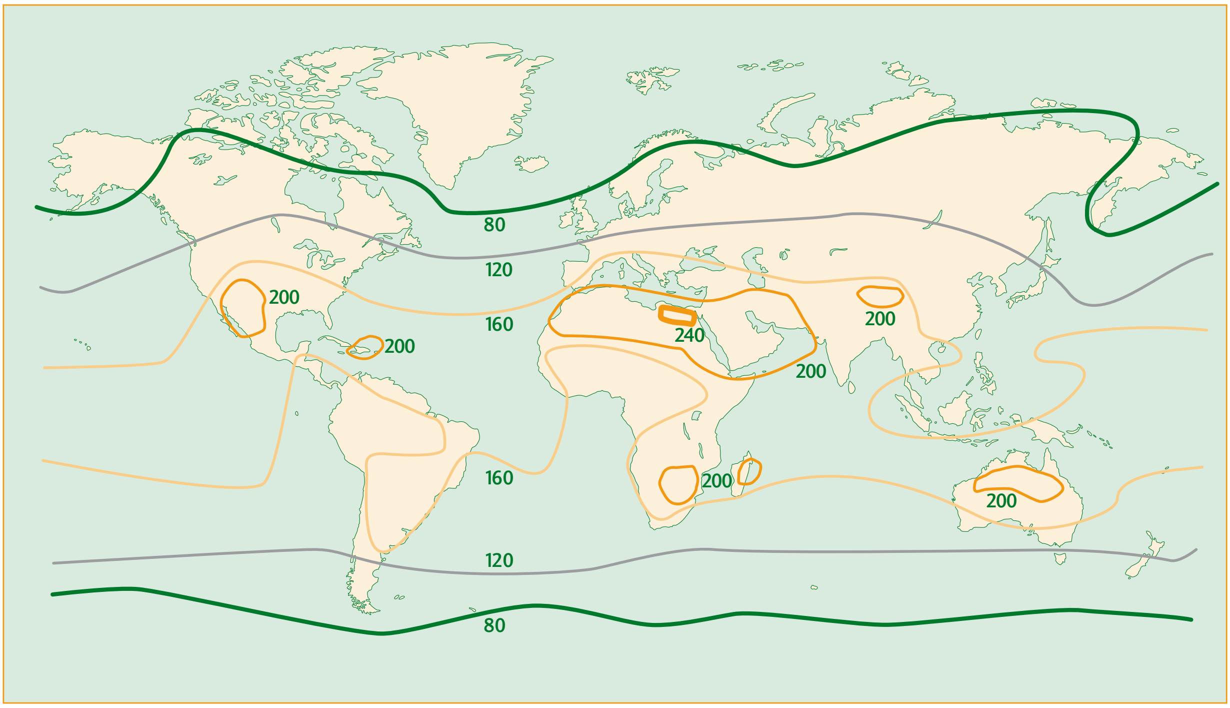


Figure 4, Tredici's map.

The lack of a high enough solar radiation rate could be resolved using advances in optic fibre, LEDs[14], etc. if these were of such a scale that the cost of artificial radiation in cultivation systems were extremely low. This option should also consider the problems deriving from cable laying and the other apparatus that would be required for this cultivation system, which also reduces the turbulence factor, favours fouling, etc. so that, even at zero cost, the artificial light system would be less efficient. In spite of these advances, it is hard to believe that artificial light would be an economically or technically viable alternative.

One possible way could be through mixotrophy with some kinds of industrial residues.

While in the case of microalgae high PAR rates and temperatures are a relevant factor for location, in the case of macroalgae these variables are not so vital[15]

[14] The alternative of the use of LEDs is being developed by various companies, for example:

> BIONAVITAS Inc. (USA) announced (February 2009) the *Light Immersion Technology* process, by which artificial light is supplied to raceways, obtaining 10 to 12 times as much production.. The company defines its system as having net energy gains with negligible costs with large scale production. The technology is based on a new generation of LEDs.
> The company BARD recently announced (November 2009) the use of artificial light 24 h/day to produce up to 8,000 litres of algae-based biodiesel m^{-2} $year^{-1}$.

[15] For example, Saccharina latissima, a possible bioenergy candidate, achieves optimum growth (which can reach 8% per day) at temperatures of 14-16 °C and light intensities of μmol m^{-2} s^{-1}. However, there are also some species of red algae in tropical waters such as *Kappaphycus, Eucheuma or Hypnea* with high productivity at very high temperature and radiation levels.

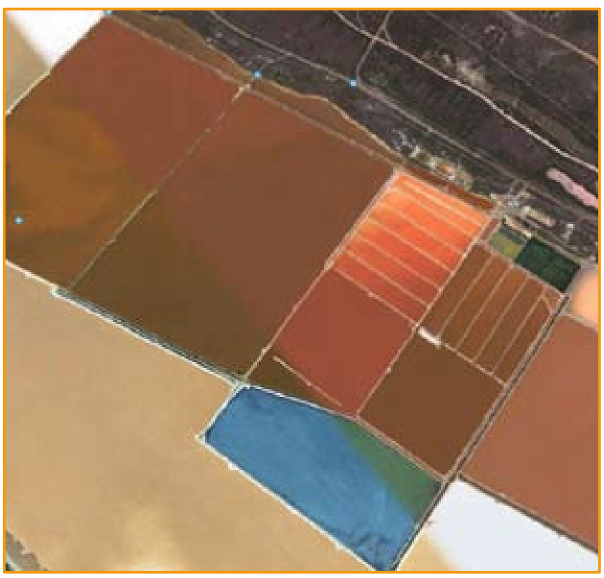
3.1.3 TYPES OF LAND

- Land preferably not designated for agricultural uses.
- Flat or with a very slight slope.
- Preferably reflective (carbonated soil, salty crust, etc.) in order to increase the effect of radiation by reflection. This option can be harnessed by photobioreactors but not by raceways.

3.1.4 MINIMUM AREA

Current industrial installations for the production of microalgae are of small scale compared to the size that would be necessary for production of algae-based biofuels. The biggest facility based on closed tubular reactors occupies an area of 1.2 ha, while microalgae production plants based on raceway reactors are on another order of magnitude at around 10-12 ha. In both cases the production is aimed at direct human consumption or consumption through compounds such as beta-carotene for the nutraceutical sector.

The minimum area necessary to ensure the sustainability of a facility for the production of algae for energy purposes would be in the order of 100 to 200 ha. Estimations made by various companies make clear the need for thousands of hectares in order to contribute significantly to the production of biofuel at a global level. PETROALGAE (USA) is considering the installation of cultivation areas of up to 5,000 ha, while the AGRAMAR Foundation's GREEN DESERTS project goes even further with estimates of 6,000 ha. To meet 1% of current demand for petroleum in Spain, it is estimated that 20,000 ha would be necessary although this area would not need to be grouped together in a single production facility (data calculated on the basis of estimations made by M. Borowitzka for Australia).



400 ha Algal biomass production plant at Hutt Lagoon (Australia April 2006).

35 ha raceway cultivation plant belonging to CYANOTHEC CORP., Hawaii (USA).

3.1.5 LAND POLLUTION

The chosen location must not be polluted by heavy metals or radioactivity, and the total absence of copper sulphates (or other copper salts) in the soil and water would be a prerequisite. On the other hand, some researchers consider that pollution by metals is not necessarily a disqualification, since resistance by the algae to some certain toxins could control the presence of contaminants in the crop. Along these lines, microalgae and cyanobacteria have been classified as heavy metal accumulators and can thus be used to regenerate land and/or waters, especially if the end use of the biomass in to obtain biofuels. The control of contaminants is very important to microalgal biotechnology, and since it is economically impossible to sterilise the culture medium, it is vital to develop resistance to ensure that only they, or at least preferentially, can grow in the cultivation environment.

3.1.6 ALTITUDE

In general the altitude of the land would not constitute an obstacle for microalgae production since this can be carried out both at sea level and at high altitude, provided that a plentiful water supply is easily available. Altitude may increase the available radiation in some places and also lower the temperature, and provided that these conditions are within the range of optimum growth for the cultivated species the effect will be positive. At all events the altitude of the production site should not involve costly pumping of water from lower altitudes. In this regard it is necessary to select places with a low, neutral or even net positive pumping work requirement of the water source in order to reduce the energy consumption of the process.

3.1.7 CO_2 CONTRIBUTION

All conventional algae production plants are based on the availability of combustion gases: that is to say they presuppose the existence of centres of CO_2 emission in close proximity to the algae production site. The use of industrial gases as a source of CO_2 is not only necessary, but may also become imperative for the industry due to the social and economic benefits deriving from the elimination of this type of pollution. Although the stimulating effect of the addition of combustion gases to the growth of algae has been demonstrated, the following drawbacks also exist:

- The absence of large CO_2 emission centres in the geographic zones where it would be possible to implement microalgae production on a large scale. Industry is not generally situated in places where climatic conditions are ideal for the location of algae production facilities. The cost of transport and distribution of the industrial gases to the cultivation site would be too high, even though CO_2 channelling systems are currently being developed, which could reduce these costs considerably.
- The low efficiency to capture CO_2 from combustion gases.
- The need for the prior conditioning of the gases.
- Possible excess acidity, depending on the composition of the gases.

IN SPITE OF THESE PROBLEMS, THE CONTRIBUTION OF FREE OR VERY LOW COST CO_2 IS FUNDAMENTAL TO THE ECONOMIC AND ENERGY VIABILITY OF THE PROCESS, AS IS A LOW ENERGY CONSUMPTION, SO THAT THE AVAILABILITY OF CO_2 SOURCES IS IMPERATIVE.

In the event of using combustion gases, an efficient use of the same is necessary in order to avoid causing re-emission to the atmosphere. In large facilities, the installation of electricity/heat generators based on biogas or residues proceeding from the biomass valorisation process could be considered.

Advances aimed at solving the abovementioned problems exist. Some companies have developed processes permitting the purging of combustion gases, with an efficiency of up to 80% in the use of CO_2[16], coupled with the use of photosynthetic microorganisms. Likewise, the employment of efficient material transfer systems and the utilisation of advanced control strategies allow enormous reductions in CO_2 losses, up to as little as 5% of the total CO_2 injected into the reactor.

AMONG THE DIFFERENT STRATEGIC PROPOSALS FOR PROVIDING CO_2 WITHOUT COST TO ALGAE PRODUCTION PLANTS, IT SHOULD ALSO BE CONSIDERED INCLUDING THEIR INTEGRATION WITH MARINE POLYFARMING (FISH, CRUSTACEANS, ETC) WHICH CAN SUPPLY CARBONATED WATER RESULTING FROM BREATHING, WITH THE REUSE OF THE CO_2 OF THE BIOMASS FERMENTERS IN SITU.

[16] Process patented by ENDESA.

An option to be assessed would be the use of CO_2 proceeding from any bacterial respiration activity such as fermentation, the digestion of sludge or fermentation of effluents from fish farms and/or swine farms (pig slurry) in which macro- or microalgae adapted to the conditions of these effluents grow.

With specific reference to macroalgae, the most important conditioning factor in the selection of the cultivation zone is undoubtedly the availability of nutrients, since the great advantage of macroalgae in comparison with microalgae is that, being benthic and/or macroscopic, their culture medium can be changed as they develop at very low cost (or cost-free in the case of gravity-fed effluents or those in the sea itself). They can thus be introduced into a medium that already contains nutrients and dissolved CO_2, and it is not necessary to enrich the water where they grow, but simply to change it. This is an essential difference, both to reduce harvest costs significantly and to allow them to be cultivated naturally in locations rich in nutrients and dissolved CO_2. The waters richest in nutrients on the Spanish coast are those under the influence of *upwelling* phenomena.

3.1.8 FERTILISERS

It is important to attempt to eliminate costs deriving from the use of fertilisers, since these involve the consumption of both materials and energy. The following options exist in this respect:

- Use industrial and/or agricultural wastewater with available nutrients (ammonium, nitrates, and phosphates).
- Use of water proceeding from wastewater treatment plants -WWTP-. In this case it would be necessary to establish the means to guarantee the supply. The possible presence of various toxins or microorganisms in these waters limits the field of application of the biomass obtained to energy purposes, excluding uses for human and/or animal food, unless adequate treatment is carried out to nullify these effects.

CONCLUSIONS

In addition to the environmental factors indicated above, socioeconomic variables that also affect the process must also be taken into account, since a biomass production plant requires technologically trained human capital, a continuous connection with a R&D system based on excellence, and to be linked to technology sectors (construction, hydraulic, chemical, IT engineering, etc.). The development of biomass production plants within the framework of a sustainable economy, the development of R&D in the form of consortiums between universities, research centres and companies will help boost knowledge and technology transfer in the production and use of algal biomass on an international scale, in order to bring innovation and economic development to zones with high potential for the cultivation of algae.

Moreover, a suitable management and commercialisation system is required for the energy product, based on market demands. In conclusion, the potential zones should be approached in an integral manner, bearing in mind the variables of the ecosystem and sociosystem, since it would be dangerous to assume that cultivation techniques and socioeconomic conditions can be transferred directly from one location to another.

THE POTENTIAL ZONES SHOULD BE APPROACHED IN AN INTEGRAL MANNER, BEARING IN MIND THE VARIABLES OF THE ECOSYSTEM AND SOCIOSYSTEM, SINCE IT WOULD BE DANGEROUS TO ASSUME THAT CULTIVATION TECHNIQUES AND SOCIOECONOMIC CONDITIONS CAN BE TRANSFERRED DIRECTLY FROM ONE LOCATION TO ANOTHER.

The great challenges Spain needs to address in order to join the industrial development of algal biotechnology are:

- The creation of algae production plants on a sufficient scale for the specific application to CO_2 abatement and sequestration (and toxic components) of combustion gases from significant sources (cement plants, refineries, glassworks, power stations, etc.).
- The integration of marine farming (fish, crustaceans and molluscs) and conventional renewable energy companies into the production of biofuel and marine hydraulic energy on a large scale. It would be necessary to foster the development of intensive, sustainable and versatile aquaculture and marine farming with the object of mitigating the current ecological problems of fish farms.
- The creation of algae production plants for high value added applications in the Spanish territory, fostering the development of a new industrial sector and the generation of new jobs associated with the same. It will be necessary to advance in accessing the biggest source of biodiversity on the planet of unknown molecules yet to be explored (microalgae and cyanobacteria) in order to boost the biomedicine, nutraceutic and dermo-cosmetic industries.
- Becoming technologically competitive at an international level.

3.2. CULTIVATION SYSTEMS

3.2.1. OPEN VERSUS CLOSED SYSTEMS

There are two basic designs for the large-scale production of microalgae: open systems in which the crop is exposed to the atmosphere, and closed systems constructed in transparent materials such as glass and polycarbonate etc., in which exposure to the atmosphere does not take place.

Open systems are essential to maximise the harnessing of solar radiation but present the following problems:

- Ultraviolet radiation and the wind cause premature shading of the photobioreactor if plastics are used as a covering.
- Contamination of raceways if these are not covered.

Open reactors are very important, but still must be improved to become reliable, stable and more productive. In a large, open industrial facility, the availability of inocula must be guaranteed through a combination of open and closed reactors.

Microalgae cultures under controlled temperature, radiation and photoperiod.
Photography courtesy of Marine Biotechnology Centre, University of Las Palmas de Gran Canaria - National Algae Bank.

The following table shows the features of the cultivation of microalgae in open and closed systems. It can be seen that each system has its advantages and drawbacks. For the production of biomass from microalgae, a new system should be used with advantages similar to those of the open system but without forgetting the closed systems.

OPEN OR CLOSE SYSTEMS?		
	CLOSED SYSTEMS	OPEN SYSTEMS
Contamination control	Easy	Difficult
Operation regime	Continous-Semicontinuous	Semicontinuous-Waterlight
Area / volume rate	High	Low
Cellular density	High	Low
Process control	Easy	Difficult
Investment	High	Low
Operation cost	High	Low
Scale up	Difficult	Easy
Light use efficiency	Good	Low

Table 1, Miguel García Guerrero. Universidad de Sevilla (Bio-Oil Conference, Oviedo, March 2008).

In the case of macroalgae, cultivation systems may be:

- On the open sea on floating structures (long lines, nets) or on the seabed.
- In lagoons or tanks on land, in this case in suspension.

3.2.2. MULTI-INTEGRATED SYSTEMS

It is important to point out that algae production systems for energy purposes must be multi-integrated at all levels since, if they are not, it is considered difficult for the plant to reach profitable production.

- Integrated carbonation:
  - Uncompressed combustion gases.
  - Respiration or fermentation CO_2.
- Integrated processing of the biomass → biorefineries:
  - The quantity of by-products that can be obtained and their quality (that is to say, their potential price on the market) condition the type of strain and of water to employ. It is estimated that the price of algal biomass after the extraction of oils, to be applied for animal feed and fertilisers, could reach 1€/kg, but it must be free of pathogens (e.g., WWTP waters could not be used without prior treatment).
  - Algae cultivation in effluents may serve as an example of a biorefinery, and is shown in the following diagram:

USE OF ALGAE AS A FILTER FOR THE EFFLUENT FROM FISH FARMS, AND AS A RESOURCE TO OBTAIN USEFUL SUBSTANCES FOR THE AGRICULTURAL, ENERGY, FISH AND BIOMEDICAL-PHARMACOLOGICAL FEEDS

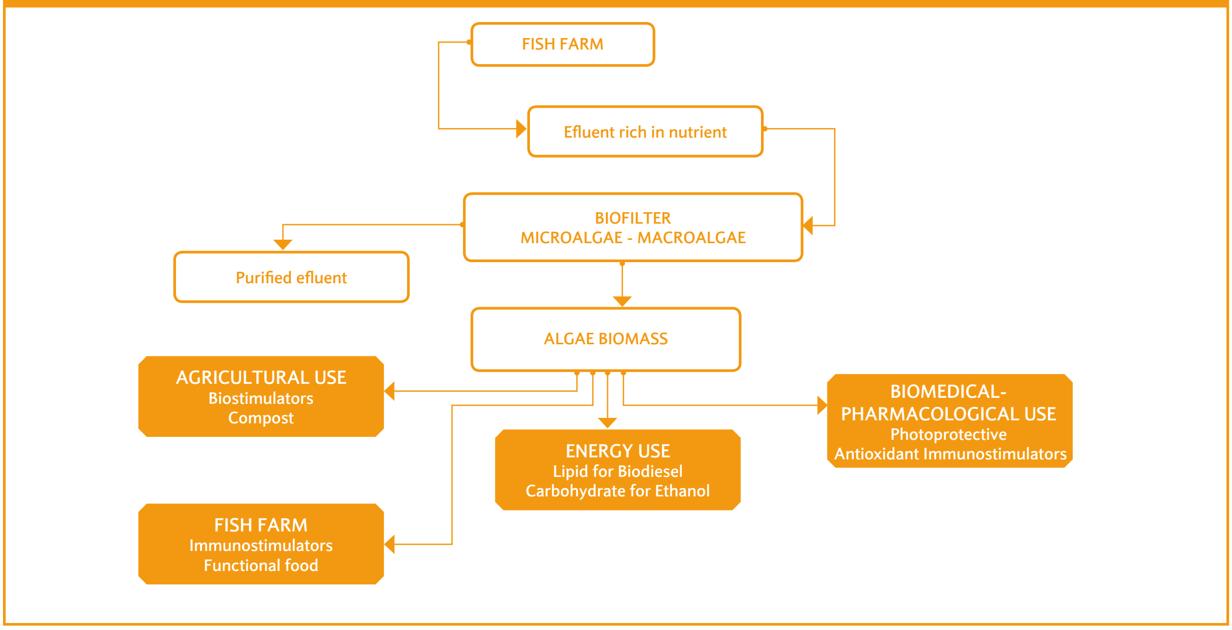


Figure 5, Example of a Biorefinery.

- Continuous production:
  - Harvest frequency should be daily, processing between a quarter and a third of the volume.
  - Preferably without double cycle (without a lipid induction phase) since this reduces biomass production.
- Integrated production:
  - Integrated marine and/or unused or unusable water polyculture. In recent years various Integrated Multi-Trophic Aquaculture (IMTA[17]) schemes have arisen in many parts of the world.
  - Intensive fish farming is currently profitable, amongst other reasons, because the eutrophication of the environment it produces is inexpensive. However, this situation is now beginning to change in industrialised countries since practical procedures are arising for the treatment of the cultivation water, one of the most significant of these being biofiltration by means of photosynthetic vegetables, especially microalgae, a technique which produces a mini-ecosystem within the cultivation system.
  - Algae are the most useful organisms for biofiltration because their productivity is the highest of all plants and they can be cultivated by inexpensive methods.

IT WOULD BE ADVISABLE TO USE TECHNICALLY SOPHISTICATED, CONTINUOUS AUTOMATIC SYSTEMS INCLUDING RESIDUE TREATMENT AT THE PLANT ITSELF AND THE USE OF INDUSTRIAL OR MUNICIPAL EFFLUENTS, EVEN IF ONLY AS A SOURCE OF NUTRIENTS.

It would be advisable to use technically sophisticated, continuous automatic systems including residue treatment at the plant itself and the use of industrial or municipal effluents, even if only as a source of nutrients.

In the specific case of macroalgae, semi-continuous and non-double cycle production criteria do not exclude remaining within the margins of profitability.

- On the open sea, macroalgae cultivation is seasonal with a harvest time similar to land-based agriculture. In general they are rapid-growth species with a harvest time of around 4-5 months. Production and processing must be considered apart. The biomass obtained, which can be harvested, dried and stored, can subsequently be continuously processed. This is a question of scaling the cultivation and the processing facility.
- To occupy marine farming facility time, crop rotation could be considered with a winter-spring species and another for summer-autumn.
- Crops in suspension in tanks, on the other hand, can work in a similar way to a bioreactor.
- Double cycle for macroalgae is understood to have little or no sense, since macroalgae have a bioenergy value due to their structural and reserve polysaccharide content although not for their lipid content, which rarely exceeds 5% of their dry weight.

[17] The following work in this field may be highlighted:
Chopin, T., Buschmann, A.H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G.P., Zertuche-González, J.A., Yarish, C., Neefus, C. (2001) *Integrating Seaweeds into Marine Aquaculture Systems: a Key Toward Sustainability*. J. Phycol. 37: 975–986.
Neori, A., T. Chopin, M. Troell, A.H. Buschmann, G.P. Kraemer, C. Halling, M. Shpigel, C. Yarish (2004) *Integrated Aquaculture: Rationale, Evolution and State of the Art Emphasizing Seaweed Biofiltration in Modern Mariculture*. Aquaculture 231: 361–391.

3.3. BIOMASS PRODUCTION TECHNOLOGIES

The desired objectives for algae-based biomass production for energy purposes, taking into account the current situation of the sector and the market, would be:

- Continuous production of the order of 100 t of dry biomass per hectare per annum.
- Positive energy balance.
- Energy consumption of less than 40 €/m^2.
- Energy consumption less than 50 W/m^3.
- Biomass production costs less than 500 €/t.

The different points of view existing in terms of the concept and calculation of the term photosynthetic efficiency, have given rise to disputes on the selection of the optimum technology for the production of algae-based biomass.

The photosynthetic efficiency of algae is not clear at present. Scientific debates take place which, while interesting, cause a certain loss of perspective.
For example,
FOR MANY YEARS GROWTH RATE WAS THE PARAMETER TO BE MAXIMISED, WHEN THIS IS REALLY AN IRRELEVANT DATUM IF CULTIVATION DENSITY IS NOT TAKEN INTO ACCOUNT WHEN THE OBJECTIVE IS TO PRODUCE BIOMASS.

In addition, the focus of this document is not the production of biomass itself, but a very different question: to determine what is the most suitable R&D&i strategy to develop a biotechnology making mega-production possible at competitive costs compared to traditional fossil fuels, and also with positive energy and climate balances.

Faced with this question, it is easy to get lost in the matrix of biological, technological, ecological, economic and even market variables, which condition the reply, amongst which the aforesaid photosynthetic efficiency stands out.

THE REDUCTION OF PRODUCTION COSTS AND MAXIMISATION OF PROFITS DEPEND ON INCREASING EFFICIENCY IN THE PRODUCTION OF THE BIOMASS. TO ACHIEVE THIS, IT WILL BE NECESSARY TO REDUCE CULTIVATION COSTS, FOR EXAMPLE FERTILISER AND CO_2 EXPENSES, AND REDUCE HARVEST COSTS. IN ADDITION, THE ADDED VALUE OF THE PRODUCT WILL HAVE TO RISE BY OBTAINING NOT ONLY BIOFUEL, BUT ALSO OTHER PRODUCTS OF COMMERCIAL INTEREST FROM THE RESIDUAL BIOMASS, DEVELOPING THE BIOREFINERY CONCEPT.

Is a production technology that meets all these requirements and limitations possible?

Currently, there is no unanimous answer to this question. Proof of this is that there is no consensus on algae-based biomass production, since the technology is in a stage of development, which does not allow us to possess fully substantiated data on an industrial scale. Achieving coordinated R&D&i is fundamental to reducing these costs in the near future.

3.3.1 RACEWAYS

95% of the production of microalgae is currently generated in raceway systems or open circular tanks. For this reason, the comparative analysis will begin with the model described in the following table:

RACEWAY TABLE[18]

The first column (REAL) contains real data from a commercial algae production plant (10 ha) operated in an ideal manner, at a suitable latitude, for the production of algae with a high lipid content. The second column (POTENTIAL) shows how it is estimated that the production system could be modified to reach the economic criteria established for algal biomass.

MICROALGAE PRODUCTION COSTS (X $US 1,000)	REAL Dunaliella (to obtain ß-carotene) 10 ha of raceway (current reality)	POTENCIAL Biofuel plant 10 ha raceway (optimised to the maximum degree)
Personnel	500 (n=20)	120 (n=8)
Electricity ($US 0.125/kW)	180	30
Fertilisers (N, P, K, Fe, etc.)	36	36
Local taxes	50	10
CO_2 ($US 500/t)	150	5
Seawater ($US 0.25/m^3)	200	5
Water	20	10
Miscellaneous	30	20
Total production costs	1.166	236
Annual production (dw t/year)	70	700
Performance (g m^{-2}día^{-1})	2	20
Biomass cost (in $US/kg dw)	17	0,34
Market price ($US/kg dw)	4.000	<0,5
Total sales (K $US/year)	100	¿?
Global market	limited	infinite

Table 2, Raceway production costs.

The drawbacks of cultivation in raceways is that it is easily contaminated, the temperature is difficult to control and that cultivation with depths of under 15 cm (due to turbulence and flow reduction) and over 30 cm (higher agitation costs and reduction of density, with the consequent increase in harvest costs) is difficult.

Another problem is that within this narrow depth margin (15-30 cm) densities are very low (0.5 g/l) and, for this reason, much larger surface areas are required (ratio of volume/total usable area between 120-150 l/m^2) than those needed by photobioreactors. Sustainable production in raceways is less than 35 t ha^{-1}year^{-1} (Richmond postulates maximums of around 60 t ha^{-1}year^{-1} and Ben-Amotz maintains that potential maximums reach 75 t ha^{-1}year^{-1}).

[18] Table presented by Dr. Ami Ben-Amotz in the Algal Biomass Summit, Seattle (USA), October 2008.

It is not completely clear at present that the open raceway system is the most profitable for the cultivation of algae for energy purposes (enormous space requirements due to the production limitations inherent in the system, contamination risks, evaporation rates, low optimum densities, etc), but there are no doubts about the strong commitments being made in this field:

- The company SEAMBIOTIC (Israel) recently announced productions of up to 45 t ha^{-1} $year^{-1}$ and costs estimated at 10 €/kg employing industrial combustion gases (on a pilot raceway scale). M.A. Borowitza estimates production costs of Dunaliella in extensive ponds at 15 €/kg and maintains that this would be profitable as a biofuel if it is reduced to 0.7 €/kg.

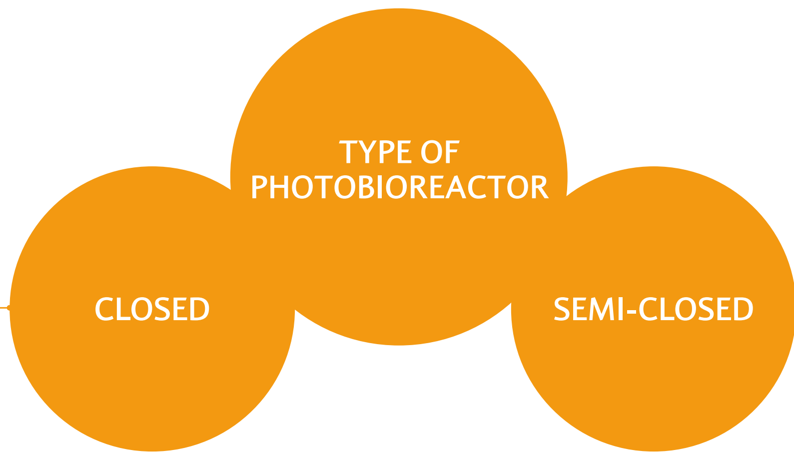
- Some Chinese companies claim to be able to achieve production costs of 3.5 €/kg (Spirulina).

- SEAMBIOTIC USA (a subsidiary of SEAMBIOTIC Israel) has reached an agreement with NASA to introduce pilot systems in the US through developing prototypes to optimise marine microalgae growth processes using flue gases from the Israeli company's power station in the city of Ashkelon. The scientific director of the programme is Dr. Ami Ben-Amotz.

Microalgae cultivation in raceway.
Photography courtesy of Marine Biotechnology Centre, University of Las Palmas de Gran Canaria - National Algae Bank.

3.3.2 PHOTOBIOREACTORS

Photobioreactors are understood to be those systems in which physical separation, usually transparent, exists between the crop and the surrounding environment, which allows better control of growth conditions and increased production, although normally at a higher cost.
Photobioreactors can be classified according to various factors, for example:[19]



WITH EXTERNAL LOOP: the crop is circulated between an external link which acts as a solar receptor and a mechanical or pneumatic bubble column system. The external link is usually made of small diameter tubes (between 1 and 10 cm) joined together to reach lengths ranging from tens to hundreds of metres. The tubes may be arranged horizontally, vertically or diagonally. Volumes of up to 700 m^3 have been scaled, and commercial facilities based on various designs exist (Pulz, 2001).

FLAT-PLATE REACTORS: formed by two vertical or inclined plastic plates (rigid or flexible) between which the crop is agitated by mechanical or hydraulic systems. The distance between the plates is usually between 1 and 20 cm and the height up to 2 m. They have the advantage of providing large cultivation surfaces exposed to light per unit of land area (up to 500 m^2 radiated/100m^2), although it is difficult to maintain adequate turbulence.

VERTICAL TUBULAR REACTORS - BUBBLE COLUMN: these consist of a vertical tube between 1 and 3 metres high and with a diameter of between 5 and 50 cm, in which air bubbles act as the agitation system. Due to their vertical position they absorb less solar radiation than horizontal arrangements, but they do not accumulate oxygen. These reactors are usually found in inoculum production systems due to the excellent control of operating conditions they provide.
A new design for photobioreactors with vortex agitation [19] suggests that it is possible to achieve productions of 130 t $ha^{-1}year^{-1}$, with volumetric production rates of 0.2 g dw $l^{-1}day^{-1}$.

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[19] System patented by REPSOL.

3.3.2.1. AGITATION

Agitation of microalgae crops is necessary to homogenise the cultivation and minimise the concentration and/or temperature gradient, and to move the cells between the inner zones of the crop with little available light to the outer areas close to the surface, which have greater exposure. With greater agitation the frequency of exposure of the cells to light rises, increasing productivity up to the saturation value. However, this rise in agitation implies greater energy consumption and thus less energy efficiency and increased production costs[20].

Moreover, excess agitation can cause damage to the cells due to shearing force, diminishing their productivity and even casing their death[21]. Agitation can be achieved by mechanical or hydraulic means. In raceway reactors low energy-consumption paddlewheels are the rule (1-10 W/m^3), while photobioreactors use centrifugal pumps and bubble columns with greater consumption (20-1,000 W/m^3).

3.3.2.2. AUTOMATION

The automation of microalgae production processes is indispensable both in order to lower production costs by reducing labour costs and, above all, to improve production. This enhancement is achieved by matching cultivation conditions to the requirements of the various strains, and by ensuring production as a consequence of maintaining the stability of the same.

Automation can be applied at many levels from simple tasks such as the automation of transfusing liquids (culture medium, crop, harvest) necessary for the continuous operation of the reactors, to the highest level, including control of cultivation parameters such as pH, temperature, agitation, dissolved oxygen, etc. In all cases, a minimum control and automation of the process is necessary to assure its stability and production: from this point on, improvements such as control of pH by CO_2 injection and/or flue gases have significant repercussions on productivity enhancement with small cost increases. However, as in any system, excessive automation can not only increase costs in an unsustainable manner, but may also cause instability within the system. Several tools are currently being developed for control and automation of microalgae production processes[22].

[20] E. Molina Grima, F. G. Acién Fernández, F. García Camacho, Yusuf Chisti, 1999, *Photobioreactors: Light Regime, Mass Transfer, and Scaleup*. Journal of Biotechnology, 70, 1-3, 231-247.

[21] C. Brindley Alías, M.C. García-Malea López, F.G. Acién Fernández, J.M. Fernández Sevilla, J.L. García Sánchez and E. Molina Grima, 2004, *Influence of Power Supply in the Feasibility of Phaeodactylum tricornutum Cultures*. Biotechnology and Bioengineering, 87(6): 723-733.

[22] Berenguel M, Rodríguez F, Acién FG, Garcia JL, 2004, *Model Predictive Control of Tubular Biological Photobioreactors*. Journal of Process Control, 14: 377-387.

	OPEN	FLAT	TUBULAR
Volume (m^3)	10^3	5.0	5.0
Gas holdup	0.01	0.02	0.01
Mass transfer coefficient (s^{-1})	0.010	0.010	0.005
Dispersion coefficient (m^2/s)	0.0001	0.030	0.040
Mixing time (s)	10^4	150	10^5
Power (W/m^3)	1	50	100
Pb_{vol} ($g\ l^{-1}day^{-1}$)	0.1	0.6	1.0
Cost (€/m^3)	500	3,000	10,000

Table 3, Summary chart of types of photobioreactors and their features (E. Molina Grima, University of Almería).

CONCLUSIONS

Production in future facilities should be above 100 t $ha^{-1}year^{-1}$. In terms of photobioreactors, it would be necessary to:

- Develop strong, ultra-violet filtering, antifouling, rigid, low-cost and recyclable plastic materials transparent to solar radiation.

- Develop systems permitting interconnectivity of modules. Another option would be to have large-scale production systems per reactor unit.

- Develop combustion gas self-aspirating systems.

Photography courtesy of University of Almeria. Chemical Engineering Department.

3.4. HARVEST TECHNOLOGIES

The main problem in algae production aimed at producing biomass lies not so much in the production as in the harvesting. In the case of microalgae, harvesting of organisms measuring between 2 and 200 µm, which are usually cultivated at low harvest densities, is very costly in equipment and energy, especially if the harvest technology is based on centrifugal systems as is currently the case. Densities in raceways are lower than in photobioreactors, so costs are even higher.

Thus it is essential to reduce or eliminate harvest costs. Centrifugal systems for large volumes is currently non-viable, so there is a need to find algae of a larger size that decant well, with maximum recycling of the water used, in the search for different, cheaper harvesting processes.

Apart from progressing in the search for new species of microalgae, it would be interesting to study in greater depth those with the feature of not being “micro” in photobioreactors (high turbulence), but “meso”, that is to say, filamentous aggregates with sizes oscillating between 0.02 and 3 cm.

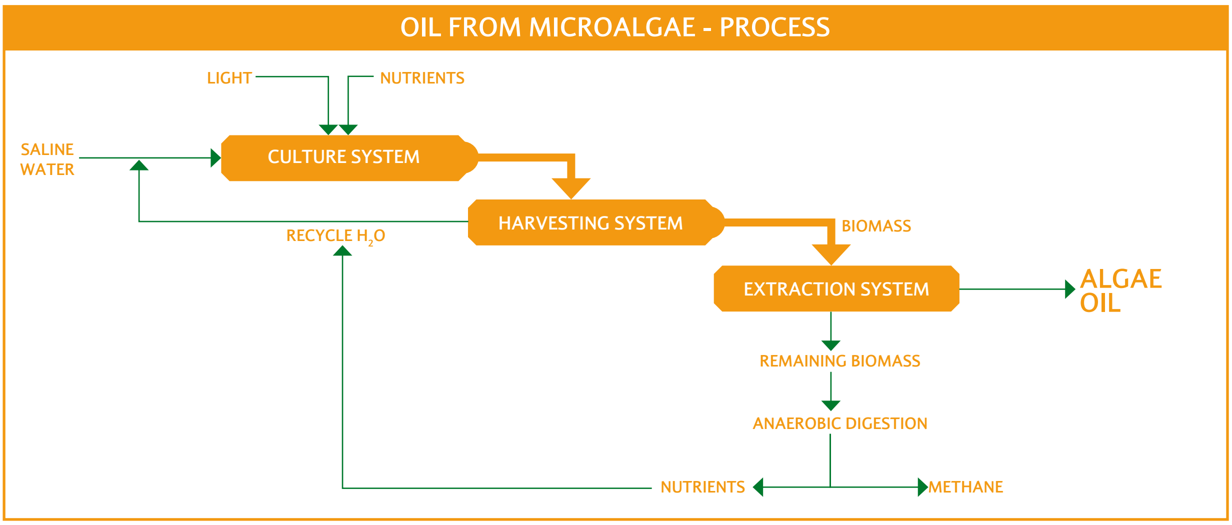

Figure 6, Diagram of the process for obtaining oil from microalgae[23].

Harvest technologies available, which are currently being studied, include the following[24]:

- Filtration: applied to mesoalgae, permits optimum recycling of the effluent.
- Flocculation - decanting.
- Nanoparticles.
- None: direct secretion of algal hydrocarbons/biodiesel to the culture medium[25].

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[23] Diagram contained in the presentation of the project *A fully Integrated Process for Biodiesel Production from Microalgae in Saline Water,* presented by professor M. Borowitza of Murdoch University (Australia).

[24] To these technologies the option developed by ALGAE VENTURE SYSTEMS (USA) would have to be added, since it significantly reduces harvest costs to below the limit considered to be the critical threshold (35 €/t). According to this company, it is possible to reduce the cost from the current figure of 625 €/t to less than 2 €/t. This 99% reduction would constitute a milestone and would change the economy of algal biotechnology.

[25] The technology being considered by SYNTHETIC GENOMICS (C. Venter) - EXXON, is the constant production of hydrocarbon-excreting strains, which would eliminate the problem of biomass (cell) harvest but substituting continuous downstream processing of the hydrocarbon exudates (which would be produced continuously).

3.5. ALGAE-BASED BIOFUELS

3.5.1 BIOFUELS FROM MICROALGAE

The determination of the ideal algae-based biofuel that should be obtained is considered by some as a question to be solved prior to others related to the production of biomass. This question raises the complexity of the biotechnology-product matrix to be resolved. Possibilities include:

- DIRECT FUEL FOR PRODUCTION OF HEAT AND/OR ELECTRICITY: application is hardly viable since the algal paste obtained after harvest contains 80 to 90% water and very high salt content, which makes combustion difficult.

- HYDROGEN: the production of metabolic hydrogen from hydrogenase-bearing microalgae, a complex process still at the laboratory study stage, requires the production of hydrocarbon-rich algae, which, under certain conditions of oxygen limitation, constitute the energy source for cellular processes of water hydrolysis and hydrogen liberation. In addition to this option, there is another way to obtain hydrogen based on gasification, synthesis gas (this is treated as another type of biofuel below) and reforming (enrichment of the mixture).

- BIOETHANOL: algal biomass contains carbohydrates, which are susceptible to be hydrolysed and fermented to ethanol by means of suitable yeasts. The monosaccharide composition of the carbohydrates present in algae is not simple, so these fermentation processes must be developed further in order to be carried out on an industrial scale. An alternative to this method is the direct production of ethanol by some cyanobacteria, the product being recovered from the culture medium[26].

- METHANE AND OPTIONALLY HYDROGEN:

  - Hydrothermal processing and recycling of CO_2 for photobioreactors with high thermal efficiency (>70%) in comparison with the thermal efficiency of methanogenic processes by anaerobic digestion (25%-35%).
  - The process begins to be profitable from 15% dry weight of biomass in the concentrate, making harvest by filtration possible (self-flocculating filamentous cyanobacteria).
  - Avoids the need for dehydration of the biomass necessary in conventional gasification and methanisation thermal processes (90% of dry weight)
  - Very short residence times (minutes), so that reactors of small size and much reduced footprint in comparison with anaerobic fermentation are sufficient.
  - Total recycling of water, nitrogen phosphorus and CO_2 is possible.

- OILS: a priori the strategy of aiming to generate lipids directly from microalgae (biodiesel or jet fuel) does not seem very profitable. A more suitable approach would be through thermochemical processes of the Fischer-Tropsch type, based on an algal biomass rich in polysaccharides. The problem is not so much the production of lipids, as knowing how to extract and process them adequately. Gasification generates gaseous, not liquid fuel, in the form of poor or synthesis gas (syngas). Liquid fuels are more valuable.

  - **Biodiesel:** some researchers[27] suggest potential productions of 18,750 l oil $ha^{-1}year^{-1}$ (assuming 20% oil in the marine diatom *Phaeodactylum tricomutum*) and lipid rates of 5 g lipids $m^{-2}day^{-1}$). Other authors (Dr. Yusuf Christi) suggest potential productions of up to 58,760 l oil $ha^{-1}year^{-1}$, assuming 30% of oil in the biomass. In this case the real data are very favourable, since they combine the best information on biomass production and lipid content in order to determine these maximum performances. Thus, they are values that are difficult to reach, since an increase in biomass production implies a reduction in lipid production, and vice versa.

[26] DOW CHEMICAL and ALGENOL have reached an agreement with the approval of the US Department of Energy (DOE). DOW CHEMICAL is developing film suitable for photobioreactors and ALGENOL the direct ethanolisation technique. This is a type of technical genetic engineering well known at laboratory level, and there are currently various projects underway to obtain alcohols with longer chains than butanol. The pilot plant is being constructed in the coastal zone of Texas (USA).

[27] Dr. Molina Grima's group. These quantities were obtained by extrapolating the production on the basis of real cultivation during 3 years in a 220 l pilot project.

According to Miguel García Guerrero[28] reactors of 50 l/m^2 with average volumetric productivity of 0.7 g of biomass $l^{-1}day^{-1}$ (or 140 l/m^2 at 0.25 g $l^{-1}day^{-1}$ = 35 g biomass $m^{-2}day^{-1}$), and with fatty acid content of 30%, would produce 10 g of oil $m^{-2}day^{-1}$. The extrapolation of area would give 0.35 tonnes of biomass (0.1 tonnes of oil $ha^{-1}day^{-1}$). The area and time extrapolation considering 300 operating days per year would yield 105 tonnes of biomass, 30 t of oil $ha^{-1}year^{-1}$.

The following are examples of the development of this method:

i. The American Society for Testing and Materials (ASTM) has just published new D7566 specification criteria for fuel suitable for aviation turbines, military included, valid for biomass and Fischer-Tropsch.

ii. Soladiesel™, a biodiesel produced by the company SOLAZYME, has met the ASTM D-975 specifications, which confer suitability for 100% (without mixture) and compatible application.

iii. The recent EXXON-Venter agreement (420 M€) to develop new oil-bearing microalgae by genetic engineering declared that, in the future, the petroleum company could potentially produce more than 20,000 litres of fuel per hectare and year. These objectives are not excessively ambitious, but they are realistic, similar to the potential of other companies.

iv. PLANKTON POWER states that, after the pilot plant (17 M€) that they are constructing on a military reserve at Cape Cod (USA), they could operate algae production plants on a large commercial scale yielding 9,400,000 l of biodiesel per year in a 40 ha plant.

v. PETROALGAE is planning the sustainable production of 50 g dw $m^{-2}day^{-1}$ (182 t $ha^{-1}year^{-1}$), and with expectations of improving to 70 g dw $m^{-2}day^{-1}$ (255 t $ha^{-1}year^{-1}$).

vi. SAPPHIRE ENERGY supplied algae-based biodiesel to a car which travelled 6,000 km in the US (September 2009), using a proprietary system called *Green Crude Production*.

With reference to algae-based biodiesel production estimates (t $ha^{-1}year^{-1}$), the performance published by the majority of authors is based on the calculation of the total lipid content, which includes all liposoluble compounds (including chlorophyll and carotene as well as other non-saponifiable compounds) of the algal cells. Another question altogether is the percentage of lipids they contain, which can be transformed into biodiesel (C-14 to C-24). In addition, the loss of performance due to the extraction of algal biomass must be assessed, especially in the case of the more oleaginous species such as those of the Chlorophyceae class.

If the calculations are based on the yield of oils transformable into extractable biodiesel, much more realistic data are obtained compared with those for the total lipid content. A priority task would be to solve the problem of lipid extraction yield and cost[29] first or simultaneously.

[28] Conference in Oviedo 12th March 2008.

[29] Suggestions:

The company ORIGIN OIL appears to have solved the problem by a single-stage process through integration of *Quantum Fracturing* technology and electromagnetic treatment of the pH (the oil floats and the biomass settles).

The public-private-military consortium formed by AMES, the University of Iowa and CATILIN has announced (April 2009) the development of a lipid extraction technique from macroalgae by means of nanoparticles which permits the extraction of lipids from algal cells.

In spite of the rapid development of projects for the production of biodiesel compared to the remaining algae-based biofuels, this is still no more than just another line of energy production. Thus, it is important to underline the need to apply the concept of biorefinery in order to achieve an integrated assessment of biomass and all its components.

- Jet fuel: this is a priority objective of the US Government-Israeli programme. The considerations on biodiesel are also valid for this field.

• HYDROCARBONS: the production of botryococcenes from the microalga *Botryococcus braunii* is relatively well known, although it has not been carried out on a significant scale. These are slow-growing fresh water species of low density and very low productivity. For these reasons they may not be considered in a priority strategy[30].

• SYNGAS: may be employed as raw material for obtaining liquid biofuel or alcohol in addition to hydrogen.

GENIFUEL has developed (2009) a very efficient system for the harvesting and gasification of algal biomass in which gasification efficiencies of 99% of the biomass have been obtained, along with the recycling of the CO_2 in the algae production plants themselves. It is based on the use of wet biomass and the *catalytic hydrothermal gasification* process, which requires very basic technology in a single-stage process. It is 400 times faster than anaerobic processes and the yield is higher.

The CO_2 is fed back to the algae production plants as a carbonation source.

IF THE CALCULATIONS ARE BASED ON THE YIELD OF OILS TRANSFORMABLE INTO EXTRACTABLE BIODIESEL, MUCH MORE REALISTIC DATA ARE OBTAINED COMPARED WITH THOSE FOR THE TOTAL LIPID CONTENT. A PRIORITY TASK WOULD BE TO SOLVE THE PROBLEM OF LIPID EXTRACTION YIELD AND COST FIRST OR SIMULTANEOUSLY.

3.5.2 BIOFUELS FROM MACROALGAE

The selection of a process for the conversion of biomass into useable energy will be conditioned by the desired final product and the physical and chemical features of the material. Macroalgae have an average basic composition of: 10-25% dry material, 75-90% humidity; 62-78% with organic material and 22-38% minerals.

Typical ligneous material is structurally based on cellulose and lignin, two components which in seaweeds are found in low quantities in comparison with wood. This fact suggests that a fermentation process similar to that used for other plant materials such as maize could also be suitable for macroalgae. Moreover, the low lipid content does not suggest their use in biodiesel production. The polysaccharides present in macroalgae require a biochemical or thermo-chemical process to break them down into their constituent monomers as a step prior to fermentation, or it will be necessary to develop a specific direct fermentation process.

Another alternative is the production of biogas by means of anaerobic fermentation[31]. This process involves the biological conversion of the organic components of the biomass into simple products such as acetates, carbon dioxide and hydrogen through the action of a group of non-methanogenic bacteria. These products can be employed in a subsequent step by a mixed population of methanogenic bacteria to produce methane and carbon dioxide. In general, non-methanogenic bacteria are rapid growth organisms, while methanogenic bacteria are usually slower growing.

[30] Notwithstanding, the majority of the work presented during the *International Phycological Congress* (Tokyo, August 2009) were related to the screening programme of species of *Botryococcus*.

[31] Examples of real applications of this technology are: the TOKYO GAS COMPANY for the use of algal beds; the Belgian company SOPEX with a facility in Morocco designed to treat agar residues processing 12 t per day and expected gas generation of 100,000 m^3 per annum. Residues are used as fertilisers.

PROCESSES

In general, all previous studies concluded that marine algae are a suitable raw material for anaerobic digestion processes, and this is demonstrated by the high conversion efficiency, high speed and good stability of the process. The presence of salt, polyphenols and sulphated polysaccharides need to be studied in each case since they may inhibit fermentation.

Anaerobic digestion of marine algae in two phases[32] also produces enhanced economic results. Separating the acid or hydrolytic stage from the methanogenic stage, it is possible to increase the concentration of methane, as a consequence reducing possible purification costs for this gas. In addition, in the case of the digestion of algae, this separation produces greater process stability by employing a first stage, which can act as a buffer for the methanogenic phase, protecting it from possible toxins that may be present during the initial loading of the process.

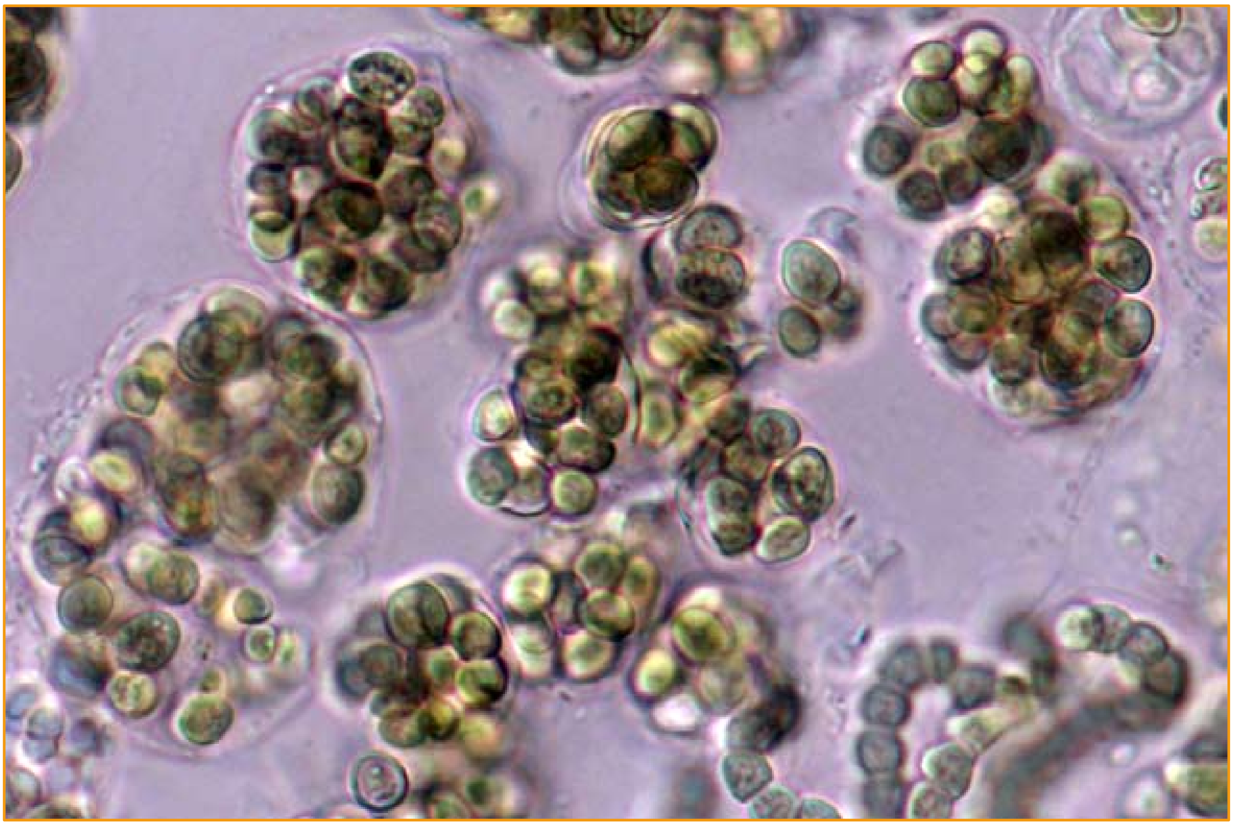
Macroalgae hardly contain any lipids, which makes the answer to this question much easier than in the case of microalgae. Perhaps the production of biogas by methanisation is the most direct, simple and viable process of energy transformation using macroalgae, although gasification is also possible. According to qualitative tests of co-digestion of slurry and algae grown in water with previously digested slurry, co-digestion enhances the anaerobic digestion by improving the C/N ratio (slurry contains excessively high levels of N).

Given the enormous quantity of slurry produced in Spain (one of the highest in Europe), the use of waters resulting from digestion of the same and of the CO_2 from biogas combustion as nutrients to grow algae to produce more biogas and obtain relatively clean water, would provide the following environmental benefits:

- Elimination of methane emissions.
- Elimination of CO_2 emissions characteristic of diesel.
- Recovery of relatively clean water and other food complements.
- Reduction of human pressure on water resources.

There are still a large number of technology gaps in the processes for obtaining bioalcohol due the difficulty in finding microorganisms or enzymes efficient or cheap enough to be able to hydrolyse the highly complex polysaccharides found in marine algae. Although using macroalgae as direct fuel would seem a priori to be the most profitable process, the high added value products they contain are totally lost. The concept of biorefinery would be obviated.

[32] Vergara, Fernández et al, *Biomass and Bioenergy* 32 (2008): 338-344.



Microscopic picture of different parts of the cellular cycle of the cyanobacterium Nostoc BNA 20-022, excretory of polysaccharides is crucial to obtain a higher yield in ethanol or methane production.
Photography courtesy of Marine Biotechnology Centre, University of Las Palmas de Gran Canaria - National Algae Bank.

3.6. SPECIES/STRAINS

3.6.1 MICROALGAE

It is important to bear in mind that the term microalgae (defined as photosynthetic organisms with dimensions of under 200 µm) is a catch-all term referring to a range of photosynthetic organisms embracing not only 11 phyla (depending on the taxonomic school) but also two kingdoms (Plantae and Bacteria). In contrast, all terrestrial plants belong to a single phylum (Chlorophytae), deriving from the marine microorganisms founders of this taxonomic phylum. This implies that there is a far greater similarity (physiological, in biochemical and pigment composition, evolutionary, etc.) between a chlorophyte microalga and any terrestrial plant than between the same microalga and another floating beside it and apparently identical, but belonging to a different phylum. Thus it is risky to talk of microalgae as one might speak of plants, and would be equally erroneous to speak of algae, or marine vegetables, without awareness of the enormous diversity (imprecision) embraced by the term.

As we have commented in the introduction to the present document, some authors claim that there are 50,000 species of microalgae, while others speak of 100,000. As a reference, it is important to point out that around 80% of worldwide industrial microalgae production is based on the cultivation of 3-5 species (when dealing with microalgae, the concept of species is also somewhat risky).

Any programme aimed at the industrial production of microalgae must:

- Carry out a permanent bioprospection programme.
- Have access to facilities, public or private (private collections and/or a National Algae Bank), for conservation and maintenance, in order to provide a biodiversity conservation service.

It is thought that the following selection criteria may be the most important:

- Total volume production (in real biomass).
- Thermal tolerance.
- Resistance to adverse cultivation conditions.
- Multi-utility potential of the biomass: range of complementary markets → biorefinery. The profitability of the energy algae production plants may foreseeably be conditioned by obtaining equivalent income for biomass by-products different from algae-based biofuel.
- Less adherence to photobioreactor material.
- Ease of harvesting (able to be harvested by filtration and/or self-flocculation-decanting).
- Mono-specificity should not be considered as a prerequisite of the crop and natural transitions should be accepted.

Some classes of microalgae, especially Chlorophyceae and diatoms are able to accumulate great quantities of lipids, up to 80% of dry weight, but under conditions of stress. Thus they accumulate lipids when cell division is compromised, which is to say when they do not grow.

SPECIES / STRAINS	LIPID CONTENT (% biomass dry weight)
Botryococcus braunii	25 - 75
Chorella sp.	28 - 32
Crypthecodinium cohnii	20
Cylindrotheca sp.	16 - 37
Dunaliella primolecta	23
Isochrysis sp.	25 - 35
Monallanthus salina	20
Nannochloris sp.	20 - 35
Nannochloropsis sp.	31 - 68
Neochloris oleoabundans	35 - 64
Nitzschia sp	45 - 47
Phaeodactylum tricornutum	20 - 30
Schizochytrium sp	50 - 77
Tetraselmis suecica	15 - 23

Table 4, Oil content of some species of microalgae[33]

[33] Table obtained from the 15th International Electronic Symposium (October 2007). Presentation by Isabel Albarracín (Faculty of Natural Sciences, UNPSJB, Argentina): *Microalgae Potential Producers of Biodiesel.*

THE GREAT CHALLENGE FOR RESEARCH IS TO OBTAIN MICROALGAL SPECIES IN WHICH THERE IS AN OPTIMUM BALANCE BETWEEN GROWTH AND LIPID ACCUMULATION ALLOWING THE PROCESS TO BE PROFITABLE.

The small size of oleaginous microalgae makes selection on the basis of flow cytometry+sorter perhaps the only alternative: present equipment does not allow sampling of filamentous species, which makes the use of centrifugal systems necessary for harvesting unless they can generate self-flocculation.

A much simpler process for selection and more efficient as an energy converter, is the cultivation of polysaccharide-bearing strains, since this microalgae cultivation process is much more efficient. However, in this case it is necessary to decide what type of polysaccharide, since current fermentation systems need to be adapted.

Based on the above, the following questions are raised:

a. Which would be the most suitable species/ strains?

- Those that produce the greatest biomass in the cheapest system.

- Preferably local strains.

90% of algal species are still to be assessed.

b. How should species/strains be obtained, conserved and patented?

- The creation of facilities, public or private (private collections and/or a National Algae Bank), for their conservation and maintenance. Although microalgae banks of reference on a world scale exist, having access to a national microalgae bank would allow access to an algae testing centre in standard and/or defined conditions as a support for groups or centres.
- It is necessary to develop processes on a pilot scheme scale in real operating conditions with natural blooms and/or inoculation of selected strains in order to identify the patentable microalgae of greatest productivity.

c. How should they be enhanced?

- Enhancement and adaptation under operating conditions:

    i. Pressure methods may be put into practice through environmental factors to improve productivity and/or obtain adaptations in the selected strains.

- Flow cytometry with sorter:

    i. Developed in the CENIT-PIIBE project.
    ii. There are at least two projects/universities in the US developing the same strategy with promising results.

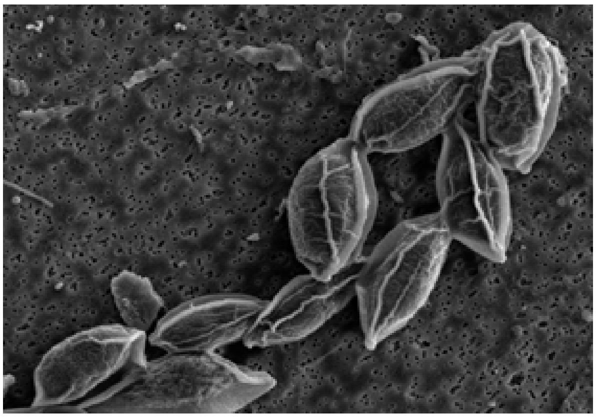
- Genetic engineering: A priori, legal problems may arise. In any event, while the systems are closed, there seems to be no difference compared to techniques already being applied to the production of other biofuels in Europe. In addition, valuable lessons can fortunately be learned from the experience of the agri-food and pharmaceutical industries. This is a line involving certain risks and costs, but which may be highly profitable. Proof of its importance is that in 2009 alone:

    i. EXXON reached an agreement with SYNTHETIC GENOMICS (C. Veter) to develop oleaginous genetically modified microalgae, investing 420 M€

    ii. TARGETEC GROWTH INTERNATIONAL (USA) announced that it could increase the performance of genetically-modified cyanobacteria by 400% for the production of oil suitable for jet fuel.

    iii. SAPPHIRE ENERGY announced in the *Military Energy & Fuel Conference* in April 2009 that it foresaw producing more than 380 M l/year by 2018 and up to 3,800 M litres of jet fuel by 2025 (which would amount to 3% of the annual US demand of 135,000 M litres of standard fuel) from cyanobacteria by means of genetic engineering.

    iv. ALLIED MINDS has an agreement with the University of Washington to explore strains that combine oleaginous nature and rapid growth, developed using the technology of Professor Ann Cattolica.



Photography courtesy of University of Almeria. Chemical Engineering Department.

3.6.2 MACROALGAE

In the case of macroalgae, the species for which the cultivation techniques are completely developed and production is high enough to consider them as candidates for extraction of biofuels and/or other products are very few. In particular, on the coasts of Spain there is sufficient technology and experience for the mass cultivation of the brown algae *Saccharina latissima*, of red algae of the *Gracilaria* genus and green algae of the *Ulva* genus. These three types of algae occupy between them all the cultivation habitats to be found in Spain with regard to conditions and environments, and, moreover, may be cultivated in both sea-borne systems and land-based tanks.

The report *A Review of the Potential of Marine Algae as a Source of Biofuel in Ireland* published in February 2009 concluded that, of all the macroalgae, the *Laminaria* and *Ulva* species are the ones with the greatest potential, and that the most profitable production process would be anaerobic fermentation with the production of biogas and alcohol. Moreover, in the latter case a specific fermentation process would need to be developed. It also explained that it is necessary to reduce raw material costs by at least 75% in comparison with present levels. It concluded by saying that the contribution of algae to the energy mix in the year 2020 will be a modest one (0.2% of fuel for transport provided by macroalgae and 1% by microalgae) and that there is considerable interest in non-energy products such as nutraceutics, pigments, proteins, functional food and other chemical components.

What productivity could these crops achieve?

On the basis of experiments carried out with crops of *Saccharina latissima* in Galicia in rope curtain systems, maximum productions of 25 t dw $ha^{-1}year^{-1}$ are estimated.

Macroalgae cultures employed in the biofiltation of fish farms effluents and flue gases.
Photography courtesy of Marine Biotechnology Centre, University of Las Palmas de Gran Canaria - National Algae Bank.

4

Road Map

Developing a national R&D&i plan with the object of attaining success in the sustainable production of algae for energy purposes is fundamental, along with a long-term financial commitment. In order to attract a similar level of aid to foster development as other renewable technologies, this programme should be based on three criteria: a positive energy balance, a positive ecological balance and on being economically competitive in comparison with conventional fossil fuels.

The following criteria and actions are proposed to ensure that the cultivation of algae for energy purposes reaches its full potential:

4.1. PRELIMINARY STEPS

- CREATION OF A DATABASE OF PROJECTS IN THE EXECUTION PHASE. The first compilation of national projects, drawn up by BIOPLAT, is attached as an appendix to this present document.

- REPORT ON TECHNOLOGIES under development and existing facilities.

- IDENTIFICATION OF TECHNOLOGICAL BARRIERS. Progress in this field should proceed by:

  - Obtaining the best species of algae. Development of a programmed, standardised campaign in the medium term (5-8 years) to:

    a. Prospect for new species.

    b. Assess their productive potential (high yield and low adherence).

    c. Identify (conventional and genomic) and conserve (conventional and cryogenic) the strains studied.

    d. Describe the physiological variables of biotechnological interest in the new species.

    e. Increase basic and applied research in the genetics, biochemistry, physiology and photobiology of algae in order to determine the possibilities of enhancing these factors.

    f. Select algae with high growth potential in exterior cultivation conditions (low solar radiation) and with a suitable biochemical profile due to the composition and richness in compounds useful for energy production (carbohydrates, lipids).

    g. Study the resistance of the selected algae to environmental factors in order to facilitate large-scale cultivation with minimum pollution and maximum strength.

  - Development of cultivation technologies: the search to increase production, energy efficiency and materials enhancement. The production of algal biomass should be associated with:

    a. Research progress in the design and operation of photobioreactors, in the capture of light and use of new materials allowing cost reductions both of installation and operation, with little maintenance and long useful life. Plastic materials for photobioreactors should be transparent to solar radiation, ultra-violet filtering, antifouling, rigid, low-cost and recyclable. The viability of the use of these reactors will have to be proven in external cultivation, minimising energy consumption and maximising their operability. It would be useful to verify productivity values on a suitable scale (demonstration plants) during at least one annual cycle.

Photography courtesy of University of Almeria. Chemical Engineering Department.

b. Preferential use of waters not suitable for agricultural use. The use of effluents proceeding from fish factories, slurry WWTP etc. would seem, along with brackish or sea water, to be the most sustainable options.

c. Integral management of nutrient programmes (CO_2 from industrial flue gases as a source of carbon, recovery of fertilisers, recycling the culture medium, etc.) permitting closing the material balances with the minimum loss.

d. Minimise the use of fertilisers, favouring the use of nitrogen-fixing organisms or algae with minimum nitrogen requirements.

e. Development of simpler and more profitable production designs and technologies.

f. Establishment of analysis methods of real life-cycles, and energy and materials balances, allowing an adequate balance to be made of the process; that is to say, acquire knowledge of what contribution of material and energy is necessary for the production of algal biomass.

g. Advances in artificial illumination systems (optical fibre, LEDs, energy-saving lamps etc,) could solve problems related to lack of solar radiation levels, if the economic and energy balances are favourable.

- Downstream development (harvest and processing): pre-concentration, dehydration, drying, oil extraction and integral biomass energy recovery.

  a. Harvesting must be based on very low-cost systems (capital and labour). The development of mesoalgae and self-flocculating multi-specific systems should be taken into account as strategies.

  b. Processing should be undertaken in integrated biorefineries. The search for oleaginous strains should be complemented with the objective of obtaining fermentable biomass.

  c. Prepare low-cost technologies (economic and energy) for recovery and transformation of the biomass through to the final product, and which permit concentration of the crop to values adequate for processing (10-20% dry weight).

  d. Develop integral harvesting of the biomass produced in addition to the production of biofuel, which takes into account the use of residual material remaining after extraction, applying in this way the concept of biorefinery to algal biomass.

• DEFINITION OF THE AREAS needing greater reinforcement (technical-economic), in order to reduce costs and achieve enhanced adaptation to Spanish conditions. Identification and assessment of all external factors, which can influence production costs. In conclusion, an analysis should be made to detect the factors (variables) having the greatest effect in order to prioritise and devote more effort in these areas. Probably the most important of these in the current situation are factors related to: the reduction of operating and maintenance costs (especially the consumption of energy, water, CO_2 and the useful life of the facilities), the recovery and commercialisation of the products, the enhancement of performance and the reduction of investment costs.

- **SCALEABLE DEMONSTRATION WITH LARGE-SCALE VISION.** As research advances, it will be necessary to have pilot facilities, which will not necessarily need to be excessively large, in which to verify and demonstrate the developments, so that data obtained permit the large-scale implementation of algae production for energy purposes. As far as possible, these pilot facilities should have easy access to CO_2 emission points and seawater and/or wastewater. The research should permit the development of industrial modules and scaleable cultivation systems, which allow large-scale sustainable production to be achieved.

- **STUDY OF ENVIRONMENTAL SYNERGIES:**

  - Integration of the aquicultural and agricultural systems. If the cultivation of freshwater microphytes for the production of biomass for energy purposes is considered, the cultivation technologies will have to be linked to the integration of the algae aquaculture system with the conventional agricultural system.

  - According to the European Renewable Energy Directive 2009/28/EC, in the case of conventional biofuels the cultivation of algae could attain some kind of ecological sustainability certificate guaranteeing the adequate use of natural systems.

- Establishment of conditions required FOR ENERGY OBTAINED FROM ALGAE TO BE CONSIDERED WITHIN THE FRAMEWORK OF THE NATIONAL POLICY ON RENEWABLE ENERGIES.

IN SCHEMATIC FORM, THE PRELIMINARY STEPS FOR THE PROPOSED PLAN TO MEET WITH SUCCESS IN THE SUSTAINABLE PRODUCTION OF ALGAE FOR ENERGY PURPOSES WOULD BE:

- **SPECIES:**
  - Prospecting.
  - Genetic modification.
- **CULTIVATION TECHNOLOGIES:**
  - Optimisation of production.
  - Energy efficiency.
  - Materials enhancement.
- **DOWNSTREAM DEVELOPMENT:**
  - Pre-concentration processes.
  - Dehydration.
  - Extraction and separation.
  - New “wet processing” technologies.
  - Biofuel production: biodiesel, bioethanol, biogas.
- **OPTIMISATION OF INPUTS:**
  - Gases.
  - Water consumption.
  - Nutrient consumption.
- **BIOREFINERY:**
  - Integral harnessing of the biomass:
    - Energy products.
    - High added value products.
    - Nutrition.
    - Aquiculture.

4.2 STAKEHOLDERS

Only through integrated research connecting the laboratory scale with the industrial plant, with the participation of companies and research groups, will steady progress be possible towards the achievement of algal biomass-based biofuel. It is not only necessary to attain more economic resources for R&D&i, but also to manage them in the best manner possible.

The following may be considered as stakeholders in this plan for production of algae for energy purposes:

- The Public Sector:
  - Ministerial departments related to innovation and energy.
  - Public research bodies.
  - Universities.
- Private sector:
  - Energy, chemical, pharmaceutical and nutritional sectors amongst others.
  - Companies of all sizes.
  - Technology centres.

4.3 COLLABORATION CRITERIA AND MOTIVATION

The production of biomass for energy purposes is currently a scientific reality, which still needs to be investigated and developed in order to become an industrial reality.

Thus, research and development should be fostered through the joint collaboration of scientists and technicians from different fields and companies involved in the sector, all of which must set the objectives and scopes required to make this type of processes viable. The work to be done should embrace the main critical points dealt with by numerous researchers and, above all, failed experiments should not be repeated in order to ensure optimum harnessing of the available resources.

Public initiatives individually applied, until now, have not been able to reach the expectations raised for the promotion of microalgae cultivation. Proof of this is that, after years of research, significant industrial development has not been achieved. In turn, it is extraordinarily difficult for the private sector to develop this without government aid. Therefore, collaboration and coordination between public and private bodies, in particular within the science-technology-company system, is fundamental for success.

4.4 COLLABORATION MODELS

These should be in line with those currently existing, and would consist of:

- Public-private consortia:
  - The creation of consortia with public financial backing to create 2 or 3 platforms of pre-industrial scale where their modular and/or up-scaleable nature could be demonstrated (areas of around 10-20 ha).
  - Each of these consortia should be composed of industrial groups, technology centres and universities.
  - Designation of a nationwide coordination centre: this centre would be answerable to the ministerial department that had provided the aid.
  - These consortia should report the results obtained to the coordinating body.

- Private consortia with public economic, technical and scientific support:
  - Intervention of the public sector in the private consortia would not be necessary. The consortia would contract these aids without exclusivity rules, thus maintaining independence from the technology centres and universities.
  - A national coordination centre would be set up linked to the public body responsible for the plan. All public research proceeding from technology centres and universities would be centralised here.

Irrespective of the collaboration model, the availability of an algal biomass R&D&i technology coordinating centre to centralise the work carried out would be advisable. This public coordinating centre should:

- Facilitate synergy, coordination and R&D critical mass.
- Foster the development of basic research groups in algal taxonomy, genetics, biochemistry and physiology to form the basis for innovation in applied projects.
- Facilitate maximum progress in the identification and solution of problems, accelerating the implementation of a new industrial ecosystem.

The organisation of a public system research network (universities, technology centres, public research bodies, etc.) with a technical coordinating centre, preferably public, on the production of algal biomass for energy purposes, would favour suitable synergies for progress in basic and applied knowledge on the cultivation of algae and the diversification of production plants. Thus, in zones with adequate radiation doses, algae strains and cultivation systems could be chosen different from those for other zones characterised by a high availability of nutrients: industrial effluents, CO_2-emitting industrial plants, etc.

4.5 FEATURES OF THE MICROALGAE SECTOR

Establishing specific objectives with reference to the production of algae-based biofuels is currently an extremely complex task due to the technological immaturity of the system. The only estimations available at present are theoretical, based on laboratory data and small pilot schemes.

The development of algae as a renewable energy source should receive different treatment to that traditionally received by other renewable energies, since it is not possible, at least at present, to base its development on the final product. In fact, large-scale technical-economic viability has not yet been proven, which demonstrates the importance of developing pre-industrial facilities. Once this development has been reached, with the capacity to extrapolate reliably the results obtained, it will be time to define the exploitation system for this new energy source.

Pilor scale production of the lipogenic microalgae *Nannochlopsis* in tubular photobioreactor.
Photography courtesy of Marine Biotechnology Centre, University of Las Palmas de Gran Canaria - National Algae Bank.

Cultivation of lipogenic microalgae in small photobioreactors (Almeida et al., 2010).
Photography courtesy of Marine Biotechnology Centre, University of Las Palmas de Gran Canaria - National Algae Bank.

4.6 TIMELINE

The following timeline could reflect what needs to be established for the development of the plan:

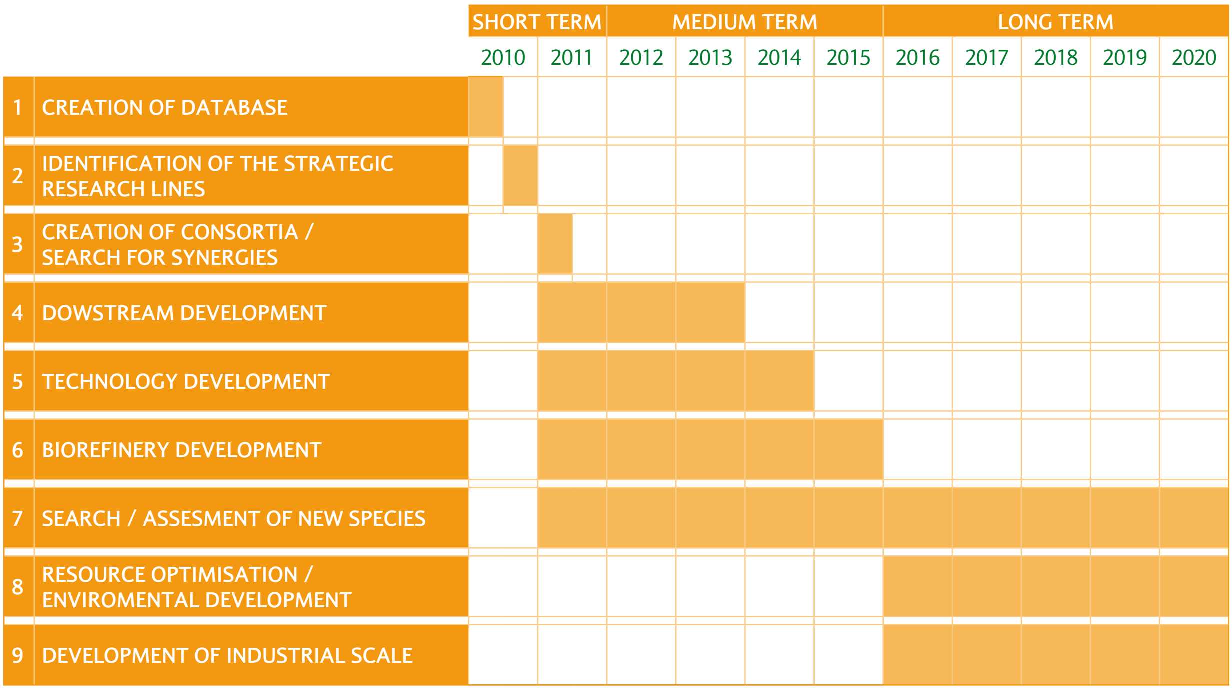


Figure 7, Timeline.

5

References

- Comprehensive Oilgae Report, 2009, Energy from Algae: Products, Market, Processes & Strategies.
- US Department of Energy, 2009, National Algal Biofuels Technology Roadmap.
- Directive 2009/28/EC of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources.
- PER 2005-2010: Plan de Energías Renovables (Spanish Renewable Energies Plan).
- G. García Reina, 1999, Marine Agronomy: Reality, Utopia or Necessity? Editorial UNED.
- Huntley, M.E., A. Nonomura, and J. de la Noüe, 1989, Algal Culture Systems, in Biotreatment of Agricultural Wastewater. Edited by M.E. Huntley, pp. 111-130, CRC Press, Boca Raton, Florida (USA).
- Jeffrey Duke, 2003, Burning Buried Sunshine: Human Consumption of Ancient Solar Energy. Department of Biology of the University of Massachusetts.
- Bioenergy Task 42: Biorefineries: Co-production of Fuels, Chemicals, Power and Materials from Biomass. International Energy Agency (IEA).
- Biotechnology and Bioprocess Engineering Vol. 14, 2009. Korean Society for Biotechnology and Bioengineering.
- Buschmann, A., Hernández-González, M. Varela D., 2008, Seaweed Future Cultivation in Chile: Perspectives and Challenges. International Journal of Environment and Pollution 33: 432-456.
- Chopin, T., Buschmann, A.H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G.P., Zertuche-González, J.A., Yarish, C., Neefus, C., 2001, Integrating Seaweeds into Marine Aquaculture System: a Key Toward Sustainability. Journal of Phycology 37: 975–986.
- Neori, A., T. Chopin, M. Troell, A.H. Buschmann, G.P. Kraemer, C. Halling, M. Shpigel, C. Yarish, 2004, Integrated Aquaculture: Rationale, Evolution and State of the Art Emphasizing Seaweed Biofiltration in Modern Mariculture. Aquaculture 231: 361–391.
- Algal Biomass Summit, Seattle (USA) October 2008.
- E. Molina Grima, F. G. Acién Fernández, F. García Camacho, Yusuf Chisti, 1999, Photobioreactors: Light Regime, Mass Transfer, and Scaleup. Journal of Biotechnology 70, 1-3, 231-247.
- C. Brindley Alías, M.C. García-Malea López, F.G. Acién Fernández, J.M. Fernández Sevilla, J.L. García Sánchez and E. Molina Grima, 2004, Influence of Power Supply in the Feasibility of *Phaeodactylum tricornutum* Cultures. Biotechnology and Bioengineering 87(6): 723-733.

- Berenguel M, Rodríguez F, Acién FG, Garcia JL, 2004, Model Predictive Control of Tubular Biological Photobioreactors. Journal of Process Control 14: 377-387.

- Vergara, Fernández and colleagues, 2008, Biomass and Bioenergy 32: 338-344.

- Isabel Albarracín, Microalgas: potenciales productoras de biodiésel, (Microalgae: Potential Producers of Biodiesel), October 2007. XV Simposio electrónico internacional. Facultad de Ciencias Naturales, UNPSJB, Argentina. (15th International Electronics Symposium, Faculty of natural Sciences, UNPSJB, Argentina).

- Peter K. Campbell, Tom Beer, David Batten, Greenhouse Gas Sequestration by Algae Energy and Greenhouse Gas Life Cycle Studies.

- Recommended Lifecycle Analysis of Algal Production Systems. June 2009. Algal Biomass Organization (ABO).

- National Renewable Energy Laboratory, US Department of Energy's Office of Fuels Development, July 1998. A Look Back at the US Department of Energy's Aquatic Species Program: Biodiesel from Algae.

Appendix 1

List of algae projects in Spain

1. LIST OF PROJECTS

	PROJECT	COORDINATING BODY
1	Algae and aquatic biomass for a sustainable production of 2nd generation biofuel aquafuel.	University of Almería.
2	Algae: Integral Solutions.	Neiker-Tecnalia, Basque Institute of Agricultural Research and Development.
3	Analysis of biological samples. Drafting of an atlas of benthic diatoms of the Duero river catchment area.	University of León.
4	*In vitro* tests for the early detection of phytotoxins in samples of populations of multi-specific phytoplankton.	IRTA, Institut de Recerca i Tecnologia Agroalimentaries.
5	Harnessing of algae as CO_2 absorbers and biodiesel and bioethanol extraction.	Agricultural Research Centre La Orden Valdesequera.
6	National Algae Bank.	Marine Biotechnology Centre University of Las Palmas de Gran Canaria.
7	BANGEN - Macaronesia Marine Organism Bank.	Marine Sciences Institute of the Canary Islands.
8	Bi-phase crop cutaneous bioactivity in microalgae extracts.	BIOAGRAMAR Foundation, Sustainable Biotechnology and Marine Agronomy.
9	BIOACU - Project for the energy recovery of microalgae crops in plants powered by renewable energies (bio-accumulators: Production of biodiesel and CO_2 emission fixing by microalgae crops).	Canary Islands Technical Institute.
10	BIOALGAL - Use of various microalgae for the extraction of active elements for the cosmetics and food industries.	Technological Centre LEITAT.
11	Marine biodiversity.	University of Almería.
12	BIOMAQUA - Development and technology integration project for integral energy harnessing of microalgae.	Technological Centre CIDAUT.
13	BIOMODULAR H2 - Solar radiation-based biohydrogen production.	Polytechnic University of Valencia.
14	BIOPURÍN - Integral mixotrophic (microalgae-bacteria) system for the biodegradation of slurry, capture of CO_2 and biofuel production.	University of Málaga.
15	BIOSOS - Sustainable Biorefinery.	Abengoa Bioenergía, S.A.
16	BIOTEC - Adaptation mechanisms of the eukaryotic microbial community (microalgae) in extremely acid environments. Resistance to heavy metals and their application in bioremediation.	INTA, National Institute of Aerospace Technique.
17	CO_2 biocapture capacity by marine microalgae: Implications for global change.	University of Cádiz.
18	Capture and sequestration of CO_2 from stationary combustion sources by photosynthetic microorganisms.	Technology Centre LEIA.
19	Marine Agronomy and Microalga Biotechnology Technology Centre.	BIOAGRAMAR Foundation, Sustainable Biotechnology and Marine Agronomy.
20	Methodological comparison for the determination of paralysing toxins in bivalves related to Paralytic Shellfish Poisoning (PSP). Application to aquaculture in Spain.	IRTA Institute of Agriculture Food Research and Technology.
21	Intensive microalgae cultivation for the production of biomass for energy purposes associated with the biofiltration of CO_2.	Marine Biotechnology Centre University of Las Palmas de Gran Canaria.
22	Development of photobioreactors for the treatment of slurry.	ITACyL, Agrarian Technology Institute of the Castilla and León Government, University of León, University of Valladolid.
23	Development of new experimental microalgae photobioreactors.	BIOAGRAMAR Foundation, Sustainable Biotechnology and Marine Agronomy.
24	Development of an industrial algae-based biodiesel production plant.	ALGAENERGY, S.A.

	PROJECT	COORDINATING BODY
25	Development of a detection system based on the analysis of ADN for the enhancement of monitoring of blooming of toxic microalgae for the fishing industry in the north east of the Mediterranean.	IRTA Institute of Agriculture Food Research and Technology.
26	Development of genetic modification technologies in lipogenic algae.	Technology Centre GAIKER-IK4.
27	Development of recovery technologies in microalgae for energy purposes.	Technology Centre GAIKER-IK4.
28	Development of a process to obtain natural colouring agents of biotechnological interest from microalgae.	University of Almería.
29	Development of a lutein production process aimed at human consumption based on microalgae.	University of Almería.
30	Development of an industrial microalgae production process as a determining factor for aquaculture.	University of Almería.
31	Developments in the food industry, pharmacy, energy and chemistry based on microalgae.	Technology Centre LEIA.
32	Determination of diarrhetic and lipophilic toxins through liquid chromographics coupled to mass spectrometry (LC-MS-MS) and cytotoxic methods for the assessment of the food quality of bivalves.	IRTA Institute of Agriculture Food Research and Technology.
33	Scaling of a heterotrophic algae production process for the production of lipid of industrial interest.	University of Almería.
34	Ecological status and vulnerability of Mediterranean aquatic ecosystems to climatic change: Functional indicators and adaptive responses to stress, temperature, UV radiation and nutrients.	University of Málaga.
35	Open ponds.	ALBIOOIL.
36	Study of microbial communities in the skin and digestive tract of sole and goldfish under pre- and probiotic treatment: bacteria and algae.	University of Málaga.
37	Study of the viability of the use of microalgae in the treatment of wastewater: Biofixing of CO_2 and biofuel production.	University of Cádiz.
38	Study of microalgae as biomass prior to the production of biofuel.	Technology Centre INASMET-Tecnalia.
39	Study of microalgae harnessing in the environment of the Guadalquivir marshes.	El Toruño Centre of the Andalusian Institute of Agricultural, Fishing and Food Training and Research and Ecological Production; Institute of Plant Photosynthetic Biochemistry University of Seville-CSIC; Pesquerías Isla Mayor S.A.
40	Study of the treatment of wastewater with high persistent heavy metal and organic compound content with microalgae of economic interest.	University of Cádiz.
41	Assessment of the cultivation of diatoms for the production of liquid and solid fuels.	University Rovira i Virgili, Tarragona.
42	FAM - Project focused on the design and development of new microalgae-based food formats.	Canary Islands Technical Institute.
43	Photosynthetic fixing of CO_2 present in industrially generated gases by cyanobacteria cultures.	Institute of Plant Biochemistry and Photosynthesis University of Seville-CSIC.
44	Flexible polymer photobioreactor in seawater.	Algasol Renewables, S.L.
45	Photoproduction of bioethanol based on cyanobacteria CO_2.	Institute of Plant Biochemistry and Photosynthesis University of Seville-CSIC.
46	Alternative biomass sources, microalgae in animal nutrition.	University of Las Palmas de Gran Canaria.
47	Photosynthetic generation of carbonated polymers coupled to the elimination of CO_2.	Institute of Plant Biochemistry and Photosynthesis, University of Seville-CSIC; University Almería.

	PROJECT	COORDINATING BODY
48	GREEN DESERTS - Integrated Aqua-Agro Biotechnologies.	BIOAGRAMAR Foundation, Sustainable Biotechnology and Marine Agronomy.
49	The importance of marine toxins in fishing products and agriculture in Catalonia: Risk assessment and proposals for management.	IRTA Institute of Agriculture Food Research and Technology.
50	CO_2 and UV radiation increment as stress factors in the modification of biodiversity and marine phytoplankton production in scenarios of climate change: Molecular bases.	University of Málaga.
51	Engineering of bioprocesses applied to the cultivation of dinoflagellates for the production of bioactive substances. Cultivation of marine dinoflagellates of alimentary, pharmaceutical and environmental interest.	University of Almería.
52	Investigation and development of technologies for the enhancement of energy efficiency, capture and assessment of CO_2.	Technology Centre LEIA.
53	LACTOMIC - Project for reuse of lactoserums from cheese-making for the production of microalgae by fermentation with high long-chain polyunsaturated fatty acid content.	Canary Islands Technical Institute.
54	MaCaNf - Sustainable cultivation of marine microalgae to obtain various products for the chemical (polymers) and cosmetics industries. Development of sustainable photobioreactors and of biomass recycling processes and harnessing for energy.	Technological Centre LEITAT.
55	Marine and freshwater microalgae.	University of Santiago de Compostela.
56	Microalgae and biodiesel.	IRTA, Institut de Recerca i Tecnologia Agroalimentaries.
57	Microecology and changes in the biogeochemical cycles of carbon and nitrogen in tidal sediments produced by macroalgae blooms.	University of Cádiz.
58	New methods for extraction of compounds of interest from microalgae: wet processing and SWE extraction.	Technology Centre LEIA.
59	To obtain algae-based compounds with immunostimulant properties.	Technology Centre AINIA.
60	Omega algae.	Monzon Biotech S.L.
61	PETROCMF - Assessment of cultivation of *Botryococcus braunii* microalgae for the treatment of slurry: To obtain biomass and biofuel.	Centro Mediterráneo de Fotobiología, S.L.
62	Pilot plant for the production of microalgae to obtain biodiesel.	Acciona Biocombustibles, S.L. (Acciona Energía, S.A.).
63	Population Dynamics and Toxicity of Harmful Microalgae in Coastal Embayments.	IRTA Institute of Agriculture Food Research and Technology.
64	Biological process for purging of combustion gases through the employment of photosynthetic organisms.	University of Almería.
65	HBC process for the production of biodiesel from algal oils.	BECTEL Ingenieros, S.L.
66	Production of biodiesel based on cyanobacteria and microalgae.	Instituto Biomar, S.A.
67	Production of biodiesel based on microalgae.	Institute of Plant Biochemistry and Photosynthesis University of Seville-CSIC.
68	Production of biodiesel based on microalgae.	University of Almería.
69	Production of Photonal: Analysis of the production of long-chain bioalcohol based on photosynthetic organisms.	Polytechnic University of Valencia.
70	PSE Microalgae - production and assessment of microalga-based biomass.	Biotecnología de Microalgas, S.L.

	PROJECT	COORDINATING BODY
71	Immune-strengthening system through microalgae-based immunostimulant compounds.	Technology Centre AINIA.
72	Iodine requirements and synthesis of thyroid hormones in marine microalgae.	El Toruño Centre of the Andalusian Institute of Agricultural, Fishing and Food Training and Research and Ecological Production.
73	Selection of hyperlipidic strains of marine microalgae through fluid cytometry.	Marine Biotechnology Centre University of Las Palmas de Gran Canaria.
74	Carbon system in biocapture reactors with marine microalgae: control of CO_2 injection and overall balances.	University of Cádiz.
75	SITE - Integral system of energy transfer.	Bio Fuel Systems, S.L.
76	SOST-CO_2 - New sustainable industrial uses of CO_2. Application of photosynthetic microorganisms for the transformation of fermentation CO_2 and transformation of CO_2 through microalgae and conversion into products.	Carburos Metálicos, S.L.
77	Sustainable and Environmentally Friendly Aquaculture for the Atlantic Region of Europe.	University of Bangor (Great Britain); El Toruño Centre of the Andalusian Institute os Agricultural, Fishing and Food Training and Research and Ecological Production.
78	Employment of microalgae with high oil content for the elimination for nutrients in wastewater, biofixing of CO_2 and biofuel production.	University of Cádiz.
79	Energy recovery of combustion gas CO_2 by fixing through microalgae.	Institute of Plant Biochemistry and Photosynthesis, University of Seville-CSIC; University Almería.
80	Energy recovery of the biostimulation capacity of microorganisms and bioactive substances: application to fish farming.	Universities of Almería, Cádiz and Málaga.
81	The vulnerability of aquatic ecosystems in the south of the Iberian Peninsula in the face of global change. Ultraviolet radiation and the supply of mineral nutrients.	University of Granada.

2. LIST OF PROJECTS BY ORGANISATION

COORDINATING BODY		PROJECT
Abengoa Bioenergía, S.A.	15	BIOSOS - Sustainable Biorefinery.
Acciona Biocombustibles, S.L. (Acciona Energía, S.A.).	62	Pilot plant for the production of microalgae to obtain biodiesel.
Agricultural Research Centre La Orden Valdesequera.	5	Harnessing of algae as CO_2 absorbers and biodiesel and bioethanol extraction.
ALBIOOIL.	35	Open ponds.
ALGAENERGY, S.A.	24	Development of an industrial algae-based biodiesel production plant.
Algasol Renewables, S.L.	44	Flexible polymer photobioreactor in seawater.
BECTEL Ingenieros, S.L.	65	HBC process for the production of biodiesel from algal oils.
BIOAGRAMAR Foundation, Sustainable Biotechnology and Marine Agronomy.	8	Bi-phase crop cutaneous bioactivity in microalgae extracts.
	19	Marine Agronomy and Microalgae Biotechnology Technology Centre.
	23	Development of new experimental microalgae photobioreactors.
	48	GREEN DESERTS - Integrated Aqua-Agro Biotechnologies.
Bio Fuel Systems, S.L.	75	SITE - Integral system of energy transfer.
Biotecnología de Microalgas, S.L.	70	PSE Microalgae - production and assessment of microalgae-based biomass.
Canary Islands Technical Institute.	9	BIOACU - Project for the energy recovery of microalgae crops in plants powered by renewable energies (bio-accumulators: Production of biodiesel and CO_2 emission fixing by microalgae crops).
	42	FAM - Project focused on the design and development of new microalgae-based food formats.
	53	LACTOMIC - Project for reuse of lactoserums from cheese-making for the production of microalgae by fermentation with high long-chain polyunsaturated fatty acid content.
Carburos Metálicos, S.L.	76	SOST-CO_2 - New sustainable industrial uses of CO_2. Application of photosynthetic microorganisms for the transformation of fermentation CO_2 and transformation of CO2 through microalgae and conversion into products.
Centro Mediterráneo de Fotobiología, S.L.	61	PETROCMF - Assessment of cultivation of *Botryococcus braunii* microalgae for the treatment of slurry: To obtain biomass and biofuel.
El Toruño Centre of the Andalusian Institute of Agricultural, Fishing and Alimentary Training and Research and Ecologic Production.	72	Iodine requirements and synthesis of thyroid hormones in marine microalgae.
El Toruño Centre of the Andalusian Institute of Agricultural, Fishing and Alimentary Training and Research and Ecologic Production; Institute of Plant Photosynthetic Biochemistry - University of Seville-CSIC; Pesquerías Isla Mayor S.A.	39	Study of microalgae harnessing in the environment of the Guadalquivir marshes.
Institute of Plant Biochemistry and Photosynthesis - University of Seville-CSIC.	43	Photosynthetic fixing of CO_2 present in industrially generated gases by cyanobacteria cultures.

COORDINATING BODY		PROJECT
Institute of Plant Biochemistry and Photosynthesis - University of Seville-CSIC.	45	Photoproduction of bioethanol based on cyanobacteria CO_2.
	67	Production of biodiesel based on microalgae.
Institute of Plant Biochemistry and Photosynthesis - University of Seville-CSIC; University Almería.	47	Photosynthetic generation of carbonated polymers coupled to the elimination of CO_2.
	79	Energy recovery of combustion gas CO_2 by fixing through microalgae.
Instituto Biomar, S.A.	66	Production of biodiesel based on cyanobacteria and microalgae.
INTA, National Institute of Aerospace Technique.	16	BIOTEC - Adaptation mechanisms of the eukaryotic microbial community (microalgae) in extremely acid environments. Resistance to heavy metals and their application in bioremediation.
IRTA, Institute of Agriculture, Food Research and Technology.	4	*In vitro* tests for the early detection of phytotoxins in samples of populations of multi-specific phytoplankton.
	20	Methodological comparison for the determination of paralysing toxins in bivalves related to Paralytic Shellfish Poisoning (PSP). Application to aquaculture in Spain.
	25	Development of a detection system based on the analysis of ADN for the enhancement of monitoring of blooming of toxic microalgae for the fishing industry in the north east of the Mediterranean.
	32	Determination of diarrhetic and lipophilic toxins through liquid chromographics coupled to mass spectrometry (LC-MS-MS) and cytotoxic methods for the assessment of the alimentary quality of bivalves.
	49	The importance of marine toxins in fishing products and agriculture in Catalonia: Risk assessment and proposals for management.
	56	Microalgae and biodiesel.
	63	Population Dynamics and Toxicity of Harmful Microalgae in Coastal Embayments.
ITACyL, Agrarian Technology Institute of the Castilla and León Government, University of León, University of Valladolid.	22	Development of photobioreactors for the treatment of slurry.
Marine Biotechnology Centre - University of Las Palmas de Gran Canaria.	6	National Algae Bank.
	21	Intensive microalgae cultivation for the production of biomass for energy purposes associated with the biofiltration of CO_2.
	73	Selection of hyperlipidic strains of marine microalgae through fluid cytometry.
Marine Sciences Institute of the Canary Islands.	7	BANGEN - Banco de organismos marinos de la Macaronesia. (Macaronesia Marine Organism Bank).
Monzon Biotech S.L.	60	Omega algae.
Neiker-Tecnalia, Basque Institute of Agricultural Research and Development.	2	Algae: Integral Solutions.
Technology Centre AINIA.	59	To obtain algae-based compounds with immunostimulant properties.
	71	Immune-strengthening system through microalgae-based immunostimulant compounds.
Technological Centre CIDAUT.	12	BIOMAQUA - Development and technology integration project for integral energy harnessing of microalgae.

COORDINATING BODY		PROJECT
Technology Centre GAIKER-IK4.	26	Development of genetic modification technologies in lipogenic algae.
	27	Development of recovery technologies in microalgae for energy purposes.
Technology Centre INASMET-Tecnalia.	38	Study of microalgae as biomass previous to the production of biofuel.
Technology Centre LEIA.	18	Capture and sequestration of CO_2 from stationary combustion sources by photosynthetic microorganisms.
	31	Developments in the food industry, pharmacy, energy and chemistry based on microalgae.
	52	Investigation and development of technologies for the enhancement of energy efficiency, capture and assessment of CO_2.
	58	New methods for extraction of compounds of interest from microalgae: Wet processing and SWE extraction.
Technological Centre LEITAT.	10	BIOALGAL - Use of various microalgae for the extraction of active elements for the cosmetics and food industries.
	54	MaCaNf - Sustainable cultivation of marine microalgae to obtain various products for the chemical (polymers) and cosmetics industries. Development of sustainable photobioreactors and of biomass recycling processes and harnessing for energy.
Polytechnic University of Valencia.	13	BIOMODULAR H_2 - Solar radiation-based biohydrogen production.
	69	Production of Photonal: Analysis of the production of long-chain bioalcohol based on photosynthetic organisms.
Universities of Almería, Cádiz and Málaga.	80	Energy recovery of the biostimulation capacity of microorganisms and bioactive substances: Application to fish farming.
University of Almería.	1	Algae and aquatic biomass for a sustainable production of 2nd generation biofuel aquafuel.
	11	Marine biodiversity.
	28	Development of a process to obtain natural colouring agents of biotechnological interest from microalgae.
	29	Development of a lutein production process aimed at human consumption based on microalgae.
	30	Development of an industrial microalgae production process as a determining factor for aquaculture.
	33	Scaling of a heterotrophic algae production process for the production of lipid of industrial interest.
	51	Engineering of bioprocesses applied to the cultivation of dinoflagellates for the production of bioactive substances. Cultivation of marine dinoflagellates of food, pharmaceutical and environmental interest.
	64	Biological process for purging of combustion gases through the employment of photosynthetic organisms.
	68	Production of biodiesel based on microalgae.

COORDINATING BODY		PROJECT
University of Bangor (Great Britain);El Toruño Centre of the Andalusian Institute of Agricultural, Fishing and Alimentary Training and Research and Ecologic Production; Pesquerías Isla Mayor, S.A.	77	Sustainable and Environmentally Friendly Aquaculture for the Atlantic Region of Europe.
University of Cádiz.	17	CO_2 biocapture capacity by marine microalgae: Implications for global change.
	37	Study of the viability of the use of microalgae in the treatment of wastewater: Biofixing of CO_2 and biofuel production.
	40	Study of the treatment of wastewater with high persistent heavy metal and organic compound content with microalgae of economic interest.
	57	Microecology and changes in the biogeochemical cycles of carbon and nitrogen in tidal sediments produced by macroalgae blooms.
	74	Carbon system in biocapture reactors with marine microalgae: Control of CO_2 injection and overall balances.
	78	Employment of microalgae with high oil content for the elimination for nutrients in wastewater, biofixing of CO_2 and biofuel production.
University of Granada.	81	The vulnerability of aquatic ecosystems in the south of the Iberial Peninsula in the face of global change. Ultraviolet radiation and the supply of mineral nutrients.
University of Las Palmas de Gran Canaria.	46	Alternative biomass sources, microalgae in animal nutrition.
University of León	3	Analysis of biological samples. Drafting of an atlas of benthic diatoms of the Duero river catchment area.
University of Málaga	34	Ecological status and vulnerability of Mediterranean aquatic ecosystems to climatic change: Functional indicators and adaptive responses to stress, temperature, UV radiation and nutrients.
	14	BIOPURÍN - Integral mixotrophic (microalgae-bacteria) system for the biodegradation of slurry, capture of CO_2 and biofuel production.
	36	Study of microbial communities in the skin and digestive tract of sole and goldfish under pre- and probiotic treatment: Bacteria and algae.
	50	CO_2 and UV radiation increment as stress factors in the modification of biodiversity and marine phytoplankton production in scenarios of climate change: Molecular bases.
University of Santiago de Compostela	55	Marine and freshwater microalgae.
University Rovira i Virgili, Tarragona.	41	Assessment of the cultivation of diatoms for the production of liquid and solid fuels.

3. LIST OF PROJECTS BY GEOGRAPHIC LOCATION

LOCATION		PROJECT		COORDINATING BODY
Andalusia.	Almería	24	Development of an industrial algae-based biodiesel production plant.	ALGAENERGY, S.A.
		11	Marine biodiversity.	University of Almería.
		28	Development of a process to obtain natural colouring agents of biotechnological interest from microalgae.	
		29	Development of a lutein production process aimed at human consumption based on microalgae.	
		30	Development of an industrial microalga production process as a determining factor for aquaculture.	
		33	Scaling of a heterotrophic algae production process for the production of lipid of industrial interest.	
		47	Photosynthetic generation of carbonated polymers coupled to the elimination of CO_2.	
		51	Engineering of bioprocesses applied to the cultivation of dinoflagellates for the production of bioactive substances. Cultivation of marine dinoflagellates of food, pharmaceutical and environmental interest.	
		51	Engineering of bioprocesses applied to the cultivation of dinoflagellates for the production of bioactive substances. Cultivation of marine dinoflagellates of food, pharmaceutical and environmental interest.	
	Almería; Cádiz; Málaga.	67	Production of biodiesel based on microalgae.	Universities of Almería, Cádiz and Málaga.
	Almería; Seville.	79	Energy recovery of combustion gas CO_2 by fixing through microalgae.	Institute of Plant Biochemistry and Photosynthesis - University of Seville-CSIC; University Almería.
		80	Energy recovery of the biostimulation capacity of microorganisms and bioactive substances: Application to fish farming.	
	Cádiz.	17	Open ponds.	ALBIOOIL.
		39	Study of microalgae harnessing in the environment of the Guadalquivir marshes.	El Toruño Centre of the Andalusian Institute of Agricultural, Fishing and Food Training and Research and Ecological Production; Institute of Plant Photosynthetic Biochemistry - University of Sevilla-CSIC; Pesquerías Isla Mayor S.A.

LOCATION		PROJECT		COORDINATING BODY
Andalusia.	Cádiz.	57	Iodine requirements and synthesis of thyroid hormones in marine microalgae.	El Toruño Centre of the Andalusian Institute of Agricultural, Fishing and Food Training and Research and Ecological Production.
		35	Study of the viability of the use of microalgae in the treatment of wastewater: Biofixing of CO_2 and biofuel production.	University of Cádiz.
		37	Study of the treatment of wastewater with high persistent heavy metal and organic compound content with microalgae of economic interest.	
		40	Microecology and changes in the biogeochemical cycles of carbon and nitrogen in tidal sediments produced by macroalgae blooms.	
		72	CO_2 biocapture capacity by marine microalgae: Implications for global change.	
		74	Carbon system in biocapture reactors with marine microalgae: Control of CO_2 injection and overall balances.	
		78	Employment of microalgae with high oil content for the elimination for nutrients in wastewater, biofixing of CO_2 and biofuel production.	
	Granada.	81	The vulnerability of aquatic ecosystems in the south of the Iberian Peninsula in the face of global change. Ultraviolet radiation and the supply of mineral nutrients.	University of Granada.
	Málaga.	61	PETROCMF - Assessment of cultivation of *Botryococcus braunii* microalgae for the treatment of slurry: To obtain biomass and biofuel.	Centro Mediterráneo de Fotobiología, S.L.
		14	BIOPURÍN - Integral mixotrophic (microalgae-bacteria) system for the biodegradation of slurry, capture of CO_2 and biofuel production.	University of Málaga.
		34	Ecological status and vulnerability of Mediterranean aquatic ecosystems to climatic change: Functional indicators and adaptive responses to stress, temperature, UV radiation and nutrients.	
		36	Study of microbial communities in the skin and digestive tract of sole and goldfish under pre- and probiotic treatment: Bacteria and algae.	

LOCATION		PROJECT		COORDINATING BODY
Andalusia.	Málaga.	50	CO_2 and UV radiation increment as stress factors in the modification of biodiversity and marine phytoplankton production in scenarios of climate change: Molecular bases.	University of Málaga.
	Seville.	43	Photosynthetic fixing of CO_2 present in industrially generated gases by cyanobacteria cultures.	Institute of Plant Biochemistry and Photosynthesis- University of Seville-CSIC.
		45	Photoproduction of bioethanol based on cyanobacteria CO_2.	
		68	Production of biodiesel based on microalgae.	University of Almería.
Aragón.	Huesca (Castejón del Puente).	60	Omega algae.	Monzon Biotech S.L.
Balearic Islands.	Balearic Islands (Majorca).	44	Flexible polymer photobioreactor in seawater.	Algasol Renewables, S.L.
Basque Country.	Álava.	18	Capture and sequestration of CO_2 from stationary combustion sources by photosynthetic microorganisms.	Technology Centre LEIA.
		31	Developments in the food industry, pharmacy, energy and chemistry based on microalgae.	
		52	Investigation and development of technologies for the enhancement of energy efficiency, capture and assessment of CO_2.	
		58	New methods for extraction of compounds of interest from microalgae: Wet processing and SWE extraction.	
		2	Algae: Integral Solutions.	Neiker-Tecnalia, Basque Institute of Agricultural Research and Development.
	Bizkaia.	26	Development of genetic modification technologies in lipogenic algae.	Technology Centre GAIKER-IK4.
		27	Development of recovery technologies in microalgae for energy purposes.	
	Guipúzcoa.	38	Study of microalgae as biomass prior to the production of biofuel.	Technology Centre INASMET-Tecnalia.
Canary Islands.	Las Palmas.	6	National Algae Bank	Marine Biotechnology Centre - University of Las Palmas de Gran Canaria.
		21	Intensive microalgae cultivation for the production of biomass for energy purposes associated with the biofiltration of CO_2.	
		73	Selection of hyperlipidic strains of marine microalgae through fluid cytometry.	
		8	Bi-phase crop cutaneous bioactivity in microalgae extracts.	BIOAGRAMAR Foundation, Sustainable Biotechnology and Marine Agronomy.

LOCATION			PROJECT	COORDINATING BODY
Canary Islands.	Las Palmas.	19	Marine Agronomy and Microalgae Biotechnology Technology Centre.	BIOAGRAMAR Foundation, Sustainable Biotechnology and Marine Agronomy.
		23	Development of new experimental microalgae photobioreactors.	
		48	GREEN DESERTS - Integrated Aqua-Agro Biotechnologies.	
		7	BANGEN Macaronesia Marine Organism Bank.	Marine Sciences Institute of the Canary Islands.
		9	BIOACU - Project for the energy recovery of microalgae crops in plants powered by renewable energies (bio-accumulators: Production of biodiesel and CO_2 emission fixing by microalgae crops).	Canary Islands Technical Institute.
		42	FAM - Project focused on the design and development of new microalgae-based food formats.	
		53	LACTOMIC - Project for reuse of lactoserums from cheese-making for the production of microalgae by fermentation with high long-chain polyunsaturated fatty acid content.	
		46	Alternative biomass sources, microalgae in animal nutrition.	University of Las Palmas de Gran Canaria.
Castilla and León.	León.	3	Analysis of biological samples. Drafting of an atlas of benthic diatoms of the Duero river catchment area.	University of León.
		66	Production of biodiesel based on cyanobacteria and microalgae.	Instituto Biomar, S.A.
	Valladolid.	22	Development of photobioreactors for the treatment of slurry.	ITACyL, Agrarian Technology Institute of the Castilla and León Government, University of León, University of Valladolid.
Castilla and León.; Community of Valencia; Basque Country.	Valladolid (CIDAUT); Valencia (AINIA); Bizkaia (GAIKER).	12	BIOMAQUA - Development and technology integration project for integral energy harnessing of microalgae.	Technological Centre CIDAUT.
Catalonia.	Barcelona.	65	HBC process for the production of biodiesel from algal oils.	BECTEL Ingenieros, S.L.
	Tarragona.	4	*In vitro* tests for the early detection of phytotoxins in samples of populations of multi-specific phytoplankton.	IRTA, Institute of Agriculture, Food Research and Technology.

LOCATION		PROJECT		COORDINATING BODY
Catalonia.	Tarragona.	20	Methodological comparison for the determination of paralysing toxins in bivalves related to Paralytic Shellfish Poisoning (PSP). Application to aquaculture in Spain.	
		25	Development of a detection system based on the analysis of ADN for the enhancement of monitoring of blooming of toxic microalgae for the fishing industry in the north east of the Mediterranean.	
		32	Determination of diarrhetic and lipophilic toxins through liquid chromographics coupled to mass spectrometry (LC-MS-MS) and cytotoxic methods for the assessment of the alimentary quality of bivalves.	
		49	The importance of marine toxins in fishing products and agriculture in Catalonia: Risk assessment and proposals for management.	
		56	Microalgae and biodiesel.	
		63	Population Dynamics and Toxicity of Harmful Microalgae in Coastal Embayments.	
		41	Assessment of the cultivation of diatoms for the production of liquid and solid fuels.	University Rovira i Virgili, Tarragona.
Community of Madrid.	Madrid.	16	BIOTEC - Adaptation mechanisms of the eukaryotic microbial community (microalgae) in extremely acid environments. Resistance to heavy metals and their application in bioremediation.	INTA, National Institute of Aerospace Technique.
Community of Valencia.	Alicante.	75	SITE - Integral system of energy transfer.	Bio Fuel Systems, S.L.
	Valencia.	71	Immune-strengthening system through microalga-based immunostimulant compounds.	Technology Centre AINIA.
		13	BIOMODULAR H_2 - Solar radiation-based biohydrogen production.	Polytechnic University of Valencia.
		69	Production of Photonal: Analysis of the production of long-chain bioalcohol based on photosynthetic organisms.	
Extremadura.	Badajoz (Finca La Orden, Guadajira).	5	Harnessing of algae as CO_2 absorbers and biodiesel and bioethanol extraction.	Agricultural Research Centre La Orden Valdesequera.
Galicia.	La Coruña (Santiago de Compostela).	55	Marine and freshwater microalgae.	University of Santiago de Compostela.
Navarre.	Navarre (Caparroso).	62	Pilot plant for the production of microalgae to obtain biodiesel.	Acciona Biocombustibles, S.L. (Acciona Energía, S.A.).

LOCATION	PROJECT		COORDINATING BODY
Spain.	15	BIOSOS - Sustainable Biorefinery.	Abengoa Bioenergía, S.A.
	76	SOST-CO_2 - New sustainable industrial uses of CO_2. Application of photosynthetic microorganisms for the transformation of fermentation CO_2 and transformation of CO_2 through microalgae and conversion into products.	Carburos Metálicos, S.L.
	59	To obtain algae-based compounds with immunostimulant properties.	Technology Centre AINIA.
	70	PSE Microalgae - production and assessment of microalgae-based biomass.	Biotecnología de Microalgas, S.L.
European Union	10	BIOALGAL - Use of various microalgae for the extraction of active elements for the cosmetics and food industries.	Technological Centre LEITAT.
	54	MaCaNf - Sustainable cultivation of marine microalgae to obtain various products for the chemical (polymers) and cosmetics industries. Development of sustainable photobioreactors and of biomass recycling processes and harnessing for energy.	
	1	Algae and aquatic biomass for a sustainable production of 2nd generation biofuel aquafuel.	University of Almería.
	77	Sustainable and Environmentally Friendly Aquaculture for the Atlantic Region of Europe.	University of Bangor (Great Britain); El Toruño Centre of the Andalusian Institute of Agricultural, Fishing and Food Training and Research and Ecological Production; Pesquerías Isla Mayor, S.A.

GEOGRAPHIC DISTRIBUTION OF THE PROJECTS

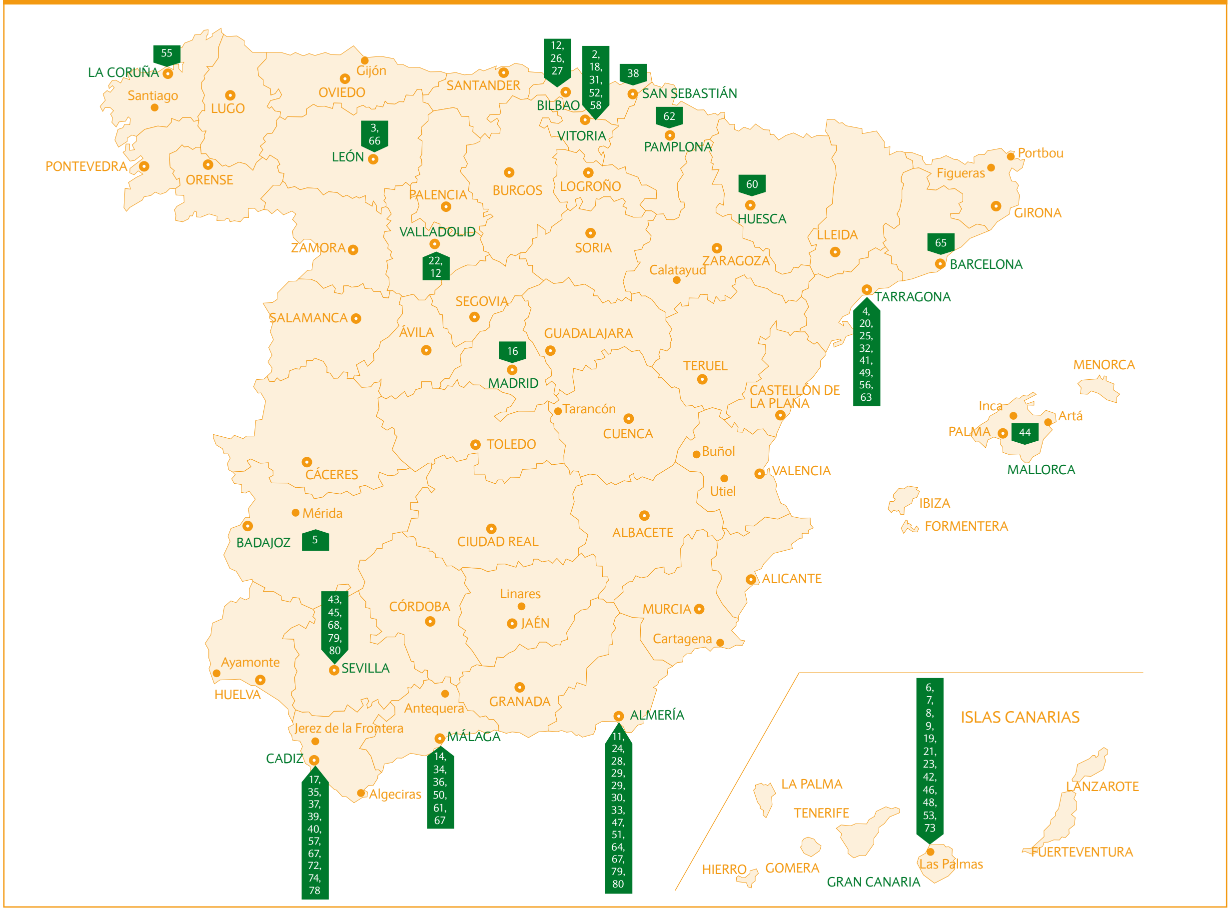


Figura 8, Algae projects map.

4. PROJECTS CLASSIFICATION BY THEMATIC AREA

The following graph shows the classification of the projects compiled according to the main development field:

PROJECTS CLASSIFICATION BY THEMATIC AREA

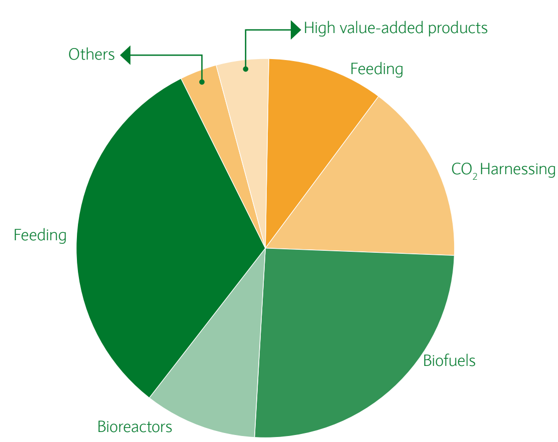


Figura 9, Project classification graph.