Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Final Report

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D'APPOLONIA
consulting, design, operation & maintenance engineering

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European Commission DG ENERGY Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Final Report

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1	Second Issue	GGB	ALV/LFA/CSM	CSM	PAR	June 2015
0	First Issue	GGB	ALV/LFA	CSM	PAR	April 2015

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ALGAE BIOENERGY SITING, COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS FINAL REPORT

1 INTRODUCTION

The technical assistance on algae bioenergy siting, commercial deployment and development analysis (hereafter: the Project), service contract number ENER/C2/2012/421-1, awarded to the Consortium constituted by D'Appolonia (DAPP), SELC – Biologia e geologia applicate (SELC) and University of Padua (UNIPD) by the European Commission, Directorate General (DG) Energy, has a duration of 15 Months.

The Project, started in January 2014, is mainly focused on the scaling up of algal bioenergy and co-product chains in European market, and it is articulated in the following tasks, besides the activities performed concerning the project management (Task5):

- Task 0 – Project start-up;
- Task 1 – Siting of algae cultivation systems;
- Task 2 – Identification of the most promising bioenergy and co-product chains;
- Task 3 – Overcoming the barriers;
- Task 4 – Final wrap up and awareness raising.

The first deliverable of the technical assistance was the Inception Report, delivered on February and consisting of the project implementation plan and of the visibility strategy.

The Interim Report, second official deliverable submitted in July 2014, had the scope to inform the EC of the progress of the assignment and of the achieved results after a period of six months of analyses, before its final completion.

The present document follows the same approach as the Interim Report, and provides a full overview of the activities carried out, of the applied approaches, and of the final figures of the analysis. Its main objective is to share the findings of the analysis over the entire time span of the assignment, which encompassed the phases of algae siting, of analysis of the most promising biofuel and co-products chains, of assessment of the main barriers and identification of a set of recommendations to overcome the latter.

The assignment has now got to its conclusion and the document is therefore focused on activities carried out during the overall 15-month period.

The Final Report is composed of the following Sections:

- Section 1 outlines the main objective and the structure of this Report;
- Section 2 illustrates the activities carried out within project start-up (Task 0) and project management (Task 5);
- Section 3 is a description of the activities performed in Task 1, the algae cultivation systems siting phase;

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- Section 4 presents the analysis of the most promising production chains for bioenergy and co-products, including a comparison of the proposed approach with the real experiences of the three FP7 projects of the AlgaeCluster (Task 2);
- Section 5 is dedicated to Task 3, the assessment of the main barriers to the development of the production chains and to the provision of a set of recommendations to overcome those barriers;
- Section 6 encompasses the description of the activities concerning the final wrap up and dissemination of the project achievements (Task 4);
- conclusions are finally drawn in Section 7.

The project team is based on six Key Experts, leading the colleagues through the pillars of the analysis, identified in a Project Manager and Environmental Assessment Expert, an Algae Cultivation Expert, a Bioenergy Process Expert, a Life Cycle Assessment Expert, a GIS Mapping and Analysis Expert and finally an Environmental Economics Expert.

Along the realization of the services, several interim technical analyses were prepared by the Key Experts of the team upon conclusion of the several work packages; these technical deliverables are enclosed in appendices to ease the readability of this document. Among them, it is possible to find a GIS database for the identification of the most promising locations for siting, SWOT analyses of both cultivation and biofuel/co-products extraction, LCAs, recommendations.

The Report is structured in a way so as to be as much intelligible as possible for an external reader who is looking for an overview of the activities. To this aim, the chapters that follow are a summary of the main findings of each project task, whereas the complete Interim Technical Reports prepared along the project development are enclosed in the Appendixes.

The technical reports enclosed in the Appendixes are the following:

- Appendix A: Microalgae cultivation systems and environmental indicators;
- Appendix B: Selection of microalgae;
- Appendix C: Best Siting Suitability Maps;
- Appendix D: Approach to the LCA;
- Appendix E: SWOT Analysis – Algae Cultivation;
- Appendix F: SWOT Analysis – Biofuel and Co-Products Chains;
- Appendix G: Barriers Analysis and Recommendations;
- Appendix H: Questionnaire for Data Collection to FP7 Projects;
- Appendix I: Slides from the Event in Seville;
- Appendix J: Abstract for LCA Workshop in Brussels;
- Appendix K: Slides from the LCA Workshop in Brussels;
- Appendix L: Slides from the Final Event in Brussels.

2 PROJECT START-UP & MANAGEMENT

2.1 WP 0.1: TEAM MOBILIZATION AND ORGANIZATION

The operational work team including representatives and Key Experts of the Consortium members was established and they have been called to explain the objectives of their involvement, the work that has been allocated to them and how they fit within the overall plan. Moreover, the cooperation mechanisms and the procedures for the internal and external communication were set, ensuring a shared communication strategy. The planning of the periodical work progress meeting was also defined.

The preliminary Visibility Strategy and the detailed Project Implementation Plan to validate the project proposal with amendments derived from the Kick-off Meeting were prepared and delivered to European Commission in form of Inception Report.

In particular, the Visibility Strategy contains indications on how the technical assistance aims at reaching the audience and how the Project will effectively communicate its activities and results. On the other hand, the project implementation plan describes all the activities envisaged within the assignment, task by task.

2.2 WP 0.2: STAKEHOLDERS' ENGAGEMENT

Stakeholder engagement encompasses a range of activities and interactions over the life of the Project, including stakeholders identification, information disclosure, stakeholders consultation and involvement.

The involvement of the stakeholders was done following a two-fold path: on one hand, starting from the available contacts of the Consortium members; on the other, through the proper introduction by the EC, a fruitful communication was established with the focal points of the three FP7 funded demonstration projects under AlgaeCluster. This phase was essential to inform them about the Project purposes, to ensure mutual cooperation as input providers in the Project chain and to define the collaboration mechanisms that are essential elements for proper project development. The phase of consultation with the stakeholders is constantly in place through the exchange of emails, the participation to events and the exchange of interim figures useful to the network of specialists working on the algae topic.

2.3 WP 0.3: DATA COLLECTION

The data collection phase was performed as the most critic and important phase of the Project. Accurate data collection is essential to maintain the integrity of the Project since its results will be highly dependent on the quality of input data. For this reason, the selection of appropriate data collection instruments and sources are of paramount importance to reduce the likelihood of errors occurring. This phase is made up of the following steps:

- identification of accurate and reliable data sources;
- data collection and analysis;
- preparation and submission of questionnaires.

The main relevant data derived from literature review (scientific publications, biofuel best practices, case studies, Consortium past experiences and European ongoing and completed projects), stakeholders involvement and consultation during meeting along with questionnaires delivered to stakeholders with a particular attention to already funded FP7 projects.

Once alternative data sources were identified, the data collection process begun. The process includes acquisition and assembly of required data and conversion to appropriate formats for the analysis. An inventory of the background and baseline data was created in order to set up the reference dataset and implement the following Project phases.

Structured and detailed questionnaires were also prepared and delivered to relevant stakeholders and implementers via email. In particular, these checklists were circulated to all the AlgaeCluster projects focal points and other identified stakeholders to collect data on different site-specific projects. These documents include specific questions concerning the whole biofuel and co-product chains under environmental, technical and economic perspectives which can help define the baseline dataset. The objective is to gather technical data related to practical case studies proven by experience and to strength the collaboration with the relevant stakeholders. The complete checklist can be found in the Appendix H.

2.4 PROJECT MANAGEMENT (TASK 5)

Project Management falls under Task 5 of the Project Implementation Plan. A detailed overview of the followed Project schedule, including the most relevant milestones and the interim deliveries can be found in the GANTT chart presented in Figure 2.1. The overall Project Coordination has been undertaken by the Project Manager, being the major responsible and contact point for the EC throughout the entire project duration for the overall project strategy implementation including project planning, performance and financial control, quality assurance, risk management and contingency planning, and administration of the Community financial contribution. In this context the following activities have been performed:

- represent the beneficiaries towards the European Commission, being the intermediary for any communication between the Commission and any beneficiary;
- receive the Community financial contribution to the project on behalf of the beneficiaries, administer the community financial contribution regarding its allocation between beneficiaries and activities;
- review the reports to verify consistency with the project tasks before transmitting them to the Commission;
- organization of official project meetings such as periodic Progress Meetings, Steering Committee meetings, Reviews of the European Commission;
- distribution of deliverables and reports to the consortium, and maintenance of a project archive in the form of a document repository to be hosted by the project website (private area with exclusive accession by the participants only);
- facilitation of internal communication management, ensuring that an adequate level of communication exists among the consortium, including through the preparation of minutes of meetings, and circulars to the consortium where appropriate;
- control over the timely implementation of the project’s duties by the team, including the collection of inputs for Periodic Reports and for the Final Report, and the preparation of Deliverables, ensuring that the project implementation is undertaken by all beneficiaries in full compliancy with the general conditions set forth by the contract.

It is worth noticing that, in order to efficiently organize the work development and limit duplication of costs, meetings , steering committees with the presence of all the Key Experts, site visits of mission and events (also pertaining to other tasks or work packages) have been as much as possible grouped and organized as different sessions of the same event. In addition, conference calls with all the key experts were organized every month for project tuning and scheduling of the required activities. Dedicated phone calls involving two or more key experts were held even more frequently, every time that a discussion on a relevant interdisciplinary topic was required before proceeding with a task of the project.

At the end of each task, a draft of the intermediate deliverables were shared among the partners for comments, reviews and discussion before the official submission. Similarly, the most relevant intermediate technical deliverables were shared with the EC – DG Energy officer to update him on the development of the Project, and receive his comments, advices and approval. During the whole duration of the project, communication was active with the representatives of the FP7 projects of the AlgaeCluster. The interaction with them was intensified in the final stages of the project, for two main reasons: the stronger technical background of the partners and the availability of updated information from both sides.

TASK	Months															
Workpackage	Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15
Task 0 – Project Start Up																
WP 0.1: Team Mobilization and Organization	M1 09/01/20	D 0.1 D.0.2														
WP 0.2: Stakeholders' Engagement		D.0.3														
WP 0.3 Data Collection			D.0.4													
Task 1 – Siting of Algae Cultivation Systems																
WP 1.1: GIS Mapping of Algae Cultivation Systems Deployment Potential						D.1.1-1.3 D.1.4										
WP 1.2: Algae Cultivation System Deployment Impact Analysis									D.1.5 D.1.6 D.1.7							
WP 1.3 Algae Cultivation System Deployment Potential Analysis										D.1.8						
Task 2 – Identification of Most Promising Bioenergy and Co-Product Chain																
WP 2.1: Bioenergy and Co-Product Chain Analysis										D.2.1						
WP 2.2: Case Studies										D.2.2						
WP2.3: Bioenergy and Co-Product Chain Deployment Potential Analysis												D.2.3				
Task 3 – Overcoming the Barriers																
WP 3.1: Barriers Analysis													D.3.1-3.2			
WP 3.2: Algae Cultivation and Bioenergy Deployment Action Plan															D.3.3	
Task 4 – Final Wrap Up And Awareness Raising																
WP 4.1: Final Report																D.4.1
WP 4.2: Final Workshop																D.4.2
WP 4.3: Dissemination Activities			D.4.3	D.4.4				D.4.5				D.4.6				D.4.7
Task 5 – Project Management																
Report		R.1					R.2							R.3		
Meeting	M1 09/01/20			M2?										M3		M4
Steering Committe				SC.1			SC2					SC.3				SC.4

Figure 2.1: Project Time Schedule

3 TASK 1 – SITING OF ALGAE CULTIVATION SYSTEMS

3.1 WP 1.1 – GIS MAPPING OF ALGAE CULTIVATION SYSTEMS DEPLOYMENT POTENTIAL

The main objective of this WP is to create high definition suitability maps in digital format for optimal site planning of the selected algal cultivation systems for different cultivation environments by means of a GIS based Spatial Decision Support System.

This system helps identify the best solution from a set of alternatives of siting algae plant and therefore it assists the decision-makers and other stakeholders in complex decision processes.

This Section provides a general description of the activities carried out as well as of the achieved results, while the specific assumptions and outcomes can be found in the Technical Report in Appendix.

3.1.1 Siting Phase Assumptions

The siting of algae cultivation systems relies on relevant assumptions that underpin proposed project activities:

- this work stands as baseline for the best siting analysis of algal cultivation plants and therefore an in-depth feasibility analysis is essential to identify the most suitable location for the specific case study;
- the threshold values used for the selection of advantageous locations represent the most suitable values and best practices currently available;
- standard minimum size for both PBR and open pond (100 ha).

The following box presents the main assumptions used in the analysis.

Foreword: the complexity and variety of processes involving microalgae impose to take onboard some assumptions allowing for a macroscopic analysis of the system being investigated. In several cases, such assumptions do not represent a threshold determining whether a process is technically feasible or not. Instead, they represent a number of sensible recommendations based on the current state of technology, some general economic indicators, and engineering good practice. In other words, it is not stated that, if such assumptions do not hold, a microalgae-based technology cannot be envisaged, but that some special (local) conditions must exist so as to justify an exceptional outcome.
Consistently to what declared above, the following assumptions are taken into account:

- **Temperature**
  An annual average temperature is used as a threshold for selecting regions suitable for algae cultivation (i.e. it is assumed that average temperature must be equal or higher than 15 °C). Note the below 15 °C, for most microalgae the growth rate is reduced dramatically.

- **Irradiation**
  A minimum annual solar radiation of 1500 kWh m^{-2} $year^{-1}$ is assumed. In fact, considering that the yield is proportional to the available light energy and that in large scale autotrophic cultivation plants, biomass conversion efficiency is not higher than 2-3%, it is economically sensible to include in the analysis only those regions with a high productivity potential.

- **Evaporation and precipitation**
  In the case of open pond technologies, annual evaporation is assumed to be less than 1000 mm/y (to reduce the technology water footprint and/or minimize pollutant/salt concentration issues), whereas rainfall is supposed not to exceed 600 mm/y (to limit dilution issues).

- **Elevation**
  Although not explicitly indicated the mapping of suitable sites for simple problem of resolution, it is assumed that no cultivation technology can be established if located at a quota that is more than 100 m higher than the quota of the available source of water (to reduce pumping costs).

- **Growth driving force**
  The analysis focuses on the autotrophic cultivation of microalgae. In fact, if the long-term objective is to achieve both security and sustainability, it makes sense to rely on solar energy and not to "transfer" the issue on the availability of a different raw materials that may be converted by microalgae. Thus, although heterotrophic cultivation could be profitable for value-added products or in some special cases where cheap carbon-based nutrients may be available, it is unlikely to represent the technology for large scale fuel production. Note that this assumption des not exclude mixotrophic approaches, where both light and nutrients are combined synergically.

Box 3.1: Assumptions on Environmental Indicators and Thresholds

3.1.2 Selection of Microalgae Cultivation Technologies

After an overview of the current stage of development of available engineering designs and practices for microalgae cultivation, the selection of a range of effective technologies was carried out. Microalgae cultivation can be done in open-culture systems (open ponds) and in highly controlled closed-culture systems (photobioreactors). For the purpose of the Project, both technologies are taken into account.

In terms of cultivation environments, the approach has been that of retaining quite a generic and broad-view perspective. Thus, most water categories have been included in the analysis, i.e. seawater, freshwater, wastewater as well as some mixed environments where the addition of a wastewater source may represent a sensible choice to minimize costs for nutrients (especially nitrogen-based ones). We decided to exclude the combination seawater plus wastewater in the case of PBRs as fouling issues may become particularly severe in such equipment configurations.

The list of the selected technologies for several cultivation conditions is provided in the Table 3.1.

Table 3.1: Selected Cultivation Technologies and Environments

Cultivation Technology	Cultivation Environment
OPEN PONDS	seawater
	freshwater
	wastewater
	seawater + wastewater
	freshwater + wastewater
PHOTOBIOREACTORS	seawater
	freshwater
	wastewater
	freshwater + wastewater

3.1.3 Selection of Microalgae Species

An in-depth and systematic investigation of microalgal strains to identify optimal microalgae species for biofuel production was carried out as essential step for the development of the following Project phases. In particular, a preliminary selection of the algal taxa and classification of the most promising microalgae were performed. Taking into account Project objectives, the microalgae are considered, excluding macroalgae species.

The most promising species of microalgae were selected, carrying out an analysis of the species used in FP7 pilot projects or reported in the most recent scientific literature and taking into account the experience of Consortium.

The methodological approach used to select microalgae species focused on biological aspects in the first phase, then practical aspects have been considered. The most relevant microalgae features as well as the factors affecting biodiesel productivity that are analyzed include:

- biomass productivity/growth rate (volumetric and areal biomass productivity);
- growth conditions;
- resistance to environmental conditions variations (temperature/PH/salinity);
- cell composition (lipid, protein, carbohydrate content);

- co-products and application areas;
- cultivation systems (open pond/PBR).

The algal strains to be cultivated should be selected based on many criteria, among which biomass productivity, cell composition and environmental growth conditions would be primary but also co-products applications and cultivation technologies represent relevant aspects to be taken into account. High lipid productivity is not the only factor that should be considered early during strain selection. Outdoor cultivation should determine whether the selected microalgae are robust enough to withstand variable local climatic conditions and whether they can dominate a culture. As for co-product availability, it is expected that microalgae that offer a multiple product portfolio as part of a biorefinery will be most applicable to large-scale commercial cultivation. Besides fatty acids with properties relevant for biodiesel production, high value products such as antioxidants, vitamins, omega-3 fatty acids should also be taken into account.

A preliminary qualitative analysis was carried out to evaluate species suitability, taking into account biological aspects. Moreover, a quantitative analysis of the identified species production in raceway ponds and PBR using different cultivation environments (freshwater, seawater and wastewater) was performed. According to all the previous criteria, ten taxa (genus/species) have been selected.

The complete list of the most promising microalgae species is provided in the Technical Report in Appendix B to compare the biomass and lipid production, growth conditions, co-product applications and culture techniques of well-known microalgae quoted from various literatures and FP7 projects.

3.1.4 Selection and Mapping of the Most Suitable Macro-Areas

According to the WP objectives, the selection and the mapping of the most advantageous locations for algae cultivation plants deployment at EU-28 scale were carried out. The analysis was based on three different levels of details: macro-areas selection, site-zones selection within the identified macro-areas and Site Territorial Unit (STU) selection within site-zones. This first phase describes the results of the selection of macro-areas suitable for algal cultivation at European scale. The methodological approach followed in this phase is illustrated in Figure 3.1.

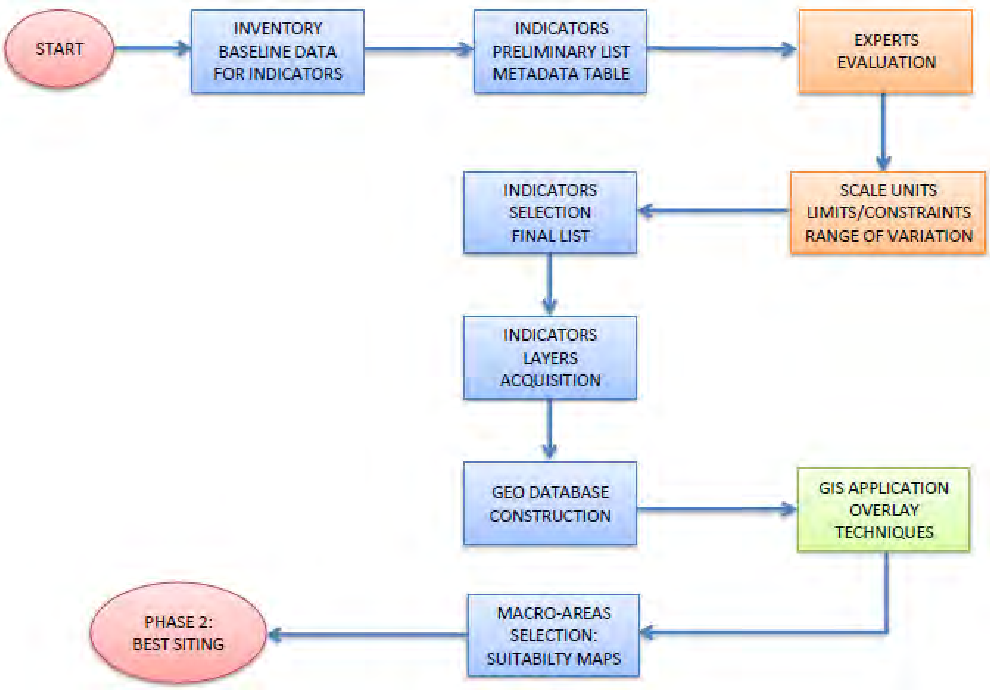


Figure 3.1: Methodological Flow-Chart of the Macro-Areas Suitability Map Phase

An initial data acquisition phase was performed: territorial data layers (shape and raster files) have been searched and downloaded from official sources (Eurostat, EEA, etc.) mainly concerning administrative boundaries, climate parameters (annual mean temperature, solar radiation, etc.), physical and elevation maps. The inventory of acquired datasets that are used in the Project is provided in the Technical Report in Appendix. Consequently, the data layers have been arranged in a geodatabase for the elaboration phase that is developed with open source GIS.

In parallel, a core set of climatic/environmental indicators to detect the potentially ideal locations that are derived from literature review (scientific studies, research papers, etc.) and experts consultation was identified and then restricted to the most relevant ones (solar irradiation and air temperature) to define suitability at macro-level. These indicators represent one of the main features that a location should have for successful growth of microalgae and were mapped at European level. For the selected indicators, threshold criteria were defined according to project experts consultation in order to filter macro-areas suitable for algae cultivation.

Preliminary selection of the macro-areas was made using solar irradiation and air temperature and three wider geographical belts were identified (non-suitable, suitable and buffer zone) applying the threshold criteria. Therefore, the final outcome of this section is the production of high definition macro-areas suitability maps in digital format, as baseline for the best siting analysis of algal cultivation plants.

Figure 3.2 shows EU-28 Administrative Units layer at NUTS 3 level overlaid to the physical map of Europe (Switzerland is included in the original NUTS database layer), highlighting three different belts based on suitability degree: non-suitable areas (brown areas), buffer zones (yellow areas) and suitable areas (green areas). The buffer zone includes intermediate areas that are near to suitability. From the suitability map analysis, it is possible to outline that the suitable areas fall within the 43° N latitude, including almost all the Mediterranean area. The selection of the macro-areas does not take into account different algae cultivation systems (open ponds, photobioreactors) that will be analyzed in the next step.

A detailed description of the aforementioned results and assumptions of this section can be found in the Technical Report of Appendix C.

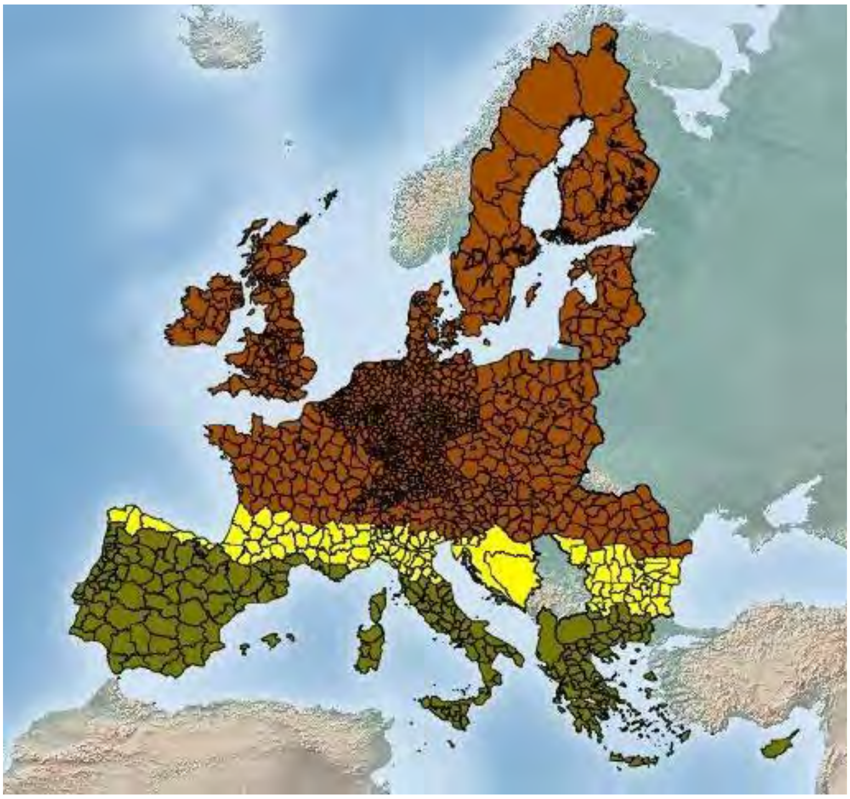


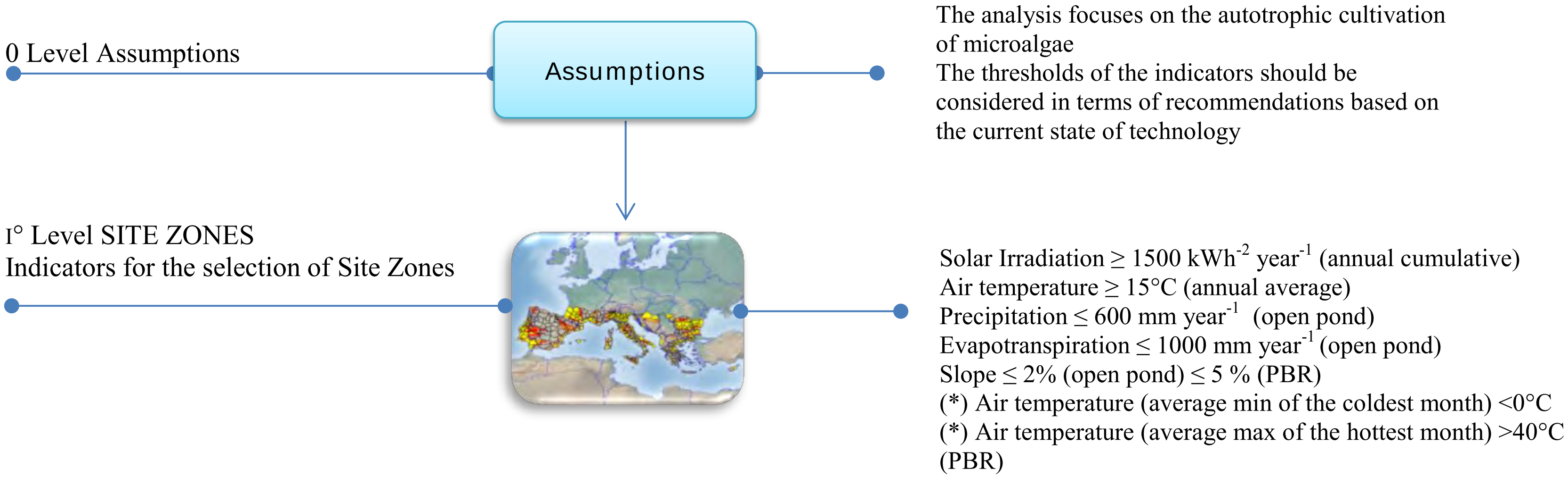
Figure 3.2: Macro-Area Suitability Map

3.1.5 Selection and Mapping of the Most Suitable Site-Zones

As previously described, three macro-areas for algae cultivation systems with different level of suitability (suitable-areas, non-suitable areas and buffer zone) were identified at European scale using as indicators annual solar irradiation and annual mean air temperature. The next step includes site-zones selection within the detected macro-areas for the two algae cultivation systems: detection of photobioreactors (PBR) suitable site zones and open ponds suitable site zones. In particular, nine different cases are considered due to the combination of the selected cultivation technologies (PBR and open pond) and environments (seawater, fresh water and wastewater).

The Site Zones are defined as *zones at regional scale, within the macro areas and the buffer zone, where to detect suitable sites for algae cultivation plants*. The Site Zones are separately detected for each major group of algae cultivation plants (PBR, Open Ponds).

The selection process was carried out applying different filters (threshold criteria for environmental/climatic indicators) to areas belonging to suitable and buffer zones. The methodological approach that was followed in this section is shown in Figure 3.3.



(*) Control parameters. Used after the selection of the Site Zones to verify the exclusion of areas having those values from the site zones.

Figure 3.3: Methodological Flow-Chart of the Site Zone Selection Phase

Results

The results of this section is the production of high definition PBR and open pond suitable site zones maps according to some relevant indicators and thresholds as presented in the flowchart of Figure 3.3.

The Site Zones maps are presented in Figure 3.4 for Open Ponds, and in Figure 3.5 for PBR. The most remarkable SZ suitable areas for the Open Ponds are:

- Southern Portugal and S-W Spain (coast and internal regions), S-E coast of Spain;
- In Italy, some parts of Sardinia, Sicily, and Apulia;
- Some parts of the Eastern coast of Greece and of Cyprus.

For the PBR, being the selection criteria less exclusive, the most evident areas result wider with respect to the Open Ponds, e.g.:

- Southern Portugal and the whole S-W Spain, almost all the Mediterranean coast of Spain;
- In Italy, wide areas of Sardinia, Sicily, Apulia and also some coastal Tyrrhenian areas and Calabria;
- Greater part of Eastern Greece, Ionian coasts of Greece and Crete;
- Almost all areas in Cyprus.

Figure 3.4: Site Zones Map for Open Ponds Systems

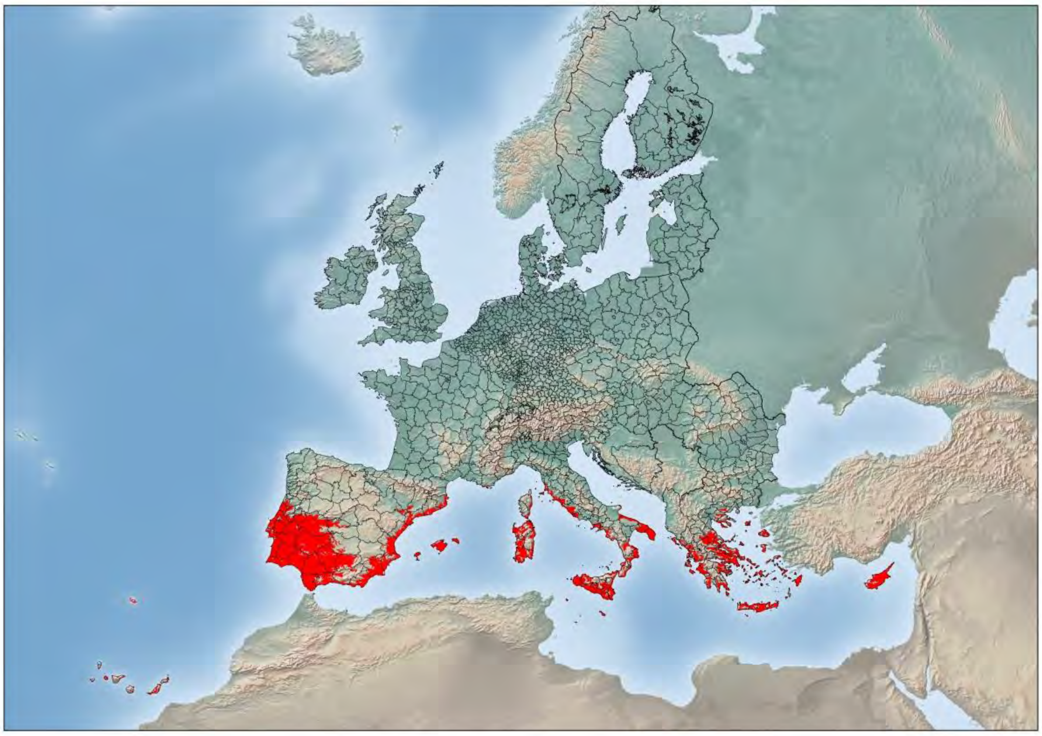


Figure 3.5: Site Zones Map for PBR Systems

3.1.6 Detection and Ranking of the Most Suitable Site Territorial Units

This step concerns the detection of Site Territorial Units within the identified site zones and the application of SDSS to rank the most suitable ones for algae cultivation.

The Site Territorial Units (STU) are defined as *areas, within the Site Zones, where it is possible to build one or more algae cultivation plants, at different classes of capability.*

The STU have been detected for each type of algae cultivation plants as defined and selected by the project experts. A total of 9 types of plants were considered for the STU selection and the S-DSS analysis, grouped in two major categories, Open Ponds and Photobioreactors. The indicators considered and the thresholds applied for extracting the STU from the Site Zones, are shown in Figure 3.6.

SITE ZONES

	OPEN PONDS Sea water	OPEN PONDS Fresh water	OPEN PONDS Waste water	OPEN PONDS Sea water Waste water	OPEN PONDS Fresh water Waste water	PBR Sea water	PBR Fresh water	PBR Waste water	PBR Fresh water Waste water
II° Level STU. Indicators for the identification of Site Territorial Units STU	Exclusion from protected areas Exclusion from urban areas Minimum area ≥ 2 km^2 Proximity to sea ≤ 1 km Elevation ≤ 100 m	Exclusion from protected areas Exclusion from urban areas Minimum area ≥ 2 km^2 Proximity to freshwater bodies ≤ 1 km	Exclusion from protected areas Minimum area ≥ 2 km^2 Distance from urban area (Corine Land Cover class 111) ≤ 5 km	Exclusion from protected areas Minimum area ≥ 2 km^2 Proximity to sea ≤ 1 km Distance from urban area (Corine Land Cover class 111) ≤ 5 km Elevation ≤ 100 m	Exclusion from protected areas Minimum area ≥ 2 km^2 Proximity to freshwater bodies ≤ 1 km Proximity to sea ≤ 1 km Distance from urban area (Corine Land Cover class 111) ≤ 5 km	Exclusion from protected areas Exclusion from urban areas Minimum area ≥ 2 km^2 Proximity to sea ≤ 1 km Elevation ≤ 100 m	Exclusion from protected areas Exclusion from urban areas Minimum area ≥ 2 km^2 Proximity to freshwater bodies ≤ 1 km	Exclusion from protected areas Minimum area ≥ 2 km^2 Distance from urban area (Corine Land Cover class 111) ≤ 5 km	Exclusion from protected areas Minimum area ≥ 2 km^2 Proximity to freshwater bodies ≤ 1 km Proximity to sea ≤ 1 km Distance from urban area (Corine Land Cover class 111) ≤ 5 km

Figure 3.6: STU Selection Indicators and Thresholds from Site Zones

The selection process detected a total of 3669 STU distributed in the different plant types. As a whole, the number of STU per type of plant ranges from 109 (OP sea water – waste water) to 651 (PBR fresh water). The size of the STU ranges from a minimum of 2 km^2 (constraint) to a maximum of 11,200 km^2. The average size is 52.8 km^2, but the frequency distribution of the STU per class of size indicates that more of the half of STU (55.5%) is from 2 to 10 km^2 in size.

The Spatial Decision Support System (S-DSS) was applied for classifying the STU in classes of suitability (capability classes). The following steps were carried out:

- a matrix (S-DSS matrix) was built for each type of cultivation plant, composed by indicators (rows) x STU (columns). The STU have been considered as alternatives, to be ranked in classes of suitability using 4 S-DSS indicators values (Table 3.2). The indicators values were extracted for each STU from the Corine Land Cover GIS layers or, in case of the composite economic indexes, elaborated from existing databases. A total of 9 S-DSS matrices were produced;
- threshold values were assigned to each indicator for detecting the suitability degree of each STU;
- a score was assigned to each STU for any given indicator, calculated on the basis of the distance of that indicator to the threshold according to utility functions;
- the sum of all scores per each STU gave the total score of capability of each STU. The STU were then classified in classes of capability (high, mid, low) per each type of algae cultivation plants according to their score;
- capability maps of the STU were produced per each type of cultivation plant, that will represent the baseline for elaborating eventual feasibility plans of algae cultivation plants.

Table 3.2: Indicators Used for the S-DSS Classification of STU

Algae Cultivation Plant Type	S-DSS Indicator	Threshold
All	Proximity to industrial plants	Within 5 km from industrial / commercial areas (CLC class 121)
All	Proximity to road networks	Within 0.5 km from the road network
All	Share of agricultural area	30% of the STU area (optimal, CLC classes from 211 to 244)
All	Economic Index	Calculated combining socio-economic indicators (5 indicators for waste water plants, 4 indicators for the other ones - no threshold)

The scores of all the STU, calculated as above described, range from 0 to 334.3, with an average value of 78.8 and standard deviation of 57.3. The STU were classified into three classes of suitability (capability classes), given by the limits of the suitability scores (average – 1/2 standard deviation) and (average + 1/2 standard deviation) as follows:

- low suitability [Score from 0 to 50.1];
- mid suitability [Score from 50.1 to 107.4, limits included];
- high suitability [Score greater than 107.4].

A total of 9 STU suitability maps have been produced, each divided in 3 parts per major geographical area interested (Spain-Portugal, Italy, Greece-Cyprus). An example of classified STU map for a given cultivation system is presented in Figure 3.7 (Note: Red=high capability; orange=mid capability; yellow=low capability).

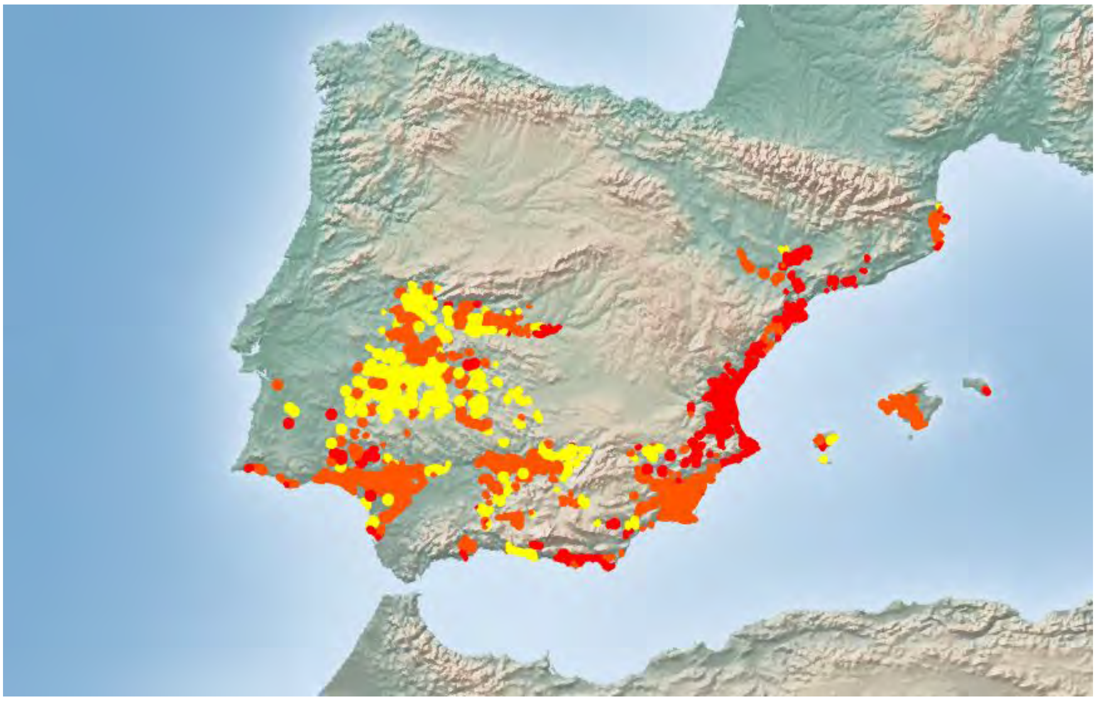


Figure 3.7: STU Classified into Capability Classes for OP / Waste Water Systems, Spain and Portugal Area

3.1.7 Economic Factors Relevant to Detection and Ranking of STU

The following description is related to parameters that have a impact on the definition of the STU described above. Due to the high relevance of such factors, it was decided to dedicate a specific description to the topic.

Approach

Economic factors for siting are decisive in algae production process. They impact costs and benefits of a plant location. A first list of indicators and related variables used in the definition of the Economic index has been drawn in the following table. Proposed indicators are inspired by the literature on algae bio-fuel (see references). They are available for EU countries at NUTS 2 and NUTS 3 levels from Eurostat and ESPON databases.[1] Using economic indicators for siting must be intended in a qualitative sense. Economic indicators help understanding, at an aggregated level, whether the situation is favourable for siting in single STU; none of the above-selected indicators is to be considered as a binding factor in the location choice. Local situation at micro level could be different and should be further investigated in a more accurate and refined feasibility study.

[1] http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database; http://database.espon.eu/db2/search

A limited number of indicators have been fixed in order to frame the proposal to the most significant ones, considering first data availability and last update, avoiding contradictory meaning (see Table 3.3). Note that some variables can provide information for several dimension or indicators at the same time. A brief description of indicators with a justification of associated variables is proposed below.

Table 3.3: Indicators and Associated Siting Variables

Indicators	N°	Variables	Nuts
Waste water	1	Population density	3
Land use	2	Share of industrial, commercial and transport units	3
Industrial plants (source of CO2)	3		
Transport infrastructure	4	Potential accessibility by road	3
Investment capacity	5	Gross Value added	2
Labour force and Skills	6	Share of population by highest level of education	2

Description of variables and indicators

1. Waste water supply

Variable used:

Population density

Unit:

Inhabitants per square kilometre (km²)

Justification:

Waste water is a source of macro-nutriments (nitrogen, phosphorus and potassium) and water supply for Algae growth and production in some plants using specific technologies (see table number below). As direct data in volume (m3) is often not available at local level, population density provides a good approximation of the population connected to wastewater collection plants.

2. Land use

Variable used:

Share of industrial, commercial and transport units

Unit:

% (hectares/total hectares area)

Justification:

Land availability associated with its cost is a key factor when siting. Not all locations are appropriate for plants. Dense urban areas for example are not expected to be suitable for bio-fuel production. On the contrary, industrial areas in cities outskirts could offer space availability and cheaper land. It must be pointed out that industrial areas provide infrastructures for settlements (roads, sewage, electric grid, etc.) and could also bring in nutriments and critical inputs in algae production.

3. CO2-nutriment

Variable used:

Share of industrial, commercial and transport units

Unit:

% (hectares/total hectares area)

Justification:

Industrial plants are an important source of CO_2, a limiting factor in algae growth. The presence of such a source could dramatically change the economic balance of a project siting in the interested areas (see the relevant literature in the 'References' section). Industrial plants delivering CO_2 are likely to be numerous in industrial units; this is the reason why the variable can be considered a good proxy in CO_2 delivering capacity.

4. Transport infrastructure

Variable used:

Potential accessibility by road

Unit:

Composite value (ESPON Project)

Justification:

Accessibility is a key location factor for industrial plants. First for buildings – in the investment phase – when infrastructures and plants must be set up, and secondly – during the production life time of the plant – when furniture, energy and nutriments have to be delivered as input to feed the production process. Road infrastructures are also very often coupled with electrical grid and water supply systems, all needed for algae production.

5. Investment capacity

Variable used:

Gross value added (GVA) in industry

Unit:

EUR Million

Justification:

The indicator "investment capacity" measures the capacity to invest in projects and produce wealth; it is a proxy which captures different characteristics from local operators and sectors and their ability to transform ideas in innovative projects and innovative projects in business. In the study the variable used is the "Gross value added in industry", which gives information on the weight and capacity of the industry sector, in a given region, compared to other regions.

It can be used as an indicator of investment capacity (in industry): a high GVA in industry will characterize a "favourable" situation for new industrial investments, while a low GVA in industry, compare to other eligible areas, will underline a low capacity of the industry sector and existing barriers in business development.

6. Labour skills

Variable used:

Share of population by highest level of education

Unit:

% (Population aged 15 years and over with a highest level of education / total population aged 15 years and over * 100)

Justification:

Development of innovative businesses, such as new investment in bio-energy sector, requires skilled labour forces. A population with a high level of education provides a good indication of local competences and professional skills directly useable in an innovative bio-fuel investment project. High level of education is also correlated with "openness" about innovation and capacity to develop new businesses.

Comparison with EU average values

In reference to open ponds technology, around 48% of the regions studied have industrial economic performance under EU average (measured in terms of Gross Value Added).[2] Many of these areas lack also infrastructures (see Table 3.4).

Table 3.4: European EU28 Average Values

Variables	EU28 Average	% of STU under EU average - Open pond	% of STU under EU average - PBR
Population density (Inhabitants per square kilometre)	**117**	65%	68%
Share of industrial, commercial and transport units (hectares per total hectares area)	**1.9%**	94%	93%
Potential accessibility by road (Composite value)	**19191791**	100%	100%
Gross Value Added (EUR Millions)	**9373**	48%	56%
Share of population by highest level of education (population with highest level of education per total population)	**12.3%**	58%	68%

***Source**: Eurostat; Espon*

[2] According to the classification made under the cohesion policy i.e. regions with GDP per capita below 75% of EU-27 average. http://ec.europa.eu/regional_policy/what/future/img/eligibility20142020. pdf

All STUs are indeed under the EU average for the accessibility by road and are endowed with less industrial zones: land in industrial, commercial and transport is lacking for 94% of the STU. They also have fewer highly skilled workers than northern Europe (58% are under the EU average for the variables Share of population by highest level of education).

For PBR STU the situation in terms of Gross Value Added is worse than in open pond technologies; the share of population with high education level is also lower.

On the other hand, investing in less developed EU regions means to potentially beneficiate of more subsidies, in bio-energy sectors, and public aids from the European Commission, central governments and local authorities.

For each variable, three classes have been defined: "favourable", "medium" and "unfavourable" (see table for thresholds). The threshold has been set, on a statistical basis, considering 1/2 or 1/5 of the standard deviation around the mean computed only for the area of interest (see Table 3.5). The High class represent the highest probability of finding favourable condition in an analysis at local level. An index is then calculated which illustrates the number of "favourable" scores reached by every Site Territorial Units (STU) for the nine technologies proposed (see Table 3.6). The index range goes from 5 (maximum) to 0 (minimum).

Table 3.5: Variables and Associated Thresholds

Variables	Associated thresholds
Population density	High: ≥ average + σ/5; average - σ/5 < Medium < average + σ/5; Low: ≤ average - σ/5
Share of industrial, commercial and transport units	High: ≥ average + σ/2; average - σ/2 < Medium < average + σ/2; Low: ≤ average - σ/2
Potential accessibility by road	
Gross Value added	
Share of population by highest level of education	

Table 3.6: Technologies and Associated Indicators for Socio-Economic Siting

Technologies	Associated indicators
OPEN PONDS seawater	2, 3, 4, 5, 6
OPEN PONDS freshwater	2, 3, 4, 5, 6
OPEN PONDS wastewater	1, 2, 3, 4, 5, 6
OPEN PONDS seawater + wastewater	1, 2, 3, 4, 5, 6
OPEN PONDS freshwater + wastewater	1, 2, 3, 4, 5, 6
PBR seawater	2, 3, 4, 5, 6
PBR freshwater	2, 3, 4, 5, 6
PBR wastewater	1, 2, 3, 4, 5, 6
PBR freshwater + wastewater	1, 2, 3, 4, 5, 6

3.1.8 Limitations

The following remarks must be raised for a complete evaluation of the situation. There are limitations that may affect some of the figures of the analyses and that have been kept clear in mind when preparing the technical reports.

- reliability and availability of data;
- average information content of pixel and need for validation;
- the criteria and thresholds used are not to be intended as constraints, instead as indicative values for recommendations in view of the current technology;
- the classification of areas is made in function of the public available data (Corine Land Cover), which could be not very precise at local scale;
- as a consequence, care should be taken when analyzing especially those areas having few km2 in size, particularly in close conditions (e.g.: coastal areas), which require deeper data acquisition at local scale. This analysis should be carried out on the STU, among the 3669 classified and mapped, which are of interest for the single stakeholders during the stage of feasibility analysis.

3.2 WP 1.2 – ALGAE CULTIVATION SYSTEMS DEPLOYMENT IMPACT ANALYSIS

Dedicated SWOT analyses were performed to identify strengths, weaknesses, opportunities and threats of algae cultivation systems. Thus, the algae production process starting with algae strains as raw material and having wet algae as final product was considered. Similarly, a separated analysis was dedicated to the biofuel production process, from cultivation to the biofuel as final product.

Following the approach of the whole assignment, based on the macro themes of biological, technical, economic and LCA aspects, the SWOT analyses were performed basing on the characteristics of selected microalgae groups and of cultivation/harvesting technologies under the technical, the economical and the life cycle points of view.

Thus, the above aspects led to the creation of five dedicated analyses of single domains:

- microalgae groups;
- microalgae harvesting and biomass processing methods;
- algae cultivation plants;
- economic parameters of algae cultivation plants;
- LCA on algae cultivation/harvesting technologies.

Further subdivisions have been adopted, based on the peculiarities of each domain, thus leading to a set SWOT within each theme (subdivision criteria are based on biology, harvesting and cultivation technologies). For a more detailed discussion, the detailed SWOT analyses performed for each aspect and subdivision are available in Appendix E.

The results of these SWOT analyses are the basis for the preparation of the overall SWOT for open ponds and photobioreactors performed within WP 1.3.

3.3 WP 1.3 – ALGAE CULTIVATION SYSTEMS DEPLOYMENT POTENTIAL ANALYSIS

The SWOT analyses performed within WP 1.2 were analyzed and collected to identify positive and negative aspects of the two considered algae cultivation plants: open ponds and photobioreactors. The outcomes of these overall SWOT analyses are shown in the following chapters.

3.3.1 Open Ponds

The main outcomes of the SWOT analyses concerning the use of open ponds for algae cultivation, presented in the previous Section, are summarized in Figure 3.8.

Open ponds are characterized by relatively low investment and operational costs, where the latter are mainly due to the generally low energy consumptions and to the easy maintenance. In particular, the use of wastewater is of interest because it reduces the consumption of carbon dioxide and fertilizers, and allows a recycle of water leading to lower water consumptions and in conclusion to a lower LCA impact.

On the other hand, open ponds need an extended surface, have a low efficiency of carbon dioxide and light use, their temperature is difficult to control and there are some issues concerning algae harvesting. Then, algae production in open ponds is still not economically competitive with other biofuels and fossil fuels production technologies, and the productivity is lower than theoretically expected.

The analysis of the SWOT outcomes allows to identify technical and economic barriers to the implementation of this kind of plants for cultivation of microalgae. In particular, the following are the most critical points identified during the study:

- large surface required for the plant;
- cultivation system applicable only to some microalgae species;
- low final density and biomass productivity;
- poor mixing and low efficient use of carbon dioxide and light;
- significant water and consequent energy consumption for pumping, mixing, harvesting;
- difficulty in controlling temperature;
- high risk of contamination.

Figure 3.8: Overall Summary of SWOT for Open Ponds

3.3.2 Photobioreactors

Figure 3.9 shows a summary of the SWOT analyses presented in the previous Section concerning algae cultivation in photobioreactors.

Figure 3.9: Overall Summary of SWOT for Photobioreactors

It is worth noting that, since photobioreactors are closed systems, they are more flexible, their size can be significantly small and the main parameters are easily controllable. In addition, their productivity is higher because of their good mixing and efficient use of light and carbon dioxide. Finally, the system is suitable for high-value products, and algae harvesting is quite easy. Also in this case, using wastewater as water source, the supply of carbon dioxide and fertilizers is reduced and consequently the costs and the LCA impact are lower.

On the other hand, photobioreactors are quite expensive to build and operate, even leading to high energy consumptions for cooling needs. Then, there are some technical issues connected to overheating of the reactors, adverse pH and carbon dioxide gradients and removal of oxygen.

Also in this case, the analysis of SWOT outcomes allows to identify technical and economic barriers to the implementation of this kind of plants for cultivation of microalgae. In particular, the following are the most critical points identified during the study:

- expensive installation due to material costs;
- expensive operation due to high energy consumptions for cooling;
- possible overheating of the reactor or additional costs for thermoregulation;
- toxic accumulation of oxygen, adverse pH and carbon dioxide gradients.

4 TASK 2 – IDENTIFICATION OF MOST PROMISING BIOENERGY AND CO-PRODUCT CHAINS

Algae are a suitable raw material for several industrial processes, aimed at the production of different substances such as biofuels, proteins for animal feeding, chemicals, ingredients for pharmaceutical, nutraceutical and cosmetic uses.

However, a process aiming at the production of biofuels has other substances only as co-products, and usually only a few co-products can be obtained from a given process. More in detail, the higher the added value of the desired co-product, the larger the complication introduced in the process. This implies for the majority of cases that there are no industrial plants targeting the combined production of fuels and co-products.

In the study, the operations were analyzed identifying five classes of production chains (Figure 4.1). Numbered from 1 to 5, production chains have an increasing degree of complication, depending on the final product and on the by-products obtained.

The basic level is constituted of the simple production of biomass, algae available for production of biofuels and co-products in external plants; in this case, the downstream production chains are separated (not necessarily located at the same place) and deal with different market approaches and models of business; the second step is biofuels without any co-products; the third chain coincides with the second in its output, but it is optimized in order to maximize environmental benefits (or the avoided costs); the fourth considers the production of biofuels according to a process having high value by-products; finally, the fifth chain follows a multi-product approach giving the same relevance to the production of biofuels and co-products.

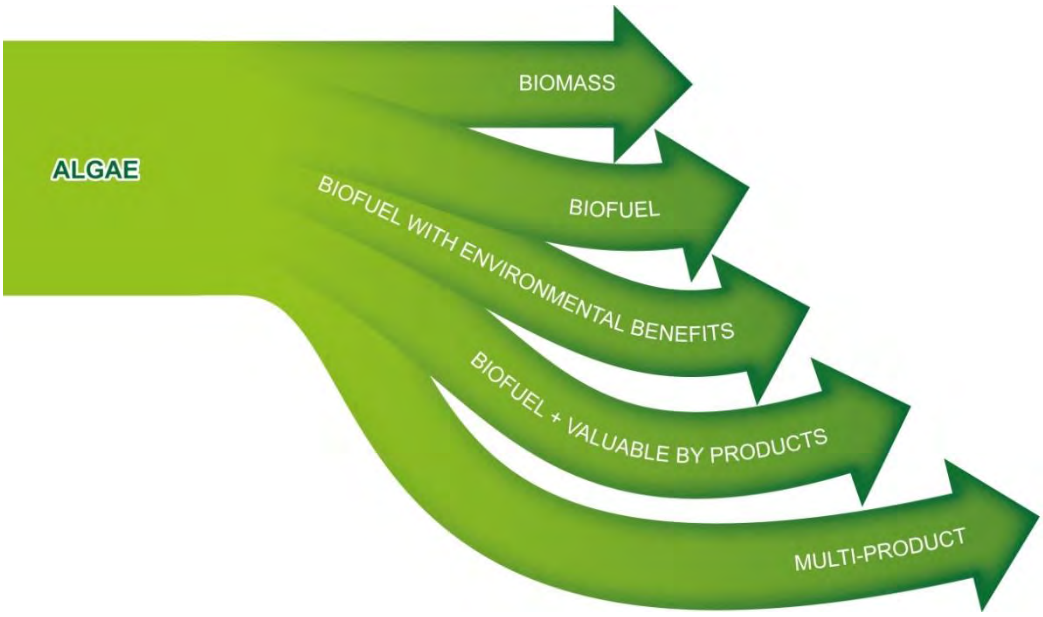


Figure 4.1: Selected Classes of Biofuels Production Chains

Figure 4.1 illustrates the five selected classes of production chains analyzed in the study:

- biomass production (Production Chain 1);
- biofuel production without co-products (Production Chain 2);
- biofuel production without co-products but with environmental benefits (Production Chain 3);
- biofuel production with valuable by-products (Production Chain 4);
- multi-product approach (Production Chain 5).

4.1 WP 2.1 – BIOENERGY AND CO-PRODUCT CHAINS ANALYSIS

The five selected production chains were analyzed basing on comments on the technological, biological and economical features of the processes, complemented by a LCA for the environmental aspects.

The LCA performed within this Task was not limited to the cultivation phase, but included the whole biofuel production chain. To do this, six case studies were analyzed by combining the most promising cultivation, harvesting/thickening technologies in the opinion of the Key Experts and including bio-oil extraction and biorefinery processes, based on input data from specific literature and LCA databases. The LCA covers 3 out of 5 production chains (1, 2 and 3) because these are the only ones having a well defined process layout accompanied by data process by process. To do a LCA of production chains 4 and 5 would mean to create a potential infinite number of process layouts, depending on the specific co-products.

As mentioned also for the siting, the analysis is based on the absence of energy demands for cooling purposes. If this is true for the Open Ponds, where the cooling is naturally achieved by means of water evaporation, the case of PBR is more complex. A forced cooling is required in the majority of cases to allow the PBRs to operate in the proper conditions. This results to be an additional energy demand that can impact very highly on the overall consumptions: lots of precise figures are not available from experimental systems but are expected in the near future, for example thanks to the outcomes of the real plants under FP7 research; the existing information suggests to consider with high care this issue because the energy consumptions for cooling may be extremely high in some cases of algae cultivation (e.g.: tubular PBR). For example, the following extract from literature (Slade and Bauen, 2013) suggests that the PBR may result very energy intense.

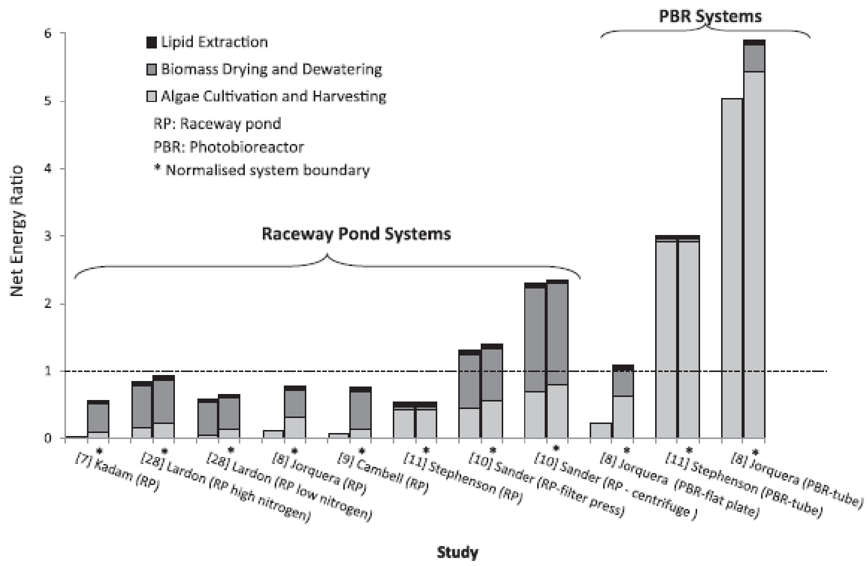


Figure 4.2: Net Energy Ratio for Micro-Algae Biomass Production

The quantitative evaluations in the present approach are without cooling demand due to the lack of specific numbers for this input flow, being aware of the fact that the final consumptions may result to be considerably higher if the expectations of such energy consumptions are confirmed by the real cases.

The general block scheme adopted for the LCA case studies is shown in Figure 4.3.

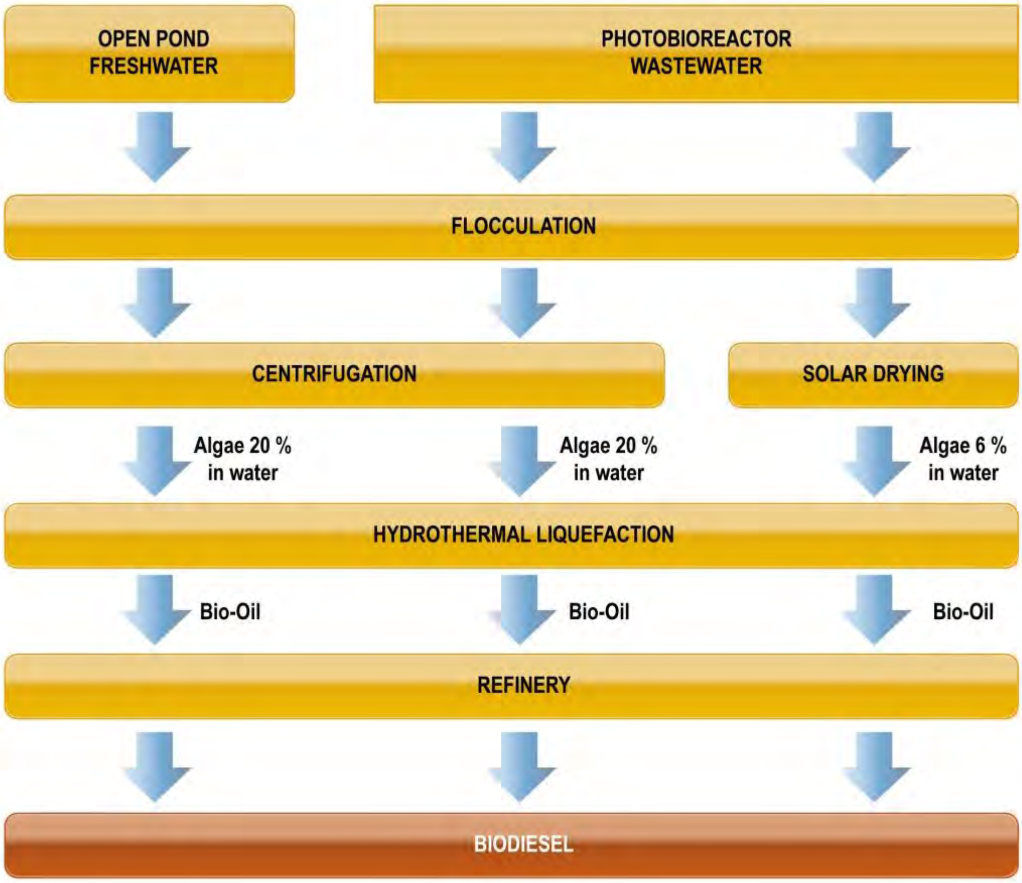


Figure 4.3: General Block Scheme of Selected Biofuel Production Chains

The results of LCAs performed on Production Chain 1 case studies are shown in Figure 4.4. In the light of the important remark made above about the energy consumptions for cooling, it can be noted that the production of algae in an open pond (1A) leads to significantly higher impacts compared to photobioreactors, because of the higher use of water per mass of produced algae, and of the consequently higher consumption of electricity. Concerning the two case studies where algae are produced in a photobioreactor, the one using centrifugation as thickening technique (1B) has a smaller impact than the one using solar drying (1C). This happens because the higher efficiency of centrifugation compared to solar drying compensates the fact that the former technique requires electricity, differently from the latter.

It is worth highlighting that the logarithmic scale in Figure 4.4 attenuates the figures of GWP100 indicator for case studies 1B and 1C, which is negative, and in particular its absolute value for case study 1C is higher than for 1B.

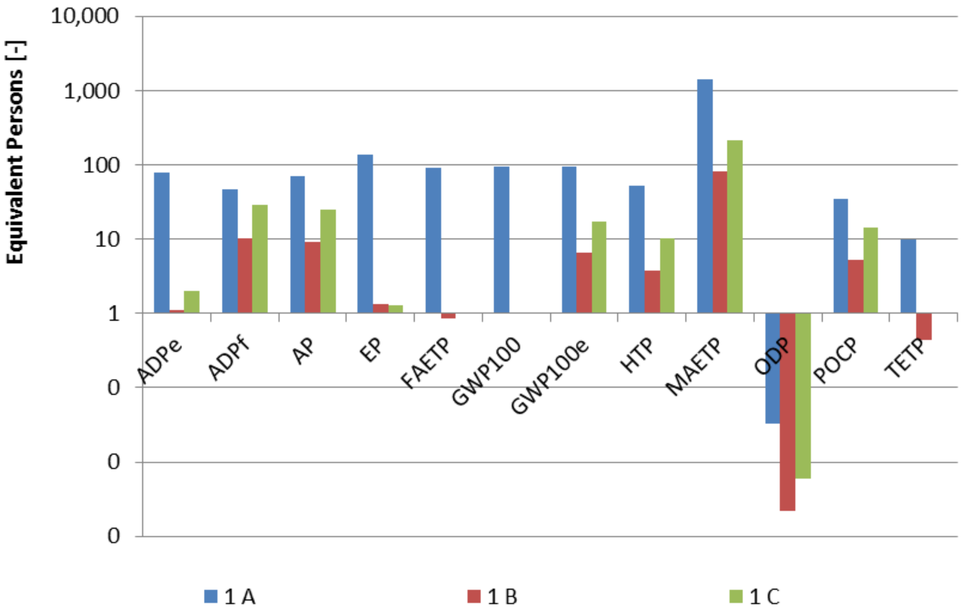


Figure 4.4: LCA Results for Production Chain 1 Case Studies

As regards the case studies of Production Chains 2 and 3, the results of the LCA are shown in Figure 4.5. Since hydrothermal liquefaction and biorefinery processes are common to the three case studies, the only differences are ascribed to the biomass production phase. Thus, the same comparisons of Production Chain 1 case studies are valid. Biofuel production using an open pond for growing algae (2) leads to significantly higher impacts compared to photobioreactors. Also in this context, concerning case studies where biofuel is produced from algae grown in a photobioreactor, when using centrifugation (3A) the impact is lower than when solar drying is used (3B).

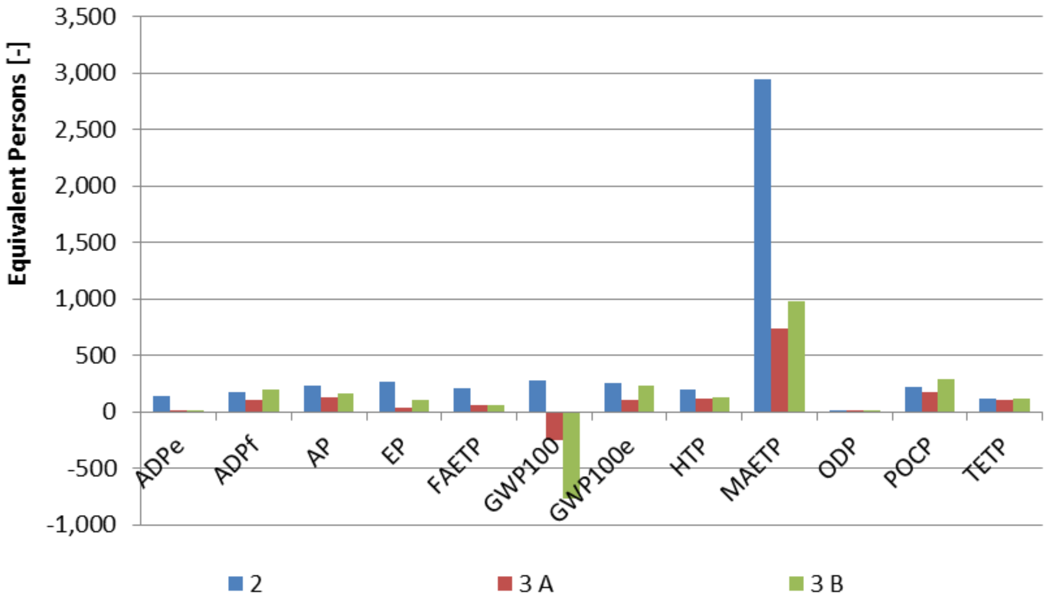


Figure 4.5: LCA Results for Production Chains 2 and 3 Case Studies

4.1.1 Production Chain 1 – Biomass Production

As regards biomass production, the results of the SWOT analysis are shown in Figure 4.6.

The main features of this production chain are that the processes are technically simple and some of them are commercially feasible.

The produced biomass potentially has different market opportunities, but the market is not structured and the demand has to be verified. Moreover, large spaces (if running on open pond) and a high amount of water are required, and transportation costs of the produced biomass to the downstream plants are high.

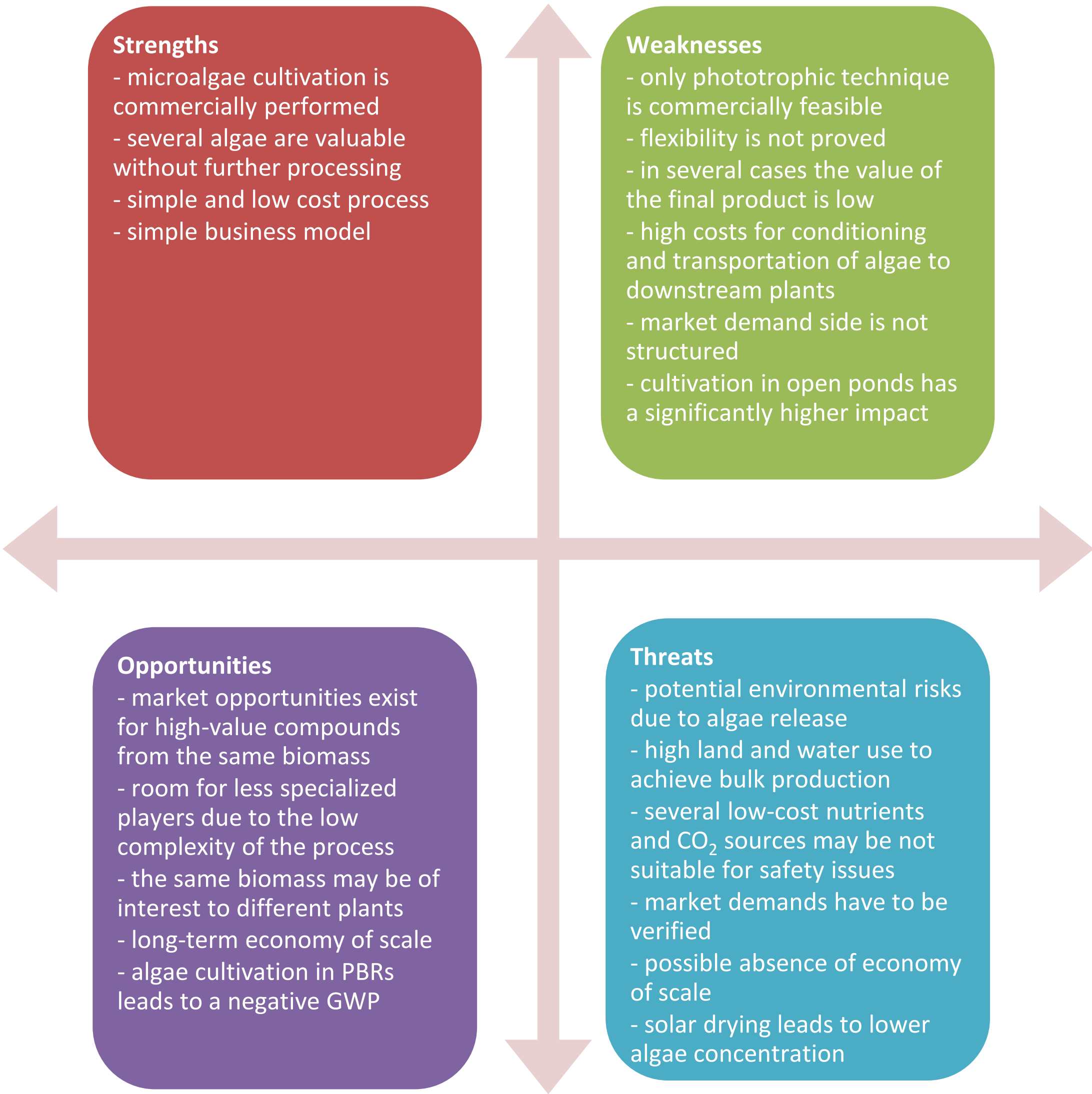


Figure 4.6: SWOT Analysis on Production Chain 1

4.1.2 Production Chain 2 – Biofuel Production without Co-Products

The main outcomes of the SWOT analysis on biofuel production without co-products are shown in Figure 4.7. It can be noticed that an accurate selection of the most suitable algae species (and possibly a genetic modification) could lead to a high biofuel productivity since these processes are moderately consolidated. The main drawbacks of this production chain are connected with the high costs, which are incomparable with those of fossil fuels. This production chain may increase its competitiveness in case of high prices for conventional energy sources.

Figure 4.7: SWOT Analysis on Production Chain 2

4.1.3 Production Chain 3 – Biofuel Production without Co-Products but with Environmental Benefits

The production of a biofuel with environmental benefits was analyzed and the outcomes of the SWOT analysis are shown in Figure 4.8. Most of the positive and negative aspects of this production chain are in common with the previous one. However, this chain is characterized by higher sustainability and lower costs, because of the use of wastewater and/or of carbon dioxide from industrial processes. On the contrary, this implies some technologic issues such as increased fouling, need for wastewater dilution and for accurate selection of suitable algae species.

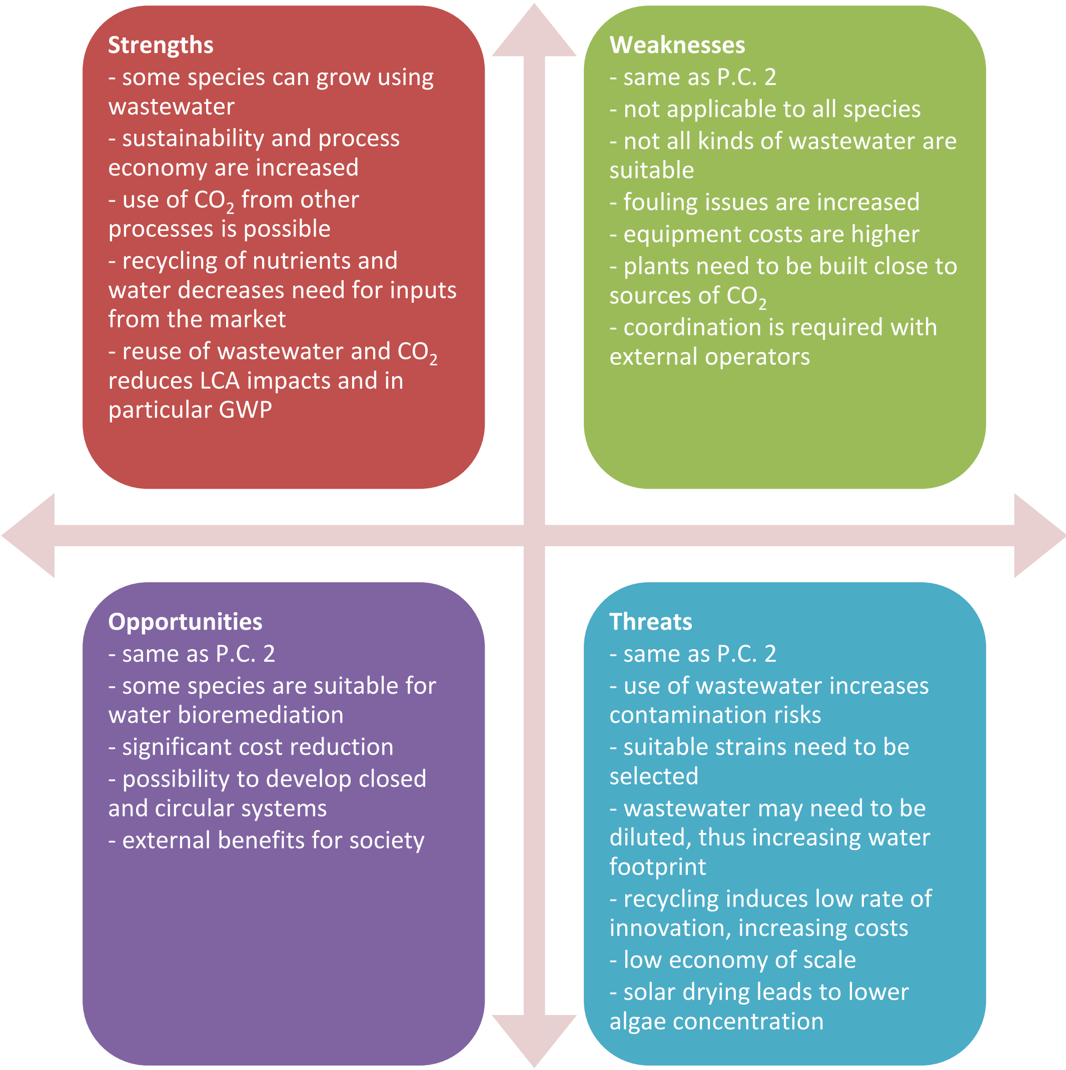


Figure 4.8: SWOT Analysis on Production Chain 3

4.1.4 Production Chain 4 – Biofuel Production with Valuable By-Products

The main outcomes of the SWOT analysis performed on the chain aimed at producing biofuel and valuable co-products are shown in Figure 4.9. The main positive aspect of this production chain is the improvement of process economics due to the production of valuable co-products that can be directly sold on the market. On the other hand, the process is significantly more complicated than the previous ones, thus requiring higher investments. In addition, the actual viability of the contemporary production of a biofuel and a co-product has to be carefully assessed.

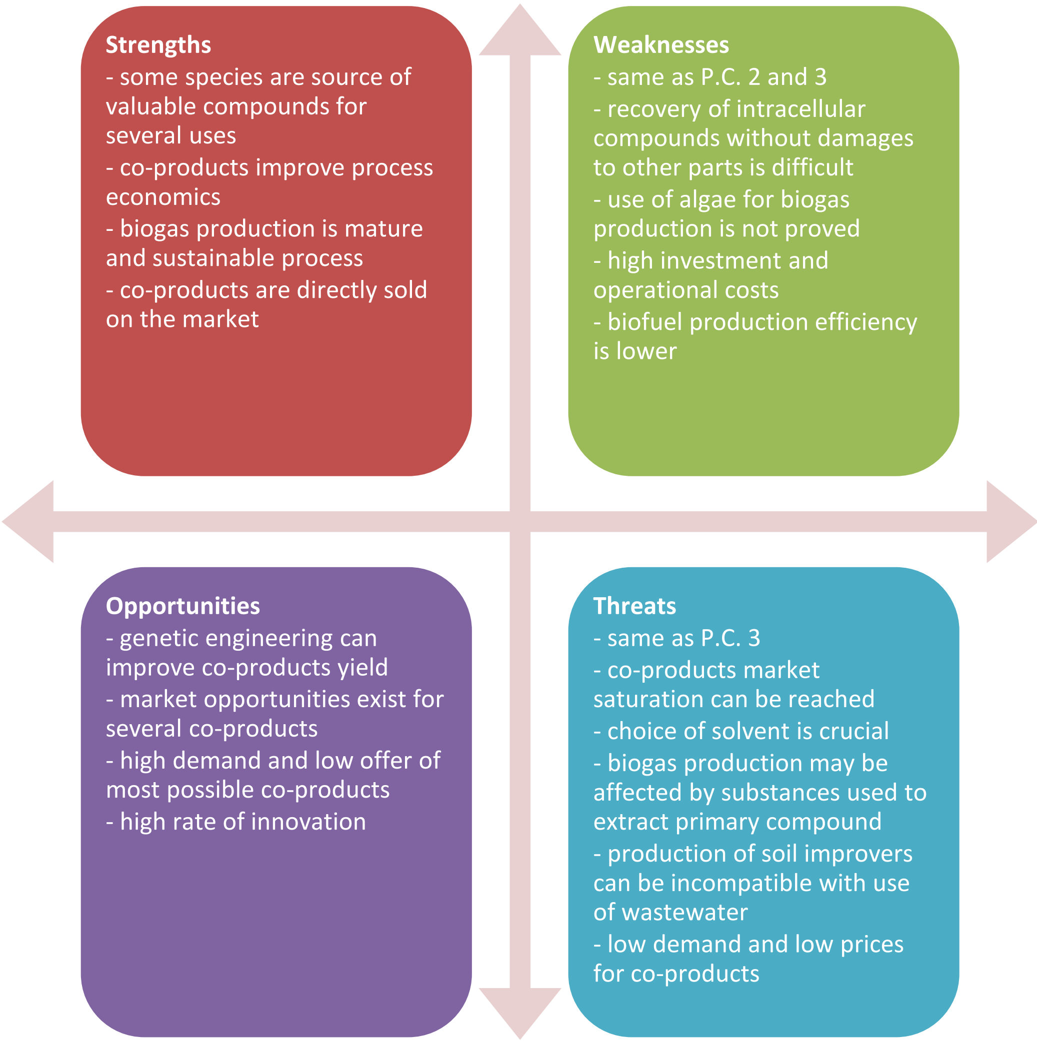


Figure 4.9: SWOT Analysis on Production Chain 4

4.1.5 Production Chain 5 – Multi Product Approach

The multi-product approach has been studied and the corresponding SWOT outcomes are shown in Figure 4.10. It can be noted that most of the positive and negative aspects correspond to those of Production Chain 4. In particular, the presence of valuable co-products improve the process economics, but the design of the process is more complicated and the investment costs are higher.

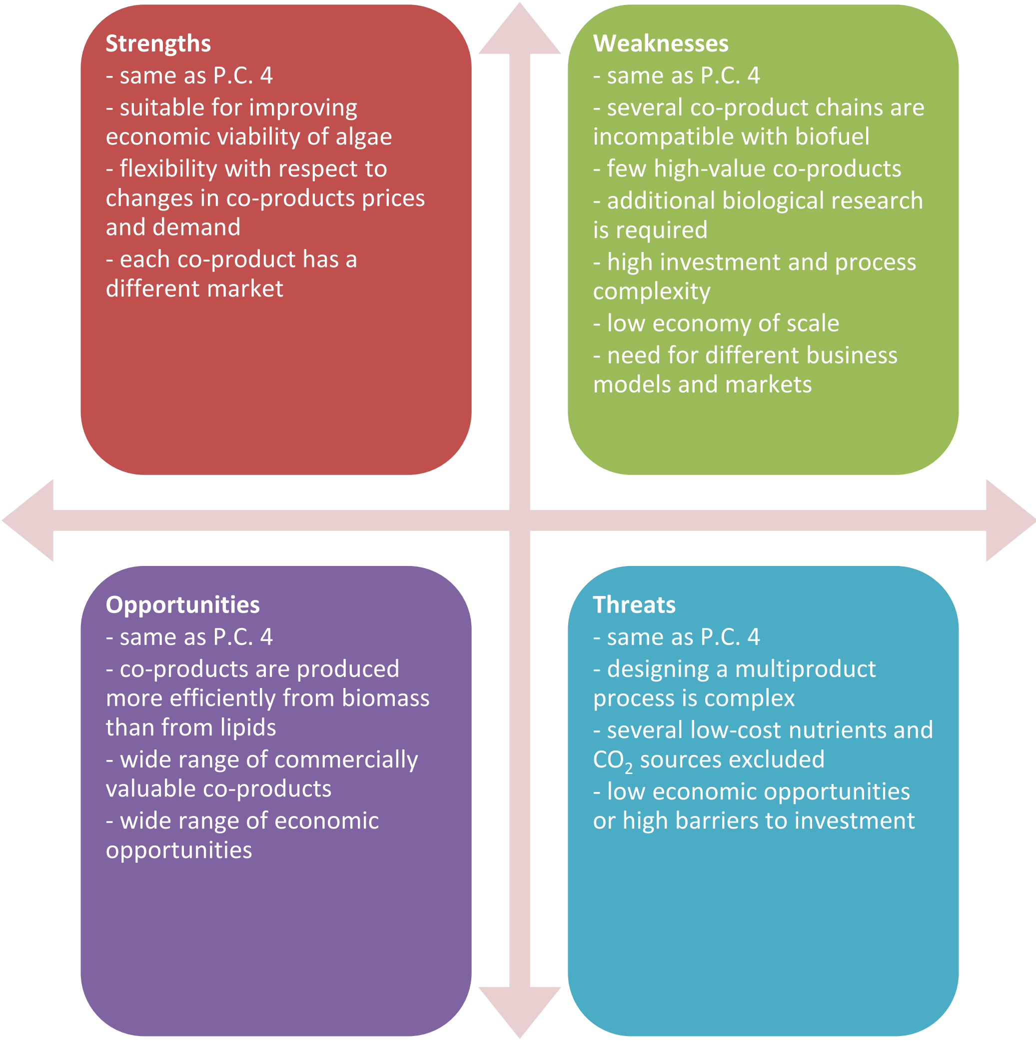


Figure 4.10: SWOT Analysis on Production Chain 5

4.2 WP 2.2 – CASE STUDIES

The analysis of the case studies (WP 2.2) and the biofuel and co-products potential analysis (WP 2.3) were conducted together, due to the tight relation between the involved subjects, both connected with the distance of the actual production chains from the commercial development.

More in detail, the gap analysis performed in WP 2.3 was extended to the pilot plants that are currently under realization within the three FP7 research projects of the AlgaeCluster: InteSusAl, Biofat and All-Gas.

To achieve this target, at the beginning of the present project, a questionnaire was prepared and submitted to the coordinator of each FP7 project, in order to get preliminary information on the demonstrative plants, such as the kind of plant and the estimated data on its consumptions and production, etc.

A second form, more focused on the activities performed in WP 2.2, was sent during the second year of the assignment. In this second questionnaire, each FP7 project was asked to self-assign a score to its pilot plant as regards the five cruces of the gap analysis (core concept of WP 2.3). In addition, it was asked to provide some updated data on energy and mass flows in the pilot plant per unit of produced algae or to confirm the validity of the assumption made using the literature.

The feedback from the FP7 has been very precious: complementary information was gathered to widen the methodological approach to the overall topics, qualitative and quantitative remarks were provided to validate or to correct those assumptions that the hands-on experience on the pilot plants has allowed to amend.

It is important to point out that the activities of research of the three FP7 projects are still ongoing when preparing this document; therefore some results from them are available and quantifiable, others are only outlined as qualitative indications of the most likely events and can only be confirmed (or complemented or contradicted, of course) upon conclusion of the respective research (end of 2015 or early 2016).

In the following sections, a short description of the pilot plants currently under realization within the FP7s is given, and a comparison of the self-assigned scores for each of the cruces is shown. This overview is aimed at highlighting the distance of the pilot projects from the acceptable configuration in a market perspective in the light of the present approach and at showing where the pilots have demonstrated proximity to that benchmark.

4.2.1 InteSusAl

A one-hectare pilot facility is being realized in Olhão, Portugal, within InteSusAl project. The plant is based on an integrated approach including heterotrophic and phototrophic algae production with a combination of raceway ponds, photobioreactors and fermenters (the fermenter is a 1 m^3 stainless steel vessel with a working volume of 800 liters, equipped with a temperature control system and fed with steam for sterilization before use and with a fixed air flow rate during normal use). Biodiesel is then produced through lipid extraction and subsequent transesterification. An important aspect of the system is the self-production of nutrients in the facility: the glycerol co-produced in transesterification will be used as a carbon source for heterotrophic algae cultivation, and the carbon dioxide produced in the heterotrophic process will be used by phototrophic algae.

The InteSusAl project also includes the realization of a demonstrative facility, with an extension of 10 hectares, whose location has still to be defined.

4.2.2 Biofat

Two 0.5-hectare pilot facilities are being realized within Biofat project: the first one in Pataias, Portugal, and the second in Camporosso, Italy. In both cases, inoculum for algae cultivation is generated in green wall panels, algae are grown in tubular photobioreactors and products are accumulated in raceway ponds. Then, algae are recovered and biodiesel is produced in a biorefinery process aimed at maximizing co-products.

In both plants, non-fossil carbon dioxide is used for algae cultivation. In the former case CO_2 comes from a beer production facility, whereas in the second case it is taken from the exhausts of a 500 kW vegetal oil-fired CHP plant.

The project also foresees a second phase with economical modeling and scale-up to a 10-hectare demo facility.

4.2.3 All-Gas

A 10 hectares pilot facility, using municipal wastewater to grow algae in an open pond, is under realization within the All-Gas project, in a facility in the south of Spain.

The produced algae are then used in an anaerobic digestion reactor to produce biogas, whereas the residues from algae digestion are used to produce fertilizers, thus obtaining a valuable co-product.

The project has a targeted algae yield of 100 t/ha/yr. The innovative design includes raceway ponds coupled with simplified photobioreactors for innoculum production. The harvested biomass will be processed to yield oils that can be transformed at an existing biodiesel plant, algae residuals that can be digested together with the wastewater solids to obtain methane and purified water for reuse.

4.2.4 Overall Figures and Rating

The following Table 4.1 summarizes the production technologies used in the three pilot sites.

Table 4.1: Production Technologies in the three Pilot Plants

Case Study	Cultivation Method	Bulk Harvesting Method	Thickening, Method	Biofuel Production Method
InteSusAl	Photobioreactor, Open Pond	Flocculation	Centrifugation	Transterification
	Fermenter	n.a.		
Biofat	Photobioreactor + Cascade Raceways	None	Filtration + Centrifugation	Not defined yet
All-Gas	Raceway Ponds + Photobioreactors	Flotation	Centrifugation	Transesterification

One of the objectives of the analysis was to assess the three pilot plants in the light of the scoring system mentioned above and further detailed in the WP3. The rating assigned to the pilot plants of the FP7 research projects is hereby comparatively analyzed. Before comparing the scores, two main points need to be highlighted:

- the scores were self-assigned by the project representatives and approved by the Key Experts, thus the point of view is internal to the single plant and not univocal to guarantee a total consistency of the comparison. In one specific case, All-Gas, no information from the project representatives arrived in due time, thus the scores were directly assigned by the Key Experts;
- the research activities of the FP7s are still ongoing (the conclusion of the research is expected for early 2016), thus some results are available and quantifiable, others are only outlined as qualitative indications of the most likely events.

Figure 4.11 compares the scores assigned to the three pilot plants and to the benchmark on the five identified cruces. More in detail, Figure 4.12 compares the total score of the three pilot plants and of the benchmark, showing also the contribution to the overall value of the scores obtained on each of the five cruces. It can be noted that the pilot plant with the highest proximity to the commercial development (i.e.: the highest total score), BioFat, reaches the 76% of the benchmark.

The meaning of cruces (defined as necessary conditions to enter the process of accessing the market), scores and benchmark, as well as the methodological approach adopted in the present analysis are presented in the following chapter, dedicated in detail to bioenergy and co-product chain deployment potential analysis (WP 2.3).

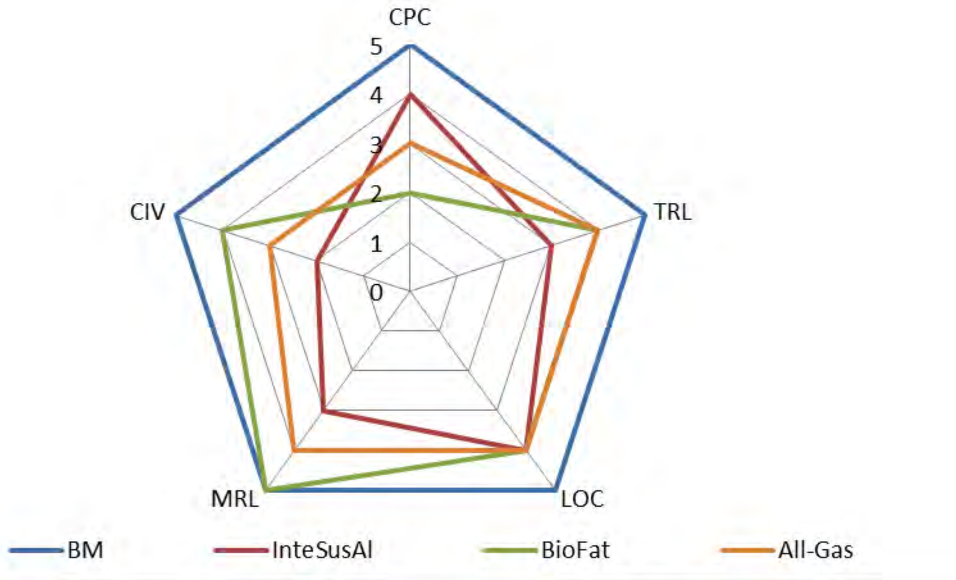


Figure 4.11: Comparison among Ratings for the Pilot Plants

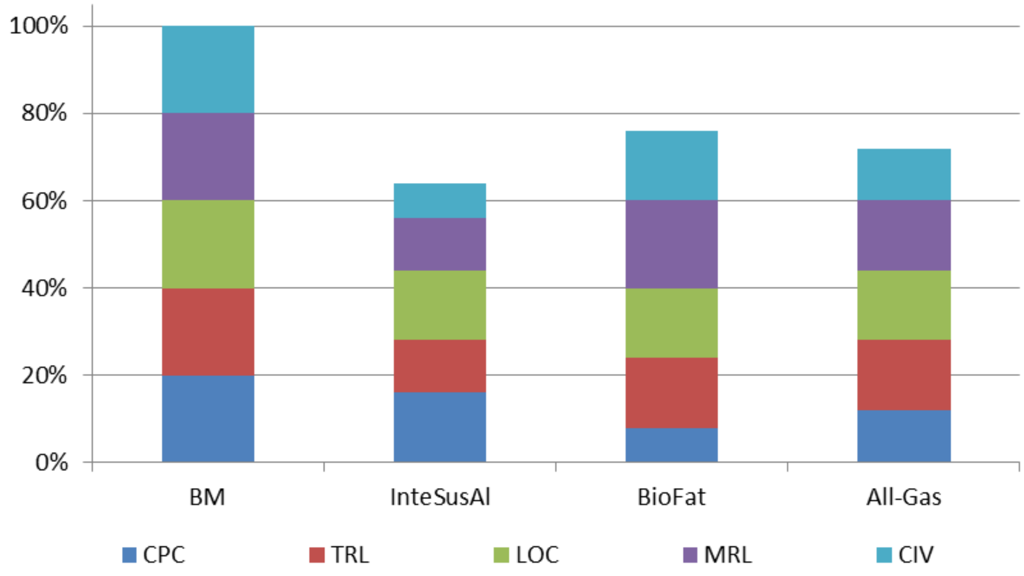


Figure 4.12: Comparison of Total Score for the Pilot Plants

4.3 WP 2.3 – BIOENERGY AND CO-PRODUCT CHAIN DEPLOYMENT POTENTIAL ANALYSIS

The outcomes of the SWOT analysis on biofuel and co-product chains were studied in order to identify the cruces that hinder the development of biofuel and co-products chains from microalgae. A crux is defined as a necessary condition to be achieved before entering the process of accessing the market. It is worth noting that after the overcoming of a crux, further barriers can exist and shall be faced. The analysis of barriers will thus follow this initial assessment of cruces.

Five main cruces are identified:

- technologies readiness level and availability (TRL), which accounts for the technologies maturity such as the presence of similar operating plants and the availability on the market of the required components;
- location suitability (LOC), including the adequacy of geographical characteristics of the site and the availability at the plant site of the necessary materials;
- competitiveness in production costs (CPC), including both plant building and operating costs;
- achievement of critical industrial volumes (CIV), considering the possibility of reaching a large volume of produced goods in a way to be steadily present on the market with items and prices that are competitive;
- market readiness level (MRL) of the new production sector of bio-fuel, considered as an overall assessment of the transparency of the business models which underpins the development of bio-fuel production chains from algae.

It can be noted that the cruces are mainly connected to economic (CPC, MRL, CIV), technological (TRL) and environmental (LOC) issues, which are the main subjects that have been analyzed in the previous steps of the Project.

The five biofuel and co-product chains were analyzed by assigning to each of them five scores, one for each of the above listed cruces, indicating the distance from the successful development of a pre-commercial plant. The scores range from 1 (maximum distance) to 5 (minimum distance, corresponding to a plant ready for commercial operation). The scores assigned to the five cruces are then summed to obtain a total score (TS, out of 25 points), which allows a better comparison among the five production chains.

The benchmark (BM) taken as a reference is a commercially active plant, such as a biofuel production plant from first or second generation crops, or a refinery of oil-derived fuels. It is clear that a score of 5 has been assigned to the BM on all the cruces, consequently showing a total score of 25 (this high score does not mean that the reference plant is intrinsically perfect, but only that it is operational).

Biofuel and co-product chains from microalgae are currently characterized by a score always lower than 5 on all cruces, since no commercial plant exists yet at industrial scale.

Table 4.2 shows the scores assigned to the five production chains and to the benchmark on the five identified cruces. The same results are schematized in the chart shown in Figure 4.13.

First of all it is worth noticing that a score of 4 is assigned to LOC crux for all production chains, since it is assumed that plant location is identified according to the minimum suitability criteria defined in the previous phases of the Project; similarly, a score of 2 is assigned to CIV for all chains, because none of them is close to the achievement of a critical industrial volume.

According to the above described assumptions, the production of biofuel with valuable co-products seems to be the most suitable production chain, especially for economic reasons, due to its high competitiveness of production costs and market readiness level for products and operators.

Also the multiproduct approach (Production Chain 5) shows a good level of proximity to commercial development, but it is penalized compared to Production Chain 4 by the higher complexity of the plant, which leads to higher costs (thus, to lower COP), and to a lower technology readiness.

Table 4.2: Rating for the Selected Production Chains

Crux	BM	PC 1	PC 2	PC 3	PC 4	PC 5
CPC	5	3	2	3	4	3
TRL	5	3.5	3.5	3	3	2.5
LOC	5	4	4	4	4	4
MRL	5	2	2.5	3	4	4
CIV	5	2	2	2	2	2
TS	**25**	**14.5**	**14**	**15**	**17**	**15.5**

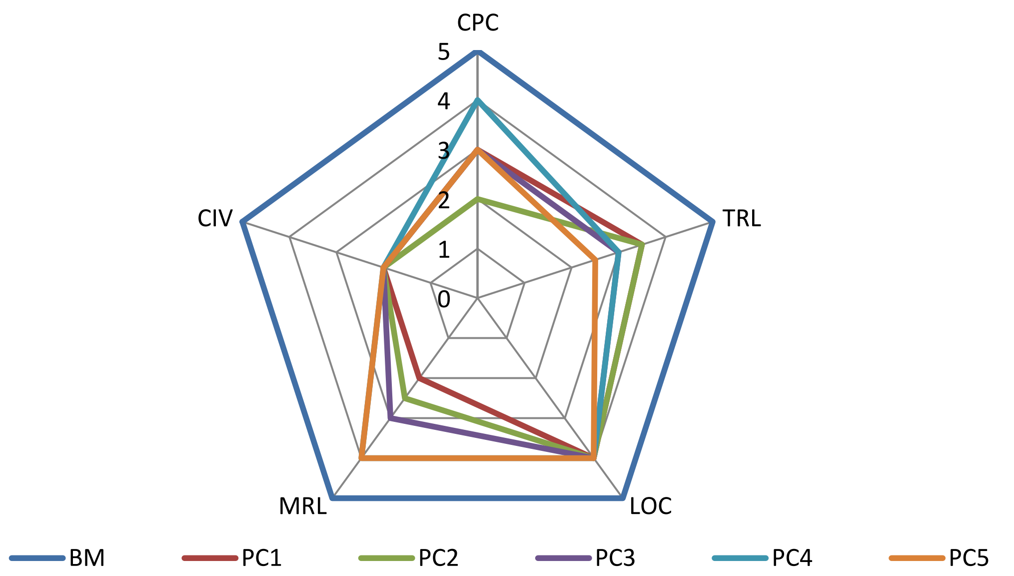


Figure 4.13: Comparison among Ratings for the Selected Production Chains

5 TASK 3 – OVERCOMING THE BARRIERS

Task 3 of the Project aims at presenting a set of guidelines to overcome the barriers that currently obstacle the development of algae-based plants producing biofuels and valuable co-products.

The above mentioned barriers were identified basing on the results of the SWOT analyses previously performed in Task 2 of the Project concerning:

- microalgae cultivation systems;
- biofuels and co-product chains.

The identified barriers are connected with technical and economical aspects, but also with policy, normative background and public acceptance.

5.1 WP 3.1 – BARRIERS ANALYSIS

5.1.1 Identification of the Barriers

It is important to start this assessment recalling the major "Barrier" originating the entire analysis of the siting, commercial deployment and development of algae bioenergy: a big distance still exists between the conventional fossil fuels and the algae-based biofuels in terms of competitiveness on the market.

The reduction of this gap is the final goal of all the panorama of specialists working on the production chains of algae-based biofuels.

Based on the weaknesses and threats of the investigated cultivation systems and production chains, a set of barriers to the development of algae-based plants was identified.

These barriers were classified according two criteria:

- according to the subject, the barriers were grouped into aspects related to technical (biological and technological), economical, policy and normative background, public acceptance;
- as regards the severity of their effects, first and second class barriers were identified. The former are characterized by macroscopic negative effects that hinder the development of a process, whereas the latter are characterized by weaker effects, which penalize a process by only reducing its performances.

It is important to specify here that there is a fundamental difference between the "cruces" identified within Task 2 of the project and these barriers. Just to recall the approach, a crux is a necessary condition to achieve before entering the process of access to the market. After the overcoming of a crux, further barriers can exist and shall be faced, and this is the current case.

The following Table 5.1 is a presentation of the identified barriers, divided into contexts and their identification as first or second class.

Table 5.1: Barriers Matrix

Context	Barrier	1st class	2nd class
Technical	Conversion Efficiency Algae-Biofuel: oil extraction and biofuel production rates are very low if compared to the input raw materials.	▲	
Technical	High amount of water needed per functional unit.		▲
Technical	The use of wastewater: although promising for the environmental benefits, it raises O&M issues and it is a barrier to the production of some valuable co-products.		▲
Technical	Large cultivation fields are needed		▲
Technical	Low biomass productivity	▲	
Technical	Low compatibility of valuable co-products and algal biofuel		▲
Technical	Use of bioengineering is necessary for the achievement of the optimal algae strains. This is linked to the barrier of public acceptance.		▲
Technical	No multiproduct plants exist or promise to be valuable	▲	
Economic	Production costs not competitive with other biofuel production chains (wood, crops) or in reference to the fossil fuel sector.	▲	
Economic	Fiscal and economic incentives not favorable to the development of algae production chains		▲
Economic	Demand only for high volume of biofuels, which requires important investments in equipment in the start-up phase of the business.		▲
Policy and normative background	Uncertain/undefined legal and policy frameworks. Patents and authorizations to start a business are not well defined or are provided at a very high cost for investors.		▲
Public acceptance	Skepticism of the population towards unknown technologies, use of bioengineering and towards highly impacting systems in terms of land occupancy. Diffidence towards land occupancy for industrial purposes vs. agricultural scopes.		▲
Public acceptance	Odors in Open Pond are an issue that can cause “NIMBY” phenomena along with the general skepticism.		▲

In addition to the analysis of the barriers, the effects of different economic scenarios on the viability of algae-based plants were analyzed. In fact, the development of a new biofuel sector from algae depends on both internal and external factors. The former are mainly related to technology and siting whereas the latter refer to the energy context and the economic situation in general. Indeed, the dynamics of conventional fuels demand and offer and the resulting price level determine for a large part the profitability of investment in the biofuel sector.

In the study, external factors were briefly analyzed and two energy price scenarios were proposed.

5.1.2 Macro Energetic Context and Scenario

The development of a new biofuel sector from algae (third generation biofuels) depends on a number of internal and external factors. Internal factors are mainly related to technology and siting while external (uncontrolled) factors refer to the energy context and the economic situation in general. Indeed, the dynamics of conventional fuels demand and offer and the resulting price level determine for a large part the profitability of investment in the biofuel sector.

It is worth noticing that low prices in fuels are not favorable to the development of new biofuel technologies, while higher prices in a context of economic growth make more profitable investments. However, in all the scenarios proposed the prices and costs gap between biofuel from algae and other fuel sectors remains significant. In a near future, technology improvement and a specific financial public support to algae production chain should be necessary in order to increase the attractiveness of investments in this sector.

5.1.2.1 Recent Energy Trends

BRICS and the other developing countries have been driving energy consumption growth in the most recent years. In particular, increase in consumption of fossil energy in China and India has been the key determinant of the current global trend. While the financial crisis has reduced energy consumption growth rates almost everywhere over the years 2011-2013, this has not inverted the positive trend in consumption (except in 2000-2011 in the EU, USA and Japan). For the next decade, experts expect a worldwide increase in energy consumption mainly driven by demographic growth and changing consumption patterns in emerging countries[3].

As far as the supply side is concerned, it is likely that the historical fuel production peak has been reached, while coal and (unconventional) gas are still abundant for some further decades[4]. The share of renewable energy in the energy mix is increasing everywhere, but it still does not cover a significant share of the energy supply. The EU shows a high dependency on fossil energy imports (ratio between imports and supply of fuels is above 50% since 2000), with some variation across MS. However, the share of renewable sources in electricity generation has been growing fast and reached a significant level in some countries and sectors.

3 "Demographic factors will continue to drive changes in the energy mix. The world population is set to rise from 7.0 billion in 2011 to 8.7 billion in 2035, led by Africa and India." in International Energy Agency (IEA), World Energy Outlook, 2013, chapter 1, p. 33.

4 International Energy Agency (IEA), "World Energy Outlook", 2013.

As regards the biofuel sector, the total consumption in EU transport in 2013 reaches 13.6 Mtoe (corresponding to around 4.7% share of total transport fuel consumption). After a decade of growth, the year 2013 was characterized by a slight decrease (by 6.8%) of consumption in Europe. This is partly due to the decrease in consumption of all transport fuels, which is a side effect of the economic crisis still affecting a significant number of Member States. Other reasons are the changes introduced in the biofuel legislation at EU level, but also the result of some changes made in national legislations during the period (e.g. the end of a favourable fiscal regime for biodiesel in Germany by the end of 2014). At Member State level the biofuel consumption and production remain concentrated in few Members States: Germany, France, Spain and Italy represent around 65% of the total EU consumption in 2013. As concerns the breakdown of biofuels, biodiesel represents more than 80% of total biofuel consumption in the transport sector.

Considering the objective of the Directive on biofuel consumption still under discussion and according to the projection in fuel consumption at EU level in 2020, biofuel consumption could rise to 22,5 Mtoe by 2020 (+60% compare to the 2013 level).

5.1.2.2 Scenario in Energy Prices

In the short run, and according to a business as usual scenario, oil prices are expected to remain relatively low. This situation is due to the existing current surplus in oil supply – with abundance in non-conventional oils put on the market and a high fossil fuel supply from middle east producers – and weaknesses on the demand side, especially from Europe where the economic situation is still under the effects of the financial crisis. In early 2015, oil prices (WTI crude oil index) are under 50$ per barrel, far below the level of prices taken into consideration in biofuel market analysis. Indeed, between July 2014 and January 2015 oil prices plunged over 55%. Therefore, the cost gap between biodiesel from algae and conventional fossil diesel has increased significantly over the last two years. In the long run, the scenario should change, as a consequence of the inversion of trends in production and consumption. Oil price is expected to increase over the period 2010-2050, reaching 140$ per barrel of oil equivalent (boe) at the end of the period, according the most recent simulations published by the European Commission. However, in both short and long term scenarios, oil prices are not sufficiently high to reduce the gap between conventional fossil fuels and biofuels from algae. In addition, it is worth noticing that inputs prices for biofuel production, such as capital, fertilizers and power are strongly linked to fossil fuel prices, as the investment costs in biofuel technology is partly due to the cost of embodied fossil energy in materials and equipment, which makes difficult the decoupling between the two price trends.

5.2 WP 3.2 – ALGAE CULTIVATION AND BIOENERGY DEPLOYMENT ACTION PLAN

Based on the analysis of the barriers, some recommendations were developed that aim at overcoming them and foster the development of algae-based biofuel production systems. In particular, the recommendations concern the topics on which research and policies should be addressed to make biofuel production from microalgae technically more efficient and economically more attractive for investors.

Provided that the overall objective is to overcome the identified barriers (although this will not be an easy process), following the same approach, some recommendations to overcome the barriers are defined considering technical, economical, policy and public acceptance aspects. These recommendations are presented below.

5.2.1 Technical Recommendations

The keyword to overcome technical barriers is process intensification, i.e. the goal is to produce more in less space (surface) and using less resources. This will require some fundamental research effort at least in the following areas:

- development of more efficient (genetically modified) algal strains with enhanced biomass and oil productivity and better resistance to outdoor irradiation conditions;
- optimizing microalgae cultivation and processing system technologies such as fuel extraction and production, or biorefinery processes to minimize resource input and costs;
- development of reliable modeling and simulation tools for effective design and optimization and to reduce the (expensive) trial and error approach which has been dominant over the last years;
- development of new approaches for process upscaling to take advantage of the economy of scale;
- upscaling available modified strains for assessing productivity increases and strain stabilities under industrially relevant outdoors cultivation conditions;
- development of alternative high-intensity cultivation techniques (e.g. based on microsystems) to maximize growth rate and biomass concentration in industrial productions;
- development of new technologies for downstream processing toward high-value added products (development of new catalysts may prove of critical importance);
- analysis and development of virtuous supply chains where multiple players can take advantage of microalgae products.

As regards biological aspects, the following recommendations were identified:

- development of suitable algal strains that allow rapid production of biomass with high lipid content and production of valuable co-products to increase biomass overall value;
- better assessment to evaluate and minimize the potential risks of outcomes of GM algae in natural environment;
- development of lab-created strains unable to survive outside open ponds or PBRs;
- incentives for the treatment of public wastewater as a source of nutrients and a potential income to reduce operating costs.

5.2.2 Economic Recommendations

There are no clear business models currently available to be proposed to potential investors in the biofuel from algae sector. The following recommendations summarize the steps that need to be done to overcome the barriers at short and medium terms (by 2020) and make more attractive investments in biofuel energy chains, taking into consideration also the macro-energy scenario. More in detail, the following actions are suggested:

- fill the normative gap at EU and Member State levels, identifying a clear financial mechanism to support the development of the sector over the next five years, while ultimately diffusing more information about business opportunities in the different Members States, e.g. on technologies and sites, relevant networks and stakeholders, administrative contact points at national level, access to capital and skilled, etc;

- propose some financial supports to investors in the early-stage of investment in biofuel projects (with the objective to pass from pilot projects to commercial plants), using grant mechanism or financial instruments (FIs), e.g. ESI funds. FIs used could refer to low-cost loans, guarantee mechanisms or venture capital for start-ups in the bioenergy sector[5];
- enhance tax concession (or other financial incentives6) mechanisms or promote the biofuel obligation approach (quotas) to biofuel production from algae (requiring fuel supply companies to incorporate a given percentage of biofuel from algae in the fuel they supply to the marketplace)7. Note that the incentives should be differentiated according to the technology used, the environmental impact (reuse of waste water) and the location of plants (e.g.: in disadvantaged areas). In addition, the financial support could be modulated according to the number of by-products derived from algae cultivation activities i.e. giving high incentive to biofuel producers and lower incentive to business oriented investments with core production of co-products and limited production of biofuel;
- support the creation of networks at national levels to share information and technologies and give supports to investors in the sector of alternative biofuels e.g. network lists, information for a better access to capital and skills, business support to investments, legislative background, etc.

5.2.3 Policy and Normative Background Recommendations

The main recommendation concerning the policy and normative background, is to harmonize EU and national legislations, especially in terms of procedures (impact assessment), authorization (accredited bodies to deliver authorizations) and patents required to growth algae. Time and costs for investors should be known in advance and be consistent with what observed in the other biofuel sectors[8].

5.2.4 Public Acceptance Recommendations

To achieve the public acceptance the keyword to chase is “consensus”. This is not something that can be obtained immediately and with limited actions, in fact it can be a long path to explore. The reasons of the long actions to carry out are due to several reasons: on one hand, there is the counterpart as a heterogeneous panorama to address with different languages and argumentations, on the other hand there are the evident technical limitations to solve and hence to convince the skeptical side of the population.

Provided that the above is clear to the project developers, consensus can be built stressing on three activities:

- awareness raising campaigns;
- research activities and following dissemination of results;
- demonstrative projects flowing into pilot systems that can prove the reliability of the technologies along with the effectiveness of the new production chains.

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5 For illustration of venture capital funds in the sector of renewable energy see for example the “State of Renewable Energies in Europe” edition 2014, published by the EurObserv’ER, p.174.

6 Other mechanism in used in the renewable energy sectors are feed-in-tariffs or premium (which guarantee a minimum price or percentages to the producers of biofuel products placed on the market).

7 See for example for a better illustration of the mechanisms mentioned here annex 9 of the “Biomass action plan” published by Commission in 2005 (COM(2005) 628 final).

8 According the Golder associates and Ecofys study, the average lead time in Member States of the total bio-energy permit procedure is ca. 23 months. For more details see “Benchmark of Bioenergy Permitting Procedures in the European Union”, January 2009 DG Tren.

5.2.5 Action Plan

The Action Plan is the summary of barriers vs. actions under a priority, duration and cost perspective.

It is based on all the analysis performed under the previous tasks and includes all the recommendations which are recognized as a priority to promote the most promising actions for a winning diffusion of algae cultivation and bioenergy practices.

The analysis allowed pinpointing recommendations to tackle all highlighted barriers – using a barrier-action approach – from the overall perspective concerning technical, economic, social and policy aspects.

A summary of the recommended actions is presented in the following Table 5.2, with an indication of the sectors, of the barriers, of the class and of the related recommendations.

In addition, the plan considers three important fields: "Priority", "Duration" and "Cost"; a score is assigned to each of them, ranging from 1 to 3 depending on effort connected to the respective solution:

- provided that all the drafted recommendations have high priority because all the mentioned barriers significantly contribute to the creation of the big gap with the conventional fuels to be reduced, the priority score can be high (score 3) if the solution must be implemented as soon as possible otherwise the intervention is not viable, medium (score 2) if the recommendation has high impact but a short delay in implementation can be accepted and low (score 1) if the benefit is relevant but there are many other issues to fix before;
- the duration scores (meant as 3 for long, 2 for medium and 1 for short duration) indicate the timing requested by the proposed action to achieve a significant result; the duration is indicated as medium or long even for events that might seem to require a short effort because they actually need a long preparation and take long time to make the receivers familiar with them (e.g.: the public acceptance issues);
- the cost scores (3 for high, 2 for medium and 1 for low cost) are indicative of the investments to be done by the scientific community (i.e.: the EC, the national institutions, the research centers, etc.) for the successful realization of the mentioned actions over the expected duration.

Table 5.2: Barriers-Recommendations Matrix

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Technical	Conversion Efficiency Algae-Biofuel: oil extraction and biofuel production rates are very low if compared to the input raw materials.	▲		Selection of the most efficient technology. Research for the development of highly innovative technologies. Research for biological advancement toward more efficient algal strains	⚠⚠⚠	🕒🕒	€€€
Technical	High amount of water needed per functional unit.		▲	Selection of the most efficient technology. Research for the development of highly innovative technologies.	⚠⚠⚠	🕒🕒	€€€
Technical	The use of wastewater: although promising for the environmental benefits, it raises O&M issues and it is a barrier to the production of some valuable co-products.		▲	Incentives for the investors in plants using WW to solve the technical barriers. Research for improvements in O&M issues to overcome the biological barriers.	⚠⚠	🕒🕒	€€
Technical	Large cultivation fields are needed		▲	Research for the development of highly innovative technologies.	⚠⚠⚠	🕒🕒	€€€
Technical	Low biomass productivity	▲		Research for the development of highly innovative technologies and more efficient algal strains.	⚠⚠⚠	🕒🕒	€€€
Technical	Low compatibility of valuable co-products and algal biofuel		▲	Accurate design to decide the most applicable combinations of product/co-products.	⚠⚠	🕒	€€

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Technical	Use of bioengineering is necessary for the achievement of the optimal algae strains. This is linked to the barrier of public acceptance.		▲	Research in the biological field of laboratory tests, technological innovation, etc.	⚠⚠	🕒🕒	€€
Technical	No multiproduct plants exist or promise to be valuable	▲		Demonstrative tests are needed to prove the technical and economical viability	⚠	🕒🕒	€€€
Economic	Production costs not competitive with other biofuel production chains (wood, crops) or in reference to the fossil fuel sector.	▲		The solution will be mainly a consequence of the technical improvements and of additional public incentives	⚠⚠⚠	🕒🕒	€€€
Economic	Fiscal and economic incentives not favorable to the development of algae production chains		▲	Put higher incentives on biofuel production, transformation and distribution processes. Incentives might be allocated under the form of grants or low-cost loans (to investments in bio fuel algae production chains), tax concession, feed-in-tariffs or premium (which guarantee a minimum price to biofuel from algae supplied on the market) or quotas (e.g., green certificates).	⚠⚠⚠	🕒	€€€

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Economic	Demand only for high volume of biofuels, which requires important investments in equipment in the start-up phase of the business.		▲	Higher economic incentives to investments in biofuel from algae production chain at the start-up stage of plant development.	⚠⚠	🕒🕒	€€
Policy and normative background	Uncertain/undefined legal and policy frameworks. Patents and authorizations to start a business are not well defined or are provided at a very high cost for investors.		▲	Strengthen the legal framework at European and national levels (defining responsibilities, bodies involved and public authorizations required).	⚠⚠	🕒	€
Public acceptance	Skepticism of the population towards unknown technologies, use of bioengineering and towards highly impacting systems in terms of land occupancy. Diffidence towards land occupancy for industrial purposes vs. agricultural scopes.		▲	Consensus building campaigns. Demonstrative projects to prove the reliability and the effectiveness.	⚠⚠⚠	🕒🕒🕒	€
Public acceptance	Odors in Open Pond are an issue that can cause “NIMBY” phenomena along with the general skepticism.		▲	Stress on research activities. Consensus building campaigns.	⚠⚠⚠	🕒🕒🕒	€

6 TASK 4 – FINAL WRAP UP AND AWARENESS RAISING

The main objective of this activity was to describe and present the final outputs and results that are derived from the project completion. In particular, the Final Report is a Technical Manual presenting the identified implications of algae cultivation system siting, the most promising bioenergy and co-products chains as well as their development perspective and providing recommendations, in the form of guidelines to the EU, the stakeholders and national authorities to overcome the existing barriers to algae cultivation systems deployment. Moreover, dissemination and communication activities (website and other promotional material) were realized to raise public awareness towards the use of algal bioenergy and to communicate project achievements.

6.1 WP 4.1 – FINAL REPORT

The first activity of the Task was the preparation of the present document, a overall presentation of all the progresses achieved during the whole life of the Assignment.

The document is structured as a sequence of chapters illustrating the five Tasks and relative Work Packages. Due to the technical nature of most of the contents, for ease of interpretation the Report is prepared as a summary of main outcomes, with a reference to the technical deliverables enclosed as appendices. In those appendices all the technical insights can be found with details.

6.2 WP 4.2 – FINAL WORKSHOP

The final event for the presentation of the project outcomes to the European Commission was held onMay 12, 2015; in agreement with the EC, the final workshop was an event open to the stakeholders of the AlgaeCluster and other interested participants, in front of the EC's officer.

The event included an overview of the project and its major results, to promote all the project outputs to the stakeholders, providing opportunities for continued and sustainable efforts in this field.

The event was organized as presentation by the Key Experts of the main results of the technical assistance (the presented slides are enclosed in Appendix L) and open discussion with the audience, based on this schedule:

- Project overview (goals, main phases, etc.);
- assessment of biologic issues;
- siting;
- technological issues;
- LCA;
- economic scenarios;
- barriers and recommendations;
- discussion and Q&A.

6.3 WP 4.3 – DISSEMINATION ACTIVITIES

All the possible channels managed by the three developers were explored for the promotion of the project and of its results.

The participation to workshops and seminars is the most effective tool and have been put into practice in two ways:

- the individual promotion of the participation in the project that the individual members of the Consortium have made during their daily job;
- the participation in dedicated seminars specifically devoted to biofuels and algae. In particular, the following events are worth quoting:
  - a seminar on LCA for algae biofuels held in Brussels in April 2014 where representatives of D'Appolonia where invited among the audience (2nd European Workshop on LCA for Algal Biofuels and Biomaterials),
  - the side-event of the Algae Cluster Meeting in Seville (May 8, 2014) where the Project was presented to the public audience, illustrating goals, status and connections with the FP7 projects of the Algae Cluster. The slides presented at the event in Seville are enclosed in the Appendix E,
  - the attendance to the event of the European Algae Biomass Association (EABA) and of the Directorates General for Energy and Research & Innovation of the European Commission in Florence, held on December 2014,
  - the 2015 edition of the "3rd European Workshop on LCA for Algal Biofuels and Biomaterials" in Brussels, scheduled for the 11th of May. In this occasion the three partners have submitted a technical abstract, titled "LCA of micro algae production chains from cultivation to biofuel" (enclosed in Appendix J), and have been selected for the presentation of the LCA experience within the Project (the presented slides are enclosed in Appendix K).

Moreover, the connections between the project and the other ongoing FP7 activities under development at European level have been assessed through frequent contacts with the focal points of the AlgaeCluster and, at documental level, have been investigated through a questionnaire during Task 1, presented in Appendix F, which was returned filled in by the mentioned focal points and with following queries during Task 2 and Task 3 for the consistency checks between our approach and the FP7's.

The website for the promotion and the communication of the activities performed within the present assignment has been developed internally by D'Appolonia and released online on April 2015. The site is available online at the address:

www.algaetofuel.eu.

To emphasize the nature of the website as the official website of a project funded by the European Commission (EU), the "*.eu*" domain was chosen.

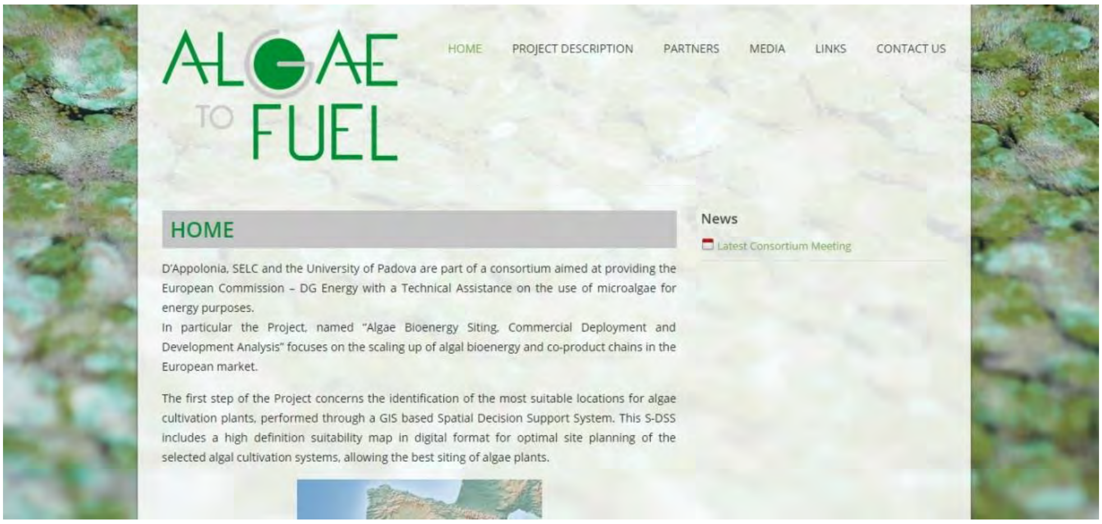

Figure 6.1: Screenshot of the Project Website Homepage

The website is divided in different sections: Home, Project Description, Partners, Media, Links and Contact Us.

The website has the objective of disseminate the project results, events and initiatives, providing essential information related to the use of microalgae for biofuel production. In the previous Figure 6.1 a screenshot of the visual appearance of the site homepage is provided.

7 CONCLUSIONS

The EU strategic policies, such as the RES Directive, the Biomass Action Plan and the EU Strategy for Biofuels, are strongly supporting biofuels with the objectives of reducing greenhouse gas emissions, boosting the decarbonisation of transport fuels, diversifying fuel supply sources and developing long-term replacements for fossil oil. Biofuels could also play a significant role in progressively reducing Europe's over-dependency on imported oil.

Biofuels currently represent the main alternative to traditional fossil based fuel. In particular, algae as a biofuel feedstock could represent a sustainable alternative type of energy crop with high productivity and low environmental impact.

Biofuels are a direct substitute for fossil fuels in transport and can readily be integrated into fuel supply systems. Although at present most biofuels are still more costly than fossil fuels, their production, also encouraged by policy measures, is increasing in countries around the world.

As for the algae-based systems, wide is the economic gap between the production costs of conventional fuels and algae-based biofuels.

Moreover, neither open ponds nor photobioreactors are mature technologies and until large-scale systems are actually built and can show demonstrated performance over many years of operation, many uncertainties will remain.

Commercial algal growth will require the development of strains and conditions for culture that allow rapid production of algal biomass; there is a need for innovation in all elements of algal biofuels production to address technical inefficiencies, which represent significant challenges to the development of economically viable large-scale algal biofuels enterprises.

One of the most important results of the analysis is the still wide distance between the cost of the kWh from algal biofuel and from conventional fuels, which is mainly connected to the high energy consumptions for cultivation.

Therefore, the economic feasibility of algal biofuel production at any scale and the feasibility of sustainable large scale production requires further research and development to become economically viable. Technical advances combined with incentive schemes will help algal biofuel production become financially viable.

To this aim, under the present assignment a comprehensive analytical work was carried out by a specialized pool of Key Experts on the most appropriate locations for future deployment in the EU taking into account the climatic, environmental and economic conditions. In parallel, the most promising bioenergy and co-product chains were identified and analyzed under technical, economic, environmental and commercial perspective also considering the main outcomes of currently funded FP7 projects on algae bioenergy. Finally, the main barriers to deployment identified based on the outcomes of the previously described activities were analyzed and the potential measures to be put in place to overcome them were assessed.

The Project, started in January 2014 and focused on the scaling up of algal bioenergy and co-product chains in European market was articulated into five main tasks, besides the project management; the result of the activities of the tasks is the present Final Report, a technical manual that includes:

- Task 0 – Project start-up: instantiation of the pool of Key Experts, validation of the methodological approach and of the implementation plan, creation of the contacts with the relevant stakeholders to involve;
- Task 1 – Siting of algae cultivation systems: creation of a GIS-based dataset identifying the most suitable locations (site territorial units) across Europe for cultivation of microalgae based on environmental, climatic and economic considerations for PBR and open pond plants; SWOT analysis on the microalgae groups, cultivation and harvesting technologies, economical issues and LCA; these processes allowed to identify the main pros and cons of PBR and open ponds under all the mentioned perspectives;
- Task 2 – Identification of the most promising bioenergy and co-product chains: five alternative biofuel production chains were analyzed highlighting, again using a SWOT approach, the main obstacles to development of commercially viable systems; the production chains were compared with the existing pilot plants of the AlgaeCluster and evaluated using a scoring system to determine their distance from commercial development;
- Task 3 – Overcoming the barriers: the main barriers emerging from the previous figures were identified and grouped; specific recommendations were provided to address them;
- Task 4 – Final wrap up and awareness raising: the outcomes of the whole analysis were included in a final report and in the project website, and were presented in a workshop to the EC and to the interested stakeholders.

GGB/ALV/LFA/PAR:cht

CREDITS

This Final Report was prepared by the technical team of the Consortium.

The Project Manager (Claudio Mordini), the Scientific Coordinator (Giorgio Giacometti), the EU Relations Expert (Lorenzo Facco) and the Senior Expert Marco Montanari, revised the present report, prepared by the whole team, section by section, depending on the topics addressed.

More specifically, the contributions to the Technical Reports were provided by the Key Experts, supported by the respective staff of non-key experts.

The Algae Bioenergy Process Expert (Fabrizio Bezzo), supported by Barbara Gris, followed the selection of microalgae cultivation technologies, the technical report of Appendix A (Microalgae cultivation systems and environmental indicators) and the technologic annexes to Appendices E and F.

The Algae Cultivation Expert (Daniele Curiel), supported by Chiara Miotti, developed the parts concerning the selection of microalgae species, the related report of Appendix B (Selection of Microalgae) and the biological annexes to Appendices E and F.

The GIS Mapping and Analysis Expert, Daniele Mion, and the Environmental Economics Expert, François Levarlet, prepared the technical report of Appendix C, the economic annexes to Appendix E and F. They were supported by Michele Alessandrini, Mauro Scimone and Gaia Galassi.

Alessandro Venturin, Life Cycle Assessment Expert, supported by Giorgio Bonvicini, prepared the LCA report of Appendix D, the LCA annexes to Appendices E and F and parts of the Final Report and of Appendix G.

A particular acknowledgment goes to Kyriakos Maniatis, officer of the European Commission DG Energy for the constant support and the timely feedback to every request during the Assignment and to the members of the AlgaeCluster (Biofat, InteSusAl and All-Gas) for the precious cooperation during the 15 months of preparation of the Study.

APPENDIX A

TECHNICAL REPORT
MICROALGAE CULTIVATION SYSTEMS AND ENVIRONMENTAL INDICATORS

Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Microalgae Cultivation Systems and Environmental Indicators

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CRITICAL ANALYSIS OF KEY TECHNOLOGIES AND OPERATION PARAMETERS IN MICROALGAE CULTIVATION FOR FUEL PRODUCTION

A.1 INTRODUCTION

The objective of this technical report is to provide the basic information for selecting the key environmental parameters and technologies to identify suitable areas for siting plants for microalgae production.

A fundamental assumption, which will not be discussed further, is about the final scope for an intensive cultivation of microalgae: microalgae will be primarily grown for the attainment of oil suitable as fuel per se or suitable for conversion into biodiesel or other standard fuels. In other words, it is always assumed that the goal is not to produce other (valued-added) chemicals or simply to produce biomass for combustion, gasification or other transformation processes.

Box A.1.1 outlines some additional hypotheses, which will be at the bases of successive analysis.

Foreword: the complexity and variety of processes involving microalgae impose to take onboard some assumptions allowing for a macroscopic analysis of the system being investigated. In several cases, such assumptions do not represent a threshold determining whether a process is technically feasible or not. Instead, they represent a number of sensible recommendations based on the current state of technology, some general economic indicators, and engineering good practice. In other words, it is not stated that, if such assumptions do not hold, a microalgae-based technology cannot be envisaged, but that some special (local) conditions must exist so as to justify an exceptional outcome.

Consistently to what declared above, the following assumptions are taken into account:

- **Temperature**
  An annual average temperature is used as a threshold for selecting regions suitable for algae cultivation (i.e. it is assumed that average temperature must be equal or higher than 15 °C). Note the below 15 °C, for most microalgae the growth rate is reduced dramatically.
- **Irradiation**
  A minimum annual solar radiation of 1500 kWh m^{-2} $year^{-1}$ is assumed. In fact, considering that the yield is proportional to the available light energy and that in large scale autotrophic cultivation plants, biomass conversion efficiency is not higher than 2-3%, it is economically sensible to include in the analysis only those regions with a high productivity potential.
- **Evaporation and precipitation**
  In the case of open pond technologies, annual evaporation is assumed to be less than 1000 mm/y (to reduce the technology water footprint and/or minimize pollutant/salt concentration issues), whereas rainfall is supposed not to exceed 600 mm/y (to limit dilution issues).
- **Elevation**
  Although not explicitly indicated the mapping of suitable sites for simple problem of resolution, it is assumed that no cultivation technology can be established if located at a quota that is more than 100 m higher than the quota of the available source of water (to reduce pumping costs).
- **Growth driving force**
  The analysis focuses on the autotrophic cultivation of microalgae. In fact, if the long-term objective is to achieve both security and sustainability, it makes sense to rely on solar energy and not to “transfer” the issue on the availability of a different raw materials that may be converted by microalgae. Thus, although heterotrophic cultivation could be profitable for value-added products or in some special cases where cheap carbon-based nutrients may be available, it is unlikely to represent the technology for large scale fuel production. Note that this assumption does not exclude mixotrophic approaches, where both light and nutrients are combined synergically.

Box A.1.1: Assumptions on Environmental Indicators and Thresholds

A.2 GENERAL COMMENTS ON MICROALGAE SELECTION

The microalgal species selection is a crucial step for the scale-up of this technology at industrial level.

Although theoretically many microalgae species may be used for producing vegetable oil, we decided to focus on species that demonstrated high specific growth rates (preferable to avoid competition with other microalgal species or other microorganisms) and a reasonable robustness in artificial environments.

Selected microalgae are: *Scenedesmus* spp, *Chlorella* spp, *Nannochloropsis* spp, *Chlorococcum* spp, *Dunaliella* spp, *Botryococcus braunii*, *Neochloris oleoabundans*, *Phaerodactylum tricornutom*, *Haematococcus pluvialis*.

A.3 MICROALGAE CULTIVATION SYSTEMS

Microalgae are found growing within nearly every biotope because of their ecological diversity and their physiological adaptability. This diversity and the fact that still there is no sound technology for industrial production explains the variety of proposed microalgal cultivation techniques. Within this multitude of technical solutions one can basically distinguish between open ponds or reactors, which are open to air, and closed systems (Pulz, 2001).

The technical viability of each microalgae cultivation system is influenced by intrinsic properties of the selected algae strain used, as well as climatic conditions and the cost of land, labour, energy, water, nutrients and the type of final product (Borowitzka, 1992; Brennan and Owende, 2010).

Large-scale production of microalgal biomass generally uses continuous culture during daylight. In this method of operation, fresh culture medium is fed at a constant rate and the same quantity of microalgal broth is withdrawn continuously (Molina Grima et al., 1999) feeding ceases during the night, but the mixing of broth must continue to prevent settling of the bio- mass (Molina Grima et al., 1999).

So far the only practicable methods for large-scale production of microalgae appear to be raceway ponds (Molina Grima et al., 1999; Terry and Raymond, 1985) and tubular or (vertical/horizontal) flat-plate photobioreactors (Molina Grima et al., 1999; Sanchez Miron et al., 1999): these methods are represented in Figure A.3.1. (Jorquera et al., 2010).

On-shore cultivation will be considered in this study. Off-shore technologies (e.g.: floating ponds) currently need to be excluded economic reasons.

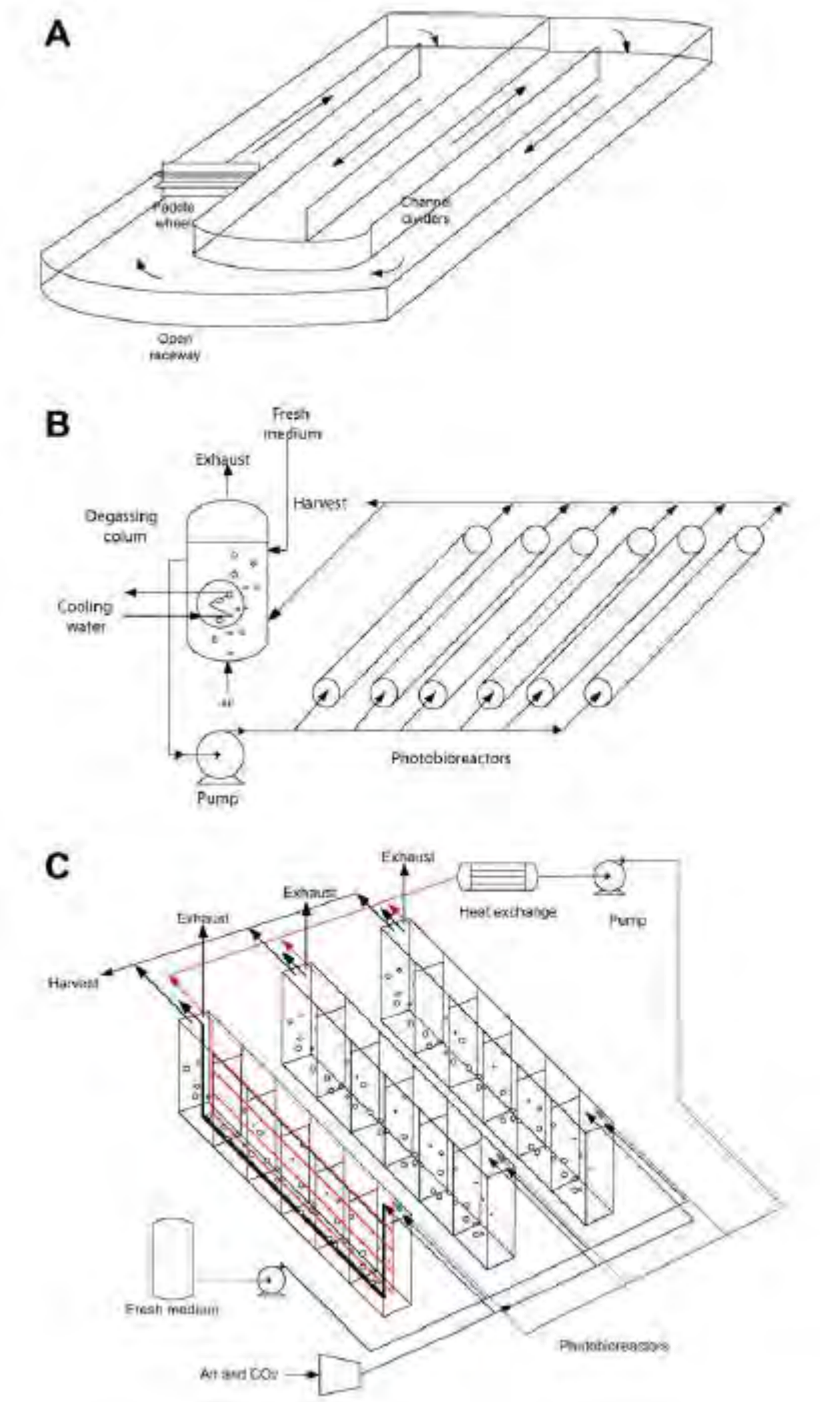

Figure A.3.1: Schematic Drawing of Three Different Cultivation Systems for Mass Production of Microalgal Biomass: (a) Raceway Pond; (b) Tubular Horizontal Photobioreactor; (c) Flat-Plate Photobioreactor

Existing commercial microalgae culture systems range in volume from about 10^2 l to >10^{10} l.

In Table A.3.1 and Table A.3.2, features, advantages and limitation of main microalgae cultivation systems are reported (Brennan and Owende, 2010; Carvalho et al., 2006).

Table A.3.1: Advantages and Limitation of Open Ponds and Photobioreactors

Production system	Advantages	Limitations
Raceway pond	• Relatively cheap • Easy to clean • Utilizes non-agricultural land • Low energy inputs • Easy maintenance	• Poor biomass productivity • Large area of land required • Limited to a few strains of algae • Poor mixing, light and CO2 utilization • Cultures are easily contaminated
Tubular photobioreactor	• Large illumination surface area • Suitable for outdoor cultures • Relatively cheap • Good biomass productivities	• Some degree of wall growth • Fouling • Requires large land space • Gradients of pH, dissolved oxygen and CO_2 along the tubes
Flat plate photobioreactor	• High biomass productivities • Easy to sterilise • Low oxygen build- • Readily tempered • Good light path • Large illumination surface area • Suitable for outdoor cultures	• Difficult scale-up • Difficult temperature control • up Small degree of hydrodynamic stress • Some degree of wall growth
Column photobioreactor	• Compact • High mass transfer • Low energy consumption • Good mixing with low shear stress • Easy to sterilize • Reduced photoinhibition and photo-oxidation	• Small illumination area • Expensive compared to open ponds • Shear stress • Sophisticated construction

Table A.3.2: Main Design Features of Open and Closed Photobioreactors

Feature	Open Systems	Closed Systems
area-to-volume ratio	large (4-10 times higher than closed counterpart)	small
algal species	restricted	flexible
main criteria for species selection	growth competition	shear-resistance
population density	low	high
harvesting efficiency	low	high
cultivation period	limited	extended
contamination	possible	unlikely
water loss through evaporation	possible	prevented
light utilization efficiency	poor/fair	fair/excellent[a]
gas transfer	poor	fair/high
temperature control	none	excellent
most costly parameters	mixing oxygen control	temperature control
capital investment	small	high

[a] Dependent on transparency of construction material

A.3.1 OPEN PONDS

Compared to closed photobioreactors, open ponds are the cheapest method of large-scale algal biomass production. Open pond production does not necessarily compete for land with existing agricultural crops, since they can be implemented in areas with marginal crop production potential (Chisti, 2008). They also have lower energy input requirement (Rodolfi et al., 2008), and regular maintenance and cleaning are easier (Ugwu et al., 2008) and therefore may have the potential to return large net energy production (Rodolfi et al., 2008).

Significant evaporative losses, the diffusion of CO_2 to the atmosphere. as well as the permanent threat of contamination and pollution, the difficulty of maintaining a constant environment for the culture, particularly its temperature, and the low cell density that can be achieved, arising from shading effects are the major drawbacks of open pond systems. (Pulz, 2001; Scott et al., 2010).

The latter point results in the need for extensive areas of land for the raceways and substantial costs for harvesting. To avoid microbial contamination, highly selective conditions have been used in some cases to guarantee dominance by the selected strain, but such conditions are not available for all species (Scott et al., 2010).

Open ponds have a variety of shapes and sizes but the most commonly used design is the raceway pond (Pulz, 2001; Schenk et al., 2008).

A.3.1.1 Raceway Ponds

Raceway ponds are the most commonly used artificial system (Jimenez et al., 2003). They are typically made of a closed loop, oval shaped recirculation channels generally between 0.2 and 0.5 m deep, with an optimal dept of 0.15-0.2 m. At these depths biomass concentrations of 1 g dry weight per litre and productivities of 60–100 mg L−1 day−1 (i.e. 10–25 g m−2 day−1) are possible (Pulz, 2001; Schenk et al., 2008). Mixing and circulation required to stabilize algae growth and productivity (Chisti, 2007).

An area is divided into a rectangular grid, with each rectangle containing a channel in the shape of an oval; a paddle wheel is used to drive water flow continuously around the circuit, as represented in figure A1.1 (Chisti, 2007; Schenk et al., 2008)

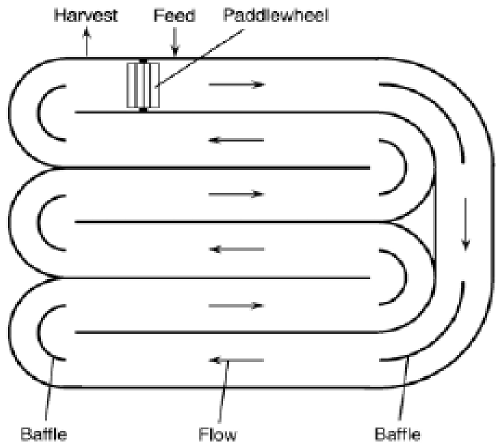

Figure A.3.2: Arial View of a Raceway Pond

In raceways, any cooling is achieved only by evaporation. Temperature fluctuates within a diurnal cycle and seasonally. Evaporative water loss can be significant. Because of significant losses to atmosphere, raceways use carbon dioxide much less efficiently than photobioreactors. Productivity is affected by contamination with unwanted algae and microorganisms that feed on algae. The biomass concentration remains low because raceways are poorly mixed and cannot sustain an optically dark zone. (Chisti, 2007)

Raceways are perceived to be less expensive than photobioreactors, because they cost less to build and operate. Although raceways are low-cost, they have a low biomass productivity com- pared with photobioreactors. (Chisti, 2007)

A.3.2 CLOSED PHOTOBIOREACTORS

A photobioreactor is a closed equipment which provides a controlled environmental and enables high productivity of algae. This system has the advantage of allowing single-species culture of microalgae for prolonged durations (Chisti, 2007) and prevent contamination with undesirable microorganism or grassers. Other benefits of closed bioreactor systems include higher areal productivities and the prevention of water loss by evaporation (Posten, 2009).

Photobioreactors have been successfully used for producing large quantities of microalgal biomass (Carvalho et al., 2006; Molina Grima et al., 1999; Pulz, 2001).

Different geometries and operating methods developed depend on the local conditions, the product to be obtained, and economic constraints. Indeed, commercially available closed photobioreactors still do not represent an optimal solution in many different regards. Even if areal and volumetric productivity is higher than in open ponds, the performance does not come close to theoretical maxima and cannot even reach values obtained at lab scale. Besides, the lack of performance, investment, and operation costs are still estimated as being far too high (Posten, 2009).

Typical configurations tested at either laboratory or pilot scale have included vertical, flat plate reactors (Lehr and Posten, 2009), annular reactors (Chini Zittelli et al., 2006), or arrangements of plastic bags operated as batches (Rodolfi et al., 2008), and various forms of tubular reactor, either pumped mechanically (Scragg et al., 2002) or by air-lift (Molina Grima et al., 1999). Controversy surrounds the cost of scale-up, however, with estimates of capital and production costs varying widely. Contamination can be avoided in closed photobioreactors, but only if operated in a sterile – or at least hygienic – manner, thus increasing operation costs.

In terms of energy, closed photobioreactors typically require energy for mixing (e.g pumping, or energy used to compress gas for sparging), and have much embodied energy in the materials of construction, although this might be offset by the higher productivity of closed systems.

Table A.3.3: Biomass Productivity Figures for Closed Photobioreactors

Species	Reactor type	Volume (l)	X_{max} (g l^{-1})	P_{aerial} (g m^{-2} day^{-1})	P_{volume} (g l^{-1} day^{-1})	PE (%)
Porphyridium cruentum	Airlift tubular	200	3	-	1.5	-
Phaerodactylum tricornutum	Airlift tubular	200	-	20	1.2	-
Phaerodactylum tricornutum	Airlift tubular	200	-	32	1.9	2.3
Chlorella sorokiniana	Inclined tubular	6	1.5	-	1.47	-
Arthrospira platensis	Undular row tubular	11	6	47.7	2.7	-
Phaerodactylum tricornutum	Outdoor helical tubular	75	-	-	1.4	15
Haematococcus pluvialis	Parallel tubular (AGM)	25000	-	13	0.05	-
Haematococcus pluvialis	Bubble column	55	1.4	-	0.06	-
Haematococcus pluvialis	Airlift tubular	55	7	-	0.41	-
Nannochloropsis sp.	Flat plate	440	-	-	0.27	-
Haematococcus pluvialis	Flat plate	25000	-	10.2	-	-
Spirulina platensis	Tubular	5.5	-	-	0.42	8.1
Arthrospira	Tubular	146	2.37	25.4	1.15	4.7
Chlorella	Flat plate	400	-	22.8	3.8	5.6
Chlorella	Flat plate	400	-	19.4	3.2	6.9
Tetraselmis	Column	ca. 1000	1.7	38.2	0.42	9.6
Chlorococcum	Parabola	70	1.5	14.9	0.09	
Chlorococcum	Dome	130	1.5	11.0	0.1	

A.4 WATERS AND GROWTH MEDIA

The choice of growth medium depends on physiology of microalgal species considered.

In addition, there are no specific reasons for which is not possible use any of the reactor described in section 2 in combination with any growth medium reported in this section. The only exclusion we imposed is about the utilization of seawater and wastewater combinations in photobioreactor as the composition of the growth medium may cause excessive fouling problems on the walls of a PBR.

A.4.1 FRESHWATER AND SEAWATER

Growth medium must provide the inorganic elements that constitute the algal cell. Essential elements include nitrogen (N), phosphorus (P), iron and in some cases silicon. Minimal nutritional requirements can be estimated using the approximate molecular formula of the microalgal biomass, that is $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ (Grobbelaar, 2004). Nutrients such as phosphorus must be supplied in significant excess because the phosphates create complexes with metal ions and. therefore, not all the added P is bioavailable. Sea water supplemented with commercial nitrate and phosphate fertilizers and a few other micronutrients is commonly used for growing marine microalgae (Molina Grima, 1999). Growth media are generally inexpensive.

A.4.2 WASTEWATER

The release of industrial and municipal wastewater poses serious environmental challenges to the receiving water bodies (Arora and Saxena, 2005; de-Bashan and Bashan, 2010). The major effect of releasing wastewater rich in organic compounds and inorganic chemicals such as phosphates and nitrates is mainly eutrophication (de-Bashan and Bashan, 2010; Godos et al., 2009; Mulbry et al., 2008; Olguín, 2003; Pizarro et al., 2006). This is a global problem that can be solved by the use of microalgae whereby the wastewater is used as feed for microalgal growth. The advantage is that while the microalgae will be removing excess nutrients in the wastewater, there will be concomitant accumulation of biomass for downstream processing (Muñoz and Guieysse, 2006; Pittman et al., 2011; Pizarro et al., 2006).

The composition of wastewater is a reflection of the life styles and technologies practiced in the producing society. It is a complex mixture of natural organic and inorganic materials as well as man-made compounds. Three quarters of organic carbon in sewage are present as carbohydrates, fats, proteins, amino acids, and volatile acids. The inorganic constituents include large concentrations of sodium, calcium, potassium, magnesium, chlorine, sulfur, phosphate, bicarbonate, ammonium salts and heavy metals.(Abdel-Raouf et al., 2012).

Different sources of pollutants include discharge of either raw or treated sewage from towns and villages, discharge from manufacturing or industrial plants, run-off from agricultural land; and leachates from solid waste disposal sites (Abdel-Raouf et al., 2012).

Particularly important is N:P ratio: the ideal value is 6:3 (Arbib et al., 2013; Olguín, 2012), for this reason, among all the available wastewaters, the most used are urban after primary treatment (Ramos Tercero et al., 2014; Samorì et al., 2013).

A dilution of wastewater using freshwater or seawater can be important and necessary to prevent inhibition phenomena that can occur if the wastewater used is lacking of some important nutrients or presents dark color or a thick surface floating layer (Valderrama et al., 2002).

A.5 ENVIRONMENTAL INDICATORS

A.5.1 LIGHT

Currently, photoautotrophic production is the only method which is technically and economically feasible for large-scale production of algae biomass for energy production (Borowitzka, 1997; Brennan and Owende, 2010).

In both indoor and outdoor microalgae cultivation systems, the light source and light intensity are critical and limiting factors affecting the performance of the phototrophic growth of microalgae (Brennan and Owende, 2010; Mata et al., 2010).

As much as 25% of the biomass produced during daylight, may be lost during the night because of respiration. The extent of this loss depends on the light level under which the biomass was grown, the growth temperature, and the temperature at night (Chisti, 2007).

Most natural plant ecosystems have a solar energy-to-biomass conversion efficiency of less than 1% (Posten and Schaub, 2009). Furthermore they only use the photosynthetically active radiation (PAR) of the solar spectrum (350–700 nm for green plants; extending to 900 nm for purple bacteria), which approximates to 45% of the incident solar energy (Stephens et al., 2010).

By contrast, microalgae can theoretically be cultivated on non-arable land and are already reported to have achieved light-to-biomass conversion efficiencies of 1–4% in conventional open pond systems (Hase et al., 2000), although typical efficiency is about 1-2%. Significantly higher productivities have been reported with closed photobioreactors (Chini Zittelli et al., 2006; M Morita et al., 2000; Masahiko Morita et al., 2000; Morita et al., 2002; Posten and Schaub, 2009; Tredici and Chini Zittelli, 1998), although also in this case medium-large scale plants exhibit an efficiency of about 2-4%.

Based on literature data, and considering the energy-biomass conversion efficiency, the annual average horizontal solar radiation is recommended to be greater than 1500 kWh m^{-2} (Sudhakar and Premalatha, 2012) is order to have a significant biomass yield for intensive large scale production.

A.5.2 TEMPERATURE

Due to the greenhouse effect, microalgae production in outdoor photo-bioreactors experience temperature fluctuations between 10 and 45 °C in temperate regions (Béchet et al., 2010), thereby including temperatures above tolerated thresholds of most commercialized algae specie (Mata et al., 2010). Indeed, most microalgae species are capable of carrying out photosynthesis and cellular division over a wide range of temperatures generally stated between 15 and 30 °C but with optimal conditions between 20 and 25 °C (Li, 1980; Ras et al., 2013).

Chisti (2007) reported that the temperature required for optimum growth of algae is around 20 to 35 °C (Chisti, 2007).

In the perspective of a large scale application, without any form of temperature control, which is energetically and economically demanding (Hindersin et al., 2014), the climatic regions most sustainable for microalgae, have annual average temperatures ≥15°C (Batten et al., 2011).

However, the only consideration of the annual average temperature is not sufficient to select the most suitable areas for siting; in fact, too low or too high temperature, extended over too long time, can irreversibly damage the microalgae, compromising not only the growth but also the vitality of the microorganism. To avoid that, cooling or heating systems are required thus increasing costs dramatically.

For this reason is necessary to pay particular attentions to daily and seasonally trend of temperature, and we suggest to discard regions in which average night temperature is typically below zero over one month per year, and geographical locations were maxim daily temperature may go over 40°C for over one month per year.

A.5.3 ELEVATION

The elevation with respect to the water source is also an important factor in locating the cultivation site. Lundquist (Lundquist et al., 2010) illustrates this with an example showing how a 100 m elevation could mean that a significant proportion (~6%) of the energy produced by the algae would be used for pumping. In some locations the need for pumping can be reduced by using natural tidal flows to feed cultivation ponds (Slade and Bauen, 2013).

A.5.4 SLOPE

Slope restrictions were set based on recommendations from the literature. A survey of the literature illustrates that there is a debate regarding minimum acceptable slope requirements for large-scale microalgae cultivation. Several authors define a requirement for the slope to be 2% or less for economic reasons considering the construction of open raceway ponds (Benemann et al., 1982; Lansford et al., 1990; Muhs et al., 2009). The DOE algae road map defines an acceptable slope of 5% or less (U.S. Department of Energy, 2010). The baseline scenario for this study assumes that a 2% slope or less is required for microalgae cultivation in open ponds (Quinn et al., 2011).

For closed PBRs a higher value might be still feasible since extensive site levelling can be assumed to be unnecessary for PBR construction. However, slope was limited to 8 % to assure the accessibility of the site, which excludes mountainous areas from the analysis (Skarka J., 2012). Here, more conservatively, we adopted a maximum slope of 5% for PBR technologies.

A.5.5 PRECIPITATION AND EVAPORATION

Rainfall influences salinity (for sea- or brackish water based systems), pH and concentratio n of nutrients of cultures in open tanks. Rainfall should ideally be lower than 500 mm/year (Necton, 1990).

The evaporation from outdoor algae ponds is a function of, mainly, air temperature, wind and relative humidity. Evaporation from reservoirs can be estimated from standard evaporation data after applying correction factors (e.g. for humidity, wind speed, etc.). However, algae ponds are not reservoirs, being much shallower and mechanically mixed, and thus are expected to have higher evaporation rates.

The optimal range of annual evaporation is between 27 and 44 inches, that correspond to a range from 686 to 1118 mm/year (Lundquist et al., 2010).

A.6 THRESHOLDS

On the basis of the assumptions (Box A.1.1) and all the information reported in section 4, thresholds for environmental indicators were defined (Table A.6.1)

Table A.6.1: Environmental Thresholds of Indicators Considered in Siting Analysis

Environmental indicator	Threshold
Light	Annual average horizontal solar radiation ≥1500 kWh m^{-2}
Temperature	Annual average ≥ 15 °C Average night temperature for a month < 0°C Maximum daily temperature for a month > 40°C (only for PBRs)
Precipitation	Annual average < 600 mm (only for open ponds)
Evaporation	Annual average 1000 mm (only for open ponds)
Elevation	Altitude gap from water source ≤100 m
Slope	Open ponds: ≤ 2% PBRs: ≤ 5%

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APPENDIX B

**TECHNICAL REPORT
SELECTION OF MICROALGAE**

Doc. No. 12-920-H3
Rev. 1 – JUNE 2015

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Selection of Microalgae

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ALGAE BIOENERGY SITING, COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS SELECTION OF MICROALGAE

B.1 INTRODUCTION

In the first phase of the project ALGA particular attention has been given to the selection of the most promising species of microalgae for biofuels production, focusing on biological aspects. It has been possible through data collection, using the available literature (e.g. print, web, etc.) and taking into account the experience of Consortium and the outcomes of already funded completed and ongoing projects (with particular attention to the activities developed within FP7 AquaFUELs framework which provided basic information and data).

In selecting the species, their most relevant features and the factors affecting biodiesel production have been considered, such as:

- biomass productivity/growth rate and growth conditions;
- resistance and adaptability to changes in environmental conditions (temperature/pH/salinity);
- cell composition (lipid, protein, carbohydrate content);
- potential uses of algae co-products and possible application areas;
- microalgae cultivation in different production systems (open pond and photobioreactor, PBR).

A preliminary qualitative analysis has been performed to evaluate species suitability, taking into account biological aspects (biomass productivity/growth rate; adaptation to different environmental conditions; lipid content; co-products). At the same time, it was performed a quantitative analysis of data regarding cultivation aspects of these species in open ponds (raceway ponds) and PBR, using different water sources. According to all the previous criteria, ten taxa (genus/species) have been selected.

B.2 PRELIMINARY ANALYSIS OF TAXA SUITABILITY

B.2.1 QUALITATIVE EVALUATION OF SELECTION CRITERIA

In the following table it is reported a summary of the most important biological criteria used for selecting microalgae [Biomass Productivity/Growth rate; adaptation to different environmental conditions (Temperature, pH, Salinity); Lipid content; co-products].

General indications are given concerning each parameter, for the suitability of every taxa for biofuels production: green (+) indicates positive aspects, red (-) corresponds to negative aspects and yellow (-/+) points out the coexistence of negative and positive ones. These indications consider both experts assessment and literature data (see chapter 3).

Table B.2.1: General Evaluation of Suitability of Microalgae

	Biomass Productivity/ Growth rate	Temperature pH - Salinity	Lipid content	Co-products
Tetraselmis suecica and Tetraselmis spp.	+	+	+	+
Neochloris oleoabundans	+	-/+	+	+
Scenedesmus spp.	+	+	+	+
Botryococcus braunii	-	-/+	+	+
Haematococcus pluvialis	-/+	-	+	+
Dunaliella salina and *Dunaliella* spp.	-/+	+	+	+
Chlorella vulgaris and *Chlorella* spp.	+	+	+	+
Chlorococcum spp.	+	+	+	+
Nannochloropsis spp.	+	+	+	+
Phaeodactylum tricornutum	+	+	+	+

Although there are few or incomplete data and negative aspects concerning some species (*Neochloris oleabundans*, *Botryococcus braunii*, *Haematococcus pluvialis* and *Dunaliella* spp.), they have been chosen because the positive properties outweigh the negative ones.

For example, *Botryococcus braunii* is considered a slow-growing microalgae and this characteristic is compensated by its high content of ether lipids and hydrocarbons which have fuel applications.

Even if *Haematococcus pluvialis* is a microalga susceptible to environmental fluctuations, it has been selected because this species is a source of lipids (potential feedstock for biodiesel production), astaxanthin and carotenoids and it can be cultivated both in open ponds and closed bioreactors.

The following table summarizes literature data regarding the possible areas of application and the co-products that can be obtained from the cultivation and processing of the selected taxa.

Table B.2.2: Application Areas and Co-Products

Application Areas	MICROALGAE: *Tetraselmis suecica* and *Tetraselmis* spp.	*Neochloris oleoabundans*	*Scenedesmus* spp.	*Botryococcus braunii*	*Haematococcus pluvialis*
Human Feed (probiotic, nutraceuticals and supplements)	probiotic [3,4]	source of carotenoids [7,8]	carotenoids and lutein (nutraceutical) [9]	source of carotenoids and lutein [10,11,12,13]	astaxanthin [9,15] and carotenoids [14,33] (nutraceuticals), nutritional supplement [28]
Aquaculture Feed	food for larval bivalves [1,2]	food in aquaculture [24]	food in aquaculture [35]		food in aquaculture and pigmenter (for salmons) [28,32]
Animal Feed	feed additive [5]		carotenoids and lutein (nutraceutical) [9]		feed additive [14,28,31]
Cosmetics	sunscreen (source of vitamin E) [5] active ingredients influencing growth of hair, pigmentation of skin [6]	active ingredients (slimming effects) [34]			
Pharmaceutical				extracts used as bacteriostatic agents [10]	astaxanthin is an antioxidant [14]
BIOFUELS	bioethanol [1]				

Application Areas	MICROALGAE: *Dunaliella salina* and *Dunaliella* spp.	*Chlorella vulgaris* and *Chlorella* spp.	*Chlorococcum* spp.	*Nannochloropsis* spp.	*Phaeodactylum tricornutum*
Human Feed (probiotic, nutraceuticals and supplements)	health food, nutritional supplement and colourant [14, 16, 17,28], β-carotene (a precursor to vitamin A) and vitamin C [20]	health food, food supplement and feed surrogates [14,30], carotenoids - canthaxanthin and astaxanthin [22,23]	potential sources of astaxanthin [25,26,27]	source of eicosapentaenoic acid (EPA, 20:5ω3) (nutritional supplement) [24], antioxidants (feed additive) [36]	source of eicosapentaenoic acid (EPA, 20:5ω3) (nutritional supplement) [24]
Aquaculture Feed	food in aquaculture and pigmenter (for fishes) [14, 16, 17,28]	food in aquaculture [9]	food source for fish larvae and rotifers [18]	food in aquaculture [28]	food in aquaculture (EPA source) [3]
Animal Feed	feed additive [28]	feed additive [28]			
Cosmetics	β-Carotene as additive to cosmetics [19]	extracts used in cosmetics [28]		extracts (antioxidants) used in cosmetics [28,36]	extracts used in cosmetics [29]
Pharmaceutical	β-carotene (a precursor to vitamin A) is antioxidant, anticarcinogen and antiheart disease agent [16, 17, 28], glycerol [18,19]	health benefits [21], skin care, sun protection and hair care products [24], antibacterial extracts [28]		extracts (antioxidants) used in pharmaceutical preparations [36]	polysaccharides (antibacterial and antiinflammatory activities) [30]
BIOFUELS					

[1] Tredici, 2010; [2] Muller-Feuga et al., 2003; [3] Tredici et al., 2009; [4] Irianto and Austin, 2002; [5] Carballo-Cárdenas et al., 2003; [6] Pertile et al., 2010; [7] Chue et al., 2012; [8] Castro-Puyana et al., 2013; [9] Mata et al., 2010; [10] Rao et al., 2006; [11] Rao et al., 2014; [12] Banerjee et al., 2002; [13] Dayananda et al., 2006; [14] Carlsson et al., 2007; [15] Cysewski and Lorenz, 2004; [16] Mendes et al., 2003; [17] Raja et al., 2007; [18] Sakthivel et al., 2011; [19] Borowitzka, 1992; [20] Brown et al., 1997; [21] Barrow and Shahidi, 2008; [22] Kitada et al., 2009; [23] Guedes et al., 2009; [24] Spolaore et al., 2006; [25] Ma and Chen, 2001; [26] Masojídek et al., 2000; [27] Liu and Lee., 2000; [28] Priyadarshani and Rath, 2012; [29] Nizard et al., 2007; [30] Guzman et al., 2003; [31] Pulz and Gross, 2004; [32] Dore and Cysewski, 2003; [33] Lorenz and Cysewski, 2000; [34] http://www.freepatentsonline.com/y2008/0038290.html (14th may, 2014); [35] Harel and Clayton, 2004; [36] Kim et al., 2012.

B.2.2 SELECTED TAXA CULTIVATION IN OPEN PONDS AND PBR

The following tables provide an evaluation of general cultivation aspects (e.g. biomass productivity, adaptability to culture media, etc.) of the selected taxa both in open ponds and photobioreactors, using different water sources (freshwater, seawater and wastewater). Wastewater can be used as a nutrient source to reduce the production and processing costs of microalgae based biofuels.

General indications are given concerning each species: a value of 5 corresponds to positive aspects, 3 points out the coexistence of negative and positive aspects, 1 corresponds to negative aspects and (?) to "incomplete information". These indications consider both experts assessment and literature data.

Although there is few or incomplete information concerning some species, most of these microalgae seem to be able to grow both in open ponds and closed bioreactors, using different pure water sources (freshwater and/or seawater) or mixed with wastewater.

Table B.2.3: Evaluation of the Selected Species Cultivation in Open Ponds Using Different Water Sources (Freshwater, Seawater and Wastewater)

		Water sources			
OPEN SYSTEM (raceway ponds)		**Seawater**	**Seawater + wastewater**	**Freshwater**	**Freshwater + wastewater**
Tetraselmis suecica and Tetraselmis spp.	Seawater/ Freshwater	5	5 (f)	5	5 (f)
Neochloris oleoabundans	Freshwater	-	-	3	(?)
***Scenedesmus* spp.**	Freshwater	-	-	5	5 (b)
Botryococcus braunii	Freshwater	-	-	3 (c,d)	3
Haematococcus pluvialis	Freshwater	-	-	5	(?)
***Dunaliella salina* and *Dunaliella* spp.**	Seawater	5	3 (e)	-	-
***Chlorella vulgaris* and *Chlorella* spp.**	Seawater/ Freshwater	-	-	5	5 (a)
***Chlorococcum* spp.**	Seawater/ Freshwater	(?)	(?)	5 (g)	5 (g)
***Nannochloropsis* spp.**	Seawater	5	5	-	-
Phaeodactylum tricornutum	Seawater	5	5	-	-

(a) Habib et al., 2008; (b) Krishna et al., 2012; (c) Metzger and Largeau, 2005; (d) Rao et al., 2014; (e) Benemann, 2009; (f) Chinnasamy et al., 2010; (g) Mahapatra & Ramachandra, 2013.

Table B.2.4: Evaluation of the Selected Species Cultivation in Photobioreactors Using different Water Sources (Freshwater, Seawater and Wastewater)

PHOTOBIOREACTORS		Water sources: Seawater	Water sources: Seawater + wastewater	Water sources: Freshwater	Water sources: Freshwater + wastewater
Tetraselmis suecica and Tetraselmis spp.	Seawater/ Freshwater	5	5 (e)	5	5 (d,e)
Neochloris oleoabundans	Freshwater	-	-	5 (f)	3 (b,g)
Scenedesmus spp.	Freshwater	-	-	5	5 (h)
Botryococcus braunii	Freshwater	-	-	5 (i)	3 (a,j)
Haematococcus pluvialis	Freshwater	-	-	5	5 (m)
Dunaliella salina and *Dunaliella* spp.	Seawater	3 (k)	3 (n)	-	-
Chlorella vulgaris and *Chlorella* spp.	Seawater/ Freshwater	-	-	5	5 (c,d,o)
Chlorococcum spp.	Seawater/ Freshwater	5 (l)	(?)	5	(?)
Nannochloropsis spp.	Seawater	5	5	-	-
Phaeodactylum tricornutum	Seawater	5	5	-	-

(a) Orpez et al., 2009; (b) Levine et al., 2011; (c) Wang et al., 2010; (d) Lowrey, 2011; (e) Chinnasamy et al., 2010; (f) Pruvost et al., 2009; (g) Wang & Lan, 2011; (h) Mata et al., 2013; (i) Rao et al., 2014; (j) Krishna et al., 2012; (k) Borowitzka, 1990; (l) Zhang & Lee, 1999; (m) Wu et al., 2013; (n) Putri & Muhaemin, 2010; (o) Ramos Tercero et al., 2014.

B.3 SELECTED MICROALGAE

In the following paragraphs the most important characteristics of the selected taxa are presented. The box below provides definition and other additional information on biological parameters concerning microalgae cultivation.

Growth rate. It is a measure of the increase in biomass over time of a microalgae population and it is determined from the exponential phase (when cells grow according to the exponential growth function). It is base on change of cell number over time and is mainly dependent on algal species, light intensity and temperature (symbol μ, unit d^{-1}).

Biomass productivity. The biomass productivity of microalgae can be represented as:

- Areal productivity (on a surface area basis) reported as grams per square meter (g/m^2), tons per acre, tons per hectare;
- Volumetric productivity reported as grams per liter (g/L/day);
- Daily productivity reported as grams per square meter (or per liter) per day ($g/m^2/day$ or g/L/day).

Doubling time days (Td). It is defined as the time in days for cells to double their initial number.

Growth conditions. Microalgae may assume many types of metabolisms to optimize the efficiency of resource utilization. There are four major types of cultivation conditions for microalgae according to the carbon and energy sources: Photoautotrophy, Heterotrophy, Mixotrophy and Photoheterotrophy (Chojnacka and Marquez-Rocha, 2004).

Photoautotrophic cultivation: the microalgae use light (e.g. sunlight) as the energy source, and inorganic carbon [e.g. carbon dioxide (CO_2) and carbonates] as the carbon source to form chemical energy through photosynthetic reactions.

Heterotrophic cultivation: the microalgae use organic compounds as carbon and energy source under dark conditions.

Mixotrophic cultivation: the microalgae perform photosynthesis as the main energy source, using both organic compounds and CO_2; in this way these organisms can live under either phototrophic or heterotrophic conditions, or both.

Photoheterotrophic cultivation: the microalgae require light when using organic compounds as the carbon source. Photoheterotrophic cultivation requires light as the energy source, while mixotrophic cultivation can use organic compounds to serve this purpose.

Box B.3.1: Definition and Other Additional Information on Biological Parameters

B.3.1 TETRASELMIS SUECICA AND TETRASELMIS SPP.

Tetraselmis is a genus of microalgae belonging to the phylum Chlorophyta (class Chlorodendrophyceae). This microorganisms grow as single, motile cells in inshore marine environments (tide pools in particular), but there are also freshwater species.

B.3.1.1 Biomass Productivity/Growth Rate

Its doubling time days (T_d) is 1,51 (Griffiths & Harrison, 2009). Literature data concerning productivity are listed below:

- *Tetraselmis suecica*:
  - productivity of 15-20 g C m^2/day with photosynthetic efficiencies of 9-10% was recorded in 24-m^2 flumes in Hawaii (Laws & Berning, 1991),
  - Pedroni et al. (2004) described a productivity of about 26 g/m^2/day in a pilot-scale open ponds and near-horizontal tubular reactors,
  - lipid productivity of 27,0-36,4 mg/L/day, volumetric productivity of biomass of 0,12-0,32 g/L/day and areal productivity of biomass of 19 g/m^2/day (Mata et al., 2010; Ahmad et al., 2011),
  - productivity of 0,46 g/L/day and 36, g/m^2/day, with a photosynthetic efficiency of 9,4%, was found in Central Italy in an experiment reproducing a full scale plant arrangement (Chini Zittelli et al., 2006),
  - in Day et al. (1991) it is reported that strain CLS161 was grown at industrial scale under heterotrophic conditions in fermenters with yields in excess of 100 g/L/day;
- *Tetraselmis sp.*: lipid productivity of 43,4 mg/L/day and volumetric productivity of biomass of 0,3 g/L/day (Mata et al., 2010; Ahmad et al., 2011);
- *Tetraselmis tetrathele*: productivity of about 30 g m^2/day, during the summer in pilot-scale open ponds in Southern Italy (photosynthetic efficiencies around 5%) (Materassi et al., 1983).

B.3.1.2 Growth Conditions

Tetraselmis is usually cultivated under photoautotrophic conditions; some species can also grow under heterotrophic or mixotrophic ones.

B.3.1.3 Temperature/pH/Salinity

Species belonging to the genus *Tetraselmis* are very robust marine microorganisms able to resist to extreme salinity, pH and temperature, adapting to rapid changes in environmental conditions.

B.3.1.4 Cell Composition

- *Tetraselmis suecica*: high protein content (up to 40-50%), carbohydrate is about 20% and lipid about 8,5-23% of the cell dry weight; this species accumulates carbohydrates under nutrient stress (nitrogen or phosphorus deprivation) (Renaud et al., 1999; Mata et al., 2010; Ahmad et al., 2011);
- *Tetraselmis sp.*: a content of 26-30% protein, 12,6–14,7% lipid, 8-9% carbohydrate and 14-17% ash as well as about 60% of polyunsaturated fatty acids over the total fatty acid content (Renaud et al., 1999; Mata et al., 2010; Ahmad et al., 2011).

B.3.1.5 Co-products/Application Areas

This genus of microalgae is an important source of protein, bioactive compounds, antioxidants, vitamins, sterols and polyunsaturated fatty acids for human and animal consumption. The most important applications/uses of *Tetraselmis* are:

- carbon biofixation for biofuels production (biodiesel, bioethanol) (Tredici, 2010);
- aquaculture (e.g. food for larval bivalves) (Muller-Feuga et al., 2003; Tredici et al., 2009);
- antibacterial activity towards aquaculture pathogens (Austin et al., 1992);
- probiotic (microalgae probiotic qualities improve health and help reduce the use of antibiotics in livestock and fish farming industry) (Tredici et al., 2009, Irianto and Austin, 2002);
- preservative in foods, additive in animal feed and sunscreen in cosmetics (high content of vitamin E) (Carballo-Cárdenas et al., 2003);
- active ingredients used in the development of cosmetic formulations influencing growth of human hair and/or pigmentation of human skin (Pertile et al., 2010).

The most widely used are the marine *T. suecica*, *T. chui* and *T. tetrathele*.

B.3.1.6 Cultivation (Open Pond/PBR)

This genus is particularly suitable for intensive mass cultivation both in open “raceway” ponds and in different kinds of closed photobioreactors (Day et al., 1991; Laws & Berning, 1991; Pedroni et al., 2004; Chini Zittelli et al., 2006).

B.3.2 NEOCHLORIS OLEOABUNDANS

Neochloris oleoabundans (or Ettlia oleoabundans) is a freshwater unicellular microalga belonging to the phylum Chlorophyta (class Chlorophyceae), which was isolated the first time from the Rub al Khali desert in Saudi Arabia (Chantanachat & Bold, 1962). There is little knowledge about this species, compared to many other green microalgae.

B.3.2.1 Biomass Productivity/Growth Rate

N. oleoabundans specific growth rate is 1,30-1,92 d^{-1} (Loera-Quezada et al., 2011; Santos et al., 2012). Under different conditions and using artificially illuminated system growth rate is 0,07-0,72 d^{-1} (Kawata et al., 1998; Gouveia et al., 2009; da Silva et al., 2009).

- biomass densities were high (2,8 g dry weight /L) at the end of a 20 days batch growth run with specific growth rate of 0,18 day^{-1} in a 2,5 m^2 raceway pond. In an outdoor cultivation, a lipid productivity of 1,6-4,8 g m^2/day was recorded in July in Portugal (da Silva et al., 2009);
- in an airlift photobioreactor without nutrient limitation, a maximal biomass areal productivity of 16,5 g/m^2/day was found. A maximal total lipids productivity of 3,8 g/m^2/day, with nitrogen starvation (to induce lipids accumulation) and without mineral limitation, was reported (Pruvost et al., 2009);
- mata et al. (2010) reported a lipid productivity (mg/L/day) up to 90,0-134 of the cell dry weight.

Under strict heterotrophic conditions in bioreactor batch cultures using glucose and cellobiose as sole carbon sources, lipid accumulation was promoted (up to 52% weight/weight) through nitrogen limitation, resulting in high lipid productivity (528,5 mg/L/day) (Morales-Sánchez et al., 2013). *N. oleoabundans* accumulates oil bodies when growing in saline conditions at high pH (Santos et al., 2012).

B.3.2.2 Growth Conditions

N. oleoabundans is usually cultivated under photoautotrophic conditions and is also able to grow using glucose and cellobiose as sole carbon sources under strict heterotrophic conditions in bioreactor batch cultures (Morales-Sánchez et al., 2013).

B.3.2.3 Temperature/pH/Salinity

There is little knowledge about this species, compared to many other green microalgae. The optimal growth temperature of *N. oleoabundans* was between 25 and 30 °C and significant inhibition to cell growth was observed at 32 °C, using artificial wastewater (Wang & Lan, 2011). Baldisserotto et al. (2012) confirmed the higher acclimatized growth of *N. oleoabundans* in brackish media, more suitable for algal growth than low-salinity ones.

B.3.2.4 Cell Composition

Lipid content up to 29,0-65,0% of the cell dry weight (Mata et al., 2010). *N. oleoabundans* is able to build up a high concentration of a range of pigment (Sakthivel et al., 2011).

B.3.2.5 Co-products/Application Areas

An important application of *N. oleoabundans* is carbon biofixation for biofuels production. This alga is an alternative source of carotenoids, feed stock for freshwater mussels and active ingredients used in the development of cosmetic formulations (Chue et al., 2012; Castro-Puyana et al., 2013).

B.3.2.6 Cultivation (Open Pond/PBR)

Although *N. oleoabundans* is a species of biotechnological interest, there is few information about its cultivation at pilot and commercial scale.

B.3.3 SCENEDESMUS SPP.

Scenedesmus is a genus of microalgae belonging to the phylum Chlorophyta (class Chlorophyceae), colonial and non-motile, found in most types of freshwater.

B.3.3.1 Biomass Productivity/Growth Rate

It is among the faster growing and highest oil producing strains tested by Rodolfi et al. (2009) and Hu et al. (2008). *Scenedesmus obliquus*: doubling time days (T_d) of 2,74 (Griffiths & Harrison, 2009) and growth rate up to 1,13 d^{-1} (Martinez et al., 1997).

Laboratory literature data:

- *Scenedesmus* sp.: maximum specific growth rates higher than 0,12 h^{-1}. Lipid productivity of 40,8–53,9 mg/L/day, volumetric productivity of biomass of 0,03–0,26 g/L/day and areal productivity of biomass of 2,43-13,52 $g/m^2/day$ (Mata et al., 2010; Ahmad et al., 2011);

- S. obliquus: growth rates of 0,04 h^{-1}. Volumetric productivity of biomass of 0,004-0,74 g/L/day (Mata et al., 2010);
- S. quadricauda: lipid productivity of 35,1 mg/L/day, volumetric productivity of biomass of 0,19 g/L/day and areal productivity of biomass of 19 $g/m^2/day$ (Mata et al., 2010; Ahmad et al., 2011).

B.3.3.2 Growth Conditions

Scenedesmus sp. can grow under photoautotrophic, heterotrophic and mixotrophic conditions.

B.3.3.3 Temperature/pH/Salinity

Scenedesmus sp. can grow in a wide range of temperature (maximum growth rate being obtained at temperatures of 30-35 °C) and pH (from 5 to 10, although optimal pH is in the range of 7,5-8,0). The optimum temperature range for *S. obliquus* growth is between 14 and 30 °C (Xu et al., 2012).

B.3.3.4 Cell Composition

Scenedesmus cells can be stressed by nutrient depletion, nitrogen or phosphorous to trigger the accumulation of lipids.

- *Scenedesmus obliquus*: lipid content of 11,0-55,0 (% dry weight biomass), protein content of 50-56 (% dry weight biomass) and carbohydrate content of 10-17 (% dry weight biomass) (Mata et al., 2010; Ravishankar et al., 2012);
- *Scenedesmus quadricauda*: lipid content of 1,9-18,4 (% dry weight biomass) and protein content of 47 (% dry weight biomass) (Mata et al., 2010; Ahmad et al., 2011; Ravishankar et al., 2012);
- *Scenedesmus* sp.: lipid content of 1,9-18,4 (%dry weight biomass) (Mata et al., 2010).

B.3.3.5 Co-products/Application Areas

The genus *Scenedesmus* is an important source of biomass for feeding animals or fishes, mainly for its high protein content; carotenoids and lutein contents (up to 1% dry weight) are useful as nutraceutical for human and animals (Mata et al., 2010).

B.3.3.6 Cultivation (Open Pond/PBR)

Scenedesmus can be cultivated in either discontinuous (batch) or continuous mode. This species is particularly suitable for outdoor large scale production because of its resistant to irradiances higher than 1700 μmol photons m^{-2} s^{-1} without photoinhibition. However, with the highest light intensities, *S. obliquus* also have a much lower productivity in terms of biomass produced per light available (Gris et al., 2013).

B.3.4 BOTRYOCOCCUS BRAUNII

Botryococcus braunii is a green colonial microalga belonging to the phylum Chlorophyta (class Trebouxiophyceae), widely distributed on all continents, that can be found in freshwater, brackish and saline lakes, reservoirs or even small pools, situated in temperate, tropical and continental zones.

B.3.4.1 Biomass Productivity/Growth Rate

B. braunii is a slow-growing microalga. Its specific growth rate is 0,49 d^{-1} (Kojima & Zhang, 1999) and doubling time (T_d) can be of 48 hours in its optimal growth environment (Quin, 2005).

- productivity of biomass of 0,02 g/L/day and of 3,0 g/m^2/day (Mata et al., 2010);
- on secondary treated domestic sewage its productivity was of about 30 mg/L/day (Sawayama et al., 1994; Sydney et al., 2011).

B.3.4.2 Growth Conditions

Botryococcus braunii can grow under photoautotrophic, heterotrophic and mixotrophic conditions.

B.3.4.3 Temperature/pH/Salinity

The optimal growth temperature is 23 °C with a light intensity of 60 W/M², a light period of 12 hours per day and a salinity of 0,15 Molar NaCl (Quin, 2005; Quin & Li, 2006).

B.3.4.4 Cell Composition

Botryococcus braunii produces various types of ether lipids and hydrocarbons; hydrocarbon production ranges from 2% to 86% and is strongly dependent upon the culture conditions (Metzger and Largeau, 2005; Dayananda et al., 2006). Lipid content up to 25-75% (cell dry weight), protein content up to 40% (cell dry weight) and carbohydrate content up to 2% (cell dry weight) (Mata et al., 2010; Priyadarshani & Rath, 2012).

B.3.4.5 Co-products/Application Areas

B. braunii is an important and valuable source of hydrocarbons, alkanes, ether lipids, fatty acids, polysaccharides (exopolysaccharides, Bailliez et al., 1985) and carotenoids which have fuel, food and feed applications. *Botryococcus* biomass has anti-oxidant properties through production of lutein (Rao et al., 2006; 2014). Hydrocarbons obtained from hydrocracked B. *braunii* have good fuel properties (Banerjee et al., 2002; Dayananda et al., 2006).

B.3.4.6 Cultivation (Open Pond/PBR)

Small scale commercial production of *B. braunii* is carried out in Portugal by A4F Algafuel S.A. Although very slowly, this species is able to grow on different types of effluents under laboratory conditions (Metzger & Largeau, 2005; Shen et al., 2008). Outdoor cultures are easily contaminated by other algae (Metzger & Largeau, 2005).

B.3.5 HAEMATOCOCCUS PLUVIALIS

Haematococcus pluvialis is a freshwater unicellular microalga belonging to the phylum Chlorophyta (class Chlorophyceae). *H. pluvialis* is commonly found in temperate climates worldwide and its typical habitats are ponds and rainwater pools.

B.3.5.1 Biomass Productivity/Growth Rate

Its optimal light intensity is < 100 µmol photons/m^2/s (Fan et al., 1994).

- Huntley and Redalje (2007) reported a photosynthetic energy conversion efficiency of 3% in outdoors systems;
- productivity of biomass of 0,05-0,06 g/L/day and of 10,2-36,4 g/m^2/day (Mata et al., 2010);
- large scale outdoors cultivation in two stage mode, photobioreactor for green cells and open ponds for production of red cells was tested in Hawaii and yielded a long term growth average of 38 tons per hectare/year with 25% oil content (Huntley & Redalje, 2007).

B.3.5.2 Growth Conditions

H. pluvialis is considered a slow growing alga and this species can grow under photoautotrophic, heterotrophic and mixotrophic conditions.

B.3.5.3 Temperature/pH/Salinity

H. pluvialis is susceptible to environmental fluctuations. Its optimal temperature is between 25 and 28 °C (Fan et al., 1994).

B.3.5.4 Cell Composition

Lipid content up to 25% of the cell dry weight (Mata et al., 2010). Under stress, this species accumulates up to 40% of cell weight of triacylglycerol (TAG) and up to 4% of astaxanthin (Boussiba et al., 1992, 1999). An increase in biomass and astaxanthin content was observed when *H. pluvialis* was grown in heterotrophic media with acetate as carbon source (Tripathi et al., 1999). Damiani et al. (2010) underlined the potential use of this microalga as a biodiesel feedstock because of its lipid content and composition.

B.3.5.5 Co-products/Application Areas

H. pluvialis is an important source of astaxanthin and carotenoids (for use in the nutraceutical and pharmaceutical industries), health food and feed additives (Dore and Cysewski, 2003; Cysewski & Lorenz, 2004; Carlsson et al., 2007; Sakthivel et al., 2011).

B.3.5.6 Cultivation (Open Pond/PBR)

H. pluvialis is cultivated both in open ponds and closed bioreactors. The most important and advanced plant for the production of astaxanthin is a ten acre production facilities (with tubular photobioreactor) at Kibbutz Qetura (Israel) (http://www.algatech.com/). Large scale outdoors cultivation in two stage mode, photobioreactor for green cells and open ponds for production of red cells was tested in Hawaii (Huntley & Redalje, 2007).

B.3.6 DUNALIELLA SALINA AND DUNALIELLA SPP.

Dunaliella is a unicellular, bi-flagellate, naked green alga belonging to the phylum Chlorophyta (class Chlorophyceae), commonly found in aquatic marine habitats like sea and inland salt lakes.

B.3.6.1 Biomass Productivity/Growth Rate

Its doubling time days (T_d) is 0,44-0,48 (Griffiths & Harrison, 2009) and specific growth rate is 0,28 d^{-1} (Garcia et al., 2007). *Dunaliella* can accumulate high concentration of β-carotene and glycerol under stress (cultivation at extreme salinity) with a reported rather low productivity (about 2 g m^{-2} day^{-1}) (Ben Amotz & Avron, 1981, 1982).

- Dunaliella salina: lipid productivity up to 116 (mg/L/day), productivity of biomass 0,22-0,34 (g/L/day), areal productivity of biomass 1,6-3,5/20-38 (g/m^2/day) (Mata et al., 2010).

B.3.6.2 Growth Conditions

The genus *Dunaliella* can grow in photoautotrophic, heterotrophic and mixotrophic culture modes. *D. tertiolecta* is a fast growing strain (Sakthivel et al., 2011).

B.3.6.3 Temperature/pH/Salinity

The genus *Dunaliella* has marine, halophilic and freshwater species. *Dunaliella* has a very wide pH tolerance ranging from pH 1 (*D. acidophila*) to pH 11 (*D. salina*) (Gimmler et al., 1989). *Dunaliella salina* can grow in extreme conditions in hypersaline waters (2-5 M NaCl) (Ravishankar et al., 2012). The optimum growth temperature for *D. salina* is between 20 and 40°C (optimal growth temperature is 22 °C) (Garcia et al., 2007).

B.3.6.4 Cell Composition

Dunaliella synthesizes very high concentration of different compounds to survive in diverse and extreme conditions: glycerol up to 10% of dry weight , β-carotene up to 6% of dry weig, proteins up to 60% of the dry cell weight (Gilmour, 1990; Oren, 2002). Lipids accumulate up to 6-18% of the dry cell weight depending on growth conditions. For *Dunaliella tertiolecta*, Takagi et al. (2006) reported an increase in the initial salt concentration from 0,5 M NaCl to 1.0 M that resulted in an increase (from 60 to 67%) of intracellular lipid content.

- Dunaliella salina: lipid content of 6,0-25,0 (% dry weight biomass), protein content of 57 (% d.w. biomass) and carbohydrate content of 32 (% dry weight biomass) (Mata et al., 2010; Ravishankar et al., 2012);
- Dunaliella sp.: lipid content of 17,5-67,0 (% dry weight biomass) (Mata et al., 2010).

B.3.6.5 Co-products/Application Areas

Throughout the world *Dunaliella* is a commercial source of β-carotene and glycerol (Ben Amotz & Avron, 1982; Borowitzka, 1992). Other important applications/uses of *Dunaliella* are: feed production in aquaculture, health food, food supplement, additive to cosmetics and pharmaceutical compounds (Mendes et al., 2003; Carlsson et al., 2007; Raja et al., 2007; Priyadarshani & Rath).

B.3.6.6 Cultivation (Open Pond/PBR)

To produce β-carotene, *Dunaliella* is cultivated on a commercial scale in several countries such as Australia, United States and China (Borowitzka, 1992), usually in open systems such as coastal shallow brackish-water ponds (Ravishankar et al., 2012).

B.3.7 CHLORELLA VULGARIS AND CHLORELLA SPP.

Chlorella is a genus of single-cell green algae, belonging to the phylum Chlorophyta (class Trebouxiophyceae) and widely distributed in fresh or salt water and in soil.

B.3.7.1 Biomass Productivity/Growth Rate

The species belonging to the genus *Chlorella* are fast growing freshwater (and marine) microalgae (μ_{max} = 0,20/h) (Demirbas, 2009); under stress they can accumulate high concentration of oil (Liang et al., 2009; Francisco et al., 2010; Hsieh and Wu, 2009; Li et al., 2010). Optimal light intensity is 100-200 μmol photons/m^2/s (Dauta et al., 1990). Growth rate up to 1 (*Chlorella protothecoides*) (Ramos Tercero et al., 2014).

- *Chlorella emersoni*: lipid productivity of 10,3-50,0 mg/L/day, volumetric productivity of biomass of 0,036–0,041 g/L/day and areal productivity of biomass of 0,91-0,97 g/m^2/day (Mata et al., 2010);
- *Chlorella protothecoides*: lipid productivity of 1214 mg/L/day and volumetric productivity of biomass of 2,00-7,70 g/L/day (Mata et al., 2010);
- *Chlorella pyrenoidosa*: volumetric productivity of biomass of 2,90-3,64 g/L/day and areal productivity of biomass of 72,5-130 g/m2/day (Mata et al., 2010);
- *Chlorella sorokiniana*: lipid productivity of 44,7 mg/L/day and volumetric productivity of biomass of 0,23-1,47 g/L/day (Mata et al., 2010);
- *Chlorella vulgaris*: lipid productivity of 11,2–40,0 mg/L/day, volumetric productivity of biomass of 0,02-0,20 g/L/day and areal productivity of biomass of 0,57-0,95 g/m^2/day (Mata et al., 2010; Ahmad et al., 2011);
- *Chlorella* sp.: Lipid productivity of 42,1 mg/L/day, volumetric productivity of biomass of 0,02-2,5 g/L/day and Areal productivity of biomass of 1,61-16,47/25 g/m^2/day (Mata et al., 2010).

B.3.7.2 Growth Conditions

Chlorella vulgaris can grow under photoautotrophic, heterotrophic and mixotrophic conditions, very rapidly in substantial volumes of hundreds of cubic meters.

B.3.7.3 Temperature/pH/Salinity

Chlorella is cosmopolitan and can be found both in freshwater and marine habitats. Some species are characterized by a tolerance to a high culture temperature (up to 40 °C). The optimum growth temperature for *Chlorella* is between 5 and 42 °C (Li et al., 2013).

B.3.7.4 Cell Composition

Under nitrogen deprivation, it was recorded a lipid content of 40-63% of dry weight in five *Chlorella* strains (among which *C. emersonii*, *C. minutissima* and *C. vulgaris*); these strains, containing high amounts of lipids, were characterized by low growth rate (Converti et al., 2009; Mata et al., 2010). *Chlorella* strains can produce a variety of carotenoids and the most important and valuable is astaxanthin; *Chlorella* contains also orange and yellow dyes pigments (the most valuable of these is beta-carotene, a precursor to vitamin A).

The amount of β-carotene in Chlorella is between 0,10% and 0,25% of dry weight (Kitada et al., 2009; Guedes et al., 2009).

- *Chlorella vulgaris*: lipid content of 5,0–58,0 (% dry weight biomass), protein content of 41-58 (% dry weight biomass) and carbohydrate content of 12-17 (% dry weight biomass) (Mata et al., 2010; Ahmad et al., 2011; Priyadarshani & Rath, 2012; Ravishankar et al., 2012);
- *Chlorella emersonii*: lipid content of 25,0-63,0 (% dry weight biomass) (Mata et al., 2010);
- *Chlorella protothecoides*: lipid content of 14,6-57,8 (% dry weight biomass) (Mata et al., 2010);
- *Chlorella pyrenoidosa*: lipid content of 2 (% dry weight biomass), protein content of 57 (% d.w. biomass) and carbohydrate content of 26 (% dry weight biomass) (Mata et al., 2010; Ravishankar et al., 2012);
- *Chlorella sorokiniana*: lipid content of 19,0–22,0 (% dry weight biomass) (Mata et al., 2010).

B.3.7.5 Co-products/Application Areas

The species belonging to the genus *Chlorella* appear to be a good option for biodiesel production because they are readily available and easily cultured in the laboratory (Ahmad et al., 2011). *Chlorella* is also an important source of health food, food supplement, feed surrogates, food in aquaculture, additive to cosmetics and pharmaceutical compounds (Guzman et al., 2003; Carlsson et al., 2007; Kitada et al., 2009; Guedes et al., 2009).

B.3.7.6 Cultivation (Open Pond/PBR)

Commercial production of *Chlorella* biomass is almost exclusively in open systems (Doucha & Lívanský, 2006, 2009; Douskova et al., 2005, 2009, 2010). Since 2000 there is also an important large-scale tubular photobioreactor that produces *Chlorella* biomass in Central Germany (Pulz, 2001). Some species of *Chlorella* have been successfully grown in tubular photobioreactors (Ravishankar et al., 2012). Other closed photobioreactors have been employed for research in small field installations (Torzillo, 1997; Pulz & Scheibenbogen, 1998; Tredici, 2004; Rodolfi et al., 2009; Frumento et al., 2013; Ramos Tercero et al. 2014).

B.3.8 CHLOROCOCCUM SPP.

Chlorococcum is a cosmopolitan genus of unicellular microalgae, belonging to the phylum Chlorophyta (class Chlorophyceae) and found in both aquatic and terrestrial habitats.

B.3.8.1 Biomass Productivity/Growth Rate

Growth rate of *Chlorococcum* was about 0,13 h^{-1}, in a horizontal 50-L tubular photobioreactor (Masojídek et al., 2000).

- in a flat-plate photobioreactor under artificial light of 2000 μmol photons m^{-2} s^{-1}, a ultra-high density culture of the marine *Chlorocococcum littorale* reached a productivity of 380 ± 20 mg/L/ h. Culture densities as high as 84 g/L were reached and daily CO_2 fixation rate was 16,7 g/L (Hu et al., 1998);
- productivity of biomass of 0,28 g/L/day (Mata et al., 2010).

B.3.8.2 Growth Conditions

Chlorococcum sp. can grow under photoautotrophic, heterotrophic and mixotrophic conditions. *Chlorococcum littorale,* a marine alga, showed exceptional tolerance to high CO_2 concentration, up to 40% (Iwasaki et al., 1998).

B.3.8.3 Temperature/pH/Salinity

Optimal growth temperature is 25 °C (Kirrolia et al., 2012). Liu & Lee (2000) indicated the optimal temperature of 35 °C and pH of 8 for the yields of secondary carotenoids and astaxanthin.

B.3.8.4 Cell composition

Lipid content up to 19,3% of the cell dry weight and lipid productivity up to 53,7 mg/L/Day (Mata et al., 2010).

B.3.8.5 Co-products/Application Areas

Several strains of *Chlorococcum* have been tested as potential sources of astaxanthin (Zhang & Lee, 1997; Liu & Lee, 2000; Masojídek et al., 2000; Ma and Chen, 2001). *Chlorococcum* has been investigated as hydrogen producer; however hydrogen yields are much lower than those obtained with other species (Schnackenberg et al., 1995; Ueno et al., 1999; Winkler et al., 2002). *Chlorococcum* was also investigated as a source of lipid for biodiesel production (Rodolfi et al., 2009; Halim et al., 2011).

B.3.8.6 Cultivation (Open Pond/PBR)

Outdoor cultures in tubular photobioreactor have been performed to verify astaxanthin yield; a mass cultivation of microalga *Chlorococcum humicola* has been carried out in open raceway pond to assess the bio-fuel potential of its biomass (Bharanidharan et al., 2013).

B.3.9 NANNOCHLOROPSIS SPP

Nannochloropsis is a genus of microalgae (comprising 6 known species) of marine, fresh and brackish water, belonging to the phylum Ochrophyta (class Eustigmatophyceae).

B.3.9.1 Biomass Productivity/Growth Rate

Nannochloropsis growth rate is 0,81 d^{-1} (Pal et al., 2011) and optimal light intensity is 100-200 µmol photons/m^2/s (*Nannochloropsis gaditana*) (Rocha et al., 2003).

- *Nannochloropsis oculata*: lipid productivity of 84,0–142,0 mg/L/day and volumetric productivity of biomass of 0,37–0,48 g/L/day (Mata et al., 2010; Ahmad et al., 2011);
- *Nannochloropsis* sp.: lipid productivity of 37,6-90,0 mg/L/day, volumetric productivity of biomass of 0,17-1,43g/L/day and Areal productivity of biomass of 1,9-5,3 g/m^2/day (Mata et al., 2010; Ahmad et al., 2011).

B.3.9.2 Growth Conditions

Nannochloropsis can grow under photoautotrophic, heterotrophic and mixotrophic conditions. However, these species grow slowly in heterotrophy (Fang et al., 2004). *Nannochloropsis oculata* showed an increase in the biomass production and lipid accumulation with a CO_2 concentration increase in the aeration of cultures (Chiu et al., 2009).

B.3.9.3 Temperature/pH/Salinity

The species belonging to the genus *Nannochloropsis* grow in seawater, with maximal growth rate in the salinity range from 25 to 30 g/L and can tolerate salinities between 10 and 35 g/L (Renaud and Parry, 1994). This genus has a low tolerance to temperatures above 30°C. Rocha et al. (2003) reported an optimal temperature of 20-30 °C for *Nannochloropsis gaditana*. Spolaore et al. (2006) estimated an optimum growth conditions as 21 °C, 52 µmol photons m^{-2} s^{-1} and pH 8,4 and 14,7 for *Nannochloropsis oculata*.

B.3.9.4 Cell Composition

After nitrogen starvation, *Nannochloropsis* is able to accumulate lipids in amounts higher than 60% of dry biomass (mainly as TAG and saturated and monounsaturated fatty acids, more suitable for biodiesel production) maintaining a high productivity (Shifrin & Chrisholm, 1980; Chini Zittelli et al. 1999; Lardon et al., 2009; Rodolfi et al., 2009; Bondioli et al., 2010). Converti et al. (2009) indicated that a variation of temperature and nitrogen concentration strongly influenced the lipid content of the microalga *Nannochloropsis oculata*.

- Rebelloso-Fuentes et al. (2001) reported the following cell composition under artificial light in a bubble-mixed 29-L photobioreactor: 29% protein, 36% carbohydrate, 18% lipid, 9% ash, and plamitic, palmitoleic, oleic and eicosapentaenoic acid (on average 2.2%) as major fatty acids;
- 22,7-29,7% lipid in *Nannochloropsis oculata* and 12-53% in *Nannochloropsis* sp. (Mata et al., 2010; Ahmad et al., 2011).
- generally, the higher the biomass productivity, the higher is EPA (eicosapentaenoic acid, omega-3) productivity.

B.3.9.5 Co-products/Application Areas

Nannochloropsis is a source of lipid for biodiesel production (Shifrin & Chrisholm, 1980; Rodolfi et al., 2009) and a source of health food (eicosapentaenoic acid - EPA, 20:5ω3), food supplement, feed surrogates, food in aquaculture, additive to cosmetics and pharmaceutical compounds (Spolaore et al., 2006; Kim et al., 2012; Priyadarshani & Rath, 2012).

B.3.9.6 Cultivation (Open Pond/PBR)

Species belonging to the genus *Nannochloropsis* have been cultured successfully for very long periods in open ponds; however, *Nannochloropsis* is mainly cultivated indoors, in different types of photobioreactors (Fulks and Main, 1991; Chini Zittelli et al., 1999; Sukenik et al., 2009). Experiments with natural, artificial or mixed light sources have been carried out in alveolar and glass panels, annular columns, biofence systems and a devised helical tubular reactor with continuous harvesting regimen (Chini Zittelli et al., 1999, 2000, 2003; Zou et al., 2000; Sandnes et al., 2005; Briassoulis et al., 2010).

B.3.10 PHAEODACTYLUM TRICORNUTUM

Phaeodactylum tricornutum belongs to the phylum Ochrophyta (class Bacillariophyta). It is a diatom characterised by three morphotypes: oval, triradiate and fusiform. This species has been found in several locations around the world, typically in coastal areas with wide fluctutations in salinity.

B.3.10.1 Biomass Productivity/Growth Rate

Optimal light intensity is < 100 µmol photons/m^2/s (Fawley et al., 1984). Doubling time days (T_d) of 1,02 (Griffiths & Harrison, 2009).

Under nutrient replete conditions, average literature data for laboratory reported: biomass growth (average doubling time), 25 h; biomass productivity 0,34 g/L/day and 20 g/m^2/day; lipid productivity 72 mg/L/day (Griffiths & Harrison, 2009).

Rodolfi et al. (2009) described a biomass productivity of 0,24 mg/L/day and a lipid productivity of 44,8 mg/L/day for F&M-M40 strain cultivated in 250-mL flasks.

Silva Benavides et al. (2013) described an optimal biomass concentration of 0,6 g/L (in open ponds) and 1,0 g/L (in PBRs) and a lipid content that ranged between 25% and 27,5% of dry weight. Productivity of cultures was higher in short light-path tubular PBRs (because of a more efficient use of light).

- in Spain, biomass productivity in an outdoor 200-L airlift tubular PBR operated in continuous was 1,2-1,9 g/L/day (19-32 g/m^2/day) (Molina et al., 2001) and, in a 75-L helical tubular PBR, biomass productivities up to 1,3 g/m^2/day with a photosynthetic efficiency up to 15% were obtained (Hall et al., 2003);
- in Portugal, in 2,2-m^2 ponds, average productivities of 4 g (ash free dry weight)/m^2/day were achieved, with an EPA productivity of 0,15 /m2/day (Veloso et al., 1991);
- EPA productivities up to 47,8 mg/L/day were achieved in the airlift tubular PBR, with biomass productivity up to 2,57 g/L/day (Molina Grima et al., 1994).
- lipid productivity of 18-57% dry weight. Productivity of biomass of 0,003-1,9 g/L/day and of 2,4-21 g/m^2/day (Mata et al., 2010).

B.3.10.2 Growth Conditions

P. tricornutum can grow under photoautotrophic and heterotrophic conditions. This species can also grow mixotrophically using different carbon sources (among which glycerol a co-product of biodiesel production) (Céron-Garcia et al., 2005, 2006; Fernández Sevilla et al., 2004; Wang et al., 2012).

B.3.10.3 Temperature/pH/Salinity

P. tricornutum shows good growth at temperatures between 15 and 25 °C (optimal temperature 21-25 °C and growth ceases at temperatures above 30°C) (Fawley, 1984). There is a reduction in the photosynthesis activity of nearly 75% at pH values above 9,0 and under 5,5.

B.3.10.4 Cell Composition

- Griffiths and Harrison (2009) signaled a total lipid content of 21% cell dry weight under nutrient replete conditions and 26% cell dry weight under N deficient conditions;
- average literature data for total oil content of: 31% dry weight (Sheehan et al., 1998), 18,7% biomass dry weight (Rodolfi et al., 2009), 18-57% dry weight (Mata et al., 2010).

B.3.10.5 Co-products/Application Areas

P. tricornutum is extensively used as a food source for the aquaculture industry because it is a source of eicosapentaenoic acid, easily cultivated and rich in oil content (Veloso et al., 1991; Molina Grima et al., 1994; Spolaore et al., 2006; Tredici et al., 2009).

Some extracts are used in cosmetics (Nizard et al., 2007); fatty acids show an antibacterial activity (Desbois et al., 2009; 2010) and polysaccharides show antibacterial and anti-inflammatory activities (Guzman-Murillo & Ascencio, 2000; Guzman et al., 2003).

B.3.10.6 Cultivation (Open Pond/PBR)

P. tricornutum is grown outdoors both in open ponds and tubular photobioreactors (Silva Benavides et al., 2013).

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APPENDIX C

TECHNICAL REPORT
BEST SITING SUITABILITY MAPS

Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

consulting, design, operation & maintenance engineering

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Best Siting Suitability Maps

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ALGAE BIOENERGY SITING,
COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS
BEST SITING SUITABILITY MAPS

C.1 INTRODUCTION

The Project foresees the analysis and selection of optimal sites for the deployment of algae cultivation plants at EU-28 scale. The analysis is developed into different levels:

(i) macro-areas selection,

(ii) site zones selection,

(iii) selection of site territorial units within the site zones, and

(iv) classification of the site territorial units into classes of suitability to host algae cultivation plants by means of spatial decision support system. This report describes the results of the final phase of the analytical process.

C.2 SELECTION OF MACRO-AREAS

The analytical process for the identification of suitable macro-areas for algae cultivation has been widely described in the Interim Report (March 2014) and is here reported in summary terms.

Methodology

The Macro-Areas are defined as *wider trans-national regional areas at European scale where algae cultivation is possible on the basis of environmental conditions.*

After the collection of the baseline layers data, consulting international literature and all the public available sources, the Macro-Areas were selected based on two main environmental factors:

- Solar Radiation ≥ 1500 kW m^{-2} yr^{-1};
- Mean annual Air Temperature ≥ 15°C.

A buffer zone was also defined, with situations near to suitability with higher variability of these factors. These areas are detected on the average by solar radiation between 1300 and 1500 kWh m^{-2} yr^{-1} and air temperature between 13°C and 15°C.

All the European areas falling outside these thresholds were excluded for the subsequent analyses.

Results: Map of Macro-Areas

From the application of the threshold values for the indicators annual solar irradiation and annual mean temperature, three areas were detected (suitable; buffer zone; non-suitable) applying the following criteria:

1. the suitable macro-areas are those with annual solar irradiation not less than 1500 kWh m^{-2} yr^{-1} and annual mean temperature not less than 15°C;
1. the non-suitable macro-areas are those falling outside the above indicated thresholds;
2. the ‘buffer zone’ includes intermediate areas where the indicators have values near the suitability and show higher variability. Such areas present variability in solar irradiation between about 1300 and 1500 kWh m-2 yr-1 and in temperature between about 13°C and 15°C. In this zone a mix of suitable and non-suitable situations is likely, depending on local characteristics.

The map of the selected Macro-Areas was produced, overlaid to the NUTS3 European EU-28 map (Fig.1).

From the analysis of the Macro-Areas map it is possible to remark:

1. the three resulting macro-areas extend along latitudinal belts, the suitable ones ranging as a whole under the 43° N latitude, including almost all the Mediterranean area;
2. the buffer zone ranges more or less in the belt between 43° and 45° N latitude, including all the Northern coast of Spain, the Southern Atlantic coast of France, the coast of Northern Italy and the Western coasts of the Black Sea;
3. the areas extending over about 45° N latitude result non-suitable based on the chosen indicator;

4. in conclusion, the Mediterranean Sea shows most of the suitable macro-areas from this analysis.

At Macro Area level, no account was taken of the different algae cultivation systems, which were analysed in the further steps.

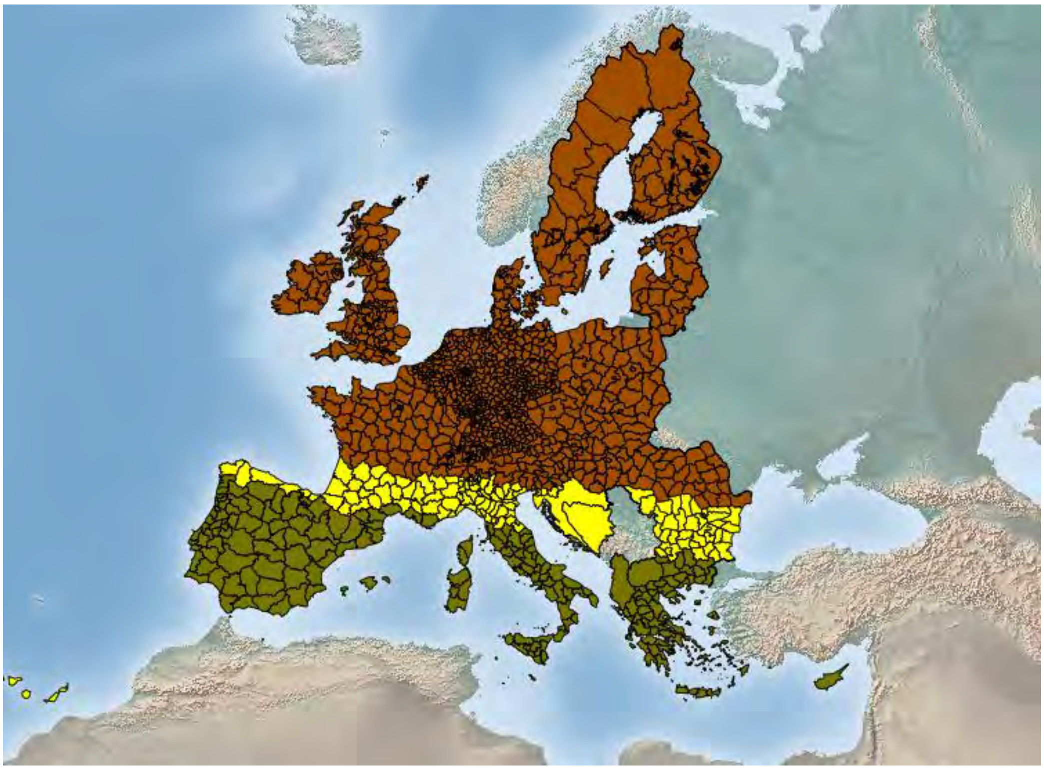

Figure C.2.1: Macro-Areas Suitability Map

Base map of Europe for the analysis and selection of suitable macro-areas for algae cultivation plants. The EU-28 Administrative Units layer at NUTS 3 level (Switzerland is included in the original database layer) is overlaid to the physical map of Europe, putting in evidence three belts different for degree of suitability for algae cultivation. Brown: non-suitable areas; yellow: buffer zone for suitability; green: suitable areas.

The suitability is evaluated based on annual solar irradiation and annual mean air temperature. Suitable areas are considered those where solar irradiation is ≥1500 kWh $m^{-2}yr^{-1}$ and mean annual air temperature is ≥ 15°. The buffer zone is defined as the one where solar irradiation and temperature are more variable, showing conditions near to the suitability (about 1300-1500 kWh m^{-2} yr^{-1} and about 13°C - 15°C).

C.3 ANALYTICAL PROCESS: FROM MACRO AREAS TO S-DSS

The following steps of the analysis for the selection of suitable areas, adding more indicators and more exclusive criteria, have been set at different levels:

Level 0 – Assumptions: definition of the limits of the selection analysis.

Level 1 – Site Zones (SZ): definition of the indicators and of the respective thresholds for the selection of the Site Zones.

Level 2 – Site Territorial Units (STU): definition of the indicators and of the respective thresholds for the selection of the Site Territorial Units.

Level 3 – Spatial Decision Support System (S-DSS): definition of the indicators and of the respective thresholds and scores for the classification of the STU in suitability classes (capability).

Level 4 – Limits and recommendations: indication of those issues that should be considered when exploring the classified STU at local level for planning purposes.

The flowchart of Fig. 2 describes the analytical process at each level, and is explained in details in the following paragraphs. All the levels of analysis, the related indicators and thresholds were developed and completed on the basis of close contacts, discussions and exchange of information among the project's experts team.

0 Level Assumptions

Assumptions

The analysis focuses on the autotrophic cultivation of microalgae
The thresholds of the indicators should be considered in terms of recommendations based on the current state of technology

I° Level SITE ZONE.
Indicators for the selection of Site Zones

Solar Irradiation ≥ 1500 kWh^{-2} $year^{-1}$ (annual cumulative)
Air temperature ≥ 15°C (annual average)
Precipitation ≤ 600 mm $year^{-1}$ (open pond)
Evapotranspiration ≤ 1000 mm $year^{-1}$ (open pond)
Slope ≤ 2% (open pond) ≤ 5 % (PBR)
(*) Air temperature (average min of the coldest month) <0°C
(*) Air temperature (average max of the hottest month) >40°C

II° Level STU.
Indicators for the identification of Site Territorial Units STU

OPEN PONDS seawater	OPEN PONDS freshwater	OPEN PONDS wastewater	OPEN PONDS seawater wastewater	OPEN PONDS freshwater wastewater	PBR seawater	PBR freshwater	PBR wastewater	PBR freshwater wastewater
Exclusion from protected areas Exclusion from urban areas Minimum area ≥ 2 km^2 Proximity to sea ≤ 1 km Elevation ≤ 100 m	Exclusion from protected areas Exclusion from urban areas Minimum area ≥ 2 km^2 Proximity to freshwater bodies ≤ 1 km	Exclusion from protected areas Minimum area ≥ 2 km^2 Distance from urban area (Corine Land Cover class 111) ≤ 5 km	Exclusion from protected areas Minimum area ≥ 2 km^2 Proximity to sea ≤ 1 km Distance from urban area (Corine Land Cover class 111) ≤ 5 km Elevation ≤ 100 m	Exclusion from protected areas Minimum area ≥ 2 km^2 Proximity to freshwater bodies ≤ 1 km Proximity to sea ≤ 1 km Distance from urban area (Corine Land Cover class 111) ≤ 5 km	Exclusion from protected areas Exclusion from urban areas Minimum area ≥ 2 km^2 Proximity to sea ≤ 1 km Elevation ≤ 100 m	Exclusion from protected areas Exclusion from urban areas Minimum area ≥ 2 km^2 Proximity to freshwater bodies ≤ 1 km	Exclusion from protected areas Minimum area ≥ 2 km^2 Distance from urban area (Corine Land Cover class 111) ≤ 5 km	Exclusion from protected areas Minimum area ≥ 2 km^2 Proximity to freshwater bodies ≤ 1 km Proximity to sea ≤ 1 km Distance from urban area (Corine Land Cover class 111) ≤ 5 km

	S-DSS	S-DSS	S-DSS	S-DSS	S-DSS	S-DSS	S-DSS	S-DSS	S-DSS
III° Level S-DSS Indicators for the classification of STU in suitability classes	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%	≤ 5 km from an industrial plant ≤ 500 m from the road network (‘) Economic index Agricultural areas max 30%
IV° Level Limits and recommendations	seawater: elevation to be evaluated at local scale (e.g. in case of flat areas over cliffs)	freshwater: elevation to be evaluated at local scale (e.g. no more than 100 m of elevation between plant areas and water sources)	seawater: elevation to be evaluated at local scale (e.g. in case of flat areas over cliffs) freshwater: elevation to be evaluated at local scale (e.g. no more than 100 m of elevation between plant areas and water sources)	seawater: elevation to be evaluated at local scale (e.g. in case of flat areas over cliffs)	freshwater: elevation to be evaluated at local scale (e.g. no more than 100 m of elevation between plant areas and water sources)	seawater: elevation to be evaluated at local scale (e.g. in case of flat areas over cliffs)	freshwater: elevation to be evaluated at local scale (e.g. no more than 100 m of elevation between plant areas and water sources)		freshwater: elevation to be evaluated at local scale (e.g. no more than 100 m of elevation between plant areas and water sources)

(*) Control parameters. Used after the selection of the Site Zones to verify the exclusion of areas having those values from the site zones.
(‘) Economic index composed of the following indicators: (1) Population density (year 2012), (2) Share of industrial, commercial and transport units, (3) Potential accessibility by Road, (4) Share of population by highest level of education, and (5) Gross Value Added in industry

Figure C.3.1: Flowchart of the Levels of Analytical Process Leading from the Identification of the Site Zones to the Classification of the Site Territorial Units into Suitability Classes through Application of Spatial Decision Support System

C.4 MAIN ASSUMPTIONS

Based on the project experts considerations, the following assumptions were established for the further analytical steps (Level 0):

- The analysis focuses exclusively on the autotrophic cultivation of the microalgae. Based on considerations of long-term objective of security and sustainability, heterotrophic cultivation seems not to be a suitable solution for large scale fuel production.
- The thresholds for each indicators should be not considered as constraints, instead as recommendations based on the current state of the technology, to be verified in details at local level;
- Indicators and thresholds have been acquired from the public available literature and projects reports, and approved by the project experts after consultation.

C.5 SELECTION OF SITE ZONES (SZ)

Methodology

The Site Zones are defined as *zones at regional scale, within the macro areas and the buffer zone, where to detect suitable sites for algae cultivation plants*. The Site Zones (Level 1 of analysis, Figure C.5.1) are separately detected for each major group of algae cultivation plants (PBR, Open Ponds).

The Site Zones were previously identified in the first project phase (Site Zones Selection, Internal Report April 2014); after review of the experts group, they have been reselected based on some modified thresholds. The selected indicators and the thresholds for the selection are described in Table C.5.1.

Table C.5.1: List of Indicators with Respective Threshold Values Used for the Selection of the Site Zones Suitable for Algal Cultivation

Indicator	Threshold	Notes
Solar Irradiation	≥ 1500 kWh^{-2} $year^{-1}$	Annual cumulative
Air temperature	≥ 15°C	Annual average
Precipitation	≤ 600 mm $year^{-1}$	Annual cumulative (applied to Open Ponds only)
Evapotranspiration	≤ 1000 mm $year^{-1}$	Annual cumulative (applied to Open Ponds only)
Slope	≤ 2% (Open Ponds) ≤ 5 % (PBR)	
Air temperature (*)	<0°C	average min of the coldest month
Air temperature (*)	>40°C	average max of the hottest month (applied to PBR only)

(*) Control parameters. Used after the selection of the Site Zones to verify the exclusion of areas having those values.

With respect to the former classification of the SZ (Site Zones Selection, Internal Report April 2014), the following modifications were applied after experts consultation:

- because the importance of elevation is in terms of difference from the elevation of available water sources, having relevance on the pumping costs (that can be detected only at local scale), the elevation was neglected from the Site Zones selection process;
- not to consider annual precipitation and annual evapotranspiration for selecting the suitable Site Zones for PBR;
- to apply different thresholds on slope for Open Ponds e PBR;
- to consider extreme values of high and low temperatures as further selection factors. It was decided to exclude those areas having the average minimum of the coldest month below 0°C and the average maximum of the hottest month over 40°C (for PBR only). These variable have been considered representative of situations as (i) continuous minimum temperature below 0°C for at least one month, and (ii) continuous maximum temperature above 40°C for at least one month. The control was made on the Site Zones after the selection process, and no areas resulted to fall in these conditions.

Results: Site Zones mapping

The Site Zones maps are presented in Figure C.5.1for Open Ponds, and in Figure C.5.2 for PBR. It is to note that the most remarkable SZ suitable areas for the Open Ponds are:

- Southern Portugal and S-W Spain (coast and internal regions), S-E coast of Spain;
- In Italy, some parts of Sardinia, Sicily, and Apulia;
- Some parts of the Eastern coast of Greece and of Cyprus.

For the PBR, being the selection criteria less exclusive, the most evident areas result wider with respect to the Open Ponds, e.g.:

- Southern Portugal and the whole S-W Spain, almost all the Mediterranean coast of Spain;
- In Italy, wide areas of Sardinia, Sicily, Apulia and also some coastal Tyrrhenian areas and Calabria;
- Greater part of Eastern Greece, Ionian coasts of Greece and Crete;
- Almost all areas in Cyprus.

Figure C.5.1: Identification of the Open Ponds Suitable Site Zones

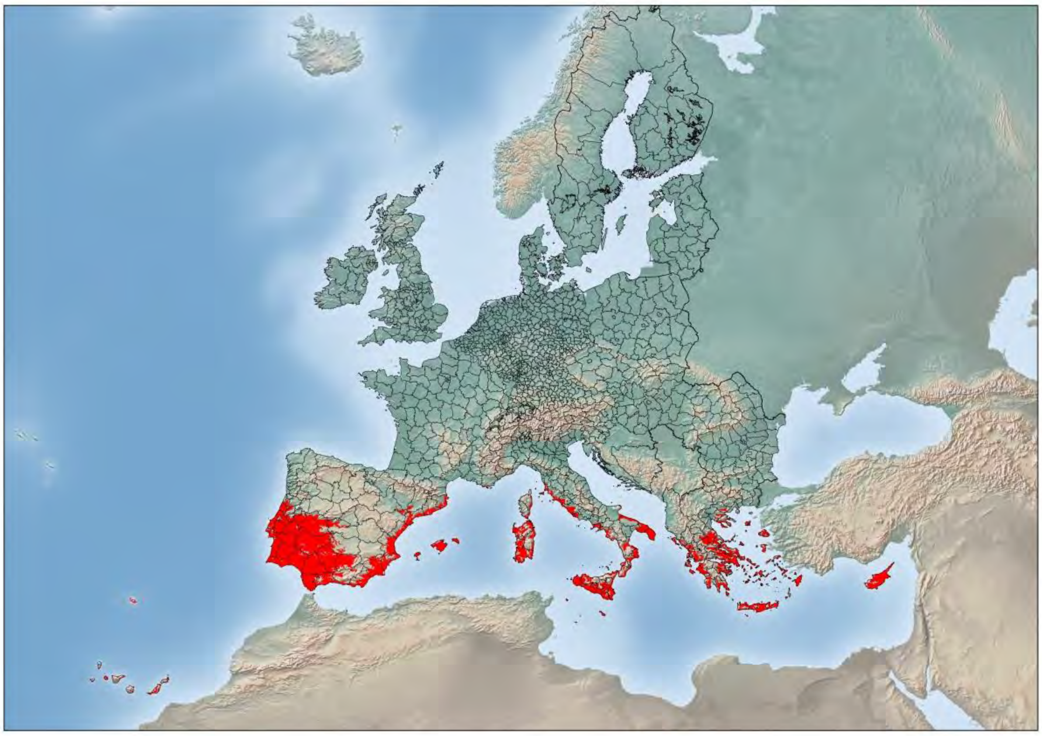

Figure C.5.2: Identification of the PBR Suitable Site Zones

In the previous Figures the EU-28 Administrative Units at NUTS 3 level belonging to the suitable macro-areas and the buffer zone are overlaid to the physical map of Europe.

C.6 SELECTION OF SITE TERRITORIAL UNITS (STU)

Methodology

The Site Territorial Units (STU) are defined as areas, *within the Site Zones, where it is possible to build one or more algae cultivation plants, at different classes of capability*.

The STU have been detected for each type of algae cultivation plants as defined and selected by the project experts. A total of 9 types of plants were considered for the STU selection and the S-DSS analysis, grouped in two major categories, Open Ponds and Photobioreactors (Table C.6.1).

Note for the following Tables: OP: Open Ponds; PBR: Photobioreactors. SW: sea water; FW: fresh water; WW: waste water.

Table C.6.1: Types of Algal Cultivation Systems considered for the STU Selection and S-DSS Analysis

Open Ponds (Raceway Ponds)	Photobioreactors (PBR)
Sea water (OP SW)	Sea water (PBR SW)
Fresh water (OP FW)	Fresh water (PBR FW)
Waste water (OP WW)	Waste water (PBR WW)
Sea water – Waste water (OP SW-WW)	Fresh water – Waste water (PBR FW-WW)
Fresh water – Waste water (OP FW-WW)	

The STU were extracted from the Site Zones combining territorial and land use indicators, through a GIS process of progressive filtering (exclusion or intersection), by overlaying the layers related to each indicator. The Corine Land Cover (CLC) 2006 digital maps (EEA) were used for the land use layers. Whereas the 2006 data are not yet available (e.g. Greece) the Corine Land Cover 2000 data were used and integrated to the 2006 data.

For each of the 9 types of plants considered, the indicators reported in Table 6.2 were applied, with the related thresholds of selection.

Concerning the threshold criteria of Table 6.2, it is to remark:

- the exclusion / inclusion of areas with relation to urban areas was set with a buffer of 5 km from the urban centres (CLC class 111) with the aim of including in the threshold also the urban suburbs;
- the elevation was applied with a limit of 100 m only for the sea water plants, with the aim of excluding unsuitable situations in the coastal areas (e.g. flat lands on high cliffs);
- considering the minimal suitable size of 100 ha for a plant, all the STU resulting with size less than 2 km^2 were subsequently discarded.

Table C.6.2: List of Indicators with Threshold Values used for the Selection of the Site Territorial Units Suitable for algal Cultivation System

Algae Cultivation Plant Type	Indicator	Threshold
OP SW	Exclusion from protected / natural reserves / designed areas	Constraint
	Exclusion from urban areas	At least 5 km from CLC class 111 areas (Continuous urban fabric)
	Proximity to sea	Within 1 km from the coast line
	Elevation	Less than 100 m above sea level
OP FW	Exclusion from protected / natural reserves / designed areas	Constraint
	Exclusion from urban areas	At least 5 km from CLC class 111 areas (Continuous urban fabric)
	Proximity to fresh water bodies	Within 1 km from rivers (CLC class 511) or lakes (CLC class 512)
OP WW	Exclusion from protected / natural reserves / designed areas	Constraint
	Proximity to urban areas	Within 5 km from CLC class 111 areas (Continuous urban fabric)
OP SW-WW	Exclusion from protected / natural reserves / designed areas	Constraint
	Proximity to sea	Within 1 km from the coast line
	Elevation	Less than 100 m above sea level
	Proximity to urban areas	Within 5 km from CLC class 111 areas (Continuous urban fabric)
OP FW-WW	Exclusion from protected / natural reserves / designed areas	Constraint
	Proximity to fresh water bodies	Within 1 km from rivers (CLC class 511) or lakes (CLC class 512)
	Proximity to urban areas	Within 5 km from CLC class 111 areas (Continuous urban fabric)
PBR SW	Exclusion from protected / natural reserves / designed areas	Constraint
	Exclusion from urban areas	At least 5 km from CLC class 111 areas (Continuous urban fabric)
	Proximity to sea	Within 1 km from the coast line
	Elevation	Less than 100 m above sea level
PBR FW	Exclusion from protected / natural reserves / designed areas	Constraint
	Exclusion from urban areas	At least 5 km from CLC class 111 areas (Continuous urban fabric)
	Proximity to fresh water bodies	Within 1 km from rivers (CLC class 511) or lakes (CLC class 512)
PBR WW	Exclusion from protected / natural reserves / designed areas	Constraint
	Proximity to urban areas	Within 5 km from CLC class 111 areas (Continuous urban fabric)
PBR FW-WW	Exclusion from protected / natural reserves / designed areas	Constraint
	Proximity to fresh water bodies	Within 1 km from rivers (CLC class 511) or lakes (CLC class 512)
	Proximity to urban areas	Within 5 km from CLC class 111 areas (Continuous urban fabric)

Results

The selection process detected a total of 3669 STU, distributed in the cultivation plant types as described in Table C.6.3. As a whole, the number of STU per type of plant ranges from 109 (OP sea water – waste water) to 651 (PBR fresh water).

The size of the STU ranges from a minimum of 2 km^2 (constraint) to a maximum of 11,200 km^2. The average size is 52.8 km^2, but the frequency distribution of the STU per class of size (Figure C.6.1) indicates that more of the half of STU (55.5%) is from 2 to 10 km^2 in size.

Table C.6.3: Number of Site Territorial Units (STU) detected by Selection process for Each Algal Cultivation System

Algae Cultivation Plant Type	N of STU
OP SW	230
OP FW	409
OP WW	566
OP SW-WW	109
OP FW-WW	246
PBR SW	496
PBR FW	651
PBR WW	619
PBR FW-WW	343
Total	3669

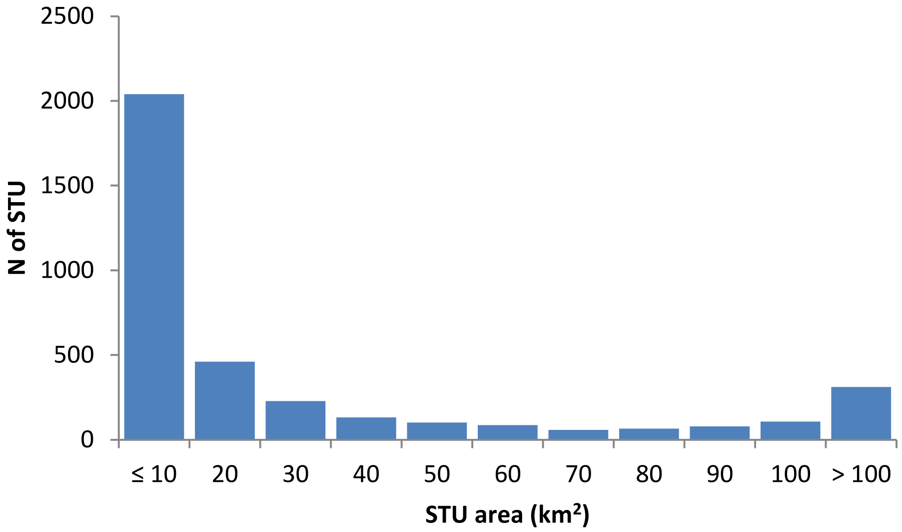

Figure C.6.1: Frequency Distribution of the 3669 detected STU According to Size Classes (km^2)

The STU have been used in the subsequent step as alternatives for the S-DSS analysis. The maps of the STU for each type of algae cultivation plant are presented after S-DSS classification into capability classes (due to the large amount of maps, they are reported separately as annex).

C.7 SPATIAL DECISION SUPPORT SYSTEM (S-DSS)

Methodology

The Spatial Decision Support System (S-DSS) was applied for classifying the STU in classes of suitability (capability classes). The following steps were carried out:

- a matrix (S-DSS matrix) was built for each type of cultivation plant, composed by indicators (rows) x STU (columns). The STU have been considered as alternatives, to be ranked in classes of suitability using 4 S-DSS indicators values (Tab. 5). The indicators values were extracted for each STU from the Corine Land Cover GIS layers or, in case of the composite economic indexes, elaborated from existing databases. A total of 9 S-DSS matrices were produced;
- threshold values were assigned to each indicator for detecting the suitability degree of each STU;
- a score was assigned to each STU for any given indicator, calculated on the basis of the distance of that indicator to the threshold according to utility functions (Fig. 6-9);
- The sum of all scores per each STU gave the total score of capability of each STU. The STU were then classified in classes of capability (high, mid, low) per each type of algae cultivation plants according to their score;
- Capability maps of the STU were produced per each type of cultivation plants, that will represent the baseline for elaborating eventual feasibility plans of algae cultivation plants.

The S-DSS indicators for ranking the STU are presented in Table C.7.1, along with the respective thresholds. The same indicators were applied to all the 9 types of cultivation plants.

Table C.7.1: List of Indicators (S-DSS indicators) with Threshold Values used for the Classification of the Site Territorial Units (STU) into Classes of Suitability (Capability Classes)

Algae Cultivation Plant Type	S-DSS Indicator	Threshold
All	Proximity to industrial plants	Within 5 km from industrial / commercial areas (CLC class 121)
All	Proximity to road networks	Within 0.5 km from the road network
All	Share of agricultural area	30% of the STU area (optimal, CLC classes from 211 to 244)
All	Economic Index	Calculated combining 4 or 5 socio-economic indicators (no threshold)

The above reported thresholds are not intended as constraint values (yes / no), instead as optimal values to which refer the suitability scores. The scores were calculated transforming the indicator values into range from 0 (minimum suitability) to 100 (maximum suitability) by means of utility functions, according to the following criteria for each indicator:

- proximity to industrial plants (Figure C.7.1): the score was calculated according to a linear function from 100 (zero distance from an industrial area) to 0 (distance from an industrial area equal of greater than twice the value of the threshold, e.g. 15 km). The distance is retrieved through GIS technique as distance of the STU polygon centroid from the nearest industrial area;
- proximity to road networks (Figure C.7.2): the score was calculated according to a linear function from 100 (zero distance from a road network) to 0 (distance from a road network equal of greater than twice the value of the threshold, e.g. 1.5 km). The distance is calculated through GIS technique as distance of the STU polygon centroid from the nearest road network;
- share of agricultural area (Figure C.7.3): the optimal value (score 100) was given to values of 30% of agricultural area into a STU; the score was then calculated according to a triangular function from 0 to 100 (in the range of agricultural area from 0% to 30%) and from 100 to 0 (in the range of agricultural area from 30% to 60% and over). This was made on the assumption that a share of 30% of agricultural area in a STU could be optimal;
- economic Index: it was calculated combining five key socio-economic indicators e.g. (1) Population density (year 2012), applied only for plants using waste water, (2) Share of industrial, commercial and transport units, (3) Potential accessibility by Road, (4) Share of population by highest level of education, and (5) Gross Value Added in industry. The indicators values were assigned to each STU by extracting the corresponding value of the same indicator of the NUTS3 including that STU. The indicator values were classified into 3 classes ("favourable", "medium" and "unfavourable"), and the final Economic Index score for each STU was given by the number of “favourable” indicators recorded, ranging from a minimum of 0 (no favourable indicators in a STU) to a maximum of 4 or 5, depending on the type of cultivation plant (all favourable indicators in a STU). The score was scaled from 0 to 100 according to a linear function (Figure C.7.4).

For each STU, the total score of suitability (Suitability Score) was given by the sum of the four indicators scores above described.

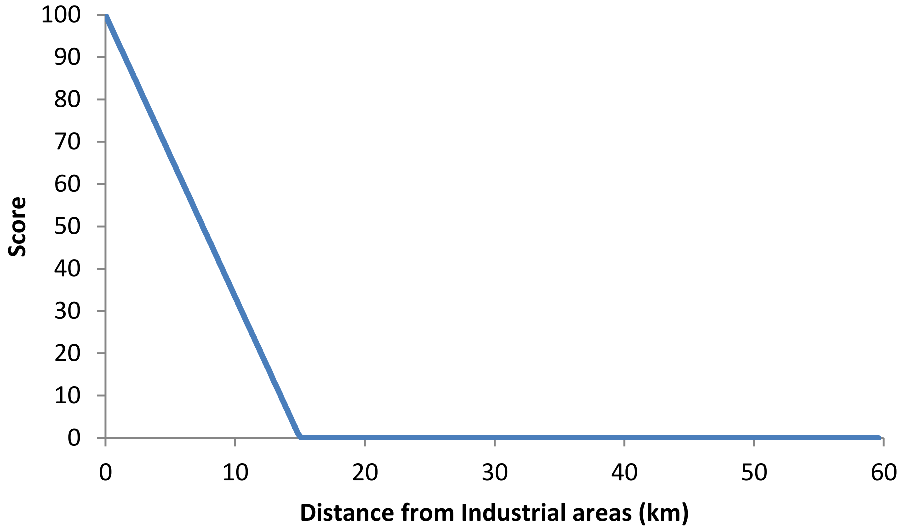

Figure C.7.1: Utility Function for the Calculation of the suitability Score in Function of the Distance of a STU from Industrial Areas

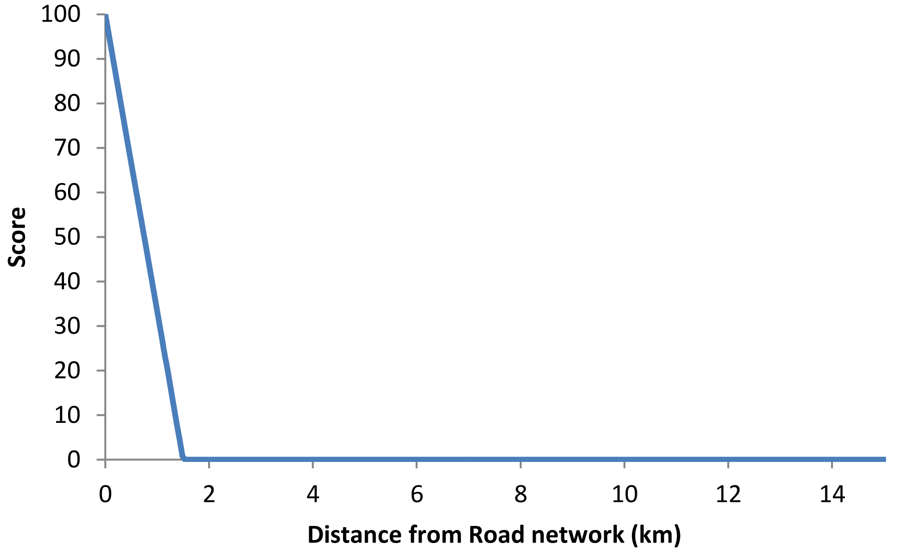

Figure C.7.2: Utility Function for the Calculation of the Suitability Score in Function of the Distance of a STU from the Road Network

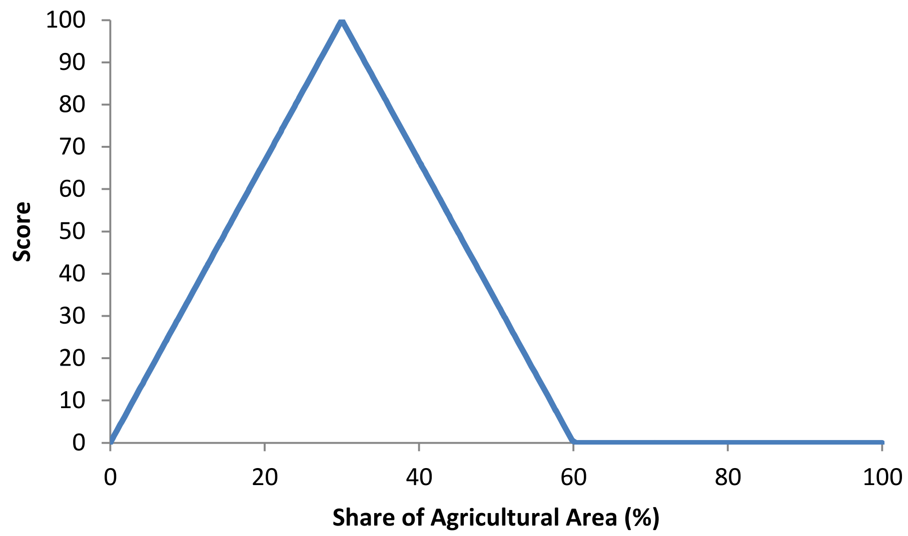

Figure C.7.3: Utility Function for the Calculation of the Suitability Score in Function of the Share of Agricultural area (%) in a STU

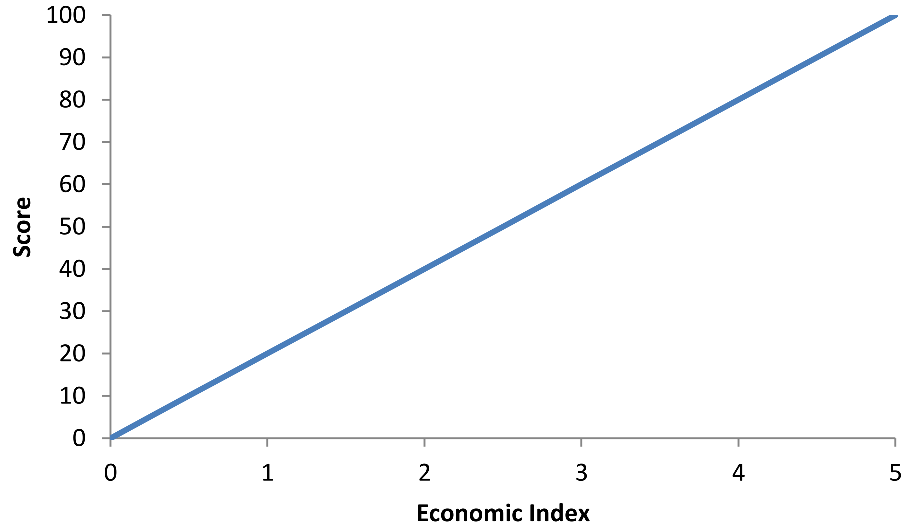

Figure C.7.4: Utility Function for the Calculation of the Suitability Score in Function of the Economic Index for a STU

Results

The scores of all the STU, calculated as above described, range from 0 to 334.3, with an average value of 78.8 and standard deviation of 57.3. The STU were classified into three classes of suitability (capability classes), given by the limits of the suitability scores (average – 1/2 standard deviation) and (average + 1/2 standard deviation) as follows:

- low suitability [Score from 0 to 50.1];

- mid suitability [Score from 50.1 to 107.4, limits included];
- high suitability [Score greater than 107.4].

The results of the suitability classification are summarized in Tab. 6, in terms of number of STU per cultivation system and capability class; 1046 STU out of 3669 (28.5%) are classified as highly capable to host algal cultivation plants, with major frequencies for PBR plants as a whole and Open Ponds using waste water.

Table C.7.2: Number of Site Territorial Units (STU) Classified into Capability Classes (Low, Mid, High) for hosting Different Algal Cultivation System

Algal Cultivation Type	Low	Mid	High	Total
OP SW	80	88	62	230
OP FW	179	167	63	409
OP WW	162	210	194	566
OP SW-WW	17	32	60	109
OP FW-WW	81	81	84	246
PBR SW	195	180	121	496
PBR FW	276	248	127	651
PBR WW	180	214	225	619
PBR FW-WW	117	116	110	343
Total	1287	1336	1046	3669

C.8 LIMITS AND RECOMMENDATIONS

The analytical process for best siting of areas suitable for algal cultivation plants implies some considerations for interpreting the results:

- the criteria and thresholds used are not to be intended as constraints, instead as indicative values for recommendations in view of the actual technology;
- the classification of areas is made in function of the public available data (Corine Land Cover), which could be not very precise at local scale;
- as a consequence, care should be taken when analysing especially those areas having few km^2 in size, particularly in close conditions (e.g. coastal areas), which require deeper data acquisition at local scale. This analysis should be carried out on the STU, among the 3669 classified and mapped, which are of interest for the single stakeholders during the stage of feasibility analysis;
- the above considerations should be intended as a “work in progress”, which has to be completed in the second part of the project, analysing in details the barriers and providing final recommendations.

C.9 BEST SITING MAPS

A total of 27 maps were produced. For each of the 9 algal cultivation systems, 3 maps were elaborated, centered respectively on Spain-Portugal, Italy and Greece-Cyprus areas for better visualization. The suitability maps are provided apart in a graphical annex (Annex 2). Herewith only the list of the figures are presented with their description.

As example, two more maps are below presented (Figure C.9.1 and Figure C.9.2) at two higher detail scale for a STU, to put in evidence the possibility of producing such detail maps for each of the 3669 STU detected.

As a whole, it is possible to detect areas with different densities of STU in function of the cultivation system. In general:

- where sea water is mainly used, the Eastern Mediterranean areas (Sardinia, Greece, Cyprus) seem more favourable;
- where fresh water and / or waste water is used, the Western Mediterranean areas (Spain and Portugal) seem more favourable;
- using waste water, it is possible to find a number of favourable areas in the most densely urbanised areas (e.g. coast of Spain);
- using PBR, the number of favourable areas is higher with respect to open ponds.

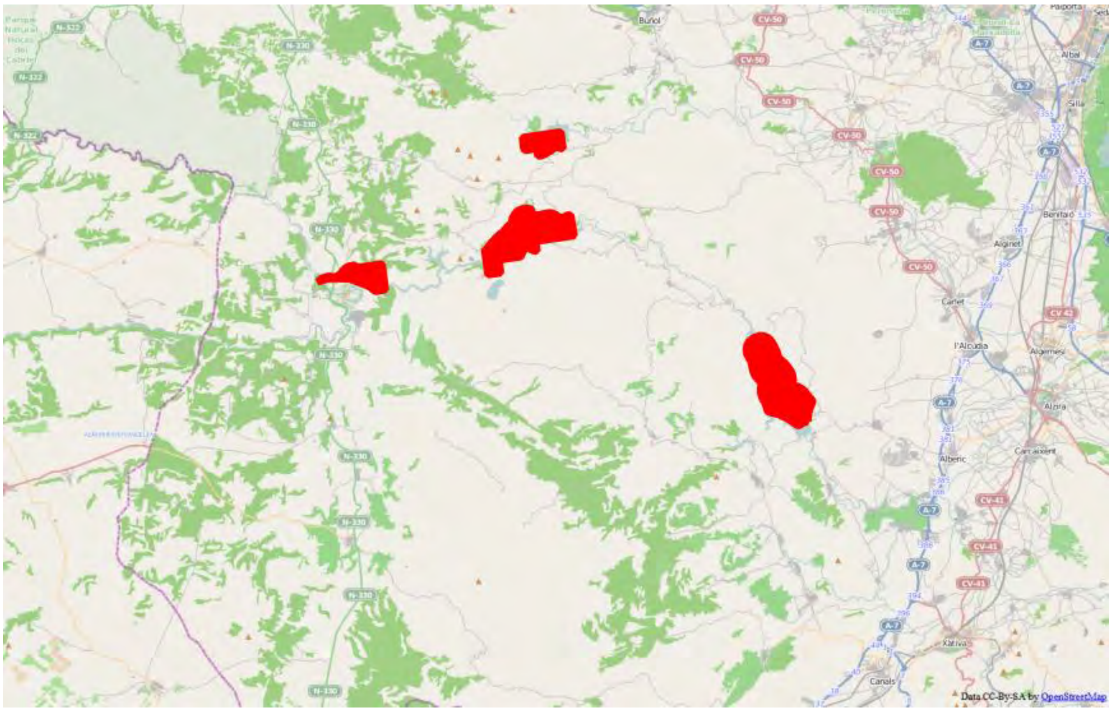

Figure C.9.1: Example of Detail Map of STU for Open Ponds Fresh Water, High Capability Class, Spain (scale 1:500,000 approx.)

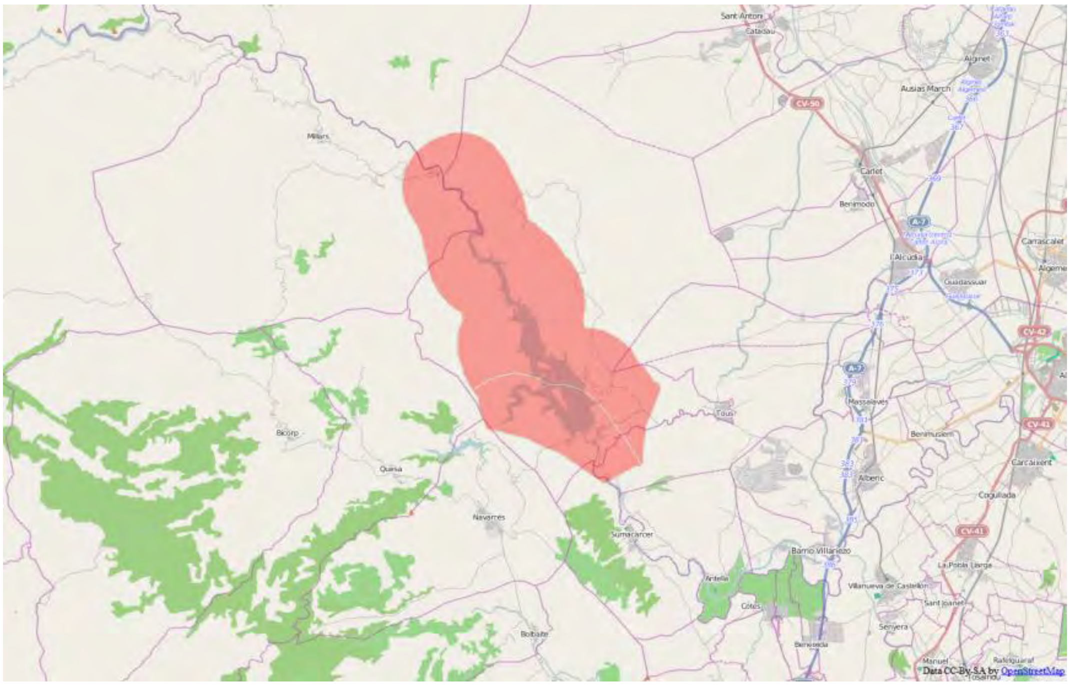

Figure C.9.2: Example of Detail Map of STU for Open Ponds fresh Water, High Capability Class, Spain (Scale 1:125,000 Approx.)

The complete list of STU per algal cultivation system in presented in the Annex 1 (Tab. A1 - A9) with the identification number, the size in km^2, NUTS3 reference and class of capability.

List of the suitability maps (.tif images in Annex 2)

Fig. 1 – STU classified into capability classes for Open Ponds / seawater systems, Spain and Portugal area. Red: high capability; orange: mid capability; yellow: low capability.

Fig. 2 – STU classified into capability classes for Open Ponds / seawater systems, Italy area. Red: high capability; orange: mid capability; yellow: low capability.

Fig. 3 – STU classified into capability classes for Open Ponds / seawater systems, Greece and Cyprus area. Red: high capability; orange: mid capability; yellow: low capability.

Fig. 4 – STU classified into capability classes for Open Ponds / fresh water systems, Spain and Portugal area. Red: high capability; orange: mid capability; yellow: low capability.

Fig. 5 – STU classified into capability classes for Open Ponds / fresh water systems, Italy area. Red: high capability; orange: mid capability; yellow: low capability.

Fig. 6 – STU classified into capability classes for Open Ponds / fresh water systems, Greece and Cyprus area. Red: high capability; orange: mid capability; yellow: low capability.

Fig. 7 – STU classified into capability classes for Open Ponds / waste water systems, Spain and Portugal area. Red: high capability; orange: mid capability; yellow: low capability.

Fig. 8 – STU classified into capability classes for Open Ponds / waste water systems, Italy area. Red: high capability; orange: mid capability; yellow: low capability.

Fig. 9 – STU classified into capability classes for Open Ponds / waste water systems, Greece and Cyprus area. Red: high capability; orange: mid capability; yellow: low capability.

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ANNEX 1

LIST OF STU CLASSIFIED INTO CAPABILITY CLASSES

ANNEX 1

List of STU classified into Capability Classes

List of Tables

Tab. A1 – List of the STU for the Open Ponds / sea water plant type (Capability Class: 1 Low; 2 Mid; 3 High)

N STU	Area km^2	NUTS3	Capability Class
1	2.192844	ITE16 Livorno	3
2	2.445377	ITE16 Livorno	2
3	2.402265	ITE1A Grosseto	3
4	2.791499	FR832 Haute-Corse	1
5	2.156809	FR832 Haute-Corse	3
6	2.467214	FR831 Corse-du-Sud	2
7	2.259883	GR115 Kavala	1
8	7.437448	GR (No NUTS)	1
9	4.384134	GR (No NUTS)	1
10	3.250071	FR831 Corse-du-Sud	2
11	2.229644	GR127 Chalkidiki	3
12	9.059798	GR127 Chalkidiki	1
13	2.705665	ITF42 Bari	2
14	3.309545	GR127 Chalkidiki	3
15	13.99878	GR411 Lesvos	2
16	10.83906	GR411 Lesvos	3
17	4.182226	GR411 Lesvos	3
18	2.635206	GR411 Lesvos	2
19	14.54995	GR411 Lesvos	2
20	3.709974	GR411 Lesvos	3
21	5.2264	ITG25 Sassari	3
22	6.244439	ITG25 Sassari	3
23	2.044964	ITG25 Sassari	3
24	2.832117	ITG25 Sassari	1
25	4.955493	ITG25 Sassari	3
26	6.306587	ITG25 Sassari	2
27	3.274495	ITG25 Sassari	2
28	4.292802	ITG25 Sassari	3
29	2.199576	ITG25 Sassari	2
30	7.55547	ITG25 Sassari	3
31	2.626288	GR127 Chalkidiki	1
32	5.380485	GR127 Chalkidiki	2
33	4.992172	GR127 Chalkidiki	3
34	4.345654	ITG25 Sassari	1
35	7.692871	GR127 Chalkidiki	2
36	3.790551	GR127 Chalkidiki	2
37	5.632131	GR127 Chalkidiki	1
38	4.285957	GR127 Chalkidiki	1
39	2.357243	GR127 Chalkidiki	1
40	5.492993	ES514 Tarragona	2
41	2.793185	ES522 Castellon	2
42	3.664643	GR125 Pieria	1
43	11.42665	GR125 Pieria	2
44	2.257368	GR411 Lesvos	3
45	2.129231	GR411 Lesvos	2
46	2.058677	GR142 Larisa	2
47	3.604396	GR411 Lesvos	2
48	3.902713	GR411 Lesvos	1
49	3.819153	GR411 Lesvos	1
50	8.18507	ITG25 Sassari	2
51	9.325503	ITG25 Sassari	2
52	2.646304	ITG25 Sassari	2
53	3.586431	ITG25 Sassari	3
54	4.432766	ITG25 Sassari	2
55	3.483308	GR411 Lesvos	1
56	2.777075	ITF44 Brindisi	3
57	7.763588	ITF44 Brindisi	3
58	4.498642	ITF44 Brindisi	2
59	2.331341	ITF42 Bari	2

60	2.145837	ITF44 Brindisi	2
61	12.13016	GR142 Larisa	1
62	13.78208	ITG25 Sassari	3
63	18.72589	ITG26 Nuoro	2
64	4.588584	ITG26 Nuoro	2
65	2.777806	ITG26 Nuoro	2
66	2	ES530 Illes Balears	1
67	2	ES530 Illes Balears	2
68	4.39324	ITF61 Cosenza	2
69	2.729281	ES530 Illes Balears	3
70	5.758619	ES530 Illes Balears	2
71	2.649479	GR143 Magnisia	1
72	6.399928	ITG27 Oristano	1
73	2.568539	GR143 Magnisia	2
74	2.047989	GR143 Magnisia	1
75	2.844114	GR242 Evvoia	3
76	2.142861	GR242 Evvoia	1
77	4.257657	GR242 Evvoia	1
78	9.214939	GR242 Evvoia	1
79	2.379128	GR242 Evvoia	1
80	3.222204	GR242 Evvoia	1
81	2.177956	GR413 Chios	1
82	9.386412	ITG27 Oristano	3
83	2.657385	ITG27 Oristano	1
84	6.575702	ITG27 Oristano	1
85	3.441363	GR242 Evvoia	1
86	6.546637	ITG26 Nuoro	2
87	19.65909	ITG26 Nuoro	2
88	19.72039	GR143 Magnisia	2
89	3.099773	GR143 Magnisia	3
90	8.157703	GR143 Magnisia	1
91	2.687018	GR244 Fthiotida	1
92	2.115024	ITG28 Cagliari	1
93	2.779374	GR244 Fthiotida	1
94	2.574347	GR244 Fthiotida	1
95	4.952776	GR244 Fthiotida	1
96	2.06931	ES530 Illes Balears	2
97	4.145742	ES530 Illes Balears	3
98	4.402786	GR244 Fthiotida	2
99	2.152468	ITG28 Cagliari	2
100	2.999753	GR241 Voiotia	1
101	2.016542	GR242 Evvoia	1
102	2.056208	GR242 Evvoia	1
103	5.724408	ES530 Illes Balears	1
104	16.21099	ITG28 Cagliari	2
105	2.323459	ITG28 Cagliari	2
106	2.123171	ITG28 Cagliari	3
107	9.674596	GR242 Evvoia	1
108	3.273353	GR242 Evvoia	3
109	3.204438	ES530 Illes Balears	1
110	4.556122	ES530 Illes Balears	2
111	2.528973	ES530 Illes Balears	2
112	2.959629	ES530 Illes Balears	2
113	6.270435	ES530 Illes Balears	1
114	3.688772	GR244 Fthiotida	1
115	2.881112	GR244 Fthiotida	1
116	3.445459	GR244 Fthiotida	1
117	2.263372	GR242 Evvoia	1
118	23.31166	GR241 Voiotia	2
119	3.139126	GR300 Attiki	2
120	3.459005	GR300 Attiki	2

121	11.31103	GR300 Attiki	3
122	3.776475	GR300 Attiki	3
123	2.732204	GR242 Evvoia	1
124	2.985741	ITG28 Cagliari	3
125	2.261782	ITG28 Cagliari	2
126	3.284785	GR422 Kyklades	1
127	2.491154	GR422 Kyklades	1
128	8.258141	ITG28 Cagliari	2
129	2.719071	GR242 Evvoia	2
130	2.397932	GR242 Evvoia	1
131	3.046828	GR242 Evvoia	2
132	2.712292	ES530 Illes Balears	3
133	3.018252	ES530 Illes Balears	2
134	3.212971	GR300 Attiki	1
135	3.262026	GR253 Korinthia	2
136	6.546709	ITG28 Cagliari	2
137	3.627016	ITG28 Cagliari	2
138	2.21797	GR422 Kyklades	2
139	2.496733	ITG28 Cagliari	1
140	3.981241	ITG28 Cagliari	1
141	2.38811	GR300 Attiki	2
142	11.78653	GR253 Korinthia	3
143	6.742942	GR253 Korinthia	3
144	5.987034	GR253 Korinthia	3
145	2.073621	CY000 Kypros / Kibris	2
146	2.061821	GR422 Kyklades	1
147	4.463064	GR422 Kyklades	2
148	2.989388	GR300 Attiki	3
149	16.13071	GR300 Attiki	3
150	7.293126	GR300 Attiki	3
151	7.045486	GR300 Attiki	3
152	4.106103	GR300 Attiki	3
153	8.038709	GR300 Attiki	2
154	8.875138	GR300 Attiki	1
155	4.584041	GR422 Kyklades	2
156	4.163087	GR300 Attiki	1
157	3.433767	GR300 Attiki	1
158	2.988158	GR251 Argolida	2
159	5.895383	GR422 Kyklades	1
160	3.308671	GR300 Attiki	2
161	3.686046	GR253 Korinthia	2
162	2.763348	GR251 Argolida	2
163	3.024342	GR300 Attiki	2
164	2.647877	GR300 Attiki	1
165	2.95034	GR422 Kyklades	1
166	2.25121	GR300 Attiki	1
167	5.254871	GR422 Kyklades	1
168	15.7669	GR422 Kyklades	1
169	2.593484	GR422 Kyklades	1
170	4.852545	GR422 Kyklades	1
171	2.364316	CY000 Kypros / Kibris	3
172	5.335029	GR422 Kyklades	1
173	2.080369	GR422 Kyklades	1
174	3.533697	GR422 Kyklades	2
175	2.686017	PT150 Algarve	3
176	4.161228	PT150 Algarve	3
177	3.127169	GR421 Dodekanisos	1
178	2.219412	GR422 Kyklades	2
179	4.401896	GR422 Kyklades	3
180	4.254674	GR422 Kyklades	2
181	2.574984	GR422 Kyklades	2

182	2.240437	CY000 Kypros / Kibris	1
183	2.847337	GR422 Kyklades	1
184	8.033607	ITG11 Trapani	2
185	3.247498	ITG11 Trapani	1
186	2.982822	ITG11 Trapani	2
187	3.479936	CY000 Kypros / Kibris	3
188	2.023643	ES611 Almeria	2
189	26.56471	CY000 Kypros / Kibris	3
190	7.096851	CY000 Kypros / Kibris	3
191	10.41542	CY000 Kypros / Kibris	3
192	5.319666	CY000 Kypros / Kibris	3
193	6.121438	CY000 Kypros / Kibris	3
194	3.554752	CY000 Kypros / Kibris	3
195	5.165048	CY000 Kypros / Kibris	3
196	4.19888	CY000 Kypros / Kibris	2
197	3.17638	CY000 Kypros / Kibris	3
198	11.77664	CY000 Kypros / Kibris	2
199	3.266728	CY000 Kypros / Kibris	3
200	3.415146	CY000 Kypros / Kibris	3
201	2.13096	CY000 Kypros / Kibris	2
202	3.662664	CY000 Kypros / Kibris	3
203	3.765546	CY000 Kypros / Kibris	3
204	2.776751	CY000 Kypros / Kibris	3
205	5.538657	GR254 Lakonia	1
206	3.716909	GR300 Attiki	3
207	4.012469	GR300 Attiki	2
208	2.239989	GR300 Attiki	2
209	5.755947	ITG14 Agrigento	2
210	8.928155	ITG19 Siracusa	3
211	3.003483	ITG19 Siracusa	2
212	6.113409	ITG18 Ragusa	1
213	3.367339	ITG18 Ragusa	2
214	5.30542	GR432 Lasithi	2
215	4.298812	GR431 Irakleio	1
216	2.652787	GR432 Lasithi	2
217	6.481312	GR431 Irakleio	1
218	3	GR434 Chania	1
219	4.597163	GR432 Lasithi	2
220	3.195067	GR432 Lasithi	2
221	2.02583	GR432 Lasithi	1
222	2.644262	GR432 Lasithi	1
223	3.357346	GR432 Lasithi	1
224	5.848642	MT002 Gozo and Comino/Ghawdex u Kemmuna	1
225	2.791339	MT002 Gozo and Comino/Ghawdex u Kemmuna	2
226	2.375958	MT001 Malta	2
227	2.383743	MT001 Malta	3
228	2.284455	MT001 Malta	2
229	3.875384	MT001 Malta	3
230	2.066746	MT001 Malta	3

Tab. A2 – List of the STU for the Open Ponds / fresh water plant type (Capability Class: 1 Low; 2 Mid; 3 High)

N STU	Area km^2	NUTS3	Capability Class
1	3.92464	FR832 Haute-Corse	3
2	7.206457	FR832 Haute-Corse	2
3	5.489417	FR832 Haute-Corse	2
4	5.705746	ES241 Huesca	2
5	14.93038	ES241 Huesca	2
6	26.88524	ES243 Zaragoza	2
7	11.26497	ES242 Teruel	3
8	101.0927	ES241 Huesca	3
9	53.75377	ES243 Zaragoza	2
10	6.214116	ES243 Zaragoza	3
11	3.417916	ES432 Caceres	2
12	4	ES432 Caceres	1
13	2.637512	ES411 Avila	1
14	11.55272	GR411 Lesvos	1
15	4.079005	GR411 Lesvos	2
16	2.958766	ITG21 Sassari	1
17	7.655893	GR127 Chalkidiki	2
18	2.556397	ITG21 Sassari	2
19	4.085348	ITG21 Sassari	2
20	13.93542	ITG22 Nuoro	2
21	12.54478	ITG22 Nuoro	2
22	6.015284	ES523 Valencia / Valencia	3
23	3	ITG23 Oristano	2
24	3.690061	ES523 Valencia / Valencia	3
25	15.84888	ES523 Valencia / Valencia	3
26	6.459388	ES422 Ciudad Real	2
27	6.13391	ES422 Ciudad Real	2
28	6.44168	ITG22 Nuoro	2
29	4.71836	ITG22 Nuoro	3
30	4.8808	ES523 Valencia / Valencia	3
31	12.96873	ITG22 Nuoro	2
32	5.015431	ITG22 Nuoro	1
33	5.034504	ES422 Ciudad Real	2
34	7.668164	ES422 Ciudad Real	1
35	3.733382	ES523 Valencia / Valencia	3
36	13.85796	ES523 Valencia / Valencia	3
37	3.467082	ES422 Ciudad Real	1
38	2.422878	ES422 Ciudad Real	1
39	9.831228	ES421 Albacete	2
40	19.31128	ES431 Badajoz	1
41	16.69063	GR241 Voiotia	2
42	2.566985	GR241 Voiotia	1
43	15.98564	GR241 Voiotia	3
44	2	ES613 Cordoba	1
45	13.06104	ES421 Albacete	2
46	2.998083	ES421 Albacete	2
47	2	ES618 Sevilla	2
48	4.040325	ITG24 Cagliari	2
49	9.432922	ITG24 Cagliari	2
50	14.09029	ITG24 Cagliari	2
51	6.155798	ITG24 Cagliari	3
52	8.595574	ES616 Jaén	2
53	2.854931	ES616 Jaén	2
54	7.07523	ES614 Granada	2
55	15.55691	ES614 Granada	2
56	10.08539	ES620 Murcia	2
57	10.45952	ES620 Murcia	2
58	13.95996	ES421 Albacete	3
59	53.26908	ES421 Albacete	1

60	22.795	ES620 Murcia	3
61	14.31297	ES620 Murcia	3
62	37.51238	ES616 Jaén	1
63	17.02677	ES616 Jaén	2
64	14.93255	ES616 Jaén	2
65	4.729597	ES616 Jaén	3
66	10.21392	ES616 Jaén	2
67	22.22874	ES616 Jaén	2
68	56.77906	ES616 Jaén	1
69	7.005128	ES613 Cordoba	2
70	18.22921	ES613 Cordoba	2
71	36.63932	ES613 Cordoba	1
72	4.800068	ES616 Jaén	3
73	28.82706	ES613 Cordoba	3
74	29.96396	ES613 Cordoba	3
75	26.6522	ES613 Cordoba	3
76	8.817137	ES613 Cordoba	1
77	4.611893	ES425 Toledo	2
78	4.501103	ES425 Toledo	2
79	7.185854	ES425 Toledo	3
80	14.05341	ES618 Sevilla	1
81	11.99483	ES618 Sevilla	1
82	16.86919	ES618 Sevilla	3
83	3.034972	ES618 Sevilla	1
84	6.166261	ES618 Sevilla	2
85	6.238009	ES432 Caceres	1
86	4.88598	ES431 Badajoz	1
87	44.46232	ES432 Caceres	2
88	5.546513	ES431 Badajoz	2
89	8.549413	ES432 Caceres	1
90	3.951463	ES431 Badajoz	1
91	4.792723	ES422 Ciudad Real	2
92	6.464315	ES422 Ciudad Real	1
93	3.845019	ES431 Badajoz	2
94	278.2647	ES431 Badajoz	2
95	73.95623	ES431 Badajoz	2
96	23.85395	ES431 Badajoz	2
97	12.29462	ES431 Badajoz	2
98	12.27786	ES432 Caceres	2
99	2.010669	ES422 Ciudad Real	1
100	123.5285	ES422 Ciudad Real	1
101	12.13197	ES431 Badajoz	1
102	69.12987	ES431 Badajoz	1
103	5.229467	ES431 Badajoz	3
104	64.72762	ES422 Ciudad Real	1
105	3.22871	ES431 Badajoz	2
106	3.114331	ES431 Badajoz	1
107	3.980934	ES431 Badajoz	1
108	3.153809	ES431 Badajoz	1
109	2.407623	ES431 Badajoz	3
110	17.67533	ES431 Badajoz	1
111	8.493105	ES431 Badajoz	1
112	11.40803	ES431 Badajoz	1
113	50.46666	ES431 Badajoz	2
114	2.920303	ES431 Badajoz	1
115	8.608858	ES432 Caceres	1
116	23.41427	ES432 Caceres	1
117	6.326783	ES432 Caceres	1
118	2.62681	ES432 Caceres	1
119	3.521325	ES425 Toledo	1
120	16.5556	ES425 Toledo	1

121	5.028463	ES425 Toledo	2
122	3.323894	ES432 Caceres	2
123	29.5093	ES432 Caceres	2
124	13.06343	ES432 Caceres	1
125	28.09279	ES425 Toledo	3
126	2.363791	ES432 Caceres	1
127	4.845328	ES425 Toledo	1
128	7.671515	ES425 Toledo	1
129	33.0395	ES411 Avila	3
130	6.977569	ES432 Caceres	2
131	6.615807	ES432 Caceres	1
132	7.997045	ES432 Caceres	2
133	3.375293	ES432 Caceres	2
134	3.425628	ES432 Caceres	1
135	3.360335	ES432 Caceres	2
136	132.0233	ES432 Caceres	2
137	10.13124	ES432 Caceres	3
138	26.66337	ES432 Caceres	2
139	24.41525	ES432 Caceres	2
140	2.380559	ES432 Caceres	1
141	60.17911	ES432 Caceres	2
142	34.91962	ES432 Caceres	1
143	8.301439	ES432 Caceres	1
144	15.08672	ES432 Caceres	2
145	5.816745	ES432 Caceres	3
146	3.286886	ES432 Caceres	3
147	4.44144	ES432 Caceres	2
148	2.274116	ES432 Caceres	1
149	28.43733	ES615 Huelva	1
150	7.545873	ES615 Huelva	1
151	95.33271	ES615 Huelva	1
152	10.53924	ES615 Huelva	1
153	2.462885	ES615 Huelva	1
154	6.745379	ES618 Sevilla	1
155	13.46586	ES618 Sevilla	1
156	5.631504	ES618 Sevilla	1
157	75.75627	ES615 Huelva	1
158	8.848053	ES618 Sevilla	2
159	6.118865	ES615 Huelva	1
160	8.169149	ES618 Sevilla	2
161	8.616453	ES618 Sevilla	1
162	8.844971	ES618 Sevilla	1
163	6.019818	ES612 Cadiz	2
164	8.518848	ES618 Sevilla	2
165	7.474819	ES618 Sevilla	2
166	6.008644	ES612 Cadiz	1
167	5.492784	ES612 Cadiz	1
168	2.117319	ES612 Cadiz	1
169	5.516733	ES618 Sevilla	1
170	6.15799	ES432 Caceres	1
171	4.821292	ES432 Caceres	1
172	37.24795	PT182 Alto Alentejo	1
173	5.917044	ES431 Badajoz	1
174	49.46168	ES431 Badajoz	2
175	25.79493	ES615 Huelva	2
176	45.02228	ES615 Huelva	2
177	22.198	ES431 Badajoz	2
178	6.041855	ES431 Badajoz	1
179	24.51972	ES431 Badajoz	2
180	11.76964	ES431 Badajoz	2
181	8.92887	ES431 Badajoz	1

182	2.262302	ES615 Huelva	1
183	5.008339	ES618 Sevilla	2
184	7.440807	ES615 Huelva	1
185	6.427141	ES615 Huelva	2
186	39.61649	ES615 Huelva	3
187	4.729859	ES615 Huelva	3
188	9.265703	ES615 Huelva	2
189	4.208407	ES615 Huelva	2
190	6.527175	PT184 Baixo Alentejo	1
191	6.658566	PT184 Baixo Alentejo	1
192	6.233924	PT184 Baixo Alentejo	2
193	8.184889	PT183 Alentejo Central	1
194	46.69107	PT183 Alentejo Central	1
195	17.80503	PT184 Baixo Alentejo	1
196	5.366761	PT184 Baixo Alentejo	1
197	3.764072	PT184 Baixo Alentejo	1
198	16.58143	PT183 Alentejo Central	2
199	10.28423	PT183 Alentejo Central	1
200	441.7974	ES431 Badajoz	1
201	22.03019	ES431 Badajoz	1
202	61.4039	PT183 Alentejo Central	1
203	22.21954	ES431 Badajoz	2
204	7.531777	ES431 Badajoz	2
205	177.3146	ES431 Badajoz	1
206	180.8594	PT183 Alentejo Central	2
207	2.197789	ES431 Badajoz	1
208	12.30063	PT183 Alentejo Central	1
209	25.50724	PT183 Alentejo Central	1
210	13.62968	PT183 Alentejo Central	2
211	9.431912	PT184 Baixo Alentejo	1
212	5.948366	PT184 Baixo Alentejo	2
213	8.032799	PT184 Baixo Alentejo	3
214	5.635862	PT184 Baixo Alentejo	2
215	5.38547	PT184 Baixo Alentejo	1
216	5.884536	PT184 Baixo Alentejo	2
217	7.347691	PT184 Baixo Alentejo	1
218	7.420774	PT184 Baixo Alentejo	1
219	12.30733	PT184 Baixo Alentejo	1
220	6.079253	PT184 Baixo Alentejo	1
221	11.02776	PT184 Baixo Alentejo	3
222	6.091587	PT184 Baixo Alentejo	1
223	6.023528	PT184 Baixo Alentejo	2
224	6.427588	PT184 Baixo Alentejo	1
225	5.811387	PT184 Baixo Alentejo	1
226	6.542631	PT184 Baixo Alentejo	2
227	32.61308	ES615 Huelva	3
228	2.588177	ES615 Huelva	2
229	83.23963	ES615 Huelva	3
230	3.275525	PT184 Baixo Alentejo	2
231	11.85462	ES615 Huelva	2
232	17.51781	PT150 Algarve	3
233	20.90673	ES615 Huelva	3
234	32.53319	PT150 Algarve	3
235	6.389467	PT150 Algarve	1
236	23.24594	ES615 Huelva	2
237	6.058806	PT184 Baixo Alentejo	1
238	6.390655	ES431 Badajoz	1
239	7.061078	PT183 Alentejo Central	1
240	5.50601	PT183 Alentejo Central	1
241	3.509388	PT183 Alentejo Central	1
242	4.266811	PT183 Alentejo Central	1

243	6.32765	PT183 Alentejo Central	1
244	6.188829	PT183 Alentejo Central	2
245	31.0993	PT184 Baixo Alentejo	1
246	7.82334	PT184 Baixo Alentejo	1
247	6.300484	PT184 Baixo Alentejo	1
248	6.492618	PT184 Baixo Alentejo	1
249	46.27794	PT181 Alentejo Litoral	1
250	4.080614	PT183 Alentejo Central	1
251	3.350832	PT183 Alentejo Central	1
252	6.69522	PT181 Alentejo Litoral	2
253	4.964012	PT183 Alentejo Central	1
254	28.82084	PT181 Alentejo Litoral	1
255	6.371361	PT181 Alentejo Litoral	1
256	5.577123	PT181 Alentejo Litoral	1
257	5.898048	PT181 Alentejo Litoral	2
258	6.44455	PT181 Alentejo Litoral	1
259	8.096854	PT184 Baixo Alentejo	1
260	5.869953	PT184 Baixo Alentejo	1
261	6.022654	PT184 Baixo Alentejo	1
262	18.02899	PT181 Alentejo Litoral	2
263	14.77156	PT181 Alentejo Litoral	2
264	6.26992	PT184 Baixo Alentejo	2
265	9.431293	PT181 Alentejo Litoral	2
266	6.043861	PT181 Alentejo Litoral	2
267	5.838412	PT181 Alentejo Litoral	2
268	13.76822	PT181 Alentejo Litoral	3
269	7.654609	PT181 Alentejo Litoral	1
270	6.02758	PT184 Baixo Alentejo	2
271	6.044331	PT184 Baixo Alentejo	1
272	38.3592	PT184 Baixo Alentejo	1
273	96.26678	PT181 Alentejo Litoral	1
274	29.28547	PT184 Baixo Alentejo	1
275	6.41725	PT184 Baixo Alentejo	1
276	5.366985	PT184 Baixo Alentejo	1
277	2.429528	PT150 Algarve	2
278	5.746996	PT150 Algarve	1
279	2.290961	PT150 Algarve	3
280	12.02227	PT150 Algarve	2
281	27.42112	PT150 Algarve	1
282	14.71567	PT150 Algarve	1
283	7.467884	CY000 Kypros / Kibris	1
284	10.07714	ITG11 Trapani	1
285	2.066879	ES611 Almeria	1
286	5.493637	ES614 Granada	1
287	6.081098	ES614 Granada	1
288	6.844373	CY000 Kypros / Kibris	3
289	5.551998	CY000 Kypros / Kibris	3
290	3.425228	CY000 Kypros / Kibris	3
291	7.150362	CY000 Kypros / Kibris	3
292	8.925275	CY000 Kypros / Kibris	3
293	11.46185	CY000 Kypros / Kibris	3
294	8.390922	CY000 Kypros / Kibris	3
295	10.11672	CY000 Kypros / Kibris	3
296	13.44073	CY000 Kypros / Kibris	3
297	6.022336	CY000 Kypros / Kibris	3
298	5.62248	CY000 Kypros / Kibris	3
299	19.60846	CY000 Kypros / Kibris	3
300	11.4361	CY000 Kypros / Kibris	3
301	5.950599	ITG19 Siracusa	2
302	8.633473	ITG19 Siracusa	3
303	7.60101	ITG16 Enna	1

304	6.28925	ITG16 Enna	1
305	5.49967	ITG16 Enna	1
306	4.689182	ITG15 Caltanissetta	2
307	2.564103	ITG15 Caltanissetta	2
308	2.383099	ITG16 Enna	2
309	9.820444	ITE1A Grosseto	3
310	4.704556	GR126 Serres	1
311	3.75013	ES241 Huesca	2
312	80.53636	GR126 Serres	1
313	5.406448	GR126 Serres	2
314	3.374432	ES514 Tarragona	3
315	57.41536	ES514 Tarragona	3
316	10.3253	ES514 Tarragona	2
317	9.249788	GR142 Larisa	2
318	11.0856	GR142 Larisa	1
319	2.535176	ES422 Ciudad Real	1
320	59.04592	ES422 Ciudad Real	2
321	3.63858	ES422 Ciudad Real	2
322	9.805104	ES422 Ciudad Real	1
323	11.69535	ITG23 Oristano	2
324	7.269949	GR141 Karditsa	2
325	22.82289	GR141 Karditsa	2
326	49.04268	GR142 Larisa	2
327	21.61819	GR142 Larisa	2
328	60.83343	GR142 Larisa	2
329	37.83464	GR241 Voiotia	1
330	10.83037	ES616 Jaén	2
331	5.567031	ES616 Jaén	1
332	9.625212	ES618 Sevilla	2
333	12.40748	ES616 Jaén	2
334	11.47317	ES613 Cordoba	2
335	80.51652	ES618 Sevilla	1
336	7.697773	ES618 Sevilla	2
337	5.940054	ES616 Jaén	2
338	4.090265	ES613 Cordoba	2
339	9.841338	ES616 Jaén	1
340	70.97317	ES616 Jaén	2
341	10.87915	ES613 Cordoba	2
342	12.40748	ES616 Jaén	2
343	11.47317	ES613 Cordoba	2
344	80.51652	ES618 Sevilla	1
345	7.697773	ES618 Sevilla	2
346	5.940054	ES616 Jaén	2
347	3.781418	ES613 Cordoba	2
348	9.841338	ES616 Jaén	1
349	70.97317	ES616 Jaén	2
350	10.87915	ES613 Cordoba	2
351	12.40748	ES616 Jaén	2
352	11.47317	ES613 Cordoba	2
353	80.51652	ES618 Sevilla	1
354	7.697773	ES618 Sevilla	2
355	5.940054	ES616 Jaén	2
356	3.781418	ES613 Cordoba	2
357	9.841338	ES616 Jaén	1
358	70.97317	ES616 Jaén	2
359	10.87915	ES613 Cordoba	2
360	2.061335	ES431 Badajoz	1
361	48.4112	ES431 Badajoz	2
362	6.701171	ES431 Badajoz	1
363	6.353182	ES431 Badajoz	2
364	2.061335	ES431 Badajoz	1

365	44.56618	ES431 Badajoz	2
366	6.701171	ES431 Badajoz	1
367	6.353182	ES431 Badajoz	2
368	30.70819	ES431 Badajoz	1
369	79.90025	ES615 Huelva	2
370	178.7003	PT183 Alentejo Central	3
371	22.21954	ES431 Badajoz	2
372	91.06916	ES431 Badajoz	1
373	30.70819	ES431 Badajoz	1
374	79.90025	ES615 Huelva	2
375	82.81415	PT183 Alentejo Central	2
376	78.0811	PT184 Baixo Alentejo	1
377	22.21954	ES431 Badajoz	2
378	91.06916	ES431 Badajoz	1
379	30.70819	ES431 Badajoz	1
380	79.90025	ES615 Huelva	2
381	21.41025	PT184 Baixo Alentejo	1
382	78.0811	PT184 Baixo Alentejo	1
383	83.53738	ES431 Badajoz	1
384	30.70819	ES431 Badajoz	1
385	77.31207	ES615 Huelva	2
386	21.41025	PT184 Baixo Alentejo	1
387	78.0811	PT184 Baixo Alentejo	1
388	83.53738	ES431 Badajoz	1
389	30.70819	ES431 Badajoz	1
390	77.18516	ES615 Huelva	2
391	21.41025	PT184 Baixo Alentejo	1
392	78.0811	PT184 Baixo Alentejo	1
393	83.53738	ES431 Badajoz	1
394	2.68644	ES618 Sevilla	2
395	3.790207	ES425 Toledo	1
396	15.31546	ES425 Toledo	2
397	40.67275	ES432 Caceres	1
398	4.274703	ES432 Caceres	1
399	18.73011	ES432 Caceres	2
400	13.1641	ES425 Toledo	3
401	16.82584	ES425 Toledo	2
402	6.094701	ES425 Toledo	2
403	38.71431	ES425 Toledo	2
404	5.426281	ES300 Madrid	3
405	6.606704	ES300 Madrid	3
406	2.394325	ES425 Toledo	3
407	3.370696	PT181 Alentejo Litoral	2
408	22.02169	PT183 Alentejo Central	1
409	7.774725	ITG11 Trapani	2

Tab. A3 – List of the STU for the Open Ponds / waste water plant type (Capability Class: 1 Low; 2 Mid; 3 High)

N STU	Area km^2	NUTS3	Capability Class
1	3.997134	FR815 Pyrenées-Orientales	1
2	4	ES512 Girona	2
3	2.850392	ES512 Girona	2
4	9.47231	ES512 Girona	3
5	5	ES512 Girona	2
6	3	ES512 Girona	2
7	16	ES512 Girona	3
8	6	ES512 Girona	2
9	2	ES512 Girona	2
10	3	ES512 Girona	2
11	9.900197	ES512 Girona	2
12	304.5685	ES512 Girona	2
13	17.16652	ES512 Girona	2
14	4	ES512 Girona	3
15	4	ES512 Girona	3
16	2	ES513 Lleida	3
17	8	ES512 Girona	3
18	19	ES513 Lleida	3
19	9.874047	ES241 Huesca	1
20	32	ES513 Lleida	3
21	3	ES513 Lleida	3
22	21.62342	ES241 Huesca	1
23	11.81979	ITF41 Foggia	3
24	2	ES511 Barcelona	3
25	6	ES511 Barcelona	3
26	2	ES511 Barcelona	3
27	2.223947	ES242 Teruel	2
28	28.31456	ES243 Zaragoza	3
29	406.1858	ES241 Huesca	3
30	8.194694	ES241 Huesca	3
31	2	ES243 Zaragoza	2
32	2	ES511 Barcelona	3
33	5	ES511 Barcelona	3
34	46.2267	ES513 Lleida	3
35	43.45107	ES514 Tarragona	3
36	162.3325	ES242 Teruel	2
37	91.93061	ES243 Zaragoza	2
38	2	ES514 Tarragona	3
39	24	ES514 Tarragona	3
40	62	ES511 Barcelona	3
41	4.735783	ES514 Tarragona	3
42	2	ES514 Tarragona	3
43	3	ES514 Tarragona	3
44	110.5238	ES243 Zaragoza	2
45	2.599891	ES514 Tarragona	3
46	2	ES511 Barcelona	3
47	3.803242	ES514 Tarragona	3
48	17	ES432 Caceres	1
49	3	ES514 Tarragona	3
50	2	ITF42 Bari	3
51	9	ITF42 Bari	3
52	5	ITF42 Bari	3
53	21.64851	ITF42 Bari	3
54	5	ITF42 Bari	1
55	2	ITF42 Bari	2
56	3	ITF42 Bari	1
57	2	ITF42 Bari	3
58	3	ITF42 Bari	3
59	4	ITF42 Bari	3

60	20	ITF42 Bari	2
61	13.96214	ITF42 Bari	3
62	22.62847	ES432 Caceres	3
63	21.83488	ITF42 Bari	3
64	24.67001	ITF42 Bari	3
65	7.184178	ITF42 Bari	3
66	24	ITF42 Bari	3
67	9	ITF42 Bari	3
68	10.61919	ITF42 Bari	3
69	11.48388	ITF42 Bari	2
70	17.88149	ITF42 Bari	2
71	41.55864	ITF42 Bari	2
72	37.95026	ITF41 Foggia	2
73	3.19731	ITF41 Foggia	1
74	23.19282	ITF41 Foggia	2
75	23.99519	ITF42 Bari	2
76	2.509671	ES300 Madrid	2
77	10	ITF42 Bari	3
78	5	ITF42 Bari	2
79	2.140657	ITG25 Sassari	2
80	4	ES432 Caceres	1
81	4	ES425 Toledo	1
82	2	ES514 Tarragona	3
83	14.21473	ITG25 Sassari	2
84	4.696976	ITG25 Sassari	1
85	2	ES425 Toledo	2
86	94.51787	ITG25 Sassari	3
87	17.41341	ITG25 Sassari	3
88	35.59352	ITG25 Sassari	2
89	2	ITF44 Brindisi	1
90	2	ITG25 Sassari	3
91	26.65067	ES522 Castellon	2
92	7	ES522 Castellon	3
93	5.592211	ITG25 Sassari	3
94	6.587537	ITG25 Sassari	1
95	9.464798	ITG25 Sassari	1
96	3.045275	ITG25 Sassari	1
97	2	ITF44 Brindisi	2
98	3	ITF43 Taranto	2
99	34.96587	ITF43 Taranto	3
100	5.879888	ITF43 Taranto	3
101	4.290365	ITF43 Taranto	3
102	2	ES432 Caceres	2
103	120.0661	ES514 Tarragona	3
104	46.70448	ES514 Tarragona	3
105	61.61027	ES514 Tarragona	3
106	446.4949	ES514 Tarragona	3
107	5.529632	ES522 Castellon	3
108	156.0091	ES522 Castellon	2
109	12.75614	ES522 Castellon	3
110	9.646917	ES522 Castellon	2
111	35.72815	ES514 Tarragona	3
112	3.911372	ES514 Tarragona	3
113	6.901023	ITF43 Taranto	3
114	7	ITF45 Lecce	2
115	4	ITF45 Lecce	2
116	8.316031	ITF43 Taranto	3
117	55.71278	ITF43 Taranto	3
118	6.62117	ITF43 Taranto	3
119	18.60474	ITF43 Taranto	3
120	4	ITF45 Lecce	2

121	2	ITF43 Taranto	3
122	2	ITF43 Taranto	3
123	2.016785	ITF43 Taranto	3
124	48.43206	ES522 Castellon	2
125	7.912846	ES522 Castellon	2
126	17	ITF45 Lecce	2
127	40.3937	ITG25 Sassari	2
128	16.90986	ITG25 Sassari	2
129	32.21977	ITG25 Sassari	1
130	3	ES522 Castellon	3
131	16.28896	ES522 Castellon	3
132	44.47213	ES522 Castellon	2
133	2.473759	ES522 Castellon	3
134	201.5649	ES522 Castellon	3
135	5.969666	ES522 Castellon	3
136	5	ITF45 Lecce	2
137	3.381269	ITF45 Lecce	2
138	636.7997	ITF43 Taranto	2
139	54.63569	ITF43 Taranto	3
140	38.4808	ITF42 Bari	3
141	91.35042	ITF42 Bari	1
142	147.3723	ITF43 Taranto	2
143	33.6613	ITF44 Brindisi	1
144	76.95032	ITF44 Brindisi	3
145	177.1782	ITF45 Lecce	2
146	53.96998	ITF45 Lecce	2
147	3.782319	ITF44 Brindisi	1
148	5	ES522 Castellon	3
149	5	ES522 Castellon	3
150	38.23516	ITF45 Lecce	2
151	74.58212	ITG26 Nuoro	2
152	32.73327	ITG25 Sassari	2
153	25.53462	ES522 Castellon	3
154	13.11634	ES523 Valencia / Valencia	3
155	25.08632	ITF45 Lecce	2
156	53.99111	ES523 Valencia / Valencia	3
157	6.610579	ES530 Illes Balears	2
158	25	ES530 Illes Balears	3
159	2.008473	ES530 Illes Balears	1
160	45.85035	GR143 Magnisia	1
161	4	ES431 Badajoz	1
162	2	ES422 Ciudad Real	1
163	6.191477	ES422 Ciudad Real	1
164	53.22977	ES422 Ciudad Real	1
165	27.45039	ES422 Ciudad Real	1
166	25.39123	ES422 Ciudad Real	1
167	62.27066	ES422 Ciudad Real	1
168	37.49106	ES422 Ciudad Real	1
169	3	ES530 Illes Balears	1
170	96.04467	GR142 Larisa	3
171	21.40769	GR143 Magnisia	2
172	51.45007	ES523 Valencia / Valencia	3
173	5.330149	ES523 Valencia / Valencia	2
174	9.425299	ES431 Badajoz	1
175	52.17046	ES422 Ciudad Real	1
176	14	ES523 Valencia / Valencia	3
177	1248.098	ES530 Illes Balears	2
178	10.07888	ES422 Ciudad Real	2
179	42.74562	ES422 Ciudad Real	1
180	10.23701	ES431 Badajoz	2
181	10	ES523 Valencia / Valencia	3

182	2	GR242 Evvoia	2
183	3	GR242 Evvoia	2
184	3348.427	ES521 Alicante / Alacant	3
185	2.315646	ES523 Valencia / Valencia	3
186	42.66049	ES523 Valencia / Valencia	3
187	18.84147	ES613 Cordoba	1
188	9.719955	ES521 Alicante / Alacant	3
189	26.14411	ES521 Alicante / Alacant	3
190	6.935651	ES421 Albacete	3
191	3.604635	ES521 Alicante / Alacant	3
192	58.59728	ES530 Illes Balears	3
193	71.25011	ES530 Illes Balears	1
194	68.35578	ES530 Illes Balears	2
195	35.63643	GR241 Voiotia	2
196	3	ITG27 Cagliari	3
197	29.72215	GR242 Evvoia	3
198	4.502624	GR241 Voiotia	2
199	3.31399	ITG27 Cagliari	2
200	3	ES521 Alicante / Alacant	3
201	408.1966	ES521 Alicante / Alacant	3
202	20.87117	ES521 Alicante / Alacant	3
203	4	ES521 Alicante / Alacant	2
204	30.16877	ITG27 Cagliari	3
205	8.278426	ITG27 Cagliari	3
206	9	ES616 Jaén	1
207	13.35788	GR300 Attiki	3
208	15	ES521 Alicante / Alacant	3
209	4	ES616 Jaén	1
210	111.3626	ES521 Alicante / Alacant	3
211	6	GR300 Attiki	3
212	24.29176	ES530 Illes Balears	1
213	2	ES521 Alicante / Alacant	3
214	20.28491	ES616 Jaén	1
215	2	ES521 Alicante / Alacant	3
216	5	ES613 Cordoba	2
217	121.9979	ES521 Alicante / Alacant	3
218	54.48969	ES421 Albacete	3
219	173.3226	ES521 Alicante / Alacant	3
220	46.52208	ES521 Alicante / Alacant	3
221	83.62506	ES620 Murcia	3
222	38.84552	ES620 Murcia	2
223	12.86553	GR300 Attiki	3
224	238.5978	ITG27 Cagliari	2
225	85.9061	ITG27 Cagliari	2
226	7	GR300 Attiki	3
227	2	GR300 Attiki	3
228	7.388866	ES620 Murcia	2
229	9.231878	ES620 Murcia	2
230	43.45563	GR300 Attiki	3
231	5	ES618 Sevilla	3
232	47.34953	ES616 Jaén	1
233	34.3221	ES616 Jaén	2
234	2	ES620 Murcia	3
235	4.171831	ES616 Jaén	1
236	2	ES620 Murcia	2
237	2	ES620 Murcia	2
238	7	ES521 Alicante / Alacant	3
239	22.53303	ES613 Cordoba	2
240	52.34526	GR422 Kyklades	1
241	2.010735	ES613 Cordoba	1
242	4.648077	ES613 Cordoba	2

243	7.333136	ES616 Jaén	2
244	52.39873	ES614 Granada	2
245	97.51497	ES614 Granada	1
246	66.85783	ES614 Granada	2
247	2	ES613 Cordoba	3
248	11	ES614 Granada	1
249	8	ES617 Malaga	1
250	3	ES620 Murcia	3
251	47.15567	GR422 Kyklades	1
252	44.44427	GR422 Kyklades	1
253	2	ITG12 Palermo	3
254	5	ITG12 Palermo	2
255	3	ITG12 Palermo	2
256	3	ES617 Malaga	1
257	3136.03	ES521 Alicante / Alacant	2
258	406.2836	ES620 Murcia	2
259	12.31597	ES421 Albacete	2
260	47.36781	ES421 Albacete	1
261	216.2247	ES421 Albacete	1
262	91.3446	ES620 Murcia	3
263	7.758475	ES620 Murcia	3
264	13.18696	ES620 Murcia	2
265	26.4122	ES620 Murcia	2
266	33.34865	ES620 Murcia	2
267	60.57889	ES620 Murcia	2
268	127.7755	ES620 Murcia	2
269	15.95464	ES421 Albacete	1
270	21.11916	ES421 Albacete	2
271	93.3768	ES620 Murcia	3
272	24.68136	ES617 Malaga	2
273	7.791263	ITG12 Palermo	2
274	3	ES617 Malaga	3
275	23	ITG12 Palermo	3
276	3	ES617 Malaga	1
277	12	ES611 Almeria	1
278	2	ITG12 Palermo	2
279	7	ITG12 Palermo	3
280	3	ITG12 Palermo	2
281	2	ITG12 Palermo	3
282	78.76273	ES611 Almeria	1
283	24.42425	ES611 Almeria	3
284	24.70949	ES611 Almeria	1
285	9.589788	ES611 Almeria	3
286	89.1497	ES611 Almeria	3
287	13	ITG12 Palermo	3
288	6	ES617 Malaga	1
289	9	ITG12 Palermo	3
290	3	ES617 Malaga	2
291	7	ITG12 Palermo	1
292	6	ITG12 Palermo	3
293	2	ITG12 Palermo	3
294	50	ITG12 Palermo	2
295	2	ITG12 Palermo	2
296	23.08907	ITG13 Messina	1
297	24.27287	ITG13 Messina	2
298	5	ES612 Cadiz	2
299	6.389639	ES611 Almeria	2
300	25.98957	ITG12 Palermo	1
301	4	ES612 Cadiz	3
302	25.77968	ITG12 Palermo	3
303	24.81936	ES611 Almeria	3

304	8	ES612 Cadiz	3
305	475.8833	ES425 Toledo	2
306	463.2052	ES425 Toledo	1
307	51.137	ES431 Badajoz	2
308	95.09113	ES613 Cordoba	1
309	3985.575	ES431 Badajoz	1
310	59.98506	ES612 Cadiz	2
311	108.129	ES612 Cadiz	1
312	1038.415	ES615 Huelva	2
313	39.04324	PT150 Algarve	2
314	131.6937	PT150 Algarve	2
315	66.60003	PT182 Alto Alentejo	2
316	25.07975	ES432 Caceres	1
317	16.87191	ES618 Sevilla	1
318	390.356	ES432 Caceres	1
319	112.3603	ES432 Caceres	2
320	26.13357	ES432 Caceres	3
321	248.0986	ES432 Caceres	1
322	229.2467	ES411 Avila	2
323	23.03919	ES411 Avila	3
324	27.21072	ES425 Toledo	1
325	334.8747	ES425 Toledo	2
326	3.501332	ES425 Toledo	1
327	11.52284	ES425 Toledo	1
328	18.2707	ES425 Toledo	2
329	52.90376	ES425 Toledo	1
330	200.6553	ES300 Madrid	3
331	2.05285	ES300 Madrid	3
332	2.688427	ES425 Toledo	2
333	2.25228	ES425 Toledo	3
334	16.76727	ES425 Toledo	1
335	113.846	ES425 Toledo	1
336	238.0351	ES432 Caceres	2
337	68.57216	ES432 Caceres	1
338	25.64648	ES432 Caceres	1
339	110.1917	ES432 Caceres	1
340	1755.29	ES431 Badajoz	2
341	6.671352	ES432 Caceres	1
342	71.87386	ES432 Caceres	2
343	85.42293	ES432 Caceres	2
344	33.57371	ES432 Caceres	2
345	4.310144	ES422 Ciudad Real	1
346	306.308	ES422 Ciudad Real	1
347	58.40914	ES422 Ciudad Real	1
348	3.887173	ES422 Ciudad Real	1
349	79.08552	ES422 Ciudad Real	1
350	1881.322	ES613 Cordoba	2
351	356.5586	ES616 Jaén	1
352	36.82882	ES616 Jaén	2
353	4.558883	ES616 Jaén	3
354	48.45284	ES616 Jaén	1
355	56.1245	ES616 Jaén	1
356	151.7246	ES616 Jaén	1
357	125.4335	ES616 Jaén	1
358	34.10907	ES616 Jaén	1
359	29.12852	ES616 Jaén	2
360	192.8524	ES616 Jaén	2
361	32.81997	ES616 Jaén	2
362	81.36951	ES616 Jaén	2
363	7.170583	ES616 Jaén	1
364	28.05872	ES613 Cordoba	1

365	233.4277	ES614 Granada	2
366	3.320909	ES614 Granada	2
367	19.37659	ES614 Granada	2
368	61.36202	ES614 Granada	2
369	98.14107	ES613 Cordoba	1
370	3.556243	ES613 Cordoba	1
371	96.85563	ES613 Cordoba	2
372	118.2671	ES613 Cordoba	2
373	84.02292	ES613 Cordoba	2
374	21.98584	ES613 Cordoba	1
375	16.46638	ES613 Cordoba	1
376	365.7475	ES613 Cordoba	2
377	191.1945	ES613 Cordoba	2
378	44.95777	ES431 Badajoz	1
379	152.327	ES431 Badajoz	1
380	17.33606	ES431 Badajoz	1
381	52.47545	ES431 Badajoz	2
382	7.52702	ES431 Badajoz	1
383	45.25574	ES431 Badajoz	1
384	86.36866	ES431 Badajoz	1
385	90.1893	ES431 Badajoz	2
386	78.0835	ES431 Badajoz	1
387	80.91229	ES431 Badajoz	1
388	79.05336	ES431 Badajoz	2
389	11.88324	ES615 Huelva	2
390	39.60656	ES615 Huelva	2
391	203.7176	ES615 Huelva	3
392	4.421491	ES618 Sevilla	2
393	37.36268	ES618 Sevilla	1
394	3.8752	ES615 Huelva	2
395	9.393196	ES618 Sevilla	2
396	2665.968	ES615 Huelva	2
397	237.002	ES613 Cordoba	1
398	8.79852	ES613 Cordoba	1
399	4.267789	ES618 Sevilla	2
400	32.79728	ES618 Sevilla	2
401	574.2997	ES612 Cadiz	2
402	27.71907	ES612 Cadiz	3
403	12.93476	ES612 Cadiz	1
404	71.26751	ES615 Huelva	1
405	64.27847	PT150 Algarve	2
406	45.22072	PT150 Algarve	3
407	84.44887	PT181 Alentejo Litoral	2
408	16.15286	ES431 Badajoz	1
409	2.487536	ES432 Caceres	1
410	59.54201	ES432 Caceres	2
411	9.770376	ES432 Caceres	1
412	8.891962	ES432 Caceres	2
413	88.75711	ES432 Caceres	2
414	95.95812	ES432 Caceres	2
415	84.2454	ES615 Huelva	2
416	73.01635	ES431 Badajoz	2
417	3.688544	ES431 Badajoz	2
418	9.361879	ES431 Badajoz	2
419	6.937471	ES618 Sevilla	2
420	94.59468	ES431 Badajoz	1
421	88.19868	ES431 Badajoz	1
422	490.4189	ES431 Badajoz	1
423	92.77599	ES431 Badajoz	2
424	603.6612	ES432 Caceres	1
425	191.7653	ES431 Badajoz	1

426	170.4072	ES431 Badajoz	2
427	86.24286	ES422 Ciudad Real	1
428	85.07849	ES431 Badajoz	1
429	192.7415	ES431 Badajoz	2
430	94.93704	ES432 Caceres	2
431	84.7306	ES616 Jaén	1
432	86.2216	ES422 Ciudad Real	1
433	3.360302	PT150 Algarve	3
434	107.7936	ES618 Sevilla	1
435	104.5751	ES615 Huelva	3
436	97.86068	ES615 Huelva	1
437	110.9822	ES615 Huelva	3
438	98.02323	ES615 Huelva	2
439	155.6233	ES615 Huelva	3
440	236.9811	ES615 Huelva	2
441	94.81668	ES615 Huelva	3
442	87.25844	ES615 Huelva	1
443	92.7555	ES615 Huelva	1
444	92.08181	PT184 Baixo Alentejo	3
445	97.00643	PT184 Baixo Alentejo	3
446	88.50033	ES431 Badajoz	1
447	161.2273	ES431 Badajoz	1
448	170.7939	PT184 Baixo Alentejo	1
449	94.94529	ES431 Badajoz	1
450	92.05975	ES431 Badajoz	1
451	217.8087	ES431 Badajoz	2
452	179.7726	ES431 Badajoz	1
453	177.6403	ES431 Badajoz	1
454	94.50954	ES431 Badajoz	1
455	89.30497	ES613 Cordoba	1
456	139.8414	ES422 Ciudad Real	1
457	87.99097	ES431 Badajoz	1
458	173.2147	ES431 Badajoz	1
459	95.54936	ES431 Badajoz	1
460	189.6753	ES431 Badajoz	3
461	93.49874	ES432 Caceres	2
462	91.6958	ES432 Caceres	1
463	90.54586	ES432 Caceres	1
464	2	ES612 Cadiz	2
465	7	ES612 Cadiz	3
466	54.42271	ITG12 Palermo	1
467	9.932651	ITG12 Palermo	2
468	5	ITG12 Palermo	1
469	7.908377	ITG11 Trapani	1
470	293.0271	ES617 Malaga	2
471	3.653148	ITG12 Palermo	3
472	2	ES617 Malaga	2
473	7.931103	ES611 Almeria	2
474	41.56966	ITG12 Palermo	1
475	17.12813	ITG12 Palermo	1
476	62.03333	ITG12 Palermo	2
477	7	ITG12 Palermo	1
478	13.68925	ITG12 Palermo	1
479	2	ITG17 Catania	3
480	17.94049	ES617 Malaga	3
481	4	ITG17 Catania	3
482	3	ES617 Malaga	3
483	33.99965	ITG12 Palermo	1
484	7	ES611 Almeria	3
485	7.305823	ITG11 Trapani	2
486	64.04403	ITG11 Trapani	3

487	720.3912	ITG11 Trapani	3
488	65.73065	ITG11 Trapani	2
489	37.39298	ITG11 Trapani	2
490	110.9662	ITG11 Trapani	2
491	370.4673	ES611 Almeria	3
492	78.95224	ES614 Granada	3
493	41.23597	ES611 Almeria	3
494	243.305	ES614 Granada	1
495	4.941433	ES611 Almeria	2
496	4	ES611 Almeria	2
497	5.938424	ITG14 Agrigento	2
498	8.406154	ITG14 Agrigento	2
499	7.384243	ITG14 Agrigento	1
500	47.56591	ES611 Almeria	3
501	52.34294	ES611 Almeria	2
502	39.65153	ES611 Almeria	3
503	37.39148	ES611 Almeria	3
504	3.604677	CY000 Kypros / Kibris	3
505	60.80245	ITG14 Agrigento	2
506	52.5213	CY000 Kypros / Kibris	3
507	56.9226	CY000 Kypros / Kibris	3
508	25.5144	CY000 Kypros / Kibris	3
509	15.94511	CY000 Kypros / Kibris	3
510	14.13886	CY000 Kypros / Kibris	3
511	91.40492	CY000 Kypros / Kibris	3
512	2	ITG14 Agrigento	2
513	2	ITG14 Agrigento	3
514	5.354225	ITG19 Siracusa	2
515	2	ITG15 Caltanissetta	2
516	302.1826	ITG18 Ragusa	2
517	2074.186	ITG12 Palermo	1
518	12.80236	ITG14 Agrigento	1
519	80.91576	ITG12 Palermo	1
520	3.240453	ITG12 Palermo	1
521	27.47458	ITG15 Caltanissetta	1
522	6.532007	ITG12 Palermo	1
523	65.69007	ITG15 Caltanissetta	2
524	78.84175	ITG15 Caltanissetta	1
525	53.622	ITG15 Caltanissetta	2
526	255.4252	ITG15 Caltanissetta	2
527	368.6696	ITG16 Enna	1
528	43.38611	ITG16 Enna	2
529	15.17525	ITG16 Enna	2
530	33.8201	ITG16 Enna	2
531	154.0627	ITG17 Catania	3
532	317.136	ITG19 Siracusa	3
533	55.72756	ITG19 Siracusa	2
534	119.5516	ITG19 Siracusa	2
535	71.19225	ITG19 Siracusa	1
536	208.1694	ITG18 Ragusa	2
537	86.22821	ITG18 Ragusa	2
538	3.377196	ITG18 Ragusa	2
539	115.7977	ITG19 Siracusa	3
540	85.04451	ITG17 Catania	2
541	45.57063	ITG17 Catania	1
542	30.21277	ITG15 Caltanissetta	2
543	25.61855	ITG18 Ragusa	2
544	37.44919	ITG15 Caltanissetta	2
545	60.48617	ITG14 Agrigento	2
546	17.63783	ITG11 Trapani	1
547	4	GR432 Lasithi	2

548	5	GR431 Irakleio	3
549	20.76205	GR431 Irakleio	2
550	95.95485	MT001 Malta	3
551	10.53836	ITG14 Agrigento	1
552	29.9821	ES702 Santa Cruz de Tenerife	2
553	4.490718	ES702 Santa Cruz de Tenerife	2
554	5.315891	ES702 Santa Cruz de Tenerife	2
555	39.93103	ES702 Santa Cruz de Tenerife	2
556	5.420531	ES702 Santa Cruz de Tenerife	3
557	71	ES702 Santa Cruz de Tenerife	3
558	2	ES702 Santa Cruz de Tenerife	3
559	30	ES702 Santa Cruz de Tenerife	3
560	69.72008	ES702 Santa Cruz de Tenerife	2
561	14	ES702 Santa Cruz de Tenerife	2
562	10	ES702 Santa Cruz de Tenerife	1
563	9	ES702 Santa Cruz de Tenerife	2
564	6	ES701 Las Palmas	1
565	3	ES701 Las Palmas	3
566	5.983637	ES701 Las Palmas	3

Tab. A4 – List of the STU for the Open Ponds / sea water - waste water plant type (Capability Class: 1 Low; 2 Mid; 3 High)

N STU	Area km^2	NUTS3	Capability Class
1	2.95111	ES512 Girona	2
2	3.586105	ES512 Girona	3
3	2.912521	ITF42 Bari	3
4	4.105762	ITF42 Bari	2
5	2.597933	ITG25 Sassari	2
6	2.676323	ITG25 Sassari	1
7	5.626257	ES514 Tarragona	2
8	4.695111	ES514 Tarragona	3
9	3.20525	ES514 Tarragona	2
10	4.109713	ES514 Tarragona	3
11	3.083746	ES522 Castellon	3
12	2.814085	ITG25 Sassari	2
13	2.409494	ITF42 Bari	2
14	5.261045	ITF44 Brindisi	1
15	9.764441	ITF44 Brindisi	1
16	3.140752	ITF44 Brindisi	2
17	4.85992	ITG25 Sassari	3
18	2.200014	ES530 Illes Balears	3
19	16.01655	ES530 Illes Balears	3
20	2.766974	GR143 Magnisia	2
21	7.31206	ES523 Valencia / Valencia	3
22	14.87158	ES530 Illes Balears	2
23	2.184342	ES530 Illes Balears	3
24	30.35268	ES530 Illes Balears	3
25	7.510951	ES530 Illes Balears	3
26	5.028345	ES530 Illes Balears	3
27	3.461641	ES523 Valencia / Valencia	3
28	13.19963	ES522 Castellon	3
29	4.193337	ES522 Castellon	3
30	3.398319	ES522 Castellon	3
31	5.211288	ES522 Castellon	3
32	4.477483	ES523 Valencia / Valencia	3
33	6.240907	ES523 Valencia / Valencia	3
34	2.563812	ES523 Valencia / Valencia	3
35	2.024219	ES523 Valencia / Valencia	3
36	12.49187	ES523 Valencia / Valencia	3
37	18.59034	ES523 Valencia / Valencia	3
38	12.2716	ES523 Valencia / Valencia	2
39	6.081897	ES530 Illes Balears	3
40	3.55629	ES530 Illes Balears	3
41	6.269466	ES530 Illes Balears	2
42	10.29221	GR242 Evvoia	3
43	7.628305	ES523 Valencia / Valencia	3
44	4.441577	ES521 Alicante / Alacant	3
45	5.457804	ES521 Alicante / Alacant	3
46	5.242164	ES521 Alicante / Alacant	3
47	4.013929	ES521 Alicante / Alacant	3
48	2.483703	ES521 Alicante / Alacant	3
49	6.93235	ES530 Illes Balears	1
50	3.974302	GR300 Attiki	3
51	8.437692	GR300 Attiki	3
52	5.866293	GR422 Kyklades	2
53	2.139522	GR422 Kyklades	1
54	2.344461	GR422 Kyklades	2
55	2.409289	ES521 Alicante / Alacant	3
56	10.78923	ES521 Alicante / Alacant	3
57	2.151328	ES521 Alicante / Alacant	3
58	7.439797	ES521 Alicante / Alacant	3

59	9.9083	ES521 Alicante / Alacant	3
60	3.330564	ES620 Murcia	2
61	2.808429	ES620 Murcia	1
62	2.481696	ES620 Murcia	3
63	3.581672	ITG12 Palermo	1
64	2.740595	ITG12 Palermo	2
65	3.184819	ITG12 Palermo	1
66	2.14303	ITG13 Messina	1
67	2.105207	ITG13 Messina	2
68	2.696794	ITG13 Messina	2
69	3.094309	ES611 Almeria	3
70	3.599134	ITG12 Palermo	1
71	4.958549	ITG12 Palermo	2
72	5.229844	ES612 Cadiz	2
73	2.231004	ES615 Huelva	3
74	4.227007	ES615 Huelva	3
75	2.028588	PT150 Algarve	3
76	6.778373	PT150 Algarve	3
77	2.76758	ITG11 Trapani	1
78	2.20108	ITG11 Trapani	1
79	2.437806	ITG11 Trapani	2
80	2.109721	ITG11 Trapani	3
81	4.488355	ITG14 Agrigento	2
82	4.458511	ITG11 Trapani	3
83	3.503546	ITG11 Trapani	2
84	2.348736	ITG11 Trapani	2
85	2.611374	ITG11 Trapani	2
86	3.85655	ES611 Almeria	3
87	2.928942	ITG14 Agrigento	2
88	3.855058	ES611 Almeria	3
89	2.313499	CY000 Kypros / Kibris	3
90	2.826412	ITG14 Agrigento	1
91	4.02679	CY000 Kypros / Kibris	3
92	3.688981	CY000 Kypros / Kibris	3
93	2.873887	CY000 Kypros / Kibris	3
94	4.649597	ITG19 Siracusa	2
95	4.014961	ITG19 Siracusa	3
96	5.483828	ITG19 Siracusa	3
97	6.897622	ITG19 Siracusa	2
98	4.332354	ITG19 Siracusa	2
99	14.05137	ITG19 Siracusa	2
100	3.567861	ITG18 Ragusa	2
101	6.764706	ITG18 Ragusa	3
102	3.687899	ITG18 Ragusa	1
103	2.577909	ITG15 Caltanissetta	1
104	2.685403	ITG14 Agrigento	2
105	2.213899	ITG11 Trapani	1
106	3.461753	GR431 Irakleio	3
107	4.289333	MT001 Malta	3
108	11.09881	MT001 Malta	3
109	8.366063	ITG14 Agrigento	1

Tab. A5 – List of the STU for the Open Ponds / fresh water – waste water plant type (Capability Class: 1 Low; 2 Mid; 3 High)

N STU	Area km^2	NUTS3	Capability Class
1	7.419789	ES512 Girona	2
2	11.50295	ES512 Girona	3
3	2.343286	ES512 Girona	2
4	6.189655	ES513 Lleida	3
5	16.57315	ES241 Huesca	1
6	91.41684	ES241 Huesca	3
7	5.898351	ES241 Huesca	2
8	3.349083	ES241 Huesca	3
9	2.636754	ES241 Huesca	2
10	4.599756	ES243 Zaragoza	3
11	108.8236	ES243 Zaragoza	3
12	12.87945	ES514 Tarragona	3
13	3.926861	ES514 Tarragona	3
14	5.391471	ES514 Tarragona	3
15	2.552432	ES514 Tarragona	3
16	20.88619	ES514 Tarragona	3
17	14.1403	ES514 Tarragona	2
18	2	ES422 Ciudad Real	1
19	25.1872	ES422 Ciudad Real	1
20	17.47219	ES422 Ciudad Real	1
21	28.5425	ES422 Ciudad Real	1
22	29.12665	GR142 Larisa	3
23	3.415835	ES523 Valencia / Valencia	3
24	4.845266	ES523 Valencia / Valencia	3
25	31.66666	ES523 Valencia / Valencia	3
26	11.06471	ES521 Alicante / Alacant	3
27	13.91142	ES616 Jaén	1
28	7.205023	ES521 Alicante / Alacant	3
29	3.668519	ITG13 Messina	1
30	5.965175	ITG13 Messina	3
31	3.480256	ES425 Toledo	2
32	98.38501	ES425 Toledo	2
33	45.34751	ES425 Toledo	1
34	3.56688	ES431 Badajoz	3
35	96.8761	ES431 Badajoz	2
36	104.8737	ES431 Badajoz	1
37	3.336826	ES431 Badajoz	2
38	91.65176	ES431 Badajoz	2
39	101.5368	ES431 Badajoz	1
40	3.332496	ES431 Badajoz	2
41	10.25005	ES431 Badajoz	2
42	123.4265	ES431 Badajoz	2
43	10.25005	ES431 Badajoz	2
44	120.0931	ES431 Badajoz	2
45	9.240512	ES615 Huelva	2
46	23.98216	ES615 Huelva	3
47	7.642638	ES615 Huelva	3
48	22.50711	ES615 Huelva	3
49	19.373	ES432 Caceres	2
50	16.44366	ES432 Caceres	2
51	17.76727	ES425 Toledo	1
52	3.589655	ES425 Toledo	1
53	40.11697	ES425 Toledo	2
54	101.5445	ES300 Madrid	3
55	2.05285	ES300 Madrid	3
56	3.958177	ES616 Jaén	2
57	66.35165	ES616 Jaén	2
58	110.8757	ES613 Cordoba	2

59	106.9344	ES616 Jaén	3
60	3.958177	ES616 Jaén	2
61	66.35165	ES616 Jaén	2
62	110.6772	ES613 Cordoba	2
63	106.3565	ES616 Jaén	3
64	26.85652	ES616 Jaén	1
65	39.01766	ES613 Cordoba	3
66	120.9342	ES618 Sevilla	1
67	63.54886	ES618 Sevilla	2
68	2.651063	ES618 Sevilla	3
69	95.05349	ES613 Cordoba	1
70	15.72383	ES618 Sevilla	2
71	15.36	ES618 Sevilla	2
72	43.80535	ES618 Sevilla	2
73	21.59518	PT181 Alentejo Litoral	1
74	88.91419	ES432 Caceres	1
75	5.908033	ES432 Caceres	2
76	83.00616	ES432 Caceres	1
77	3.510404	ES431 Badajoz	2
78	11.51401	ES431 Badajoz	2
79	3.650127	ES618 Sevilla	1
80	7.671759	PT184 Baixo Alentejo	2
81	30.1417	ES431 Badajoz	2
82	6.328313	ES614 Granada	3
83	15.92707	ES243 Zaragoza	3
84	10.42474	ES243 Zaragoza	3
85	7.593665	ES513 Lleida	3
86	7.798096	ES513 Lleida	3
87	17.42004	ES514 Tarragona	3
88	5.736696	ES243 Zaragoza	3
89	32.97375	ES243 Zaragoza	1
90	5.491802	ES432 Caceres	3
91	2.044313	ES432 Caceres	1
92	13.65134	ITG21 Sassari	3
93	3.469047	ES522 Castellon	3
94	5.798375	ITF44 Brindisi	3
95	11.62535	ES523 Valencia / Valencia	3
96	2.153722	ES431 Badajoz	1
97	7.857034	ES422 Ciudad Real	1
98	9.552397	ES523 Valencia / Valencia	3
99	8.899597	ES523 Valencia / Valencia	3
100	11.13345	ES523 Valencia / Valencia	3
101	3.838828	ES421 Albacete	2
102	6.326272	ES521 Alicante / Alacant	3
103	9.061272	ITG24 Cagliari	2
104	5.946725	ITG24 Cagliari	3
105	23.08449	ES614 Granada	2
106	6.213702	ES620 Murcia	2
107	5.187416	ES620 Murcia	3
108	5.962722	ES521 Alicante / Alacant	3
109	5.869566	ES620 Murcia	2
110	5.772016	ES521 Alicante / Alacant	3
111	21.19356	ES521 Alicante / Alacant	3
112	3.903705	ES620 Murcia	3
113	6.282173	ES620 Murcia	3
114	4.659011	ES421 Albacete	1
115	4.431159	ES620 Murcia	3
116	5.856324	ES611 Almeria	2
117	3.129509	ES425 Toledo	2
118	2.838765	ES425 Toledo	2
119	42.31633	ES431 Badajoz	1

120	4.458061	ES431 Badajoz	1
121	19.1024	ES431 Badajoz	2
122	11.47408	ES431 Badajoz	2
123	2.106856	ES431 Badajoz	1
124	7.435467	ES431 Badajoz	3
125	5.447297	ES431 Badajoz	3
126	6.077362	ES431 Badajoz	1
127	6.901877	ES431 Badajoz	3
128	5.839082	ES431 Badajoz	3
129	12.24526	ES431 Badajoz	1
130	4.328846	ES612 Cadiz	3
131	4.144676	ES615 Huelva	3
132	6.178504	ES615 Huelva	1
133	2.816854	ES615 Huelva	2
134	4.56031	ES615 Huelva	3
135	8.226002	ES615 Huelva	3
136	2.884732	PT150 Algarve	3
137	3.735136	PT150 Algarve	3
138	3.87096	ES618 Sevilla	1
139	5.167648	ES432 Caceres	3
140	13.54975	ES432 Caceres	3
141	7.523394	ES432 Caceres	3
142	10.48387	ES432 Caceres	1
143	50.98956	ES432 Caceres	2
144	48.91199	ES432 Caceres	3
145	11.01554	ES411 Avila	3
146	6.004706	ES425 Toledo	2
147	7.580957	ES425 Toledo	2
148	22.28177	ES425 Toledo	1
149	27.46145	ES425 Toledo	2
150	50.05385	ES432 Caceres	3
151	6.334019	ES432 Caceres	1
152	7.486642	ES432 Caceres	1
153	2.765651	ES432 Caceres	1
154	6.410097	ES432 Caceres	1
155	27.36914	ES432 Caceres	3
156	46.82537	ES432 Caceres	1
157	14.17976	ES432 Caceres	3
158	10.86308	ES432 Caceres	3
159	8.203194	ES432 Caceres	3
160	10.60832	ES432 Caceres	2
161	5.700007	ES432 Caceres	1
162	6.731952	ES432 Caceres	2
163	8.984404	ES432 Caceres	2
164	4.866212	ES432 Caceres	1
165	3.689374	ES432 Caceres	2
166	3.932055	ES432 Caceres	1
167	2.750243	ES431 Badajoz	1
168	37.95274	ES616 Jaén	2
169	2.354713	ES616 Jaén	3
170	3.024849	ES616 Jaén	1
171	32.59383	ES616 Jaén	1
172	21.11694	ES616 Jaén	2
173	4.044089	ES616 Jaén	1
174	8.640051	ES616 Jaén	2
175	12.30979	ES613 Cordoba	2
176	3.417102	ES613 Cordoba	1
177	8.373408	ES613 Cordoba	3
178	3.588683	ES431 Badajoz	1
179	6.427641	ES431 Badajoz	1
180	10.19316	ES615 Huelva	2

181	4.304158	ES615 Huelva	2
182	8.015845	ES615 Huelva	2
183	11.02426	ES618 Sevilla	2
184	5.3706	ES618 Sevilla	2
185	8.128125	ES618 Sevilla	1
186	17.1443	ES618 Sevilla	2
187	5.022128	ES615 Huelva	2
188	14.06058	ES618 Sevilla	2
189	5.025402	ES612 Cadiz	1
190	5.288316	ES615 Huelva	1
191	6.163528	ES615 Huelva	1
192	5.316236	ES615 Huelva	1
193	7.153508	ES432 Caceres	1
194	29.04761	ES432 Caceres	1
195	5.907836	ES432 Caceres	1
196	34.43336	ES431 Badajoz	2
197	3.688544	ES431 Badajoz	2
198	9.277592	ES431 Badajoz	2
199	6.201339	ES431 Badajoz	1
200	8.572112	ES432 Caceres	1
201	16.94262	ES432 Caceres	2
202	16.55897	ES431 Badajoz	2
203	40.16662	ES431 Badajoz	1
204	5.707073	ES422 Ciudad Real	1
205	6.805721	ES422 Ciudad Real	2
206	9.129619	ES431 Badajoz	2
207	25.59184	ES431 Badajoz	3
208	35.97151	ES432 Caceres	1
209	11.47971	ES615 Huelva	2
210	11.02246	ES615 Huelva	1
211	7.316645	ES615 Huelva	2
212	6.390497	ES615 Huelva	3
213	5.249096	ES615 Huelva	1
214	16.4469	ES615 Huelva	1
215	6.085907	PT184 Baixo Alentejo	3
216	7.715314	PT184 Baixo Alentejo	2
217	5.258418	PT184 Baixo Alentejo	1
218	5.985412	PT184 Baixo Alentejo	1
219	16.75253	ES431 Badajoz	1
220	5.351092	PT183 Alentejo Central	2
221	10.63955	ES431 Badajoz	1
222	18.01495	ES431 Badajoz	1
223	13.16236	ES431 Badajoz	1
224	6.739019	ES422 Ciudad Real	1
225	32.21415	ES431 Badajoz	2
226	5.361628	ES431 Badajoz	2
227	74.54537	ES431 Badajoz	3
228	10.95439	ES432 Caceres	1
229	7.798282	ES432 Caceres	2
230	3.578386	ES432 Caceres	1
231	5.470741	ITG14 Agrigento	1
232	9.331173	ITG11 Trapani	2
233	7.164386	ITG11 Trapani	2
234	3.967964	ES614 Granada	1
235	6.135326	ITG14 Agrigento	1
236	6.04225	ITG14 Agrigento	1
237	10.37545	ITG14 Agrigento	1
238	9.9384	ITG16 Enna	1
239	6.588232	ITG15 Caltanissetta	3
240	7.461624	ITG17 Catania	3
241	11.88926	ITG16 Enna	1

242	8.458889	ITG16 Enna	1
243	5.293567	ITG16 Enna	3
244	5.113641	ITG19 Siracusa	3
245	5.760858	ITG19 Siracusa	3
246	6.316651	ITG19 Siracusa	3

Tab. A6 – List of the STU for the PBR / sea water plant type

N STU	Area km^2	NUTS3	Capability Class
1	4.778	FR825 Var	3
2	2.778	FR825 Var	3
3	2.228	FR811 Aude	3
4	8.359	FR811 Aude	2
5	2.013	FR832 Haute-Corse	2
6	2.449	FR832 Haute-Corse	1
7	2.748	FR832 Haute-Corse	2
8	2.859	ITE16 Livorno	3
9	2.626	ITE16 Livorno	3
10	5.184	ITE16 Livorno	3
11	4.007	ITE1A Grosseto	2
12	5.508	FR832 Haute-Corse	2
13	3.020	FR832 Haute-Corse	1
14	2.701	ITE16 Livorno	3
15	2.202	ITE16 Livorno	2
16	2.461	ITE16 Livorno	2
17	3.542	FR832 Haute-Corse	3
18	3.961	FR832 Haute-Corse	3
19	3.140	FR832 Haute-Corse	2
20	14.306	FR832 Haute-Corse	2
21	24.522	FR832 Haute-Corse	1
22	2.157	FR832 Haute-Corse	3
23	2.656	FR831 Corse-du-Sud	2
24	3.683	GR115 Kavala	2
25	3.540	FR831 Corse-du-Sud	3
26	2.633	FR831 Corse-du-Sud	3
27	2.260	GR115 Kavala	1
28	2.511	ITE1A Grosseto	3
29	3.356	ITE41 Viterbo	2
30	7.437	GR (No NUTS)	1
31	4.384	GR (No NUTS)	1
32	3.250	FR831 Corse-du-Sud	2
33	2.051	FR831 Corse-du-Sud	2
34	2.110	GR (No NUTS)	1
35	4.934	ES514 Tarragona	3
36	8.925	GR411 Lesvos	1
37	16.330	GR411 Lesvos	2
38	4.734	GR411 Lesvos	3
39	18.543	GR411 Lesvos	2
40	5.436	GR411 Lesvos	3
41	4.943	GR411 Lesvos	2
42	35.249	GR411 Lesvos	1
43	2.230	GR127 Chalkidiki	3
44	9.060	GR127 Chalkidiki	1
45	7.853	GR127 Chalkidiki	2
46	3.444	GR127 Chalkidiki	3
47	2.626	GR127 Chalkidiki	1
48	5.380	GR127 Chalkidiki	2
49	2.303	GR127 Chalkidiki	1
50	8.167	GR127 Chalkidiki	2
51	4.183	GR127 Chalkidiki	2
52	9.982	GR127 Chalkidiki	1
53	7.560	GR127 Chalkidiki	1
54	4.391	GR127 Chalkidiki	1
55	3.240	GR127 Chalkidiki	1
56	3.665	GR125 Pieria	1
57	11.427	GR125 Pieria	2
58	2.059	GR142 Larisa	2
59	8.452	GR411 Lesvos	1

60	13.794	GR411 Lesvos	1
61	3.162	GR411 Lesvos	1
62	30.312	GR411 Lesvos	2
63	21.906	GR411 Lesvos	2
64	6.507	GR411 Lesvos	1
65	3.720	GR411 Lesvos	3
66	8.998	GR411 Lesvos	2
67	5.837	GR411 Lesvos	2
68	9.407	GR411 Lesvos	2
69	2.980	GR411 Lesvos	2
70	6.967	GR411 Lesvos	2
71	3.922	GR411 Lesvos	3
72	5.823	GR411 Lesvos	2
73	3.818	GR411 Lesvos	1
74	4.831	GR222 Kerkyra	2
75	17.171	ITG21 Sassari	3
76	6.410	ITG21 Sassari	3
77	2.045	ITG21 Sassari	3
78	2.832	ITG21 Sassari	1
79	4.955	ITG21 Sassari	3
80	7.307	ITG21 Sassari	2
81	13.938	ITG21 Sassari	3
82	20.205	ITG22 Nuoro	2
83	4.589	ITG22 Nuoro	2
84	3.743	ITG21 Sassari	2
85	4.319	ITG21 Sassari	3
86	2.200	ITG21 Sassari	2
87	6.521	ITG21 Sassari	3
88	3.802	ITG21 Sassari	2
89	19.328	ITG21 Sassari	2
90	9.185	ITG21 Sassari	2
91	4.332	ITG21 Sassari	3
92	4.888	ITG21 Sassari	1
93	4.346	ITG21 Sassari	1
94	2.778	ITG22 Nuoro	2
95	9.834	ITF42 Bari	2
96	2.331	ITF42 Bari	1
97	2.402	ITF44 Brindisi	2
98	2.146	ITF44 Brindisi	1
99	14.334	ITF44 Brindisi	2
100	5.259	ITF44 Brindisi	1
101	2.491	ITF44 Brindisi	3
102	15.744	ITF45 Lecce	2
103	10.979	ITF45 Lecce	1
104	2.482	ITF41 Foggia	3
105	3.164	ES530 Illes Balears	1
106	2.004	GR143 Magnisia	2
107	2.000	GR143 Magnisia	2
108	9.583	ITF61 Cosenza	1
109	3.274	GR143 Magnisia	1
110	27.989	ES530 Illes Balears	3
111	5.736	ES530 Illes Balears	2
112	8.613	ES530 Illes Balears	2
113	6.395	ES530 Illes Balears	3
114	26.524	ES530 Illes Balears	2
115	3.096	GR143 Magnisia	1
116	3.710	GR143 Magnisia	2
117	4.099	GR143 Magnisia	1
118	2.579	GR143 Magnisia	2
119	2.048	GR143 Magnisia	1
120	26.849	GR222 Kerkyra	1

121	2.835	GR222 Kerkyra	1
122	11.657	GR222 Kerkyra	2
123	4.792	GR222 Kerkyra	1
124	23.000	GR222 Kerkyra	1
125	2.095	GR222 Kerkyra	2
126	2.628	GR222 Kerkyra	3
127	8.637	GR413 Chios	2
128	2.172	GR413 Chios	1
129	8.348	GR242 Evvoia	3
130	8.066	GR242 Evvoia	2
131	2.393	GR242 Evvoia	1
132	5.086	GR242 Evvoia	1
133	2.223	GR413 Chios	1
134	3.880	GR212 Thesprotia	1
135	2.312	GR212 Thesprotia	1
136	2.206	GR212 Thesprotia	1
137	12.130	GR142 Larisa	1
138	19.720	GR143 Magnisia	2
139	4.082	GR143 Magnisia	3
140	8.256	GR143 Magnisia	1
141	2.687	GR244 Fthiotida	1
142	3.280	GR244 Fthiotida	1
143	2.487	GR244 Fthiotida	2
144	2.031	GR222 Kerkyra	1
145	2.856	ITF61 Cosenza	1
146	4.769	ES530 Illes Balears	2
147	3.125	ES530 Illes Balears	1
148	10.266	ES530 Illes Balears	1
149	2.069	ES530 Illes Balears	2
150	4.146	ES530 Illes Balears	3
151	2.876	ES530 Illes Balears	2
152	3.010	GR413 Chios	1
153	10.475	GR413 Chios	2
154	3.736	GR413 Chios	2
155	7.835	GR413 Chios	1
156	11.716	GR413 Chios	1
157	6.698	GR413 Chios	1
158	3.241	GR413 Chios	2
159	2.186	GR413 Chios	2
160	5.837	ES530 Illes Balears	1
161	3.204	ES530 Illes Balears	1
162	4.556	ES530 Illes Balears	2
163	2.195	ES530 Illes Balears	2
164	2.251	ES530 Illes Balears	3
165	2.585	ES530 Illes Balears	2
166	3.088	ES530 Illes Balears	2
167	7.463	ES530 Illes Balears	2
168	9.471	GR224 Lefkada	1
169	2.618	GR412 Samos	2
170	3.922	GR412 Samos	1
171	4.512	GR412 Samos	2
172	2.214	GR412 Samos	3
173	2.065	GR412 Samos	3
174	3.323	GR245 Fokida	1
175	2.075	GR245 Fokida	1
176	9.218	GR245 Fokida	2
177	2.917	GR245 Fokida	2
178	3.306	ES530 Illes Balears	2
179	3.350	ES530 Illes Balears	2
180	2.951	ES530 Illes Balears	3
181	5.638	GR232 Achaia	1

182	12.182	ITG24 Cagliari	3
183	5.431	ITG24 Cagliari	2
184	3.653	ITG24 Cagliari	3
185	15.811	GR224 Lefkada	2
186	4.116	GR224 Lefkada	1
187	2.401	GR224 Lefkada	1
188	5.324	GR231 Aitoloakarnania	1
189	5.927	GR231 Aitoloakarnania	2
190	2.349	GR214 Preveza	2
191	3.400	GR214 Preveza	3
192	5.896	GR421 Dodekanisos	1
193	5.836	GR223 Kefallinia	2
194	7.358	GR223 Kefallinia	2
195	5.882	GR422 Kyklades	1
196	4.264	GR422 Kyklades	2
197	2.218	GR422 Kyklades	2
198	3.014	GR422 Kyklades	1
199	3.177	GR422 Kyklades	1
200	10.752	ITG24 Cagliari	3
201	3.627	ITG24 Cagliari	2
202	2.575	ITG24 Cagliari	2
203	2.497	ITG24 Cagliari	1
204	4.236	ITG24 Cagliari	1
205	7.781	ITG24 Cagliari	3
206	4.411	ITG24 Cagliari	3
207	4.986	ITG24 Cagliari	3
208	3.338	ITG24 Cagliari	3
209	2.733	ITG24 Cagliari	2
210	3.044	ITG24 Cagliari	1
211	69.420	ITG23 Oristano	3
212	2.657	ITG23 Oristano	1
213	15.470	ITG23 Oristano	1
214	28.100	ITG22 Nuoro	2
215	7.769	ITG22 Nuoro	1
216	8.055	ITG22 Nuoro	3
217	17.111	ITG24 Cagliari	2
218	14.718	ITG24 Cagliari	2
219	3.095	ITG24 Cagliari	2
220	4.383	GR223 Kefallinia	1
221	2.060	GR223 Kefallinia	1
222	3.019	GR223 Kefallinia	2
223	3.226	GR422 Kyklades	1
224	5.012	GR422 Kyklades	2
225	2.243	GR422 Kyklades	1
226	3.045	GR223 Kefallinia	2
227	5.278	GR223 Kefallinia	3
228	2.535	GR422 Kyklades	1
229	3.628	GR422 Kyklades	1
230	8.039	GR300 Attiki	2
231	9.875	GR300 Attiki	1
232	4.584	GR422 Kyklades	2
233	2.022	GR422 Kyklades	1
234	5.268	GR421 Dodekanisos	2
235	7.882	GR421 Dodekanisos	1
236	3.243	GR422 Kyklades	1
237	50.520	ITF63 Catanzaro	1
238	9.454	ITF65 Reggio di Calabria	2
239	2.385	ITF63 Catanzaro	2
240	9.814	ITF61 Cosenza	3
241	3.655	ITF61 Cosenza	3
242	21.289	ITF61 Cosenza	1

243	10.987	ITF61 Cosenza	2
244	3.180	ITF62 Crotone	3
245	13.862	ITF62 Crotone	2
246	8.260	ITF62 Crotone	1
247	11.283	ITF62 Crotone	1
248	16.089	ITF63 Catanzaro	1
249	2.043	GR422 Kyklades	1
250	2.006	GR421 Dodekanisos	1
251	4.163	GR300 Attiki	1
252	4.436	GR300 Attiki	1
253	2.831	ITF64 Vibo Valentia	1
254	4.746	ITF64 Vibo Valentia	2
255	2.737	GR422 Kyklades	1
256	5.895	GR422 Kyklades	1
257	9.971	GR221 Zakynthos	1
258	13.933	GR421 Dodekanisos	2
259	3.879	GR421 Dodekanisos	2
260	2.443	GR421 Dodekanisos	2
261	7.915	GR421 Dodekanisos	2
262	28.485	GR422 Kyklades	1
263	2.593	GR422 Kyklades	1
264	23.810	GR232 Achaia	1
265	17.625	GR233 Ileia	1
266	5.939	GR232 Achaia	1
267	6.170	GR232 Achaia	2
268	2.751	GR233 Ileia	1
269	2.736	GR300 Attiki	2
270	2.962	GR421 Dodekanisos	1
271	3.821	GR421 Dodekanisos	2
272	2.051	GR242 Evvoia	2
273	2.143	GR242 Evvoia	1
274	12.951	GR242 Evvoia	2
275	14.106	GR242 Evvoia	3
276	13.674	GR242 Evvoia	1
277	18.349	GR242 Evvoia	3
278	3.105	GR242 Evvoia	2
279	4.431	GR242 Evvoia	2
280	2.263	GR242 Evvoia	1
281	3.655	GR242 Evvoia	2
282	3.028	GR242 Evvoia	2
283	2.398	GR242 Evvoia	1
284	5.076	GR242 Evvoia	2
285	5.530	GR242 Evvoia	3
286	2.542	GR242 Evvoia	2
287	2.017	GR242 Evvoia	1
288	2.234	GR242 Evvoia	2
289	39.666	GR241 Voiotia	2
290	3.459	GR300 Attiki	2
291	12.245	GR300 Attiki	3
292	32.614	GR300 Attiki	3
293	7.293	GR300 Attiki	3
294	7.721	GR300 Attiki	3
295	2.852	GR300 Attiki	3
296	4.600	GR241 Voiotia	2
297	3.042	GR245 Fokida	1
298	5.040	GR244 Fthiotida	1
299	2.209	GR244 Fthiotida	2
300	28.914	GR244 Fthiotida	1
301	7.757	GR244 Fthiotida	1
302	20.078	GR244 Fthiotida	1
303	2.847	GR244 Fthiotida	1

304	3.689	GR244 Fthiotida	1
305	8.866	GR244 Fthiotida	2
306	3.059	GR241 Voiotia	1
307	2.732	GR242 Evvoia	1
308	4.675	GR242 Evvoia	2
309	2.180	GR242 Evvoia	1
310	2.474	GR242 Evvoia	1
311	23.638	GR242 Evvoia	1
312	3.348	GR300 Attiki	3
313	3.193	GR253 Korinthia	2
314	6.743	GR253 Korinthia	3
315	2.241	GR253 Korinthia	2
316	3.686	GR253 Korinthia	2
317	3.149	GR251 Argolida	2
318	3.024	GR300 Attiki	2
319	11.852	GR300 Attiki	1
320	4.281	GR300 Attiki	2
321	5.696	GR251 Argolida	1
322	2.479	GR251 Argolida	1
323	4.680	GR251 Argolida	1
324	3.711	GR251 Argolida	1
325	6.709	GR252 Arkadia	1
326	4.535	GR253 Korinthia	1
327	2.405	GR253 Korinthia	1
328	23.226	GR253 Korinthia	2
329	2.680	GR253 Korinthia	2
330	4.467	GR253 Korinthia	2
331	3.213	GR300 Attiki	1
332	2.499	GR300 Attiki	2
333	5.906	GR251 Argolida	1
334	5.754	GR300 Attiki	3
335	2.634	GR422 Kyklades	2
336	4.853	GR422 Kyklades	1
337	2.762	GR422 Kyklades	2
338	3.152	GR422 Kyklades	1
339	2.393	GR422 Kyklades	1
340	6.533	GR422 Kyklades	1
341	3.477	GR422 Kyklades	1
342	34.370	ITF65 Reggio di Calabria	1
343	9.524	ITF65 Reggio di Calabria	1
344	2.206	ITF65 Reggio di Calabria	1
345	4.417	ITF65 Reggio di Calabria	2
346	9.816	ITF65 Reggio di Calabria	2
347	3.534	GR422 Kyklades	2
348	2.494	GR422 Kyklades	1
349	2.378	GR422 Kyklades	1
350	3.338	GR421 Dodekanisos	1
351	2.219	GR422 Kyklades	2
352	4.769	GR422 Kyklades	3
353	10.164	GR422 Kyklades	2
354	2.395	CY000 Kypros / Kibris	2
355	10.944	GR421 Dodekanisos	3
356	4.451	GR421 Dodekanisos	3
357	9.520	GR421 Dodekanisos	1
358	6.233	GR421 Dodekanisos	1
359	7.288	GR421 Dodekanisos	1
360	14.091	GR421 Dodekanisos	1
361	7.961	GR421 Dodekanisos	1
362	2.390	GR421 Dodekanisos	2
363	3.211	GR421 Dodekanisos	1
364	10.569	GR421 Dodekanisos	3

365	4.824	GR421 Dodekanisos	1
366	7.166	GR422 Kyklades	1
367	7.288	GR422 Kyklades	1
368	4.024	CY000 Kypros / Kibris	3
369	5.960	GR255 Messinia	1
370	13.148	GR255 Messinia	1
371	6.746	GR255 Messinia	1
372	2.660	GR255 Messinia	1
373	2.137	CY000 Kypros / Kibris	3
374	8.330	CY000 Kypros / Kibris	2
375	4.348	CY000 Kypros / Kibris	1
376	2.994	CY000 Kypros / Kibris	2
377	12.096	CY000 Kypros / Kibris	3
378	3.167	CY000 Kypros / Kibris	1
379	5.492	CY000 Kypros / Kibris	2
380	90.817	CY000 Kypros / Kibris	3
381	9.248	CY000 Kypros / Kibris	3
382	13.684	CY000 Kypros / Kibris	3
383	17.416	CY000 Kypros / Kibris	3
384	17.880	CY000 Kypros / Kibris	3
385	4.838	CY000 Kypros / Kibris	3
386	5.554	CY000 Kypros / Kibris	3
387	5.493	CY000 Kypros / Kibris	3
388	3.557	CY000 Kypros / Kibris	3
389	4.691	CY000 Kypros / Kibris	3
390	3.033	CY000 Kypros / Kibris	2
391	6.329	CY000 Kypros / Kibris	3
392	3.974	CY000 Kypros / Kibris	3
393	2.377	CY000 Kypros / Kibris	3
394	4.706	CY000 Kypros / Kibris	3
395	22.036	CY000 Kypros / Kibris	3
396	4.788	CY000 Kypros / Kibris	2
397	3.212	CY000 Kypros / Kibris	1
398	2.074	CY000 Kypros / Kibris	2
399	2.790	CY000 Kypros / Kibris	3
400	2.302	GR254 Lakonia	2
401	7.287	ES522 Castellon	3
402	4.692	ES522 Castellon	3
403	3.776	ES514 Tarragona	3
404	12.192	ES620 Murcia	2
405	6.543	ES611 Almeria	3
406	4.563	ES611 Almeria	3
407	2.751	ES611 Almeria	3
408	2.493	ES611 Almeria	2
409	7.689	PT150 Algarve	3
410	3.701	PT150 Algarve	3
411	2.292	PT172 PenÝnsula de Set·bal	3
412	3.861	PT172 PenÝnsula de Set·bal	3
413	11.198	PT171 Grande Lisboa	3
414	2.120	PT16B Oeste	1
415	7.203	PT16B Oeste	2
416	6.037	PT16B Oeste	1
417	3.413	PT16B Oeste	1
418	4.219	PT16B Oeste	2
419	6.617	PT16B Oeste	3
420	3.102	PT163 Pinhal Litoral	1
421	2.791	PT163 Pinhal Litoral	1
422	4.850	PT162 Baixo Mondego	2
423	5.793	PT162 Baixo Mondego	1
424	8.995	PT162 Baixo Mondego	2
425	4.430	PT161 Baixo Vouga	2

426	4.564	ES512 Girona	2
427	3.080	ES514 Tarragona	3
428	8.208	ES514 Tarragona	3
429	2.233	ES514 Tarragona	3
430	3.872	ES523 Valencia / Valencia	3
431	2.210	ES521 Alicante / Alacant	3
432	2.672	ES620 Murcia	3
433	8.456	ES514 Tarragona	3
434	3.114	GR254 Lakonia	1
435	6.353	GR254 Lakonia	1
436	2.040	GR254 Lakonia	1
437	16.307	GR254 Lakonia	1
438	2.331	GR254 Lakonia	1
439	3.717	GR300 Attiki	3
440	4.012	GR300 Attiki	2
441	4.120	GR421 Dodekanisos	2
442	3.654	GR421 Dodekanisos	1
443	13.585	ITG17 Catania	3
444	3.350	ITG19 Siracusa	2
445	11.012	ITG18 Ragusa	2
446	7.823	ITG18 Ragusa	2
447	10.944	ITG14 Agrigento	2
448	2.106	ITG14 Agrigento	2
449	2.719	ITG14 Agrigento	2
450	15.229	ITG11 Trapani	2
451	2.931	ITG11 Trapani	1
452	5.387	ITG11 Trapani	1
453	4.262	ITG12 Palermo	3
454	2.501	GR300 Attiki	2
455	3.911	GR432 Lasithi	1
456	5.849	MT002 Gozo and Comino/Ghawdex u Kemmuna	1
457	3.464	MT002 Gozo and Comino/Ghawdex u Kemmuna	2
458	4.551	GR432 Lasithi	2
459	5.686	GR432 Lasithi	2
460	4.972	GR432 Lasithi	1
461	3.019	GR432 Lasithi	1
462	4.058	GR432 Lasithi	1
463	4.483	GR432 Lasithi	1
464	2.572	GR431 Irakleio	3
465	13.311	GR433 Rethymni	1
466	7.456	GR434 Chania	1
467	19.183	GR434 Chania	1
468	9.658	GR434 Chania	1
469	3.905	GR434 Chania	2
470	29.140	GR433 Rethymni	1
471	4.388	GR433 Rethymni	1
472	3.144	GR433 Rethymni	2
473	3.287	GR431 Irakleio	3
474	2.917	GR431 Irakleio	3
475	2.842	GR431 Irakleio	2
476	4.843	GR431 Irakleio	3
477	4.964	GR431 Irakleio	3
478	8.894	GR431 Irakleio	1
479	11.107	GR431 Irakleio	1
480	2.653	GR432 Lasithi	2
481	5.135	GR432 Lasithi	1
482	3.195	GR432 Lasithi	2
483	2.420	GR432 Lasithi	3
484	2.026	GR432 Lasithi	1

485	2.644	GR432 Lasithi	1
486	3.357	GR432 Lasithi	1
487	5.450	GR432 Lasithi	2
488	3.196	GR434 Chania	3
489	2.569	GR431 Irakleio	3
490	2.705	GR432 Lasithi	2
491	2.376	MT001 Malta	2
492	4.720	MT001 Malta	3
493	2.284	MT001 Malta	2
494	5.344	MT001 Malta	3
495	3.199	MT001 Malta	3
496	10.514	GR434 Chania	1

Tab. A7 – List of the STU for the PBR / fresh water plant type (Capability Class: 1 Low; 2 Mid; 3 High)

N STU	Area km^2	NUTS3	Capability Class
1	3.669	ES114 Pontevedra	3
2	2.000	ES114 Pontevedra	3
3	16.958	ITE16 Livorno	3
4	2.000	PT114 Grande Porto	3
5	2.998	PT115 Tâmega	2
6	5.000	PT115 Tâmega	2
7	2.961	PT115 Tâmega	3
8	3.000	PT115 Tâmega	2
9	2.000	PT115 Tâmega	3
10	3.909	PT115 Tâmega	2
11	2.000	PT115 Tâmega	3
12	2.000	PT115 Tâmega	2
13	13.295	PT115 Tâmega	1
14	11.852	PT115 Tâmega	2
15	8.964	PT117 Douro	1
16	19.506	PT117 Douro	1
17	12.141	PT117 Douro	1
18	2.923	PT117 Douro	1
19	4.936	PT117 Douro	2
20	16.972	PT117 Douro	2
21	33.271	PT117 Douro	1
22	3.000	PT117 Douro	3
23	6.855	PT117 Douro	2
24	3.000	PT117 Douro	1
25	2.570	PT117 Douro	2
26	6.340	PT117 Douro	2
27	2.930	ES415 Salamanca	3
28	3.154	FR832 Haute-Corse	2
29	2.865	GR115 Kavala	1
30	120.664	GR115 Kavala	1
31	2.751	ITE1A Grosseto	3
32	9.820	ITE1A Grosseto	3
33	2.978	ITE43 Roma	3
34	26.278	GR142 Larisa	1
35	4.809	ITF35 Salerno	2
36	5.328	ITF35 Salerno	2
37	3.685	ITG21 Sassari	2
38	3.841	ITG21 Sassari	2
39	2.064	ITG21 Sassari	2
40	2.535	ES422 Ciudad Real	1
41	59.569	ES422 Ciudad Real	2
42	3.639	ES422 Ciudad Real	2
43	9.805	ES422 Ciudad Real	1
44	59.244	ES422 Ciudad Real	2
45	22.866	GR212 Thesprotia	1
46	72.871	GR142 Larisa	2
47	143.895	GR141 Karditsa	1
48	42.317	GR141 Karditsa	1
49	22.823	GR141 Karditsa	2
50	18.424	GR142 Larisa	2
51	3.000	GR231 Aitoloakarnania	1
52	2.671	GR243 Evrytania	3
53	2.000	ES616 Jaén	3
54	46.852	GR231 Aitoloakarnania	1
55	6.554	GR231 Aitoloakarnania	2
56	2.848	GR231 Aitoloakarnania	1
57	42.160	GR231 Aitoloakarnania	1
58	4.682	GR231 Aitoloakarnania	1
59	7.360	GR211 Arta	3

60	4.905	GR231 Aitoloakarnania	1
61	2.532	GR231 Aitoloakarnania	1
62	3.881	GR231 Aitoloakarnania	1
63	39.953	GR231 Aitoloakarnania	1
64	8.933	GR231 Aitoloakarnania	1
65	28.490	GR231 Aitoloakarnania	1
66	11.695	ITG23 Oristano	2
67	114.009	GR233 Ileia	1
68	8.353	GR233 Ileia	1
69	10.368	GR244 Fthiotida	1
70	11.213	GR244 Fthiotida	2
71	90.560	GR241 Voiotia	1
72	2.034	GR255 Messinia	1
73	62.990	ES514 Tarragona	3
74	3.473	ES514 Tarragona	3
75	82.468	ES615 Huelva	2
76	3.684	PT181 Alentejo Litoral	2
77	69.901	PT16B Oeste	2
78	63.096	PT162 Baixo Mondego	2
79	35.732	PT162 Baixo Mondego	3
80	25.304	PT164 Pinhal Interior Norte	2
81	4.275	ES432 Caceres	1
82	10.333	ES432 Caceres	2
83	7.312	ES425 Toledo	1
84	19.837	ES425 Toledo	2
85	22.090	ES432 Caceres	2
86	98.093	ES616 Jaén	2
87	19.388	ES616 Jaén	1
88	2.061	ES431 Badajoz	1
89	54.086	ES431 Badajoz	2
90	6.701	ES431 Badajoz	1
91	123.672	ES431 Badajoz	1
92	39.975	PT185 Leziria do Tejo	2
93	49.945	PT16C Médio Tejo	3
94	136.883	ES432 Caceres	1
95	121.665	PT166 Pinhal Interior Sul	3
96	214.994	ES431 Badajoz	3
97	2.686	ES618 Sevilla	2
98	82.880	ES618 Sevilla	1
99	7.698	ES618 Sevilla	2
100	4.109	ES613 Cordoba	2
101	22.212	ES613 Cordoba	3
102	9.841	ES616 Jaén	1
103	12.407	ES616 Jaén	2
104	11.473	ES613 Cordoba	2
105	8.480	ES432 Caceres	2
106	44.098	ES432 Caceres	1
107	3.161	ES422 Ciudad Real	1
108	3.967	ES523 Valencia / Valencia	3
109	13.855	ES514 Tarragona	2
110	13.164	ES425 Toledo	2
111	43.215	ES425 Toledo	2
112	21.811	ES425 Toledo	2
113	6.095	ES425 Toledo	2
114	5.426	ES300 Madrid	3
115	6.607	ES300 Madrid	3
116	2.394	ES425 Toledo	2
117	10.830	ES616 Jaén	2
118	3.750	ES241 Huesca	2
119	8.761	ES431 Badajoz	2
120	9.625	ES618 Sevilla	2

121	22.151	PT183 Alentejo Central	1
122	4.521	ES432 Caceres	2
123	3.521	ES425 Toledo	1
124	4.501	ES425 Toledo	2
125	4.985	ES425 Toledo	2
126	2.011	ES422 Ciudad Real	1
127	3.845	ES431 Badajoz	2
128	3.229	ES431 Badajoz	2
129	2.408	ES431 Badajoz	3
130	4.929	PT162 Baixo Mondego	3
131	3.689	PT162 Baixo Mondego	2
132	3.360	ES432 Caceres	2
133	3.426	ES432 Caceres	1
134	17.805	PT184 Baixo Alentejo	1
135	7.532	ES431 Badajoz	2
136	97.698	ES431 Badajoz	1
137	2.784	ES615 Huelva	2
138	3.733	ES523 Valencia / Valencia	3
139	79.557	ES615 Huelva	2
140	59.407	PT162 Baixo Mondego	2
141	30.803	PT162 Baixo Mondego	3
142	3.790	ES425 Toledo	1
143	15.315	ES425 Toledo	2
144	18.730	ES432 Caceres	2
145	44.566	ES431 Badajoz	2
146	116.140	ES431 Badajoz	1
147	120.870	PT166 Pinhal Interior Sul	3
148	78.081	PT184 Baixo Alentejo	1
149	21.410	PT184 Baixo Alentejo	1
150	3.800	ES613 Cordoba	2
151	40.673	ES432 Caceres	1
152	38.714	ES425 Toledo	2
153	16.826	ES425 Toledo	2
154	6.353	ES431 Badajoz	2
155	25.683	GR254 Lakonia	1
156	4.384	ITG13 Messina	1
157	6.144	ITG13 Messina	1
158	7.835	ITG13 Messina	2
159	3.619	ITG13 Messina	3
160	4.465	ITG13 Messina	1
161	6.836	ITG13 Messina	1
162	10.600	ITG11 Trapani	2
163	4.248	ITG12 Palermo	2
164	16.813	ITG16 Enna	2
165	3.999	PT115 Tâmega	2
166	3.000	PT115 Tâmega	3
167	2.000	PT115 Tâmega	2
168	3.000	PT115 Tâmega	2
169	3.077	FR832 Haute-Corse	1
170	7.243	FR832 Haute-Corse	3
171	7.206	FR832 Haute-Corse	2
172	6.623	FR832 Haute-Corse	2
173	5.777	FR832 Haute-Corse	1
174	2.473	GR115 Kavala	1
175	5.348	PT164 Pinhal Interior Norte	1
176	6.414	PT164 Pinhal Interior Norte	1
177	15.644	PT164 Pinhal Interior Norte	1
178	8.317	FR831 Corse-du-Sud	1
179	16.469	GR411 Lesvos	2
180	4.079	GR411 Lesvos	2
181	7.663	GR127 Chalkidiki	2

182	4.000	ITG21 Sassari	2
183	14.760	ITF35 Salerno	3
184	19.762	ITG22 Nuoro	2
185	9.139	ITG21 Sassari	1
186	41.705	ITG21 Sassari	2
187	5.983	ITG21 Sassari	1
188	14.582	ITG22 Nuoro	2
189	5.849	ITG21 Sassari	2
190	12.965	ITG21 Sassari	1
191	5.526	ITG21 Sassari	2
192	7.842	ITG21 Sassari	2
193	6.459	ES422 Ciudad Real	2
194	6.134	ES422 Ciudad Real	2
195	5.255	GR212 Thesprotia	1
196	8.018	GR141 Karditsa	1
197	4.718	ITG22 Nuoro	3
198	3.000	ITG22 Nuoro	2
199	4.000	ITG22 Nuoro	2
200	11.000	GR (Lake)	1
201	8.850	GR (Lake)	3
202	3.467	ES422 Ciudad Real	1
203	2.423	ES422 Ciudad Real	1
204	11.821	ES421 Albacete	1
205	8.186	ES521 Alicante / Alacant	2
206	13.061	ES421 Albacete	1
207	3.998	ES421 Albacete	1
208	9.937	ES616 Jaén	3
209	99.112	GR231 Aitoloakarnania	2
210	50.926	GR231 Aitoloakarnania	3
211	2.553	GR231 Aitoloakarnania	1
212	2.906	GR231 Aitoloakarnania	2
213	27.028	GR231 Aitoloakarnania	3
214	2.445	GR231 Aitoloakarnania	1
215	24.089	GR231 Aitoloakarnania	2
216	2.658	GR231 Aitoloakarnania	1
217	2.888	GR231 Aitoloakarnania	1
218	23.402	ES616 Jaén	1
219	6.442	ITG22 Nuoro	2
220	7.462	ITG22 Nuoro	1
221	9.066	ITG23 Oristano	2
222	79.860	ITG23 Oristano	2
223	24.625	ITG21 Sassari	2
224	5.123	ITG24 Cagliari	2
225	4.040	ITG24 Cagliari	2
226	32.714	ITG22 Nuoro	2
227	7.592	ITG22 Nuoro	1
228	21.797	ITG24 Cagliari	3
229	5.745	ITG24 Cagliari	1
230	9.433	ITG24 Cagliari	1
231	15.090	ITG24 Cagliari	2
232	3.069	ITG24 Cagliari	2
233	6.156	ITG24 Cagliari	2
234	6.353	ITG23 Oristano	2
235	5.887	ITF62 Crotone	2
236	7.589	ITF61 Cosenza	3
237	11.324	ITF61 Cosenza	2
238	10.808	GR232 Achaia	1
239	2.233	GR232 Achaia	1
240	12.066	GR232 Achaia	3
241	33.939	GR232 Achaia	3
242	2.491	GR242 Evvoia	2

243	17.694	GR300 Attiki	3
244	50.905	GR241 Voiotia	3
245	37.691	GR241 Voiotia	2
246	8.880	ITF65 Reggio di Calabria	2
247	5.646	CY000 Kypros / Kibris	2
248	7.028	CY000 Kypros / Kibris	3
249	5.552	CY000 Kypros / Kibris	3
250	7.228	CY000 Kypros / Kibris	3
251	7.150	CY000 Kypros / Kibris	3
252	6.183	CY000 Kypros / Kibris	3
253	6.695	CY000 Kypros / Kibris	3
254	8.925	CY000 Kypros / Kibris	3
255	11.462	CY000 Kypros / Kibris	3
256	8.825	CY000 Kypros / Kibris	3
257	10.117	CY000 Kypros / Kibris	3
258	3.871	CY000 Kypros / Kibris	3
259	13.536	CY000 Kypros / Kibris	3
260	6.268	CY000 Kypros / Kibris	3
261	6.685	CY000 Kypros / Kibris	3
262	20.165	CY000 Kypros / Kibris	3
263	11.548	CY000 Kypros / Kibris	3
264	10.393	CY000 Kypros / Kibris	1
265	10.085	ES620 Murcia	2
266	11.460	ES620 Murcia	1
267	13.960	ES421 Albacete	2
268	56.269	ES421 Albacete	1
269	23.184	ES620 Murcia	3
270	4.004	ES611 Almeria	2
271	39.512	ES616 Jaén	1
272	8.524	ES614 Granada	3
273	17.656	ES614 Granada	2
274	5.035	ES422 Ciudad Real	2
275	7.668	ES422 Ciudad Real	1
276	2.067	ES611 Almeria	1
277	5.494	ES614 Granada	1
278	32.871	ES616 Jaén	2
279	15.510	ES616 Jaén	2
280	4.730	ES616 Jaén	3
281	10.214	ES616 Jaén	2
282	3.164	ES616 Jaén	3
283	22.229	ES616 Jaén	2
284	56.779	ES616 Jaén	1
285	7.005	ES613 Cordoba	2
286	6.134	ES614 Granada	2
287	7.886	ES614 Granada	1
288	9.924	ES616 Jaén	2
289	34.425	ES613 Cordoba	2
290	2.855	ES616 Jaén	2
291	52.547	ES613 Cordoba	1
292	4.800	ES616 Jaén	3
293	29.021	ES613 Cordoba	3
294	30.937	ES613 Cordoba	3
295	6.669	ES613 Cordoba	3
296	13.946	ES613 Cordoba	2
297	31.538	ES613 Cordoba	3
298	46.205	ES613 Cordoba	3
299	8.817	ES613 Cordoba	1
300	15.109	ES613 Cordoba	3
301	16.292	ES617 Malaga	3
302	7.606	ES617 Malaga	3
303	8.223	ES617 Malaga	3

304	24.548	ES617 Malaga	2
305	26.673	ES617 Malaga	3
306	11.342	ES617 Malaga	2
307	6.056	ES613 Cordoba	2
308	7.812	ES425 Toledo	3
309	6.350	ES514 Tarragona	3
310	3.323	ES514 Tarragona	3
311	57.401	ES243 Zaragoza	3
312	8.625	ES522 Castellon	3
313	11.283	ES522 Castellon	3
314	44.502	ES523 Valencia / Valencia	3
315	11.112	ES523 Valencia / Valencia	3
316	15.234	ES523 Valencia / Valencia	3
317	11.368	ES521 Alicante / Alacant	3
318	13.858	ES523 Valencia / Valencia	3
319	2.454	ES521 Alicante / Alacant	3
320	14.313	ES620 Murcia	3
321	14.265	ES242 Teruel	3
322	135.729	ES241 Huesca	3
323	53.754	ES243 Zaragoza	2
324	80.218	ES613 Cordoba	1
325	5.801	ES613 Cordoba	1
326	4.411	ES613 Cordoba	1
327	14.053	ES618 Sevilla	1
328	12.816	ES618 Sevilla	1
329	26.040	ES618 Sevilla	2
330	34.639	ES618 Sevilla	2
331	14.790	ES618 Sevilla	2
332	48.680	ES431 Badajoz	1
333	2.286	ES618 Sevilla	1
334	5.385	ES618 Sevilla	2
335	6.191	ES618 Sevilla	2
336	7.126	ES618 Sevilla	2
337	2.574	ES618 Sevilla	1
338	8.769	ES613 Cordoba	3
339	22.267	ES618 Sevilla	3
340	27.875	ES613 Cordoba	2
341	6.238	ES432 Caceres	1
342	4.886	ES431 Badajoz	1
343	49.462	ES432 Caceres	2
344	5.547	ES431 Badajoz	2
345	8.549	ES432 Caceres	1
346	3.951	ES431 Badajoz	1
347	4.793	ES422 Ciudad Real	2
348	6.464	ES422 Ciudad Real	1
349	291.600	ES431 Badajoz	2
350	80.956	ES431 Badajoz	2
351	23.854	ES431 Badajoz	2
352	13.295	ES431 Badajoz	2
353	12.278	ES432 Caceres	2
354	125.529	ES422 Ciudad Real	1
355	12.132	ES431 Badajoz	1
356	70.130	ES431 Badajoz	1
357	5.229	ES431 Badajoz	3
358	65.728	ES422 Ciudad Real	1
359	4.250	ES431 Badajoz	1
360	4.241	ES431 Badajoz	2
361	3.114	ES431 Badajoz	1
362	3.981	ES431 Badajoz	1
363	3.154	ES431 Badajoz	1
364	10.631	ES431 Badajoz	1

365	17.675	ES431 Badajoz	1
366	8.493	ES431 Badajoz	1
367	11.488	ES431 Badajoz	1
368	52.457	ES431 Badajoz	2
369	2.920	ES431 Badajoz	1
370	8.609	ES432 Caceres	1
371	39.798	ES432 Caceres	1
372	5.914	ES432 Caceres	2
373	6.327	ES432 Caceres	1
374	22.516	ES432 Caceres	1
375	16.556	ES425 Toledo	1
376	5.028	ES425 Toledo	2
377	63.248	ES425 Toledo	2
378	29.509	ES432 Caceres	2
379	8.893	ES425 Toledo	1
380	7.672	ES425 Toledo	1
381	35.740	ES411 Avila	3
382	2.638	ES411 Avila	1
383	6.978	ES432 Caceres	2
384	6.616	ES432 Caceres	1
385	7.997	ES432 Caceres	2
386	6.063	ES432 Caceres	3
387	3.556	ES432 Caceres	2
388	15.203	ES432 Caceres	3
389	132.023	ES432 Caceres	2
390	26.663	ES432 Caceres	2
391	25.415	ES432 Caceres	2
392	2.381	ES432 Caceres	1
393	67.761	ES432 Caceres	2
394	75.877	ES432 Caceres	1
395	36.036	ES432 Caceres	1
396	10.131	ES432 Caceres	3
397	8.301	ES432 Caceres	1
398	5.817	ES432 Caceres	3
399	3.287	ES432 Caceres	3
400	4.441	ES432 Caceres	2
401	2.274	ES432 Caceres	1
402	50.396	ES612 Cadiz	1
403	8.631	ES615 Huelva	1
404	98.121	ES615 Huelva	1
405	10.539	ES615 Huelva	1
406	2.463	ES615 Huelva	1
407	6.745	ES618 Sevilla	1
408	13.466	ES618 Sevilla	1
409	5.743	ES618 Sevilla	1
410	80.834	ES615 Huelva	1
411	8.848	ES618 Sevilla	2
412	6.119	ES615 Huelva	1
413	8.169	ES618 Sevilla	2
414	8.616	ES618 Sevilla	1
415	8.845	ES618 Sevilla	1
416	6.082	ES612 Cadiz	2
417	15.400	ES618 Sevilla	2
418	7.475	ES618 Sevilla	2
419	20.293	ES618 Sevilla	2
420	43.004	ES618 Sevilla	1
421	6.281	ES612 Cadiz	1
422	9.563	ES612 Cadiz	1
423	6.433	ES612 Cadiz	1
424	8.465	ES618 Sevilla	1
425	14.274	ES612 Cadiz	2

426	54.141	ES612 Cadiz	2
427	28.706	ES612 Cadiz	1
428	19.019	ES612 Cadiz	2
429	39.388	ES612 Cadiz	2
430	77.315	ES612 Cadiz	2
431	20.574	ES612 Cadiz	2
432	6.911	ES612 Cadiz	1
433	5.342	ES612 Cadiz	1
434	5.995	ES612 Cadiz	1
435	6.074	ES612 Cadiz	1
436	6.158	ES432 Caceres	1
437	4.821	ES432 Caceres	1
438	50.722	PT182 Alto Alentejo	1
439	14.025	ES431 Badajoz	1
440	50.462	ES431 Badajoz	2
441	26.391	ES615 Huelva	2
442	51.972	ES615 Huelva	2
443	23.198	ES431 Badajoz	2
444	6.042	ES431 Badajoz	1
445	24.520	ES431 Badajoz	2
446	11.770	ES431 Badajoz	2
447	8.929	ES431 Badajoz	1
448	2.262	ES615 Huelva	1
449	5.009	ES618 Sevilla	2
450	7.441	ES615 Huelva	1
451	2.077	ES615 Huelva	2
452	6.427	ES615 Huelva	2
453	43.115	ES615 Huelva	3
454	4.730	ES615 Huelva	3
455	9.266	ES615 Huelva	2
456	4.208	ES615 Huelva	2
457	31.458	PT164 Pinhal Interior Norte	1
458	21.945	PT164 Pinhal Interior Norte	3
459	133.334	PT162 Baixo Mondego	3
460	23.581	PT169 Beira Interior Sul	2
461	7.162	PT169 Beira Interior Sul	1
462	5.473	PT169 Beira Interior Sul	2
463	20.713	PT169 Beira Interior Sul	3
464	7.078	PT182 Alto Alentejo	1
465	5.659	PT182 Alto Alentejo	1
466	5.654	PT182 Alto Alentejo	2
467	5.975	PT182 Alto Alentejo	2
468	12.658	PT182 Alto Alentejo	2
469	38.247	PT166 Pinhal Interior Sul	2
470	70.324	PT182 Alto Alentejo	2
471	6.131	PT182 Alto Alentejo	1
472	5.734	PT185 Leziria do Tejo	2
473	179.999	PT164 Pinhal Interior Norte	2
474	4.527	PT162 Baixo Mondego	1
475	13.654	PT161 Baixo Vouga	3
476	6.862	PT183 Alentejo Central	1
477	5.876	PT182 Alto Alentejo	1
478	90.662	PT182 Alto Alentejo	2
479	6.281	PT182 Alto Alentejo	1
480	8.720	PT182 Alto Alentejo	1
481	6.326	PT182 Alto Alentejo	1
482	6.515	PT182 Alto Alentejo	1
483	5.828	PT183 Alentejo Central	1
484	5.881	PT182 Alto Alentejo	1
485	6.761	PT182 Alto Alentejo	1
486	6.563	PT182 Alto Alentejo	1

487	6.089	PT182 Alto Alentejo	1
488	7.186	PT182 Alto Alentejo	1
489	6.429	PT182 Alto Alentejo	2
490	6.690	PT183 Alentejo Central	1
491	7.137	PT183 Alentejo Central	1
492	5.424	PT183 Alentejo Central	1
493	7.775	PT183 Alentejo Central	1
494	5.641	PT182 Alto Alentejo	1
495	5.735	PT182 Alto Alentejo	1
496	5.935	PT182 Alto Alentejo	1
497	12.644	PT182 Alto Alentejo	1
498	5.795	PT183 Alentejo Central	1
499	6.199	PT183 Alentejo Central	1
500	6.918	PT183 Alentejo Central	1
501	6.507	PT183 Alentejo Central	1
502	6.093	PT183 Alentejo Central	1
503	5.632	PT183 Alentejo Central	1
504	6.246	PT183 Alentejo Central	1
505	6.546	PT183 Alentejo Central	1
506	5.905	PT182 Alto Alentejo	2
507	6.527	PT184 Baixo Alentejo	1
508	6.659	PT184 Baixo Alentejo	1
509	6.234	PT184 Baixo Alentejo	2
510	8.185	PT183 Alentejo Central	1
511	48.182	PT183 Alentejo Central	1
512	5.367	PT184 Baixo Alentejo	1
513	3.764	PT184 Baixo Alentejo	1
514	16.581	PT183 Alentejo Central	2
515	10.284	PT183 Alentejo Central	1
516	179.056	ES431 Badajoz	1
517	181.044	PT183 Alentejo Central	2
518	2.198	ES431 Badajoz	1
519	12.301	PT183 Alentejo Central	1
520	26.308	PT183 Alentejo Central	1
521	13.630	PT183 Alentejo Central	2
522	9.432	PT184 Baixo Alentejo	1
523	5.948	PT184 Baixo Alentejo	2
524	8.033	PT184 Baixo Alentejo	3
525	5.636	PT184 Baixo Alentejo	2
526	5.385	PT184 Baixo Alentejo	1
527	5.885	PT184 Baixo Alentejo	2
528	7.348	PT184 Baixo Alentejo	1
529	7.421	PT184 Baixo Alentejo	1
530	12.307	PT184 Baixo Alentejo	1
531	6.079	PT184 Baixo Alentejo	1
532	11.028	PT184 Baixo Alentejo	3
533	6.092	PT184 Baixo Alentejo	1
534	6.024	PT184 Baixo Alentejo	2
535	6.428	PT184 Baixo Alentejo	1
536	5.811	PT184 Baixo Alentejo	1
537	6.543	PT184 Baixo Alentejo	2
538	36.613	ES615 Huelva	3
539	86.410	ES615 Huelva	3
540	3.608	PT184 Baixo Alentejo	2
541	11.855	ES615 Huelva	2
542	17.518	PT150 Algarve	3
543	23.907	ES615 Huelva	3
544	35.533	PT150 Algarve	3
545	6.389	PT150 Algarve	1
546	24.246	ES615 Huelva	2
547	6.059	PT184 Baixo Alentejo	1

548	6.391	ES431 Badajoz	1
549	7.061	PT183 Alentejo Central	1
550	5.506	PT183 Alentejo Central	1
551	12.238	PT183 Alentejo Central	2
552	9.612	PT183 Alentejo Central	2
553	6.268	PT183 Alentejo Central	1
554	6.288	PT183 Alentejo Central	1
555	5.470	PT183 Alentejo Central	2
556	5.605	PT183 Alentejo Central	1
557	5.951	PT183 Alentejo Central	1
558	5.591	PT183 Alentejo Central	1
559	5.657	PT183 Alentejo Central	1
560	8.134	PT183 Alentejo Central	1
561	6.001	PT183 Alentejo Central	1
562	6.563	PT183 Alentejo Central	1
563	6.189	PT183 Alentejo Central	2
564	18.775	PT183 Alentejo Central	1
565	5.208	PT183 Alentejo Central	1
566	34.099	PT184 Baixo Alentejo	1
567	7.823	PT184 Baixo Alentejo	1
568	6.300	PT184 Baixo Alentejo	1
569	6.493	PT184 Baixo Alentejo	1
570	8.632	PT185 Leziria do Tejo	2
571	7.705	PT16B Oeste	2
572	5.313	PT163 Pinhal Litoral	2
573	5.206	PT162 Baixo Mondego	3
574	8.543	PT162 Baixo Mondego	3
575	8.571	PT172 PenÝnsula de Set·bal	3
576	5.339	PT172 PenÝnsula de Set·bal	2
577	13.413	PT172 PenÝnsula de Set·bal	3
578	5.891	PT185 Leziria do Tejo	2
579	11.127	PT185 Leziria do Tejo	2
580	5.523	PT185 Leziria do Tejo	2
581	6.324	PT185 Leziria do Tejo	1
582	8.290	PT185 Leziria do Tejo	2
583	5.979	PT183 Alentejo Central	2
584	6.114	PT183 Alentejo Central	2
585	6.268	PT183 Alentejo Central	2
586	5.546	PT185 Leziria do Tejo	2
587	5.583	PT185 Leziria do Tejo	3
588	3.370	PT185 Leziria do Tejo	3
589	5.747	PT185 Leziria do Tejo	3
590	5.644	PT185 Leziria do Tejo	2
591	6.825	PT181 Alentejo Litoral	3
592	5.840	PT181 Alentejo Litoral	3
593	8.187	PT183 Alentejo Central	2
594	7.667	PT183 Alentejo Central	2
595	5.733	PT183 Alentejo Central	3
596	5.395	PT181 Alentejo Litoral	1
597	5.571	PT183 Alentejo Central	1
598	50.911	PT181 Alentejo Litoral	1
599	5.498	PT181 Alentejo Litoral	1
600	6.016	PT183 Alentejo Central	1
601	8.039	PT181 Alentejo Litoral	1
602	6.695	PT181 Alentejo Litoral	2
603	5.335	PT183 Alentejo Central	1
604	5.641	PT183 Alentejo Central	1
605	5.795	PT183 Alentejo Central	1
606	5.886	PT183 Alentejo Central	1
607	9.530	PT183 Alentejo Central	1
608	6.577	PT185 Leziria do Tejo	2

609	28.821	PT181 Alentejo Litoral	1
610	6.371	PT181 Alentejo Litoral	1
611	5.577	PT181 Alentejo Litoral	1
612	5.898	PT181 Alentejo Litoral	2
613	6.445	PT181 Alentejo Litoral	1
614	7.135	PT181 Alentejo Litoral	3
615	8.097	PT184 Baixo Alentejo	1
616	5.870	PT184 Baixo Alentejo	1
617	6.023	PT184 Baixo Alentejo	1
618	18.029	PT181 Alentejo Litoral	2
619	14.772	PT181 Alentejo Litoral	2
620	6.270	PT184 Baixo Alentejo	2
621	9.431	PT181 Alentejo Litoral	2
622	6.044	PT181 Alentejo Litoral	2
623	5.838	PT181 Alentejo Litoral	2
624	13.768	PT181 Alentejo Litoral	3
625	7.655	PT181 Alentejo Litoral	1
626	6.028	PT184 Baixo Alentejo	2
627	6.044	PT184 Baixo Alentejo	1
628	38.359	PT184 Baixo Alentejo	1
629	98.688	PT181 Alentejo Litoral	1
630	29.285	PT184 Baixo Alentejo	1
631	6.417	PT184 Baixo Alentejo	1
632	5.367	PT184 Baixo Alentejo	1
633	2.601	PT150 Algarve	2
634	5.747	PT150 Algarve	1
635	2.291	PT150 Algarve	3
636	12.022	PT150 Algarve	2
637	27.421	PT150 Algarve	1
638	19.794	PT150 Algarve	1
639	10.301	ITG18 Ragusa	2
640	5.951	ITG19 Siracusa	2
641	13.299	ITG19 Siracusa	3
642	8.227	ITG16 Enna	1
643	6.311	ITG16 Enna	1
644	5.500	ITG16 Enna	1
645	9.293	ITG15 Caltanissetta	2
646	6.291	ITG15 Caltanissetta	2
647	6.052	ITG15 Caltanissetta	2
648	3.246	ITG16 Enna	2
649	4.240	ITG12 Palermo	1
650	10.077	ITG11 Trapani	1
651	9.379	ITG11 Trapani	2

Tab. A8 – List of the STU for the PBR / waste water plant type

N STU	Area km^2	NUTS3	Capability Class
1	2.000	ES114 Pontevedra	3
2	9.000	ES114 Pontevedra	3
3	27.013	ITC31 Imperia	2
4	2.554	ES114 Pontevedra	3
5	2.502	ITC31 Imperia	3
6	24.419	ITC31 Imperia	2
7	11.916	FR823 Alpes-Maritimes	3
8	8.091	ES114 Pontevedra	3
9	8.000	FR823 Alpes-Maritimes	3
10	2.997	FR823 Alpes-Maritimes	3
11	3.000	FR823 Alpes-Maritimes	3
12	6.000	FR823 Alpes-Maritimes	3
13	6.578	ITE16 Livorno	3
14	3.000	FR825 Var	3
15	2.880	FR825 Var	3
16	4.320	FR825 Var	3
17	36.923	FR825 Var	3
18	3.378	FR815 Pyrenées-Orientales	2
19	31.296	ITE16 Livorno	3
20	64.318	ITE16 Livorno	3
21	29.875	ITE16 Livorno	3
22	47.566	ITE16 Livorno	3
23	26.259	ITE16 Livorno	3
24	3.371	FR832 Haute-Corse	1
25	31.177	PT117 Douro	1
26	2.000	FR832 Haute-Corse	3
27	13.000	ES512 Girona	3
28	6.000	ES511 Barcelona	3
29	9.874	ES241 Huesca	1
30	5.000	ES511 Barcelona	3
31	3.000	ES513 Lleida	3
32	2.000	ES512 Girona	3
33	11.820	ITF41 Foggia	3
34	66.000	ES511 Barcelona	3
35	6.278	FR832 Haute-Corse	3
36	2.224	ES242 Teruel	2
37	3.843	ITF41 Foggia	2
38	3.000	ES511 Barcelona	3
39	2.000	ES432 Caceres	2
40	96.316	ITE1A Grosseto	3
41	21.061	ITE41 Viterbo	1
42	38.971	ITE41 Viterbo	1
43	20.120	ITE41 Viterbo	2
44	19.628	ITE41 Viterbo	2
45	87.372	ITE43 Roma	3
46	74.558	ITE43 Roma	3
47	646.992	ITE43 Roma	3
48	58.035	ITE43 Roma	3
49	5.713	ITE43 Roma	3
50	91.292	ITE43 Roma	3
51	103.975	ITE44 Latina	3
52	56.727	ITE43 Roma	3
53	70.063	ITE43 Roma	3
54	19.695	ITE43 Roma	3
55	14.355	ITE43 Roma	3
56	90.124	ITE41 Viterbo	3
57	13.346	ITE43 Roma	3
58	98.249	ITE43 Roma	3
59	5.838	GR122 Thessaloniki	3

60	2.204	ES514 Tarragona	2
61	2.241	ES514 Tarragona	3
62	2.000	ES425 Toledo	2
63	2.000	ES432 Caceres	1
64	10.776	ITF34 Avellino	3
65	36.308	ITF33 Napoli	3
66	819.055	ITF31 Caserta	3
67	4.551	ITF33 Napoli	3
68	9.629	ITF35 Salerno	2
69	203.720	ITF33 Napoli	3
70	6.511	ITF33 Napoli	3
71	10.386	ITF33 Napoli	3
72	36.869	ITF33 Napoli	2
73	3.000	ES432 Caceres	2
74	2.900	ITF35 Salerno	1
75	4.000	ITG22 Nuoro	3
76	5.606	ITF35 Salerno	2
77	112.512	ITF35 Salerno	3
78	21.918	ITF35 Salerno	3
79	25.680	ITF35 Salerno	3
80	101.209	ITF35 Salerno	2
81	61.908	ITF35 Salerno	2
82	31.444	ITF35 Salerno	3
83	6.384	ITF35 Salerno	2
84	2.178	ITF35 Salerno	1
85	5.113	PT181 Alentejo Litoral	2
86	149.707	ITG21 Sassari	2
87	123.188	ITG21 Sassari	3
88	17.519	ITG22 Nuoro	2
89	3.684	ITG22 Nuoro	2
90	76.219	ITG22 Nuoro	3
91	47.175	ITG21 Sassari	3
92	42.019	ITG21 Sassari	2
93	62.861	ITG21 Sassari	1
94	3.926	ITG21 Sassari	3
95	66.746	IT (Lake)	1
96	52.815	ITG21 Sassari	2
97	157.474	ITG21 Sassari	2
98	41.735	ITG21 Sassari	1
99	1038.896	ITF42 Bari	3
100	60.280	ITF42 Bari	3
101	110.466	ITF42 Bari	1
102	214.315	ITF43 Taranto	2
103	40.831	ITF44 Brindisi	1
104	120.629	ITF44 Brindisi	3
105	2367.840	ITF43 Taranto	1
106	338.528	ITF45 Lecce	1
107	219.595	ITF45 Lecce	1
108	384.671	ITF43 Taranto	2
109	13.587	ITF43 Taranto	3
110	2.147	ITF42 Bari	2
111	77.169	ITF42 Bari	1
112	2.186	ITF43 Taranto	2
113	7.529	ITF43 Taranto	2
114	4.656	ITF43 Taranto	2
115	121.991	ITF41 Foggia	2
116	5.952	ITF41 Foggia	2
117	2.000	GR143 Magnisia	2
118	70.246	ITF35 Salerno	2
119	37.356	ITF35 Salerno	2
120	5.341	ITF35 Salerno	1

121	3.832	ES530 Illes Balears	3
122	36.413	ITF61 Cosenza	1
123	29.732	ES530 Illes Balears	1
124	75.210	ES530 Illes Balears	3
125	368.996	ES530 Illes Balears	2
126	2.008	ES530 Illes Balears	2
127	61.274	GR143 Magnisia	1
128	2.000	ES422 Ciudad Real	1
129	2.570	ES530 Illes Balears	1
130	27.547	GR222 Kerkyra	3
131	6.191	ES422 Ciudad Real	1
132	53.230	ES422 Ciudad Real	1
133	27.450	ES422 Ciudad Real	1
134	25.391	ES422 Ciudad Real	1
135	62.271	ES422 Ciudad Real	1
136	37.491	ES422 Ciudad Real	1
137	21.408	GR143 Magnisia	2
138	93.974	GR141 Karditsa	3
139	96.374	GR144 Trikala	3
140	110.614	GR142 Larisa	3
141	48.309	ITF61 Cosenza	1
142	25.692	ITF61 Cosenza	1
143	2.000	ES422 Ciudad Real	2
144	52.170	ES422 Ciudad Real	1
145	13.482	ITF61 Cosenza	1
146	2666.044	ES530 Illes Balears	1
147	59.081	GR413 Chios	1
148	3.000	ITF61 Cosenza	2
149	13.651	ITF61 Cosenza	2
150	6.560	ITF61 Cosenza	2
151	7.133	ITF61 Cosenza	3
152	78.246	ES530 Illes Balears	1
153	70.565	ES530 Illes Balears	3
154	70.356	ES530 Illes Balears	2
155	6.936	ES421 Albacete	3
156	23.891	ES616 Jaén	1
157	4.000	ES521 Alicante / Alacant	2
158	7.000	ES521 Alicante / Alacant	2
159	42.976	ITG24 Cagliari	2
160	52.639	ES521 Alicante / Alacant	2
161	2.276	ES530 Illes Balears	1
162	26.802	ES530 Illes Balears	1
163	31.287	GR232 Achaia	3
164	27.228	ITG24 Cagliari	2
165	62.341	GR231 Aitoloakarnania	3
166	22.930	GR231 Aitoloakarnania	3
167	9.975	ITF64 Vibo Valentia	1
168	436.811	ITG24 Cagliari	2
169	39.068	ITG24 Cagliari	3
170	73.097	ITG24 Cagliari	3
171	107.455	ITG24 Cagliari	2
172	88.066	ITG24 Cagliari	3
173	31.287	GR422 Kyklades	1
174	16.289	ITF61 Cosenza	2
175	81.174	ITF61 Cosenza	2
176	56.579	ITF61 Cosenza	3
177	59.453	ITF61 Cosenza	1
178	53.861	ITF62 Crotone	3
179	88.189	ITF62 Crotone	2
180	69.603	ITF62 Crotone	2
181	88.360	ITF62 Crotone	2

182	150.528	ITF63 Catanzaro	2
183	53.065	ITF63 Catanzaro	2
184	45.779	ITF63 Catanzaro	2
185	80.543	ITF62 Crotone	2
186	3.620	ITF61 Cosenza	2
187	12.016	ITF61 Cosenza	2
188	96.979	ITF62 Crotone	2
189	58.538	GR422 Kyklades	1
190	124.344	ITF65 Reggio di Calabria	2
191	126.122	ITF64 Vibo Valentia	3
192	142.673	ITF64 Vibo Valentia	3
193	2.000	ITG13 Messina	2
194	6.000	ES614 Granada	1
195	38.936	GR221 Zakynthos	3
196	58.970	ITF65 Reggio di Calabria	3
197	4.903	ITF65 Reggio di Calabria	3
198	51.103	GR422 Kyklades	1
199	94.057	GR233 Ileia	3
200	453.172	GR300 Attiki	3
201	78.923	GR300 Attiki	3
202	56.617	GR300 Attiki	3
203	66.490	GR251 Argolida	1
204	44.190	GR253 Korinthia	1
205	49.525	GR253 Korinthia	1
206	82.218	GR244 Fthiotida	3
207	73.719	GR242 Evvoia	3
208	87.294	GR241 Voiotia	3
209	49.140	GR422 Kyklades	1
210	2.000	ITG12 Palermo	2
211	4.000	ITG12 Palermo	2
212	24.372	ITG13 Messina	1
213	24.273	ITG13 Messina	2
214	3.000	ITG12 Palermo	1
215	32.000	ES617 Malaga	1
216	6.000	ITG12 Palermo	1
217	17.619	ITG11 Trapani	2
218	11.000	ES612 Cadiz	3
219	5.653	ITG12 Palermo	2
220	8.910	ITG12 Palermo	1
221	2.000	ITG12 Palermo	2
222	14.689	ITG12 Palermo	1
223	2.099	CY000 Kypros / Kibris	3
224	56.642	CY000 Kypros / Kibris	3
225	75.965	CY000 Kypros / Kibris	3
226	61.458	CY000 Kypros / Kibris	3
227	24.283	CY000 Kypros / Kibris	3
228	193.849	CY000 Kypros / Kibris	3
229	3.000	ITG16 Enna	1
230	3973.060	ES511 Barcelona	3
231	11199.596	ES521 Alicante / Alacant	2
232	262.481	PT172 PenÝnsula de Set·bal	3
233	359.373	PT171 Grande Lisboa	3
234	538.291	ES425 Toledo	2
235	463.205	ES425 Toledo	1
236	55.137	ES431 Badajoz	1
237	447.968	ES616 Jaén	2
238	3.015	FR815 Pyrenées-Orientales	3
239	51.507	ES512 Girona	3
240	449.095	ES514 Tarragona	3
241	39.697	ES514 Tarragona	3
242	1142.259	ES514 Tarragona	3

243	256.280	ES522 Castellon	2
244	102.379	ES611 Almeria	3
245	230.939	ES611 Almeria	3
246	26.927	ES611 Almeria	3
247	63.196	ES611 Almeria	3
248	50.391	ES611 Almeria	3
249	913.325	ES611 Almeria	3
250	385.125	ES614 Granada	1
251	120.755	ES617 Malaga	3
252	896.841	ES617 Malaga	3
253	130.536	ES617 Malaga	3
254	585.386	ES612 Cadiz	3
255	42.261	ES612 Cadiz	3
256	150.905	ES612 Cadiz	3
257	64.991	ES612 Cadiz	3
258	504.696	ES612 Cadiz	3
259	46.420	ES612 Cadiz	3
260	138.590	ES612 Cadiz	2
261	76.268	ES615 Huelva	1
262	1153.767	ES615 Huelva	2
263	75.421	PT150 Algarve	2
264	54.527	PT150 Algarve	2
265	147.227	PT150 Algarve	2
266	48.221	PT150 Algarve	3
267	39.574	PT181 Alentejo Litoral	3
268	97.143	PT172 PenÝnsula de Set·bal	3
269	24.465	PT172 PenÝnsula de Set·bal	3
270	117.022	PT16B Oeste	3
271	47.235	PT16B Oeste	1
272	23.574	PT16B Oeste	3
273	55.267	PT16B Oeste	3
274	74.119	PT162 Baixo Mondego	3
275	3.018	PT162 Baixo Mondego	3
276	4.789	PT161 Baixo Vouga	3
277	122.487	PT162 Baixo Mondego	3
278	7.319	ES432 Caceres	1
279	3.857	ES432 Caceres	1
280	237.408	ES432 Caceres	2
281	429.721	ES432 Caceres	1
282	188.255	ES432 Caceres	1
283	37.847	ES432 Caceres	3
284	266.016	ES411 Avila	2
285	24.940	ES411 Avila	2
286	10.406	ES411 Avila	1
287	65.982	ES411 Avila	2
288	337.875	ES425 Toledo	2
289	25.677	ES425 Toledo	1
290	2.510	ES300 Madrid	2
291	2.699	ES425 Toledo	3
292	18.271	ES425 Toledo	2
293	52.904	ES425 Toledo	1
294	200.655	ES300 Madrid	3
295	6.053	ES300 Madrid	3
296	2.688	ES425 Toledo	2
297	2.252	ES425 Toledo	3
298	16.767	ES425 Toledo	1
299	131.885	ES425 Toledo	1
300	257.173	ES432 Caceres	3
301	68.572	ES432 Caceres	1
302	26.167	ES432 Caceres	1
303	125.180	ES432 Caceres	1

304	1756.290	ES431 Badajoz	2
305	6.671	ES432 Caceres	1
306	89.698	ES432 Caceres	2
307	111.320	ES432 Caceres	1
308	35.574	ES432 Caceres	2
309	4.310	ES422 Ciudad Real	1
310	306.308	ES422 Ciudad Real	1
311	58.409	ES422 Ciudad Real	1
312	3.887	ES422 Ciudad Real	1
313	79.086	ES422 Ciudad Real	1
314	4.559	ES616 Jaén	3
315	48.453	ES616 Jaén	1
316	132.249	ES616 Jaén	1
317	418.501	ES616 Jaén	1
318	21.117	ES616 Jaén	1
319	123.928	ES616 Jaén	1
320	2.713	ES616 Jaén	1
321	7.333	ES616 Jaén	2
322	62.087	ES614 Granada	2
323	100.516	ES614 Granada	1
324	67.858	ES614 Granada	3
325	20.409	ES616 Jaén	2
326	149.880	ES616 Jaén	2
327	113.639	ES616 Jaén	3
328	391.843	ES616 Jaén	2
329	45.778	ES616 Jaén	1
330	130.994	ES613 Cordoba	1
331	7.514	ES614 Granada	1
332	573.604	ES614 Granada	3
333	47.248	ES614 Granada	2
334	268.405	ES614 Granada	2
335	440.387	ES613 Cordoba	1
336	46.098	ES617 Malaga	1
337	102.521	ES617 Malaga	3
338	203.357	ES617 Malaga	1
339	88.555	ES614 Granada	2
340	81.369	ES611 Almeria	3
341	40.870	ES611 Almeria	2
342	273.701	ES611 Almeria	2
343	48.617	ES620 Murcia	2
344	507.958	ES620 Murcia	2
345	112.400	ES620 Murcia	2
346	149.035	ES620 Murcia	2
347	15.955	ES421 Albacete	1
348	21.119	ES421 Albacete	2
349	219.272	ES421 Albacete	1
350	13.316	ES421 Albacete	2
351	52.510	ES421 Albacete	1
352	87.235	ES620 Murcia	3
353	45.605	ES620 Murcia	3
354	57.107	ES421 Albacete	3
355	126.188	ES521 Alicante / Alacant	3
356	17.858	ES521 Alicante / Alacant	3
357	54.400	ES523 Valencia / Valencia	3
358	5.330	ES523 Valencia / Valencia	2
359	8.155	ES523 Valencia / Valencia	2
360	17.820	ES523 Valencia / Valencia	3
361	110.219	ES522 Castellon	3
362	71.141	ES522 Castellon	3
363	57.802	ES522 Castellon	2
364	52.719	ES514 Tarragona	3

365	3.911	ES514 Tarragona	3
366	3.674	ES514 Tarragona	2
367	2.313	ES514 Tarragona	3
368	190.121	ES513 Lleida	3
369	110.524	ES243 Zaragoza	2
370	45.746	ES241 Huesca	3
371	102.931	ES243 Zaragoza	2
372	177.333	ES242 Teruel	2
373	553.649	ES241 Huesca	3
374	19.160	ES514 Tarragona	2
375	12.418	ES512 Girona	3
376	66.124	ES612 Cadiz	3
377	86.112	ES612 Cadiz	3
378	53.998	ES617 Malaga	3
379	93.503	ES617 Malaga	2
380	82.086	ES617 Malaga	1
381	35.551	ES617 Malaga	1
382	1752.775	ES613 Cordoba	2
383	172.940	ES612 Cadiz	2
384	71.856	ES613 Cordoba	3
385	65.143	ES615 Huelva	3
386	2.001	ES615 Huelva	2
387	64.585	ES615 Huelva	3
388	2.067	ES615 Huelva	2
389	18.823	ES615 Huelva	3
390	13.251	ES615 Huelva	2
391	180.615	ES431 Badajoz	1
392	29.331	ES618 Sevilla	2
393	423.325	ES431 Badajoz	1
394	88.719	ES431 Badajoz	1
395	411.521	ES431 Badajoz	2
396	3.810	ES431 Badajoz	1
397	11.262	ES431 Badajoz	1
398	83.285	ES431 Badajoz	1
399	168.741	ES431 Badajoz	2
400	3.069	ES615 Huelva	3
401	2.360	ES431 Badajoz	1
402	195.670	ES431 Badajoz	2
403	59.119	PT182 Alto Alentejo	2
404	80.732	ES431 Badajoz	2
405	101.116	ES618 Sevilla	1
406	139.495	ES431 Badajoz	2
407	3.689	ES431 Badajoz	1
408	92.071	ES431 Badajoz	1
409	4452.224	ES431 Badajoz	1
410	78.084	ES431 Badajoz	1
411	781.692	ES613 Cordoba	3
412	292.799	ES613 Cordoba	2
413	167.316	ES613 Cordoba	1
414	44.318	ES613 Cordoba	1
415	86.125	ES613 Cordoba	3
416	85.463	PT16B Oeste	3
417	86.243	ES422 Ciudad Real	1
418	609.661	ES432 Caceres	1
419	177.676	ES613 Cordoba	1
420	94.595	ES431 Badajoz	1
421	87.144	ES431 Badajoz	2
422	109.160	ES514 Tarragona	3
423	543.746	ES613 Cordoba	2
424	89.492	ES611 Almeria	3
425	83.997	ES612 Cadiz	1

426	90.199	ES431 Badajoz	1
427	490.419	ES431 Badajoz	1
428	97.482	ES620 Murcia	3
429	92.591	PT163 Pinhal Litoral	3
430	80.355	ES615 Huelva	3
431	97.345	PT16B Oeste	3
432	190.956	ES618 Sevilla	1
433	158.104	PT16C Médio Tejo	2
434	176.371	ES432 Caceres	2
435	86.222	ES422 Ciudad Real	1
436	10.079	ES422 Ciudad Real	2
437	42.746	ES422 Ciudad Real	1
438	295.444	ES612 Cadiz	1
439	137.506	ES612 Cadiz	2
440	838.385	ES612 Cadiz	2
441	107.794	ES618 Sevilla	1
442	104.575	ES615 Huelva	3
443	3158.231	ES615 Huelva	2
444	97.861	ES615 Huelva	1
445	110.982	ES615 Huelva	3
446	98.023	ES615 Huelva	3
447	156.623	ES615 Huelva	3
448	87.495	ES618 Sevilla	2
449	281.423	ES615 Huelva	3
450	236.981	ES615 Huelva	2
451	94.817	ES615 Huelva	3
452	88.258	ES615 Huelva	2
453	90.624	ES615 Huelva	2
454	89.328	ES615 Huelva	1
455	92.755	ES615 Huelva	1
456	92.082	PT184 Baixo Alentejo	3
457	89.412	ES431 Badajoz	2
458	97.006	PT184 Baixo Alentejo	3
459	88.500	ES431 Badajoz	1
460	161.227	ES431 Badajoz	1
461	170.794	PT184 Baixo Alentejo	1
462	94.945	ES431 Badajoz	1
463	91.643	ES431 Badajoz	1
464	94.434	ES431 Badajoz	2
465	92.060	ES431 Badajoz	1
466	97.020	PT181 Alentejo Litoral	2
467	217.809	ES431 Badajoz	2
468	192.914	ES431 Badajoz	1
469	95.293	PT183 Alentejo Central	3
470	105.088	PT183 Alentejo Central	3
471	91.960	PT182 Alto Alentejo	2
472	179.773	ES431 Badajoz	1
473	177.640	ES431 Badajoz	1
474	94.510	ES431 Badajoz	1
475	105.095	ES431 Badajoz	2
476	90.220	PT171 Grande Lisboa	2
477	89.567	ES432 Caceres	2
478	93.051	PT171 Grande Lisboa	2
479	241.085	ES431 Badajoz	1
480	93.996	PT185 Leziria do Tejo	3
481	110.434	ES612 Cadiz	1
482	147.652	ES611 Almeria	2
483	94.762	ES612 Cadiz	3
484	483.236	ES612 Cadiz	1
485	102.568	ES611 Almeria	2
486	94.970	ES611 Almeria	3

487	275.552	ES612 Cadiz	1
488	115.640	ES618 Sevilla	3
489	99.999	ES618 Sevilla	3
490	183.355	ES618 Sevilla	3
491	254.930	ES618 Sevilla	3
492	100.488	ES618 Sevilla	1
493	280.000	ES613 Cordoba	3
494	115.943	ES618 Sevilla	3
495	175.390	ES613 Cordoba	3
496	101.286	ES618 Sevilla	2
497	89.305	ES613 Cordoba	1
498	876.992	ES613 Cordoba	2
499	421.325	ES613 Cordoba	2
500	2414.226	ES613 Cordoba	2
501	95.119	ES613 Cordoba	2
502	90.194	ES613 Cordoba	2
503	91.106	ES431 Badajoz	1
504	100.957	ES613 Cordoba	1
505	284.425	ES431 Badajoz	1
506	189.817	ES431 Badajoz	3
507	91.722	ES616 Jaén	2
508	194.255	ES613 Cordoba	2
509	122.423	ES431 Badajoz	1
510	173.590	ES431 Badajoz	1
511	89.383	ES431 Badajoz	1
512	139.841	ES422 Ciudad Real	1
513	89.991	ES431 Badajoz	1
514	174.215	ES431 Badajoz	1
515	176.357	ES431 Badajoz	2
516	198.685	ES431 Badajoz	2
517	95.549	ES431 Badajoz	1
518	189.675	ES431 Badajoz	3
519	93.499	ES432 Caceres	2
520	91.696	ES432 Caceres	1
521	107.206	PT185 Leziria do Tejo	3
522	186.216	ES432 Caceres	2
523	94.302	ES432 Caceres	1
524	95.043	PT16B Oeste	3
525	99.186	PT16C Médio Tejo	2
526	93.388	PT169 Beira Interior Sul	3
527	186.621	PT163 Pinhal Litoral	3
528	251.064	ES432 Caceres	1
529	90.546	ES432 Caceres	1
530	95.355	ES432 Caceres	2
531	90.191	ES432 Caceres	2
532	95.555	ES432 Caceres	2
533	8.293	ITG19 Siracusa	2
534	2.000	ITG19 Siracusa	2
535	20.000	ES630 Ceuta	3
536	1973.844	ITG15 Caltanissetta	1
537	4965.972	ITG11 Trapani	1
538	859.876	ITG13 Messina	2
539	17.742	ITG13 Messina	2
540	580.719	ITG13 Messina	1
541	19.921	ITG19 Siracusa	2
542	56.553	ITG19 Siracusa	1
543	130.552	ITG19 Siracusa	2
544	81.036	ITG19 Siracusa	1
545	212.172	ITG18 Ragusa	2
546	637.194	ITG15 Caltanissetta	2
547	75.129	ITG15 Caltanissetta	2

548	70.454	ITG14 Agrigento	2
549	62.256	ITG14 Agrigento	2
550	76.575	ITG11 Trapani	2
551	49.333	ITG11 Trapani	2
552	137.399	ITG11 Trapani	2
553	24.659	ITG11 Trapani	1
554	29.483	ITG12 Palermo	2
555	12.802	ITG14 Agrigento	1
556	140.536	ITG12 Palermo	1
557	3.240	ITG12 Palermo	1
558	7.426	ITG12 Palermo	1
559	26.581	ITG12 Palermo	1
560	10.025	ITG12 Palermo	2
561	77.170	ITG12 Palermo	2
562	46.017	ITG16 Enna	2
563	21.510	ITG16 Enna	2
564	3.306	ITG16 Enna	1
565	6.629	ITG12 Palermo	2
566	118.578	ITG12 Palermo	2
567	254.603	ITG12 Palermo	1
568	38.205	ITG18 Ragusa	2
569	3.377	ITG18 Ragusa	2
570	13.182	ITG18 Ragusa	1
571	17.722	ITG18 Ragusa	2
572	2.556	ITG19 Siracusa	3
573	85.568	ITG15 Caltanissetta	2
574	11.700	ITG13 Messina	2
575	98.302	ITG15 Caltanissetta	1
576	24.621	ITG11 Trapani	1
577	55.437	(No NUTS)	2
578	12.000	ES640 Melilla	3
579	63.322	GR434 Chania	3
580	66.138	GR431 Irakleio	3
581	43.035	GR432 Lasithi	2
582	125.228	MT001 Malta	3
583	14.399	ITG14 Agrigento	2
584	29.982	ES702 Santa Cruz de Tenerife	2
585	6.506	ES702 Santa Cruz de Tenerife	2
586	5.316	ES702 Santa Cruz de Tenerife	2
587	56.716	ES702 Santa Cruz de Tenerife	2
588	76.000	ES702 Santa Cruz de Tenerife	3
589	48.559	ES702 Santa Cruz de Tenerife	3
590	6.000	ES702 Santa Cruz de Tenerife	3
591	28.053	ES701 Las Palmas	1
592	34.000	ES702 Santa Cruz de Tenerife	3
593	99.004	ES702 Santa Cruz de Tenerife	2
594	40.856	ES702 Santa Cruz de Tenerife	2
595	83.070	ES701 Las Palmas	3
596	23.000	ES702 Santa Cruz de Tenerife	2
597	6.000	ES702 Santa Cruz de Tenerife	2
598	22.660	ES702 Santa Cruz de Tenerife	2
599	16.000	ES702 Santa Cruz de Tenerife	2
600	9.522	ES701 Las Palmas	2
601	32.884	ES701 Las Palmas	3
602	5.000	ES701 Las Palmas	1
603	13.328	ES701 Las Palmas	1
604	54.861	ES701 Las Palmas	2
605	8.000	ES701 Las Palmas	1
606	3.000	ES701 Las Palmas	3
607	6.000	ES701 Las Palmas	3
608	10.000	ES701 Las Palmas	2

609	2.000	ES701 Las Palmas	3
610	30.442	ES701 Las Palmas	2
611	159.678	ES701 Las Palmas	3
612	43.000	ES701 Las Palmas	3
613	21.000	ES701 Las Palmas	2
614	42.000	ES701 Las Palmas	2
615	3.779	ES701 Las Palmas	2
616	3.000	ES701 Las Palmas	1
617	161.566	ES701 Las Palmas	2
618	227.227	ES701 Las Palmas	1
619	20.139	ES701 Las Palmas	1

Tab. A9 – List of the STU for the PBR / fresh water – waste water plant type (Capability Class: 1 Low; 2 Mid; 3 High)

N STU	Area km2	NUTS3	Capability Class
1	6.592	ES114 Pontevedra	2
2	18.883	PT117 Douro	1
3	64.985	ITE43 Roma	3
4	3.471	ITE43 Roma	3
5	3.916	ITE43 Roma	3
6	3.079	ITF35 Salerno	2
7	2.000	ES422 Ciudad Real	1
8	25.187	ES422 Ciudad Real	1
9	17.472	ES422 Ciudad Real	1
10	28.543	ES422 Ciudad Real	1
11	17.958	GR144 Trikala	2
12	30.338	GR142 Larisa	3
13	8.963	GR233 Ileia	2
14	3.353	GR244 Fthiotida	2
15	3.669	ITG13 Messina	1
16	5.965	ITG13 Messina	2
17	30.368	ES511 Barcelona	3
18	17.680	ES512 Girona	2
19	12.253	ES512 Girona	3
20	31.691	ES511 Barcelona	3
21	55.613	ES511 Barcelona	3
22	9.205	ES521 Alicante / Alacant	3
23	4.845	ES523 Valencia / Valencia	2
24	3.416	ES523 Valencia / Valencia	2
25	11.065	ES521 Alicante / Alacant	3
26	31.816	ES523 Valencia / Valencia	3
27	3.480	ES425 Toledo	2
28	98.385	ES425 Toledo	2
29	45.348	ES425 Toledo	1
30	96.380	ES514 Tarragona	3
31	6.841	ES614 Granada	3
32	8.653	ES617 Malaga	3
33	17.702	ES612 Cadiz	3
34	10.207	ES615 Huelva	2
35	2.815	PT150 Algarve	3
36	24.982	ES615 Huelva	3
37	22.079	ES615 Huelva	3
38	24.887	ES615 Huelva	3
39	25.987	PT171 Grande Lisboa	3
40	35.943	PT162 Baixo Mondego	3
41	18.557	ES432 Caceres	2
42	17.767	ES425 Toledo	1
43	3.590	ES425 Toledo	1
44	40.117	ES425 Toledo	2
45	101.544	ES300 Madrid	3
46	6.053	ES300 Madrid	3
47	2.935	ES616 Jaén	1
48	31.658	ES616 Jaén	1
49	13.958	ES616 Jaén	1
50	4.119	ES514 Tarragona	3
51	33.015	ES514 Tarragona	3
52	4.523	ES241 Huesca	3
53	2.637	ES241 Huesca	2
54	4.600	ES243 Zaragoza	3
55	123.524	ES243 Zaragoza	3
56	153.716	ES241 Huesca	3
57	96.876	ES431 Badajoz	2
58	104.874	ES431 Badajoz	1
59	3.567	ES431 Badajoz	3

60	3.337	ES431 Badajoz	2
61	91.652	ES431 Badajoz	2
62	101.537	ES431 Badajoz	1
63	151.914	ES431 Badajoz	1
64	3.719	ES431 Badajoz	2
65	148.194	ES431 Badajoz	1
66	5.908	ES432 Caceres	2
67	88.914	ES432 Caceres	1
68	83.006	ES432 Caceres	1
69	34.373	ES514 Tarragona	3
70	35.588	PT16C Médio Tejo	2
71	15.724	ES618 Sevilla	2
72	15.360	ES618 Sevilla	2
73	43.910	ES618 Sevilla	2
74	3.650	ES618 Sevilla	1
75	259.381	ES618 Sevilla	3
76	7.672	PT184 Baixo Alentejo	2
77	30.142	ES431 Badajoz	2
78	23.420	PT181 Alentejo Litoral	1
79	6.669	PT171 Grande Lisboa	2
80	16.848	PT171 Grande Lisboa	2
81	160.492	ES613 Cordoba	2
82	159.649	ES613 Cordoba	2
83	99.672	ES613 Cordoba	1
84	113.884	ES613 Cordoba	2
85	118.234	ES616 Jaén	3
86	78.118	ES616 Jaén	2
87	113.686	ES613 Cordoba	2
88	116.375	ES616 Jaén	3
89	78.118	ES616 Jaén	2
90	4.360	ES431 Badajoz	2
91	11.514	ES431 Badajoz	2
92	27.650	PT185 Leziria do Tejo	3
93	3.477	ES432 Caceres	1
94	7.187	ES432 Caceres	1
95	19.373	ES432 Caceres	2
96	19.370	ES432 Caceres	2
97	3.031	ITG12 Palermo	2
98	13.166	ITG13 Messina	1
99	23.353	ITG13 Messina	1
100	8.827	ITG13 Messina	1
101	22.028	ITG13 Messina	2
102	10.304	ITG13 Messina	3
103	17.278	ITG13 Messina	2
104	41.263	ITG13 Messina	3
105	31.962	ITG13 Messina	2
106	33.516	ITG13 Messina	2
107	8.256	ITG11 Trapani	3
108	2.398	ITG12 Palermo	3
109	5.762	ITE16 Livorno	3
110	2.106	ITE44 Latina	3
111	10.894	ITF31 Caserta	3
112	3.151	ITF33 Napoli	3
113	15.905	ITG21 Sassari	3
114	8.480	ITF44 Brindisi	3
115	3.839	ES421 Albacete	2
116	4.508	ES521 Alicante / Alacant	3
117	12.139	ITG24 Cagliari	2
118	5.947	ITG24 Cagliari	2
119	6.441	ITG24 Cagliari	2
120	2.837	ITG24 Cagliari	2

121	7.943	ES514 Tarragona	3
122	9.353	ES511 Barcelona	3
123	3.816	ES620 Murcia	2
124	8.095	ES620 Murcia	3
125	5.625	ES620 Murcia	3
126	4.431	ES620 Murcia	3
127	6.214	ES620 Murcia	2
128	6.141	ES620 Murcia	3
129	7.783	ES522 Castellon	3
130	7.356	ES521 Alicante / Alacant	3
131	9.666	ES523 Valencia / Valencia	3
132	8.900	ES523 Valencia / Valencia	3
133	11.133	ES523 Valencia / Valencia	3
134	6.040	ES521 Alicante / Alacant	3
135	7.239	ES521 Alicante / Alacant	3
136	2.942	ES521 Alicante / Alacant	3
137	6.585	ES521 Alicante / Alacant	3
138	10.928	ES521 Alicante / Alacant	3
139	6.777	ES620 Murcia	2
140	5.786	ES521 Alicante / Alacant	3
141	23.194	ES521 Alicante / Alacant	3
142	3.904	ES620 Murcia	3
143	19.197	ES425 Toledo	2
144	3.130	ES425 Toledo	2
145	2.839	ES425 Toledo	2
146	46.316	ES431 Badajoz	1
147	35.658	ES616 Jaén	1
148	24.675	ES616 Jaén	2
149	4.006	ES514 Tarragona	3
150	7.513	ES611 Almeria	2
151	7.889	ES617 Malaga	3
152	5.619	ES612 Cadiz	1
153	4.329	ES612 Cadiz	2
154	5.695	ES612 Cadiz	1
155	5.288	ES615 Huelva	1
156	6.164	ES615 Huelva	1
157	5.316	ES615 Huelva	1
158	4.145	ES615 Huelva	3
159	6.179	ES615 Huelva	1
160	2.817	ES615 Huelva	2
161	10.276	ES615 Huelva	3
162	8.682	ES615 Huelva	3
163	4.264	PT150 Algarve	3
164	3.735	PT150 Algarve	3
165	11.050	ES432 Caceres	3
166	5.168	ES432 Caceres	3
167	13.550	ES432 Caceres	3
168	7.523	ES432 Caceres	3
169	6.644	ES432 Caceres	3
170	10.484	ES432 Caceres	1
171	72.440	ES432 Caceres	2
172	11.016	ES411 Avila	2
173	24.089	ES425 Toledo	2
174	8.878	ES425 Toledo	2
175	22.282	ES425 Toledo	1
176	2.699	ES425 Toledo	3
177	27.461	ES425 Toledo	2
178	64.243	ES432 Caceres	3
179	6.334	ES432 Caceres	1
180	7.487	ES432 Caceres	1
181	2.766	ES432 Caceres	1

182	6.410	ES432 Caceres	1
183	27.369	ES432 Caceres	3
184	46.825	ES432 Caceres	1
185	14.180	ES432 Caceres	3
186	10.863	ES432 Caceres	3
187	8.203	ES432 Caceres	3
188	10.608	ES432 Caceres	2
189	5.700	ES432 Caceres	1
190	6.732	ES432 Caceres	2
191	8.984	ES432 Caceres	2
192	4.866	ES432 Caceres	1
193	3.689	ES432 Caceres	2
194	3.932	ES432 Caceres	1
195	2.750	ES431 Badajoz	1
196	4.044	ES616 Jaén	1
197	32.773	ES614 Granada	2
198	6.433	ES614 Granada	2
199	25.334	ES613 Cordoba	1
200	3.968	ES614 Granada	1
201	4.087	ES614 Granada	1
202	8.928	ES620 Murcia	3
203	4.659	ES421 Albacete	1
204	11.625	ES523 Valencia / Valencia	3
205	6.303	ES522 Castellon	3
206	28.524	ES514 Tarragona	3
207	22.153	ES243 Zaragoza	3
208	11.045	ES243 Zaragoza	3
209	41.954	ES243 Zaragoza	1
210	5.737	ES243 Zaragoza	3
211	7.594	ES513 Lleida	2
212	7.798	ES513 Lleida	2
213	8.619	ES612 Cadiz	1
214	9.924	ES617 Malaga	1
215	6.422	ES618 Sevilla	1
216	6.173	ES617 Malaga	1
217	20.335	ES617 Malaga	2
218	6.001	ES617 Malaga	2
219	3.288	ES613 Cordoba	2
220	4.455	ES613 Cordoba	2
221	6.314	ES613 Cordoba	2
222	2.449	ES613 Cordoba	3
223	5.797	ES618 Sevilla	2
224	3.937	ES431 Badajoz	1
225	2.889	ES431 Badajoz	1
226	4.651	ES432 Caceres	1
227	7.158	ES431 Badajoz	1
228	4.458	ES431 Badajoz	1
229	52.242	ES431 Badajoz	3
230	2.107	ES431 Badajoz	1
231	25.850	ES431 Badajoz	3
232	6.077	ES431 Badajoz	1
233	6.902	ES431 Badajoz	3
234	7.374	ES431 Badajoz	3
235	12.792	ES431 Badajoz	1
236	3.589	ES431 Badajoz	1
237	7.263	ES613 Cordoba	2
238	5.707	ES422 Ciudad Real	1
239	6.806	ES422 Ciudad Real	2
240	8.572	ES432 Caceres	1
241	16.943	ES432 Caceres	2
242	2.204	ES613 Cordoba	1

243	33.011	ES613 Cordoba	1
244	3.108	ES613 Cordoba	1
245	48.561	ES431 Badajoz	1
246	11.343	ES612 Cadiz	2
247	6.201	ES431 Badajoz	1
248	9.405	ES618 Sevilla	1
249	23.249	ES432 Caceres	3
250	8.917	ES432 Caceres	1
251	7.857	ES422 Ciudad Real	1
252	8.286	ES612 Cadiz	1
253	5.569	ES612 Cadiz	1
254	7.328	ES612 Cadiz	2
255	14.417	ES618 Sevilla	2
256	6.951	ES618 Sevilla	1
257	4.611	ES618 Sevilla	1
258	11.480	ES615 Huelva	2
259	11.024	ES618 Sevilla	2
260	5.368	ES618 Sevilla	2
261	6.064	ES618 Sevilla	2
262	8.700	ES618 Sevilla	1
263	17.144	ES618 Sevilla	2
264	5.593	ES618 Sevilla	1
265	5.022	ES615 Huelva	2
266	11.022	ES615 Huelva	1
267	7.317	ES615 Huelva	2
268	6.980	ES615 Huelva	3
269	11.192	ES615 Huelva	2
270	8.608	ES615 Huelva	2
271	6.809	ES615 Huelva	3
272	8.495	ES615 Huelva	2
273	5.249	ES615 Huelva	1
274	16.447	ES615 Huelva	1
275	6.086	PT184 Baixo Alentejo	3
276	7.715	PT184 Baixo Alentejo	2
277	5.258	PT184 Baixo Alentejo	1
278	5.985	PT184 Baixo Alentejo	1
279	16.753	ES431 Badajoz	1
280	5.351	PT183 Alentejo Central	2
281	16.559	ES431 Badajoz	2
282	10.640	ES431 Badajoz	1
283	18.015	ES431 Badajoz	1
284	13.162	ES431 Badajoz	1
285	6.062	ES432 Caceres	2
286	4.179	ES612 Cadiz	2
287	15.760	ES612 Cadiz	1
288	41.967	ES612 Cadiz	2
289	11.856	ES611 Almeria	1
290	5.579	ES618 Sevilla	2
291	5.256	ES618 Sevilla	1
292	3.597	ES618 Sevilla	1
293	10.077	ES613 Cordoba	3
294	14.670	ES613 Cordoba	3
295	3.975	ES613 Cordoba	2
296	7.243	ES618 Sevilla	1
297	11.068	ES616 Jaén	2
298	37.970	ES616 Jaén	2
299	2.752	ES616 Jaén	3
300	3.052	ES616 Jaén	1
301	10.456	ES613 Cordoba	2
302	2.203	ES431 Badajoz	1
303	9.130	ES431 Badajoz	2

304	6.739	ES422 Ciudad Real	1
305	45.698	ES431 Badajoz	1
306	28.743	ES431 Badajoz	2
307	32.214	ES431 Badajoz	2
308	5.362	ES431 Badajoz	2
309	74.545	ES431 Badajoz	3
310	10.954	ES432 Caceres	1
311	7.798	ES432 Caceres	2
312	6.062	ES432 Caceres	2
313	6.000	ES432 Caceres	1
314	25.455	ES432 Caceres	1
315	6.741	PT16C Médio Tejo	3
316	48.912	ES432 Caceres	3
317	3.578	ES432 Caceres	1
318	36.389	ES432 Caceres	1
319	5.908	ES432 Caceres	1
320	30.045	ES432 Caceres	1
321	7.462	ITG17 Catania	3
322	6.112	ITG19 Siracusa	2
323	5.801	ITG19 Siracusa	2
324	8.952	ITG19 Siracusa	2
325	14.624	ITG16 Enna	1
326	21.757	ITG16 Enna	1
327	5.294	ITG16 Enna	3
328	6.042	ITG14 Agrigento	1
329	6.135	ITG14 Agrigento	1
330	7.659	ITG14 Agrigento	1
331	10.552	ITG14 Agrigento	1
332	2.189	ITG12 Palermo	3
333	15.212	ITG12 Palermo	1
334	9.331	ITG11 Trapani	2
335	12.732	ITG14 Agrigento	1
336	7.343	ITG12 Palermo	1
337	17.665	ITG12 Palermo	1
338	3.968	ITG13 Messina	3
339	6.295	ITG17 Catania	2
340	7.339	ITG11 Trapani	2
341	9.938	ITG16 Enna	1
342	2.189	ITG15 Caltanissetta	1
343	6.588	ITG15 Caltanissetta	3

ANNEX 2
STU MAPS

Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Best Siting Suitability Maps – Annex 2

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STU MAPS

The following figures illustrate the maps produced for the Site Territorial Units at European level.

In each map, it shall be noted that Red means high capability, Orange mid capability and Yellow low capability.

Figure 1: STU Classified into Capability Classes for Open Ponds / Seawater Systems, Spain and Portugal area

Figure 2: STU Classified into Capability Classes for Open Ponds / Seawater Systems, Italy area

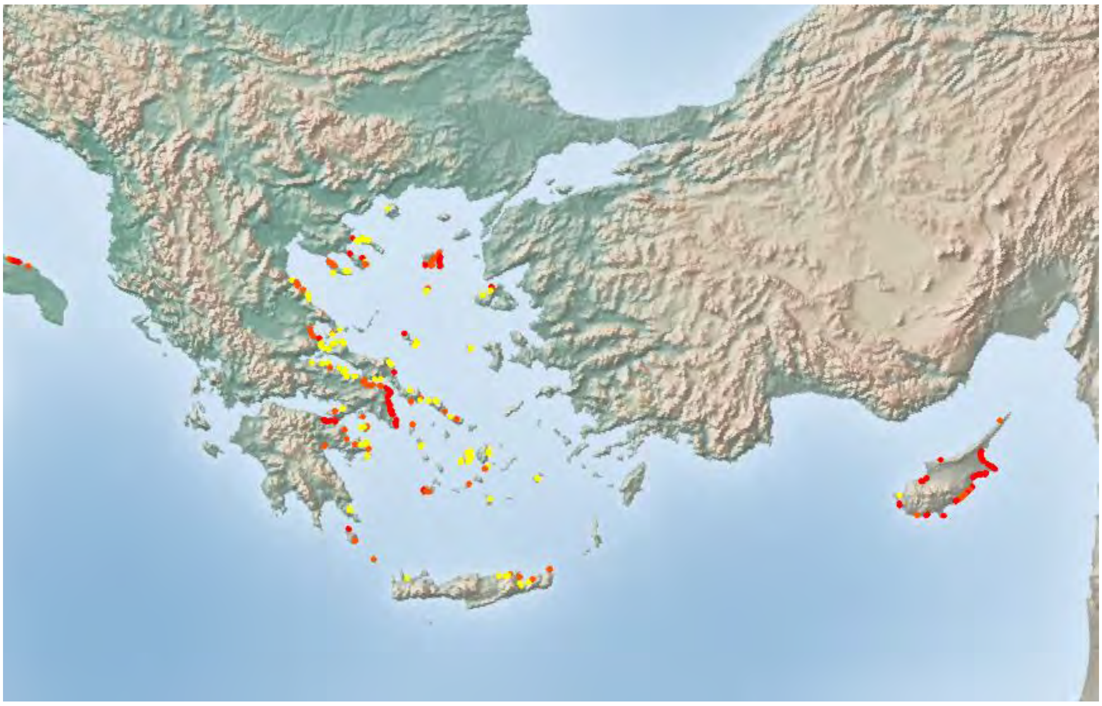

Figure 3: STU Classified into Capability Classes for Open Ponds / Seawater Systems, Greece and Cyprus Area

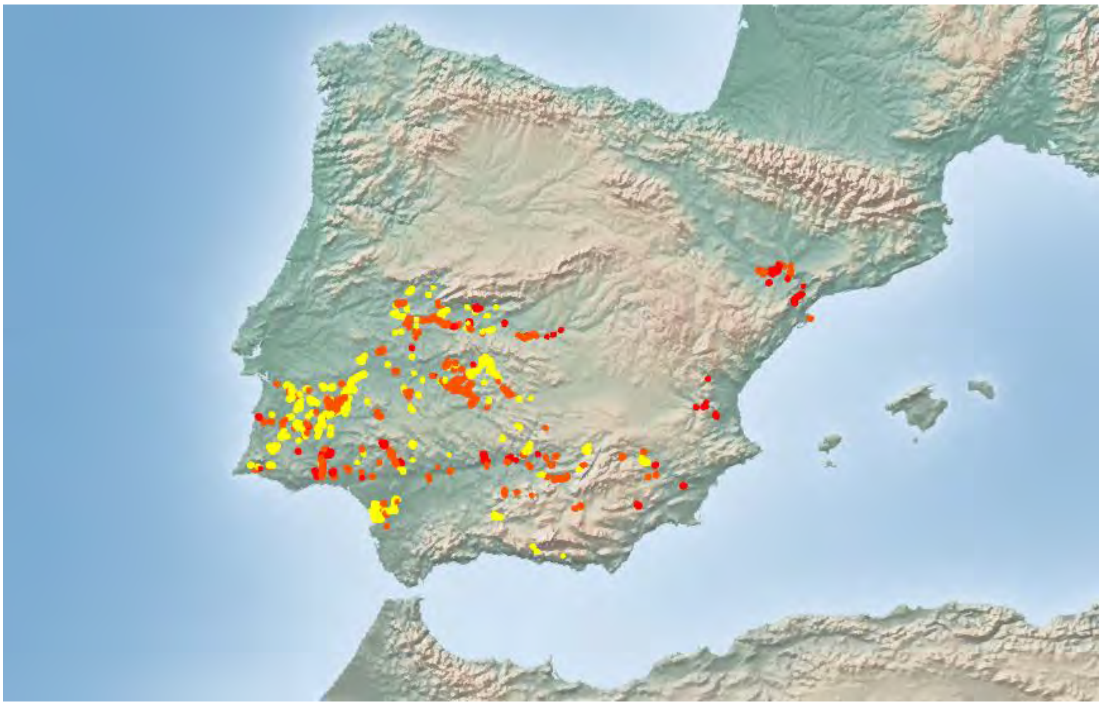

Figure 4: STU Classified into Capability Classes for Open Ponds / Fresh Water Systems, Spain and Portugal area

Figure 5: STU Classified into Capability Classes for Open Ponds / Fresh Water Systems, Italy area

Figure 6: STU Classified into Capability Classes for Open Ponds / Fresh Water Systems, Greece and Cyprus area

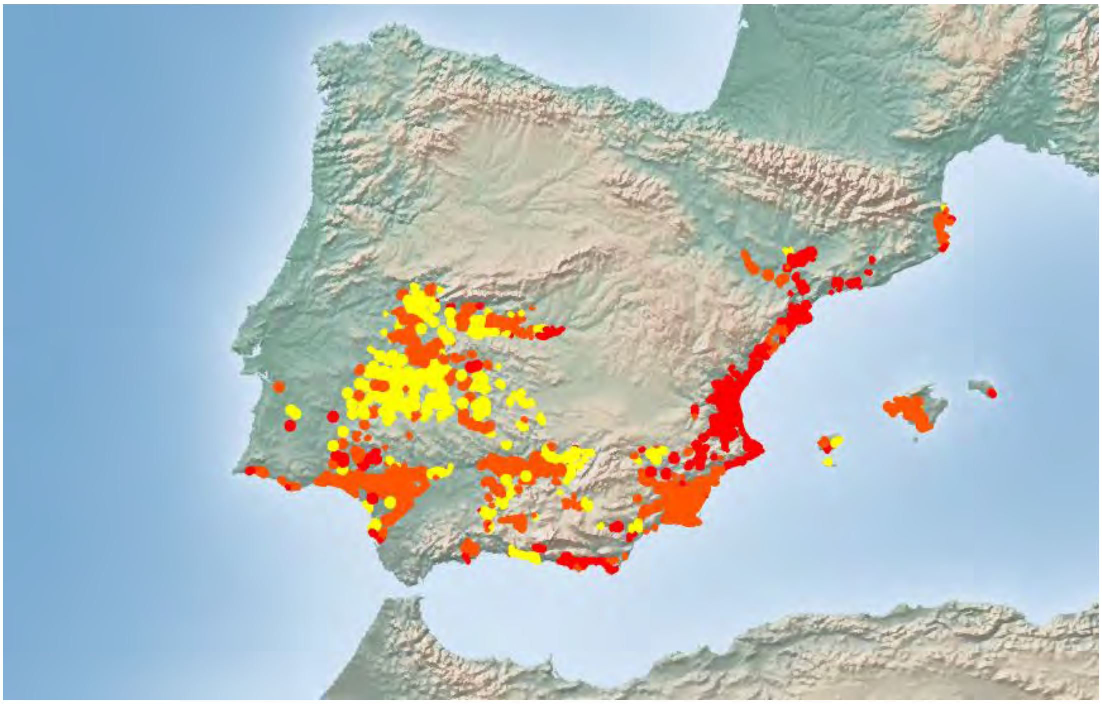

Figure 7: STU Classified into Capability Classes for Open Ponds / Waste Water systems, Spain and Portugal Area

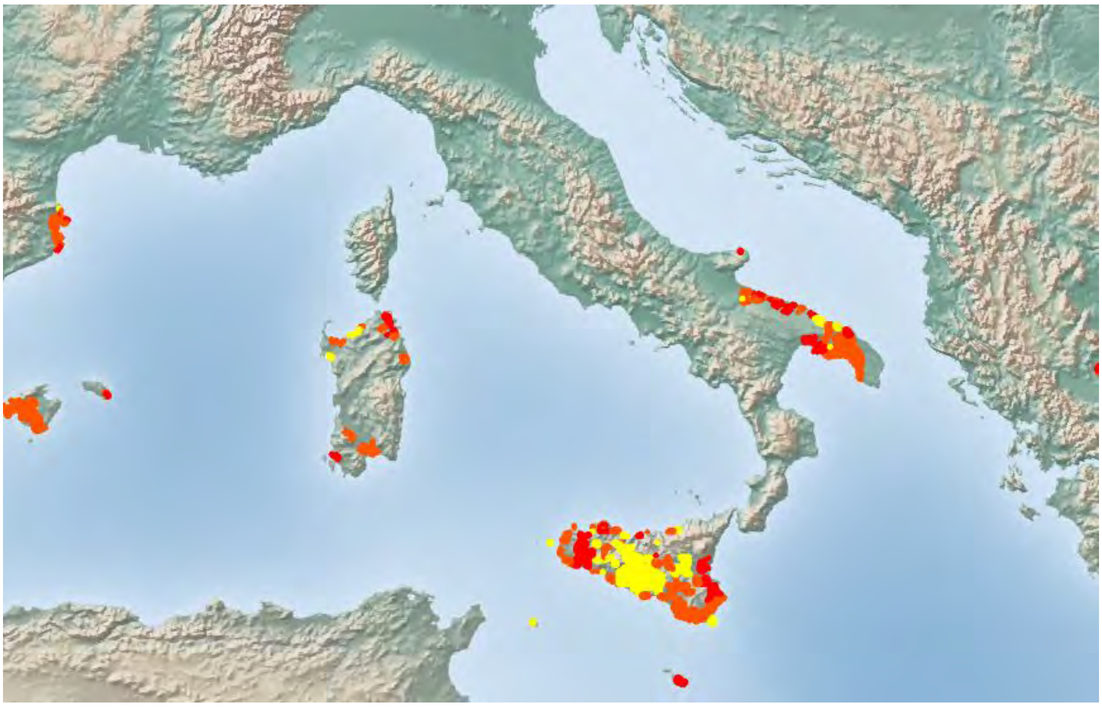

Figure 8: STU Classified into Capability Classes for Open Ponds / Waste Water systems, Italy Area

Figure 9: STU Classified into Capability Classes for Open Ponds / Waste Water Systems, Greece and Cyprus Area

Figure 10: STU Classified into Capability Classes for Open Ponds / Sea Water – Waste Water Systems, Spain and Portugal Area

Figure 11: STU Classified Into Capability Classes for Open Ponds / Sea Water - Waste Water Systems, Italy Area

Figure 12: STU Classified into Capability Classes for Open Ponds / Sea Water - Waste Water Systems, Greece and Cyprus Area

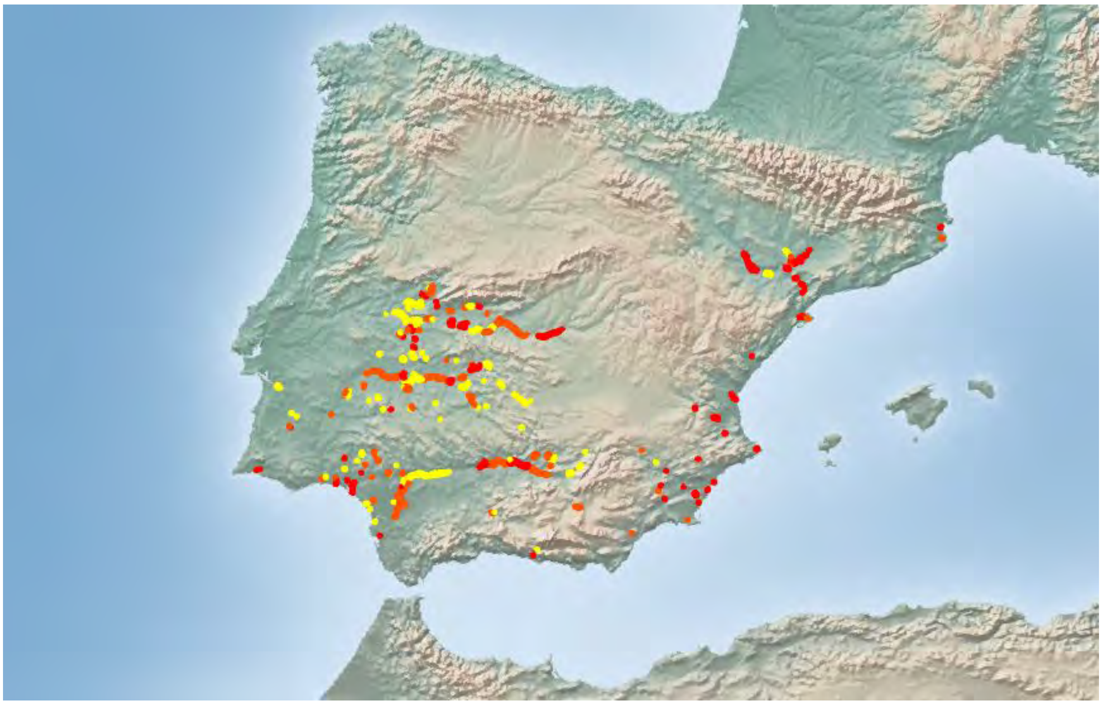

Figure 13: STU classified into Capability Classes for Open Ponds / Fresh Water - Waste Water Systems, Spain and Portugal Area

Figure 14: STU Classified into Capability Classes for Open Ponds / Fresh Water - Waste Water Systems, Italy Area

Figure 15: STU Classified into Capability Classes for Open Ponds / Fresh Water - Waste Water Systems, Greece and Cyprus Area

Figure 16: STU Classified Into Capability Classes for PBR / sea Water Systems, Spain and Portugal Area

Figure 17: STU Classified into Capability Classes for PBR / Sea Water Systems, Italy Area

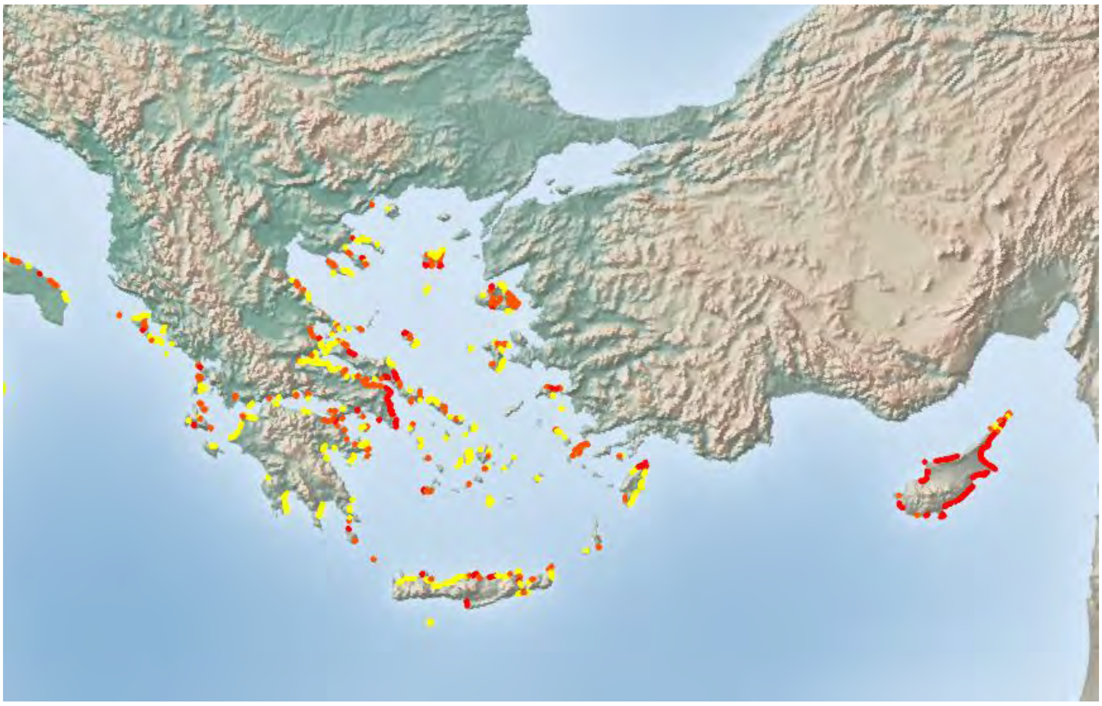

Figure 18: STU Classified into Capability Classes for PBR / sea Water Systems, Greece and Cyprus Area

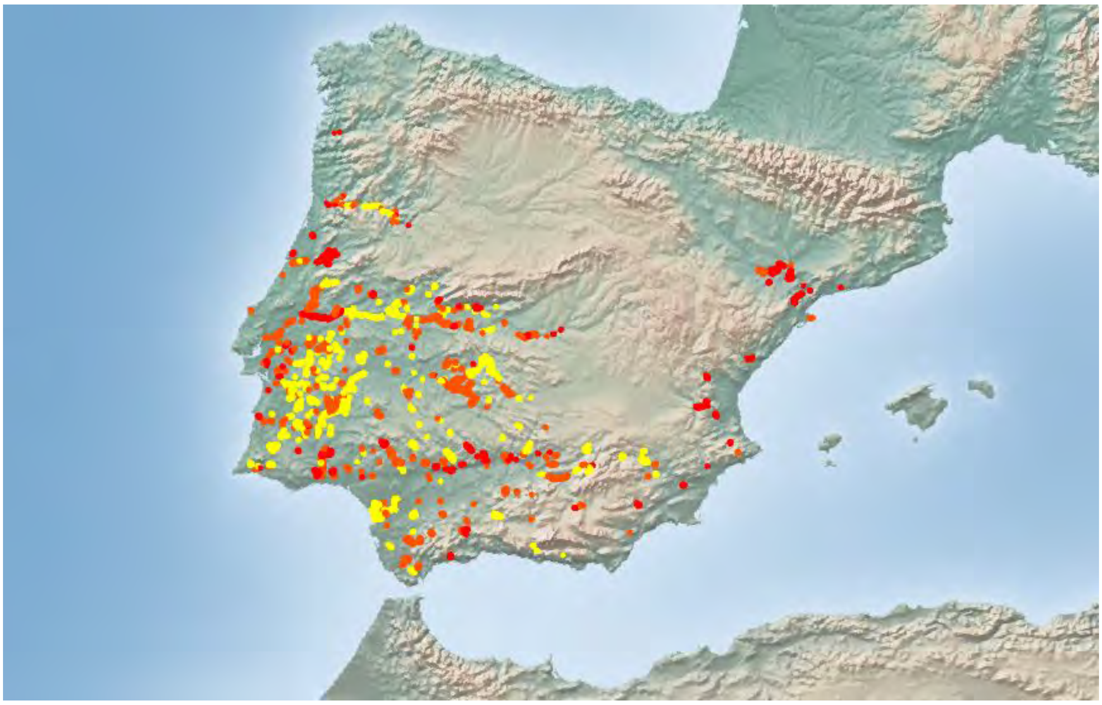

Figure 19: Classified into Capability Classes for PBR / Fresh Water Systems, Spain and Portugal Area

Figure 20: Classified into Capability Classes for PBR / Fresh Water Systems, Italy Area

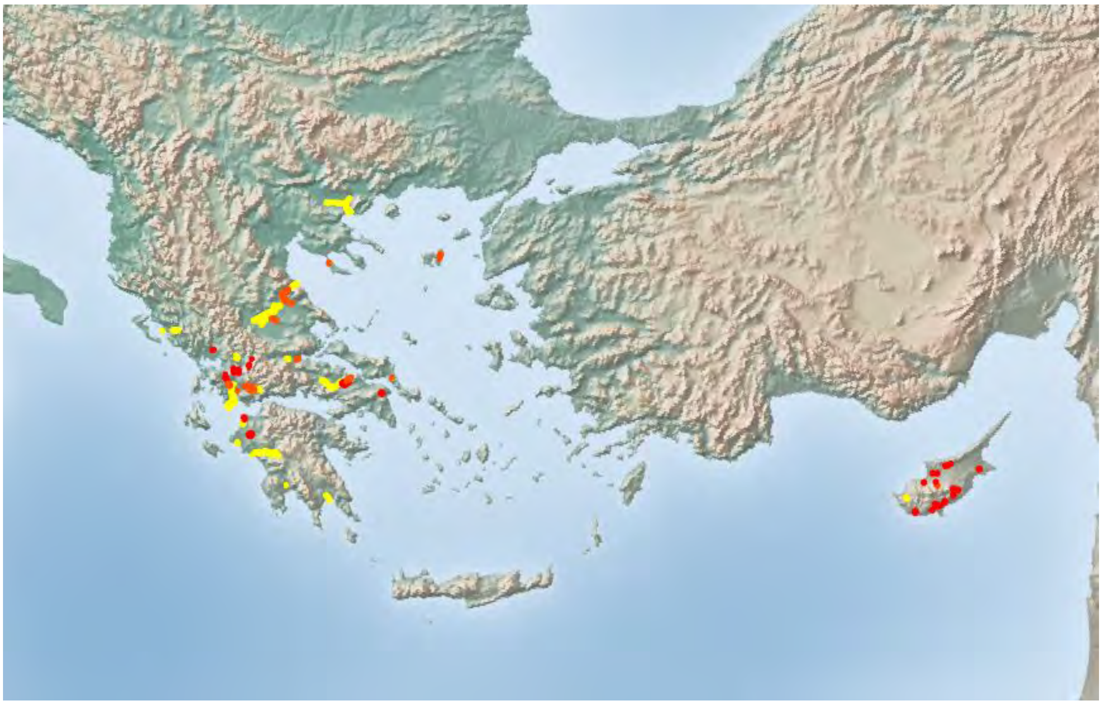

Figure 21: STU Classified into Capability Classes for PBR / Fresh Water Systems, Greece and Cyprus Area

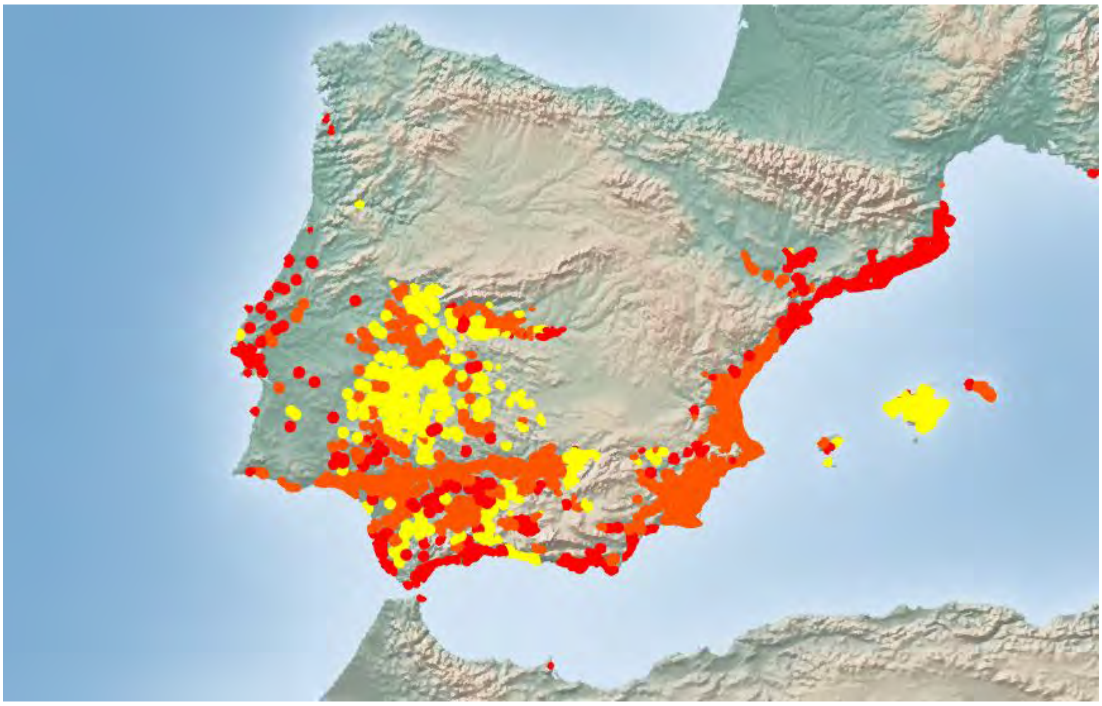

Figure 22: STU Classified into Capability Classes for PBR / Waste Water Systems, Spain and Portugal Area

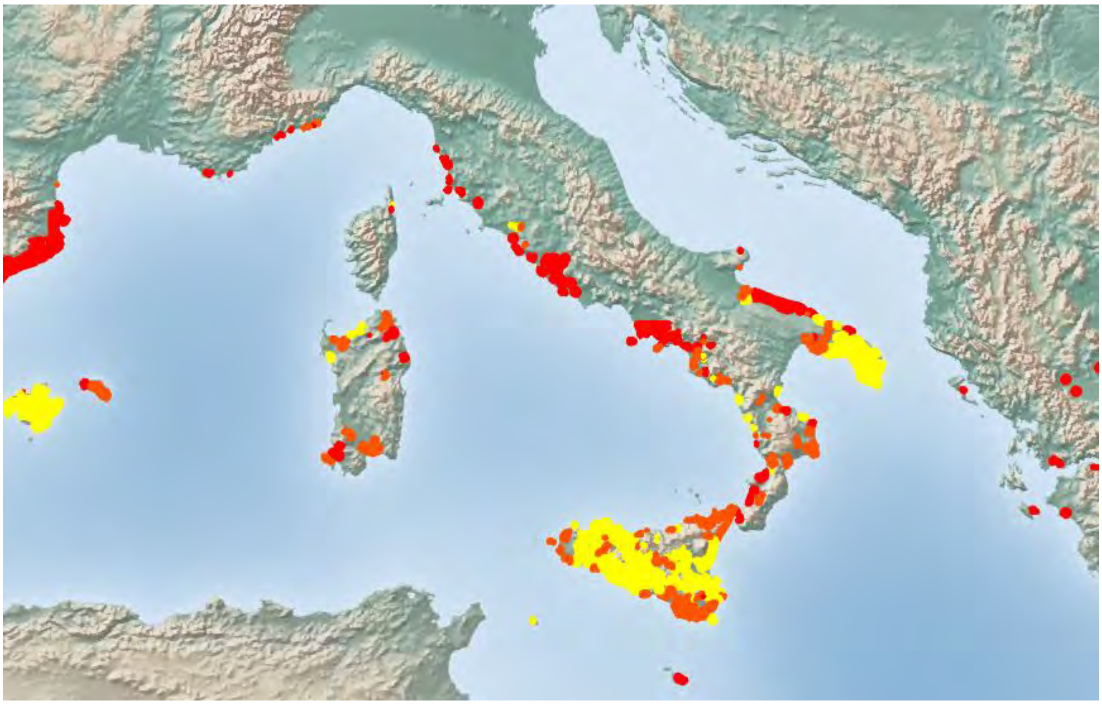

Figure 23: STU Classified into Capability Classes for PBR / Waste Water Systems, Italy Area

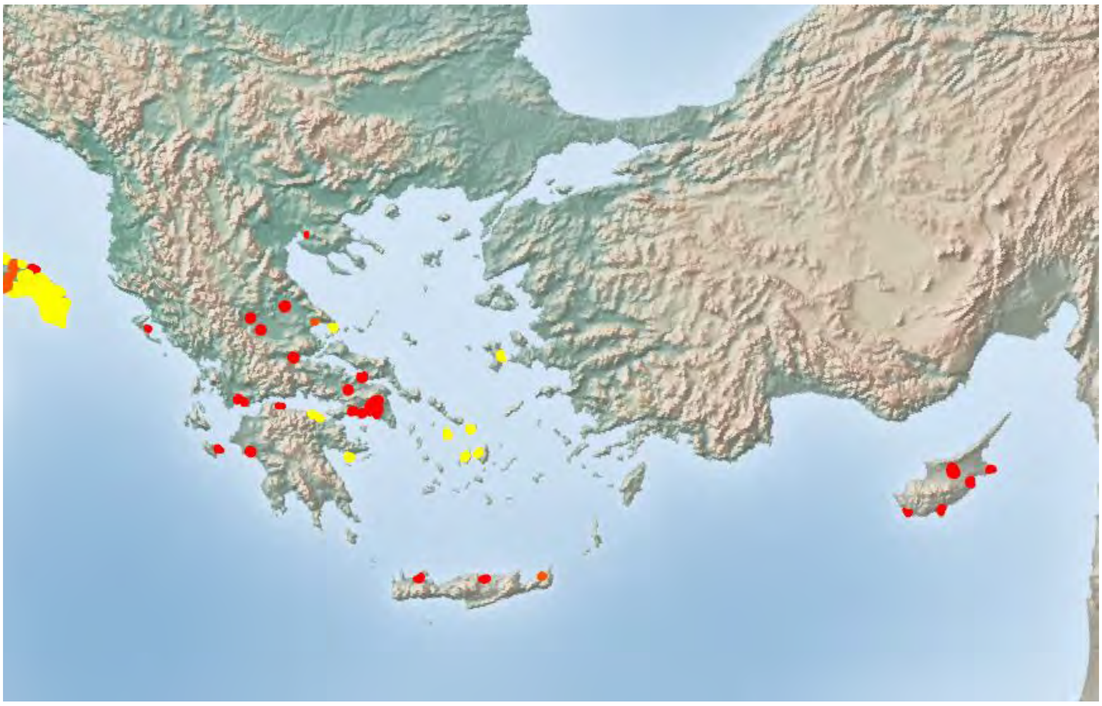

Figure 24: STU Classified into Capability Classes for PBR / Waste Water Systems, Greece and Cyprus Area

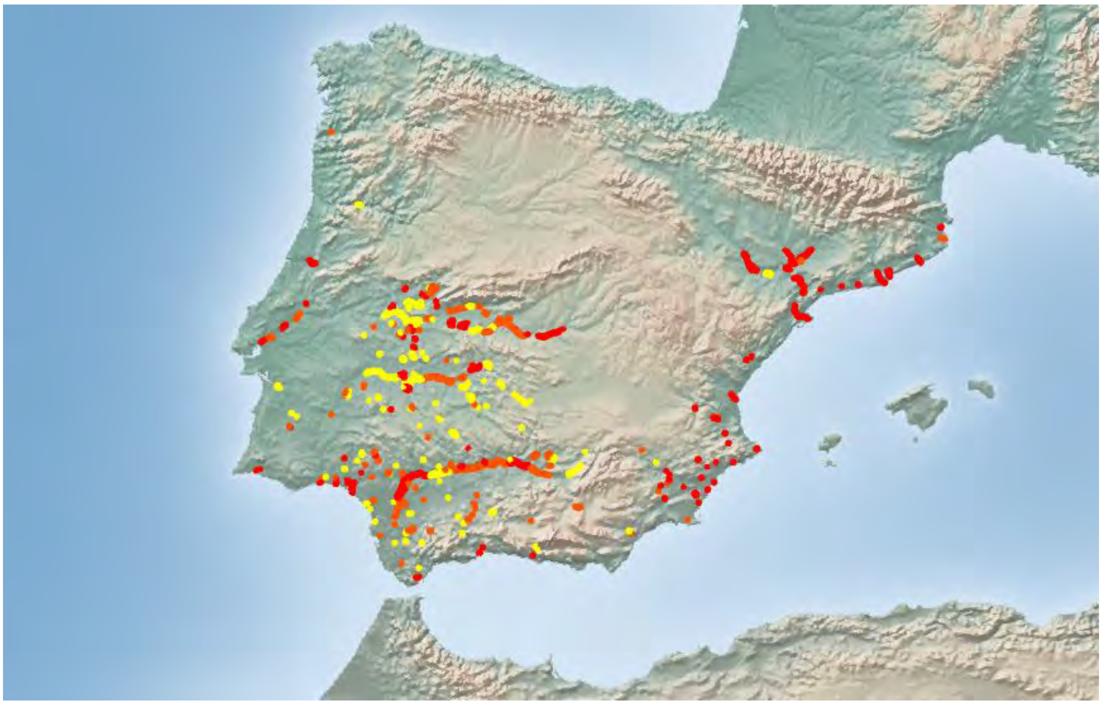

Figure 25: STU Classified into Capability Classes for PBR / FRESH Water - waste Water Systems, Spain and Portugal Area

Figure 26: STU Classified into Capability Classes for PBR / Fresh Water - Waste Water Systems, Italy Area

Figure 27: STU Classified into Capability Classes for PBR / Fresh Water - Waste Water Systems, Greece and Cyprus Area

APPENDIX D

**TECHNICAL REPORT
APPROACH TO THE LCA**

Doc. No. 12-920-H3
Rev. 1 – JUNE 2015

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

LCA Approach

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LCA APPROACH

D.1 INTRODUCTION ON LCA APPROACH

Scope of this report is the presentation of the methodological approach to the Life Cycle Assessment (LCA) that will be adopted for the relevant tasks of the Project.

The LCA is a methodology for identification and evaluation of the environmental impacts of a product or a service.

LCA addresses the environmental aspects and potential environmental impacts (e.g. use or resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e.: cradle-to-grave).

There are four phases in an LCA study:

a. the goal and scope definition phase;
b. the inventory analysis phase;
c. the impact assessment phase;
d. the interpretation phase.

The environmental impacts to consider and to address are not only the ones related to the production phase but also those associated to upstream and downstream activities.

Figure D.1.1: Cradle to Grave Concept

The life cycle considers all the processes related to the operation of a product: from the extraction of raw materials through production, use and maintenance, till reuse and final disposal of waste.

The environmental impacts through the full life cycle consist of all the substances taken from the environment (input) and of the emissions released into the environment (output).

The LCA evaluates the impacts using several categories of impact that describe the effects on the environment. These impacts are evaluating by the identification and the quantification of data related to:

- raw materials consumptions;
- energy consumptions;
- waste generation;
- emissions (air, water and soil).

The results of LCA are useful to:

- describe the overall environmental impact of a product;
- compare the environmental impacts of different products with the same function;
- identify the steps of a life cycle having higher environmental impacts;
- support the design of new products or services;
- draw strategies to adopt to improve the environmental performance.

The international standards which a LCA relies on are part of the ISO 14000 "Environmental Management – Life Cycle Assessment; LCA standards are ISO 14040:2006 "Principles and framework" and ISO 14044:2006 "Requirements and guidelines".

The reference guidance at international level for the LCA is the handbook issued by the Joint Research Centre (JRC) of the European Commission "ILCD Handbook – General guide for Life Cycle Assessment - Detailed Guidance". The document draws the path to follow for a LCA study, as explained in the following chapters of the present document. When dealing with the impact assessment, a second guidance document from the JRC has high relevance, the handbook "Recommendations for Life Cycle Impact Assessment in the European context".

D.2 KEY STEPS FOR A LCA

The following chart illustrates the four key steps of a LCA, the presented with more details in the Chapters and sub-chapters from 2.1 to 2.4.

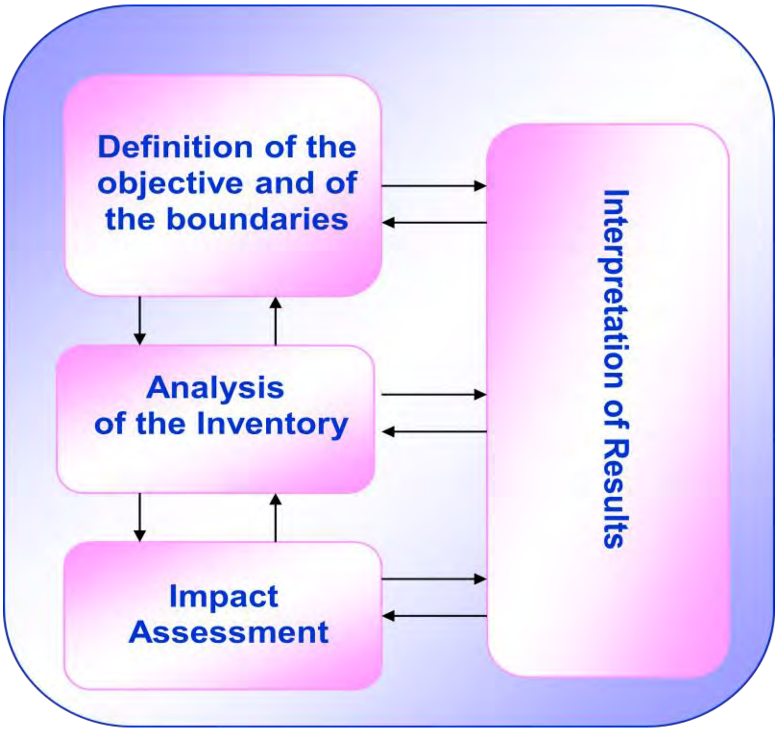

Figure D.2.1: Framework for LCA (from ISO 14040:2006)

D.2.1 DEFINITION OF THE OBJECTIVE AND OF THE BOUNDARIES

This phase requires the definition of the needs to address:

- comparison of products or relationships between a product and a standard (e.g.: environmental labels)?;
- enhancement of the environmental aspects of a product or design of a new product?;
- to answer specific strategic questions related to the market position of a company or to get information on a product.

What is needed to settle accurately are the foreseen applications and the beneficiaries of the study.

D.2.1.1 Initial Boundaries of the System

Before the analysis starts it is needed:

- to define the processes included in the life cycle of the analyzed system;
- to spot the phases, processes or data that can be dismissed.

All data must be referred to a functional unit, that must be defined.

D.2.1.2 Data Quality Requisites

The assessment must indicate:

- factors related to time, geography and technologies;
- precision, completeness and representativeness of data;
- consistency and replicability of the methodologies for data collection;
- data sources and representativeness;
- uncertainty of information.

D.2.2 ANALYSIS OF THE INVENTORY (LIFE CYCLE INVENTORY)

This is the core of LCA and it is the most time-demanding step. The reliability of the results of a study strictly depends on the data used in this phase.

The Inventory is a list of all the flows of input and output materials at the process units composing the system.

In this phase some key-steps can be identified:

1. definition of the flowchart;
2. data gathering;
3. allocation of impacts;
4. management of data and use of proper software.

Each step is described below.

D.2.2.1 Flowchart

It is a qualitative representation of all the relevant processes involved in life cycle of the system under assessment. Its main goal is to provide a overview of the most relevant processes and environmental interventions.

In order to create the flowchart of the process:

- to identify the main processes for the core activity;
- to add initial and final phases (resources, components, auxiliary consumptions, wastes);
- to combine processes or to split them, as more appropriate.

D.2.2.2 Data Gathering

Typical data sources and respective relevant hints to consider are presented below in the summary table:

Table D.2.1: Data Gathering Process

Source of data	Relevant aspects
real processes (plant, production sites, etc.)	Questionnaires, reports, technical manuals, etc.
models or estimates	Process models, projections, etc.
databases from literature	Transparency, Prices, Copyright, Applicability
databases and other confidential reports	Secrecy, applicability, transparency

D.2.2.3 Allocation

It is not always easy to gather data referred to a single product. Typical information is referred to a whole production process; it is important to allocate impacts to the single pieces of a process (for example: it is common to have aggregated data for the whole production process of a product, in say ton/year, and it is important to convert it into kg/piece).

D.2.2.4 Management of Data

The actions to carry out for a effective management of the gathered data are:

- to transform data into a proper format for further processing;
- to calculate the specific quantities/sizes of the relevant components of the system under assessment;
- to make the correct sums and balances of the environmental impacts.

D.2.2.5 Dedicated Software

The sector specific software contain all the useful databases that allow to create the expected balances; so, a software is provided with specific databases for: raw materials, fuels, transport systems, waste management systems, etc.

They also are able to handle typical processes, using pre-configured blocks for the most typical industrial applications.

The outcomes are in the form of tables and charts where input and output information is presented along with the respective flows.

D.2.3 EVALUATION OF IMPACTS (LIFE CYCLE IMPACT ASSESSMENT – LCIA)

Scope of this step is to evaluate the effect of potential environmental impacts, through the interpretation of the results of the Inventory Analysis.

The LCIA makes a conversion of every flow identified in the Inventory into a “impact”. The impact is represented by a set of parameters apt to define the environmental behavior of a product or of a process. The information provided by the impact is a relative evaluation (i.e.: not an absolute definition), due to the fact that it is tailored to a “functional unit”.

How to calculate the impacts:

As anticipated, all the inventory data, both input and output, are correlated with the environmental impacts. Several categories of impact can be listed, as indicated in the chart below.

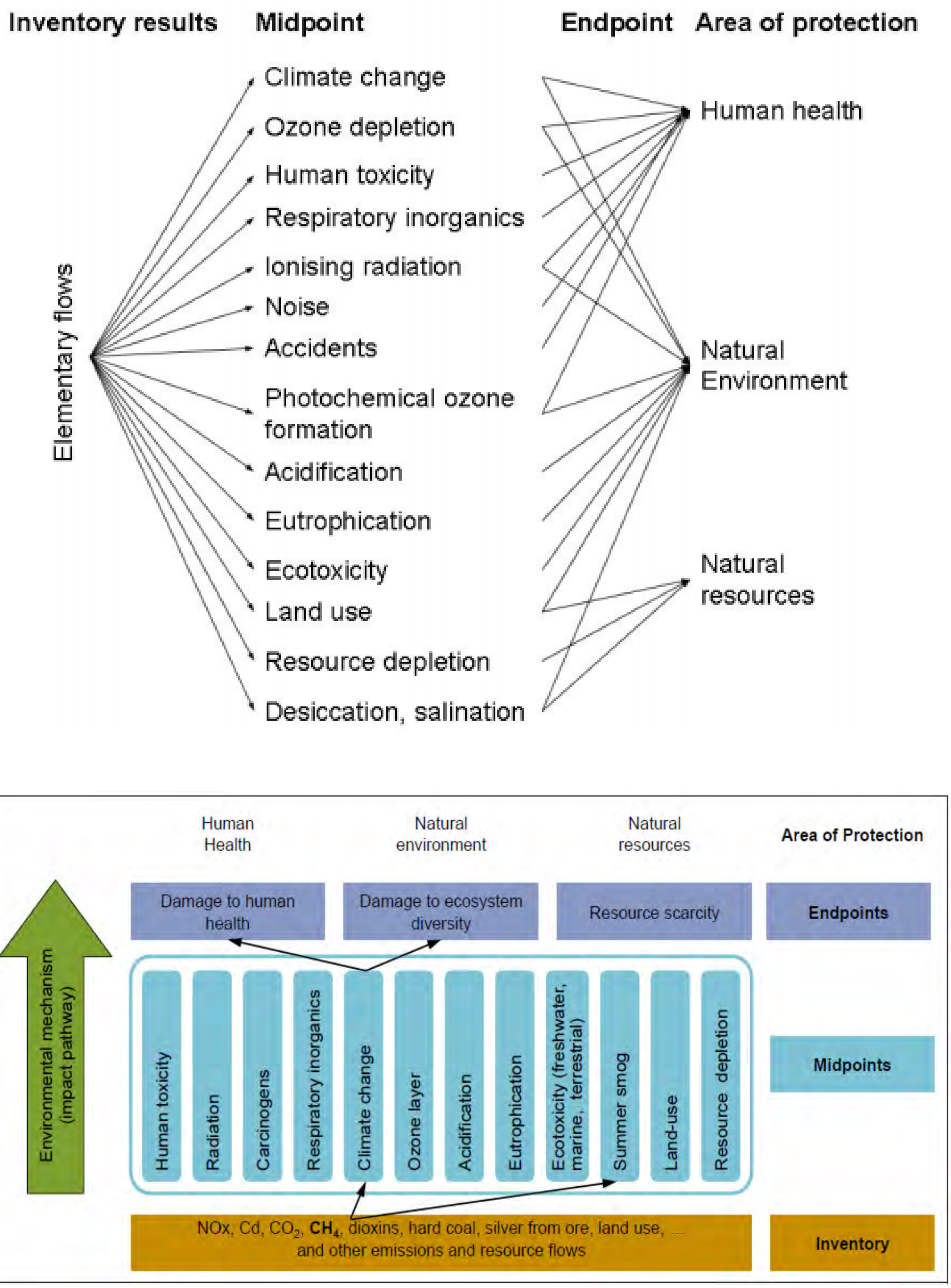

Figure D.2.2: LCIA Process and Indicators

D.2.3.1 Normalization

Normalization is a way to relate to a common reference the different characterized impact scores. The values obtained for the environmental impacts are related to a common reference, the same for every category. This is a optional step in a LCA analysis.

It is useful for an eased interpretation of results, in terms of:

- to understand the respective importance of each indicator;
- to provide indications on significance of impacts;
- to ease the acknowledgment of results.

D.2.3.2 Weighting

There are cases in which the adoption of a unique score is preferable to a set of values hard to compare one to each other. This is, in particular, helpful for products having very different environmental profiles.

Adopting “weights” for each environmental impact and then applying them to the measured values can help obtain a reliable index of the total impact.

The definition of the Weighting from IRC is: “Where a ranking and/or weighting is performed of the different environmental impact categories reflecting the relative importance of the impacts considered in the study.”

D.2.4 INTERPRETING THE RESULTS

The Interpretation phase of an LCA has two main purposes:

- during the iterative steps of the LCA and for all kinds of deliverables, the interpretation phase serves to steer the work towards improving the Life Cycle Inventory and review the scope and goal definition and the LCIA;
- if the iterative steps of the LCA have resulted in the final LCI model and results, the interpretation phase serves to derive robust conclusions and recommendations.

The results, duly checked and evaluated, will say if there is final consistency with the objectives, if the assessment is complete, if recommendations can be raised.

APPENDIX E

TECHNICAL REPORT
ALGAE CULTIVATION SYSTEMS DEPLOYMENT ANALYSIS

Doc. No. 12-920-H3
Rev. 1 – JUNE 2015

D'APPOLONIA
consulting, design, operation & maintenance engineering

UNIVERSITÀ DEGLI STUDI DI PADOVA

SELC biologia e geologia applicate

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Algae Cultivation Systems Deployment Analysis

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ABBREVIATIONS AND ACRONYMS

C	Centrifugation
FI	Filtration
FL	Flocculation
FT	Flotation
FW	Freshwater
GMP	Good Manufacturing Practice, following ISO and EC guidelines
GS	Gravity Sedimentation
GWP	Global Warming Potential
HL	Hydrothermal Liquefaction
HRAP	High Rate Algal Pond
OP	Open Pond
PBR	Photobioreactor
SD	Solar Drying
SE	Solvent Extraction
SFE	Supercritical Fluid Extraction
SW	Seawater
UA	Ultrasonic Aggregation
WW	Wastewater

SUMMARY REPORT
ALGAE BIOENERGY SITING,
COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS
ALGAE CULTIVATION SYSTEMS DEPLOYMENT ANALYSIS

E.1 INTRODUCTION

This Report summarizes the results of the SWOT analysis on microalgae cultivation systems, performed within Work Package 1.3 of the Project.

A detailed overview of the Project schedule and the plan of milestones and deliveries is shown in the GANTT chart presented in Figure E.1.1. The red dotted line is put at the period of preparation of this appendix within the project development.

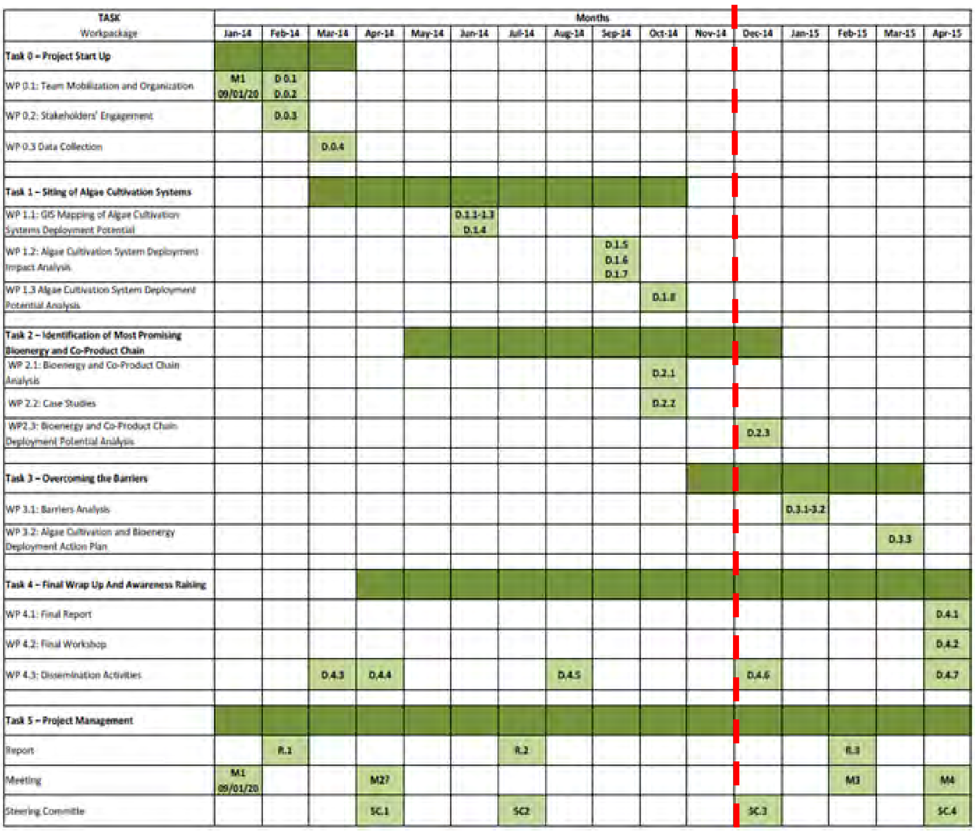

Figure E.1.1: Project Time Schedule

In particular, this document collects the results of the SWOT analyses performed to identify strengths, weaknesses, opportunities and threats of algae cultivation systems. Thus, in this document the algae production process starting with algae strains as raw material and having wet algae as final product is considered. A further dedicated study will focus on the SWOT analyses of the biofuel production process, having wet algae as raw material and biofuel as final product.

In this study, the SWOT analyses are performed basing on the characteristics of selected microalgae groups and of cultivation/harvesting technologies under the technical, the economical and the life cycle points of view.

Thus, the study is articulated following the five main themes that have been identified and that have led to the creation of five dedicated analyses of single domains:

- microalgae groups;
- microalgae harvesting and biomass processing methods;
- algae cultivation plants;
- economic parameters of algae cultivation plants;
- LCA on algae cultivation/harvesting technologies.

Although the five analyses are performed basing on different kinds of group (algal species, cultivation techniques, harvesting methods, sources of water, etc.), the final output of this Report is an overall SWOT analysis for the two main algae cultivation techniques that have been identified within the assignment and adopted in our methodological approach: open ponds and photobioreactors. In fact, in the results, strengths, weaknesses, opportunities and threats are listed for each kind of cultivation plant.

The topics introduced above are illustrated in the present report using the following structure:

- Section 1 introduces the contents, the objective and the structure of this report;
- Section 2 shows the main findings of the SWOT analyses performed on microalgae groups, cultivation/harvesting technologies under the technical, the economical and the life cycle points of view;
- Section 3 illustrates the main results of the SWOT analyses, comparing the figures of open ponds and photobioreactors;
- Section 4 includes the conclusions.

As stated above, the narrative sections of the Report include a summary of the main findings of each SWOT analysis; to complete the analyses with more details, the full single technical reports have been enclosed in the Annexes.

The technical reports enclosed in the Annexes are the following:

- Annex 1: SWOT analysis of microalgae groups;
- Annex 2: SWOT analysis of microalgae harvesting and biomass processing methods;
- Annex 3: SWOT analysis on algae cultivation plants;
- Annex 4: SWOT analysis on algae cultivation plants – economic parameters;
- Annex 5: SWOT analysis on algae cultivation/harvesting technologies – LCA approach.

E.2 FIGURES FROM THE SWOT ANALYSIS

The following paragraphs describe the main findings of the performed SWOT analyses. As seen in the previous Section, the study is articulated in the following five themes:

- microalgae groups;
- microalgae harvesting and biomass processing methods;
- algae cultivation plants;
- algae cultivation plants – economic parameters;
- algae cultivation/harvesting technologies – LCA approach.

Further subdivisions have been adopted, based on the peculiarities of each domain, thus leading to a set SWOT within each theme (subdivision criteria are based on biology, harvesting and cultivation technologies).

The complete technical reports for the five themes are enclosed in the Annexes.

E.2.1 THEME 1 – ANALYSIS OF MICROALGAE GROUPS

To perform the SWOT analysis on microalgae, it was chosen to identify groups of species having similar characteristics. Groups were formed by dividing selected macroalgal species according to the available literature data and to the experience of Consortium and the outcomes of already completed and ongoing funded projects.

Species were scored and grouped according to a set of criteria, related to:

1. biological aspects relevant to biofuels production (biomass productivity, growth rate, lipid composition);
2. potential uses of algae co-products and possible application areas;
3. general indications concerning their cultivation both in open ponds and photobioreactors, using different water sources (freshwater, seawater and wastewater);
4. processing of microalgae biomass (e.g.: harvesting, thickening and dewatering);
5. environmental impacts (e.g.: potentially harmful effects of microalgae on human health and aquatic ecosystems).

To elaborate the information, a data matrix was prepared containing, for each species, assessments of the considered criteria, expressed in terms of a score: 5 corresponds to positive aspects, 3 indicates the coexistence of negative and positive aspects, 1 corresponds to negative aspects. Because of the lack of information or the presence of incomplete data, it was not possible to assign a score to each species concerning some criteria.

The species were then grouped according to the similarities highlighted in the above described matrix, and the following three main groups were identified:

1. Group 1: Chlorophyta Dunaliella salina, Dunaliella spp., Ochrophyta Nannochloropsis spp. and Phaeodactylum tricornutum;
2. Group 2: 4 Chlorophyta Chlorella vulgaris and Chlorella spp., Scenedesmus spp., Chlorococcum spp., Tetraselmis suecica and Tetraselmis spp;
3. Group 3: 3 Chlorophyta Botryococcus braunii, Haematococcus pluvialis and Neochloris oleoabundans.

Concerning this SWOT analysis on microalgal groups, an important remark must be highlighted about the grouping criteria; groups are made up of species that share many common characteristics (such as biological aspects and potential application areas). However, this does not mean that the species of the same group present a complete similarity in reference to all the selection criteria.

This issue could be partially solved, following alternative paths, by:

- increasing the level of similarity within the groups and their number and by a partial redistribution of some species between the groups;
- performing a SWOT analysis for each species.

These alternatives emerged during the consultations with the FP7 projects of the AlgaeCluster. Anyway, the aim of this study is to express a general opinion on algae cultivation plants, therefore not related to each single case.

For this reason a groups-based approach is deemed appropriate for the purposes of the analysis.

E.2.1.1 Group 1

The Group 1 is composed of three marine species/genera (*Dunaliella salina* and *Dunaliella* spp., *Nannochloropsis* spp. and *Phaeodactylum tricornutum*, but freshwater species of *Dunaliella* and *Nannochloropsis* have also been described). These microalgae show a good response to cultivation in open ponds and closed photobioreactors and can be successfully grown using seawater and seawater mixed with wastewater. Their lipid content and productivity, together with a good growth rate, make them suitable for biofuel production. Moreover they are cultivated as sources of valuable compounds widely used in aquaculture, cosmetics, pharmaceutical and human food industries.

The following Figure E.2.1 summarizes the evaluation of Group 1 algae suitability, regarding different cultivation plants and water sources, and different harvesting methods.

OPEN POND				
SW	FW	WW	SW+WW	FW+WW
✓	✗	✗	✓	✗

PHOTOBIOREACTOR				
SW	FW	WW	SW+WW	FW+WW
✓	✗	✗	⊖	✗

HARVESTING TECHNIQUES					
FL	FT	GS	C	FI	UA
✓	✓	✗	✓	✗	✗

✓ suitable
✗ not investigated
⊖ not applicable

Figure E.2.1: Cultivation Plants and Water Sources for Group 1 Species

SWOT analysis on Group 1 is shown in the following paragraphs and graphically recalled at the end of Section 2.1.1.

E.2.1.1.1 Strengths

The following bullets recall the strengths of algae belonging to Group 1:

- CULTIVATION PLANTS: literature reports that these microalgae are able to grow in open ponds and closed photobioreactors, using seawater and seawater mixed with wastewater (D'Elia et al, 1979; Chini Zittelli et al., 1999; Craggs et al., 1996; Ravishankar et al., 2012; Sukenik et al., 2009; Silva Benavides et al., 2013; Dong et al., 2014; Chinnasamy et al., 2010);
- PRODUCTIVITY: these species have good lipid content and productivity and a good growth rate (Dunaliella is a fast growing alga) (Ahmad et al., 2011; Griffiths and Harrison, 2009; Takagi et al., 2006; Mata et al., 2010; Pal et al., 2011; Rodolfi et al., 2009).

E.2.1.1.2 Weaknesses

The main weaknesses of algae belonging to Group 1 are:

- BIOMASS PROCESSING: Dunaliella species are very sensitive to shear damage (e.g. during pumping of the culture for circulation in closed systems) (Borowitzka, 1990);
- CULTIVATION PLANTS: there is the possibility of contamination by other species of microalgae and protozoa (Boussiba et al., 1987; Borowitzka, 1990).

E.2.1.1.3 Opportunities

The main opportunities to point out concerning algae belonging to Group 1 are:

- CULTIVATION PLANTS: wastewater can be used as a nutrient source to reduce the production and processing costs of microalgae based biofuels (Chamoli Bhatt et al., 2014);
- CULTIVATION PLANTS: these species can be used for bioremediation treatment of industrial wastewater (Putri and Muhaemin, 2010; Priyadarshani et al., 2011; Qari et al., 2014);
- APPLICATION AREAS: these species are widely used in aquaculture, cosmetics, pharmaceutical, human food industries (Borowitzka, 1992; Spolaore et al., 2006; Nizard et al., 2007; Tredici et al., 2009; Priyadarshani and Rath, 2012; Kim et al., 2012).

E.2.1.1.4 Threats

The following main threat was identified for algae belonging to Group 1:

- ENVIRONMENTAL IMPACTS: it is possible that cultivated algae will escape into the environment (e.g. because of the emissions to water courses) even with strict regulations (Slade and Bauen, 2013). The subsequent impacts are unknown.

E.2.1.1.5 Summary of SWOT for Group 1

Figure E.2.2 shows a summary of the SWOT analysis on Group 1 presented in the previous paragraphs. It is worth highlighting that algae belonging to this group show a good flexibility to cultivation in different plants, which represents a strong pro compared to the cons.

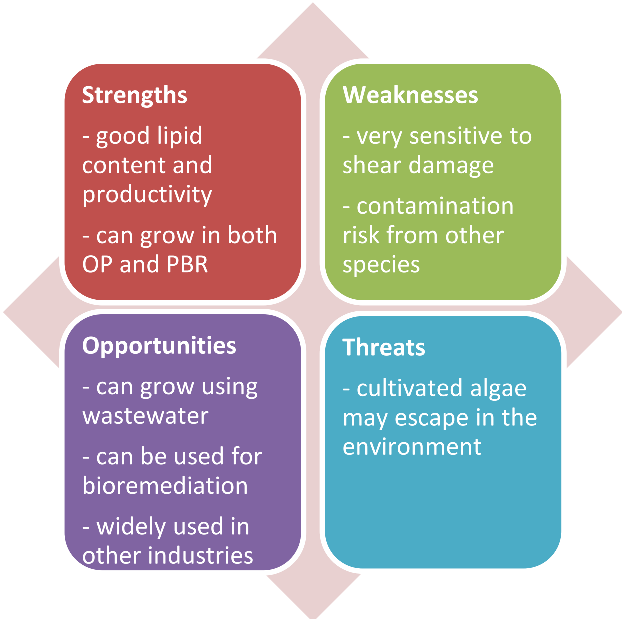

Figure E.2.2: Summary of SWOT for Group 1

E.2.1.2 Group 2

The Group 2 is composed of four species/genera: three freshwater species (*Scenedesmus* spp., *Chlorococcum* spp., *Chlorella vulgaris* and *Chlorella* spp.) and one marine species (*Tetraselmis suecica* and *Tetraselmis* spp.). These microalgae show a good response and adaptation ability to cultivation in open ponds and closed photobioreactors, using freshwater, wastewater and freshwater mixed with wastewater. They are suitable for biofuel production because of their growth rate, lipid content and productivity, and are widely used in aquaculture and human food industries. Particular attention should be paid to the cultivation of *Chlorella*, *Scenedesmus* and *Chlorococcum*, known to be significant propagators of allergic reactions such as dermatitis.

The following Figure E.2.3 summarizes the evaluation of Group 2 suitability, regarding different cultivation plants, different water sources and harvesting methods.

OPEN POND				
SW	FW	WW	SW+WW	FW+WW
✗	✓	✓	✗	✓

PHOTOBIOREACTOR				
SW	FW	WW	SW+WW	FW+WW
✗	✓	✓	⊖	✓

HARVESTING TECHNIQUES					
FL	FT	GS	C	FI	UA
✓	✓	✗	✓	✗	✗

✓ suitable
✗ not investigated
⊖ not applicable

Figure E.2.3: Cultivation Plants and Water Sources for Group 2 Species

The SWOT analysis on Group 2 is shown in the following paragraphs and graphically recalled at the end of Section 2.1.2.

E.2.1.2.1 Strengths

The following list recalls the strengths of algae belonging to Group 2:

- CULTIVATION PLANTS: these microalgae can grow in open ponds and closed photobioreactors, using freshwater, wastewater and freshwater mixed with wastewater, showing good adaptation ability (Chinnasamy et al., 2010; Krishna et al., 2012; Mata et al., 2013; Habib and Parvin, 2008; Wang et al., 2010; Ramos Tercero et al., 2014; Mahapatra and Ramachandra, 2013; Zhang and Lee, 1999);
- PRODUCTIVITY: literature reports that these species have good lipid content and productivity and a good growth rate (Chlorella and Scenedesmus are fast growing algae) (Griffiths and Harrison, 2009; Ahmad et al., 2011; Mata et al., 2010; Chini Zitelli et al., 2006; Ravishankar et al., 2012; Gris et al., 2013; Demirbas, 2009; Rodolfi et al., 2009; Doucha and Lívanský, 2009; Masojídek et al., 2000; Bharanidharan et al., 2013).

E.2.1.2.2 Weaknesses

The main weakness identified for algae belonging to Group 2 is:

- CULTIVATION PLANTS: possibility of contamination by other species of microalgae and protozoa (Bínová et al., 1998).

E.2.1.2.3 Opportunities

The following bullets recall the opportunities of algae belonging to Group 2:

- CULTIVATION PLANTS: wastewater can be used as a nutrient source to reduce the production and processing costs of microalgae based biofuels (Chamoli Bhatt et al., 2014);
- CULTIVATION PLANTS: these species can be used for bioremediation treatment of industrial wastewater (Chinnasamy et al., 2010; Krishna et al., 2012; Kshirsagar, 2013; Priyadarshani et al., 2011; Ahmad et al., 2013);
- APPLICATION AREAS: these species are widely used in aquaculture and human food industries (Tredici et al., 2009; Mata et al., 2010; Guedes et al., 2009; Ma and Chen, 2001; Muller-Feuga et al., 2003; Harel and Clayton, 2004; Sakthivel et al., 2011).

E.2.1.2.4 Threats

Threats identified for algae belonging to Group 2 are:

- ENVIRONMENTAL IMPACTS: Chlorella, Scenedesmus and Chlorococcum are known to be significant propagators of allergenic diseases or cause dermatitis in some people (Genitsaris et al., 2011; Dubey et al., 2010);
- ENVIRONMENTAL IMPACTS: Chlorella is the most frequent air-dispersed allergenic alga over short distances (< 1 km) (Genitsaris et al., 2011);
- ENVIRONMENTAL IMPACTS: it is possible that cultivated algae will escape into the environment (e.g. because of the emissions to water courses) even with strict regulations (Slade and Bauen, 2013). The subsequent impacts are unknown.

E.2.1.2.5 Summary of SWOT for Group 2

The following Figure E.2.4 shows a summary of the outcomes of the SWOT analysis on algae belonging to Group 2, presented in the previous paragraphs.

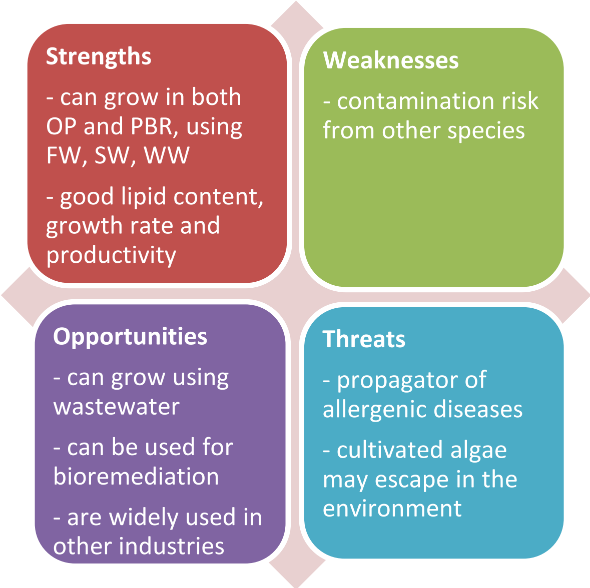

Figure E.2.4: Summary of SWOT for Group 2

Similarly to Group 1, also algae belonging to Group 2 show fair energy characteristics and a good adaptability to cultivation in different plants, which overtake weaknesses and threats.

E.2.1.3 Group 3

The Group 3 is composed of three freshwater species (*Botryococcus braunii*, *Haematococcus pluvialis* and *Neochloris oleoabundans*). These microalgae can be grown in open ponds and closed photobioreactors, using freshwater and freshwater mixed with wastewater; however *H. pluvialis* and *B. braunii* are susceptible to environmental fluctuations. The lipid content and composition make them suitable for biofuel production although their growth rate and productivity are lower than those of the other two groups. Moreover they are cultivated as sources of valuable compounds widely used in aquaculture and human food industries.

The following Figure E.2.5 summarizes the evaluation of Group 3 suitability, regarding different cultivation plants and water sources, and different harvesting methods.

OPEN POND				
SW	FW	WW	SW+WW	FW+WW
✗	✓	✗	✗	✗

PHOTOBIOREACTOR				
SW	FW	WW	SW+WW	FW+WW
✗	✓	✗	⊖	✓

HARVESTING TECHNIQUES					
FL	FT	GS	C	FI	UA
✓	✓	✗	✗	✗	✗

✓ suitable
✗ not investigated
⊖ not applicable

Figure E.2.5: Cultivation Plants and Water Sources for Group 3 Species

The SWOT analysis on Group 3 is shown in the following paragraphs and graphically recalled at the end of Section 2.1.3.

E.2.1.3.1 Strengths

This is the most relevant strength of algae belonging to Group 3:

- CULTIVATION PLANTS: these microalgae are able to grow in open ponds using freshwater and in closed photobioreactors using freshwater and freshwater mixed with wastewater (Pruvost et al., 2009; Wang and Lan, 2011; Metzger and Largeau, 2005; Rao et al., 2014; Orpez et al., 2009; Krishna et al., 2012; Wu et al., 2013).

E.2.1.3.2 Weaknesses

The following are the weaknesses identified for algae belonging to Group 3:

- PRODUCTIVITY: these species have good lipid content but both a relatively slow growth rate and a low lipid productivity of Botryococcus braunii and Haematococcus pluvialis have been determined (Masojídek et al., 2000; Orpez et al., 2009; Mata et al., 2010; Rao et al., 2014; Qin, 2005; Priyadarshani and Rath, 2012; Metzger and Largeau, 2005; Huntley and Redalje, 2007);
- PRODUCTIVITY: the culture conditions of Botryococcus braunii in open systems are less controlled than in closed reactors, consequently the biomass productivity is low compared with closed photobioreactors (Rao et al., 2014);
- PRODUCTIVITY: a relatively slow growth rate of Botryococcus braunii has been determined using the residual water (proceeding from secondary treatment) as culture medium (Orpez et al., 2009);
- PRODUCTIVITY: Haematococcus pluvialis and Botryococcus braunii are susceptible to environmental fluctuations (Fan et al., 1994; Qin et al., 2005);
- CULTIVATION PLANTS: outdoor cultures of Botryococcus braunii and Haematococcus pluvialis are easily contaminated by other algae (Masojídek et al., 2000; Metzger and Largeau, 2005).

E.2.1.3.3 Opportunities

The following list recalls the opportunities of algae belonging to Group 3:

- PRODUCTIVITY: wastewater can be used as a nutrient source to reduce the production and processing costs of microalgae based biofuels (Chamoli Bhatt et al., 2014);
- PRODUCTIVITY: these species can be used for bioremediation treatment of industrial wastewater (Banerjee et al., 2002; Wang and Lan, 2011; Wu et al., 2013);
- APPLICATION AREAS: literature reports that these species are widely used in human food industries (Mata et al., 2010; Chue et al., 2012; Priyadarshani and Rath, 2012). Haematococcus pluvialis and Neochloris oleoabundans are also used as aquaculture feed (Spolaore et al., 2006; Priyadarshani and Rath, 2012).

E.2.1.3.4 Threats

The main threats for algae belonging to Group 3 are here listed:

- ENVIRONMENTAL IMPACTS: blooms of Botryococcus braunii have been shown to be toxic to a variety of aquatic micro-organisms and fishes (Chiang et al., 2004);
- ENVIRONMENTAL IMPACTS: it is possible that cultivated algae will escape into the environment (e.g. because of the emissions to water courses) even with strict regulations (Slade and Bauen, 2013). The subsequent impacts are unknown.

E.2.1.3.5 Summary of SWOT for Group 3

Figure E.2.6 graphically summarizes the outcomes of the SWOT analysis on Group 3. In this case, weaknesses and threats seem to prevail over strengths and opportunities. In particular, the slow growth rate and the toxicity of some of the species characterize this group of algae as more problematic than the previous Groups.

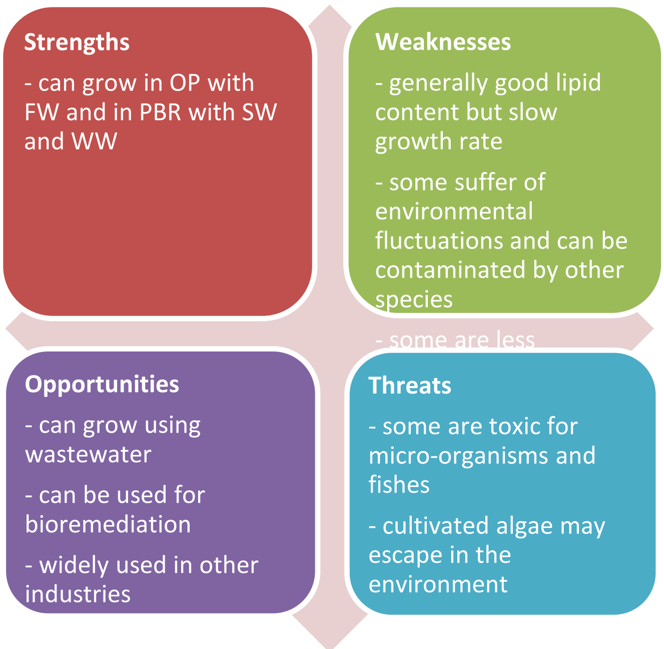

Figure E.2.6: Summary of SWOT for Group 3

E.2.2 THEME 2 – MICROALGAE HARVESTING AND BIOMASS PROCESSING METHODS

The choice of harvesting technique is dependent on characteristics of microalgae, e.g. size, density, and the value of the target products (Olaizola, 2003). Generally, microalgae harvesting is a two-stage process, involving:

1. Bulk harvesting: aimed at separation of biomass from the bulk suspension. The concentration factors for this operation are generally 100–800 times to reach 2–7% total solid matter. This will depend on the initial biomass concentration and technologies employed, including flocculation, flotation or gravity sedimentation;
2. Thickening: the aim is to concentrate the slurry through techniques such as centrifugation, filtration and ultrasonic aggregation, hence, is generally a more energy intensive step than bulk harvesting (Brennan and Owende, 2010).

In the following Sections, flocculation, flotation and gravity sedimentation will be analyzed among the bulk harvesting techniques, whereas centrifugation, filtration and ultrasonic aggregation will be studied as thickening techniques.

E.2.2.1 Flocculation

Flocculation is a preparatory step prior to other harvesting methods such as filtration, flotation or gravity sedimentation (Brennan and Owende, 2010; Milledge and Heaven, 2013; Molina Grima et al., 2003).

Since microalgae cells carry a negative charge that prevents natural aggregation of cells in suspension, addition of flocculants such as multivalent cations and cationic polymers neutralises or reduces the negative charge. It may also physically link one or more particles through a process called bridging, to facilitate the aggregation (Molina Grima et al., 2003).

Increasing the size of particles by the aggregation of algal cells through flocculation can increase the rate of settling or flotation (Mata et al., 2010).

Multivalent metal salts like ferric chloride ($FeCl_3$), aluminium sulphate ($Al_2(SO_4)_3$) and ferric sulphate ($Fe_2(SO_4)_3$) are suitable flocculants.

The SWOT analysis on Flocculation is shown in the following paragraphs and graphically recalled at the end of Section 2.2.1.

E.2.2.1.1 Strengths

The following breakdown list recalls the strengths of Flocculation:

- possibility to handle large quantities of microalgal suspension (Uduman et al., 2010);
- possibility to handle a wide range of microalgae (Uduman et al., 2010);
- suggested as the most reliable and cost-effective method (Milledge and Heaven, 2013);
- compared to other technologies, it is more reliable than flotation but less than filtration and centrifugation.

E.2.2.1.2 Weaknesses

These are the most relevant weaknesses of Flocculation:

- quite expensive (Benemann et al., 1980);
- high dosage of multivalent salt is required to achieve satisfactory result (Lam and Lee, 2012);
- produces large quantity of sludge that increases the difficulty to dehydrate the biomass (Lam and Lee, 2012);
- efficiency highly dependent on pH level (Chen et al., 2010; Renault et al., 2009);
- low cell recovery;
- highly dependent on the species;
- - flocculant separation is expensive.

E.2.2.1.3 Opportunities

Concerning the main opportunities of Flocculation, these points were identified:

- cationic polyelectrolytes more effective at flocculating freshwater microalgae than metal salts, achieving high biomass concentration (concentration factor up to 35 times) at lower dosage rates of 2–25 mg/l (Granados et al., 2012);
- flocculation of some microalgae can be achieved by adjustment of pH (Molina Grima et al., 2003; Shelef et al., 1984) (Molina Grima et al., 2003);
- organic polymeric flocculant, which is biodegradable and less toxic, offers an alternative and environmental friendly way to aggregate suspended particles (Lam and Lee, 2012);
- microbial flocculant or biofocculant has emerged as a new research trend in flocculation technology (Lam and Lee, 2012);
- interrupting the carbon dioxide supply to an algal system can cause algae in it to flocculate on its own, which is called autoflocculation (Amin, 2009).

E.2.2.1.4 Threats

The identified threats of Flocculation are listed here:

- flocculants may be algae species-specific (Mohn, 1988; Molina Grima et al., 2003; Oswald, 1988; Shen et al., 2009);
- recovery and recycling of the flocculants can be problematic (Mohn, 1988; Molina Grima et al., 2003; Oswald, 1988; Shen et al., 2009);
- inorganic flocculants can also have negative effects on microalgal viability and can colour and modify microalgal growth media, preventing recycling and reuse (Molina Grima et al., 2003; Papazi et al., 2010; Schenk et al., 2008);
- the dosage of flocculants to flocculate marine microalgae has been found to be 5–10 times higher than that for freshwater microalgae (Knuckey et al., 2006; Milledge and Heaven, 2013; Uduman et al., 2010);
- the shape, size and composition of flocs can be very diverse depending on microalgal species and flocculant (Jago et al., 2007);
- inorganic flocculants can be toxic (Harith et al., 2009);

- extreme pH may cause microalgal damage and death and could be unreliable and uneconomic on a commercial scale (Benemann and Oswald, 1996; Lee et al., 2009);
- polymeric flocculant (especially cationic type) is ineffective for marine microalgae due to inhibition by high ionic strength of seawater (Bilanovic et al., 1988) (Lam and Lee, 2012);
- flocculation using multivalent metal salts will contaminate the algal biomass (Mohn, 1988);
- bioflocculation, induced by environmental stresses such as extreme pH, temperature or nutrient depletion, may cause cell composition changes and is generally considered as too unreliable to be economical on a commercial scale (Benemann and Oswald 1996).

E.2.2.1.5 Summary of SWOT for Flocculation

The following Figure E.2.7 shows a summary of the SWOT analysis on Flocculation.

Although it is probably the most cost-effective harvesting method, it is worth noting that it is expensive and characterized by several threats that suggest, if possible, to adopt a simpler and less impacting harvesting method.

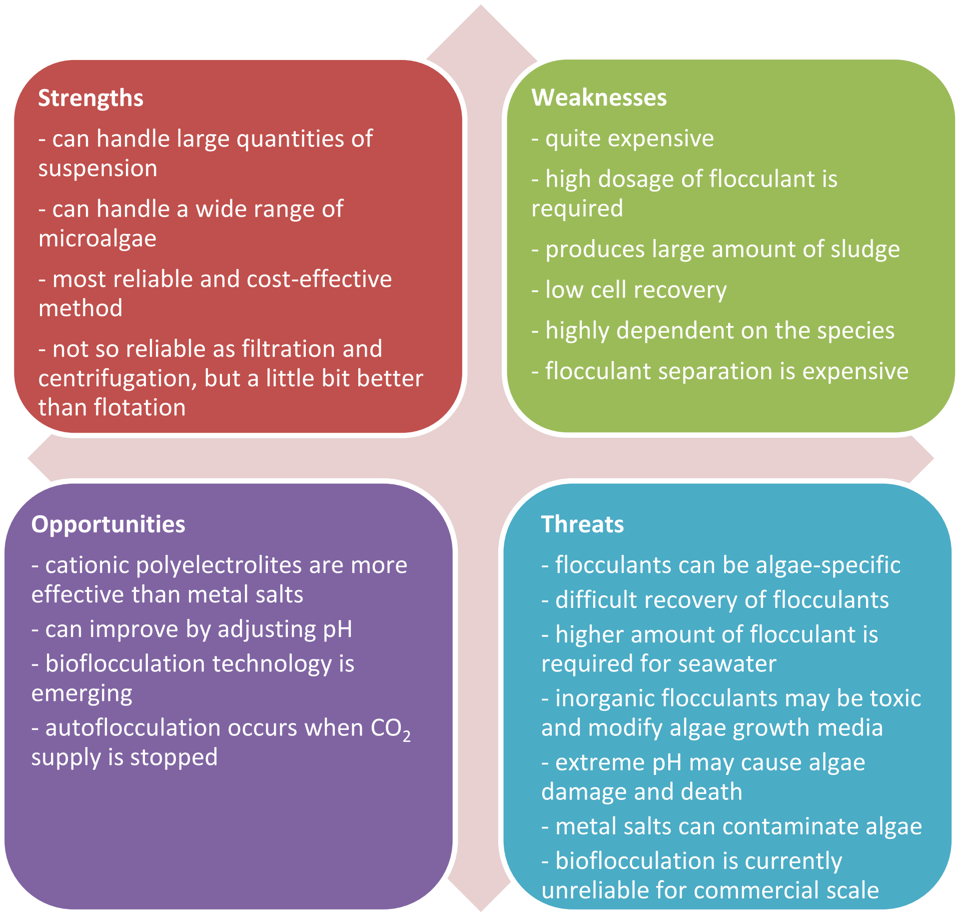

Figure E.2.7: Summary of SWOT for Flocculation

E.2.2.2 Flotation

Flotation methods are based on the trapping of algae cells using dispersed micro-air bubbles and therefore, unlike flocculation, does not require any addition of chemicals (Wang et al., 2008). Some strains naturally float at the surface of the water as the microalgal lipid content increase (Bruton et al., 2009). Flotation can be promoted by addition of air bubbles (Singh et al., 2011).

The SWOT analysis on Flotation is shown in the following paragraphs and graphically recalled at the end of Section 2.2.2.

E.2.2.2.1 Strengths

The most relevant strengths to point out for Flotation are:

- does not require any addition of chemicals (Wang et al., 2008);
- some microalgal strains natural float at the surface of the water when their lipid content increases (Gultom and Hu, 2013).

E.2.2.2.2 Weaknesses

The following main weaknesses were identified for Flotation:

- its technical and economic viability is limited (Gultom and Hu, 2013);
- it is very dependent on algae species and culture.

E.2.2.2.3 Opportunities

The main opportunity to point out for Flotation is:

- could be more useful in salt rather than fresh water (Oswald, 1988).

E.2.2.2.4 Threats

The following list recalls the threats of Flotation:

- the addition of flocculants is required in most cases for flotation to be effective (Edzwald, 1993; Mohn, 1988);
- if small bubbles are required, the energy usage for the flotation processes will be very high, which inevitably results in high operational costs and therefore a required high investment (Gultom and Hu, 2013);
- the costs can be even greater when the costs of flocculants are included (Gultom and Hu, 2013);
- electrolytic flotation method is very energy-intensive (Gultom and Hu, 2013);
- there is very limited evidence of its technical or economic viability (Gultom and Hu, 2013; Milledge and Heaven, 2013).

E.2.2.2.5 Summary of SWOT for Flotation

The following Figure E.2.8 graphically recalls the outcomes of the SWOT analysis on Flotation. It can be noted that this method appears to be promising for algae bulk harvesting, but its technical and economic viabilities need to be accurately verified.

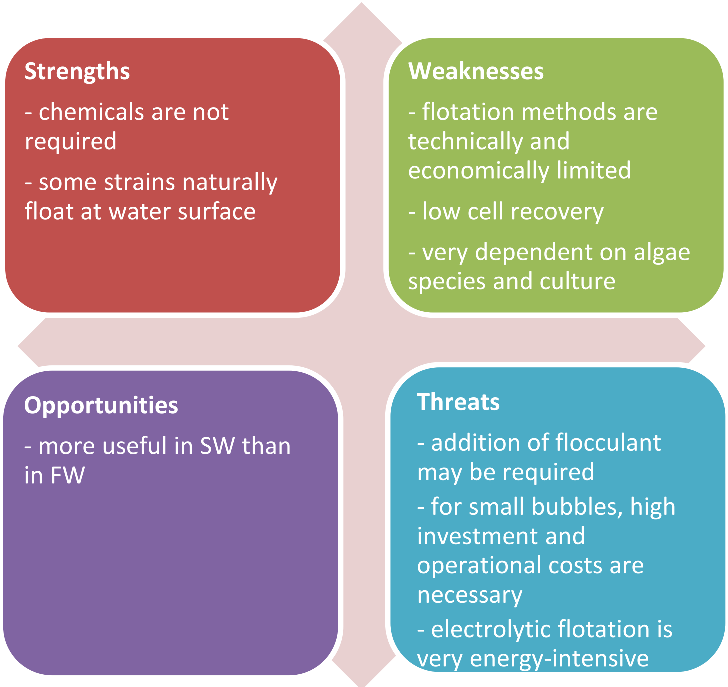

Figure E.2.8: Summary of SWOT for Flotation

E.2.2.3 Gravity Sedimentation

In sedimentation gravitational forces cause liquid or solid particles to separate from a liquid of different density, but the process can be extremely slow especially if density difference or particle size is small. Sedimentation can be described by Stokes' Law which assumes that sedimentation velocity is proportional to the square of the (Stokes') radius of the cells and the difference in density between the microalgal cells and the medium as shown below:

$$Setting\ velocity = \frac{2}{9} g \frac{r^2}{\eta} (\rho_s - \rho_l)$$

where r is cell radius, g is fluid dynamic viscosity and ρ_s and ρ_l are the solid and liquid densities. (Milledge and Heaven, 2013).

The SWOT analysis on Gravity Sedimentation is shown in the following paragraphs and graphically recalled at the end of Section 2.2.3.

E.2.2.3.1 Strengths

The following main strength was identified for Gravity Sedimentation:

- energy consumption of settlement harvesting is generally low (Milledge and Heaven, 2013).

E.2.2.3.2 Weaknesses

Concerning weaknesses of Gravity Sedimentation, it is worth noting two items:

- slow process;
- low cell recovery and solid concentrations (Mata et al., 2010; Shen et al., 2009) with cell recoveries of 60–65% (Collet et al., 2011; Ras et al., 2011) and solid concentrations of up to 1.5% total suspended solids (Uduman et al., 2010).

E.2.2.3.3 Opportunities

The main identified opportunity for Gravity Sedimentation is:

- settlement of colonial and larger microalgae could be useful as a pre-concentration step for use with other harvesting techniques (Milledge and Heaven, 2013).

E.2.2.3.4 Threats

Gravity Sedimentation is affected by these threats:

- needle like or long cylindrical microalgae being particularly resistant to settling (Choi et al., 2006);
- smaller algae (Chlorella) and motile microalgae (Euglena, Chlorognium) do not readily settle out of suspension (Nurdogan and Oswald, 1996);
- the settlement of microalgae varies between species, but can also alter within the same species (Milledge and Heaven, 2013);
- settlements rates have been shown to vary with light intensity (Lam and Lee, 2012);
- nutrient deficiency has been shown to decrease settlement rate (Lam and Lee, 2012);
- sinking rate increases in older cells especially in senescent cells (non-dividing cells between maturity and death) (Smayda, 1970) and spore-producing cells (Lam and Lee, 2012);
- microalgae with a high lipid content are likely to settle less readily due to the lower density (Lam and Lee, 2012).

E.2.2.3.5 Summary of SWOT for Gravity Sedimentation

The graph shown in Figure E.2.9 summarizes the SWOT analysis performed on Gravity Sedimentation. This method is suitable for application because of the simplicity and extremely low energy consumption, but a main barrier has to be overcome, which is the slowness of the process.

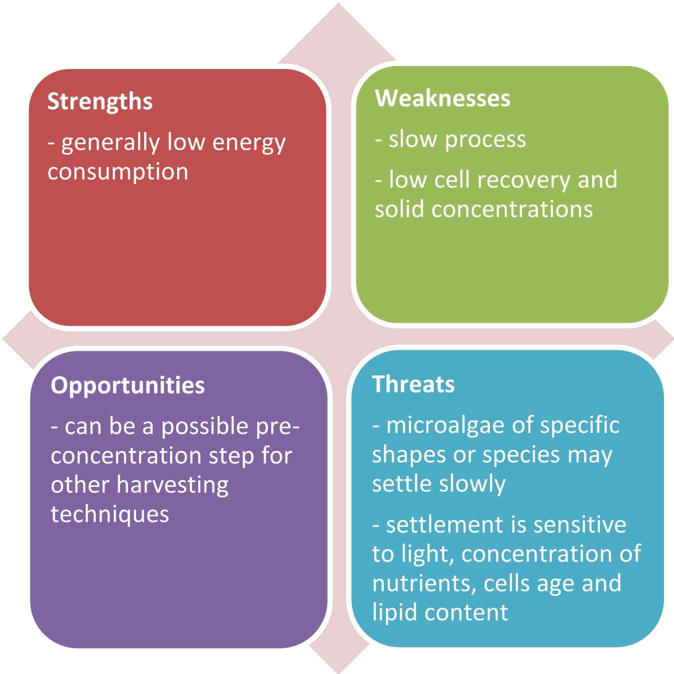

Figure E.2.9: Summary of SWOT for Gravity Sedimentation

E.2.2.4 Centrifugation

In centrifugation, gravity is replaced as the force driving separation by a much greater force (Milledge and Heaven, 2013).

The SWOT analysis on Centrifugation is shown in the following paragraphs and graphically recalled at the end of Section 2.2.4.

E.2.2.4.1 Strengths

The following strengths were identified for Centrifugation:

- centrifuges can process large volumes relatively rapidly and the biomass can remain fully contained during recovery (Molina Grima et al., 2003);
- harvesting efficiency of >95% (Heasman et al., 2000);
- almost all types of microalgae can be separated reliably and without difficulty by centrifugation (Mohn, 1988).

E.2.2.4.2 Weaknesses

Two main weaknesses were pointed out for Centrifugation:

- high energy costs (Bosma et al., 2003);
- potentially higher maintenance requirements due to freely moving parts (Bosma et al., 2003).

E.2.2.4.3 Opportunities

The most relevant opportunities for Centrifugation are:

- it is suitable for high value products (Molina Grima et al., 2003);
- it can be able to separate contaminants if the densities are different enough.

E.2.2.4.4 Threats

The following is the main threat regarding Centrifugation:

- a cell harvest efficiency of >95% was obtained only at 13,000×g. The harvest efficiency declined to 60% at 6000×g and 40% at 1300×g (Molina Grima et al., 2003).

E.2.2.4.5 Summary of SWOT for Centrifugation

The following Figure E.2.10 shows a summary of the SWOT analysis on Centrifugation. Although energy consumptions are quite high, the high efficiency and flexibility to different species propose this method as one of the most reliable thickening techniques.

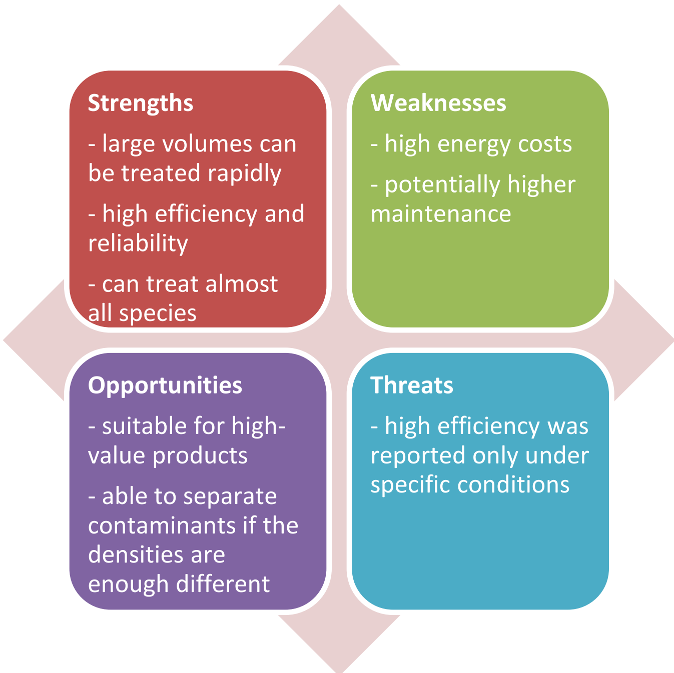

Figure E.2.10: Summary of SWOT for Centrifugation

E.2.2.5 Filtration

Filtration occurs when fluids flowing through a filter due to a difference in pressure, leave solid particles behind the filter. When a low filtration time is required, the liquid is forced to flow through the filter by a pump.

The SWOT analysis on Filtration is shown in the following paragraphs and graphically recalled at the end of Section 2.2.5.

E.2.2.5.1 Strengths

The most important strengths of Filtration are:

- for processing of low broth volumes (<2m^3/day), membrane filtration can be more cost effective compared to centrifugation;
- the cell recovery and the separation efficiency are high.

E.2.2.5.2 Weaknesses

The following points recall the weaknesses identified for Filtration:

- conventional filtration cannot be used to harvest algae species approaching bacterial dimensions (<30 mm);
- owing to the cost for membrane replacement and pumping in larger scales of production (>20m^3/day), centrifugation may be a more economic method of harvesting the biomass (MacKay and Salusbury, 1988);
- ultrafiltration is a possible alternative for recovery, in particular of very fragile cells, but has not been generally used for microalgae (Mata et al., 2010; Molina Grima et al., 2003), and operating costs are high and maintenance costs very high (Mata et al., 2010; Purchas, 1981);
- membrane replacement and pumping are the major cost contributors to membrane filtration processes (Molina Grima et al., 2003).

E.2.2.5.3 Opportunities

Concerning opportunities of Filtration, the following points need to be highlighted:

- for recovery of smaller algae cells (<30 mm), membrane microfiltration and ultra-filtration are technically viable alternatives to conventional filtration (Petruševski et al., 1995);
- filter presses have found wide application in industry due to the simple design, flexibility and capability to handle a wide range of slurries, and have been used to reduce the number of bacteria and yeast in wine (Brennan et al., 1969; Richardson et al., 2002);
- microfiltration is suitable for fragile cells (Petrusevski et al., 1995);
- generally, microfiltration can be more cost-effective than centrifugation if only small volumes (e.g.: <2 m^3/day) are to be filtered (Molina Grima et al., 2003)

E.2.2.5.4 Threats

Filtration is affected by the following threats:

- conventional filtration process is most appropriate for harvesting of relatively large (>70 mm) microalgae;
- membrane filtration has not been widely used for producing microalgal biomass on a large scale and could be less economic than centrifugation at commercial scale (Molina Grima et al., 2003);
- concerning presses, although the equipment is relatively cheap, labour costs can be high and cake washing is not always effective (Brennan et al., 1969; Richardson et al., 2002);
- filtration can be relatively slow (Molina Grima et al., 2003);

- recovery by precoat filtration is not suitable if contamination of the biomass with filter aid cannot be tolerated. This would generally be the case if the biomass is intended for use as aquaculture feed, or further processing is required for extracting intracellular products from the biomass (Molina Grima et al., 2003);
- large-scale processes for producing algal biomass do not generally use membrane filtration (Molina Grima et al., 2003);
- for larger scale of production (e.g.: higher than 20 m^3/day), centrifugation may be a more economic method of recovering the biomass (MacKay and Salusbury, 1988);
- membrane fouling and clogging due to the small size of the microalga (Bosma et al., 2003).

E.2.2.5.5 Summary of SWOT for Filtration

The following Figure E.2.11 graphically shows the outcomes of the SWOT analysis on Filtration. It can be noted that the overall assessment on the performances of this technique strongly depends on the characteristics of algae, but for large ones this could be one of the most efficient thickening methods.

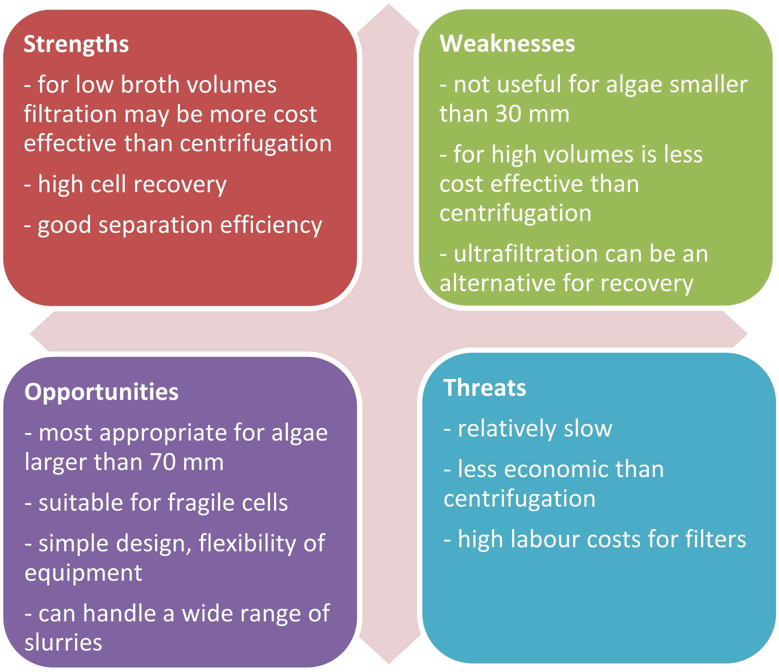

Figure E.2.11: Summary of SWOT for Filtration

E.2.2.6 Ultrasonic Aggregation

Gentle, acoustically induced aggregation followed by enhanced sedimentation can also be used to harvest microalgae biomass (Bosma et al., 2003; Show et al., 2013).

The SWOT analysis on Ultrasonic Aggregation is shown in the following paragraphs and graphically recalled at the end of Section 2.2.6.

E.2.2.6.1 Strengths

The following list recalls the strengths of Ultrasonic Aggregation:

- it can be operated continuously without inducing shear stress on the biomass, which could destroy potentially valuable metabolites (Bosma et al., 2003);
- non-fouling technique (Bosma et al., 2003);
- absence of mechanical failures because this device has no freely moving parts (Bosma et al., 2003);
- efficiencies higher than 90% were recorded at high biomass concentrations and flow rates in the range 4–6 l/d (Bosma et al., 2003; Show et al., 2013);
- as much as 92% of the algae biomass could be harvested with a concentration factor of 11.

E.2.2.6.2 Weaknesses

The main weakness identified for Ultrasonic Aggregation is:

- attempts to harvest at higher efficiency were unfruitful due to small size and low particle density of the microalgae (Bosma et al., 2003; Show et al., 2013).

E.2.2.6.3 Opportunities

No specific opportunities have emerged from the analysis of Ultrasonic Aggregation.

E.2.2.6.4 Threats

The main threat to point out for Ultrasonic Aggregation is:

- feed flow rate, biomass concentration and ratio between harvest and feed flows had a significant effect on the concentration factor (Bosma et al., 2003; Show et al., 2013).

E.2.2.6.5 Summary of SWOT for Ultrasonic Aggregation

In Figure E.2.12 a summary of the SWOT analysis on Ultrasonic Aggregation is presented. It can be noted that this thickening method still has to be investigated because few details are available in literature. However, the method appears to be promising since its efficiency is high and it avoids problems that are frequent in other thickening methods such as shear stresses and fouling. The main barrier to be overcome is the low efficiency for small sizes and low particle densities.

Figure E.2.12: Summary of SWOT for Ultrasonic Aggregation

E.2.3 THEME 3 – ALGAE CULTIVATION PLANTS

As seen in the previous steps of the Project, it is basically possible to distinguish between open ponds and closed photobioreactors, which so far are the only practicable methods for large-scale production of microalgae (Molina Grima et al., 1999; Terry and Raymond, 1985; Sanchez Miron et al., 1999).

Within the present analysis, a further distinction is performed, since peculiarities of algae cultivation plants using wastewater, both in suspended and in immobilized cultures, suggest to consider them separately.

E.2.3.1 Open Ponds

Open ponds are the cheapest method of large-scale algal biomass production. They do not necessarily compete for land with existing agricultural crops, since they can be implemented in areas with marginal crop production potential. Open ponds also have lower energy needs and their maintenance and cleaning are easier. Therefore, they may have the potential to return large net energy production.

Among the drawbacks of open ponds are significant evaporative losses, the diffusion of CO_2 to the atmosphere, the permanent threat of contamination and pollution, the difficulty of maintaining a constant environment for the culture, and the low cell density due to the large film width of the culture (between 15 and 30 cm). Open ponds require extensive areas for the raceways and consequently, costs for biomass harvesting are significantly high.

Open ponds have a variety of shapes and sizes but the most commonly used design is the raceway pond. The SWOT analysis on Open Ponds is shown in the following paragraphs and graphically recalled at the end of Section 2.3.1.

E.2.3.1.1 Strengths

These are the most relevant strengths of Open Ponds:

- made of less expensive materials, their construction involves lower costs require less energy for mixing (Jorquera et al., 2010);
- easy to clean;
- low energy inputs;
- easy maintenance.

E.2.3.1.2 Weaknesses

Concerning weaknesses, Open Ponds are characterized by the following points:

- low final density of microalgae and low growth rate (Jorquera et al., 2010);
- large area of land required (Jorquera et al., 2010);
- low efficiency of light utilization (Jorquera et al., 2010);
- potentially carbon limited due to poor gas/liquid mass transfer (Christenson and Sims, 2011; Jorquera et al., 2010);
- lack of temperature control (Jorquera et al., 2010).

E.2.3.1.3 Opportunities

It is worth highlighting that opportunities of Open Ponds are:

- temperature partially regulated through evaporation;
- techniques to enhance CO_2 absorption into the culture media such as aerators or bubbling may improve the overall biomass productivity (Rawat et al., 2013);
- improved mixing can minimize impacts of both CO_2 and light limitation thus improving algae growth rate (Rawat et al., 2013).

E.2.3.1.4 Threats

The following are threats affecting Open Ponds:

- poor mixing;
- high risk of culture contamination (Jorquera et al., 2010);
- limited as to the type of microalgae that can be used for cultivation (Jorquera et al., 2010);
- evaporative losses result in changes to ionic composition of the media and potentially detrimental effects on culture growth (Rawat et al., 2013);
- changes in temperature, photo- period and seasonal variation are beyond control in open systems and directly affect productivity (Rawat et al., 2013).

E.2.3.1.5 Summary of SWOT for Open Ponds

The following Figure E.2.13 graphically summarizes the outcomes of the SWOT analysis on Open Ponds. This cultivation plants are characterized by significant pros, mainly connected with their ease, and their low installation and operational costs. However, several technical barriers to their diffusion exist and need to be overcome in order to make this cultivation plant viable on large scale. The most interesting measures to overcome these barriers are connected to an increase of the production efficiency in terms of use of water, carbon dioxide and light.

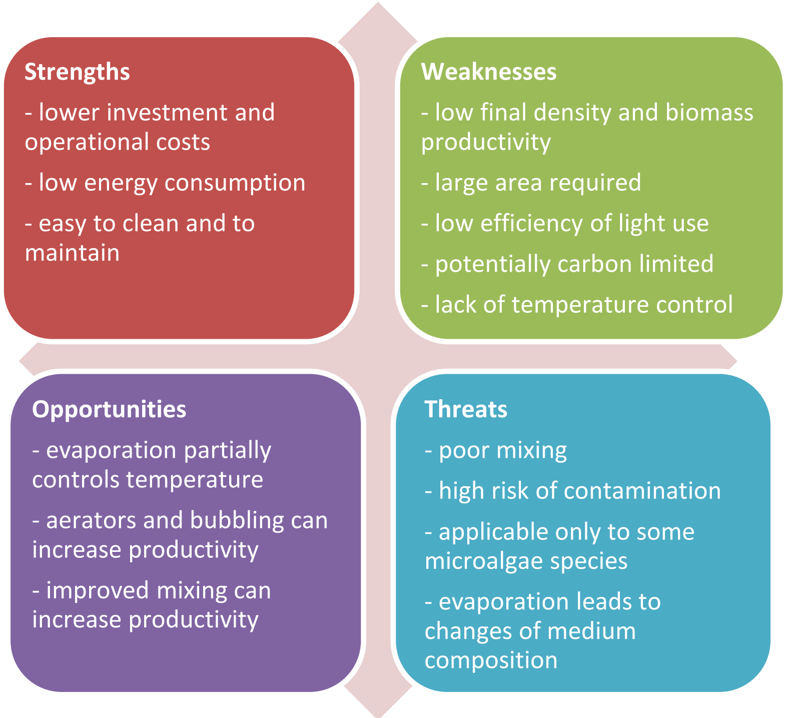

Figure E.2.13: Summary of SWOT for Open Ponds

E.2.3.2 Photobioreactors

A photobioreactor (PBR) is a closed equipment for algae cultivation, enabling a high growth rate because of its closed controlled environment. Typical configurations include vertical, flat plate reactors, annular reactors, or arrangements of plastic bags operated as batches.

PBRs allow the culture of single microalgae species for prolonged times, and prevent water loss by evaporation as well as contamination with undesirable microorganisms.

Although successfully used to produce large quantities of microalgal biomass, PBRs still have some issues: their performance is far from theoretical maxima and cannot reach values obtained at lab scale; moreover, investment and operation costs are still too high. In terms of energy costs, closed PBRs require a significant amount of energy for mixing.

The SWOT analysis on Photobioreactors is shown in the following paragraphs and graphically recalled at the end of Section 2.3.2.

E.2.3.2.1 Strengths

The following points represent the main strengths of Photobioreactors:

- regulation and control of nearly all the biotechnologically important parameters (Pulz, 2001);
- reduced contamination risk (Pulz, 2001);
- no CO_2 losses (Pulz, 2001);
- reproducible cultivation conditions (Pulz, 2001);
- controllable hydrodynamics, and temperature (Pulz, 2001);
- higher volumetric productivity than open ponds (Jorquera et al., 2010);
- better capture of radiant energy than open ponds (Jorquera et al., 2010);
- more optimal use of the cultivation area and variable energy consumption values for mixing and gas/liquid mass transfer (Jorquera et al., 2010);
- only cultivation system suitable for the production of high-value products for applications in pharmaceuticals and cosmetics, because of its ability to keep consistent production conditions and thus to be GMP-relevant (Pulz, 2001).

E.2.3.2.2 Weaknesses

Weaknesses for Photobioreactors are here listed:

- made of expensive materials and high construction costs (Jorquera et al., 2010);
- high energy consumption for pumping to generate turbulent flow for optimized gas/liquid mixing and mass transfer (Jorquera et al., 2010);
- need for costly and energy consuming temperature control (no possibility to exploit evaporation).

E.2.3.2.3 Opportunities

The following bullets recall the opportunities of Photobioreactors:

- can be designed in a variety of configuration (Jorquera et al., 2010; Pulz, 2001);
- may be located indoors or outdoors (Molina Grima et al., 2003).

E.2.3.2.4 Threats

The main threat to point out for Photobioreactors is:

- except the very recent industrial applications, tubular reactors have not achieved significant adoption both because of operational challenges (toxic accumulation of oxygen, adverse pH and CO_2 gradients, overheating, bio-fouling) and high equipment and maintenance costs (Christenson and Sims, 2011; Mata et al., 2010).

E.2.3.2.5 Summary of SWOT for Photobioreactors

Figure E.2.14 shows a summary of the SWOT analysis on Photobioreactors.

Differently from open ponds, the main drawbacks of photobioreactors concern their installation and operational costs. Provided that this economic barrier is overcome, photobioreactors show a high potential for their diffusion, due to their high efficiency and flexibility.

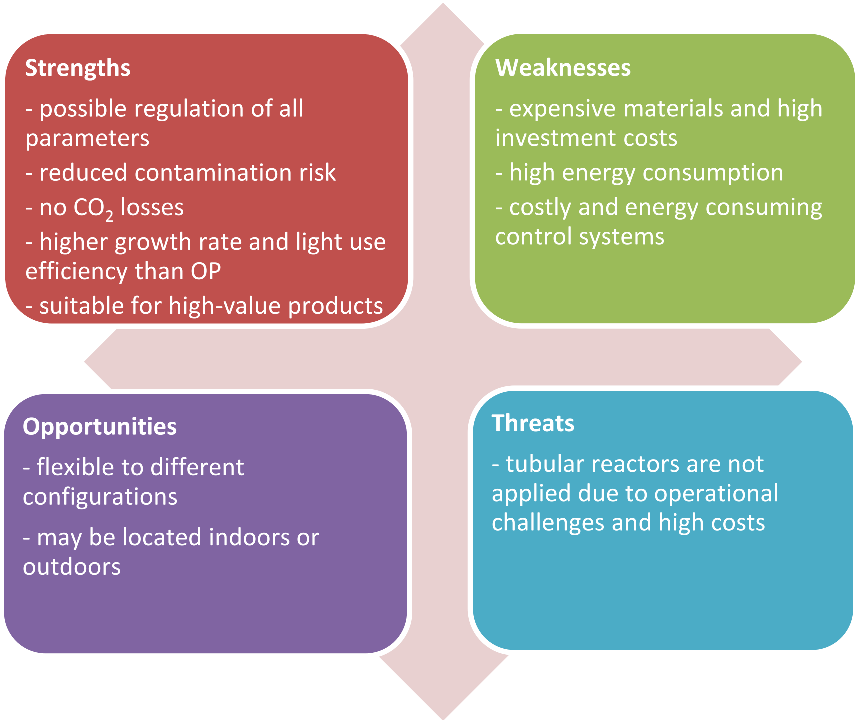

Figure E.2.14: Summary of SWOT for Photobioreactors

E.2.3.3 Wastewater Suspended Cultures

Algae cultivation plants using wastewater show peculiarities that suggest to consider them separately in a SWOT analysis.

E.2.3.3.1 Open Ponds

The SWOT analysis on Open Ponds in Wastewater Suspended Cultures is shown in the following paragraphs and graphically recalled at the end of Section 2.3.3.1. In particular, considerations refer to HRAPs or Raceway Ponds.

E.2.3.3.1.1 *Strengths*

The following is the main strength of Open Ponds in Wastewater Suspended Cultures:

- raceways are relatively inexpensive to build and operate.

E.2.3.3.1.2 *Weaknesses*

Weaknesses identified for Open Ponds in Wastewater Suspended Cultures are:

- often suffer low productivity due to contamination, poor mixing, dark zones, and inefficient use of CO_2 (Chisti, 2007; Christenson and Sims, 2011; Mata et al., 2010);
- cannot be used for high-value products (particularly in pharmaceutical, nutraceutical, food/feed applications).

E.2.3.3.1.3 *Opportunities*

The main opportunity to point out for Open Ponds in Wastewater Suspended Cultures is:

- high evaporation rate helps somewhat with temperature regulation through evaporative cooling (Christenson and Sims, 2011).

E.2.3.3.1.4 *Threats*

These bullets recall the threats of Open Ponds in Wastewater Suspended Cultures:

- raceway ponds should theoretically have production levels of 50– 60 g/(m^{2}d), but in practice, productivity does not go beyond 10–20 g/(m^{2}d) (Christenson and Sims, 2011; Shen et al., 2009);
- significant challenges of biomass recovery (Christenson and Sims, 2011).

E.2.3.3.1.5 *Summary of SWOT for Open Ponds in Wastewater Suspended Cultures*

In Figure E.2.15 the results of the SWOT analysis on Open Ponds in Wastewater Suspended Cultures are summarized. It can be noted that the same considerations given for open ponds are valuable, with advantages related to low costs and drawbacks connected to low productivity and technical issues.

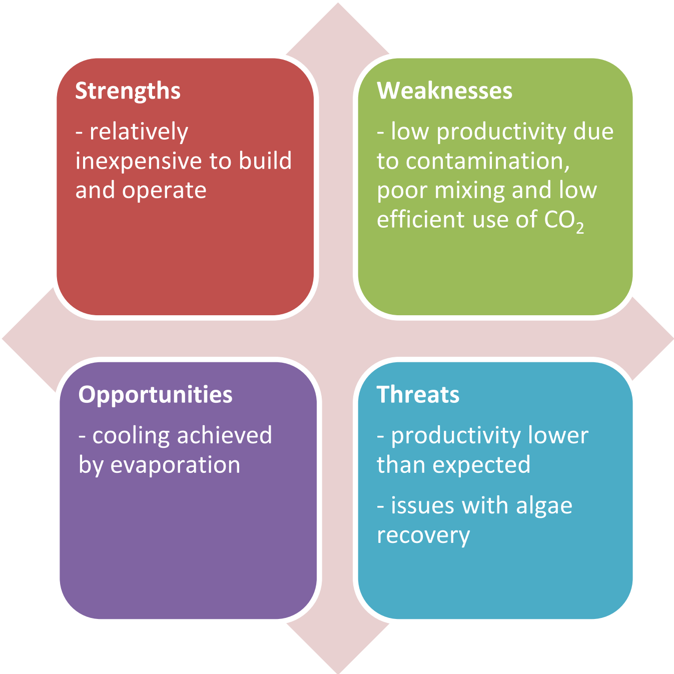

Figure E.2.15: Summary of SWOT for Open Ponds in Wastewater Suspended Cultures

E.2.3.3.2 Photobioreactors

The SWOT analysis on Photobioreactors in Wastewater Suspended Cultures is shown in the following paragraphs and graphically recalled at the end of Section 2.3.3.2.

E.2.3.3.2.1 *Strengths*

The following are the strengths of Photobioreactors in Wastewater Suspended Cultures:

- tubular photobioreactors can give better pH and temperature control (Christenson and Sims, 2011);
- better protection against culture contamination (Christenson and Sims, 2011);
- better mixing (Christenson and Sims, 2011);
- less evaporative loss (Christenson and Sims, 2011);
- higher cell densities (Christenson and Sims, 2011);
- reported productivities generally are in the range 20–40 g/(m^2d) (Christenson and Sims, 2011; Shen et al., 2009).

E.2.3.3.2.2 *Weaknesses*

Concerning weaknesses of Photobioreactors in Wastewater Suspended Cultures, the following points were identified:

- toxic accumulation of oxygen (Christenson and Sims, 2011; Mata et al., 2010);
- adverse pH and CO_2 gradients (Christenson and Sims, 2011; Mata et al., 2010);
- overheating (Christenson and Sims, 2011; Mata et al., 2010);
- high equipment and maintenance costs (Christenson and Sims, 2011; Mata et al., 2010);
- cannot be used for high-value products (particularly in pharmaceutical, nutraceutical, food/feed applications).

E.2.3.3.2.3 *Opportunities*

Photobioreactors in Wastewater Suspended Cultures show the following main opportunity:

- helical designs are considered the easiest to scale up (Carvalho et al., 2006; Christenson and Sims, 2011).

E.2.3.3.2.4 *Threats*

Two main threats were identified for Photobioreactors in Wastewater Suspended Cultures:

- oxygen removal can be a challenging issue (Christenson and Sims, 2011);
- significant challenges of biomass recovery (Christenson and Sims, 2011).

E.2.3.3.2.5 *Summary of SWOT for Photobioreactors in Wastewater Suspended Cultures*

The following Figure E.2.16 recalls the outcomes of the SWOT analysis on Photobioreactors in Wastewater Suspended Cultures. In this case, some differences exist with reference to photobioreactors using freshwater or seawater. In fact, although high productivity and good control of parameters are still among the pros, and high costs are still among the cons, several drawbacks are introduced by the use of wastewater. Probably it is advisable to avoid using wastewater in photobioreactors before these technical issues are solved.

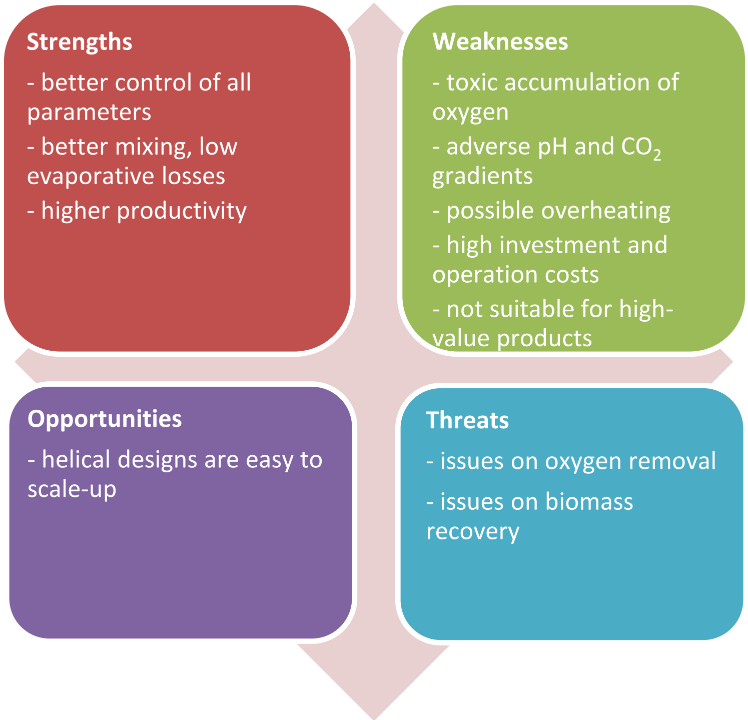

Figure E.2.16: Summary of SWOT for Photobioreactors in Wastewater Suspended Cultures

E.2.3.4 Wastewater Immobilized Cultures

The SWOT analysis on Wastewater Immobilized Cultures is shown in the following paragraphs and graphically recalled at the end of Section 2.3.4.

E.2.3.4.1 Strengths

Wastewater Immobilized Cultures show these strengths:

- efficient nutrient removal (Christenson and Sims, 2011);
- result in enhanced hydrocarbon production, increased cellular pigment, lipid content, and lipid variety (Christenson and Sims, 2011);
- if enough surface area is provided, algae biofilm growth can be more than suspended growth (Christenson and Sims, 2011);
- algal biofilms could play a large role in overcoming the major challenges to production and harvesting of microalgae (Christenson and Sims, 2011).

E.2.3.4.2 Weaknesses

The main weaknesses affecting Wastewater Immobilized Cultures are:

- high cost of the immobilization matrix (Christenson and Sims, 2011);
- cannot be used for high-value products (particularly in pharmaceutical, nutraceutical, food/feed applications).

E.2.3.4.3 Opportunities

The opportunities of Wastewater Immobilized Cultures are here listed:

- surface attached algal biofilms can offer the same increased culture density and lower land and water requirements of matrix-immobilized cultures without the associated costs of the matrix (Christenson and Sims, 2011);
- algal biofilm system can better integrate production, harvesting, and dewatering operations, than suspended cultures (Christenson and Sims, 2011);
- algae biofilms are likely to be benefited by bacteria present in wastewater (Christenson and Sims, 2011).

E.2.3.4.4 Threats

Concerning threats of Wastewater Immobilized Cultures, the following points were identified:

- such designs have thus far been confined to the laboratory (Christenson and Sims, 2011);
- at the scale necessary for wastewater treatment and biofuel production, the cost of the polymeric matrix becomes prohibitive (Christenson and Sims, 2011).

E.2.3.4.5 Summary of SWOT for Wastewater Immobilized Cultures

Figure E.2.17 summarizes the SWOT on Wastewater Immobilized Cultures. It is possible to note that in this case, although not suitable for high-value products exactly as the other plants using wastewater, this technology shows significant pros. The outcomes of the SWOT suggest to address research on this kind of cultivation plants, currently used only in laboratories, in order to scale it up to industrial level.

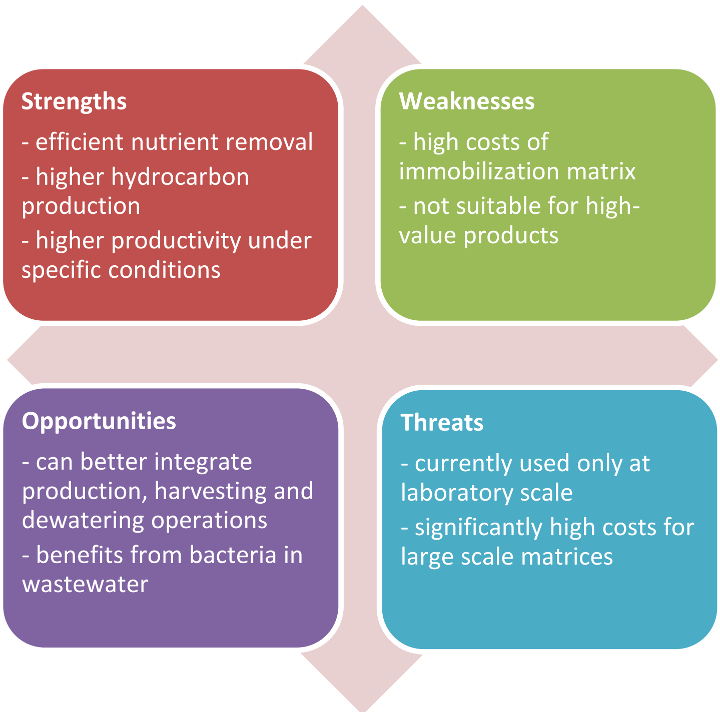

Figure E.2.17: Summary of SWOT for Wastewater Immobilized Cultures

E.2.4 THEME 4 – ECONOMIC PARAMETERS

An economic assessment of algae production processes in use, based on a full knowledge of costs and benefits of the set of technologies proposed, is a first step for a better understanding of what should be done (in terms of improvement of technologies and production methods) to reduce the risks to invest in bio-fuel production from algae.

Economic assessment of micro-algae production systems deals with costs and benefits considered as key parameters for decision making process. It is worth noticing that biodiesel and bio-fuel production from algae exhibits still high production and commercialization costs compared to other bio-fuels and remains currently non-competitive with fossil energy sources. Further improvements in reducing costs and developing by-products and external benefits from algae production are necessary to overcome the economic barriers still present in this sector.

The approach adopted in literature to address the economic issues of micro-algae production systems is mainly based on a process chain analysis: at each component of the chain - from algae cultivation to bio-fuel transformation and commercialization - the economic costs and benefits (products) of a given technology are associated. Note that the investment phase and the operational phase are often clearly distinguished by authors, as they engender different monetary flows and are related to different periods of the investment lifecycle (equipment in the initial phase versus raw materials in production phase). Total production cost is given by the sum of depreciation costs (cost of capital over the plant lifecycle) and operational costs.

The production costs are mainly related to:

- land requirement (surface);
- size and type of equipment;
- lifetime of the investments;
- maintenance costs;
- energy and nutriments consumption during processing and harvesting;
- labor and engineering costs, in both investment and production phases.

Co-products and services delivered by the algae production are related to bio-fuel, bio-ethanol and bio-methane, feed for animals, biomass for energy production, fertilizer use and others (pigments and chemicals). Other indirect benefits (or avoided costs) should also be mentioned to draw a clear picture of the economic situation. Such elements derive from external costs and benefits not always considered in economic calculations, for example the storage of carbon dioxide by algae or the use of wastewater as source of nutriments. In the case of wastewater, benefits come from the reduction of inputs to be purchased, as nutriments are directly delivered by the wastewater flow, the wastewater treatment costs not covered by the community and the reduction of eutrophication, and related ecological costs, due to wastewater release in ecosystems. However a more in-depth analysis of direct and indirect environmental effects should be provided by lifecycle assessments.

In addition, in a complete cost benefit analysis framework, other externalities should also be taken into consideration, since producing bio-fuels allow avoiding all direct and indirect costs deriving from fossil fuel extraction and refining.

In this SWOT analysis the economic parameters have been re-elaborated in order to provide a clear picture of the advantages and drawbacks when investing in a specific technology compared to another. Data used have been provided based on a literature review.

The difficulties emerged during the analysis are mainly related to the fact that:

- the dates of publication differ (from 2007 to 2014), some of them are more recent and updated than others;
- prices are not always reported at a detailed level;
- the quality and details of data reported are not always certain: many data provided derive from laboratory experiments or pilot cases and must be considered as forecasts based on hypothesis made at micro-levels; no industrial scale plant is functioning according to the market conditions up to now;
- measurement units are often different and hinder comparisons between technologies and for similar technologies hinder comparisons between countries: dimensions are expressed in € and $ for different periods of time; size of plants are expressed in cubic meters, hectares, gallons, liters, barrels or tons depend on the country of origin and the scope of the study.

If preliminary results emerging from the literature clearly show that costs highly depend on the technology used, significant improvements in the cost-benefit balance should be achieved through:

- minimizing energy demand from production process at site level; taking advantage from the re-use of by-products (biomass from algae production process) or the energy supply from low cost energy source (energy from co-generation plants, energy deriving from waste treatments or non-renewable power plants);
- water recycling (on site) or free water supply from natural artificial sources;
- access to low cost nutriment sources; at a lower price than common fertilizer market prices;
- access to a free source of CO_2 (in recycling by-product from power plants or cemeteries);
- delivering by-products able to compete with (and substitute) market products at a reasonable high (and not saturated) demand.

In the following Sections the results of the SWOT are presented. Considering the high heterogeneity of the data provided by the literature, the analysis has mainly been delivered on a qualitative basis, considering the alternative options (technologies) under discussion for which economic considerations are available.

E.2.4.1 Open Ponds

The economic SWOT analysis on Open Ponds is shown in the following paragraphs and graphically recalled at the end of Section 2.4.1.

E.2.4.1.1 Strengths

The following points sum up the economic strengths of Open Ponds:

- limited equipment cost;

- land costs highly depending on location (siting); with a large range which sprays from low - plants located in marginal, industrial or dismissed sites - to relatively high if we consider a location in arable, coastal or urbanized areas;
- low energy and power needs (compared to PBRs); but this depends on the plant location, the production process and the harvesting, drying and lipid extraction process used (which could be energy demanding when drying is required);
- use (free) CO_2 from coal combustion, cement industry or other biomass source. But this implies a location near industrial areas able to provide such an input;
- co-products (delivered at market price): animal and human nutrition, bioethanol, biomethane, fertilizers, nutraceuticals, cosmetics, pharmaceutical;
- low cost of some methods of harvesting: bioflocculation (use no chemical flocculants), auto-flocculation, sedimentation, solar drying and membrane filtration;
- using marine algae strains (living in seawater) with less nutriments needs and no competition for freshwater with other uses.

E.2.4.1.2 Weaknesses

The following list recalls the economic weaknesses of Open Ponds:

- land surface for industrial application not below 100 hectares (see previous point); ponds require also flat terrains;
- costs for activities aim at improving infrastructures for the proper functioning of installations (facilitating access to electricity, transports and communication networks); however costs highly depend on the location choice;
- fertilizers costs of (nitrogen, phosphorous and potassium) could be high in the absence of alternatives (wastewater for example); transportation costs should also be considered;
- fresh water or seawater needs (also to compensate evaporation); more elevation (needs for pumping), evaporation or need for clean freshwater also implies more energy requirement; the possibility or not of recycling (re-circulating water) also impacts on the cost of water supply;
- high costs of some methods of harvesting: centrifugation (gravity is replaced by a much greater force), ultra-filtration, flotation (addition air bubbles to the medium is energy intensive), spray and freeze drying.

E.2.4.1.3 Opportunities

Open Ponds show the following main economic opportunities:

- development of circular and close systems of production and consumption, thereof recycling water and nutrients and re-using by-products for energy producing;
- technological improvement in production process (algae productivity, lipid extraction, etc.) and significant drop in production costs;
- high fossil fuel energy prices.

E.2.4.1.4 Threats

Threats affecting Open Ponds under the economic point of view are:

- limited opportunities in developing new markets for by-products e.g. limited demand, persistent logistic or legal barriers;
- low rate of innovation as production costs are still high compared to other bio-fuels or fossil fuels production chains;
- low economy of scale with no advantages in developing large-scale plants i.e. no mass production savings in the case of an industrial development of algae production process.

E.2.4.1.5 Summary of Economic SWOT for Open Ponds

From the economic point of view, a summary of the SWOT on Open Ponds is shown in Figure E.2.18. As seen in the previous section, the main advantage of this cultivation plant is economic, since it has low investment and operational costs. However, the technical issues such as large surface and high amount of water required are among the economic drawbacks.

Figure E.2.18: Summary of Economic SWOT for Open Ponds

E.2.4.2 Photobioreactors

The economic SWOT analysis on Photobioreactors is shown in the following paragraphs and graphically recalled at the end of Section 2.4.2.

E.2.4.2.1 Strengths

Photobioreactors are characterized by the following economic strengths:

- reduced land requirements;
- low water use;
- use (free) CO_2 from coal combustion, cement industry or other biomass source. But this implies a location near industrial areas able to provide such an input;
- co-products (delivered at market price): animal and human nutrition, bioethanol, biomethane, fertilizers, nutraceuticals, cosmetics, pharmaceutical;
- low cost of some methods of harvesting: bioflocculation (use no chemical flocculants), autoflocculation (use Ca^{++} and Mg^{++} ions at high pH), sedimentation, solar drying and membrane filtration.

E.2.4.2.2 Weaknesses

The following bullets recall the economic weaknesses of Photobioreactors:

- high equipment costs, since costs of technologies and materials for the reactor are significantly higher than the open ponds costs of installation;
- high power and energy consumption;
- high staff and employees cost, due to the high number of people needed for the operations and the maintenance;
- high costs of some methods of harvesting: centrifugation (gravity is replaced by a much greater force), ultrafiltration, flotation (addition air bubbles to the medium is energy intensive), spray and freeze drying.

E.2.4.2.3 Opportunities

The main economic opportunities identified for Photobioreactors are:

- development of circular and close systems of production and consumption, thereof recycling water and nutriments and re-using by-products for energy producing;
- technological improvement in production process (algae productivity, lipid extraction, etc.) and significant drop in production costs;
- high fossil fuel energy prices.

E.2.4.2.4 Threats

Concerning the economic threats of Photobioreactors, these are the main points:

- limited opportunities in developing new markets for by-products e.g. limited demand, persistent logistic or legal barriers;
- low rate of innovation as production costs are still high compared to other bio-fuels or fossil fuels production chains;
- low economy of scale with no advantages in developing large-scale plants i.e. no mass production savings in the case of an industrial development of algae production process.

E.2.4.2.5 Summary of Economic SWOT for Photobioreactors

The following Figure E.2.19 recalls the economic SWOT on Photobioreactors. The opposite considerations to those given for open ponds are valuable: although water consumption is low and these plants have low land requirements, installation and production costs are still high to make this plant competitive. A possible solution for overcoming this barrier could be constituted by a system of public incentives.

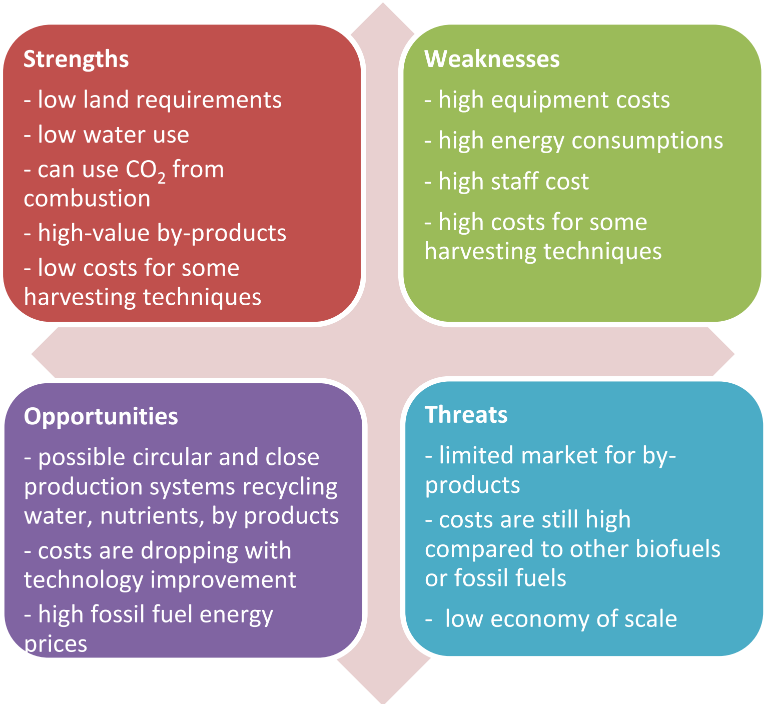

Figure E.2.19: Summary of Economic SWOT for Photobioreactors

E.2.4.3 Wastewater Suspended Cultures

E.2.4.3.1 Open Ponds

The economic SWOT analysis on Open Ponds in Wastewater Suspended Cultures is shown in the following paragraphs and graphically recalled at the end of Section 2.4.3.1.

E.2.4.3.1.1 *Strengths*

Open Ponds in Wastewater Suspended Cultures are characterized by these strengths:

- low cost of equipment;
- land costs highly depending on location (siting); with a large range which sprays from low - plants located in marginal, industrial or dismissed sites - to relatively high if we consider a location in arable, coastal or urbanized areas;
- credits linked to water depuration; the use of wastewater for algae growth can reduce production cost to about 50%;
- no external CO_2 and fertilizer sources are required: using wastewater, there is no needs to buy on the market raw materials for growing algae;

- co-products (provided at market price): animal feed, bioethanol, biomethane, fertilizer and biomass to be used for energy production (heat and power);
- low cost of some methods of harvesting: bioflocculation (use no chemical flocculants), autoflocculation (use Ca^{++} and Mg^{++} ions at high pH), sedimentation, solar drying and membrane filtration.

E.2.4.3.1.2 *Weaknesses*

The following are the main economic weaknesses pointed out for Open Ponds in Wastewater Suspended Cultures:

- high quantity of wastewater required. The plant would therefore be best localized close to metropolitan areas;
- land surface for industrial application should not be less than 100 hectares (see previous point); ponds require also flat terrains;
- high costs of some methods of harvesting: centrifugation (gravity is replaced by a much greater force), ultrafiltration, flotation (addition air bubbles to the medium is energy intensive), spray and freeze drying.

E.2.4.3.1.3 *Opportunities*

The main economic opportunities of Open Ponds in Wastewater Suspended Cultures are:

- development of circular and close systems of production and consumption, thereof recycling water and nutriments and re-using by-products for energy producing;
- technological improvement in production process (algae productivity, lipid extraction, etc.) and significant drop in production costs;
- high fossil fuel energy prices.

E.2.4.3.1.4 *Threats*

Threats affecting Open Ponds in Wastewater Suspended Cultures under the economic aspect are here listed:

- limited opportunities in developing new markets for by-products e.g. limited demand, persistent logistic or legal barriers;
- low rate of innovation as production costs are still high compared to other bio-fuels or fossil fuels production chains;
- low economy of scale with no advantages in developing large-scale plants i.e. no mass production savings in the case of an industrial development of algae production process.

E.2.4.3.1.5 *Summary of Economic SWOT for Open Ponds in Wastewater Suspended Cultures*

The following Figure E.2.20 summarizes the economic SWOT on Open Ponds in Wastewater Suspended Cultures.

In addition to pros and cons typical of open ponds, the main advantage is that using wastewater allows savings in terms of consumption of carbon dioxide and of fertilizers.

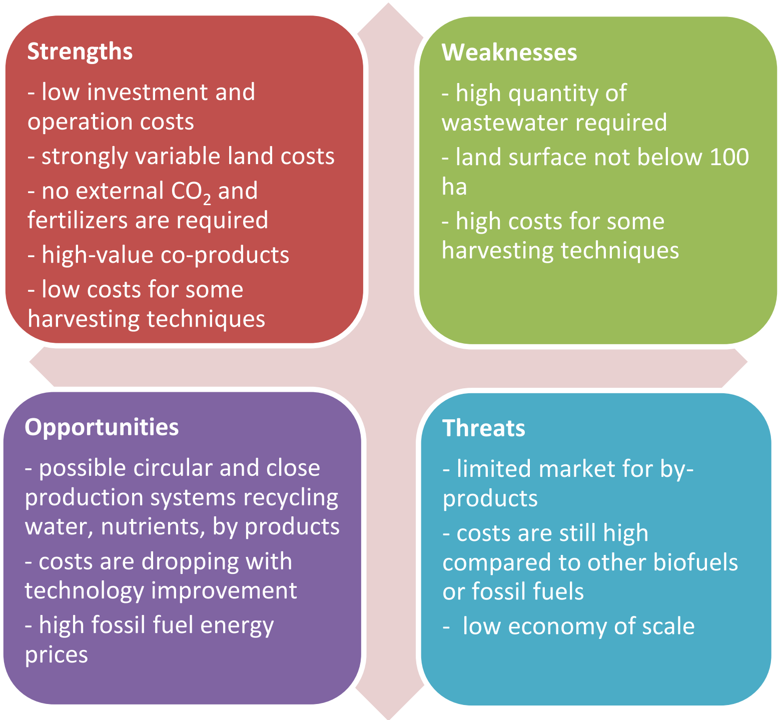

Figure E.2.20: Summary of Economic SWOT for Open Ponds in Wastewater Suspended Cultures

E.2.4.3.2 Photobioreactors

The economic SWOT analysis on Photobioreactors in Wastewater Suspended Cultures is shown in the following paragraphs and graphically recalled at the end of Section 2.4.3.2.

E.2.4.3.2.1 *Strengths*

In Wastewater Suspended Cultures, photobioreactors are characterized by these economic strengths:

- no external CO_2 and fertilizer sources are required: using wastewater, there is no needs to buy on the market raw materials for growing algal;
- limited water use since water comes from wastewater and the losses due to evaporation are replaced by re-cycling the culture medium;
- co-products (provided at market price): animal feed, bioethanol, biomethane, fertilizer and biomass to be used for energy production (heat and power);
- low cost of some methods of harvesting: bioflocculation (use no chemical flocculants), autoflocculation (use Ca^{++} and Mg^{++} ions at high pH), sedimentation, solar drying and membrane filtration.

E.2.4.3.2.2 *Weaknesses*

The following list recalls the economic weaknesses of Photobioreactors in Wastewater Suspended Cultures:

- high equipment cost, since technologies and materials' costs for the reactor are significantly higher than the open ponds installation costs (for example, for the PBRs with LED technology the equipment cost is about 648 M$, while with open ponds it is no more than 1-1.5 M$);
- high power and energy consumption;
- high staff and employees cost, due to the high number of people needed for the operations and the maintenance (about 36 people for a 100 ha plant);
- high costs of some methods of harvesting: centrifugation (gravity is replaced by a much greater force), ultrafiltration, flotation (addition air bubbles to the medium is energy intensive), spray and freeze drying.

E.2.4.3.2.3 *Opportunities*

The economic opportunities to point out concerning Photobioreactors in Wastewater Suspended Cultures are:

- development of circular and close systems of production and consumption, thereof recycling water and nutriments and re-using by-products for energy producing;
- technological improvement in production process (algae productivity, lipid extraction, etc.) and significant drop in production costs;
- high fossil fuel energy prices.

E.2.4.3.2.4 *Threats*

These are the economic threats of Photobioreactors in Wastewater Suspended Cultures:

- limited opportunities in developing new markets for by-products e.g. limited demand, persistent logistic or legal barriers;
- low rate of innovation as production costs are still high compared to other bio-fuels or fossil fuels production chains;
- low economy of scale with no advantages in developing large-scale plants i.e. no mass production savings in the case of an industrial development of algae production process.

E.2.4.3.2.5 *Summary of Economic SWOT for Photobioreactors in Wastewater Suspended Cultures*

The SWOT on Photobioreactors in Wastewater Suspended Cultures, under an economic perspective, are shown in Figure E.2.21. Similarly to open ponds, in addition to pros and cons typical of the plant, the main economic benefit is that using wastewater allows savings in terms of consumption of carbon dioxide and of fertilizers.

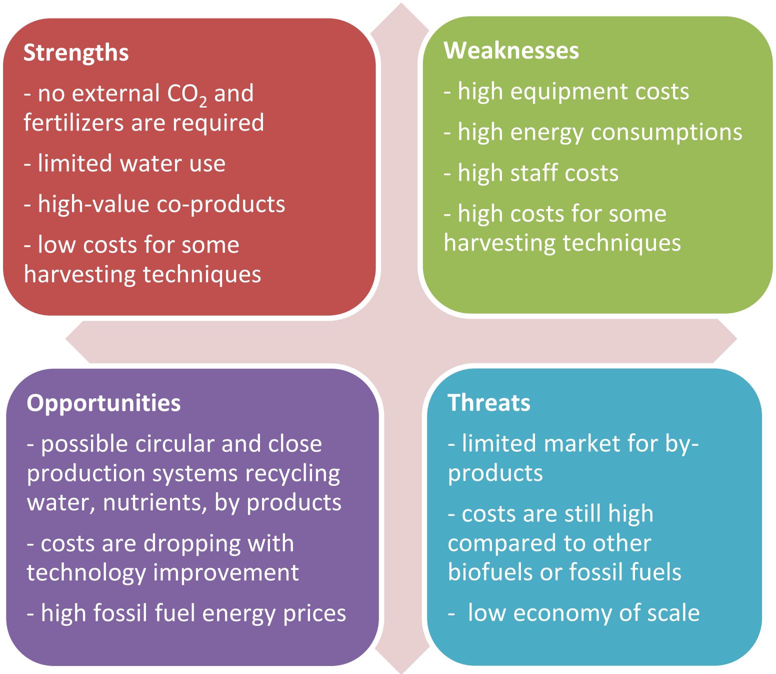

Figure E.2.21: Summary of Economic SWOT for Photobioreactors in Wastewater Suspended Cultures

E.2.5 THEME 5 – LIFE CYCLE ASSESSMENT

The LCA on the selected case studies was performed according to a Cradle-to-Gate approach using GaBi® software. A general block scheme was defined, able to represent all the algae production processes under investigation, by simply changing the values of mass and energy flows typical of the specific process. These values were taken either from the GaBi database or, for values that are not included in the latter, from specific literature on algae cultivation technologies.

The system boundaries were defined so that the system includes the whole impacts for electricity generation and water treatment. Concerning water and carbon dioxide, the energy requirements and consequent impacts for their supply to the plant are included in the system. Finally, nutrients and other reactants are considered to be available directly at the plant, without any additional impact.

Eight case studies corresponding to different combinations of algae cultivation, bulk harvesting and thickening techniques were considered, and for each of them two sub-cases were considered, corresponding to the use of wastewater and freshwater as sources of water. Moreover, the electricity mix for EU-27 was selected, but a further sensitivity analysis of the impact of the electricity mix composition on the LCA indicators was performed.

Among assumptions and limitations of the study, it is worth highlighting that LCA was performed by neglecting the energy and mass flows connected to the construction of the cultivation plant, the water and carbon dioxide feeding pipelines, and all the required equipment. This hypothesis may significantly affect the environmental indicators, but the choice was done to perform a comparative analysis among cultivation plants ready for operation at a specific site. Moreover, these values were not considered because no reliable data were available in literature.

Concerning the water supplied to the plant, seawater was assimilated to freshwater because the involved impacts are equivalent in the cases that water is withdrawn from a river or from the sea, provided that the distances of the plants from the sources of water are comparable. On the other hand, wastewater is considered separately because using it to grow algae reduces the impacts connected to wastewater treatment.

The analysis of PBR is based on the available data from literature. There is, for sure, a cooling need to consider, whose impact is reported to be highly significant. However, due to the lack of specific numbers for this input flow, the impact of cooling can be only figured out in qualitative terms at this stage of maturity of the algae systems (awaiting for reliable data from pilot realizations). This scenario including the energy used for cooling has been outlined quoting literature, whereas the quantitative figures are here presented in absence of cooling demand, well aware of the more than likely event that the final consumptions may result to be considerably higher.

The following paragraphs present the SWOT analysis based on the results of the LCA. The main grouping is performed between the selected cultivation techniques (open ponds, photobioreactors), whereas the impacts of harvesting/thickening processes and of water source changes are discussed within each group.

More details on the assumptions and the procedures applied to perform the LCA, and on its results are reported in Annex 5.

E.2.5.1 Open Ponds

The LCA based SWOT analysis on Open Ponds is shown in the following paragraphs and graphically recalled at the end of Section 2.5.1.

E.2.5.1.1 Strengths

Basing on the LCA analysis, the following strength of Open Ponds was identified:

- open ponds using wastewater have a lower life cycle impact compared to those using freshwater, because they can recycle 80% of their output water.

E.2.5.1.2 Weaknesses

The main weakness of Open Ponds to be pointed out basing on the outcomes of LCA analysis is:

- the life cycle impact for algae production in open ponds is quite high due to the high amount of water and energy required.

E.2.5.1.3 Opportunities

The following two are the opportunities of Open Ponds based on LCA analysis:

- using gravity sedimentation instead of the currently more used flocculation as bulk harvesting technique reduces the resources and energy consumptions thus leading to a lower life cycle impact;
- using filtration instead of the currently more used centrifugation as thickening technique reduces the resources and energy consumptions thus leading to a lower life cycle impact.

E.2.5.1.4 Threats

The main threat affecting Open Ponds according to the results of LCA analysis is:

- in this study the life cycle impact of open ponds construction phase was not considered, thus the real impact of algae production will be higher than calculated.

E.2.5.1.5 Summary of LCA SWOT for Open Ponds

The following Figure E.2.22 shows a summary of the LCA based SWOT analysis on Open Ponds. Under this perspective, open ponds show a high impact because of their significant consumption of water and energy per unit of mass of algae; on the other hand, the potential to reduce this impact is mainly connected to the choice of the water source, and of the harvesting and thickening techniques.

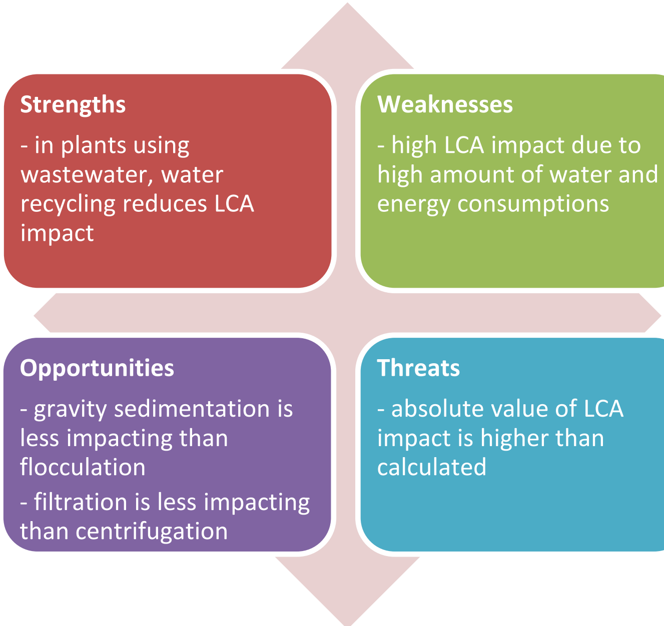

Figure E.2.22: Summary of LCA SWOT for Open Ponds

E.2.5.2 Photobioreactors

The LCA based SWOT analysis on Photobioreactors is shown in the following paragraphs and graphically recalled at the end of Section 2.5.2.

E.2.5.2.1 Strengths

This list recalls the strengths of Photobioreactors, based on LCA outcomes:

- the life cycle impact for algae production in photobioreactors is quite low due to the low amount of water and energy required, provided that the energy consumptions related to cooling are excluded from the analysis in lack of reliable data from existing systems;
- photobioreactors using wastewater have a lower life cycle impact because they can recycle 80% of their output water;

- algae production in photobioreactors has a negative Global Warming Potential over the whole life cycle since the carbon dioxide used in algae growth is higher than the emissions due to electricity production.

E.2.5.2.2 Weaknesses

The following main weaknesses were identified for Photobioreactors basing on LCA analysis:

- very high energy consumptions in the cultivation phase are expected for cooling purposes, although not quantified in real cases;
- in this study the life cycle impact of photobioreactors construction phase was not considered, thus the real impact of algae production will be higher than calculated.

E.2.5.2.3 Opportunities

Photobioreactors are characterized by two main opportunities, according to LCA analysis:

- using gravity sedimentation instead of the currently more used flocculation as bulk harvesting technique reduces the resources and energy consumptions thus leading to a lower life cycle impact;
- using filtration instead of the currently more used centrifugation as thickening technique reduces the resources and energy consumptions thus leading to a lower life cycle impact.

E.2.5.2.4 Threats

The following main threat was identified for Photobioreactors basing on LCA results:

- the life cycle impact of photobioreactors construction should be significantly higher than that of open ponds, thus the difference between the two cultivation techniques would be smaller.

E.2.5.2.5 Summary of LCA SWOT for Photobioreactors

The LCA based SWOT for Photobioreactors are shown in Figure E.2.23. These plants are characterized by a significantly low LCA and a negative GWP, with a potential further reduction of impacts connected to the choice of water source, harvesting and thickening techniques. The drawback is that the impacts of the construction phase, not considered in the analysis, are not negligible, thus leading to a higher absolute value for the overall LCA impact.

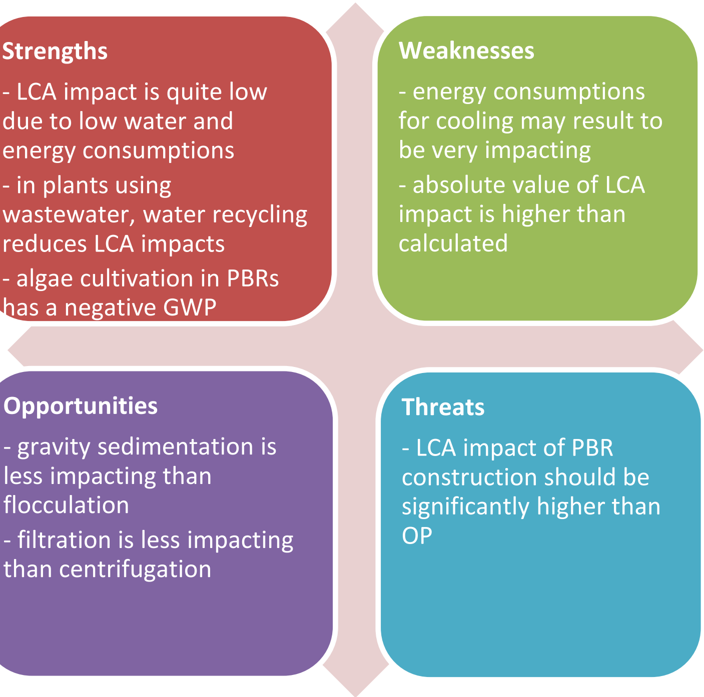

Figure E.2.23: Summary of LCA SWOT for Photobioreactors

E.3 SWOT MAIN FINDINGS

E.3.1 OPEN PONDS

The main outcomes of the SWOT analyses concerning the use of open ponds for algae cultivation, presented in the previous Section, are summarized in Figure E.3.1.

Figure E.3.1: Overall Summary of SWOT for Open Ponds

By analyzing the overall SWOT, it can be noted that open ponds are characterized by relatively low investment and operational costs, where the latter are mainly due to the generally low energy consumptions and to the easy maintenance. In particular, the use of wastewater is of interest because it reduces the consumption of carbon dioxide and fertilizers, and allows a recycle of water leading to lower water consumptions and in conclusion to a lower LCA impact.

On the other hand, open ponds need an extended surface, have a low efficiency of carbon dioxide and light use, their temperature is difficult to control and there are some issues concerning algae harvesting. Then, algae production in open ponds is still not economically competitive with other biofuels and fossil fuels production technologies, and the productivity is lower than theoretically expected.

The analysis of SWOT outcomes allows to identify technical and economic barriers to the implementation of this kind of plants for cultivation of microalgae. In particular, the following are the most critical points identified during the study:

- large surface required for the plant;
- cultivation system applicable only to some microalgae species;
- low final density and biomass productivity;
- poor mixing and low efficient use of carbon dioxide and light;
- significant water and consequent energy consumption for pumping, mixing, harvesting;
- difficulty in controlling temperature;
- high risk of contamination.

E.3.2 PHOTOBIOREACTORS

Figure E.3.2 shows a summary of the SWOT analyses presented in the previous Section concerning algae cultivation in photobioreactors.

It is worth noting that, since photobioreactors are closed systems, they are more flexible, their size can be significantly small and the main parameters are easily controllable. In addition, their productivity is higher because of their good mixing and efficient use of light and carbon dioxide. Finally, the system is suitable for high-value products, and algae harvesting is quite easy. Also in this case, using wastewater as water source, the supply of carbon dioxide and fertilizers is reduced and consequently the costs and the LCA impact are lower.

On the other hand, photobioreactors are quite expensive to build and operate, even because of high energy consumptions. Then, there are some technical issues connected to overheating of the reactors, adverse pH and carbon dioxide gradients and removal of oxygen.

Also in this case, the analysis of SWOT outcomes allows to identify technical and economic barriers to the implementation of this kind of plants for cultivation of microalgae. In particular, the following are the most critical points identified during the study:

- expensive installation due to material costs;
- expensive operation due to high energy consumptions for cooling;
- possible overheating of the reactor, or additional costs for thermoregulation;
- toxic accumulation of oxygen, adverse pH and carbon dioxide gradients.

Strengths

- low land requirements
- higher growth rate than OP
- possible regulation of all parameters
- no CO_2 losses, low evaporation, low water use
- good mixing and light use efficiency
- can use CO_2 from combustion
- in case wastewater is used, no need for external CO_2 and fertilizers
- suitable for high-value products
- low costs for some harvesting techniques
- quite low LCA impact due to low water and energy consumption
- in case wastewater is used, water recycling reduces LCA impact

Weaknesses

- expensive materials and high investment costs
- high energy consumption for cooling
- high staff cost
- toxic accumulation of oxygen, adverse pH and CO_2 gradients
- possible overheating or additional costs for thermoregulation
- wastewater plants are not suitable for high-value products
- high costs for some harvesting techniques
- absolute value of LCA impact is higher than calculated

Opportunities

- flexible to different configurations
- may be located indoors or outdoors
- helical designs are easy to scale-up
- possible circular and close production systems recycling water, nutrients, by products
- costs drop with technology improvement
- high fossil fuel energy prices
- gravity sedimentation and filtration have lower LCA impact than flocculation and centrifugation

Threats

- tubular reactors are not applied for biofuel production due to operational challenges and high costs
- issues on oxygen removal
- issues on biomass recovery
- costs are still high compared to other biofuels or fossil fuels
- limited market for by-products
- low economy of scale
- LCA impact of PBR construction should be significantly higher than OP

Figure E.3.2: Overall Summary of SWOT for Photobioreactors

E.4 CONCLUSIONS

This work focused on a SWOT analysis on algae cultivation plants, aimed at identifying strengths, weaknesses, opportunities and threats connected to the use of open ponds and photobioreactors for algae production. In particular, a dedicated SWOT analysis was performed on the following five themes:

- microalgae groups;
- microalgae harvesting and biomass processing methods;
- algae cultivation plants;
- algae cultivation plants – economic parameters;
- algae cultivation/harvesting technologies – LCA approach.

The SWOT on the above listed themes were analyzed and collected to identify pros &cons of the two considered algae cultivation plants. Single SWOT were performed for the sub-processes constituting the five themes and then an overall SWOT for open ponds and an overall SWOT for photobioreactors were prepared, which allowed to determine the main technical and economic barriers to the development and the diffusion of these kinds of algae cultivation plants.

The most relevant barriers concerning open ponds are:

- large surface required for the plant;
- cultivation system applicable only to some microalgae species;
- low final density and biomass productivity;
- poor mixing and low efficient use of carbon dioxide and light;
- significant water and consequent energy consumption for pumping, mixing, harvesting;
- difficulty in controlling temperature;
- high risk of contamination.

Concerning photobioreactors, the main barriers are:

- expensive installation due to material costs;
- expensive operation due to high energy consumptions for cooling;
- possible overheating of the reactor;
- toxic accumulation of oxygen, adverse pH and carbon dioxide gradients.

The analysis of the barriers and the definition of guidelines aimed at their overcoming will be the object of a further study within Task 3. Similarly, the SWOT analysis of algae processing and biofuels production technologies will be analyzed in a further study within Work Package 2.3, in order to cover the overall process of biofuel production from algae.

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ANNEX 1
SWOT ANALYSIS – MICROALGAE GROUPS

Doc. No. 12-920-H3
Rev. 1 – JUNE 2015

consulting, design, operation & maintenance engineering

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

SWOT Analysis of Microalgae Groups

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**ALGAE BIOENERGY SITING,
COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS
SWOT ANALYSIS MICROALGAE GROUPS**

1 INTRODUCTION

In the following paragraphs, the previously selected macroalgal species have been divided into groups using the available literature data (e.g. print, web, etc.) and taking into account the experience of Consortium and the outcomes of already funded completed and ongoing projects[1].

Species have been scored and grouped according to a set of criteria related to:

1. biological aspects relevant to biofuels production (biomass productivity, growth rate, lipid composition);
2. potential uses of algae co-products and possible application areas;
3. general indications concerning their cultivation both in open ponds and photobioreactors, using different water sources (freshwater, seawater and wastewater);
4. processing of microalgae biomass (e.g. harvesting, thickening and dewatering);
5. environmental impacts (e.g. potential harmful effects of microalgae on human health and aquatic ecosystems).

A data matrix has been prepared to elaborate the information, containing, for each species, assessments of each considered criteria, giving them a score: a value of 5 corresponds to positive aspects, 3 points out the coexistence of negative and positive aspects, 1 corresponds to negative aspects. Because of the lack of information or the presence of incomplete data, it has not been possible to assign a score to each species concerning some criteria.

From this data matrix, a similarity one was constructed and a cluster analysis was performed to select groups of algae according to their similarity (see figure 1.1).

Data analysis has led to the identification of the following three main groups:

1. Group 1: 1 Chlorophyta Dunaliella salina and Dunaliella spp. and 2 Ochrophyta Nannochloropsis spp. and Phaeodactylum tricornutum;
2. Gropu 2: 4 Chlorophyta Chlorella vulgaris and Chlorella spp., Scenedesmus spp., Chlorococcum spp., Tetraselmis suecica and Tetraselmis spp;
3. Group 3: 3 Chlorophyta Botryococcus braunii, Haematococcus pluvialis and Neochloris oleoabundans.

[1] With particular attention to the activities developed within FP7 AquaFUELs framework.

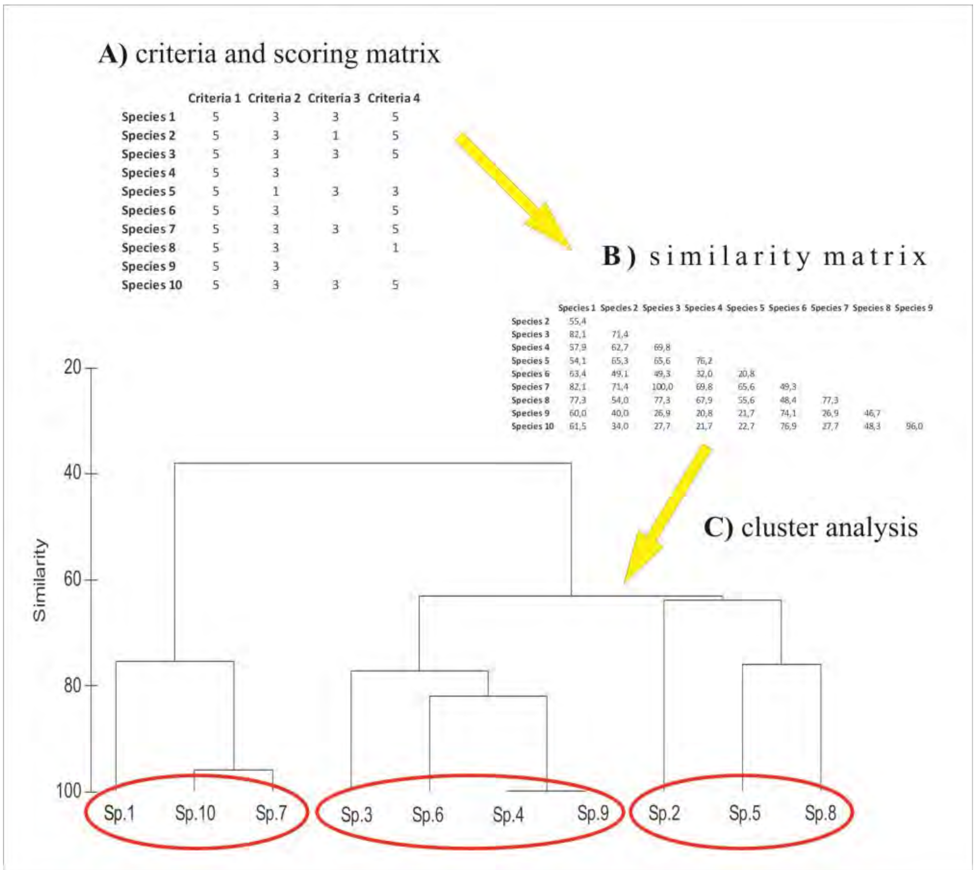

Figure 1.1: Data Analysis Process

1.1 *GROUP 1*

The group 1 is composed of three marine species/genus (*Dunaliella salina* and *Dunaliella* spp., *Nannochloropsis* spp. and *Phaeodactylum tricornutum*) (freshwater species of *Dunaliella* and *Nannochloropsis* have also been described). These microalgae show a good response to cultivation in open ponds and closed photobioreactors and can be successfully grown using seawater and seawater mixed with wastewater. Their lipid content and productivity, together with a good growth rate, make them suitable for biofuel production. Moreover they are cultivated as sources of valuable compounds widely used in aquaculture, cosmetics, pharmaceutical and human food industries.

The following tables summarize the evaluation of microalgae groups suitability, regarding:

a) different cultivation plants and considering different water sources;

b) different harvesting and biomass processing methods.

	Open Pond					Photobioreactor			
a)	sw	fw	ww	sw+ww	fw+ww	sw	fw	ww	fw+ww
	x	?	?	x	?	x	?	?	?

(sw = seawater; fw = freshwater; ww = wastewater) x = sufficient/good response of all the species of group 1 to cultivation;

? = few, incomplete or conflicting data concerning some or all of species of group 1.

b)

Harvesting						Biomass processing			
FL	FT	GS	C	FI	UA	SD	SE	SFE	HL
x	x	?	x	?	?	x	?	?	?

(FL = flocculation; FT = flotation; GS = gravity sedimentation; C = centrifugation; FI = filtration; UA = ultrasonic aggregation; SD = solar drying; SE = solvent extraction; SFE = supercritical fluid extraction; HL = hydrothermal liquefaction)

x = sufficient/good response of all the species of group 1 to processing method;

? = few, incomplete or conflicting data concerning some or all of species of group 1.

1.1.1 Strengths

- CULTIVATION PLANTS: literature reports that these microalgae are able to grow in open ponds and closed photobioreactors, using seawater and seawater mixed with wastewater (D'Elia et al, 1979; Chini Zittelli et al., 1999; Craggs et al., 1996; Ravishankar et al., 2012; Sukenik et al., 2009; Silva Benavides et al., 2013; Dong et al., 2014; Chinnasamy et al., 2010);
- PRODUCTIVITY: these species have good lipid content and productivity and a good growth rate (*Dunaliella* is a fast growing alga) (Ahmad et al., 2011; Griffiths and Harrison, 2009; Takagi et al., 2006; Mata et al., 2010; Pal et al., 2011; Rodolfi et al., 2009).

1.1.2 Weaknesses

- BIOMASS PROCESSING: *Dunaliella* species are very sensitive to shear damage (e.g. during pumping of the culture for circulation in closed systems) (Borowitzka, 1990);
- CULTIVATION PLANTS: there is the possibility of contamination by other species of microalgae and protozoa (Boussiba et al., 1987; Borowitzka, 1990).

1.1.3 Opportunities

- CULTIVATION PLANTS: wastewater can be used as a nutrient source to reduce the production and processing costs of microalgae based biofuels (Chamoli Bhatt et al., 2014);
- CULTIVATION PLANTS: these species can be used for bioremediation treatment of industrial wastewater (Putri and Muhaemin, 2010; Priyadarshani et al., 2011; Qari et al., 2014);
- APPLICATION AREAS: these species are widely used in aquaculture, cosmetics, pharmaceutical, human food industries (Borowitzka, 1992; Spolaore et al., 2006; Nizard et al., 2007; Tredici et al., 2009; Priyadarshani and Rath, 2012; Kim et al., 2012).

1.1.4 Threats

- ENVIRONMENTAL IMPACTS: it is possible that cultivated algae will escape into the environment (e.g. because of the emissions to water courses) even with strict regulations (Slade and Bauen, 2013). The subsequent impacts are unknown.

1.2 *GROUP 2*

The group 2 is composed of four species/genus: three freshwater species (*Scenedesmus* spp., *Chlorococcum* spp., *Chlorella vulgaris* and *Chlorella* spp.) and one marine species (*Tetraselmis suecica* and *Tetraselmis* spp.). These microalgae show a good response and adaptation ability to cultivation in open ponds and closed photobioreactors, using freshwater, wastewater and freshwater mixed with wastewater. They are suitable for biofuel production because of their growth rate, lipid content and productivity and are widely used in aquaculture and human food industries. Particular attention should be paid to the cultivation of *Chlorella*, *Scenedesmus* and *Chlorococcum*, known to be significant propagator of allergic reactions such as dermatitis.

The following tables summarize the evaluation of microalgae groups suitability regarding:

a) different cultivation plants and considering different water sources;

b) different harvesting and biomass processing methods.

a)

Open Pond					Photobioreactor			
sw	fw	ww	sw+ww	fw+ww	sw	fw	ww	fw+ww
?	x	x	?	x	?	x	x	x

(sw = seawater; fw = freshwater; ww = wastewater)

x = sufficient/good response of all the species of group 2 to cultivation;

? = few, incomplete or conflicting data concerning some or all of species of group 2.

b)

Harvesting						Biomass processing			
FL	FT	GS	C	FI	UA	SD	SE	SFE	HL
x	x	?	x	?	?	x	?	?	?

(FL = flocculation; FT = flotation; GS = gravity sedimentation; C = centrifugation; FI = filtration; UA = ultrasonic aggregation; SD = solar drying; SE = solvent extraction; SFE = supercritical fluid extraction; HL = hydrothermal liquefaction)

x = sufficient/good response of all the species of group 2 to processing method;

? = few, incomplete or conflicting data concerning some or all of species of group 2.

1.2.1 Strengths

- CULTIVATION PLANTS: these microalgae can grow in open ponds and closed photobioreactors, using freshwater, wastewater and freshwater mixed with wastewater, showing good adaptation ability (Chinnasamy et al., 2010; Krishna et al., 2012; Mata et al., 2013; Habib and Parvin, 2008; Wang et al., 2010; Ramos Tercero et al., 2014; Mahapatra and Ramachandra, 2013; Zhang and Lee, 1999);

- PRODUCTIVITY: literature reports that these species have good lipid content and productivity and a good growth rate (*Chlorella* and *Scenedesmus* are fast growing algae) (Griffiths and Harrison, 2009; Ahmad et al., 2011; Mata et al., 2010; Chini Zitelli et al., 2006; Ravishankar et al., 2012; Gris et al., 2013; Demirbas, 2009; Rodolfi et al., 2009; Doucha and Lívanský, 2009; Masojídek et al., 2000; Bharanidharan et al., 2013).

1.2.2 Weaknesses

- CULTIVATION PLANTS: possibility of contamination by other species of microalgae and protozoa (Bínová et al., 1998).

1.2.3 Opportunities

- CULTIVATION PLANTS: wastewater can be used as a nutrient source to reduce the production and processing costs of microalgae based biofuels (Chamoli Bhatt et al., 2014);
- CULTIVATION PLANTS: these species can be used for bioremediation treatment of industrial wastewater (Chinnasamy et al., 2010; Krishna et al., 2012; Kshirsagar, 2013; Priyadarshani et al., 2011; Ahmad et al., 2013);
- APPLICATION AREAS: these species are widely used in aquaculture and human food industries (Tredici et al., 2009; Mata et al., 2010; Guedes et al., 2009; Ma and Chen, 2001; Muller-Feuga et al., 2003; Harel and Clayton, 2004; Sakthivel et al., 2011).

1.2.4 Threats

- ENVIRONMENTAL IMPACTS: *Chlorella*, *Scenedesmus* and *Chlorococcum* are known to be significant propagators of allergenic diseases or cause dermatitis in some people (Genitsaris et al., 2011; Dubey et al., 2010);
- ENVIRONMENTAL IMPACTS: *Chlorella* is the most frequent air-dispersed allergenic alga over short distances (< 1 km) (Genitsaris et al., 2011);
- ENVIRONMENTAL IMPACTS: it is possible that cultivated algae will escape into the environment (e.g. because of the emissions to water courses) even with strict regulations (Slade and Bauen, 2013). The subsequent impacts are unknown.

1.3 *GROUP 3*

The group 3 is composed of three freshwater species (*Botryococcus braunii*, *Haematococcus pluvialis* and *Neochloris oleoabundans*). These microalgae can be grown in open ponds and closed photobioreactors, using freshwater and freshwater mixed with wastewater; however *H. pluvialis* and *B. braunii* are susceptible to environmental fluctuations. The lipid content and composition make them suitable for biofuel production although their growth rate and productivity are lower than those of the other two groups. Moreover they are cultivated as sources of valuable compounds widely used in aquaculture and human food industries.

The following tables summarize the evaluation of microalgae groups suitability regarding:

a) different cultivation plants and considering different water sources;

b) different harvesting and biomass processing methods.

a)

Open Pond					Photobioreactor			
sw	fw	ww	sw+ww	fw+ww	sw	fw	ww	fw+ww
?	x	?	?	?	?	x	?	x

(sw = seawater; fw = freshwater; ww = wastewater)

x = sufficient/good response of all the species of group 3 to cultivation;
? = few, incomplete or conflicting data concerning some or all of species of group 3.

b)

Harvesting						Biomass processing			
FL	FT	GS	C	FI	UA	SD	SE	SFE	HL
x	x	?	?	?	?	x	?	?	x

(FL = flocculation; FT = flotation; GS = gravity sedimentation; C = centrifugation; FI = filtration; UA = ultrasonic aggregation; SD = solar drying; SE = solvent extraction; SFE = supercritical fluid extraction; HL = hydrothermal liquefaction)

x = sufficient/good response of all the species of group 3 to processing method;

? = few, incomplete or conflicting data concerning some or all of species of group 3.

1.3.1 Strengths

- CULTIVATION PLANTS: these microalgae are able to grow in open ponds using freshwater and in closed photobioreactors using freshwater and freshwater mixed with wastewater (Pruvost et al., 2009; Wang and Lan, 2011; Metzger and Largeau, 2005; Rao et al., 2014; Orpez et al., 2009; Krishna et al., 2012; Wu et al., 2013).

1.3.2 Weaknesses

- PRODUCTIVITY: these species have good lipid content but both a relatively slow growth rate and a low lipid productivity of *Botryococcus braunii* and *Haematococcus pluvialis* have been determined (Masojídek et al., 2000; Orpez et al., 2009; Mata et al., 2010; Rao et al., 2014; Qin, 2005; Priyadarshani and Rath, 2012; Metzger and Largeau, 2005; Huntley and Redalje, 2007);
- PRODUCTIVITY: the culture conditions of *Botryococcus braunii* in open systems are less controlled than in closed reactors, consequently the biomass productivity is low compared with closed photobioreactors (Rao et al., 2014);
- PRODUCTIVITY: a relatively slow growth rate of *Botryococcus braunii* has been determined using the residual water (proceeding from secondary treatment) as culture medium (Orpez et al., 2009);
- PRODUCTIVITY: *Haematococcus pluvialis* and *Botryococcus braunii* are susceptible to environmental fluctuations (Fan et al., 1994; Qin et al., 2005);
- CULTIVATION PLANTS: outdoor cultures of *Botryococcus braunii* and *Haematococcus pluvialis* are easily contaminated by other algae (Masojídek et al., 2000; Metzger and Largeau, 2005).

1.3.3 Opportunities

- PRODUCTIVITY: wastewater can be used as a nutrient source to reduce the production and processing costs of microalgae based biofuels (Chamoli Bhatt et al., 2014);
- PRODUCTIVITY: these species can be used for bioremediation treatment of industrial wastewater (Banerjee et al., 2002; Wang and Lan, 2011; Wu et al., 2013);
- APPLICATION AREAS: literature reports that these species are widely used in human food industries (Mata et al., 2010; Chue et al., 2012; Priyadarshani and Rath, 2012). *Haematococcus pluvialis* and *Neochloris oleoabundans* are also used as aquaculture feed (Spolaore et al., 2006; Priyadarshani and Rath, 2012)

1.3.4 Threats

- ENVIRONMENTAL IMPACTS: blooms of *Botryococcus braunii* have been shown to be toxic to a variety of aquatic micro-organisms and fishes (Chiang et al., 2004);
- ENVIRONMENTAL IMPACTS: it is possible that cultivated algae will escape into the environment (e.g. because of the emissions to water courses) even with strict regulations (Slade and Bauen, 2013). The subsequent impacts are unknown.

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ANNEX 2
SWOT ANALYSIS – MICROALGAE HARVESTING AND BIOMASS PROCESSING METHODS

Doc. No. 12-920-H3
Rev. 1 – JUNE 2015

D'APPOLONIA
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Algae Bioenergy Siting, Commercial Deployment and Development Analysis

SWOT Analysis Microalgae Harvesting and Biomass Processing Methods

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**ALGAE BIOENERGY SITING,
COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS
SWOT ANALYSIS MICROALGAE HARVESTING AND BIOMASS PROCESSING METHODS**

1 MICROALGAE HARVESTING METHODS

The choice of harvesting technique is dependent on characteristics of microalgae, e.g. size, density, and the value of the target products (Olaizola, 2003). Generally, microalgae harvesting is a two-stage process, involving:

1. Bulk harvesting: aimed at separation of biomass from the bulk suspension. The concentration factors for this operation are generally 100–800 times to reach 2–7% total solid matter. This will depend on the initial biomass concentration and technologies employed, including **flocculation**, **flotation** or **gravity sedimentation**;
2. Thickening: the aim is to concentrate the slurry through techniques such as **centrifugation**, **filtration** and **ultrasonic aggregation**, hence, is generally a more energy intensive step than bulk harvesting (Brennan and Owende, 2010).

1.1 FLOCCULATION

Flocculation is a preparatory step prior to other harvesting methods such as filtration, flotation or gravity sedimentation (Brennan and Owende, 2010; Milledge and Heaven, 2013; Molina Grima et al., 2003).

Since microalgae cells carry a negative charge that prevents natural aggregation of cells in suspension, addition of flocculants such as multivalent cations and cationic polymers neutralises or reduces the negative charge. It may also physically link one or more particles through a process called bridging, to facilitate the aggregation (Molina Grima et al., 2003).

Increasing the size of particles by the aggregation of algal cells through flocculation can increase the rate of settling or flotation (Mata et al., 2010).

Multivalent metal salts like ferric chloride ($FeCl_3$), aluminium sulphate ($Al_2(SO_4)_3$) and ferric sulphate ($Fe_2(SO_4)_3$) are suitable flocculants.

1.1.1 Strengths

- Possibility of handle large quantities of microalgal suspension (Uduman et al., 2010);
- Possibility of handle a wide range of microalgae (Uduman et al., 2010);
- Suggested as the most reliable and cost-effective method (Milledge and Heaven, 2013).

1.1.2 Weaknesses

- Quite expensive (Benemann et al., 1980);
- High dosage of multivalent salt is required to achieve satisfactory result (Lam and Lee, 2012);
- Produces large quantity of sludge that increases the difficulty to dehydrate the biomass (Lam and Lee, 2012);
- The efficiency is highly dependent on pH level (Chen et al., 2010; Renault et al., 2009).

1.1.3 Opportunities

- Cationic polyelectrolytes more effective at flocculating freshwater microalgae than metal salts, achieving high biomass concentration (concentration factor up to 35 times) at lower dosage rates of 2–25 mg l^{-1} (Granados et al., 2012);
- Flocculation of some microalgae can be achieved by adjustment of pH (Molina Grima et al., 2003; Shelef et al., 1984) (Molina Grima et al., 2003);
- Organic polymeric flocculant, which is biodegradable and less toxic, offers an alternative and environmental friendly way to aggregate suspended particles (Lam and Lee, 2012);
- Microbial flocculant or biofocculant has emerged as a new research trend in flocculation technology (Lam and Lee, 2012);
- Interrupting the carbon dioxide supply to an algal system can cause algae in it to flocculate on its own, which is called autoflocculation (Amin, 2009).

1.1.4 Threats

- Flocculants may be algae species-specific (Mohn, 1988; Molina Grima et al., 2003; Oswald, 1988; Shen et al., 2009);
- Recovery and recycling of the flocculants can be problematic (Mohn, 1988; Molina Grima et al., 2003; Oswald, 1988; Shen et al., 2009);
- Inorganic flocculants can also have negative effects on microalgal viability and can colour and modify microalgal growth media, preventing recycling and reuse (Molina Grima et al., 2003; Papazi et al., 2010; Schenk et al., 2008);
- The dosage of flocculants to flocculate marine microalgae has been found to be 5–10 times higher than that for freshwater microalgae (Knuckey et al., 2006; Milledge and Heaven, 2013; Uduman et al., 2010);
- The shape, size and composition of flocs can be very diverse depending on microalgal species and flocculant (Jago et al., 2007);
- Inorganic flocculants can be toxic (Harith et al., 2009);
- Extreme pH may cause microalgal damage and death and could be unreliable and uneconomic on a commercial scale (Benemann and Oswald, 1996; Lee et al., 2009);
- Polymeric flocculant (especially cationic type) is ineffective for marine microalgae due to inhibition by high ionic strength of seawater (Bilanovic et al., 1988) (Lam and Lee, 2012);
- Flocculation using multivalent metal salts will contaminate the algal biomass (Mohn, 1988);
- Bioflocculation, induced by environmental stresses such as extreme pH, temperature or nutrient depletion, may cause cell composition changes and is generally considered as too unreliable to be economical on a commercial scale (Benemann and Oswald 1996).

1.2 FLOTATION

Flotation methods are based on the trapping of algae cells using dispersed micro-air bubbles and therefore, unlike flocculation, does not require any addition of chemicals (Wang et al., 2008). Some strains naturally float at the surface of the water as the microalgal lipid content increase (Bruton et al., 2009). Flotation can be promoted by addition of air bubbles (Singh et al., 2011).

1.2.1 Strengths

- It does not require any addition of chemicals (Wang et al., 2008);
- Some microalgal strains natural float at the surface of the water when their lipid content increases (Gultom and Hu, 2013).

1.2.2 Weaknesses

- Flotation methods are limited in technical and economic viability (Gultom and Hu, 2013).

1.2.3 Opportunities

- It could be more useful in salt rather than fresh water (Oswald, 1988).

1.2.4 Threats

- The addition of flocculants is required in most cases for flotation to be effective (Edzwald, 1993; Mohn, 1988);
- If small bubbles are required, the energy usage for the flotation processes will be very high, which inevitably results in high operational costs and therefore a required high investment (Gultom and Hu, 2013);
- The costs can be even greater when the costs of flocculants are included (Gultom and Hu, 2013);
- Electrolytic flotation method is very energy-intensive (Gultom and Hu, 2013);
- There is very limited evidence of its technical or economic viability (Gultom and Hu, 2013; Milledge and Heaven, 2013).

1.3 GRAVITY SEDIMENTATION

In sedimentation gravitational forces cause liquid or solid particles to separate from a liquid of different density, but the process can be extremely slow especially if density difference or particle size is small. Sedimentation can be described by Stokes' Law which assumes that sedimentation velocity is proportional to the square of the (Stokes') radius of the cells and the difference in density between the microalgal cells and the medium as shown below:

$$Setting\ velocity = \frac{2}{9} g \frac{r^2}{\eta} (\rho_s - \rho_l)$$

where r is cell radius, g is fluid dynamic viscosity and ρ_s and ρ_l are the solid and liquid densities. (Milledge and Heaven, 2013)

1.3.1 Strengths

- Energy consumption of settlement harvesting is generally low (Milledge and Heaven, 2013).

1.3.2 Weaknesses

- Slow process;
- Low cell recovery and solid concentrations (Mata et al., 2010; Shen et al., 2009) with cell recoveries of 60–65% (Collet et al., 2011; Ras et al., 2011) and solid concentrations of up to 1.5% total suspended solids (Uduman et al., 2010).

1.3.3 Opportunities

- Settlement of colonial and larger microalgae could be useful as a pre-concentration step for use with other harvesting techniques (Milledge and Heaven, 2013).

1.3.4 Threats

- Needle like or long cylindrical microalgae being particularly resistant to settling (Choi et al., 2006);
- Smaller algae (*Chlorella*) and motile microalgae (*Euglena*, *Chlorognium*) do not readily settle out of suspension (Nurdogan and Oswald, 1996);
- The settlement of microalgae varies between species, but can also alter within the same species (Milledge and Heaven, 2013);
- Settlements rates have been shown to vary with light intensity (Lam and Lee, 2012);
- Nutrient deficiency has been shown to decrease settlement rate (Lam and Lee, 2012);
- Sinking rate increases in older cells especially in senescent cells (non-dividing cells between maturity and death) (Smayda, 1970) and spore-producing cells (Lam and Lee, 2012);
- Microalgae with a high lipid content are likely to settle less readily due to the lower density (Lam and Lee, 2012).

1.4 CENTRIFUGATION

In centrifugation, gravity is replaced as the force driving separation by a much greater force (Milledge and Heaven, 2013).

1.4.1 Strengths

- Centrifuges can process large volumes relatively rapidly and the biomass can remain fully contained during recovery (Molina Grima et al., 2003);
- Harvesting efficiency of >95% (Heasman et al., 2000);
- Almost all types of microalgae can be separated reliably and without difficulty by centrifugation (Mohn, 1988).

1.4.2 Weaknesses

- High energy costs (Bosma et al., 2003);
- Potentially higher maintenance requirements due to freely moving parts (Bosma et al., 2003).

1.4.3 Opportunities

- Suitable for high value products (Molina Grima et al., 2003).

1.4.4 Threats

- A cell harvest efficiency of >95% was obtained only at 13,000×g. The harvest efficiency declined to 60% at 6000×g and 40% at 1300×g (Molina Grima et al., 2003).

1.5 FILTRATION

1.5.1 Strengths

- For processing of low broth volumes (<2m^3 per day), membrane filtration can be more cost effective compared to centrifugation.

1.5.2 Weaknesses

- Conventional filtration cannot be used to harvest algae species approaching bacterial dimensions (<30 mm);
- Owing to the cost for membrane replacement and pumping in larger scales of production (>20m^3 per day), centrifugation may be a more economic method of harvesting the biomass (MacKay and Salusbury, 1988);
- Ultrafiltration is a possible alternative for recovery, in particular of very fragile cells, but has not been generally used for microalgae (Mata et al., 2010; Molina Grima et al., 2003), and operating costs are high and maintenance costs very high (Mata et al., 2010; Purchas, 1981);
- Membrane replacement and pumping are the major cost contributors to membrane filtration processes (Molina Grima et al., 2003).

1.5.3 Opportunities

- For recovery of smaller algae cells (<30 mm), membrane microfiltration and ultra-filtration are technically viable alternatives to conventional filtration (Petruševski et al., 1995);
- Filter presses have found wide application in industry due to the simple design, flexibility and capability to handle a wide range of slurries, and have been used to reduce the number of bacteria and yeast in wine (Brennan et al., 1969; Richardson et al., 2002);
- Microfiltration is suitable for fragile cells (Petrusevski et al., 1995);
- Generally, microfiltration can be more cost-effective than centrifugation if only small volumes (e.g., <2 m^3 day^{-1}) are to be filtered (Molina Grima et al., 2003).

1.5.4 Threats

- Conventional filtration process is most appropriate for harvesting of relatively large (>70 mm) microalgae;
- Membrane filtration has not been widely used for producing microalgal biomass on a large scale and could be less economic than centrifugation at commercial scale (Molina Grima et al., 2003);
- Concerning filter presses, although the equipment is relatively cheap, labour costs can be high and cake washing is not always effective (Brennan et al., 1969; Richardson et al., 2002);
- Filtration can be relatively slow (Molina Grima et al., 2003);
- Recovery by precoat filtration is not suitable if contamination of the biomass with filter aid cannot be tolerated. This would generally be the case if the biomass is intended for use as aquaculture feed, or further processing is required for extracting intracellular products from the biomass (Molina Grima et al., 2003);
- Large-scale processes for producing algal biomass do not generally use membrane filtration (Molina Grima et al., 2003);
- For larger scale of production (e.g., >20 m^3 day^{-1}), centrifugation may be a more economic method of recovering the biomass (MacKay and Salusbury, 1988);
- Membrane fouling and clogging due to the small size of the microalga (Bosma et al., 2003).

1.6 ULTRASONIC AGGREGATION

Gentle, acoustically induced aggregation followed by enhanced sedimentation can also be used to harvest microalgae biomass (Bosma et al., 2003; Show et al., 2013).

1.6.1 Strengths

- It can be operated continuously without inducing shear stress on the biomass, which could destroy potentially valuable metabolites (Bosma et al., 2003);
- Non-fouling technique (Bosma et al., 2003);
- Absence of mechanical failures because this device has no freely moving parts (Bosma et al., 2003);
- Efficiencies higher than 90% were recorded at high biomass concentrations and flow rates between 4 and 6 l d^{-1} (Bosma et al., 2003; Show et al., 2013);
- As much as 92% of the algae biomass could be harvested with a concentration factor of 11.

1.6.2 Weaknesses

- Attempts to harvest at higher efficiency were unfruitful due to small size and low particle density of the microalgae (Bosma et al., 2003; Show et al., 2013).

1.6.3 Opportunities

- n.a.

1.6.4 Threats

- Feed flow rate, biomass concentration and ratio between harvest and feed flows had a significant effect on the concentration factor (Bosma et al., 2003; Show et al., 2013).

2 BIOMASS PROCESSING METHODS

2.1 DRYING + EXTRACTION

Unlike terrestrial energy crops, extensive drying of microalgae biomass is required for biofuels production as the presence of water will inhibit several downstream processes, such as lipid extraction and transesterification (Lam and Lee, 2012).

2.1.1 Solar Drying

2.1.1.1 Strengths

- Assumed to be the best method to dry wet microalgae paste after the harvesting process (Lam and Lee, 2012).

2.1.1.2 Weaknesses

- In the case of temperate countries, is necessary to couple solar drying to heat generated from fossil fuels is required to dry microalgae biomass continuously to ensure optimum biomass production for each cycle of culture (Lam and Lee, 2012).

2.1.1.3 Opportunities

- n.a.

2.1.1.4 Threats

- Drying is not feasible in temperate countries due to limited sunlight at certain time of the year.

After harvesting and drying microalgae biomass, the subsequent step is lipid extraction. Although the energy consumed in lipid extraction from dried microalgae biomass contributed a relatively small portion to the overall energy life cycle of microalgae biofuels (around 5–10%) (Sander and Murthy, 2010; Stephenson et al., 2010), but this process is still very important. Effective lipid extraction is required particularly for microalgae with low lipid content as losing the lipid during extraction process may bring a significant impact towards the production cost of microalgae biofuels (Ranjan et al., 2010). Different from terrestrial energy crops, lipid extraction from microalgae biomass is relatively difficult due to the presence of thick cell wall that prevents the release of intra-lipid (Lam and Lee, 2012).

2.1.2 Solvent Extraction

2.1.2.1 Strengths

- Chemical solvent has high selectivity and solubility towards lipid and therefore, even inter-lipid can be extracted out through diffusion across microalgae cell wall (Ranjan et al., 2010);
- n-hexane, methanol, ethanol and mixed methanol–chloroform (2:1 v/v) (Bligh and Dyer method) are effective to extract microalgae lipid.

2.1.2.2 Weaknesses

- High toxicity towards human and surrounding environment;
- n-hexane, methanol and chloroform are highly toxic compounds that can cause safety and health hazards if proper precaution steps are not taken;
- Diffusion is always the rate limiting factor in the overall mechanism, this factor becomes more serious in microalgae as the cell wall further prohibits solvent from diffusing into the inner cell for lipid extraction.

2.1.2.3 Opportunities

- Use of ethanol, emerged as a greener solvent since it has low toxicity level and can be derived from renewable sources such as sugar-based plant (e.g. sugar cane and sweet sorghum) and lignocellulosic material (e.g. wood and corn stover);
- Cells disruption method can be introduced to enhance solvent diffusion efficiency and consequently, to improve microalgae lipid recovery rate.

2.1.2.4 Threats

- Extraction efficiency is highly dependent on microalgae strains;
- It is not sustainable to use n-hexane and methanol since both solvents are conventionally derived from non-renewable fossil fuels;
- Ethanol always give low extraction efficiency, mainly because ethanol is an azeotrop mixture (with 5% of water) and the presence of water may possibly reduce its extraction efficiency.

2.1.3 Supercritical Fluid Extraction

2.1.3.1 Strengths

- Non-toxic and provide non-oxidizing environment to avoid degradation of extracts;
- Low critical temperature (around 31 °C) which prevent thermal degradation of product;
- High diffusivity and low surface tension which allow penetration of pores smaller than those accessible by chemical solvents;
- Easy separation of CO_2 at ambient temperature after extraction (Jaime et al., 2007; Mendes et al., 2003; Ota et al., 2009);
- The lipid yield attained from the wet-paste is even higher than dry biomass suggesting that energy consumed in drying process can be reduced through supercritical technology;
- Facilitated the extraction of polar lipids and improve total lipid yield extracted.

2.1.3.2 Weaknesses

- High cost of operation and safety related issues

2.1.3.3 Opportunities

- n.a.

2.1.3.4 Threats

- Microalgae strains and culture conditions plays a significant role in determining the appropriate lipid extraction methods;
- The energy required in separating pure CO_2 from atmosphere and re compressing the CO_2 after each extraction should not be ignored.

2.2 HYDROTHERMAL LIQUEFACTION

The water content of the biomass will directly impede transesterification efficiency and caused incomplete biodiesel conversion. Drying of wet microalgae biomass consumed exceptional huge amount of energy typically in temperate countries where sunlight is not available throughout the year. Furthermore, external heat which is usually generated from non- renewable sources (e.g. natural gas and coal) makes the drying process unsustainable for long term practice. In this regard, hydrothermal liquefaction could be an alternative way to produce bio-oil from microalgae through aqueous-conversion method, in which freshly harvested wet microalgae biomass are directly processed without drying. Microalgae are expected to be an excellent biomass feedstock for this technology because their small size will enhance rapid thermal transfer up to the required processing temperature (Heilmann et al., 2010). During hydrothermal liquefaction, water is heated to sub-critical condition (200 to 350 °C) under pressurized condition in order to reduce its dielectric constant. The dielectric constant can even drop to similar value as ethanol and thus, able to solubilise less polar compounds (Duan and Savage, 2011; Kumar et al., 2011). In other words, water at sub-critical condition can serve as an effective solvent but is significantly less corrosive than other chemical solvents (Lam and Lee, 2012).

2.2.1 Strengths

- Freshly harvested wet microalgae biomass are directly processed without drying (Lam and Lee, 2012);
- The process gave a positive energy (Lam and Lee, 2012);
- Allows the biomass to be converted wet with very high water contents, thus eliminating a major cost and energy consumption associated with drying (Biller and Ross, 2011);
- Algae are therefore especially suited for conversion by hydrothermal liquefaction and can be harvested as a wet slurry (Biller and Ross, 2011);
- In algal biodiesel production, the lipids produce the bulk of the biofuel, whereas in hydrothermal processing, the proteins and carbohydrates can also be converted to bio-oil;
- For both high lipid microalgae (Brown et al., 2010; Sawayama et al., 1999) and low lipid microalgae (Ross et al., 2010; Yang et al., 2004);
- In most cases, the yields of bio-crude are 10–15% higher than the lipid content of the microalgae suggesting that oil is also derived from the carbohydrate and protein fractions;
- Lipids can be extracted while wet and upgraded to produce a crude oil like product (Biller et al., 2011);
- Conventional lipid extraction methods only produce oil from the lipid fraction while hydrothermal liquefaction can produce oil also from the carbohydrate and protein fraction.

2.2.2 Weaknesses

- LC-GHG emissions of producing algal biofuels using HTL as a conversion process and utilizing waste sources of water and nutrients for algal growth need to be fully assessed for commercial-scale applications. The greenhouse gas emissions from transporting larger volumes of water along with algal biomass may lead to prominent climate change impacts in the life cycle of algal bio-jet fuel (Fortier et al., 2014);
- Process not yet fully optimized and tested for microalgal biomass;
- The products should be analyzed in sufficient detail to perform closed mass and energy balances on the process, as well as determining the suitability of the oil phase as a feedstock for upgrading to transportation fuels (Johnson, 2012).

2.2.3 Opportunities

- Also for residues from lipid extraction (Torri et al., 2012).

2.2.4 Threats

- Chemical solvent such as dichloromethane (DCM) is required to extract bio-oil from aqueous phase or thermal treated bio-char in which significantly reduce the process viability in industrial scale.
- Separation of the chemical solvent from aqueous phase and bio-oil is necessary and possibly increase the overall energy input in the system.
- The aqueous phase may contains high concentration of organic matter that requires wastewater treatment before it can be discharged into water sources.
- There are more than 1000 different components in the bio-oil produced and therefore more research are required to completely utilized all these components effectively (Lam and Lee, 2012).

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ANNEX 3
SWOT ANALYSIS – ALGAE CULTIVATION PLANTS

Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

SWOT Analysis Algae Cultivation Plants

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**ALGAE BIOENERGY SITING,
COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS
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1 MICROALGAE CULTIVATION PLANTS

1.1 OPEN PONDS

1.1.1 Strengths

- Made of less expensive materials, their construction involves lower costs require less energy for mixing (Jorquera et al., 2010);
- Easy to clean;
- Low energy inputs;
- Easy maintenance.

1.1.2 Weaknesses

- Low final density of microalgae and poor biomass productivity (Jorquera et al., 2010);
- Large area of land required (Jorquera et al., 2010);
- Low efficiency of light utilization (Jorquera et al., 2010);
- Potentially carbon limited due to poor gas/liquid mass transfer (Christenson and Sims, 2011; Jorquera et al., 2010);
- Lack of temperature control (Jorquera et al., 2010).

1.1.3 Opportunities

- Temperature partially regulated through evaporation;
- Techniques to enhance CO_2 absorption into the culture media such as aerators or bubbling may improve the overall biomass productivity (Rawat et al., 2013);
- Improved mixing can minimise impacts of both CO_2 and light limitation thus improving productivity (Rawat et al., 2013).

1.1.4 Threats

- Poor mixing;
- High risk of culture contamination (Jorquera et al., 2010);
- Limited as to the type of microalgae that can be used for cultivation (Jorquera et al., 2010);
- Evaporative losses result in changes to ionic composition of the media and potentially detrimental effects on culture growth (Rawat et al., 2013);
- Changes in temperature, photo- period and seasonal variation are beyond control in open systems and directly affect productivity (Rawat et al., 2013).

1.2 PHOTOBIOREACTORS

1.2.1 Strengths

- Regulation and control of nearly all the biotechnologically important parameters (Pulz, 2001);
- Reduced contamination risk (Pulz, 2001);
- No CO_2 losses (Pulz, 2001);
- Reproducible cultivation conditions (Pulz, 2001);
- Controllable hydrodynamics, and temperature (Pulz, 2001);
- Higher volumetric productivity than open ponds (Jorquera et al., 2010);
- Better capture of radiant energy than open ponds (Jorquera et al., 2010);
- More optimal use of the cultivation area and variable energy consumption values for mixing and gas/liquid mass transfer (Jorquera et al., 2010);
- Only cultivation system suitable for the production of high-value products for applications in pharmaceuticals and cosmetics, because of its ability to keep consistent production conditions and thus to be GMP-relevant (GMP: good manufacturing practice following ISO and EC guidelines) (Pulz, 2001).

1.2.2 Weaknesses

- Made of expensive materials and high construction costs (Jorquera et al., 2010);
- High energy consumption for pumping to generate turbulent flow for optimized gas/liquid mixing and mass transfer (Jorquera et al., 2010);
- Need for costly and energy consuming temperature control (no possibility to exploit evaporation).

1.2.3 Opportunities

- Can be designed in a variety of configuration (Jorquera et al., 2010; Pulz, 2001);
- May be located indoors or outdoors (Molina Grima et al., 2003).

1.2.4 Threats

- Tubular reactors have not achieved significant adoption both because of operational challenges (toxic accumulation of oxygen, adverse pH and CO_2 gradients, overheating, bio-fouling) and high equipment and maintenance costs (Christenson and Sims, 2011; Mata et al., 2010).

1.3 WASTEWATER

Suspended cultures

1.3.1 Open Ponds (HRAPs, High Rate Algal Ponds or Raceway Ponds)

1.3.1.1 Strengths

- Raceways are relatively inexpensive to build and operate.

1.3.1.2 Weaknesses

- Often suffer low productivity due to contamination, poor mixing, dark zones, and inefficient use of CO_2 (Chisti, 2007; Christenson and Sims, 2011; Mata et al., 2010);
- Cannot be used for high-value products (particularly in pharmaceutical, nutraceutical, food/feed applications).

1.3.1.3 Opportunities

- High evaporation rate helps somewhat with temperature regulation through evaporative cooling (Christenson and Sims, 2011).

1.3.1.4 Threats

- Raceway ponds should theoretically have production levels of 50– 60 gm^{-2} day^{-1}, but in practice, productivity does not go beyond 10–20 gm^{-2} day^{-1} (Christenson and Sims, 2011; Shen et al., 2009);
- Significant challenges of biomass recovery (Christenson and Sims, 2011).

1.3.2 PBR

1.3.2.1 Strengths

- Tubular photobioreactors can give better pH and temperature control (Christenson and Sims, 2011);
- Better protection against culture contamination (Christenson and Sims, 2011);
- Better mixing (Christenson and Sims, 2011);
- Less evaporative loss (Christenson and Sims, 2011);
- Higher cell densities (Christenson and Sims, 2011);
- Reported productivities generally range from 20 to 40 gm^{-2} day^{-1} (Christenson and Sims, 2011; Shen et al., 2009).

1.3.2.2 Weaknesses

- Toxic accumulation of oxygen (Christenson and Sims, 2011; Mata et al., 2010);
- Adverse pH and CO_2 gradients (Christenson and Sims, 2011; Mata et al., 2010);
- Overheating (Christenson and Sims, 2011; Mata et al., 2010);
- High equipment and maintenance costs (Christenson and Sims, 2011; Mata et al., 2010);
- Cannot be used for high-value products (particularly in pharmaceutical, nutraceutical, food/feed applications).

1.3.2.3 Opportunities

- Helical designs are considered the easiest to scale up (Carvalho et al., 2006; Christenson and Sims, 2011).

1.3.2.4 Threats

- Oxygen removal can be a challenging issue (Christenson and Sims, 2011);
- Significant challenges of biomass recovery (Christenson and Sims, 2011).

1.3.3 Immobilized Cultures (Matrix-Immobilized Microalgae and Algae Biofilms)

1.3.3.1 Strengths

- Efficient nutrient removal (Christenson and Sims, 2011);
- Result in enhanced hydrocarbon production, increased cellular pigment, lipid content, and lipid variety (Christenson and Sims, 2011);
- If enough surface area is provided, algae biofilm growth can be more than suspended growth (Christenson and Sims, 2011);
- Algal biofilms could play a large role in overcoming the major challenges to production and harvesting of microalgae (Christenson and Sims, 2011).

1.3.3.2 Weaknesses

- High cost of the immobilization matrix (Christenson and Sims, 2011);
- Cannot be used for high-value products (particularly in pharmaceutical, nutraceutical, food/feed applications).

1.3.3.3 Opportunities

- Surface attached algal biofilms can offer the same increased culture density and lower land and water requirements of matrix-immobilized cultures without the associated costs of the matrix (Christenson and Sims, 2011);
- Algal biofilm system can better integrate production, harvesting, and dewatering operations, than suspended cultures (Christenson and Sims, 2011);
- Algae biofilms are likely to be benefited by bacteria present in wastewater (Christenson and Sims, 2011).

1.3.3.4 Threats

- Such designs have thus far been confined to the laboratory (Christenson and Sims, 2011);
- At the scale necessary for wastewater treatment and biofuel production, the cost of the polymeric matrix becomes prohibitive (Christenson and Sims, 2011).

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ANNEX 4
SWOT ANALYSIS – ALGAE CULTIVATION PLANTS –
ECONOMIC PARAMETERS

Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

European Commission
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Algae Bioenergy Siting, Commercial Deployment and Development Analysis

SWOT Analysis Algae Cultivation Plants – Economic Parameters

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1 ECONOMIC APPROACH

An economic assessment of algae production processes in use, based on a full knowledge of costs and benefits of the set of technologies proposed, is a first step for a better understanding of what should be done (in terms of improvement of technologies and production methods) to reduce the risks to invest in bio-fuel production from algae.

Economic assessment of micro-algae production systems deals with costs and benefits considered as key parameters for decision making process. It is worth noticing than biodiesel and bio-fuel production from algae exhibits still high production and commercialization costs compared to other bio-fuel and remain currently non-competitive with fossil energy sources. Further improvements in reducing costs and developing by-products and external benefits from algae production are necessary to overcome the economic barriers still present in this sector.

The approach adopted in literature to address the economic issues of micro-algae production systems is mainly based on a process chain analysis: at each component of the chain - from algae cultivation to bio-fuel transformation and commercialization - the economic costs and benefits (products) of a given technology are associated (see flowchart below). Note that the investment phase and the operational phase are often clearly distinguished by authors, as they engender different monetary flows and are related to different periods of the investment lifecycle (*equipment* in the initial phase versus *raw materials* in production phase). Total production cost is given by the sum of depreciation costs (cost of capital over the plant lifecycle) and operational costs.

The production costs are mainly related to:

- land requirement (surface);
- size and type of equipment;
- lifetime of the investments;
- maintenance costs;
- energy and nutriments consumption during processing and harvesting;
- labour and engineering costs, in both investment and production phases.

Co-products and services delivered by the algae production are related to bio-fuel, bio-ethanol and bio-methane, feed for animals, biomass for energy production, fertilizer used and others (pigments and chemicals). Other indirect benefits (or avoided costs) should also be mentioned to draw a clear picture of the economic situation. Such elements derived from external costs and benefits not always considered in economic calculations, for example the storage of carbon dioxide by algae or the use of wastewater as source of nutriments. In the case of wastewater, benefits come from the reduction of inputs to be purchased, as nutriments are directly delivered by the wastewater flow, the wastewater treatment costs not covered by the community and the reduction of eutrophication, and related ecological costs, due to wastewater release in ecosystems[1]. However a more in-depth analysis of direct and indirect environmental effects should be provided by lifecycle assessments (see section of this report).

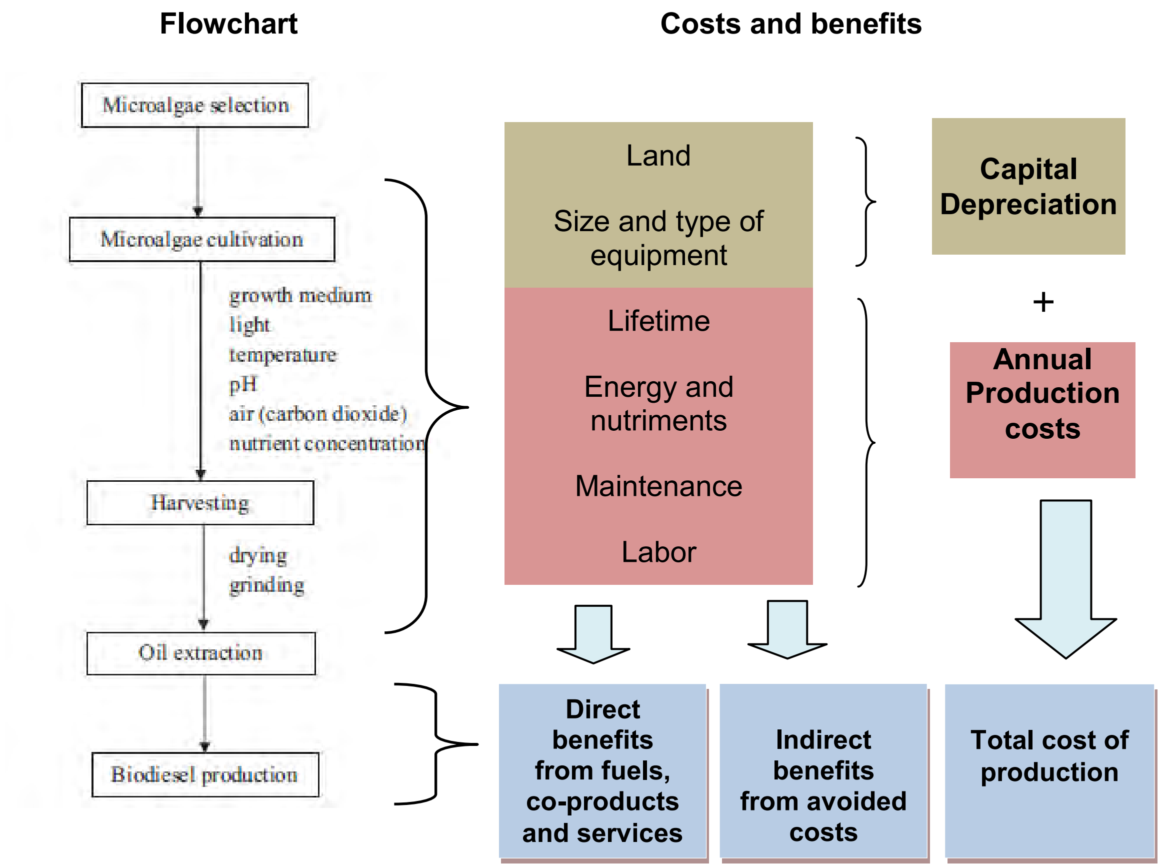

Figure 1.1: Flowchart for Production of Biodiesel from Algae and associated Costs and Benefits
(Sources: adapted from Ahmad A.L. et al.; Aquafuels project)

A brief illustration of main costs and benefits reported in literature is given hereafter in table 1 below (in brackets, column notes, and the reference of the article from which information and data have been collected and reported in bibliography).

[1] In addition, in a complete cost benefit analysis framework, other externalities should also be taken into consideration, since producing bio-fuels allow avoiding all direct and indirect costs deriving from fossil fuel extraction and refining.

		OPEN PONDS			PHOTOBIOREACTOR		
		Quantity/volume	Price	Notes	Quantity/volume	Price	Notes
Investment costs							
Land			~ 10.000 $/ha	[17]			
		2.5 - 7.0 km^2		for a susteinable and productive plant [14]			
		5 - 14 km^2		Total land area includes roads, buildings, other infrastructure [14]			
Equipments			1.0 - 1.53 M$	for 50 ha plant [2]		26.5 - 648 M$	for 50 ha plant: 26.5 is for PBRs with solar-lit; 648 is for PBRs
Installation							
Ingeneering							
Production costs							
Raw materials:			2.22 - 11.8 M$	[2]		3.42 - 166 M$	[2]
	CO_2	145.000 ton/yr	40 $/ton	[8]	145.000 ton/yr	40 $/ton	[8]
		1.8 kg		for 1 kg of biomass [14]	1.8 kg		for 1 kg of biomass [14]
	N	5100 ton/yr	407 $/ton	[8]	5100 ton/yr	407 $/ton	[8]
		50 -80 kg		for 1 kg of biomass [14]	50 -80 kg		for 1 kg of biomass [14]
	P	5 kg		for 1 kg of biomass [14]	5 kg		for 1 kg of biomass [14]
	Chitosan		4.84 $/lb	for flocculation [8]		4.84 $/lb	for flocculation [8]
	Butan		0.94 $/lb	for solvent extraction [8]		0.94 $/lb	for solvent extraction [8]
	Water:						
	-use	10.000 MM gal/yr	0.05 - 1000 $/gal	[8]	3.000 MM gal/yr	0.05 - 1000 $/gal	[8]
	-evaporation	570 gal/gal lipid		[8] or 10 L/m^2/day [11]	250 gal/gal lipid		[8] or 0.5 L/m^2/day [11]
	-blowdown	430 gal/gal lipid		[8]	50 gal/gal lipid		[8]
Utilities							
Energy consumption			1.90 - 7.42 M$	[2]		4.65 - 11.5 M$	[2]
		1 W/m^2	0.08 $/kWh	[11] [8]	500 W/m^2	0.08 $/kWh	[11] [8]
	General artificial light source	X	X	X	40.32 kW/h		[1]
	LEDs	X	X	X	20.16 kW/h		[1]
	Optical fiber with metal-halide lamp	X	X	X	36 kW/h		[1]
	Optical fiber with solar energy	X	X	X	1.0 kW/h		[1]
	LED with wind power or solar panels	X	X	X	0.0 kW/h		[1]
Labor and supervision		~18 people	for the administrative personnel total cost: 375.000 $; for operations personnel total cost: 748.000 $	for 100 ha plant: 4 for administrative, 14 for operations [0] [17]	~36 people		for 100 ha plant: 4 for administrative, 32 for operations [0]
Other:							
	maintenance		1.60 - 1.69 M$	[2]		7.66 - 337 M$	[2]
	start-up		1.41 - 1.49 M$	[2]		25.7 - 629 M$	[2]
	fixed costs		4.50 M$	[2]		4.50 M$	[2]
Total cost of production			4.95 €/kg	[6] or 4-6 $/kg [2]		4.15 - 5.96 €/kg	[6] or 20-30 $/kg, to 206 $/kg for LED technology [2]
Benefits and co-product							
Biodiesel/biofuel		9.3 MM/gal/yr	8.52 $/gal	[8]	9.3 MM/gal/yr	18.10 $/gal	[8]
	with hyrotreating:		9.84 $/gal	[8]		20.53 $/gal	[8]
Biomass		3.3 - 5.0 kg/h	~1.6 - 1.8 €/kg	[2] [11]	8.3 - 97.9 kg/h	9 - 10 €/kg	[2] [11]
		100 t/ha/yr		[13]			
		30 g/m^2/day (109 ton/ha/yr)		for unit light energy [18]	25 - 365 ton/ha/yr		using solar light [18]
Co-products:							
	Animal feed	X		[0] [2]	Y		[0] [2]
	Heat and power generation	X		es. methane and ethanol [0] [2]	Y		es.methane and ethanol [0] [2]
	Nutritional and cosmetics	X		es. beta-carotene [0] [2]	Y		es. beta-carotene[0] [2]
	Pigments and pharmaceuticals	X		[11]	Y		[11]
	Wastewater treatment	X	4,950,000 $/yr	[0] [2] [18]	Y		[0] [2]
Lipid productivity		179 mg/L/day		[1]	3700 mg/L/day		[1]
Oil yield		100- 130 m^3/ha		[1] [6]	172 m^3/ha		[1] [6]
		13.580 - 20.370 l/ha/yr		[12]			
		20.000 - 25.000 L/ha/yr		up to 40.000 L/ha/yr with mutant algae [13]			
Limitations		Water evaporation, High contamination (invasive algal species and patogens), sensible to enivironmental changes			High cost of technologies and materials, high power needs		
Advantages		Low cost of technologies and installation, low power needs			Optimum growth conditions, high productivity, no contamination		
Total cost of fuel		**9.30 $/GGE (gallon gasoline equivalent) [8]**			**19.39 $/GGE [8]**		
		20.71 $/bbl (without producing electricity and with wastewater credits) [18]					
		0.19 $/kWh (with producing electricity and with wastewater credits) [18]					
Woody biomass pellet		**~ 0.2 - 0.4 €/kg**					

In this report the economic parameters has been re-elaborated through a SWOT analysis in order to provide a clear picture of the advantages and drawbacks when investing in a specific technology compared to another. Data used have been provided based on a literature review (see bibliography below).

The difficulties emerged during the analysis are mainly related to the fact that:

- the dates of publication differ (from 2007 to 2014), some of them are more recent and updated than others;
- price are not always reported at a detailed level;
- the quality and details of data reported is not always certain: many data provided derive from laboratory experiments or pilot cases and must be considered as forecasts based on hypothesis made at micro-levels; no scale industrial plant is functioning according to the market conditions up to until now;
- measurement units are often different and hinder comparisons between technologies and for similar technologies hinder comparisons between countries: dimensions are expressed in € and $ for different periods of time; size of plants are expressed in m3, hectare, gallons, litres, barrels or tons depend on the country of origin and the scope of the study.

If preliminary results emerging from the literature clearly show that costs highly depend on the technology used (see table 1 above), significant improvements in the cost-benefit balance should be achieved through:

- minimizing energy demand from production process at site level; taking advantage from the re-use of by-products (biomass from algae production process) or the of energy supply from low cost energy source (energy from co-generation plants, energy deriving from waste treatments or non-renewable power plants);
- water recycling (on site) or free water supply from natural artificial sources;
- access to low cost nutriment sources; at a lower price than common fertilizer market prices;
- access to a free source of CO_2 (in recycling by-product from power plants or cemeteries);
- delivering by-products able to compete with (and substitute) market products at a reasonable high (and not saturated) demand.

In the following sections we present the results of the SWOT. Considering the high heterogeneity of the data provided by the literature, the analysis has mainly been delivered on a qualitative basis, considering the alternative options (technologies) under discussion for which economic considerations are available.

2 MICROALGAE PLANTS

2.1 OPEN PONDS

2.1.1 Strengths

Investment phase

- Limited equipment costs;
- Land costs highly depending on location (siting); with a large range which sprays from low - plants located in marginal, industrial or dismissed sites - to relatively high if we consider a location in arable, coastal or urbanised areas.

Production phase

- Low energy and power needs (compared to PBRs); but depends on: 1) the plant location, 2) the production process and 3) the harvesting, drying and lipid extraction process used (which could be energy demanding when drying is required);
- Use (free) CO_2 from coal combustion, cement industry or other biomass source. But this implies a location near industrial areas able to provide such an input;
- Co-products (delivered at market price): animal feed, bioethanol, biomethane, fertilizer and biomass;
- Low cost of some methods of harvesting: bioflocculation (use no chemical flocculants), auto-flocculation, sedimentation, solar drying and membrane filtration;
- Using marine algae strains (living in seawater) with less nutriments needs and no competition for freshwater with other uses.

2.1.2 Weaknesses

Investment phase

- Land surface for industrial application not below 100 hectares (see previous point); ponds require also flat terrains;
- Costs for activities aim at improving infrastructures for the proper functioning of installations (facilitating access to electricity, transports and communication networks); however costs highly depend on the location choice.

Production phase

- Fertilizers costs (nitrogen, phosphorous and potassium) could be high in the absence of alternatives; transportation costs for nutriments should also be considered;
- Fresh water or seawater needs (also to compensate evaporation); more elevation (needs for pumping), evaporation or need for clean freshwater also implies more energy requirement; the possibility or not of recycling (re-circulating water) also impacts on the cost of water supply;
- High costs of some methods of harvesting: centrifugation (gravity is replaced by a much greater force), ultra-filtration, flotation (addition air bubbles to the medium is energy intensive), spray and freeze drying.

2.1.3 Opportunities

- Development of circular and close systems of production and consumption, thereof recycling water and nutriments and re-using by-products for energy producing;
- Technological improvement in production process (algae productivity, lipid extraction, ...) and significant drop in production costs;
- High fossil fuel energy prices.

2.1.4 Threats

- Limited opportunities in developing new markets for by-products e.g. limited demand, persistent logistic or legal barriers;
- Low rate of innovation as production costs are still high compared to other bio-fuels or fossil fuels production chains;
- Low economy of scale with no advantages in developing large-scale plants i.e. no mass production savings in the case of an industrial development of algae production process.

2.2 PHOTOBIOREACTORS

2.2.1 Strengths

Investment phase

- Reduced land requirements;
- Low water use (basic needs is about 3000 MM gal/year).

Production phase

- Use (free) CO_2 from coal combustion, cement industry or other biomass source. But this implies a location near industrial areas able to provide such an input;
- Co-products (at market price): animal feed, bioethanol, biomethane, fertilizer and biomass to be used for energy production (heat and power);
- Low cost of some methods of harvesting: bioflocculation (use no chemical flocculants), autoflocculation (use Ca++ and Mg++ ions at high pH), sedimentation, solar drying and membrane filtration.

2.2.2 Weaknesses

Investment phase

- High equipment costs, since costs of technologies and materials for the reactor are significantly higher than the open ponds costs of installation (for example, for the PBRs with LED technology the cost of the equipment is about 648 M$, while for the open ponds it's about 1-1.5 M$).

Production phase

- High power and energy consumption;
- High staff and employees cost, due to the high number of people needed for the operations and the maintenance (~ 36 people for a 100 ha plant);

- High costs of some methods of harvesting: centrifugation (gravity is replaced by a much greater force), ultrafiltration, flotation (addition air bubbles to the medium is energy intensive), spray and freeze drying.

2.2.3 Opportunities

- Development of circular and close systems of production and consumption, thereof recycling water and nutriments and re-using by-products for energy producing;
- Technological improvement in production process (algae productivity, lipid extraction, ...) and significant drop in production costs;
- High fossil fuel energy prices.

2.2.4 Threats

- Limited opportunities in developing new markets for by-products e.g. limited demand, persistent logistic or legal barriers;
- Low rate of innovation as production costs are still high compared to other bio-fuels or fossil fuels production chains;
- Low economy of scale with no advantages in developing large-scale plants i.e. no mass production savings in the case of an industrial development of algae production process.

2.3 WASTEWATER

2.3.1 Open Ponds (HRAPs, High Rate Algal Ponds or Raceway Ponds)

2.3.1.1 Strengths

Investment phase

- Low cost of equipment;
- Land costs highly depending on location (siting); with a large range which sprays from low - plants located in marginal, industrial or dismissed sites - to relatively high if we consider a location in arable, coastal or urbanised areas.

Production phase

- Credits linked to water depuration; the use of wastewater for algae growth can reduce production costs to about 50%;
- No external CO_2 and fertilizer sources are required: using wastewater, there is no needs to buy on the market raw materials for growing algae;
- Co-products (provided at market price): animal feed, bioethanol, biomethane, fertilizer and biomass to be used for energy production (heat and power);
- Low cost of some methods of harvesting: bioflocculation (use no chemical flocculants), autoflocculation (use Ca++ and Mg++ ions at high pH), sedimentation, solar drying and membrane filtration.

2.3.1.2 Weaknesses

- High quantity of wastewater required. The plant would therefore be best localized close to metropolitan areas;
- Land surface for industrial application should not be less than 100 hectares (see previous point); ponds require also flat terrain;
- High costs of some methods of harvesting: centrifugation (gravity is replaced by a much greater force), ultrafiltration, flotation (addition air bubbles to the medium is energy intensive), spray and freeze drying.

2.3.1.3 Opportunities

- Development of circular and close systems of production and consumption, thereof recycling water and nutriments and re-using by-products for energy producing;
- Technological improvement in production process (algae productivity, lipid extraction, ...) and significant drop in production costs;
- High fossil fuel energy prices.

2.3.1.4 Threats

- Limited opportunities in developing new markets for by-products e.g. limited demand, persistent logistic or legal barriers;
- Low rate of innovation as production costs are still high compared to other bio-fuels or fossil fuels production chains;
- Low economy of scale with no advantages in developing large-scale plants i.e. no mass production savings in the case of an industrial development of algae production process.

2.3.2 PBRs

2.3.2.1 Strengths

- No external CO_2 and fertilizer sources are required: using wastewater, there is no needs to buy on the market raw materials for growing algal;
- Limited water use since water comes from wastewater and the losses due to evaporation are replaced by re-cycling the culture medium;
- Co-products (provided at market price): animal feed, bioethanol, biomethane, fertilizer and biomass to be used for energy production (heat and power);
- Low cost of some methods of harvesting: bioflocculation (use no chemical flocculants), autoflocculation (use Ca^{++} and Mg^{++} ions at high pH), sedimentation, solar drying and membrane filtration.

2.3.2.2 Weaknesses

Investment phase

- High equipment cost, since technologies and materials' costs for the reactor are significantly higher than the open ponds installation costs.

Production phase

- High power and energy consumption;
- High staff and employees cost, due to the high number of people needed for the operations and the maintenance (~ 36 people for a 100 ha plant);
- High costs of some methods of harvesting: centrifugation (gravity is replaced by a much greater force), ultrafiltration, flotation (addition air bubbles to the medium is energy intensive), spray and freeze drying.

2.3.2.3 Opportunities

- Development of circular and close systems of production and consumption, thereof recycling water and nutriments and re-using by-products for energy producing;
- Technological improvement in production process (algae productivity, lipid extraction, ...) and significant drop in production costs;
- High fossil fuel energy prices.

2.3.2.4 Threats

- Limited opportunities in developing new markets for by-products e.g. limited demand, persistent logistic or legal barriers;
- Low rate of innovation as production costs are still high compared to other bio-fuels or fossil fuels production chains;
- Low economy of scale with no advantages in developing large-scale plants i.e. no mass production savings in the case of an industrial development of algae production process.

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ANNEX 5
SWOT ANALYSIS – LCA ON MICROALGAE CULTIVATION/HARVESTING TECHNOLOGIES

Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

consulting, design, operation & maintenance engineering

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

LCA on Microalgae Cultivation/Harvesting Technologies – SWOT Analysis

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COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS
LCA ON MICROALGAE CULTIVATION/HARVESTING TECHNOLOGIES –
SWOT ANALYSIS**

1 INTRODUCTION

Task 1 of the study on the potential for the use of algal biofuels is related to the assessment of constraints and opportunities related to the processes of siting, cultivation and harvesting of the algae; then the assessment of the processes that bring from algae to biofuel and by-products will follow in Task 2.

This report, following an overall approach focused on the assessment of cultivation techniques, technological considerations, economical analyses and environmental impacts, focuses on the application of Life Cycle Assessment (LCA) technique to the selected microalgae cultivation processes for what the environmental impacts are concerned.

Therefore, this part of LCA is limited to the steps from cultivation to harvesting, whereas the complementary steps leading to the production of biofuel (i.e.: the biorefinery processes, aimed at producing biodiesel from algae) will be performed in a following dedicated study, thus completing the overall cycle of the process.

By combining cultivation, harvesting/thickening technologies and input resources, sixteen case studies were analyzed, basing on input data from specific literature and LCA databases.

The results of the assessments in terms of environmental indicators and of mass/energy balances were then determined and interpreted to perform a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis on the different algae production processes.

This contributes to the preparation of the overall SWOT analysis including the biological, technical and economic considerations, to the barrier analysis and the definition of guidelines to overcome the identified barriers.

2 LIFE CYCLE ASSESSMENT

2.1 LAYOUT OF THE PROCESS

The LCA on the selected case studies was performed using GaBi® software. The first step of the analysis was the definition of the block scheme shown in Figure 2.1, which represents the main components and flows for each algae production process. This block scheme is valid for all the considered plants, which differ one from each other only for the values of involved mass and energy flows.

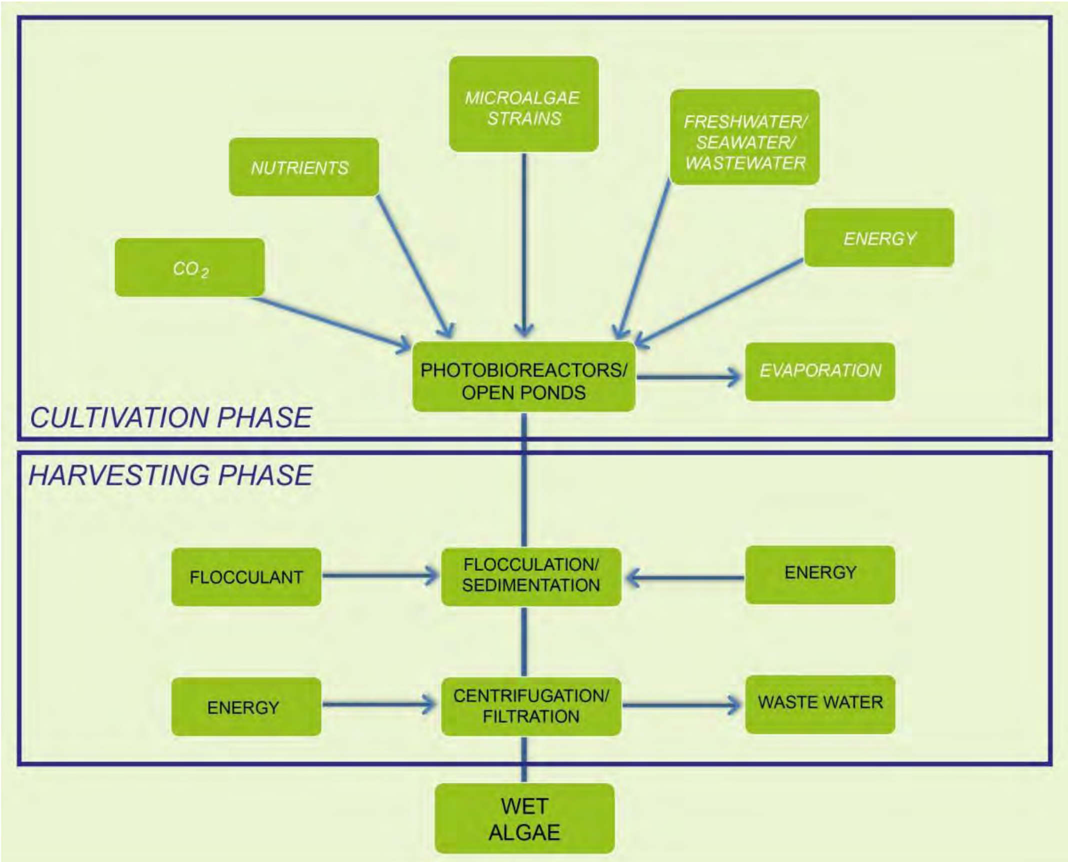

Figure 2.1: Block Scheme for Algae Cultivation/Harvesting

Then, a more general block scheme, able to represent all the selected algae production processes was defined, in terms of:

- identifying common blocks (“Growth mode” for “OP” and “PBR”; “Harvesting mode” for “Flocculation”, “Gravity sedimentation”, “Centrifugation”, “Filtration”);
- collecting in a single block different kinds of inputs (“Water” for “Wastewater”, “Seawater”, “Freshwater”; “Nutrient source” for “Fertilizer”, “Carbon dioxide”, etc).

This allowed to build a GaBi Plan able to represent all the algae production processes under investigation, by simply changing the values of mass and energy flows typical of the specific process. The general scheme used for all the LCAs (except for the values of mass and energy flows) performed within the present study is shown in Figure 2.2.

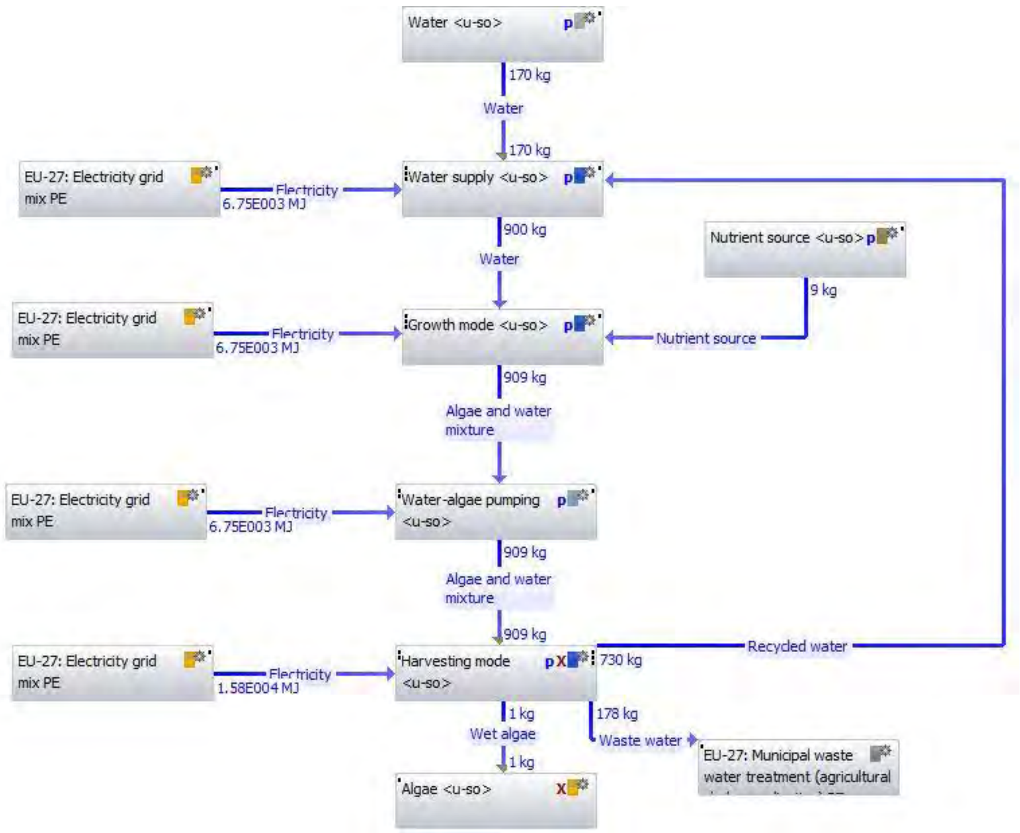

Figure 2.2: GaBi Block Scheme for Waste Water Open Pond

2.2 METHODOLOGY

In this study, the selected algae cultivation processes were analyzed according to a Cradle-to-Gate approach using GaBi software.

GaBi is a software, developed by PE International (now "Thinkstep"), which allows to easily model process chains, by describing a production technology or service through its input and output flows. The selected technology can be described by using its structural information and creating parts with material inventories and production processes. Processes and flows already existing in the internal databases can be used, or new items can be defined by the user according to experimental values or literature data. Once the system is completely defined in terms of involved processes, mass and energy flows, several Impact Assessment Methodologies can be adopted to determine the results.

The standard database provided with GaBi is the Professional database, which has the advantage of being internally consistent and includes more than 5000 LCI (life cycle inventory) records, based on previous works of PE International. In addition, the Swiss Ecoinvent database is available, which includes thousands of LCI records in the fields of agriculture, energy supply, transport, biofuels and biomaterials, chemicals, construction and packaging materials, basic and precious metals, metals processing, ICT and electronics, waste treatment.

Within the present study, the system boundaries were defined so that the system includes the whole impacts for electricity generation and water treatment. Concerning water and carbon dioxide, the energy requirements and consequent impacts for their supply to the plant are included in the system. Finally, nutrients and other reactants (e.g. flocculant agent) are considered to be available directly at the plant, without any additional impact.

The functional unit considered in this study is the unit of mass (1 kg) of produced algae, which is the desired final product.

As seen above and shown in the GaBi scheme in Figure 2.2, the main values influencing the LCA of an algae production technology, besides those already present in GaBi databases (connected to electricity supply and water treatment) are the mass and energy flows entering the system.

More in detail, the involved energy flows are the electricity consumptions for supplying and circulating water and carbon dioxide, growing algae, pumping algae-water slurry, harvesting and thickening algae. On the other hand, the involved mass flows are the amount of water, carbon dioxide, fertilizers and other nutrients, flocculant agent, per unit of produced algae.

In this study, values for all the above mass and energy flows were defined for each of the eight selected case studies shown in Table 2.1. In the table, the indication of algae cultivation, bulk harvesting and thickening methods for each case is presented. It is worth noting that for each of the eight case studies, two sub-cases were considered, corresponding to the use of wastewater and freshwater as input of water.

Table 2.1: Summary of the Selected Case Studies

Case Study	Cultivation Method	Bulk Harvesting Method	Thickening Method
OP 1	Open Pond	Flocculation	Centrifugation
OP 2	Open Pond	Flocculation	Filtration
OP 3	Open Pond	Gravity Sedimentation	Centrifugation
OP 4	Open Pond	Gravity Sedimentation	Filtration
PBR 1	Photobioreactor	Flocculation	Centrifugation
PBR 2	Photobioreactor	Flocculation	Filtration
PBR 3	Photobioreactor	Gravity Sedimentation	Centrifugation
PBR 4	Photobioreactor	Gravity Sedimentation	Filtration

2.3 ASSUMPTIONS AND LIMITATIONS

This study is based on a series of assumptions, hereby listed, aimed at creating a standardized overview of the processes for the main technological solutions and at highlighting the boundary conditions that differ from case to case.

The present LCA study is mainly based on values taken from the GaBi database and, for values that are not included in the latter, from specific literature on algae cultivation technologies.

First of all, it is worth highlighting that LCA studies were performed by neglecting the energy and mass flows connected to the construction of the cultivation plant, the water and carbon dioxide feeding pipelines, and all the required equipment. This hypothesis may significantly affect the environmental indicators, but the choice was done to perform a comparative analysis among cultivation plants ready for operation at a specific site.

Moreover, these values were not considered because no reliable data were available in literature.

Concerning the water supplied to the plant, seawater was assimilated to freshwater because the involved impacts (e.g.: the energy required for water pumping) are equivalent in the cases that water is withdrawn from a river or from the sea, provided that the distances of the plants from the sources of water are comparable. On the other hand, wastewater is considered separately because using wastewater to grow algae reduces the impacts connected to wastewater treatment.

The analysis of PBR is based on the available data from literature. There is, for sure, a cooling need to consider, whose impact is reported to be highly significant. However, due to the lack of specific numbers for this input flow, the impact of cooling can be only figured out in qualitative terms at this stage of maturity of the algae systems (awaiting for reliable data from pilot realizations). This scenario including the energy used for cooling has been outlined quoting literature, whereas the quantitative figures are here presented in absence of cooling demand, well aware of the more than likely event that the final consumptions may result to be considerably higher.

Finally, the study has considered that the plants under analysis are built in an eligible location that meets the minimal requirements in terms of solar irradiation, temperature, distance from water bodies, etc, with respect to the site-characterization which was at the basis of our analysis for the assessment of the site territorial units. Thus, being all the systems above the threshold of eligibility, no differences are considered among plants regarding their geographical location.

As anticipated, the values emerging from the balances of this first step of LCA are not representative of the entire life cycle for biofuel production, but they only represent a hint for the comparison of the cultivation techniques under the point of view of their environmental impacts. The second part of the LCA cycle (core of Task 2) will complete this analysis and provide the overall picture.

2.4 INPUT DATA

The values on energy and mass flows for each case study were calculated by adapting the data available in literature, and in particular in Benemann (2014), Meyer (2012), Slade (2013), Soulliere (2014), Stephenson (2010), Tredici (2014).

The values are shown in Table 2.2 for each of the selected technologies, and are expressed per mass unit of produced algae.

Concerning the sub-cases corresponding to the change of water source, they are analyzed by directly changing the Flow parameter as input of the Water process in GaBi. In addition, when wastewater cultivation processes are considered, a recycle of 80% of the wastewater in output from algae harvesting process can be recirculated back to the cultivation system.

Table 2.2: LCA Parameters for each Algae Cultivation System

Parameter	OP 1	OP 2	OP 3	OP 4	PBR 1	PBR 2	PBR 3	PBR 4
Mass flows [kg]								
Water	900	900	900	900	22.5	22.5	22.5	22.5
Carbon dioxide	8.75	8.75	8.75	8.75	2.62	2.62	2.62	2.62
Fertilizer	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Flocculant	0.35	0.35	0	0	0.35	0.35	0	0
Energy flows [kWh]								
Water feeding	0.875	0.875	0.875	0.875	0.025	0.025	0.025	0.025
Cultivation	0.49	0.49	0.49	0.49	0.015	0.015	0.015	0.015
Cooling	-	-	-	-	n.a.	n.a.	n.a.	n.a.
Carbon dioxide feeding	0.175	0.175	0.175	0.175	0.05	0.05	0.05	0.05
Water-algae pumping	0.218	0.218	0.218	0.218	0.025	0.025	0.025	0.025
Bulk harvesting	0.006	0.006	0	0	0.006	0.006	0	0
Thickening	0.27	0.091	0.27	0.091	0.027	0.009	0.027	0.009

Finally, concerning the electricity supply, in the LCA analysis the EU-27 mix (shown in Figure 2.3) was selected; a further sensitivity analysis of the impact of the electricity mix composition on the indicators is shown in paragraph 2.5.4. It is worth highlighting that EU-27 mix was used instead of EU-28 because GaBi database is not updated to the 2014 configuration of EU-28.

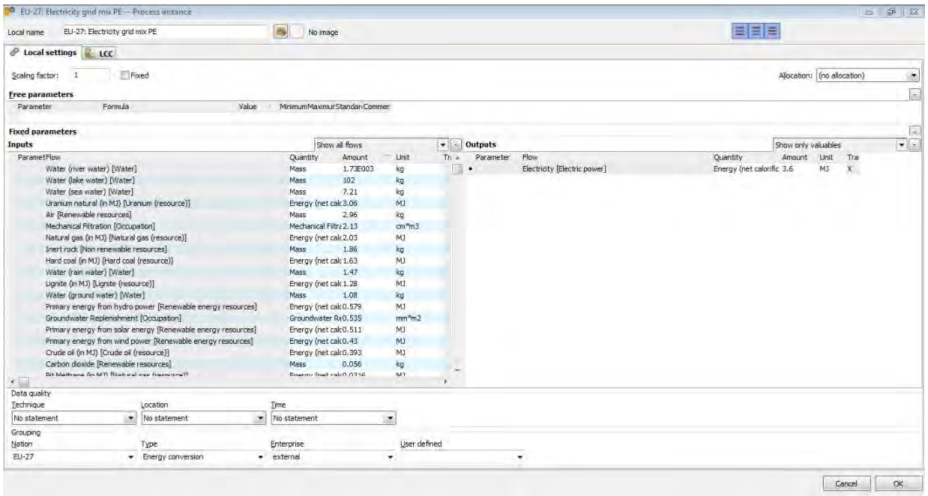

Figure 2.3: Example from EU-27 Electricity Grid Mix Parameters

2.5 LCA IMPACT ASSESSMENT

The results of the LCAs performed using GaBi are presented in this paragraph. The CML 2001 (version April 2013) method was used to aggregate impacts into twelve indicators, which are listed in Table 2.3 with their abbreviation and their proper measurement unit.

Table 2.3: Legend for LCA Indicators

Abbreviation	Parameter	Measurement Unit
ADPe	Abiotic Depletion elements	[kg Sb-Equiv.]
ADPf	Abiotic Depletion fossil	[MJ]
AP	Acidification Potential	[kg SO2-Equiv.]
EP	Eutrophication Potential	[kg Phosphate-Equiv.]
FAETP	Freshwater Aquatic Ecotoxicity Potential	[kg DCB-Equiv.]
GWP100	Global Warming Potential (100 years)	[kg CO2-Equiv.]
GWP100e	Global Warming Potential, excluding biogenic carbon (100 years)	[kg CO2-Equiv.]
HTP	Human Toxicity Potential	[kg DCB-Equiv.]
MAETP	Marine Aquatic Ecotoxicity Potential	[kg DCB-Equiv.]
ODP	Ozone Layer Depletion Potential (steady state)	[kg R11-Equiv.]
POCP	Photochemical Ozone Creation Potential	[kg Ethene-Equiv.]
TETP	Terrestric Ecotoxicity Potential	[kg DCB-Equiv.]

Finally, the results were normalized in terms of "person equivalent", by dividing each indicator by the nominal value shown in Table 2.4, corresponding to the average yearly impact of a person. To allow a better comparison, results are shown in the following graphs with reference to 1000 tons of produced algae instead of 1 kg. Complete data on indicators and mass balances for the case studies are shown in Appendix A.

Table 2.4: Values for Person Equivalent Normalization

Parameter	Value	Measurement Unit
ADPe	0.013	[kg Sb-Equiv.]
ADPf	75,550	[MJ]
AP	36.2	[kg SO2-Equiv.]
EP	39.8	[kg Phosphate-Equiv.]
FAETP	449.7	[kg DCB-Equiv.]
GWP100	11,210	[kg CO2-Equiv.]
GWP100e	11,210	[kg CO2-Equiv.]
HTP	1,076	[kg DCB-Equiv.]
MAETP	95,780	[kg DCB-Equiv.]
ODP	0.022	[kg R11-Equiv.]
POCP	3.72	[kg Ethene-Equiv.]
TETP	249.7	[kg DCB-Equiv.]

2.5.1 Open Ponds

Figure 2.4 shows a comparison of the results of LCAs performed on the eight case studies using an open pond as cultivation system.

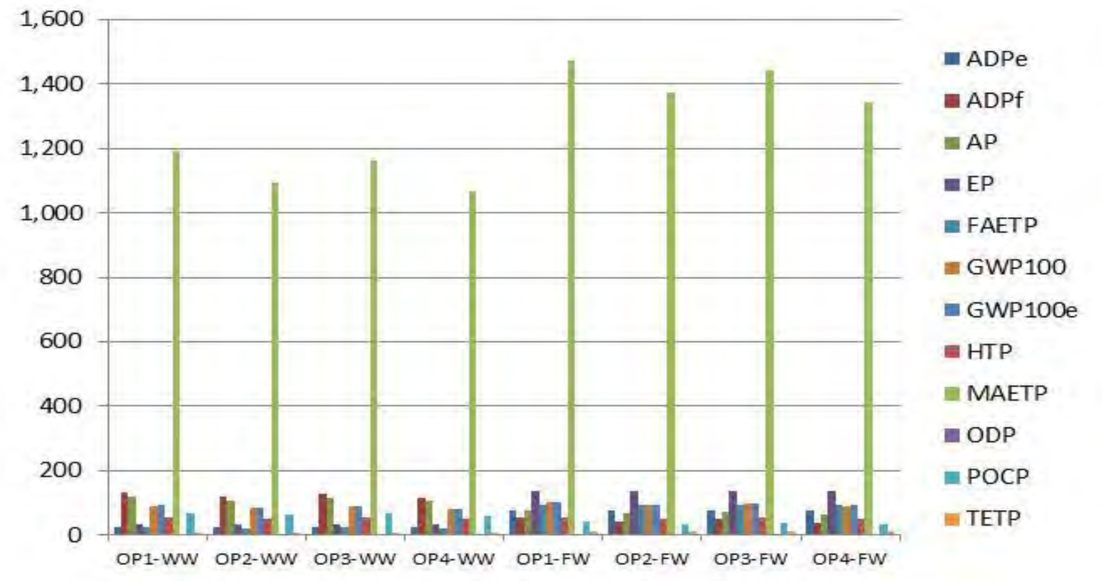

Figure 2.4: Comparison of LCA Indicators for OP Cultivation Systems

It can be noted, as expected, that the algae cultivation plants using wastewater have a slightly lower impact than those using freshwater. This mainly happens because plants using wastewater can recycle 80% of the output water, whereas those using freshwater have a higher consumption of resources and a higher impact for wastewater treatment.

In addition to LCA indicators, mass balances were calculated for each case study. In particular, Table 2.1 shows a summary of the mass balances of algae cultivation systems using wastewater: the detail of the flows that are included in each category are presented in Appendix A.

Table 2.5: Mass Balances for OP Cultivation Systems using Wastewater

Flows [kg]	OP1	OP2	OP3	OP4
Total flows	8,294	7,612	8,084	7,402
Resources	4,139	3,806	4,037	3,704
Deposited goods	3.39	3.06	3.29	2.95
Emissions to air	17.27	15.74	16.80	15.26
Emissions to fresh water	4,118	3,772	4,012	3,666
Emissions to sea water	15.32	14.03	14.92	13.63
Emissions to agricultural soil	$3.52{\cdot}10^{-7}$	$3.23{\cdot}10^{-7}$	$3.43{\cdot}10^{-7}$	$3.14{\cdot}10^{-7}$
Emissions to industrial soil	$2.27{\cdot}10^{-5}$	$2.07{\cdot}10\text{-}^{5}$	$2.21{\cdot}10^{-5}$	$2.01{\cdot}10^{-5}$

However, even from the summary presented in Table 2.5, it can be noted that the lowest mass balance correspond to OP2 and OP4 case studies, having a lower electricity consumption for harvesting/thickening and consequently lower mass flows connected to electricity production.

2.5.2 Photobioreactors

Figure 2.5 shows a comparison of the results of LCAs performed on the eight case studies using a photobioreactor as cultivation system. The same considerations given on open ponds are valuable, and in particular also in this case plants using wastewater have a slightly lower impact than those using freshwater.

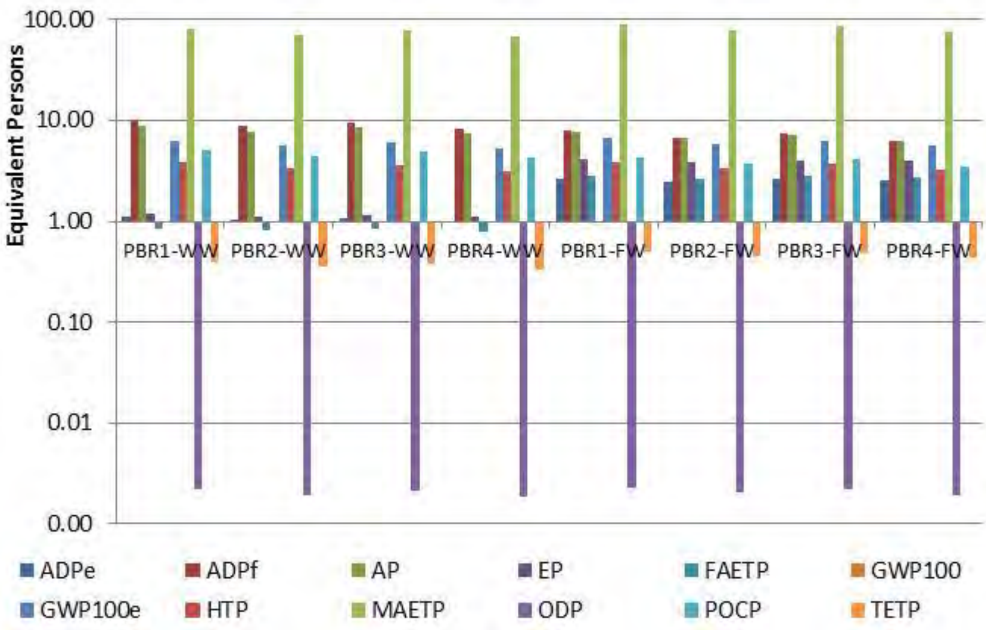

Figure 2.5: Comparison of LCA Indicators for PBR Cultivation Systems

The graph in a logarithmic scale does not allow to note that GWP100 indicator is negative for all the case studies: this happens because the amount of carbon dioxide required for algae growth is higher than the amount released during the production phase of the electricity consumed by the plant. This agrees with the value of GWP100e indicator, which is positive, because it does not account for the contribution of biogenic carbon dioxide flows as algae growth consumption is.

As per open ponds, also for photobioreactors mass balances were calculated and their complete version is shown in Appendix A.

Table 2.6 shows the summary of the mass flows involved in algae production in photobioreactors using wastewater. Also in this case, the lowest values correspond to those case studies having a lower electricity consumption.

Table 2.6: Mass Balances for PBR Cultivation Systems using Wastewater

Flows [kg]	PBR1	PBR2	PBR3	PBR4
Total flows	572.4	503.8	549.1	481.1
Resources	282.4	248.9	271.0	237.8
Deposited goods	0.26	0.23	0.25	0.22

Flows [kg]	PBR1	PBR2	PBR3	PBR4
Emissions to air	1.2	1.1	1.2	1.0
Emissions to fresh water	287.5	252.6	275.6	241.1
Emissions to sea water	1.1	0.9	1.0	0.9
Emissions to agricultural soil	$2.4 \cdot 10^{-8}$	$2.1 \cdot 10^{-8}$	$2.3 \cdot 10^{-8}$	$2.0 \cdot 10^{-8}$
Emissions to industrial soil	$1.6 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$

2.5.3 Comparisons

The previous paragraphs showed the results of LCAs separately for case studies with open pond and photobioreactors. Figure 2.6 shows an overall comparison among the sixteen case studies, aimed at identifying the differences in order of magnitude among the impacts.

In fact, it can be noted that the production of a unit of mass of algae in open ponds has a life cycle impact up to twenty times higher than production in photobioreactors. This is due to the higher efficiency of this kind of cultivation method, which operates with a lower consumption of both energy and resources per unit of produced algae.

If environmental impacts connected to construction of open ponds and photobioreactors had been taken into account, probably the difference would have been less significant. However, as stated in paragraph 2.3, this choice was done to perform a comparative analysis among cultivation plants ready for operation at a specific site, thus plants are considered only downstream their construction phase.

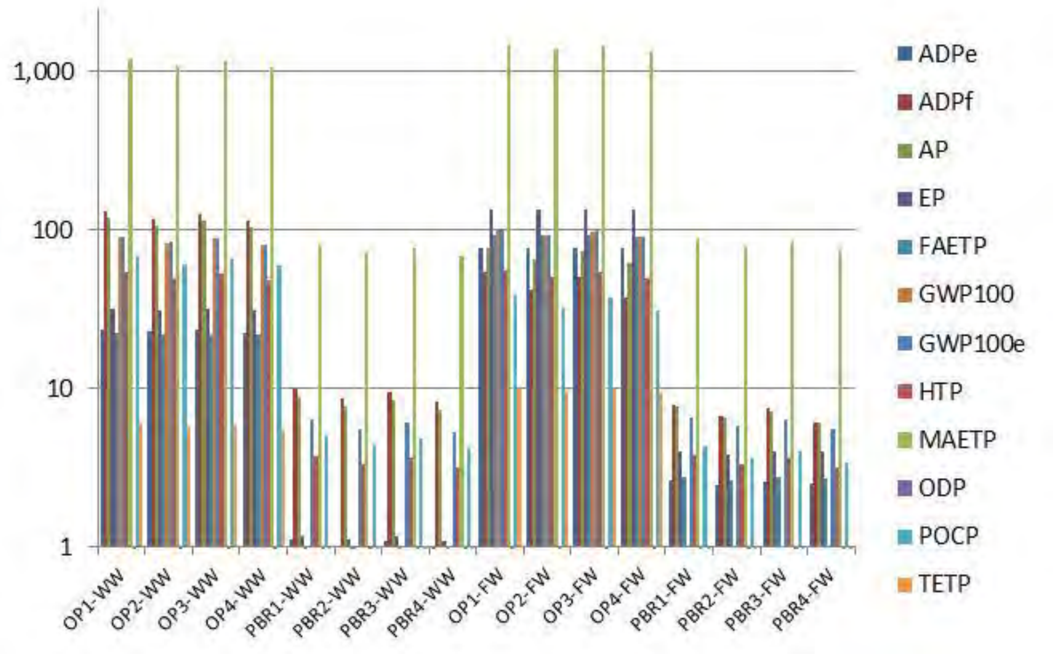

Figure 2.6: Comparison of LCA Indicators for OP/PBR Cultivation Systems

From a mass balance perspective, Figure 2.7 shows a comparison between mass flows involved in algae production in open ponds and photobioreactors. It can be noted that, also in this analysis, photobioreactors are characterized by a lower impact, since they involve significantly lower flows (both resources in input and emissions in output) for producing a unit of mass of algae.

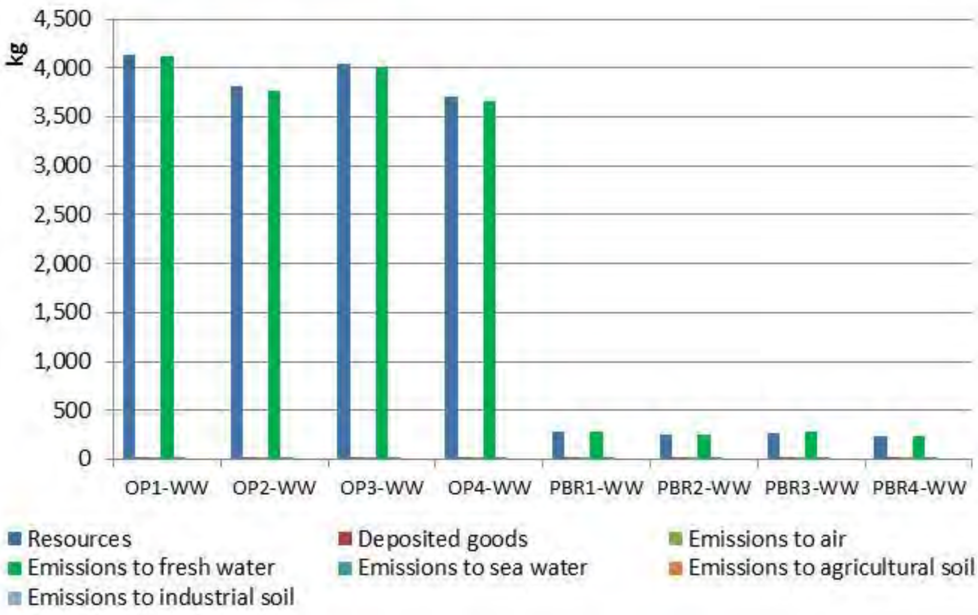

Figure 2.7: Comparison of Mass Balances for OP/PBR Cultivation Systems

2.5.4 Uncertainties on the Energy Demand for Cooling

As mentioned in Chapter 2.3, the above analysis is based on the absence of energy demands for cooling purposes. If this is true for the Open Ponds, where the cooling is naturally achieved by means of water evaporation, the case of PBR is more complex. A forced cooling is required in the majority of cases to allow the PBRs to operate in the proper conditions. This results to be an additional energy demand that can impact very highly on the overall consumptions: lots of precise figures are not available from experimental systems but are expected in the near future, for example thanks to the outcomes of the real plants under FP7 research; the existing information suggests to consider with high care this issue because the energy consumptions for cooling may be extremely high in some cases (e.g.: tubular PBR).

This is evident, at least limited to the literature analysis, for example looking at the chart below (Figure 2.8 – extract from Slade and Bauen, 2013). The expectations from the quoted literature say that very high consumptions can occur in the phase of algae cultivation for PBR systems (mainly tubular), thus leading to a unbalanced scenario in which energy consumptions are much higher than the energy content of the obtained biomass. The outlined scenarios for flat plate PBR are a bit more favorable, and close to the outcomes of the present analysis (at least, comparable without orders of magnitude of difference).

The quantitative evaluations in the present approach are without cooling demand due to the lack of specific numbers for this input flow, having in mind that the final consumptions may result to be considerably higher if the expectations of such energy consumptions are confirmed by the real cases.

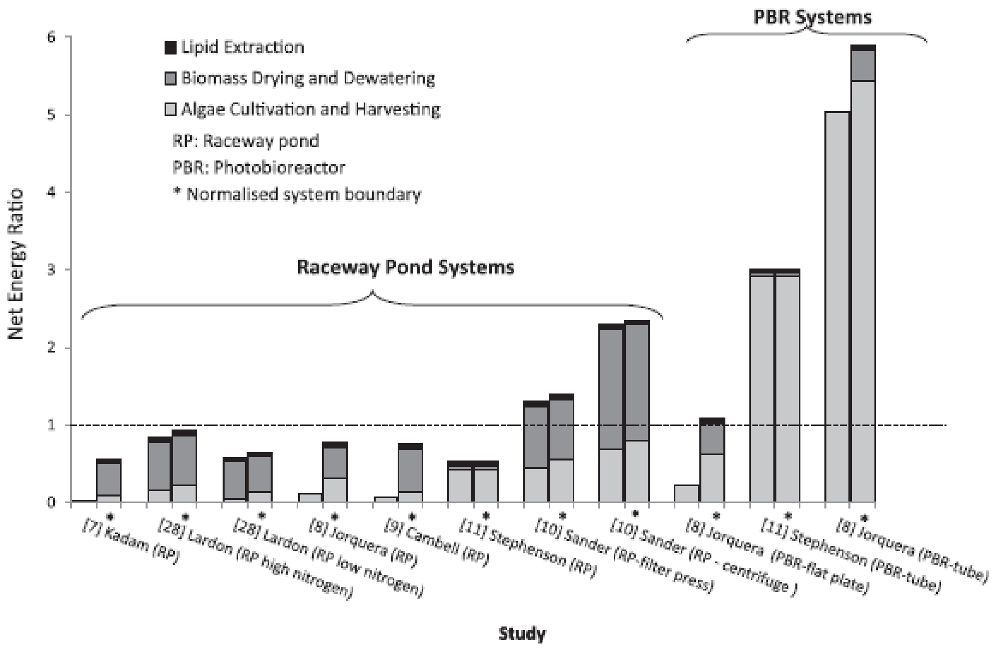

Figure 2.8: Net Energy Ratio for Micro-Algae Biomass Production

2.5.5 Sensitivity Analysis

As stated in paragraph 2.4, EU-27 electricity mix was considered in LCAs. This choice allows to perform a comparative analysis among the life cycle impacts of the selected algae cultivation systems. However, from an absolute perspective, the impact of a cultivation system (i.e.: the number of equivalent persons for each parameter) can be significantly different according to the composition of the electricity mix of the specific Country.

For this reason, a sensitivity analysis was performed in order to assess the order of magnitude of the error that can be introduced by applying the results of the present study to a specific plant in a specific location. A case study (OP1-WW) among the sixteen was analyzed by changing the electricity mix: in addition to EU-27, France, Germany, Greece, Italy, Portugal, Spain were considered. The LCA indicators were calculated using GaBi, normalized according to a person equivalent approach, and finally divided by the EU-27 value to calculate the relative value.

Figure 2.9 shows a comparison of the twelve environmental indicators among the six selected countries, considering 1 as EU-27 value. It can be noted that significant differences exist, and impacts can be up to seven times higher or lower than those calculated basing on the average EU-27 electricity grid mix.

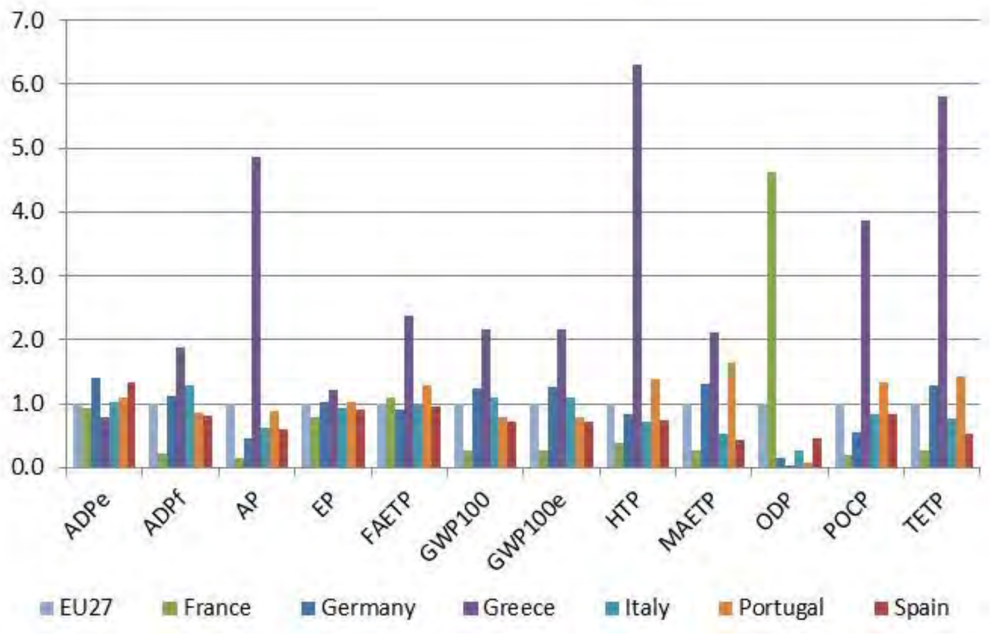

Figure 2.9: Sensitivity Analysis to Electricity Grid Mix

Basing on the above considerations, it is suggested to use the EU-27 electricity grid mix only to perform a comparison among the selected technologies, and to adopt data corresponding to the actual Country of installation of the plant if a particular case study has to be analyzed.

3 SWOT ANALYSIS ON LCA RESULTS

The following paragraphs present the SWOT analysis based on the results of the LCA shown in the previous sections. The main grouping is performed between the selected cultivation techniques (open ponds, photobioreactors), whereas the impact of harvesting/thickening processes and of water source change are discussed within each group.

It is worth noting that the present SWOT analysis only refers to the LCA aspects, disregarding the other economic and technical aspects (e.g.: photobioreactors have a good performance under a LCA perspective but they are more expensive than open ponds; gravity sedimentation/filtration give a good LCA performance but are much slower process compared to flocculation/centrifugation, etc).

3.1 OPEN PONDS

3.1.1 Strengths

- Open ponds using wastewater have a lower life cycle impact compared to those using freshwater, because they can recycle 80% of their output water.

3.1.2 Weaknesses

- The life cycle impact for algae production in open ponds is quite high due to the high amount of water and energy required.

3.1.3 Opportunities

- Using gravity sedimentation instead of the currently more used flocculation as bulk harvesting technique reduces the resources and energy consumptions thus leading to a lower life cycle impact;
- Using filtration instead of the currently more used centrifugation as thickening technique reduces the resources and energy consumptions thus leading to a lower life cycle impact.

3.1.4 Threats

- In this study the life cycle impact of open ponds construction phase was not considered, thus the real impact of algae production will be higher than calculated.

3.2 PHOTOBIOREACTORS

3.2.1 Strengths

- The life cycle impact for algae production in photobioreactors is quite low due to the low amount of water and energy required, provided that the energy consumptions related to cooling are excluded from the analysis in lack of reliable data from existing systems;
- Photobioreactors using wastewater have a lower life cycle impact because they can recycle 80% of their output water;
- Algae production in photobioreactors has a negative Global Warming Potential over the whole life cycle since the carbon dioxide used in algae growth is higher than the emissions due to electricity production.

3.2.2 Weaknesses

- very high energy consumptions in the cultivation phase are expected for cooling purposes, although not quantified in real cases;
- in this study the life cycle impact of photobioreactors construction phase was not considered, thus the real impact of algae production will be higher than calculated.

3.2.3 Opportunities

- Using gravity sedimentation instead of the currently more used flocculation as bulk harvesting technique reduces the resources and energy consumptions thus leading to a lower life cycle impact;
- Using filtration instead of the currently more used centrifugation as thickening technique reduces the resources and energy consumptions thus leading to a lower life cycle impact.

3.2.4 Threats

- In this study the life cycle impact of photobioreactors construction phase was not considered, thus the real impact of algae production will be higher than calculated;
- The life cycle impact of photobioreactors construction should be significantly higher than that of open ponds, thus the difference between the two cultivation techniques would be smaller.

4 CONCLUSIONS

This report presents the results of the LCA studies performed on selected algae cultivation and harvesting/thickening techniques. In particular, open ponds and photobioreactors were considered for cultivation, whereas flocculation and gravity sedimentation were considered for harvesting, and centrifugation, filtration for thickening. By combining these techniques, and two kinds of supplied water (wastewater and freshwater), a total number of sixteen case studies was identified.

LCA was performed according to a Cradle-To-Gate approach using GaBi software, whose internal databases were integrated with data concerning mass and energy consumptions of the different processes, taken from studies available in literature.

The comparison among the results of the LCAs allowed to identify the main differences between open ponds and photobioreactors. It was concluded that in general photobioreactors have a lower life cycle impact compared to open ponds, since they use less water and energy for unit of produced algae. More in detail, processes including gravity sedimentation and filtration as harvesting and thickening techniques have a lower life cycle impact compared to processes using flocculation and centrifugation because of their lower energy consumption.

The analysis of PBR is affected by a important hypothesis concerning the energy demand for cooling in the cultivation phase. Since no data are available in literature and real cases are being tested in this period, the quantitative analysis was done without the cooling-related consumptions, whereas the expected qualitative impact of cooling (expected to penalize the energy balances) was indicated.

Since the LCAs were performed to compare different technologies, disregarding the location of the plant, impacts from EU-27 electricity grid mix were considered. However, a sensitivity analysis was performed by studying the impact of the electricity mix for six different Countries, and it was concluded that significant differences exist. Thus, it is suggested to use the results of this study only as a comparison among technologies and, when necessary, to assess the absolute values of LCA indicators for the specific Country where the plant is to be realized.

Basing on the above summarized results, a SWOT analysis was performed. It is worth noting that the interpretation of LCA results and the consequent SWOT analysis only take into account the life cycle impact of the selected algae cultivation/harvesting/thickening techniques, and not the other economical and technical aspects connected to their costs and their efficiency.

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APPENDIX A
LCA DETAILED RESULTS

LCA DETAILED RESULTS

This appendix contains the detailed LCA results for each case study, expressed in terms of indicators and mass balances.

A.1. OPEN PONDS

Table A.1: LCA Indicators for Open Pond Case Studies (Not Normalized)

	OP1-WW	OP2-WW	OP3-WW	OP4-WW	OP1-FW	OP2-FW	OP3-FW	OP4-FW	Measurement Unit
ADPe	$3.10 \cdot 10^{-7}$	$2.98 \cdot 10^{-7}$	$3.06 \cdot 10^{-7}$	$2.94 \cdot 10^{-7}$	$1.01 \cdot 10^{-6}$	$1.00 \cdot 10^{-6}$	$1.01 \cdot 10^{-6}$	$9.98 \cdot 10^{-6}$	[kg Sb-Equiv.]
ADPf	9.89	8.92	9.59	8.62	4.12	3.15	3.82	2.85	[MJ]
AP	$4.31 \cdot 10^{-3}$	$3.91 \cdot 10^{-3}$	$4.19 \cdot 10^{-3}$	$3.78 \cdot 10^{-3}$	$2.77 \cdot 10^{-3}$	$2.37 \cdot 10^{-3}$	$2.65 \cdot 10^{-3}$	$2.24 \cdot 10^{-3}$	[kg SO2-Equiv.]
EP	$1.27 \cdot 10^{-3}$	$1.25 \cdot 10^{-3}$	$1.26 \cdot 10^{-3}$	$1.24 \cdot 10^{-3}$	$5.41 \cdot 10^{-3}$	$5.38 \cdot 10^{-3}$	$5.40 \cdot 10^{-3}$	$5.38 \cdot 10^{-3}$	[kg Phosphate-Equiv.]
FAETP	0.0105	0.0098	0.0099	0.0097	0.0415	0.0413	0.0414	0.0412	[kg DCB-Equiv.]
GWP100	1.016	0.930	0.990	0.904	1.126	1.040	1.099	1.014	[kg CO2-Equiv.]
GWP100e	1.02	0.94	0.99	0.91	1.13	1.05	1.11	1.02	[kg CO2-Equiv.]
HTP	0.0582	0.0532	0.0566	0.0516	0.0599	0.0549	0.0584	0.0534	[kg DCB-Equiv.]
MAETP	114.1	104.9	111.3	102.0	140.9	131.7	138.1	128.8	[kg DCB-Equiv.]
ODP	$6.99 \cdot 10^{-10}$	$6.40 \cdot 10^{-10}$	$6.81 \cdot 10^{-10}$	$6.22 \cdot 10^{-10}$	$7.71 \cdot 10^{-10}$	$7.12 \cdot 10^{-10}$	$7.53 \cdot 10^{-10}$	$6.94 \cdot 10^{-10}$	[kg R11-Equiv.]
POCP	$2.52 \cdot 10^{-4}$	$2.28 \cdot 10^{-4}$	$2.45 \cdot 10^{-4}$	$2.21 \cdot 10^{-4}$	$1.46 \cdot 10^{-4}$	$1.22 \cdot 10^{-4}$	$1.38 \cdot 10^{-4}$	$1.14 \cdot 10^{-4}$	[kg Ethene-Equiv.]
TETP	6.17	5.72	6.03	5.58	10.01	9.56	9.87	9.42	[kg DCB-Equiv.]

Table A.2: Complete Balances for Open Pond Case Studies

Flows [kg]	OP1-WW	OP2-WW	OP3-WW	OP4-WW
Total flows	**8,294**	**7,612**	**8,084**	**7,402**
Resources	**4,139**	**3,806**	**4,037**	**3,704**
Energy resources	0.4554	0.4141	0.4427	0.4014
Land use	0	0	0	0
Material resources	4,138	3,806	4,036	3,703
Deposited goods	**3.394**	**3.056**	**3.290**	**2.952**
Radioactive waste	0.0026	0.0023	0.0025	0.0023
Stockpile goods	3.391	3.054	3.288	2.950
Emissions to air	**17.27**	**15.73**	**16.79**	**15.26**
Heavy metals to air	$1.76 \cdot 10^{-6}$	$1.62 \cdot 10^{-6}$	$1.72 \cdot 10^{-6}$	$1.57 \cdot 10^{-6}$
Inorganic emissions to air	12.66	11.56	12.32	11.26
Organic emissions to air (group VOC)	0.0064	0.0062	0.0064	0.0062

Flows [kg]	OP1-WW	OP2-WW	OP3-WW	OP4-WW
Other emissions to air	4.596	4.164	4.463	4.031
Particles to air	$2.11 \cdot 10^{-4}$	$1.88 \cdot 10^{-4}$	$2.04 \cdot 10^{-4}$	$1.81 \cdot 10^{-4}$
Pesticides to air	$-6.85 \cdot 10^{-13}$	$-6.85 \cdot 10^{-13}$	$-6.85 \cdot 10^{-13}$	$-6.85 \cdot 10^{-13}$
Radioactive emissions to air	$1.69 \cdot 10^{-13}$	$1.55 \cdot 10^{-13}$	$1.65 \cdot 10^{-13}$	$1.50 \cdot 10^{-13}$
Emissions to fresh water	**4,118**	**3,772**	**4,012**	**3,666**
Analytical measures to fresh water	0.0057	0.0056	0.0057	0.0056
Heavy metals to fresh water	$5.17 \cdot 10^{-4}$	$4.78 \cdot 10^{-4}$	$5.05 \cdot 10^{-4}$	$4.65 \cdot 10^{-4}$
Inorganic emissions to fresh water	0.0135	0.0128	0.0133	0.0125
Organic emissions to fresh water	0.0011	0.0011	0.0011	0.0011
Other emissions to fresh water	3,923	3,593	3,822	3,492
Particles to fresh water	$6.27 \cdot 10^{-4}$	$5.75 \cdot 10^{-4}$	$6.11 \cdot 10^{-4}$	$5.59 \cdot 10^{-4}$
Radioactive emissions to fresh water	195.3	178.9	190.3	173.9
Emissions to sea water	**15.32**	**14.02**	**14.92**	**13.62**
Analytical measures to sea water	$1.01 \cdot 10^{-6}$	$8.97 \cdot 10^{-7}$	$9.74 \cdot 10^{-7}$	$8.63 \cdot 10^{-7}$
Heavy metals to sea water	$8.41 \cdot 10^{-8}$	$7.70 \cdot 10^{-8}$	$8.19 \cdot 10^{-8}$	$7.48 \cdot 10^{-8}$
Inorganic emissions to sea water	$6.44 \cdot 10^{-4}$	$5.92 \cdot 10^{-4}$	$6.28 \cdot 10^{-4}$	$5.76 \cdot 10^{-4}$
Organic emissions to sea water	$3.81 \cdot 10^{-7}$	$3.50 \cdot 10^{-7}$	$3.72 \cdot 10^{-7}$	$3.41 \cdot 10^{-7}$
Other emissions to sea water	15.32	14.02	14.92	13.62
Particles to sea water	$2.42 \cdot 10^{-5}$	$2.04 \cdot 10^{-5}$	$2.31 \cdot 10^{-5}$	$1.92 \cdot 10^{-5}$
Radioactive emissions to sea water	0	0	0	0
Emissions to agricultural soil	**$3.52 \cdot 10^{-7}$**	**$3.23 \cdot 10^{-7}$**	**$3.43 \cdot 10^{-7}$**	**$3.14 \cdot 10^{-7}$**
Heavy metals to agricultural soil	$3.52 \cdot 10^{-7}$	$3.23 \cdot 10^{-7}$	$3.43 \cdot 10^{-7}$	$3.14 \cdot 10^{-7}$
Emissions to industrial soil	**$2.27 \cdot 10^{-5}$**	**$2.07 \cdot 10^{-5}$**	**$2.21 \cdot 10^{-5}$**	**$2.01 \cdot 10^{-5}$**
Heavy metals to industrial soil	$1.81 \cdot 10^{-9}$	$1.66 \cdot 10^{-9}$	$1.77 \cdot 10^{-9}$	$1.62 \cdot 10^{-9}$
Inorganic emissions to industrial soil	$2.27 \cdot 10^{-5}$	$2.07 \cdot 10^{-5}$	$2.21 \cdot 10^{-5}$	$2.01 \cdot 10^{-5}$
Organic emissions to industrial soil	$8.59 \cdot 10^{-11}$	$7.87 \cdot 10^{-11}$	$8.37 \cdot 10^{-11}$	$7.65 \cdot 10^{-11}$
Other emissions to industrial soil	$1.78 \cdot 10^{-18}$	$1.63 \cdot 10^{-18}$	$1.73 \cdot 10^{-18}$	$1.58 \cdot 10^{-18}$

A.2. PHOTOBIOREACTORS

Table A.3: LCA Indicators for Photobioreactor Case Studies (Not Normalized)

	PBR1-WW	PBR2-WW	PBR3-WW	PBR4-WW	PBR1-FW	PBR2-FW	PBR3-FW	PBR4-FW	Measurement Unit
ADPe	$1.45\cdot10^{-8}$	$1.33\cdot10^{-8}$	$1.41\cdot10^{-8}$	$1.29\cdot10^{-8}$	$3.41\cdot10^{-8}$	$3.20\cdot10^{-8}$	$3.37\cdot10^{-8}$	$3.25\cdot10^{-8}$	[kg Sb-Equiv.]
ADPf	0.7564	0.6584	0.7231	0.6260	0.5951	0.5059	0.5628	0.4657	[MJ]
AP	0.000319	0.000279	0.000306	0.000265	0.000276	0.000238	0.000263	0.000222	[kg SO2-Equiv.]
EP	0.000047	0.000045	0.000046	0.000043	0.000161	0.000154	0.000161	0.000158	[kg Phosphate-Equiv.]
FAETP	0.000382	0.000362	0.000375	0.000355	0.001258	0.001194	0.001251	0.001231	[kg DCB-Equiv.]
GWP100	-2.537	-2.541	-2.536	-2.544	-2.530	-2.538	-2.533	-2.541	[kg CO2-Equiv.]
GWP100e	0.0711	0.0624	0.0681	0.0595	0.0741	0.0653	0.0712	0.0626	[kg CO2-Equiv.]
HTP	0.00408	0.00358	0.00391	0.00341	0.00412	0.00362	0.00395	0.00346	[kg DCB-Equiv.]
MAETP	7.765	6.831	7.448	6.523	8.501	7.540	8.193	7.268	[kg DCB-Equiv.]
ODP	$4.85\cdot10^{-11}$	$4.26\cdot10^{-11}$	$4.65\cdot10^{-11}$	$4.06\cdot10^{-11}$	$5.04\cdot10^{-11}$	$4.45\cdot10^{-11}$	$4.85\cdot10^{-11}$	$4.26\cdot10^{-11}$	[kg R11-Equiv.]
POCP	$1.89\cdot10^{-5}$	$1.65\cdot10^{-5}$	$1.81\cdot10^{-5}$	$1.57\cdot10^{-5}$	$1.59\cdot10^{-5}$	$1.37\cdot10^{-5}$	$1.51\cdot10^{-5}$	$1.27\cdot10^{-5}$	[kg Ethene-Equiv.]
TETP	0.40	0.35	0.38	0.33	0.50	0.45	0.49	0.44	[kg DCB-Equiv.]

Table A.4: Complete Balances for Photobioreactor Case Studies

Flows [kg]	PBR1-WW	PBR2-WW	PBR3-WW	PBR4-WW
Total Flows	**572.39**	**503.76**	**549.08**	**481.11**
Resources	**282.36**	**248.87**	**270.98**	**237.81**
Energy resources	0.0330	0.0289	0.0316	0.0275
Land use	0	0	0	0
Material resources	282.33	248.84	270.95	237.78
Deposited goods	**0.2615**	**0.2274**	**0.2499**	**0.2162**
Radioactive waste	0.000181	0.000159	0.000174	0.000152
Stockpile goods	0.2613	0.2273	0.2497	0.2161
Emissions to air	**1.2392**	**1.0848**	**1.1867**	**1.0338**
Heavy metals to air	$1.22\cdot10^{-7}$	$1.07\cdot10^{-7}$	$1.17\cdot10^{-7}$	$1.02\cdot10^{-7}$
Inorganic emissions to air	0.8975	0.7866	0.8598	0.7499
Organic emissions to air (group VOC)	0.000269	0.000251	0.000263	0.000245
Other emissions to air	0.3414	0.2979	0.3266	0.2835
Particles to air	$1.72\cdot10^{-5}$	$1.49\cdot10^{-5}$	$1.64\cdot10^{-5}$	$1.42\cdot10^{-5}$

Flows [kg]	PBR1-WW	PBR2-WW	PBR3-WW	PBR4-WW
Pesticides to air	$-1.92\cdot10^{-14}$	$-1.92\cdot10^{-14}$	$-1.92\cdot10^{-14}$	$-1.92\cdot10^{-14}$
Radioactive emissions to air	$1.18\cdot10^{-14}$	$1.03\cdot10^{-14}$	$1.13\cdot10^{-14}$	$9.87\cdot10^{-15}$
Emissions to fresh water	**287.46**	**252.64**	**275.63**	**241.15**
Analytical measures to fresh water	0.000204	0.000195	0.000201	0.000193
Heavy metals to fresh water	$3.41\cdot10^{-5}$	$3.01\cdot10^{-5}$	$3.28\cdot10^{-5}$	$2.88\cdot10^{-5}$
Inorganic emissions to fresh water	0.000765	0.000687	0.000739	0.000661
Organic emissions to fresh water	$3.31\cdot10^{-5}$	$3.27\cdot10^{-5}$	$3.30\cdot10^{-5}$	$3.26\cdot10^{-5}$
Other emissions to fresh water	273.91	240.74	262.64	229.79
Particles to fresh water	$4.33\cdot10^{-5}$	$3.80\cdot10^{-5}$	$4.15\cdot10^{-5}$	$3.63\cdot10^{-5}$
Radioactive emissions to fresh water	13.548	11.897	12.987	11.352
Emissions to sea water	**1.0664**	**0.9361**	**1.0221**	**0.8931**
Analytical measures to sea water	$8.26\cdot10^{-8}$	$7.15\cdot10^{-8}$	$7.88\cdot10^{-8}$	$6.78\cdot10^{-8}$
Heavy metals to sea water	$5.85\cdot10^{-9}$	$5.14\cdot10^{-9}$	$5.61\cdot10^{-9}$	$4.90\cdot10^{-9}$
Inorganic emissions to sea water	$4.38\cdot10^{-5}$	$3.85\cdot10^{-5}$	$4.20\cdot10^{-5}$	$3.68\cdot10^{-5}$
Organic emissions to sea water	$2.59\cdot10^{-8}$	$2.28\cdot10^{-8}$	$2.49\cdot10^{-8}$	$2.18\cdot10^{-8}$
Other emissions to sea water	1.0663	0.9361	1.0221	0.8931
Particles to sea water	$2.58\cdot10^{-6}$	$2.19\cdot10^{-6}$	$2.45\cdot10^{-6}$	$2.07\cdot10^{-6}$
Radioactive emissions to sea water	0	0	0	0
Emissions to agricultural soil	**$2.42\cdot10^{-8}$**	**$2.13\cdot10^{-8}$**	**$2.32\cdot10^{-8}$**	**$2.03\cdot10^{-8}$**
Heavy metals to agricultural soil	$2.42\cdot10^{-8}$	$2.13\cdot10^{-8}$	$2.32\cdot10^{-8}$	$2.03\cdot10^{-8}$
Emissions to industrial soil	**$1.59\cdot10^{-6}$**	**$1.40\cdot10^{-6}$**	**$1.53\cdot10^{-6}$**	**$1.33\cdot10^{-6}$**
Heavy metals to industrial soil	$1.26\cdot10^{-10}$	$1.10\cdot10^{-10}$	$1.21\cdot10^{-10}$	$1.05\cdot10^{-10}$
Inorganic emissions to industrial soil	$1.59\cdot10^{-6}$	$1.40\cdot10^{-6}$	$1.52\cdot10^{-6}$	$1.33\cdot10^{-6}$
Organic emissions to industrial soil	$5.96\cdot10^{-12}$	$5.24\cdot10^{-12}$	$5.72\cdot10^{-12}$	$5.00\cdot10^{-12}$
Other emissions to industrial soil	$1.24\cdot10^{-19}$	$1.09\cdot10^{-19}$	$1.19\cdot10^{-19}$	$1.04\cdot10^{-19}$

APPENDIX F

TECHNICAL REPORT
BIOENERGY AND CO-PRODUCT CHAIN DEPLOYMENT POTENTIAL ANALYSIS

Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Bioenergy and Co-Product Chain Deployment Potential Analysis

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F.1 INTRODUCTION

This report summarizes the results of the potential analysis on algae bioenergy and co-product chains, performed within Task 2 of the Project.

Under the present assignment, the analysis focuses on the actual viability, under a technical, economic and environmental perspective, of the production chains. In particular, the barriers that currently prevent the commercial development of biofuels production plants will be identified and studied in a dedicated following report, where a set of guidelines aimed at overcoming them will be presented. This should help identify the main causes of the techno-economic gap between the production of biofuels and that of conventional fuels from fossil origin, and address actions aimed at the reduction of this gap.

In this study, the most relevant production chains are analyzed under the biological, technological, economic and environmental points of view, by taking into consideration their capability of producing both biofuels and other co-products. For each of the selected production chains, a SWOT analysis is performed, on whose basis a rating is assigned to identify the distance of the specific production chain from the actual viability. In light of this approach, the demonstration plants of the FP7 Projects are compared with the five selected classes, thus assessing also their strengths, weaknesses, opportunities and threats and their distance from the actual development.

The five production chains taken into consideration in the following sections are:

- biomass production;
- biofuel production without co-products;
- biofuel production without co-products but with environmental advantages;
- biofuel production with valuable by-products;
- multi-product approach.

The topics introduced above are illustrated in the present report using the following structure:

- Section 1 introduces the content, the objectives and the structure of this report;
- Section 2 presents the five classes of production chains that are analyzed in this study;
- Section 3 shows the SWOT analyses performed on the five classes of production chains taking into account biological, technological, economic and environmental aspects;
- Section 4 appoints a rating to each of the selected classes of production chains, to identify their distance from actual commercial development;
- Section 5 assesses the pilot plants being realized within the FP7 research projects according to the above defined gap analysis;
- Section 6 summarizes the conclusions of the study.

F.2 BIOFUEL PRODUCTION CHAINS

Algae are a suitable raw material for several industrial processes, aimed at the production of different substances such as biofuels, proteins for animal feeding, chemicals, ingredients for pharmaceutical, nutraceutical and cosmetic uses.

However, a process aiming at the production of biofuels has other substances only as co-products, and usually only a few co-products can be obtained from a given process. More in detail, the higher the added value of the desired co-product, the larger the complication introduced in the process. This implies for the majority of cases that there are no industrial plants targeting the combined production of fuels and co-products.

In this study, production chains were analyzed identifying five classes of production chains (Figure F.2.1). Numbered from 1 to 5, production chains have an increasing degree of complication, depending on the final product and the by-products obtained.

The basic level is constituted of the simple production of biomass, algae available for production of biofuels and co-products in external plants; in this case, the downstream production chains are separated (not necessarily located at the same place) and deal with different market approaches and models of business; the second step is biofuels without any co-product; the third chain coincides with the second in its output, but it is optimized in order to maximize environmental benefits (or the avoided costs); the fourth considers the production of biofuels according to a process having high value by-products; finally, the fifth chain follows a multi-product approach giving the same relevance to the production of biofuels and co-products.

Figure F.2.1 illustrates the five selected classes of production chains analyzed in this study.

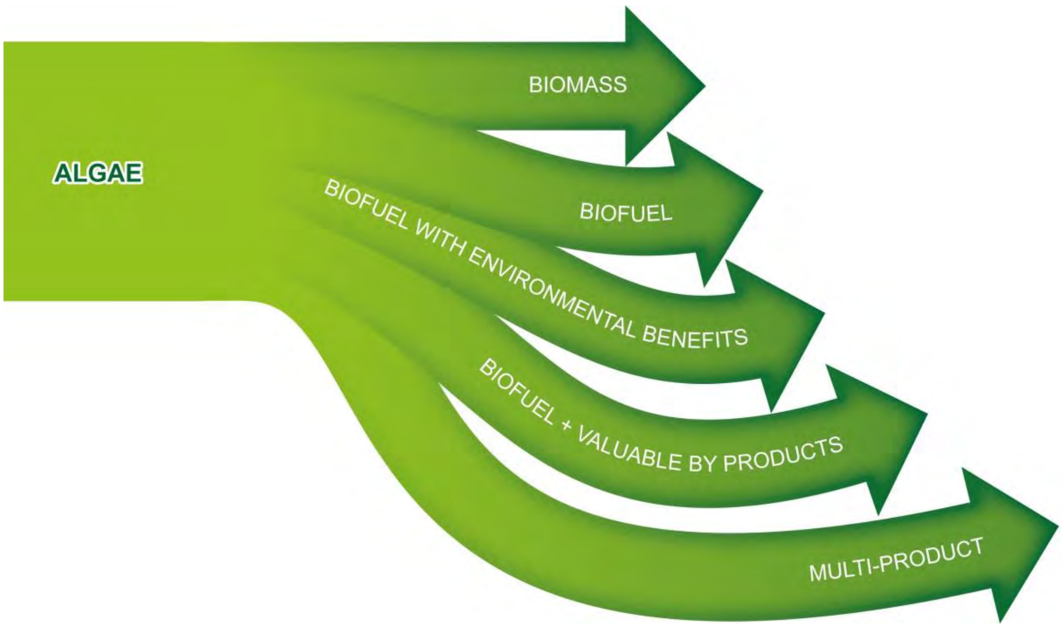

Figure F.2.1: Selected Classes of Biofuels Production Chains

The following chapters are dedicated to the presentation of the general features of the production chains and flow into some economic considerations for each. The five selected classes of production chains introduced above are hereby recalled:

- biomass production (Production Chain 1);
- biofuel production without co-products (Production Chain 2);
- biofuel production without co-products but with environmental benefits (Production Chain 3);
- biofuel production with valuable by-products (Production Chain 4);
- multi-product approach (Production Chain 5).

F.2.1 PRODUCTION CHAIN 1

Production Chain 1 covers the basic steps of algae cultivation and is a segment of the further production chains. In fact, the chain covers algae production process in its first stages, without considering their transformation, oil extraction and transport to biorefineries, other energy production plants or industries that transform algae into commercialized products.

The fact that this production chain aims only at producing algae without considering any further processing leads to similarities with aquaculture or farming as business model. The business scheme is shown in Figure F.2.2.

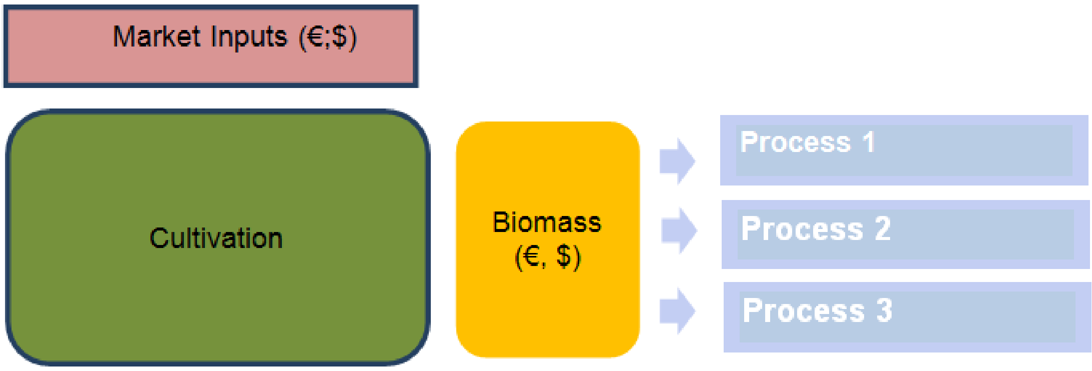

Figure F.2.2: Schematic Business Model for Production Chain 1

F.2.2 PRODUCTION CHAIN 2

Production Chain 2 coincides with the mere production of biofuel from algae and thus includes processes aimed at the production of biofuel that are not optimized to achieve valuable by-products or at least environmental or economic benefits.

The process of production is unique (or relates to a few number of technologies) and has a direct relationship between inputs (as nutriments, water, energy) and output (biogas or biofuel). In this case, inputs are bought on the market (as fertilizers) or are directly available on site (with no connection with other facilities required).

The energy market for fuels is the only market targeted by investors (with no other market opportunities elsewhere for co-products), as Figure F.2.3 summarizes.

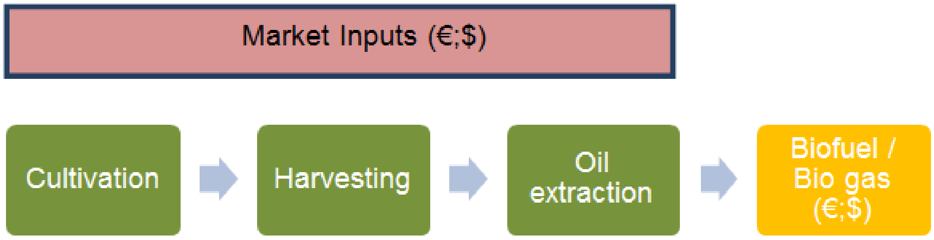

Figure F.2.3: Schematic Business Model for Production Chain 2

F.2.3 PRODUCTION CHAIN 3

In this case, the overall layout of the process coincides with the previous production chain. The strong difference lies in the fact that biofuel is produced without co-products but with environmental benefits (or avoided costs), such as the use of wastewater as cultivation medium, which reduces environmental costs for wastewater treatment, or the reduction of GHG emissions in atmosphere due to the use of CO_2 from energy/industrial plants.

Production Chain 3 shows similarities with Production Chain 2, but with specific improvements for the following aspects:

- benefits from algae biofuel production derive not only from the fuel traded but also include external benefits for the community in terms of avoided costs for instance in wastewater treatment and reuse of CO2 emitted by energy/industrial plants;
- the production chain is more complex than the previous one, since some inputs used in the algae production process are outputs coming from other processes of production/consumption close to the same area;
- inputs from external sources are at the origin of environmental costs and their reuse is an advantage for the whole community, since it procures a public benefit;
- the reuse of inputs needs a connection to public facilities or production plants, thus requiring additional investments.

The underlying business model requires an agreement between the investor and the other external operators or facilities. A compensation must be paid from the latter to the former for the costs of treatment avoided (costs not sustained or not paid elsewhere) or the avoided credits paid (in case of a CO_2 permit credit system). This kind of business model is schematized in Figure F.2.4.

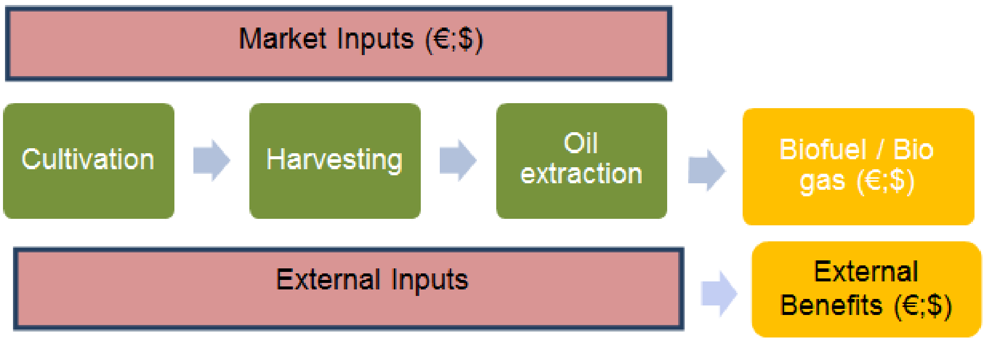

Figure F.2.4: Schematic Business Model for Production Chain 3

F.2.4 PRODUCTION CHAIN 4

This chain is characterized by the production of valuable by-products in addition to biofuel, such as soil improvers for agriculture or biogas from anaerobic digestion of production residues. This allows to gather additional sources of revenue provided by the valorization (i.e.: trade) of by-products.

Also in this case, the production chain shows similarities with Production Chain 2, but the process is more complex, since by-products must be extracted with filters or purification equipment. Moreover, the yield in biofuel is lower than in the other cases as by-products consume part of the biomass available to biofuel production.

The general business model for this production chain is schematized in Figure F.2.5. It can be noted that different products are provided to different markets with different trends: investors should develop different strategies to commercialize by-products in separated markets at different places. The opportunity costs of investment do not only rely on the production of fuel but are also related to the different prices of by-products.

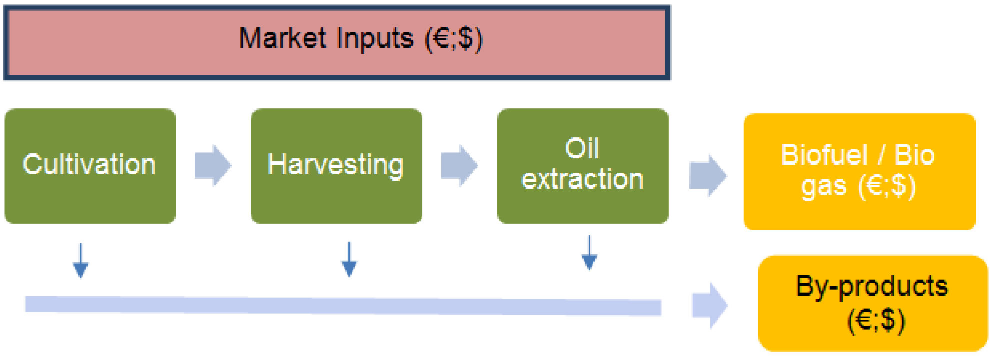

Figure F.2.5: Schematic Business Model for Production Chain 4

F.2.5 PRODUCTION CHAIN 5

Like the previous one, this production chain aims at the production of biofuel and valuable co-products, thus the same considerations in terms of commercialized products and market opportunities are valuable.

The main difference is in the scale of equipment and land requirement, since the number of production processes involved is potentially high, not to say infinite. In addition, the complexity of the whole process increases proportionally with the number of technologies and inputs used and the number of products commercialized.

Then, it is worth noticing that markets are significantly different in terms of sectors, stakeholders, technologies and consumers, depending on the product considered; such a diversity should require separated business approaches, i.e. different investors or pools of investors, different strategies of commercialization and different margins and expected benefits. Taking into consideration these features, the theoretical business model for Production Chain 5 is shown in Figure F.2.6.

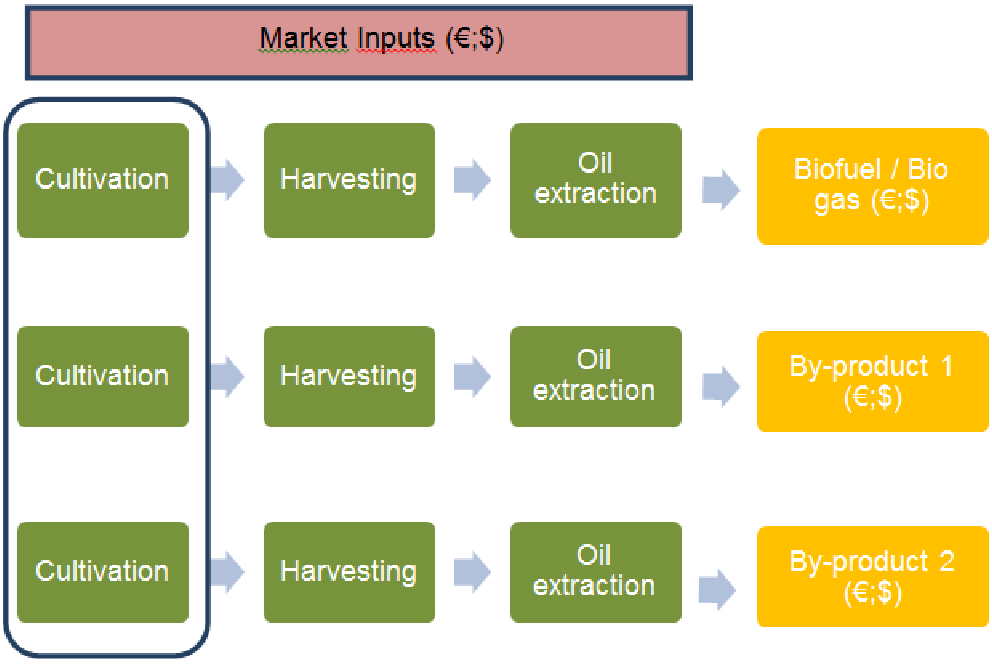

Figure F.2.6: Schematic Business Model for Production Chain 5

F.3 SWOT ANALYSIS

As introduced in the previous section, the SWOT analysis is articulated in five main clusters, corresponding to the five selected production chains:

- biomass production (Production Chain 1);
- biofuel production without co-products (Production Chain 2);
- biofuel production without co-products but with environmental benefits (Production Chain 3);
- biofuel production with valuable by-products (Production Chain 4);
- multi-product approach (Production Chain 5).

The analysis is based on comments on the technological, biological and economical features of the processes constituting the five chains, complemented by a LCA for the environmental aspects, which is also enclosed in the dedicated Appendix A for the sake of completeness.

The following sections summarize strengths, weaknesses, opportunities and threats for the five production chains.

F.3.1 PRODUCTION CHAIN 1

The SWOT analysis on Production Chain 1 is shown in the following paragraphs and graphically recalled at the end of Section 3.1.5.

F.3.1.1 Strengths

The strengths that characterize Production Chain 1 are:

- microalgae are currently cultivated on a commercial scale in several countries (e.g.: large-scale culture of Chlorella, Haematococcus and Dunaliella);
- the production of raw biomass is less expensive;
- several algae (e.g.: spirulina) are valuable without further processing;
- the process is generally simple;
- the required investments and operating costs are limited, since they are only related to the first stage of the production chain;
- the business model is simple, close to farming or aquaculture.

F.3.1.2 Weaknesses

The following bullet list shows the weaknesses identified on Production Chain 1:

- nowadays only phototrophic cultivation is commercially feasible for large-scale production of algae biomass;
- presently there is no significant algal production capacity (except for some nutraceutics);
- the flexibility (i.e.: possibility to adapt the plant to different types of algae biomass so as to meet market requests) of these plants is not demonstrated;
- in several cases, the final product has a very low value, since the complexity level of processing technology is lower;

- the costs for conditioning and transport of algae to other plants and facilities are high, since not necessarily plants are located at the same place;
- the demand side must be structured and allow a market segmentation between algae production and algae transformation in bio-fuel or other products;
- algae cultivation in open ponds has a significantly high impact, due to the high consumption of water and electricity.

F.3.1.3 Opportunities

The main opportunities offered by Production Chain 1 are presented in the following breakdown list:

- market opportunities exist for high-value compounds from the same biomass;
- the complexity level of processing technology is lower, thus there is room for less specialized players (e.g.: from the agricultural business);
- since the focus is not on the final product, the same biomass may be of interest to different producers (food, pharma, chemical sectors) for different valuable compounds in the biomass: increased market opportunities;
- a long-term economy of scale exists (with a significant decrease in prices);
- algae cultivation in photobioreactors leads to a negative GWP, because the amount of carbon dioxide absorbed in algae growth compensates GHG emissions due to electricity generation and other processes.

F.3.1.4 Threats

The following bullets list is representative of the main threats discovered on Production Chain 1:

- potential environmental risks exist due to the release of algae (some species are toxic for micro-organism and fishes and/or propagate allergenic diseases) and risk of contamination by other species of micro-organisms;
- a bulk production is probably needed, thus requiring land and water resources;
- biomass transport may be complicated (decomposition of biomass to be avoided; stabilizing pretreatments may be required);
- several low-cost nutrients (wastewater) and CO_2 sources (some combustion processes like incineration) may have to be excluded because of safety and regulatory restrictions on final biomass usage;
- the market demand for such a product has to be verified;
- there might be no economy of scale, due to high transport and transformation costs of algae;
- the use of solar drying as thickening technique does not require electricity but produces mixtures with a lower algae concentration.

F.3.1.5 Summary of SWOT for Production Chain 1

Finally, the figures of the previous analysis are put together in Figure F.3.1, displaying the combined outcomes of the SWOT analysis on Production Chain 1.

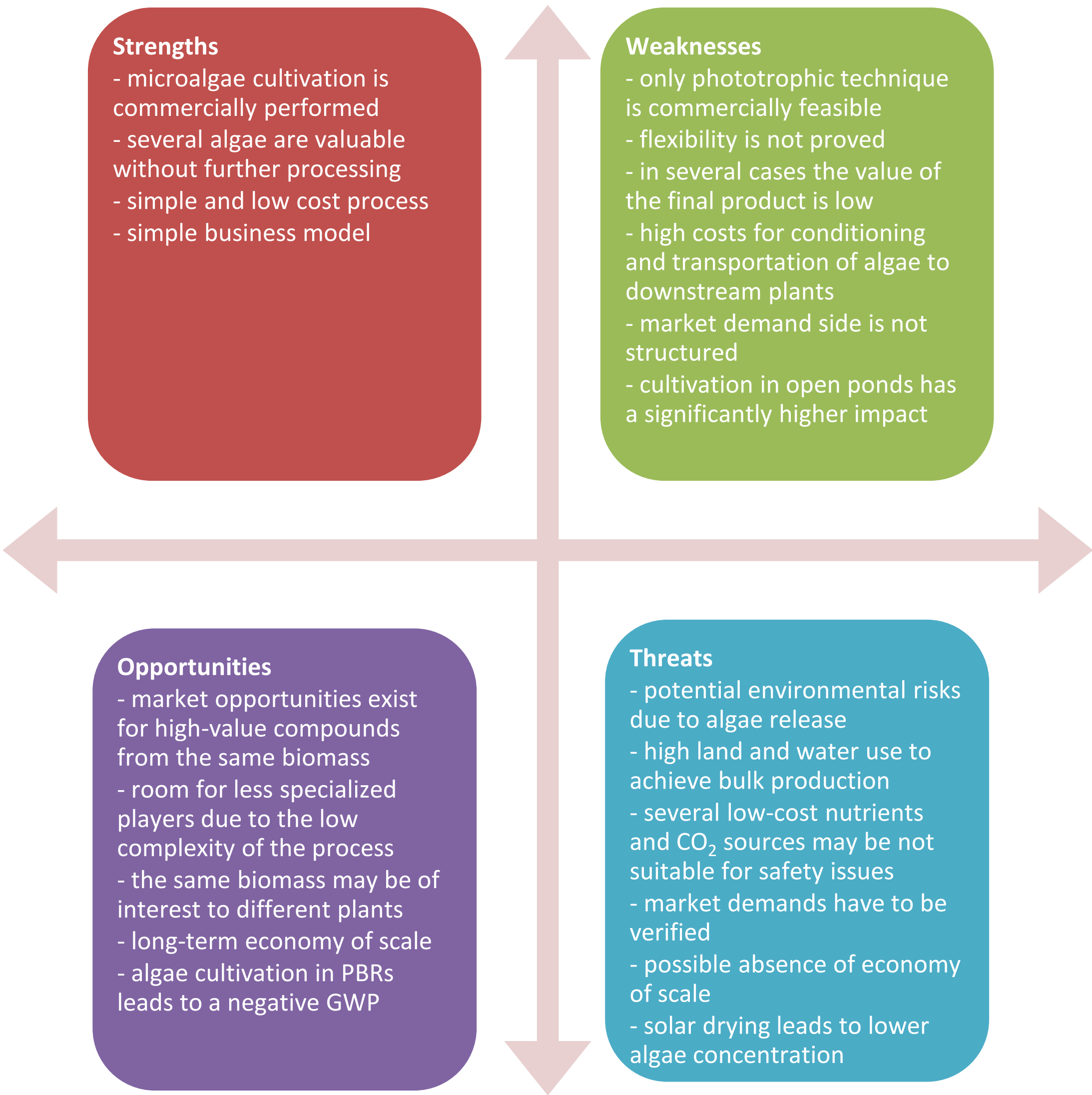

Figure F.3.1: SWOT Analysis on Production Chain 1

F.3.2 PRODUCTION CHAIN 2

The SWOT analysis on Production Chain 2 is shown in the following paragraphs and graphically recalled at the end of Section 3.2.5.

F.3.2.1 Strengths

The following bullets summarize the identified strengths emerging from the analysis of the strengths of Production Chain 2:

- some species can synthesize and accumulate a significant amount of lipids and hydrocarbons and thus show a good suitability for biodiesel production;
- differently from (non) food-based crops (first and second generation biofuels), microalgae biomass can be harvested more than once a year;
- processes of this production chain are moderately consolidated;
- the design of these processes is lean and easier to optimize;
- inputs are available directly on markets (easy to identify on marketplaces), without the need for additional inter-connections with other phases of the process or with other production facilities off-site;
- products (biofuel or biogas) are simply sold on the marketplace;
- algae cultivation in photobioreactors leads to a negative GWP, because the amount of carbon dioxide absorbed in algae growth compensates GHG emissions due to electricity generation and other processes.

F.3.2.2 Weaknesses

The following weaknesses are identified for Production Chain 2:

- since a part of algal biomass produced during the day can be lost through respiration during the night, costs to maintain an overnight production have to be considered (Chisti, 2007);
- the growth rate of several promising species for biofuel productions is reported to be very low;
- this production chain might be economically unattractive (Wijffels and Barbosa, 2010);
- there is a single source for revenues;
- the profitability gap with existing fuel production technologies is unlikely to be filled in the short-medium term (Wijffels et al., 2010);
- the downstream processes still has to be fully consolidated;
- the costs of fertilizers (e.g.: nitrogen, phosphorus and potassium) and other costs of inputs, could be high in the absence of market alternatives; moreover, transportation costs should also be considered;
- algae cultivation in open ponds has a significantly high impact, due to the high consumption of water and electricity.

F.3.2.3 Opportunities

The opportunities identified for Production Chain 2 are hereby listed:

- the use of genetic engineering is suitable to increase oil content;
- microalgal strains capable of simplifying the design and improving the downstream economics (e.g.: microalgae secreting oils) can be used;
- the exploitation of nutrient and CO_2 sources from other industrial processes (residues and wastes, flue gas, etc.) is possible;
- single-product cultures allow for higher biological specialization and more targeted genetic intervention;
- a technological improvement in production process (algae productivity, lipid extraction, etc.), a high economy of scale from mass production, a high yield and a significant drop in production costs are possible;
- high fossil fuel energy prices justify the initial investment.

F.3.2.4 Threats

The main threats affecting Production Chain 2 are:

- potential environmental risks exist due to release of algae (some species are toxic for micro-organism and fishes and/or propagate allergenic diseases);
- a suitable design of downstream processes may require a long time;
- to make microalgae really interesting as a source of biofuels, costs for production need to be reduced and the scale of productions needs to be increased significantly: that may pose some issues on the identification of suitable location (Wijffels et al., 2010);
- large scale production may result rather intensive in terms of water footprint;
- the processes are characterized by a low rate of innovation (no economy of scale, low yield), with the result that production costs are still high compared to other bio-fuels or fossil fuels production chains;
- low fossil fuel energy prices might threaten the development of these processes;
- the use of solar drying as thickening technique does not require electricity but produces mixtures with a lower algae concentration.

F.3.2.5 Summary of SWOT for Production Chain 2

Figure F.3.2 shows a summary of the SWOT analysis on Production Chain 2 presented in the previous paragraphs.

Figure F.3.2: SWOT Analysis on Production Chain 2

F.3.3 PRODUCTION CHAIN 3

The SWOT analysis on Production Chain 3 is shown in the following paragraphs and graphically recalled at the end of Section 3.3.5.

F.3.3.1 Strengths

The main strengths that were identified for Production Chain 3 are the following:

- some species are able to grow using freshwater or seawater mixed with wastewater (sewage, industrial, agricultural ones) and/or provision of extra CO_2, supplied by emissions sources (e.g.: power plants, petroleum refinery, etc);
- sustainability and process economy are increased (Brennan and Owende, 2010);
- the use of (free) CO_2 from coal combustion, cement industry or other biomass source is possible;

- the recycling (reuse) of nutriments, water and energy coming from other external processes/facilities, decreases the requirement of market inputs and reduces operating costs;
- the use of wastewater as algae growth medium significantly reduces impacts, because water can be recycled back to the cultivation plant, thus reducing resources consumption and avoiding environmental costs for wastewater treatment;
- the use of carbon dioxide from power stations or other combustion plants as nutrient for algae growth contributes to reduce impacts, and in particular GWP, because it avoids emissions to atmosphere.

F.3.3.2 Weaknesses

The following list summarizes weaknesses identified for Production Chain 3:

- the same weaknesses presented for Production Chain 2 are worth;
- it may not be applicable to all microalgae;
- not any type of wastewater can be used;
- fouling issues are increased;
- equipment costs are higher (compared to what it is necessary to invest in previous production chains) due to the need to connect different processes/facilities to the system and to control inflows from other external industrial or power plants;
- it is necessary to localize plants near industrial areas able to provide CO_2 as input;
- coordination is necessary between investors and external operators.

F.3.3.3 Opportunities

Concerning opportunities, the following are those to be highlighted for Production Chain 3:

- the same opportunities presented for Production Chain 2 are still valid;
- some species can be used for bioremediation treatment of industrial wastewater;
- this approach allows to combine biomass production for biofuels and wastewater or flue gas treatment;
- significant cost reductions are achievable;
- the development of circular and closed systems of production and consumption is possible, thus recycling water and nutriments and re-using by-products for producing energy (large reduction in operating costs in the long term);
- external benefits for the society (avoided costs, reduction of emissions) exist.

F.3.3.4 Threats

The main threats affecting Production Chain 3 are:

- the same threats highlighted for Production Chain 2 are still valid;
- the use of wastewater increases the possibility of contamination by other species of micro-organisms;
- microalgae strains must be able to grow in waste water and show high CO_2 utilization rate, tolerance of trace constituents of flue gas, water temperature and pollutant content;

- wastewater may need to be diluted significantly and thus water footprint may still be critical or affect economic viability;
- recycling induces low rate of innovation, which results in production costs remaining high compared to other bio-fuels or fossil fuels production chains;
- low economy of scale in recycling and reusing leads to the absence of advantages in developing large-scale plants (i.e.: no mass production savings in the case of an industrial development of algae production process);
- the use of solar drying as thickening technique does not require electricity but produces mixtures with a lower algae concentration.

F.3.3.5 Summary of SWOT for Production Chain 3

Figure F.3.3 shows a summary of the SWOT analysis on Production Chain 3.

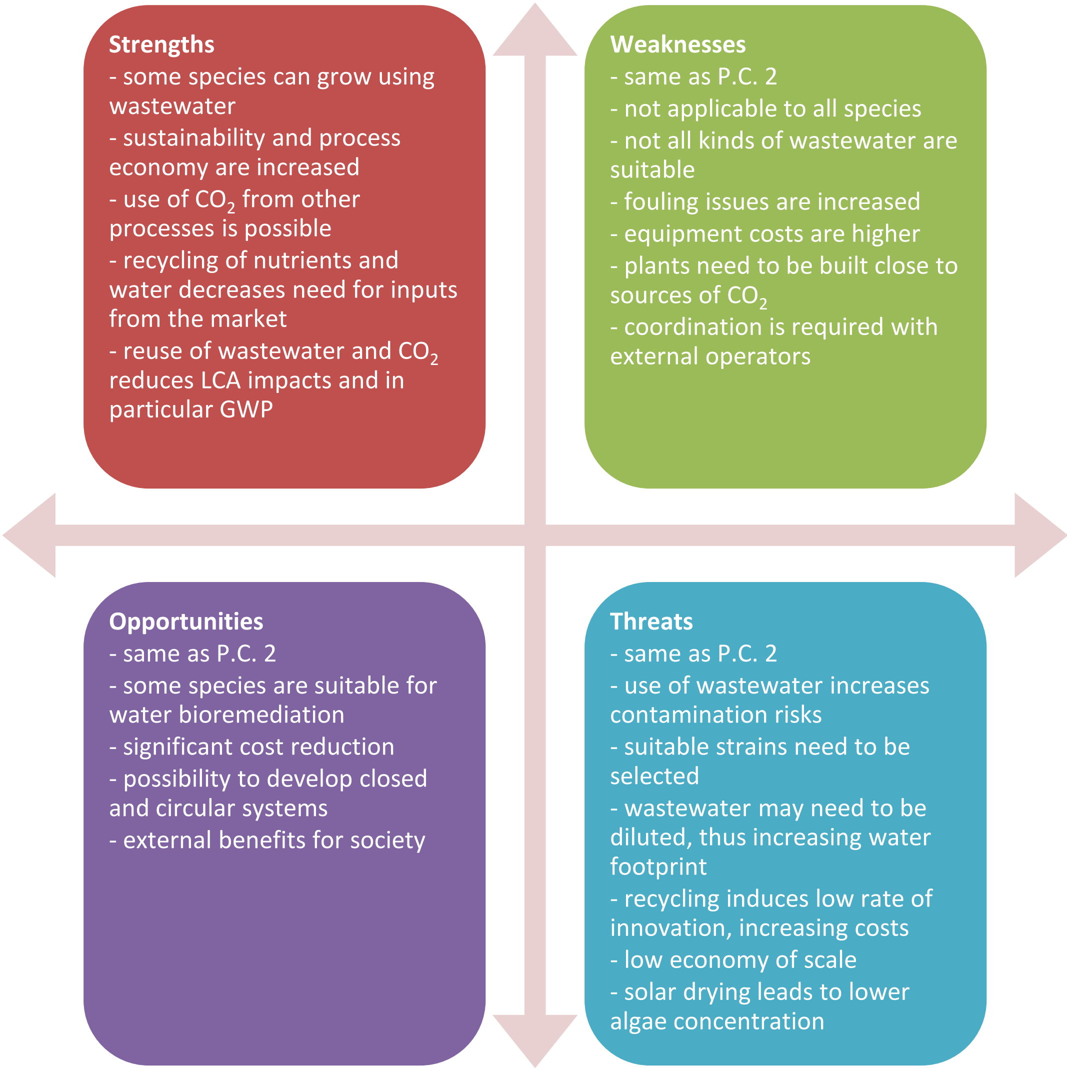

Figure F.3.3: SWOT Analysis on Production Chain 3

F.3.4 PRODUCTION CHAIN 4

The SWOT analysis on Production Chain 4 is shown in the following paragraphs and graphically recalled at the end of Section 3.4.5.

F.3.4.1 Strengths

Production Chain 4 is characterized by the following strengths:

- some species are a source of valuable compounds and widely used in aquaculture, cosmetics, pharmaceutical, nutraceuticals, human food industries;
- economic balance is improved thanks to additional co-products (Wijffels and Barbosa, 2010);
- biogas production is a relatively inexpensive and mature process, energetically sustainable;
- co-products are produced and delivered at market price, including material for animal feeding, bioethanol, biomethane, fertilizer and biomass (with a proportional increase of benefits from biofuel production chain).

F.3.4.2 Weaknesses

The following bullets list the weaknesses identified for Production Chain 4:

- the same weaknesses of Production Chains 2 and 3 are still valid;
- the recovery of intracellular metabolites at large scale without damaging other fractions is difficult;
- the literature does not provide a complete screening on biogas production from different species, and although biogas is a mature process, the successful exploitation of microalgae biomass is not fully demonstrated;
- investment and production costs are high due to the need to complete the production chain (new equipment) and collect and transform different by-products before trading;
- biofuel production efficiency (per input unit) is low, since part of the biomass is used for co-products.

F.3.4.3 Opportunities

Opportunities identified for Production Chain 4 are:

- genetic engineering can be used to improve specific traits and production of valuable co-products;
- market opportunities exist for new microalgal high-value products (Borowitzka, 2013);
- the possibility to develop a broad line of co-products with profitable markets exists, sin ce the demand is high and the offer is still limited;
- the innovation rate is high.

F.3.4.4 Threats

Concerning Production Chain 4, these main threats were identified:

- the same threats affecting Production Chain 3 are still valid;
- more companies are focusing in the production and commercialization of valuable compounds from microalgae, thus approaching to market saturation (Cuellar-Bermudez et al., 2014);
- the solvent (or solvent mix) used for lipid extraction is crucial to ensure the good performance of the reaction;
- anaerobic digestion may be susceptible to toxic of chemicals used in the extraction of the primary compound (FAO Aquatic Biofuels Working Group, 2010);
- production of soil improvers may be incompatible with wastewater usage;
- no real opportunity in developing new markets for by-products exists, since market is not profitable (low prices), the demand is low (no real margin in developing the supply) or the supply is already sufficient (not enough demand to absorb the additional supply).

F.3.4.5 Summary of SWOT for Production Chain 4

Figure F.3.4 shows a summary of the SWOT analysis on Production Chain 4.

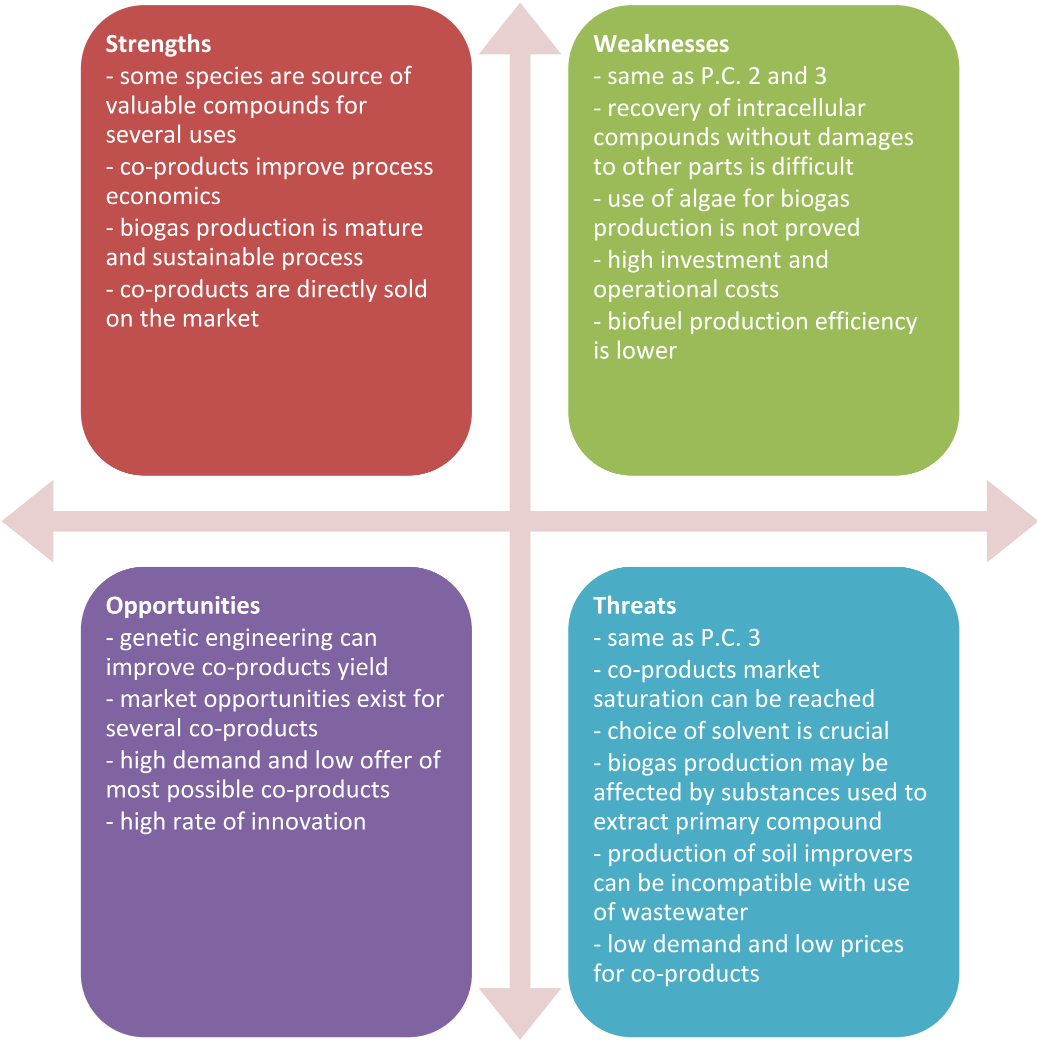

Figure F.3.4: SWOT Analysis on Production Chain 4

F.3.5 PRODUCTION CHAIN 5

The SWOT analysis on Production Chain 5 is shown in the following paragraphs and graphically recalled at the end of Section 3.5.5.

F.3.5.1 Strengths

The main strengths of Production Chain 5 are the following:

- the same strengths of Production Chain 4 are still valid;
- co-producing algal biofuels and high-value products is suggested as a strategy to address the challenge of making algal biofuels economically viable ("Economics of Coproduct Production from Large-Scale Algal Biofuels Systems," 2012);
- there is flexibility with respect to change in demand and/or values of products;

- different market opportunities exist for a wide range of products; products are developed separately, using different technologies, with no risk of contamination of algae biomass or no limitation in the supply of 'pure' biomass in the different production processes (which would enable economy of scale or reduction in losses).

F.3.5.2 Weaknesses

The weaknesses identified for Production Chain 5 are:

- the same weaknesses for Production Chain 4 are still valid;
- several value-added product chains start from primary algae products such as polysaturated fatty acids, thus hindering the possibility of producing fuels, too;
- except for some nutraceutics and pharmaceutical compounds, there is no established production of value-added products from algae;
- capital investment and process complexity may increase significantly, at least for bulk productions;
- in several cases, competition with oil-derived molecules may be strong;
- additional biological research is necessary for identifying suitable strains;
- extraction/separation process for valuable molecules still quite ineffective and costly;
- high investment and operating costs with no real economy of scale, due to the number of production lines and technologies used in producing, transforming and trading products from algae production;
- different business models and markets should be developed at the same time, by the same investor or pool of operators, in order to satisfy very diverse demands from a variety of regions or countries.

F.3.5.3 Opportunities

The opportunities discovered for Production Chain 5 are:

- the same opportunities of Production Chain 4 are still valid;
- a multiproduct approach may be much more effective if raw materials are obtained directly from biomass rather than from extracted lipids;
- potentials for a very wide range of commercially valuable products exist: lipids for biodiesel, lipids as a feedstock for the chemical industry and ω-3 fatty acids, proteins and carbohydrates for food, feed and bulk chemicals (Wijffels et al., 2010);
- this production chain captures a wide range of economic opportunities, developing different lines of products with high added value, in order also to compensate the potential losses in bio-fuel production.

F.3.5.4 Threats

Production Chain 5 was found to be affected by the following threats:

- the same threats affecting Production Chain 4 are still valid;

- the production of high-value products in niche markets is usually incompatible with that of biofuels, because the latter has a potentially much larger market (e.g.: ω-3-fatty acids and other polyunsaturated fatty acids have roughly a 10 times lower concentration in algae than lipids for biodiesel) (Review paper Algae-based biofuels: applications and co-products, FAO 2010);
- designing a multiproduct process is usually complex and sometimes is not feasible; processes may need to be designed to produce a single value-added product, thus hindering their flexibility;
- several low cost nutrients (wastewater) and CO_2 sources (combustion processes like incineration) may have to be excluded because of safety and regulatory restrictions on final products;
- low economic opportunities or high barriers in developing new activities exist, since products with a low added value are not able to compensate the potential losses in bio-fuel production.

F.3.5.5 Summary of SWOT for Production Chain 5

Figure F.3.5 shows a summary of the SWOT analysis on Production Chain 5 presented in the previous paragraphs.

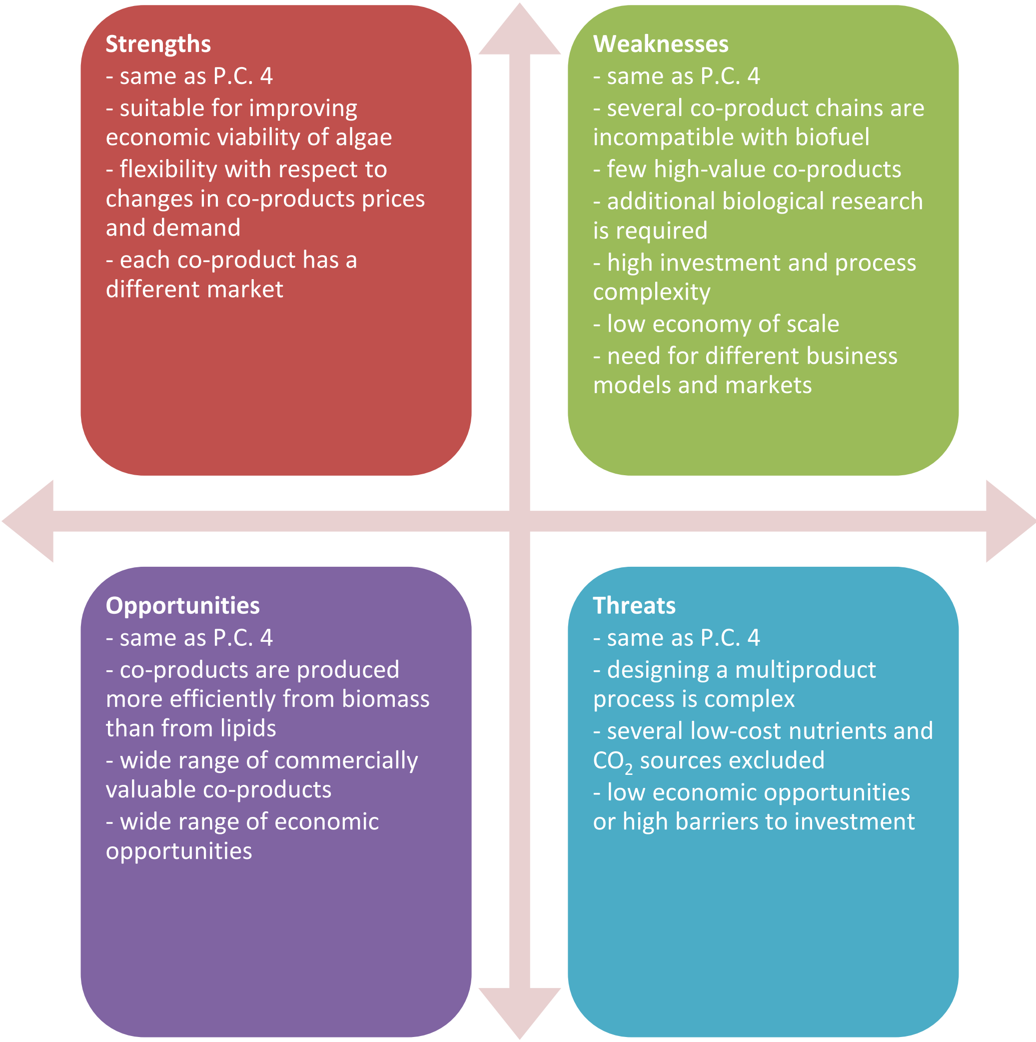

Figure F.3.5: SWOT Analysis on Production Chain 5

F.4 RATING

The outcomes of the SWOT analysis presented in the previous chapter were studied in order to identify the cruces that hinder the development of biofuel and co-products chains from microalgae. A crux is a necessary condition to achieve before entering the process of access to the market. It is worth noting that after the overcoming of a crux, further barriers can exist and shall be faced. The analysis of barriers will thus follow this initial assessment of cruces.

Five main cruces are identified:

- technologies readiness level and availability (TRL), which accounts for the technologies maturity such as the presence of similar operating plants and the availability on the market of the required components;
- location suitability (LOC), including the adequacy of geographical characteristics of the site and the availability at the plant site of the necessary materials;
- competitiveness in production costs (CPC), including both plant building and operating costs;
- achievement of critical industrial volumes (CIV), considering the possibility of reaching a large volume of produced goods in a way to be steadily present on the market with items and prices that are competitive;
- market readiness level (MRL) of the new production sector of bio-fuel, considered as an overall assessment of the transparency of the business models which underpins the development of bio-fuel production chains from algae.

It can be noted that the cruces are mainly connected to economic (CPC, MRL, CIV), technological (TRL) and environmental (LOC) issues, which are the main subjects that have been analyzed in the previous steps of the Project.

The five biofuel and co-product chains were analyzed by assigning to each of them five scores, one for each of the above listed cruces, indicating the distance from the successful development of a pre-commercial plant. The scores range from 1 (maximum distance) to 5 (minimum distance, corresponding to a plant ready for commercial operation). The scores assigned on the five cruces are then summed to obtain a total score (TS, out of 25 points), which allows a better comparison among the five production chains.

The benchmark (BM) taken as a reference is a commercially active plant, such as a biofuel production plant from first or second generation crops, or a refinery of oil-derived fuels. It is clear that a score of 5 has been assigned to the BM on all the cruces, consequently showing a total score of 25 (this high score does not mean that the reference plant is intrinsically perfect, but only that it is operational). Biofuel and co-product chains from microalgae are currently characterized by a score always lower than 5 on all cruces, since no commercial plant exists yet at industrial scale.

The meaning of scores from 1 to 5 for each of the identified cruces is presented in the evaluation matrix shown in Table F.4.1.

Table F.4.2 shows the scores assigned to the five production chains and to the benchmark on the five identified cruces. The same results are schematized in the chart shown in Figure F.4.1.

Table F.4.1: Evaluation Matrix

Score	CPC	TRL	LOC	MRL	CIV
1	Production chain with absolute lack of competitiveness in production costs compared to other fuel and biofuel production chains.	The technology is at extremely low TRL. The concept is available but no prove of implementation in working environment is available.	The site is not suitable for the installation of an algae cultivation plant, due to geographical issues and lack of availability of water, carbon dioxide, nutrients and other materials. Capital and knowledge are also lacking at site level	Production chain with almost no reference market model for investors; no clear normative background, especially in terms of patents and authorizations needed to start the business.	This production chain is in a pilot phase, thus very far from the achievement of a consistent industrial diffusion.
2	Production chain still not competitive in production costs compared to other fuel and biofuel production technologies. The gap from a viable solution can be reduced in the medium term.	Technology with poor availability, non solid and with relevant lacks in terms of real scale application. Basic components and constituents are not yet available or are immature, and strongly limit its implementation.	Location showing a sufficient degree of suitability for the installation of an algae cultivation plant only on some of the geographical characteristics. In addition, the supply of most of the required materials is difficult.	Production chain with limited and non-proven capacity to acquire shares of the market and no possibility of transfer to different markets.	The production chain is in a pre-industrial diffusion scale and a critical industrial volume is not reachable at the moment.

Score	CPC	TRL	LOC	MRL	CIV
3	Production chain having a sufficient degree of competitiveness in production costs with respect to the current state of the art in the sector.	Technology having a good degree of maturity, with ancillary items yet to be developed or adapted, or some adaptation missing (e.g.: to make it work autonomously, to make it robust, etc.).	The site is suitable under a geographical perspective, but its location leads to difficult supply of at least one among water and other required materials.	Production chain tackling the issue of barriers within a specified field technological domain. It is expected to overcome the economic barriers and provide with a profitable business model at medium terms	The production chain is developed and is starting to be implemented; a consistent industrial diffusion of the final product is foreseen in the medium term, at least in specific areas.
4	Production chain having a good competitiveness in production costs compared to other fuel and biofuel production chains.	Technology totally assessed, perfectly working and at high degree of maturity. Minimum adaptations are required to improve the performances.	Location that meets the minimum requirements in terms of both geographical characteristics and availability of water, carbon dioxide, nutrients and other necessary material.	Production chain with recognized capacity to generate revenues and whose products will positively be received from markets. The normative and economic barriers have been overcome at a reasonable cost.	Production chain that is widely implemented in only a few countries. Critical industrial volume is reached only in some areas.

Score	CPC	TRL	LOC	MRL	CIV
5	Production chain having outstanding competitiveness in costs with respect to the current state of the art in the sector.	Technology at the highest level of TRL. Completely assessed, scalable and ready for the installation. No limitations and need for adaptation of the technology in the different cases of installation.	Location characterized by excellent features on geographical parameters and availability of water, carbon dioxide, nutrients and other necessary material. Capital for investment and skilled employers are available to develop the activity at the level required.	Optimal production chain, capable of fast assessment and rapid growth in differentiated markets and whose products generate a demand in the marketplace; no other barriers hinder the development of the sector.	Fully developed production chain, having a wide diffusion in different countries, thus achieving a critical industrial volume.

First of all it is worth noticing that a score of 4 has been assigned to LOC crux for all production chains, since it has been assumed that plant location is identified according to the minimum suitability criteria defined in the previous phases of the Project; similarly, a score of 2 has been assigned to CIV for all chains, because none of them is close to the achievement of a critical industrial volume.

According to the above described assumptions, the production of biofuel with valuable co-products seems to be the most suitable production chain, especially for economic reasons, due to its high competitiveness of production costs and market readiness level for products and operators.

Also the multiproduct approach (Production Chain 5) shows a good level of proximity to commercial development, but it is penalized compared to Production Chain 4 by the higher complexity of the plant, which leads to higher costs (thus, to lower COP), and to a lower technology readiness.

Table F.4.2: Rating for the Selected Production Chains

Crux	BM	PC 1	PC 2	PC 3	PC 4	PC 5
CPC	5	3	2	3	4	3
TRL	5	3.5	3.5	3	3	2.5
LOC	5	4	4	4	4	4
MRL	5	2	2.5	3	4	4
CIV	5	2	2	2	2	2
TS	**25**	**14.5**	**14**	**15**	**17**	**15.5**

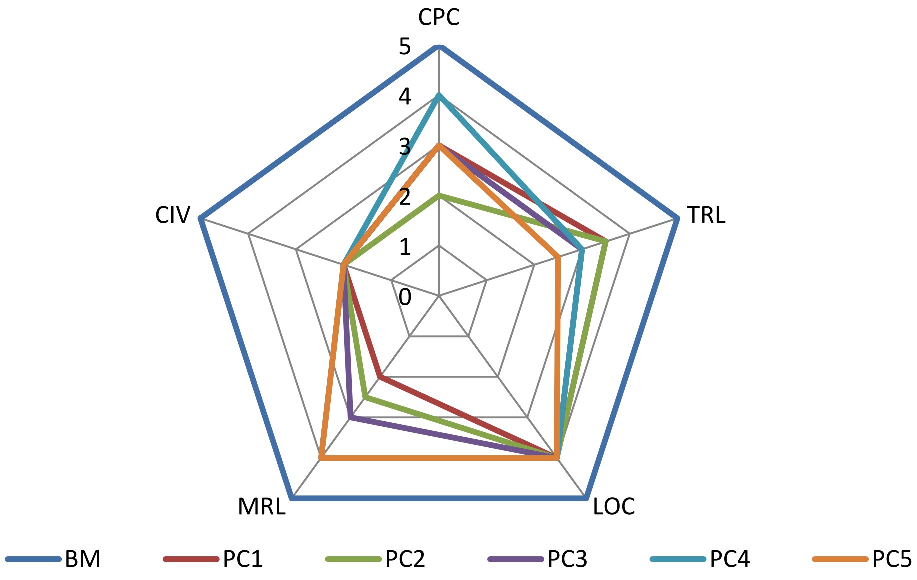

Figure F.4.1: Comparison among Ratings for the Selected Production Chains

More in detail, Figure F.4.2 compares the TS of the five production chains and of the BM, showing also the contribution to the overall value of the scores obtained on each of the five cruces. It can be noted that the chain with the highest proximity to the commercial development, Production Chain 4, reaches the 68% of the benchmark.

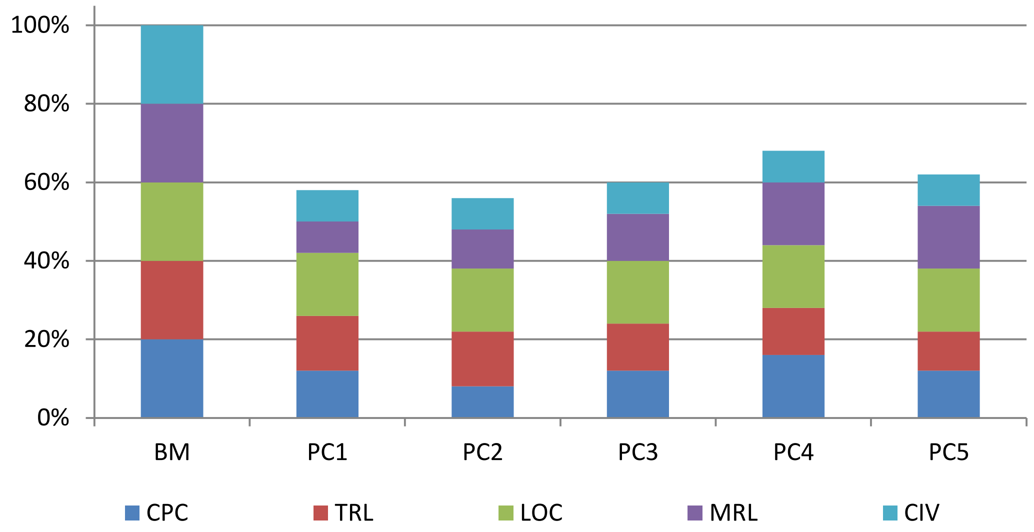

Figure F.4.2: Comparison of Total Score for the Selected Production Chains

F.5 RATING OF FP7 DEMONSTRATION PLANTS

The gap analysis presented in the previous section was extended to the pilot plants that are currently under realization within the three FP7 research projects of the AlgaeCluster.

In particular, at the beginning of the present project, a questionnaire was prepared and submitted to the coordinator of each FP7 project, in order to get preliminary information on the demonstrative plants, such as the kind of plant and the estimated data on its consumptions and production, etc.

A second form, more focused on the activities performed in this work package, was sent during the second year of the analyses. In this second questionnaire, each FP7 project was asked to self-assign a score to its pilot plant as regards the five cruces of the gap analysis. In addition, it was asked to provide some updated data on energy and mass flows in the pilot plant per unit of produced algae or to confirm the validity of the assumption made using the literature.

The feedback from the FP7 has been very precious: complementary information was gathered to widen the methodological approach to the overall topics, qualitative and quantitative remarks were provided to validate or to correct those assumptions that the hands-on experience on the pilot plants has allowed to amend.

It is important to point out that the activities of research of the three FP7 projects are still ongoing when preparing this document; therefore some results from them are available and quantifiable, others are only outlined as qualitative indications of the most likely events and can only be confirmed (or complemented or contradicted, of course) upon conclusion of the respective research.

The following chapters present the outcomes of the data collection phase from the FP7s, including the analysis of the self-assigned scores and, where possible (Biofat), of the energy and mass flows in the pilot plant. This overview is aimed at highlighting the distance of the pilot projects from the acceptable configuration in a market perspective and at showing where the pilots have demonstrated proximity to that benchmark.

F.5.1 INTESUSAL

A 1 hectare pilot facility is being realized in Olhão, Portugal, within InteSusAl project. The plant is based on an integrated approach including heterotrophic and phototrophic algae production with a combination of raceway ponds, photobioreactors and fermenters (a 1 m^3 stainless steel vessel with a working volume of 800 liters, equipped with a temperature control system and fed with steam for sterilization before use and with a fixed air flow rate during normal use). Biodiesel is then produced through lipid extraction and subsequent transesterification. An important aspect of the system is the self-production of nutrients in the facility: the glycerol co-produced in transesterification will be used as a carbon source for heterotrophic algae cultivation, and the carbon dioxide produced in heterotrophic process will be used by phototrophic algae.

The InteSusAl project also includes the realization of a demonstrator facility, with an extension of 10 hectares, whose location has still to be defined.

Table F.5.3 summarizes the production technologies used in the pilot plant being realized within InteSusAl project.

Table F.5.1: Production Technologies in InteSusAl Pilot Plant

Case Study	Cultivation Method	Bulk Harvesting Method	Thickening, Method	Biofuel Production Method
InteSusAl	Photobioreactor, Open Pond	Flocculation	Centrifugation	Transterification
	Fermenter	n.a.		

As regards the rating of the pilot plant, the self-assigned scores are shown in Table F.5.2, and compared with the benchmark in Figure F.5.1. It can be noted that the maximum score is reached in the CPC crux, because of the self-production of nutrients within the plant that reduces biofuel production costs. However the total score, 16/25, is in line with the outcomes of the gap analysis performed on the selected production chains.

Table F.5.2: Rating for InteSusAl Pilot Plant

Node	Benchmark	InteSusAl
CPC	5	4
TRL	5	3
LOC	5	4
MRL	5	3
CIV	5	2
TS	25	16

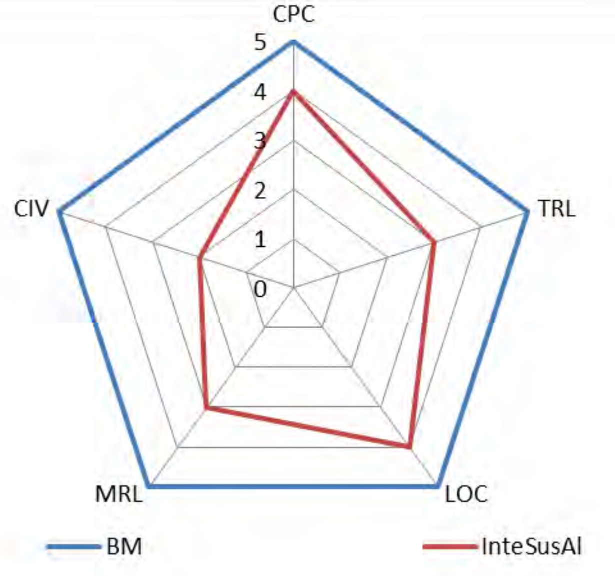

Figure F.5.1: Rating of InteSusAl Pilot Plant vs. Benchmark

F.5.2 BIOFAT

Two pilot facilities are being realized within Biofat project: the first one in Pataias, Portugal, and the second in Camporosso, Italy. In both cases, inoculum for algae cultivation is generated in green wall panels, algae are grown in tubular photobioreactors and products are accumulated in raceway ponds. Then, algae are recovered and biodiesel is produced in a biorefinery process aimed at maximizing co-products.

In both plants, non-fossil carbon dioxide is used for algae cultivation. In the former case CO_2 comes from a beer production facility, whereas in the second case it is taken from the exhausts of a 500 kW vegetal oil-fired CHP plant.

Table F.5.3 summarizes the production technologies used in Biofat pilot plants.

Table F.5.3: Production Technologies in Biofat Pilot Plants

Case Study	Cultivation Method	Bulk Harvesting Method	Thickening Method	Biofuel Production Method
Biofat	Photobioreactor + Cascade Raceways	None	Filtration + Centrifugation	Not defined yet

About the Biofat pilot plant in Pataias, some interim data regarding energy and mass flows (April 2015 configuration) were made available and are shown in Table F.5.4. It can be noted that all the values are in line with those considered in the LCA except for cultivation and, to a lesser extent, for thickening. The reason of the much higher consumption for cultivation is the high energy demand for cooling, which was not considered in the LCA because of the lack of reliable data.

Table F.5.4: Energy and Mass Flows at Biofat Pilot Plant

Parameter	Biofat
Mass flows [kg]	
Water	50
Carbon dioxide	2
Fertilizer	0.20
Flocculant	0
Energy flows [kWh]	
Water feeding	0.05
Cultivation	10
Carbon dioxide feeding	n.a.
Water-algae pumping	0.14
Bulk harvesting	0
Thickening	2.5

As regards the rating of the pilot plant, the self-assigned scores are shown in Table F.5.5, and compared with the benchmark in Figure F.5.2. In this case, the top score is found in the MRL crux, because of the maximized production of valuable co-products. It is worth noticing that the total score, 19/25, is higher than the best cases studies analyzed among the selected production chains.

Table F.5.5: Rating for Biofat Pilot Plant

Node	Benchmark	Biofat
CPC	5	2
TRL	5	4
LOC	5	4
MRL	5	5
CIV	5	4
TS	25	19

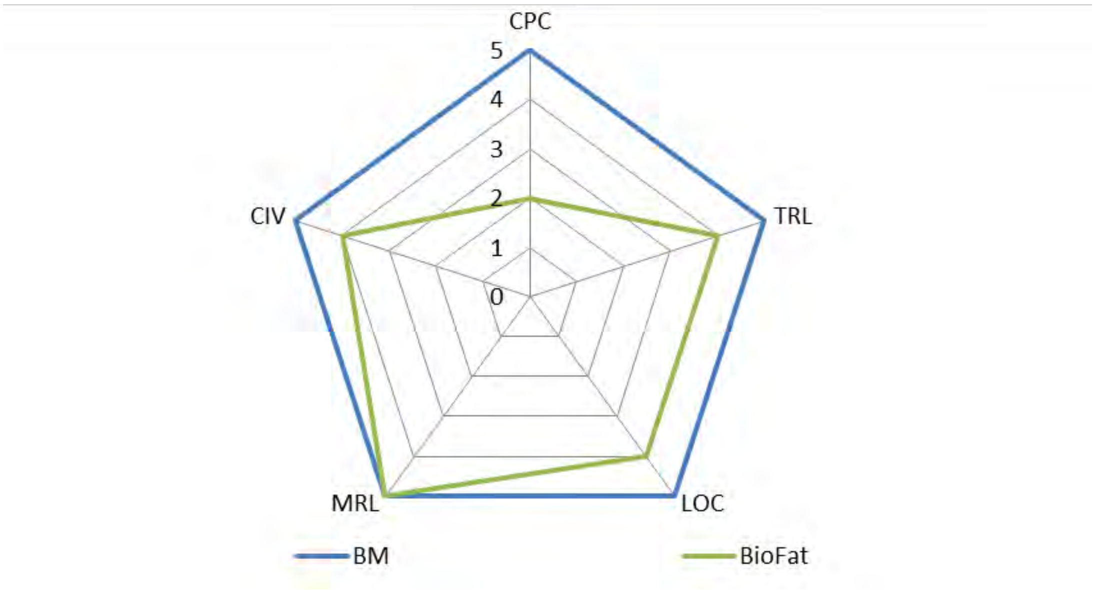

Figure F.5.2: Rating of Biofat Pilot Plant vs. Benchmark

F.5.3 ALL-GAS

A 10 hectares pilot facility, using municipal wastewater to grow algae in an open pond, is under realization within the All-Gas project. The produced algae are then used in an anaerobic digestion reactor to produce biogas, whereas the residues from algae digestion are used to produce fertilizers, thus obtaining a valuable co-product.

No information was made available in due time from the All-Gas project concerning the self-evaluation of their plant according to the gap analysis. Thus, as regards the rating of the pilot plant, the scores shown in Table F.5.6 are the result of an independent evaluation by the Key Experts, and are compared with the benchmark in Figure F.5.3.

In this case, the top scores are found in the MRL and TRL cruces, because of the use of a consolidated technology as biogas production is, and of the maximization of co-products. It is worth noticing that the total score, 18/25, is in line with the outcomes of the gap analysis performed on the selected production chains.

Table F.5.6: Rating for All-Gas Pilot Plant

Node	Benchmark	All-Gas
CPC	5	3
TRL	5	4
LOC	5	4
MRL	5	4
CIV	5	3
TS	25	18

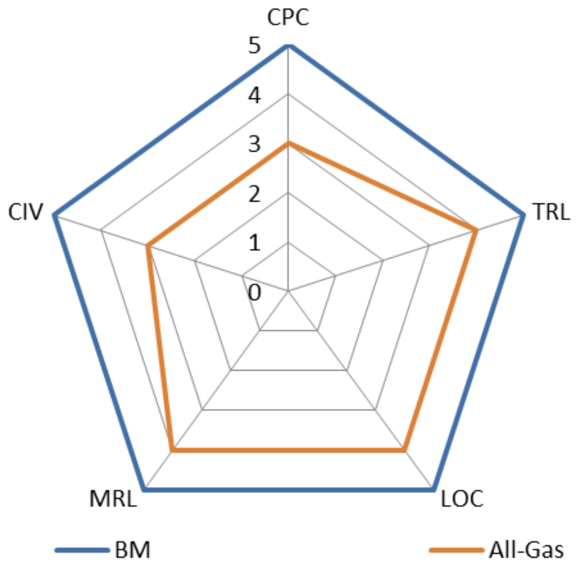

Figure F.5.3: Rating of All-Gas Pilot Plant vs. Benchmark

F.5.4 OVERALL RATING

The rating assigned in the previous chapters to the pilot plants of the FP7 research projects is hereby comparatively analyzed. Before comparing the scores, two main points need to be highlighted:

- the scores were self-assigned by the project representatives and approved by the Key Experts, thus the point of view is internal to the single plant and not univocal to guarantee a total consistency of the comparison;
- the research activities of the FP7s are still ongoing (the closure of the research is expected for 2016), thus some results are available and quantifiable, others are only outlined as qualitative indications of the most likely events.

Figure F.5.4 compares the scores assigned to the three pilot plants and to the benchmark on the five identified cruces. More in detail, Figure F.5.5 compares the TS of the three pilot plants and of the BM, showing also the contribution to the overall value of the scores obtained on each of the five cruces.

It can be noted that the pilot plant with the highest proximity to the commercial development (i.e.: the highest TS), BioFat, reaches the 76% of the benchmark.

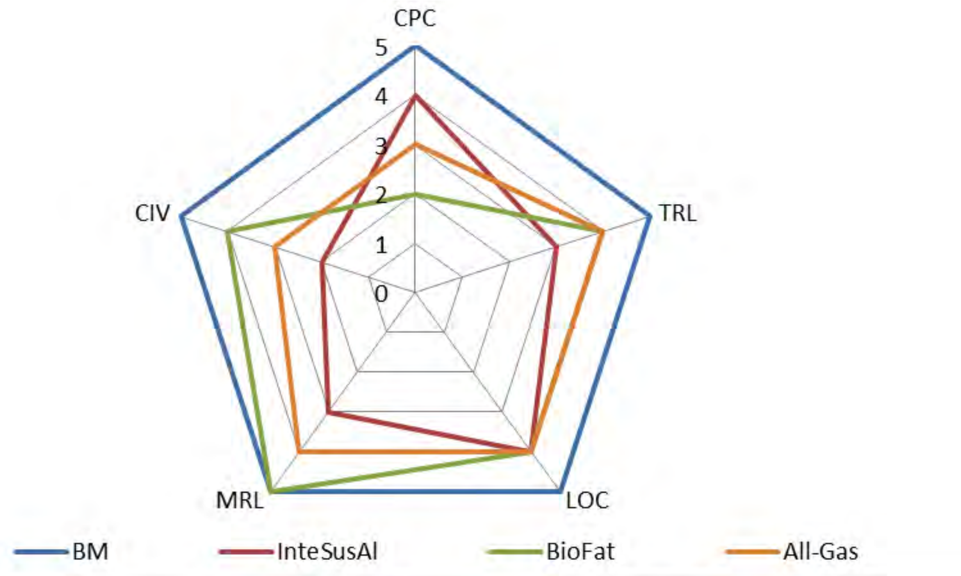

Figure F.5.4: Comparison among Ratings for the Pilot Plants

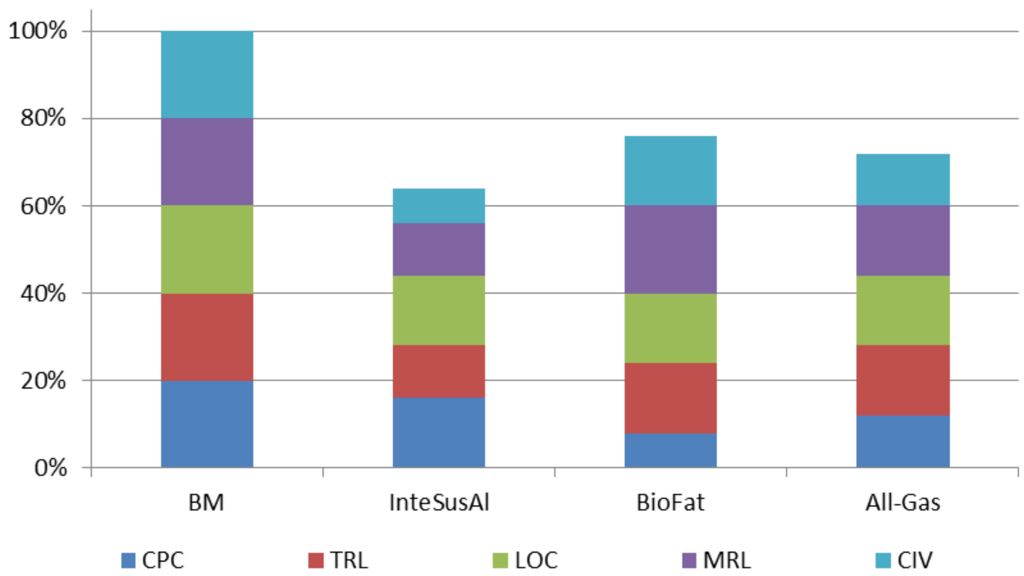

Figure F.5.5: Comparison of Total Score for the Pilot Plants

F.6 CONCLUSIONS

This report summarizes the results of the potential analysis on algae bioenergy and co-product chains, performed within Task 2 of the assignment.

In this study, the most relevant production chains were analyzed under the biological, technological, economic and environmental points of view, by taking into consideration their capability of producing biofuels and other co-products.

The five production chains taken into consideration are:

- biomass production;
- biofuel production without co-products;
- biofuel production without co-products but with environmental benefits;
- biofuel production with valuable by-products;
- multi-product approach.

For each production chain, a SWOT analysis was performed to identify positive and negative aspects of the selected processes.

Based on the outcomes of this analysis, five cruces (necessary conditions to be achieved before accessing the market) were identified for the biofuel and co-product chains:

- technologies readiness level and availability (TRL);
- location suitability (LOC);
- competitiveness in production costs (CPC);
- achievement of critical industrial volumes (CIV);
- market readiness level (MRL).

A rating from 1 to 5 was assigned to each of the five production chains on each of the listed cruces, indicating its distance from the commercial operation on that specific aspect. The highest proximity to the commercial development was found for Production Chain 4, representing a multi-product plant, which reached the 68% of the maximum score.

Following the same approach, the three FP7 research projects of the AlgaeCluster were asked to self-assign a score to their pilot plants on each identified crux, thus allowing a comparison with the considered production chains and a link with the SWOT analysis.

To conclude, the outcomes of the SWOT analysis and of the cruces assessment will be considered in a following step of the assignment, within Task 3 of the Project, in which the barriers hindering the development of algae-based plants are discussed and some recommendation to overcome them are given.

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ANNEX 1

LCA ON BIOFUELS AND CO-PRODUCTS PRODUCTION CHAINS

Doc. No. 12-920-H3
Rev. 1 - JUNE 2015

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

LCA on Biofuels and Co-Products Production Chains – SWOT Analysis

UNIVERSITÀ DEGLI STUDI DI PADOVA

SELC biologia e geologia applicate

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ABBREVIATIONS AND ACRONYMS

FW	Freshwater
GHG	Greenhouse Gases
HTL	Hydrothermal Liquefaction
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
OP	Open Pond
PBR	Photobioreactor
SWOT	Strengths, Weaknesses, Opportunities, Threats
WW	Wastewater

ALGAE BIOENERGY SITING,
COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS
LCA ON BIOFUELS AND CO-PRODUCTS PRODUCTION CHAINS –
SWOT ANALYSIS

1 INTRODUCTION

The present report follows Task 1 of the Project, which focused on the assessment of constraints and opportunities related to the siting, cultivation and harvesting of algae. In particular the present study focuses on the assessment of processes bringing from algae to biofuel and co-products, and is part of Task 2.

This report, following an overall approach focused on the assessment of cultivation techniques, technological considerations, economical analyses and environmental impacts, focuses on the application of Life Cycle Assessment (LCA) technique to the selected processes for algae cultivation, harvesting and production of biofuel and co-products.

Therefore, this part of LCA is not limited but includes the whole biofuel production chain. To do this, six case studies were analyzed by combining cultivation, harvesting/thickening technologies and including bio-oil extraction and biorefinery processes, based on input data from specific literature and LCA databases.

It is clear that this LCA covers a wider range of processes compared with the one performed within Task 1. However, the results of the previous LCA, technical and economic analyses were taken into consideration in the present study, when selecting the most suitable processes to be included in the biofuel and co-products production chain.

The results of the assessments in terms of environmental indicators and of mass/energy balances were then determined and interpreted to perform a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis on the different algae production processes.

This contributes to the preparation of the overall SWOT analysis including the biological, technical and economic considerations, to the barrier analysis and the definition of guidelines to overcome the identified barriers.

2 LIFE CYCLE ASSESSMENT

2.1 LAYOUT OF THE PROCESS

The LCA on the selected case studies was performed using GaBi® software. The first step of the analysis was the definition of the block scheme shown in Figure 2.1, which represents the main process for each considered production chain: cultivation, harvesting, thickening, bio-oil and biofuel production. This block scheme includes all the considered case studies, which differ one from each other only for the system boundaries, for the used technology and for the values of involved mass and energy flows. It is worth to note that the above described block scheme only covers the first three out of the five production chains to be assessed within Task 2 of the Project:

- biomass production (Production Chain 1);
- biofuel production without co-products (Production Chain 2);
- biofuel production without co-products but with environmental benefits (Production Chain 3);
- biofuel production with valuable by-products (Production Chain 4);
- multi-product approach (Production Chain 5).

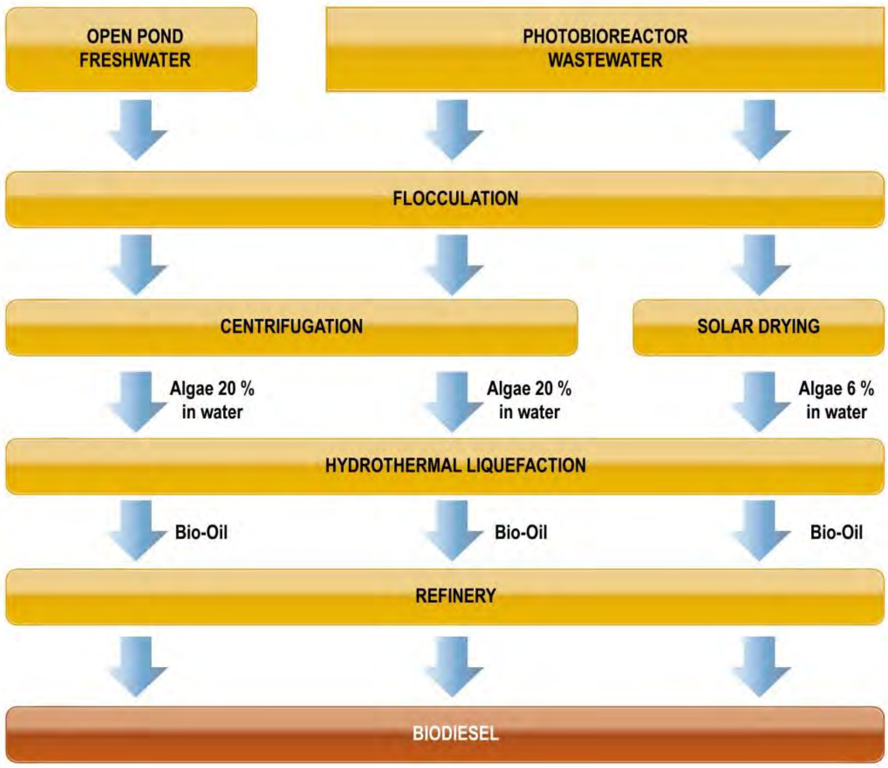

Figure 2.1: General Block Scheme of Selected Biofuel Production Chains

This happens because out of the five production chains only three are eligible for a LCA. In fact, no standardized or prevailing co-product, technology or plant exists for Production Chains 4 and 5. These production chains can only be defined in terms of general categories, but there is no single process layout within them that can be representative for the entire chain. Every industrial solution may be different based on the "output-mix". For example, possible output-mixes concern production of proteins for animal feeding, chemicals, ingredients for pharmaceutical, nutraceutical and cosmetic uses. Moreover, data on energy and resources consumptions of most of these processes are not available in literature or in existing LCIs.

Finally, to recap, the three production chains that are eligible for a LCA give origin to six case studies: three for Production Chain 1, one for Production Chain 2 and two for Production Chain 3. A GaBi plan was built for each of the selected case studies, which includes the specific involved processes and values. A plan used for one of the LCAs performed within the present study is shown in Figure 2.2.

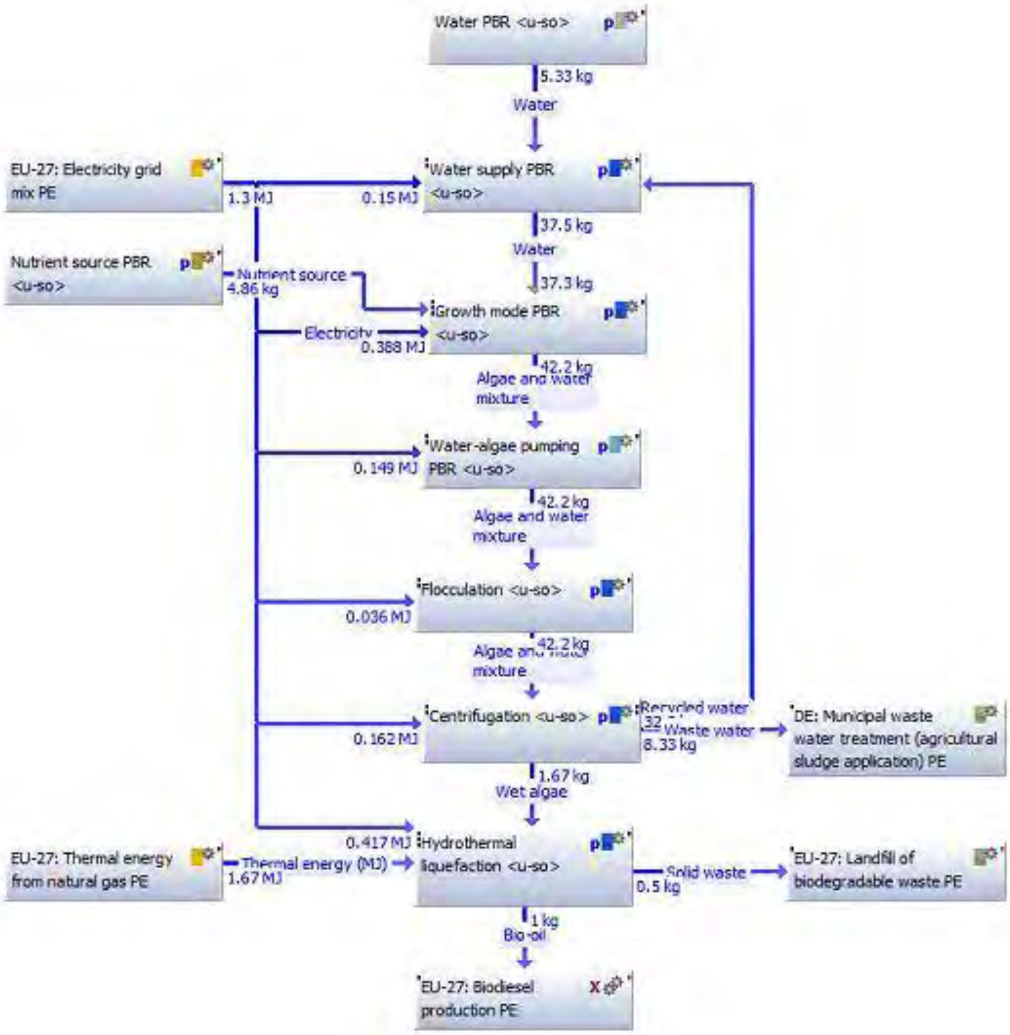

Figure 2.2: GaBi Scheme for one of the Case Studies

As shown in both the above shown Figures, the selected case studies include an open pond fed with freshwater and a photobioreactor fed with wastewater as algae cultivation systems. These systems were selected basing on the outcomes of studies performed within Task 1 of the Project, including LCA, technical and economical considerations.

Harvesting of the produced algae is performed through flocculation, which in some cases may not be the most suitable technique, but was selected because it is characterized by the highest life cycle impact concerning energy and resources use.

After harvesting, thickening is performed either through centrifugation or solar drying. These technologies differ under the two following aspects: on one hand, the former requires electricity whereas the latter only uses solar radiation as heat source; on the other hand the former is characterized by a significantly higher efficiency compared to the latter. In particular, it is assumed to reach a 20% concentration of algae in water when using centrifugation, and a 6% concentration when using solar drying.

Hydrothermal liquefaction (HTL) is the most suitable technique for bio-oil production from relatively wet algae, thus is the only solution that is considered in this analysis. It is assumed that algae-water mixture is sent to the HTL reactor without further processing, thus bio-oil yield is higher (60%) for input with 20% algae concentration and lower (20%) for input material with 6% algae.

Finally, for all the case studies, the bio-oil produced through HTL is sent to biorefinery processes to produce biodiesel, which is the final desired product.

2.2 METHODOLOGY

In the present study, the selected case studies on biofuels and co-products production chains were analyzed using GaBi software according to a Cradle-to-Grave approach on some of the sub-processes and to a Cradle-to-Gate approach on the remaining ones.

GaBi is a software, developed by PE International, which allows to easily model process chains, by describing a production technology or service through its input and output flows. The selected technology can be described by using its structural information and creating parts with material inventories and production processes. Processes and flows already existing in the internal databases can be used, or new items can be defined by the user according to experimental values or literature data. Once the system is completely defined in terms of involved processes, mass and energy flows, several Impact Assessment Methodologies can be adopted to determine the results.

The standard database provided with GaBi is the Professional database, which has the advantage of being internally consistent and includes more than 5,000 LCI (Life Cycle Inventory) records, based on previous works of PE International. In addition, the Swiss Ecoinvent database is available, which includes thousands of LCI records in the fields of agriculture, energy supply, transport, biofuels and biomaterials, chemicals, construction and packaging materials, basic and precious metals, metals processing, ICT and electronics, waste treatment.

Within the present study, the system boundaries were defined so that the system includes the whole impacts for electricity generation, waste and water treatment. Concerning water and carbon dioxide, the energy requirements and consequent impacts for their supply to the plant are included in the system. Finally, nutrients and other reactants (e.g. flocculant agent) are considered to be available directly at the plant, without any additional impact.

As seen above and shown in the GaBi scheme in Figure 2.2, the main values influencing the LCA of a production chain, besides those already present in GaBi databases (connected to electricity supply, refinery, waste and water treatment) are mass and energy flows entering the system boundaries.

More in detail, the involved energy flows are the electricity consumptions for supplying and circulating water and carbon dioxide, growing algae, pumping algae-water slurry, harvesting and thickening algae, as well as for bio-oil production. In addition, hydrothermal liquefaction also requires heat, produced with direct natural gas combustion. On the other hand, the involved mass flows are the amount of water, carbon dioxide, fertilizers and other nutrients, flocculant agent, per unit of produced algae. Finally, biorefinery processes, like waste and water treatment and electricity generation are "aggregated processes" and include data from LCI directly in GaBi.

In this study, values for all the above mass and energy flows were defined for each of the six selected case studies shown in Table 2.1. In the table, the indication of algae cultivation, kind of water source, bulk harvesting and thickening methods, biofuel production technology for each case is presented.

Table 2.1: Summary of the Selected Case Studies

Case Study	Cultivation Plant	Water Source	Bulk Harvesting Method	Thickening Method	Biofuel Production Method
1 A	Open Pond	Freshwater	Flocculation	Centrifugation	-
1 B	Photobioreactor	Wastewater	Flocculation	Centrifugation	-
1 C	Photobioreactor	Wastewater	Flocculation	Solar Drying	-
2	Open Pond	Freshwater	Flocculation	Centrifugation	HTL + Biorefinery
3 A	Photobioreactor	Wastewater	Flocculation	Centrifugation	HTL + Biorefinery
3 B	Photobioreactor	Wastewater	Flocculation	Solar Drying	HTL + Biorefinery

2.3 ASSUMPTIONS AND LIMITATIONS

This study is based on a series of assumptions, hereby listed, aimed at creating a standardized overview of the processes for the main technological solutions and at highlighting the boundary conditions that differ from case to case.

The present LCA study is mainly based on values taken from the GaBi database and, for values that are not included in the latter, from specific literature on bioenergy from algae.

First of all, it is worth highlighting that LCA studies were performed by neglecting the energy and mass flows connected to the construction of the plants, the water, natural gas and carbon dioxide feeding pipelines, and all the required equipment. This hypothesis may significantly affect the environmental indicators, but the choice was done to perform a comparative analysis among plants ready for operation at a specific site. Moreover, these values were not considered because no reliable data were available in literature.

Then, the study has considered that the plants under analysis are built in an eligible location that meets the minimal requirements in terms of solar irradiation, temperature, distance from water bodies, etc., with respect to the site-characterization which was at the basis of our analysis for the assessment of the site territorial units. Thus, being all the systems above the threshold of eligibility, no differences are considered among plants regarding their geographical location.

2.4 INPUT DATA

The values on energy and mass flows for each case study were calculated by adapting the data available in literature, and in particular in Benemann (2014), Meyer (2012), Slade (2013), Soulliere (2014), Stephenson (2010), Tredici (2014) for algae cultivation and in Fortier (2014), Frank (2013), Liu (2013), Passell (2013) for biofuel production.

The considered values are shown in Table 2.2 for each of the selected case studies, and are expressed per mass unit of produced algae: further scaling is directly performed by GaBi.

Table 2.2: LCA Parameters for each Production Chain

Parameter	1 A	1 B	1 C	2	3 A	3 B
Mass flows [kg]						
Water	900	22.5	22.5	900	22.5	22.5
Carbon dioxide	8.75	2.62	2.62	8.75	2.62	2.62
Fertilizer	0.31	0.31	0.31	0.31	0.31	0.31
Flocculant	0.35	0.35	0.35	0.35	0.35	0.35
Natural gas	-	-	-	0.028	0.028	0.028
Energy flows [kWh]						
Water feeding	0.875	0.025	0.025	0.875	0.025	0.025
Cultivation	0.49	0.015	0.015	0.49	0.015	0.015
Carbon dioxide feeding	0.175	0.050	0.050	0.175	0.050	0.050
Water-algae pumping	0.218	0.025	0.025	0.218	0.025	0.025
Bulk harvesting	0.006	0.006	0.006	0.006	0.006	0.006
Thickening	0.27	0.027	-	0.27	0.027	-
Hydrothermal liquefaction	-	-	-	0.069	0.069	0.069

It is worth noticing that when wastewater cultivation processes are considered and centrifugation is used as thickening method (i.e.: case study 1A, 1B, 2, 3A), a recycle of 80% of the wastewater in output from algae harvesting process can be recirculated back to the cultivation system.

Finally, concerning the electricity supply, in the LCA analysis the EU-27 mix (shown in Figure 2.3) was selected; a further sensitivity analysis of the impact of the electricity mix composition on the indicators is shown in paragraph 0. It is worth highlighting that EU-27 mix was used instead of EU-28 because GaBi database is not updated to the 2014 configuration of EU-28.

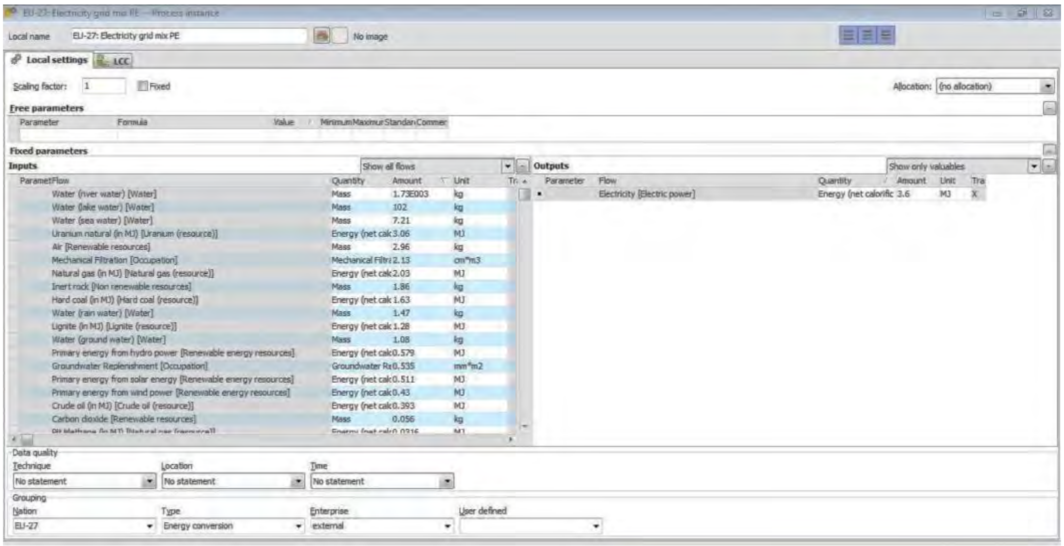

Figure 2.3: Example from EU-27 Electricity Grid Mix Parameters

2.5 LCA IMPACT ASSESSMENT

The results of the LCAs performed using GaBi are presented in the present paragraph. The CML 2001 (version April 2013) method was used to aggregate impacts into twelve indicators, which are listed in Table 2.3 with their abbreviation and their proper measurement unit.

Table 2.3: Legend for LCA Indicators

Abbreviation	Parameter	Measurement Unit
ADPe	Abiotic Depletion elements	[kg Sb-Equiv.]
ADPf	Abiotic Depletion fossil	[MJ]
AP	Acidification Potential	[kg SO2-Equiv.]
EP	Eutrophication Potential	[kg Phosphate-Equiv.]
FAETP	Freshwater Aquatic Ecotoxicity Potential	[kg DCB-Equiv.]
GWP100	Global Warming Potential (100 years)	[kg CO2-Equiv.]
GWP100e	Global Warming Potential, excluding biogenic carbon (100 years)	[kg CO2-Equiv.]
HTP	Human Toxicity Potential	[kg DCB-Equiv.]
MAETP	Marine Aquatic Ecotoxicity Potential	[kg DCB-Equiv.]
ODP	Ozone Layer Depletion Potential (steady state)	[kg R11-Equiv.]
POCP	Photochemical Ozone Creation Potential	[kg Ethene-Equiv.]
TETP	Terrestric Ecotoxicity Potential	[kg DCB-Equiv.]

For a consistency check, the indicators calculated according to IPCC AR5 method, recently introduced in GaBi, were also determined and compared with GWP100 indicators of CML 2001 method. This comparison was performed because AR5 indicators are currently used by InteSusAl FP7 project in their LCA analysis, since they are based on 2013 GWP data and have a consistent approach to feedback cycles, differently from the CML ones that are based on 2007 data and sometimes show inconsistencies with feedback cycles.

However, a good correspondence (difference below 10%) was found between the global warming potential indicators determined according to AR5 and CML methods. The complete set of AR5 indicators and their comparison with CML 2001 ones is shown in Appendix A.

Finally, the results were normalized in terms of "person equivalent", by dividing each indicator by the nominal value shown in Table 2.4, corresponding to the average annual impact of a person. To allow a better comparison, results are shown in the following graphs with reference to 1,000 tons of produced algae or biodiesel instead of 1 kg. Complete data on indicators and mass balances for the case studies are shown in Appendix A.

Table 2.4: Values for Person Equivalent Normalization

Parameter	Value	Measurement Unit
ADPe	0.013	[kg Sb-Equiv.]
ADPf	75,550	[MJ]
AP	36.2	[kg SO2-Equiv.]
EP	39.8	[kg Phosphate-Equiv.]
FAETP	449.7	[kg DCB-Equiv.]
GWP100	11,210	[kg CO2-Equiv.]
GWP100e	11,210	[kg CO2-Equiv.]
HTP	1,076	[kg DCB-Equiv.]
MAETP	95,780	[kg DCB-Equiv.]
ODP	0.022	[kg R11-Equiv.]
POCP	3.72	[kg Ethene-Equiv.]
TETP	249.7	[kg DCB-Equiv.]

2.5.1 Production Chain 1

The boundaries of the three case studies analyzed on Production Chain 1 are highlighted in the general block diagram shown in Figure 2.4.

For these three case studies, the considered functional unit is the unit of mass of dry algae: more in detail, a 20% concentration of algae in water is considered. Thus, for comparison reasons, in case study 1 C, characterized by 6% water in algae, all the values are scaled to the same amount of dry algae.

The results of LCAs performed on Production Chain 1 case studies are shown in Figure 2.5. It can be noted that the production of algae in an open pond (1A) leads to significantly higher impacts compared to photobioreactors, because of the higher use of water per mass of produced algae, and of the consequently higher consumption of electricity. Concerning the two case studies where algae are produced in a photobioreactor, the one using centrifugation as thickening technique (1B) has a smaller impact than the one using solar drying (1C). This happens because the higher efficiency of centrifugation compared to solar drying compensates the fact that the former technique requires electricity, differently from the latter.

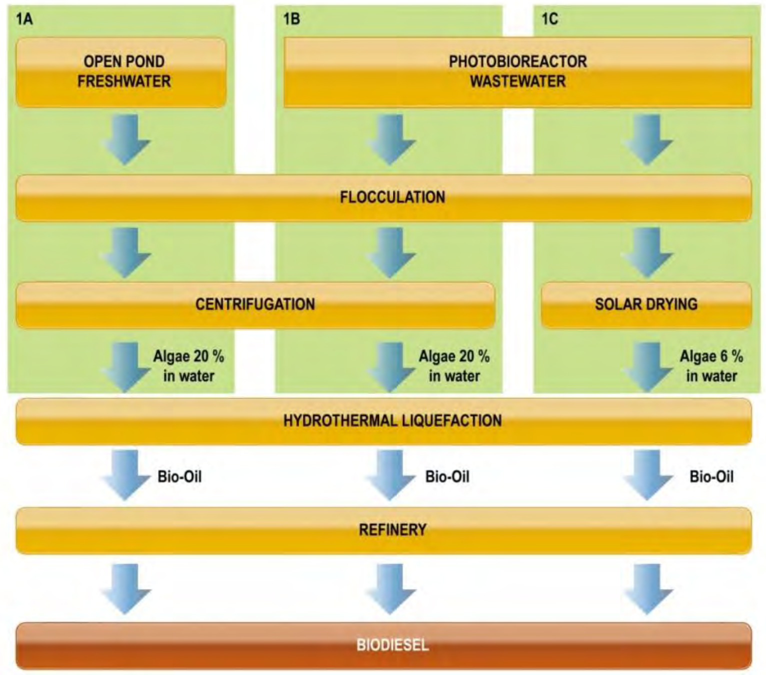

Figure 2.4: Case Studies for Production Chain 1

It is worth highlighting that the logarithmic scale in Figure 2.5 attenuates the figures of GWP100 indicator for case studies 1B and 1C, which is negative, and in particular its absolute value for case study 1C is higher than for 1B.

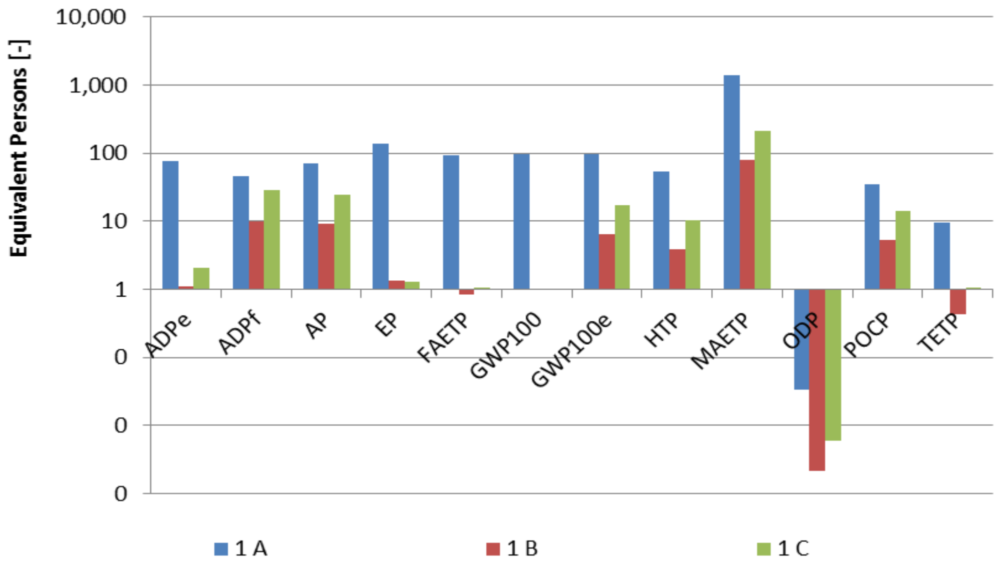

Figure 2.5: LCA Results for Production Chain 1 Case Studies

In addition to LCA indicators, mass balances were calculated for each case study. In particular, Table 2.5 shows a summary of the mass balances of biomass production systems of Production Chain 1: the detail of the flows that are included in each category are presented in Appendix A. However, even from the summary presented in Table 2.5, it can be noted that the lowest mass balances correspond to case study 1B, which is characterized by lower electricity and resources consumption per unit of produced dry algae.

Table 2.5: Mass Balances for Production Chain 1 Case Studies

Flows [kg]	1 A	1 B	1 C
Total flows	9,379.89	548.06	961.21
Resources	5,061.97	280.17	744.84
Deposited goods	0.9982	0.2621	0.7517
Emissions to air	14.056	1.240	3.411
Emissions to fresh water	4,287.15	265.32	209.32
Emissions to sea water	15.70	1.0588	$2.45 \cdot 10^{-7}$
Emissions to agricultural soil	$3.86 \cdot 10^{-7}$	$2.46 \cdot 10^{-8}$	$6.49 \cdot 10^{-8}$
Emissions to industrial soil	$2.19 \cdot 10^{-5}$	$1.59 \cdot 10^{-6}$	$3.38 \cdot 10^{-10}$

2.5.2 Production Chains 2 and 3

The three case studies considered in Production Chains 2 and 3 are highlighted in the general block diagram shown in Figure 2.6. For these case studies, the considered functional unit is the unit of mass of biodiesel produced from bio-oil extracted from algae by hydrothermal liquefaction.

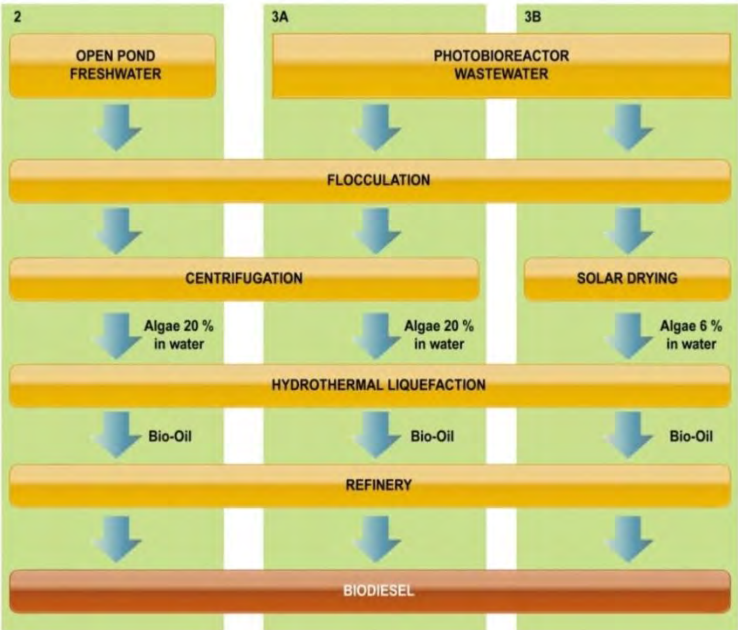

Figure 2.6: Case Studies for Production Chains 2 and 3

Production Chains 2 and 3 are bundled due to the fact that they eventually are the same process, but with different preventive measures such as the use of wastewater and recycled carbon dioxide for Production Chain 3 processes, which lead to environmental benefits.

The results of LCAs performed on Production Chains 2 and 3 case studies are shown in the following Figure 2.7.

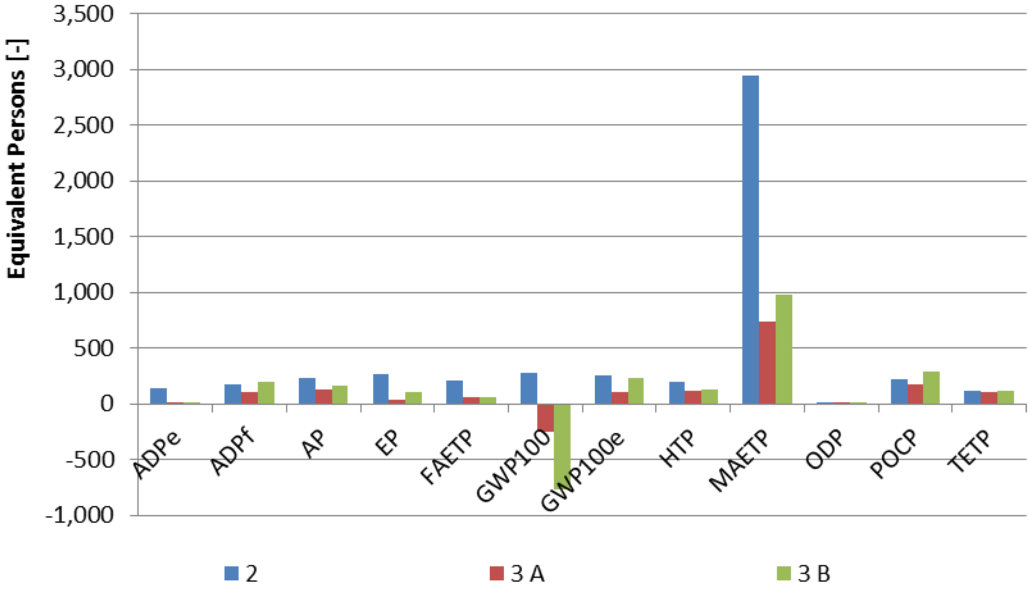

Figure 2.7: LCA Results for Production Chains 2 and 3 Case Studies

Since, as shown in Figure 2.6, hydrothermal liquefaction and biorefinery processes are common to the three case studies, the only differences are ascribed to the biomass production phase. Thus, the same comparisons of Production Chain 1 case studies are valuable. Biofuel production using an open pond for growing algae (2) leads to significantly higher impacts compared to photobioreactors. Also in this context, concerning case studies where biofuel is produced from algae grown in a photobioreactor, when using centrifugation (3A) the impact is lower than when solar drying is used (3B).

Table 2.6: Mass Balances for Production Chains 2 and 3 Case Studies

Flows [kg]	2	3 A	3 B
Total flows	16,509.40	1,789.26	2,058.48
Resources	8,867.02	897.10	1,422.19
Deposited goods	2.4945	1.2681	3.0582
Emissions to air	75.59	54.24	61.10
Emissions to fresh water	7,536.93	833.62	567.17
Emissions to sea water	27.44	3.023	4.948
Emissions to agricultural soil	$2.71 \cdot 10^{-5}$	$2.65 \cdot 10^{-5}$	$2.66 \cdot 10^{-5}$
Emissions to industrial soil	0.00197	0.00193	0.00770

The mass balances of Production Chains 2 and 3 case studies are summarized in Table 2.6, whereas the details of the flows included in each category are presented in Appendix A. It can be noted that the lowest mass balance corresponds to case study 3A, characterized by lower electricity and resources consumption per unit of produced biodiesel.

2.5.3 Sensitivity Analysis

As stated in paragraph 2.4, EU-27 electricity mix was considered in LCAs. This choice allows to perform a comparative analysis among the life cycle impacts of the selected algae cultivation systems. However, from an absolute perspective, the impact of a cultivation system (i.e.: the number of equivalent persons for each parameter) can be significantly different according to the composition of the electricity mix of the specific Country.

For this reason, a sensitivity analysis was performed in order to assess the order of magnitude of the error that can be introduced by applying the results of the present study to a specific plant in a specific location. One out of the six case studies, number 2, was analyzed by changing the electricity mix: in addition to EU-27, France, Germany, Greece, Italy, Portugal, Spain were considered, because identified as “promising regions” during Task 1 of the Project. The LCA indicators were calculated using GaBi, normalized according to a person equivalent approach, and finally divided by the EU-27 value to calculate the relative value.

Figure 2.8 shows a comparison of the twelve environmental indicators among the six selected countries, considering 1 as EU-27 value. It can be noted that significant differences exist, and impacts can be up to seven times higher or lower than those calculated basing on the average EU-27 electricity grid mix.

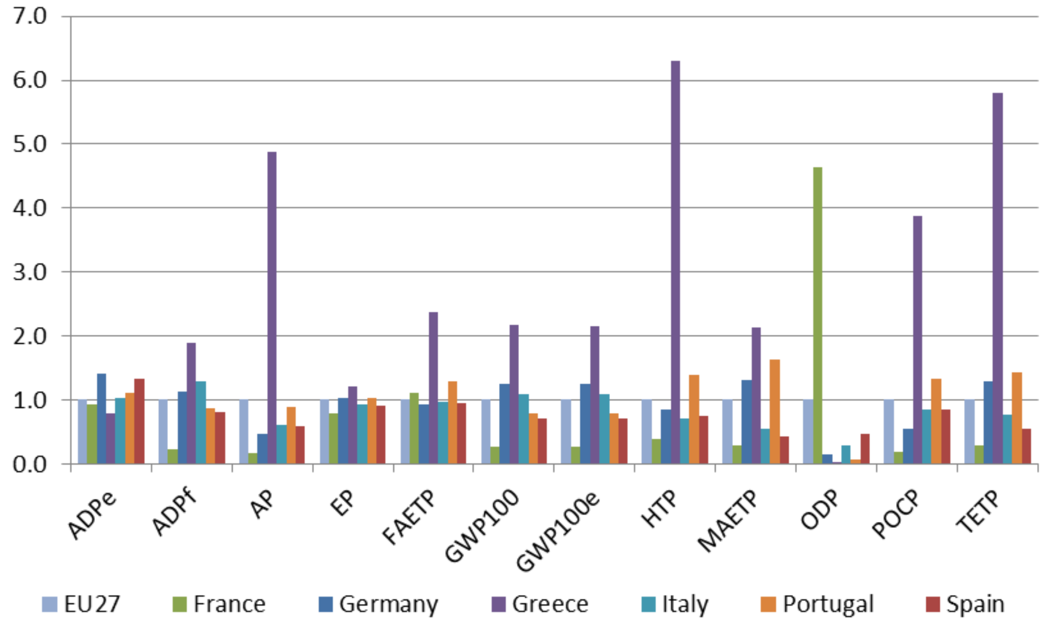

Figure 2.8: Sensitivity Analysis to Electricity Grid Mix

Basing on the above considerations, it is suggested to use the EU-27 electricity grid mix only to perform a comparison among the selected technologies, and to adopt data corresponding to the actual Country of installation of the plant if a particular case study has to be analyzed.

3 SWOT ANALYSIS ON LCA RESULTS

The following paragraphs present a SWOT analysis based on the results of the LCA shown in the previous sections. Strengths, weaknesses, opportunities and threats are presented without distinguishing between Production Chain 1 and Production Chains 2 and 3, because the only differences among the identified case studies are located in upstream processes to bio-oil production. In fact, as previously discussed, hydrothermal liquefaction and biorefinery processes are used in all the analyzed biofuels production chains.

It is important to note that the present SWOT analysis only refers to the LCA aspects, disregarding the other economic and technical aspects. In fact, it may happen that a technology, plant or process is preferable under an life cycle and environmental perspective but is not economically or technically convenient.

3.1 STRENGTHS

One main strength was identified:

- GWP for case studies with photobioreactors is negative, because the amount of carbon dioxide absorbed in algae growth compensates GHG emissions due to electricity generation and other processes.

3.2 WEAKNESSES

The main weakness that was found out basing on a LCA approach is:

- biomass production in open ponds has a significantly high impact, due to the high consumption of water and electricity; in particular, the large use of water leads to a much higher MAETP compared to case studies with PBRs.

3.3 OPPORTUNITIES

The following bullets summarize the LCA-based opportunities for biofuels production:

- the use of wastewater as algae growth medium significantly reduces impacts, because 80% of water can be recycled back to the cultivation plant, thus reducing resources consumption and avoiding environmental costs for wastewater treatment;
- the use, as algae nutrient source, of carbon dioxide from power stations or other combustion plants contributes to reduce impacts, and in particular GWP, because it avoids its emission to atmosphere;
- the replacement of flocculation with other harvesting technologies may reduce the absolute value of biofuel production impact; however, this does not influence the comparison among the environmental performance of the case studies.

3.4 THREATS

The main identified threat affecting the production of biofuels from algae is:

- the use of solar drying as thickening technique does not require electricity but produces mixtures with a lower algae concentration, which leads to a lower bio-oil yield and consequently a lower production of biodiesel.

4 CONCLUSIONS

The present report illustrates the results of LCA studies performed on selected biomass and biofuels production chains from algae. In particular, the following alternatives were considered among the technological choices for the processes: open ponds and photobioreactors for cultivation, flocculation as harvesting technique, centrifugation and solar drying for thickening, hydrothermal liquefaction to extract bio-oil and biorefinery processes for biodiesel production. By opportunely combining these processes, and considering wastewater and freshwater as growth mediums for algae, six case studies were identified and analyzed under a life cycle perspective.

LCAs were performed according to a Cradle-To-Grave and Cradle-To-Gate approaches based on the specificities of the processes, always using GaBi software, whose internal databases were integrated with data concerning mass and energy consumptions of the different processes, taken from studies and LCIs available in literature.

The comparison among the results of the LCAs allowed to identify the main differences among the available technologies.

It was concluded that, in general, algae cultivation in photobioreactors has a lower life cycle impact compared to open ponds, because of the lower use of water and energy. In addition, the use of wastewater as growth medium and of carbon dioxide from power stations or combustion plants as nutrient source is preferable because it reduces the overall impact on the environment. Finally, the use of centrifugation is preferable to solar drying as concerns thickening of algae-water mixtures because, although it requires more electricity, it increases algae concentration in water and consequently bio-oil yield and biodiesel production.

Since LCAs were performed to compare different technologies, disregarding the location of the plant, impacts from EU-27 electricity grid mix were considered. However, a sensitivity analysis was performed by studying the impact of the electricity mix for six different Countries, and it was concluded that significant differences exist. Thus, it is suggested to use the results of this study only as a comparison among technologies and, when necessary, to assess the absolute values of LCA indicators for the specific Country of interest.

Basing on the above summarized results, a SWOT analysis was performed. It is worth noticing that the interpretation of LCA results and the consequent SWOT analysis only take into account the life cycle impact of the selected biomass and biofuels production chains, and not the other economical and technical aspects connected to their costs and their efficiency.

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APPENDIX A
DETAILED LCA RESULTS

A DETAILED LCA RESULTS

This appendix contains the detailed LCA results for each case study, expressed in terms of indicators and mass balances.

A.1. PRODUCTION CHAIN 1

Table A.1: LCA Indicators for Production Chain 1 Case Studies (Not Normalized)

	1A	1B	1C	Measurement Unit
ADPe	$1.0 \cdot 10^{-6}$	$1.4 \cdot 10^{-8}$	$2.6 \cdot 10^{-8}$	[kg Sb-Equiv.]
ADPf	3.50	0.76	2.20	[MJ]
AP	0.0025	$3.3 \cdot 10^{-4}$	$9.0 \cdot 10^{-4}$	[kg SO2-Equiv.]
EP	0.0054	$5.3 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$	[kg Phosphate-Equiv.]
FAETP	0.041	$3.8 \cdot 10^{-8}$	$4.5 \cdot 10^{-4}$	[kg DCB-Equiv.]
GWP100	1.10	-2.50	-8.50	[kg CO2-Equiv.]
GWP100e	1.10	0.074	0.19	[kg CO2-Equiv.]
HTP	0.0057	0.0041	0.0110	[kg DCB-Equiv.]
MAETP	130	7.7	21	[kg DCB-Equiv.]
ODP	$7.3 \cdot 10^{-10}$	$4.8 \cdot 10^{-11}$	$1.3 \cdot 10^{-10}$	[kg R11-Equiv.]
POCP	$1.3 \cdot 10^{-4}$	$2.0 \cdot 10^{-5}$	$5.3 \cdot 10^{-5}$	[kg Ethene-Equiv.]
TETP	0.0024	0.00011	0.00025	[kg DCB-Equiv.]

Table A.2: Complete Balances for Production Chain 1 Case Studies

Flows [kg]	1A	1B	1C
Total flows	**9,379.89**	**548.06**	**961.21**
Resources	**5,061.97**	**280.17**	**744.84**
Energy resources	-0.669	-0.966	-3.241
Land use	0	0	0
Material resources	5,062.64	281.14	748.08
Deposited goods	**0.9982**	**0.2621**	**0.7517**
Radioactive waste	0.00270	0.00018	0.00048
Stockpile goods	0.9955	0.2620	0.7512
Emissions to air	**14.051**	**1.240**	**3.411**
Heavy metals to air	$1.91 \cdot 10^{-6}$	$1.21 \cdot 10^{-7}$	$3.26 \cdot 10^{-7}$

Flows [kg]	1A	1B	1C
Inorganic emissions to air	11.42	0.89	2.45
Organic emissions to air (group VOC)	0.0243	0.0002	0.0003
Other emissions to air	2.6034	0.3433	0.9602
Particles to air	$-2.81\cdot10^{-5}$	$1.71\cdot10^{-5}$	$5.11\cdot10^{-5}$
Pesticides to air	$-3.49\cdot10^{-12}$	$-2.24\cdot10^{-14}$	$3.18\cdot10^{-14}$
Radioactive emissions to air	$1.71\cdot10^{-14}$	$1.17\cdot10^{-14}$	$1.05\cdot10^{-14}$
Emissions to fresh water	**4,287.15**	**265.32**	**209.32**
Analytical measures to fresh water	0.0250	0.0002	0.0002
Heavy metals to fresh water	$7.18\cdot10^{-4}$	$3.41\cdot10^{-5}$	$8.86\cdot10^{-5}$
Inorganic emissions to fresh water	0.0316	0.0006	0.0017
Organic emissions to fresh water	0.0055	$3.45\cdot10^{-5}$	$7.43\cdot10^{-6}$
Other emissions to fresh water	4,081.98	251.84	172.862
Particles to fresh water	$6.81\cdot10^{-4}$	$4.27\cdot10^{-5}$	$1.15\cdot10^{-4}$
Radioactive emissions to fresh water	205.10	13.48	36.46
Emissions to sea water	**15.708**	**1.058**	**2.877**
Analytical measures to sea water	$-1.88\cdot10^{-7}$	$8.14\cdot10^{-8}$	$2.45\cdot10^{-7}$
Heavy metals to sea water	$8.66\cdot10^{-8}$	$5.83\cdot10^{-9}$	$1.58\cdot10^{-8}$
Inorganic emissions to sea water	$7.66\cdot10^{-4}$	$4.37\cdot10^{-5}$	$1.16\cdot10^{-4}$
Organic emissions to sea water	$4.52\cdot10^{-7}$	$2.59\cdot10^{-8}$	$6.88\cdot10^{-8}$
Other emissions to sea water	15.708	1.058	2.876
Particles to sea water	$-6.32\cdot10^{-5}$	$2.51\cdot10^{-6}$	$8.61\cdot10^{-6}$
Radioactive emissions to sea water	0	0	0
Emissions to agricultural soil	$\mathbf{3.86\cdot10^{-7}}$	$\mathbf{2.46\cdot10^{-8}}$	$\mathbf{6.49\cdot10^{-8}}$
Heavy metals to agricultural soil	$3.86\cdot10^{-7}$	$2.46\cdot10^{-8}$	$6.49\cdot10^{-8}$
Emissions to industrial soil	$\mathbf{2.19\cdot10^{-5}}$	$\mathbf{1.59\cdot10^{-6}}$	$\mathbf{4.32\cdot10^{-6}}$
Heavy metals to industrial soil	$1.91\cdot10^{-9}$	$1.26\cdot10^{-10}$	$3.38\cdot10^{-10}$
Inorganic emissions to industrial soil	$2.19\cdot10^{-5}$	$1.59\cdot10^{-6}$	$4.32\cdot10^{-6}$
Organic emissions to industrial soil	$8.99\cdot10^{-11}$	$6.02\cdot10^{-12}$	$1.61\cdot10^{-11}$
Other emissions to industrial soil	$1.85\cdot10^{-18}$	$1.25\cdot10^{-19}$	$3.33\cdot10^{-19}$

A.2. PRODUCTION CHAINS 2 AND 3

Table A.3: LCA Indicators for Production Chains 2 and 3 Case Studies (Not Normalized)

	2	3A	3B	Measurement Unit
ADPe	$1.8 \cdot 10^{-6}$	$1.8 \cdot 10^{-7}$	$2.1 \cdot 10^{-7}$	[kg Sb-Equiv.]
ADPf	13.0	8.2	15.0	[MJ]
AP	0.0084	0.0048	0.0060	[kg SO2-Equiv.]
EP	0.010	0.0014	0.0041	[kg Phosphate-Equiv.]
FAETP	0.094	0.026	0.026	[kg DCB-Equiv.]
GWP100	3.20	-2.80	-8.6	[kg CO2-Equiv.]
GWP100e	2.80	1.20	2.6	[kg CO2-Equiv.]
HTP	0.21	0.12	0.13	[kg DCB-Equiv.]
MAETP	280	70	93	[kg DCB-Equiv.]
ODP	$1.3 \cdot 10^{-9}$	$1.4 \cdot 10^{-10}$	$2.2 \cdot 10^{-10}$	[kg R11-Equiv.]
POCP	$8.3 \cdot 10^{-4}$	$6.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	[kg Ethene-Equiv.]
TETP	0.03	0.026	0.028	[kg DCB-Equiv.]

Table A.4: Complete Balances for Production Chains 2 and 3 Case Studies

Flows [kg]	2	3A	3B
Total flows	**16,509.49**	**1,789.26**	**2,058.48**
Resources	**8,867.02**	**897.10**	**1,422.19**
Energy resources	0.7331	0.2373	0.4203
Land use	0	0	0
Material resources	8,866.29	896.86	1,421.77
Deposited goods	**0**	**0**	**0**
Radioactive waste	2.4945	1.2681	3.0582
Stockpile goods	0.0047	0.0005	0.0008
Emissions to air	**2.4897**	**1.2676**	**3.0572**
Heavy metals to air	75.59	54.24	61.10
Inorganic emissions to air	$4.32 \cdot 10^{-6}$	$1.33 \cdot 10^{-6}$	$1.69 \cdot 10^{-6}$
Organic emissions to air (group VOC)	69.72	52.17	56.28
Other emissions to air	0.0601	0.0200	0.0624

Flows [kg]	2	3A	3B
Particles to air	5.81	2.04	4.75
Pesticides to air	0.00024	0.00032	0.00092
Radioactive emissions to air	$-5.82 \cdot 10^{-12}$	$-3.20 \cdot 10^{-14}$	$2.15 \cdot 10^{-14}$
Emissions to fresh water	**$3.08 \cdot 10^{-13}$**	**$4.20 \cdot 10^{-14}$**	**$6.33 \cdot 10^{-14}$**
Analytical measures to fresh water	7,536.93	833.62	567.17
Heavy metals to fresh water	0.0420	0.0006	0.0007
Inorganic emissions to fresh water	$1.25 \cdot 10^{-3}$	$1.16 \cdot 10^{-4}$	$1.79 \cdot 10^{-4}$
Organic emissions to fresh water	0.1636	0.1120	0.1155
Other emissions to fresh water	$9.95 \cdot 10^{-3}$	$7.62 \cdot 10^{-4}$	$7.22 \cdot 10^{-4}$
Particles to fresh water	7,178.29	794.46	503.12
Radioactive emissions to fresh water	0.0096	0.0085	0.0089
Emissions to sea water	**358.41**	**39.03**	**63.92**
Analytical measures to sea water	27.440	3.023	4.948
Heavy metals to sea water	$3.43 \cdot 10^{-5}$	$3.48 \cdot 10^{-5}$	$3.60 \cdot 10^{-5}$
Inorganic emissions to sea water	$3.98 \cdot 10^{-6}$	$3.84 \cdot 10^{-6}$	$3.90 \cdot 10^{-6}$
Organic emissions to sea water	0.0329	0.0317	0.0321
Other emissions to sea water	$1.95 \cdot 10^{-5}$	$1.88 \cdot 10^{-5}$	$1.90 \cdot 10^{-5}$
Particles to sea water	27.40	2.99	4.91
Radioactive emissions to sea water	$1.91 \cdot 10^{-4}$	$3.01 \cdot 10^{-4}$	$3.58 \cdot 10^{-4}$
Emissions to agricultural soil	**0**	**0**	**0**
Heavy metals to agricultural soil	$2.71 \cdot 10^{-5}$	$2.65 \cdot 10^{-5}$	$2.66 \cdot 10^{-5}$
Emissions to industrial soil	**$2.71 \cdot 10^{-5}$**	**$2.65 \cdot 10^{-5}$**	**$2.66 \cdot 10^{-5}$**
Heavy metals to industrial soil	0.0019	0.0019	0.0077
Inorganic emissions to industrial soil	$8.30 \cdot 10^{-8}$	$8.01 \cdot 10^{-8}$	$3.15 \cdot 10^{-7}$
Organic emissions to industrial soil	0.0019	0.0019	0.0077
Other emissions to industrial soil	$1.79 \cdot 10^{-10}$	$3.88 \cdot 10^{-11}$	$5.13 \cdot 10^{-11}$

A.3. COMPARISON CML2001 – IPCC AR5

Parameter	1A	1B	1C	2	3A	3B	Measurement Unit
CML 2001 – GWP100	1.100	-2.500	-8.500	3.200	-2.800	-8.600	[kg CO2-Equiv.]
CML 2001 – GWP100e	1.100	0.074	0.190	2.800	1.200	2.600	[kg CO2-Equiv.]
IPCC AR5 – GWP100i	1.218	-2.530	-8.488	2.973	-3.295	-10.433	[kg CO2-Equiv.]
IPCC AR5 – GWP20i	2.549	-2.516	-8.469	5.988	-2.477	-7.935	[kg CO2-Equiv.]
IPCC AR5 – GTP100i	0.672	-2.536	-8.497	1.713	-3.654	-11.526	[kg CO2-Equiv.]
IPCC AR5 – GTP20i	2.123	-2.521	-8.475	5.034	-2.729	-8.706	[kg CO2-Equiv.]
IPCC AR5 – GWP100e	1.227	0.074	0.191	3.054	1.111	2.386	[kg CO2-Equiv.]
IPCC AR5 – GWP20e	2.558	0.088	0.211	6.079	1.938	4.923	[kg CO2-Equiv.]
IPCC AR5 – GTP100e	0.682	0.068	0.183	1.794	0.751	1.293	[kg CO2-Equiv.]
IPCC AR5 – GTP20e	2.133	0.084	0.205	5.124	1.686	4.152	[kg CO2-Equiv.]

APPENDIX G

TECHNICAL REPORT
BARRIERS ANALYSIS AND RECOMMENDATIONS

Doc. No. 12-920-H3
Rev. 1 – JUNE 2015

D'APPOLONIA
consulting, design, operation & maintenance engineering

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SELC biologia e geologia applicate

European Commission
DG ENERGY
Brussels, Belgium

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Guidelines Report

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**ALGAE BIOENERGY SITING,
COMMERCIAL DEPLOYMENT AND DEVELOPMENT ANALYSIS
GUIDELINES REPORT**

G.1 INTRODUCTION

This Report is part of Task 3 of the Project and is aimed at presenting the guidelines to overcome the barriers that currently obstacle the development of algae-based plants producing biofuels and valuable co-products.

The above mentioned barriers were identified basing on the results of the SWOT analyses previously performed in Task 2 of the Project concerning:

- microalgae cultivation systems;
- biofuels and co-products chains.

The identified barriers are connected with technical and economical aspects, but also with policy, normative background and public acceptance.

The barriers were grouped into two different groups according to the severity of their effects: first level barriers are characterized by macroscopic negative effects that hinder the development of a process; on the other hand, second level barriers are characterized by weaker effects, which penalize a process by reducing its performances.

Based on the analysis of the barriers, some recommendations were developed that aim at overcoming them and foster the development of algae-based biofuel production systems. In particular, the recommendations concern the topics on which research and policies should be addressed to make biofuel production from microalgae technically more efficient and economically more attractive for investors.

The topics introduced above are illustrated in the present report according to the following structure:

- Section 1 introduces the contents, the objective and the structure of this report;
- Section 2 describes the identified barriers;
- Section 3 presents the recommendations;
- Section 4 draws the conclusions.

G.2 BARRIERS

It is important to start this assessment recalling the major "Barrier" originating the entire analysis of the siting, commercial deployment and development of algae bioenergy: a big distance still exists between the conventional fossil fuels and the algae-based biofuels in terms of competitiveness on the market. The reduction of this gap is the final goal of all the panorama of specialists working on the production chains of algae-based biofuels.

Looking at the several facets of "the Barrier", all the issues can be connected to four macro fields of barriers to the development of a successful production chain for algal biofuel: they are the technical and economical aspects, the policy & normative background and the public acceptance. Under these four classes fall all those issues that generate a negative consequence on the chain. Those consequences can be for example:

- need to deepen the research in biological aspects and technologies;
- tangled procedural paths and relations with the institutions;
- controversies with the civil society;
- stall in the investment phase (eventually, quit);
- delay in the availability of the winning technology;
- overall, low competitiveness of the production chain.

In the analysis, the barriers are classified based on two different classes of severity of the effects that they may generate: first level barriers are characterized by macroscopic negative effects that hinder the development of a process; on the other hand, second level barriers are characterized by weaker effects (if compared to class 1), which penalize a process by reducing its performances. Possible solutions to the identified barriers are finally outlined in Section 3.

It is important to specify here that there is a fundamental difference between the "cruces" identified within Task 2 of the project and these barriers. Just to recall the approach, a crux is a necessary condition to achieve before entering the process of access to the market. After the overcoming of a crux, further barriers can exist and shall be faced, and this is the current case.

In the following chapters of the report, the barriers are assessed in terms of technical, economic, policy and normative background and public acceptance barriers. The analysis of the economic aspects is extended to a number of likely scenarios based on the expected trends in energy prices.

G.2.1 TECHNICAL BARRIERS

Among the technical barriers, two aspects are included: on one hand, the technologies for the cultivation of microalgae and the production chains for biofuels and co-products; on the other hand, the biological aspects connected with the selection of the most suitable microalgae species.

Table G.2.1 summarizes the identified technical barriers with their classification (1st or 2nd class barrier). The following sub-sections describe more in detail the detected issues concerning biological and technological aspects.

Table G.2.1: Technical Barriers

Barrier	1st class	2nd class
Conversion Efficiency Algae-Biofuel: oil extraction and biofuel production rates are very low if compared to the input raw materials.	▲	
High amount of water needed per functional unit.		▲
The use of wastewater: although promising for the environmental benefits, it raises O&M issues and it is a barrier to the production of some valuable co-products.		▲
Large cultivation fields are needed		▲
Low biomass productivity	▲	
Low compatibility of valuable co-products and algal biofuel		▲
Use of bioengineering is necessary for the achievement of the optimal algae strains. This is linked to the barrier of public acceptance.		▲
No multiproduct plants exist or promise to be valuable	▲	

G.2.1.1 Microalgae Strains Selection

Some of the technical barriers that must be overcome to achieve a successful commercial biofuels production are related to various aspects of algal biology, such as growth rate and lipid biosynthesis.

Algal technologies provide the possibility of producing specialized strains through genetic engineering with an improved photosynthetic biomass conversion efficiency, a capability to grow under specific controlled condition (i.e.: high concentration of CO_2), leading to higher productivities in biomass and product yield (i.e.: lipid).

However, it is important to point out the possible escape of genetically modified (GM) algae from cultivation systems into the environment, with potential alteration of natural ecosystems (i.e.: harmful algal blooms, wild species outcompeted by GM ones) and health impacts (i.e.: toxins productions). Then again, outside controlled laboratory conditions, GM algae (or artificially selected ones) sometimes result more vulnerable to predators and natural competing strains.

Biodiesel production from microalgae can be more profitable if combined with wastewater treatments and the production of valuable co-products. However it is necessary to treat wastewater to remove pathogens, heavy metals, chemical and toxic compounds, with consequently higher operating costs.

G.2.1.2 Microalgae Cultivation and Biofuel Production

The major technical barrier is the productivity of microalgae in industrial cultivation environments. The efficiency of conversion of light into biomass is typically 1-2% in open ponds and 3-5% in PBRs. This means that a very large area is needed to reach a significant productivity as required in the fuel market. As a result, capital and operational costs are very high and also the exploitation of natural resources (i.e.: water) may lead a significant environmental burden.

The use of wastewater as source of nutrients may reduce some costs and increase the process environmental benefits, but obviously does not affect the light conversion efficiency issues.

Some promising alternatives may derive from the bioengineering effort to enhance microalgae performance through mutation and selection as well as more sophisticated genetic engineering techniques. However, no clear solution has been found yet and several strains that performed well at a lab scale did not demonstrate to be robust enough to guarantee a consistent performance in a large scale environment.

Additional barriers are represented by the lack of consolidated technologies to recover oil or convert biomass into fuel: although some technologies seem more promising than other, at the moment there is no clear champion and once again costs are still an issue. The recovery step is further exacerbated by the dilution of microalgae cultivation systems, which make the concentration step complex and often energy intensive.

The exploitation of value-added products from microalgae may help the overall process economics, but this is something where technology effectiveness has yet to be proved (new catalysts may have to be developed) and it is still uncertain whether new products may compensate for the increase in technological complexity and costs.

G.2.2 ECONOMIC BARRIERS

The barriers which hurdle the development of new technologies in biofuel production system from microalgae are still significant also as regards economic aspects. The intensity of barriers to be addressed depends on the technology used to produce biofuel (PBRs or open ponds), the localization of plants, the institutional arrangements and the normative framework in place in the country.

Table G.2.2 summarizes the identified economic barriers with their classification (1st or 2nd level). The following sub-sections describe more in detail the detected issues and analyze some possible scenarios connected to the macro-energetic context and some possible scenarios.

Table G.2.2: Economic Barriers

Barrier	1st class	2nd class
Production costs not competitive with other biofuel production chains (wood, crops) or in reference to the fossil fuel sector.	▲	
Fiscal and economic incentives not favorable to the development of algae production chains		▲
Demand only for high volume of biofuels, which requires important investments in equipment in the start-up phase of the business.		▲

G.2.2.1 Economic Barriers

An important economic barrier for entry in biofuel sector is related to the requirement in technology and knowledge to produce biofuels and co-products at market conditions. Only a limited number of investors are able to control the complexity of processes involved in fuel production, transport and distribution. Considering also the diversity of the situations at site-level, the access to technology might be limited to a limited number of operators determining a situation of potential underinvestment.

Although small installations have been tested as pilots during last years, no clear data exist on the optimal size of a biofuel plant from algae. To be attractive and profitable it is likely that biofuels from algae should be produced at a significant scale. This scale is both determined by technical considerations (the critical mass to optimise a specific process under the technology used) and by economic factors (related to the minimum biofuel quantity to be produced in order to meet the potential demand on the marketplace). In that context, important investments should be needed in the early phases of plant development, in terms of equipment (especially for PBR technology), land surface (in case of open ponds) and other inputs required.

It is worth noting that the possible public incentives should be differentiated according the technology used, the environmental impact (i.e.: reuse of waste water) and the location of the plant. In particular, the differentiation should be based on the share of biofuel and co-products within the production chain (i.e.: high incentive to producers of biofuel, low incentive to business oriented investments with core production of co-products and limited production of biofuel).

G.2.2.2 Macro Energetic Context and Scenario

The development of a new biofuel sector from algae (third generation biofuels) depends on a number of internal and external factors. Internal factors are mainly related to technology and siting while external (uncontrolled) factors refer to the energy context and the economic situation in general. Indeed, the dynamics of conventional fuels demand and offer and the resulting price level determine for a large part the profitability of investment in the biofuel sector.

In this study, external factors are briefly analyzed and two energy price scenarios are proposed. It is worth noticing that low prices in fuels are not favorable to the development of new biofuel technologies, while higher prices in a context of economic growth make more profitable investments. However, in all the scenarios proposed the prices and costs gap between biofuel from algae and other fuel sectors remains significant. In a near future, technology improvement and a specific financial public support to algae production chain should be necessary in order to increase the attractiveness of investments in this sector.

G.2.2.2.1 Recent Energy Trends

BRICS and the other developing countries have been driving energy consumption growth in the most recent years. In particular, increase in consumption of fossil energy in China and India (as shown in Figure G.2.1 and Figure G.2.2) has been the key determinant of the current global trend. While the financial crisis has reduced energy consumption growth rates almost everywhere over the years 2011-2013, this has not inverted the positive trend in consumption (except in 2000-2011 in the EU, USA and Japan). For the next decade, experts expect a worldwide increase in energy consumption mainly driven by demographic growth and changing consumption patterns in emerging countries[1].

[1] "Demographic factors will continue to drive changes in the energy mix. The world population is set to rise from 7.0 billion in 2011 to 8.7 billion in 2035, led by Africa and India." in International Energy Agency (IEA), World Energy Outlook, 2013, chapter 1, p. 33.

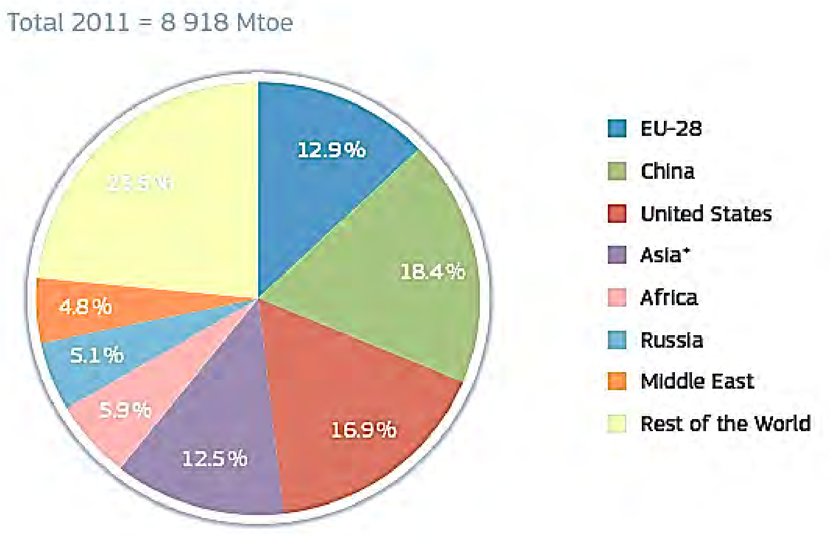

Figure G.2.1: World Final Energy Consumption by Region

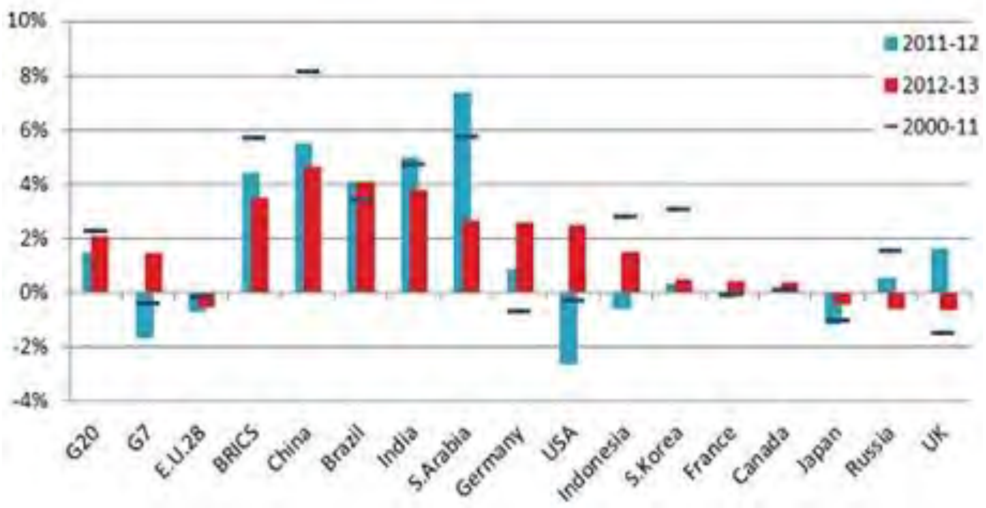

Figure G.2.2: Energy Consumption Growth in the Major G20 Countries (%/year)

Within the EU, buildings have currently the highest share of energy consumption, together with transport. Industry and agriculture have reduced their consumption over the last decade, mainly due to the lower energy intensity.

As far as the supply side is concerned, it is likely that the historical fuel production peak has been reached, while coal and (unconventional) gas are still abundant for some further decades[2]. The share of renewable energy in the energy mix is increasing everywhere, but it still does not cover a significant share of the energy supply. The EU shows a high dependency on fossil energy imports (ratio between imports and supply of fuels is above 50% since 2000), with some variation across MS. However, the share of renewable sources

[2] International Energy Agency (IEA), "World Energy Outlook", 2013.

in electricity generation has been growing fast and reached a significant level in some countries and sectors.

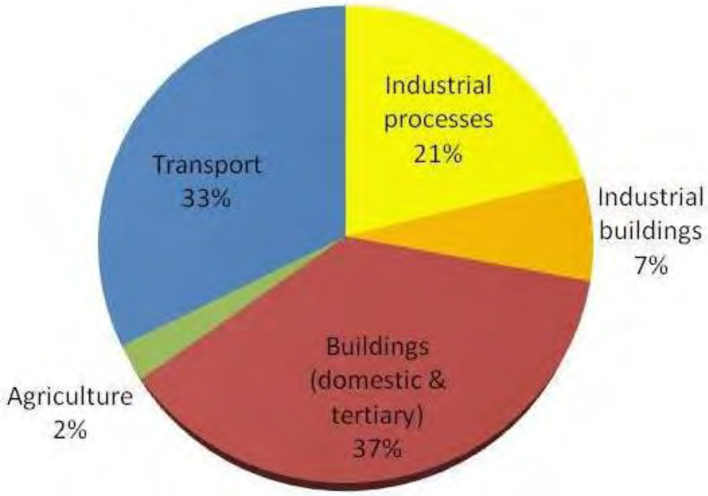

Figure G.2.3: Share of Total EU Energy Consumption

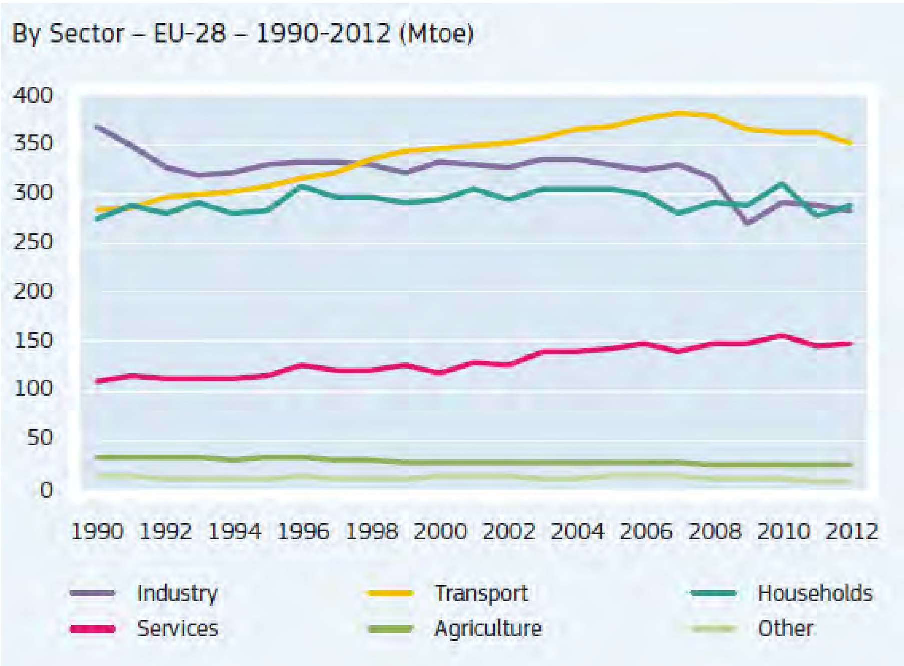

Figure G.2.4: EU Final Energy Consumption by Sector

As regards the biofuel sector, the total consumption in EU transport in 2013 reaches 13.6 Mtoe (corresponding to around 4.7% share of total transport fuel consumption). After a decade of growth, the year 2013 was characterized by a slight decrease (by 6.8%) of consumption in Europe. This is partly due to the decrease in consumption of all transport fuels, which is a side effect of the economic crisis still affecting a significant number of Member States. Other reasons are the changes introduced in the biofuel legislation at EU level, but also the result of some changes made in national legislations during the period (e.g.

the end of a favorable fiscal regime for biodiesel in Germany by the end of 2014). At Member State level the biofuel consumption and production remain concentrated in few Members States: Germany, France, Spain and Italy represent around 65% of the total EU consumption in 2013. As concerns the breakdown of biofuels, biodiesel represents more than 80% of total biofuel consumption in the transport sector.

Considering the objective of the Directive on biofuel consumption still under discussion and according to the projection in fuel consumption at EU level in 2020, biofuel consumption could rise to 22,5 Mtoe by 2020 (+60% compare to the 2013 level).

G.2.2.2.2 Scenario in Energy Prices

In the short run, and according to a business as usual scenario, oil prices are expected to remain relatively low. This situation is due to the existing current surplus in oil supply – with abundance in non-conventional oils put on the market and a high fossil fuel supply from middle east producers – and weaknesses on the demand side, especially from Europe where the economic situation is still under the effects of the financial crisis. In early 2015, oil prices (WTI crude oil index) are under 50$ per barrel, far below the level of prices taken into consideration in biofuel market analysis. Indeed, between July 2014 and January 2015 oil prices plunged over 55%.

Therefore, the cost gap between biodiesel from algae and conventional fossil diesel has increased significantly over the last two years. In the long run, the scenario should change, as a consequence of the inversion of trends in production and consumption. Oil price is expected to increase over the period 2010-2050, reaching 140$ per barrel of oil equivalent (boe) at the end of the period, according the most recent simulations published by the European Commission.

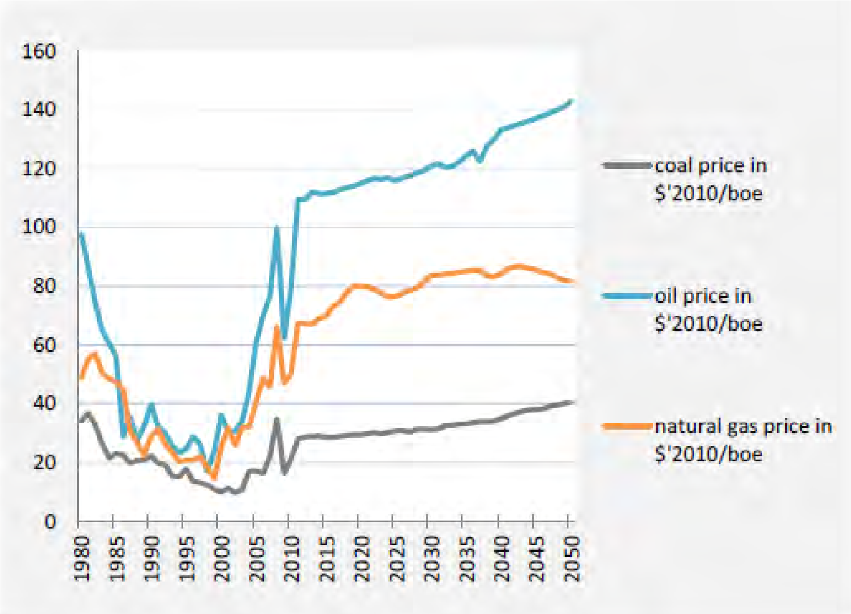

Figure G.2.5: Fossil Fuels Price Forecasts

However, in both short and long term scenarios, oil prices are not sufficiently high to reduce the gap between conventional fossil fuels and biofuels from algae. In addition, it is worth noticing that inputs prices for biofuel production, such as capital, fertilizers and power are strongly linked to fossil fuel prices, as the investment costs in biofuel technology is partly due to the cost of embodied fossil energy in materials and equipment, which makes difficult the decoupling between the two price trends.

G.2.3 POLICY AND NORMATIVE BACKGROUND BARRIER

A main barrier was identified concerning the policy and the normative background, as shown in Table G.2.3. The barrier is considered as "second class" because it only makes more difficult the realization of an algae-based biofuel production plant, without preventing it.

Table G.2.3: Policy and Normative Background Barrier

Barrier	1st class	2nd class
Uncertain/undefined legal and policy frameworks. Patents and authorizations to start a business are not well defined or are provided at a very high cost for investors.		▲

At EU policy level, the current line is towards the decrease of supports to the first biofuel generation (bioethanol or biodiesel outputs from the conversion of food crops) and the promotion of the second and third biofuel generations which demonstrate a better ecological footprint in terms of land changes (positive Indirect Land Use Change effect) and CO_2 emissions and storage. However, no EU wide political agreement has been reached up until now on the target for biofuel incorporation in transport fuel. The previous target of 10% by 2020, set under the Directive 2009/28/EC, has not been reconfirmed and no minimum objective has been proposed for third generation biofuel, as fuel from algae[3].

Furthermore, it is worth noticing that at national level algae strains used for fuel production could require long administrative procedures to be authorized for commercialization. In addition, the acquisition of patents could be also necessary and make more expensive the initial investments (in intangibles) required.

G.2.4 PUBLIC ACCEPTANCE BARRIERS

The fourth kind of barriers impacting on the development of biofuel production processes from microalgae is connected with public acceptance.

Table G.2.4: Public Acceptance Barriers

Barrier	1st class	2nd class
Skepticism of the population towards unknown technologies, use of bioengineering and towards highly impacting systems in terms of land occupancy. Diffidence towards land occupancy for industrial purposes vs. agricultural scopes.		▲
Odors in Open Pond are an issue that can cause "NIMBY" phenomena along with the general skepticism.		▲

[3] For the last legislative developments at EU level see for example: "EU ENERGY COUNCIL DRAFT DIRECTIVE ON INDIRECT LAND USE CHANGE", published by the International Council on Clean Transportation, in July 2014

The detected barriers of this type with their classification are summarized in Table G.2.4. It can be noted that both are second class barriers because they do not hinder but they only make more difficult the realization of an algae-based biofuel production plant.

The barriers connected with the public acceptance are typically a consequence of the scarce confidence of the population towards innovation. If the final users of a given technology or of a product are a bit more familiar with new technologies, the majority of population requires plenty of awareness campaigns before getting acquainted with a change. This intrinsic diffidence is therefore reflected in the acceptance of a new technology, especially if it encompasses definitions such as “genetically modified”, “hectares of land occupancy”, “possible odors”.

Moreover, the barriers are partly a consequence of technological issues: the diffidence linked to the odors is connected with the warranties that must come from the industrial players. Also, the technical progresses needed in the conversion rates (sunlight to biomass) shall be of great help to reduce possible repulsions against huge lands destined to algae cultivation.

G.3 RECOMMENDATIONS

As mentioned at the beginning of this report, the identified barriers are relevant issues that call for actions in order to improve the situation of the production chains, but that can be addressed and, hopefully, solved in a short- medium-term time span, thus reducing the overall gap between conventional and algae-based fuels.

The following chapters present the recommendations outlined on the basis of the barriers identified in the previous section. In particular, like the barriers, the recommendations are connected with technical and economic aspects, as well as with policy, normative background and public acceptance.

G.3.1 TECHNICAL RECOMMENDATIONS

The keyword to overcome technical barriers is process intensification, i.e. the goal is to produce more in less space (surface) and using less resources. This will require some fundamental research effort at least in the following areas:

- development of more efficient (genetically modified) algal strains with enhanced biomass and oil productivity and better resistance to outdoor irradiation conditions;
- optimizing microalgae cultivation and processing system technologies such as fuel extraction and production, or biorefinery processes to minimize resource input and costs;
- development of reliable modelling and simulation tools for effective design and optimization and to reduce the (expensive) trial and error approach which has been dominant over the last years;
- development of new approaches for process upscaling to take advantage of the economy of scale;
- upscaling available modified strains for assessing productivity increases and strain stabilities under industrially relevant outdoors cultivation conditions;
- development of alternative high-intensity cultivation techniques (e.g. based on microsystems) to maximize growth rate and biomass concentration in industrial productions;
- development of new technologies for downstream processing toward high-value added products (development of new catalysts may prove of critical importance);
- analysis and development of virtuous supply chains where multiple players can take advantage of microalgae products.

As regards biological aspects, the following recommendations were identified:

- development of suitable algal strains that allow rapid production of biomass with high lipid content and production of valuable co-products to increase biomass overall value;
- better assessment to evaluate and minimize the potential risks of outcomes of GM algae in natural environment;
- development of lab-created strains unable to survive outside open ponds or PBRs;
- incentives for the treatment of public wastewater as a source of nutrients and a potential income to reduce operating costs.

G.3.2 ECONOMIC RECOMMENDATIONS

There are no clear business models currently available to be proposed to potential investors in the biofuel from algae sector. The following recommendations summarize the steps that need to be done to overcome the barriers at short and medium terms (by 2020) and make more attractive investments in biofuel energy chains, taking into consideration also the macro-energy scenario. More in detail, the following actions are suggested:

- fill the normative gap at EU and Member State levels, identifying a clear financial mechanism to support the development of the sector over the next five years, while ultimately diffusing more information about business opportunities in the different Members States, e.g. on technologies and sites, relevant networks and stakeholders, administrative contact points at national level, access to capital and skilled, etc;
- propose some financial supports to investors in the early-stage of investment in biofuel projects (with the objective to pass from pilot projects to commercial plants), using grant mechanism or financial instruments (FIs), e.g. ESI funds. FIs used could refer to low-cost loans, guarantee mechanisms or venture capital for start-ups in the bioenergy sector[4];
- enhance tax concession (or other financial incentives[5]) mechanisms or promote the biofuel obligation approach (quotas) to biofuel production from algae (requiring fuel supply companies to incorporate a given percentage of biofuel from algae in the fuel they supply to the marketplace)[6]. Note that the incentives should be differentiated according to the technology used, the environmental impact (i.e.: reuse of waste water) and the location of plants (e.g.: in disadvantaged areas). In addition, the financial support could be modulated according to the number of by-products derived from algae cultivation activities i.e. giving high incentive to biofuel producers and lower incentive to business oriented investments with core production of co-products and limited production of biofuel;
- support the creation of networks at national levels to share information and technologies and give supports to investors in the sector of alternative biofuels e.g. network lists, information for a better access to capital and skills, business support to investments, legislative background, etc.

G.3.3 POLICY AND NORMATIVE BACKGROUND RECOMMENDATIONS

The main recommendation concerning the policy and normative background, is to harmonize EU and national legislations, especially in terms of procedures (impact assessment), authorization (accredited bodies to deliver authorizations) and patents required to growth algae. Time and costs for investors should be known in advance and be consistent with what observed in the other biofuel sectors[7].

[4] For illustration of venture capital funds in the sector of renewable energy see for example the “State of Renewable Energies in Europe” edition 2014, published by the EurObserv’ER, p.174.

[5] Other mechanism in used in the renewable energy sectors are feed-in-tariffs or premium (which guarantee a minimum price or percentages to the producers of biofuel products placed on the market).

[6] See for example for a better illustration of the mechanisms mentioned here annex 9 of the “Biomass action plan” published by Commission in 2005 (COM(2005) 628 final).

[7] According the Golder associates and Ecofys study, the average lead time in Member States of the total bio-energy permit procedure is ca. 23 months. For more details see “Benchmark of Bioenergy Permitting Procedures in the European Union”, January 2009 DG Tren.

G.3.4 PUBLIC ACCEPTANCE RECOMMENDATIONS

To achieve the public acceptance the keyword to chase is "consensus". This is not something that can be obtained immediately and with limited actions, in fact it can be a long path to explore. The reasons of the long actions to carry out are due to several reasons: on one hand, there is the counterpart as a heterogeneous panorama to address with different languages and argumentations, on the other hand there are the evident technical limitations to solve and hence to convince the skeptical side of the population.

Provided that the above is clear to the project developers, consensus can be built stressing on three activities:

- awareness raising campaigns;
- research activities and following dissemination of results;
- demonstrative projects flowing into pilot systems that can prove the reliability of the technologies along with the effectiveness of the new production chains.

G.4 CONCLUSIONS

The activities described in this Report are part of Task 3 of the Project and are based on the SWOT analyses performed within Task 2 concerning microalgae cultivation systems and biofuels and co-products chains.

Based on the weaknesses and threats of the investigated cultivation systems and production chains, a set of barriers to the development of algae-based plants was identified. These barriers were classified according two criteria:

- according to the subject, the barriers were grouped in technical (biological and technological), economical, policy and normative background, public acceptance aspects;
- as regards the severity of their effects, first and second class barriers were identified. The former are characterized by macroscopic negative effects that hinder the development of a process, whereas the latter are characterized by weaker effects, which penalize a process by only reducing its performances.

Provided that the overall objective is to overcome the barriers (although this will not be an easy process), following the same approach, some recommendations to overcome the barriers are defined considering technical, economical, policy and public acceptance aspects.

The technical recommendations mainly deal with process intensification and genetic modification of microalgae strains. As regards process technologies, a set of topics was identified, regarding both microalgae cultivation and biofuel production, on which research should focus. On the biological side, it is suggested to address research to the development of genetically modified microalgae strains that increase biofuel productivity and reduce contamination risks in case of outcomes in natural environment.

As regards economic and policy subjects, the recommendations mainly aim at making more attractive the investments in the sector of biofuel production from microalgae. In this context, it is suggested as first basic step to fill the normative gap and harmonize EU and MS legislations for procedures and authorization. Then, economic incentives and a financial support would give a significant contribution to the diffusion of algae-based systems.

The analysis allowed pinpointing recommendations to tackle all highlighted barriers – using a barrier-action approach – from the overall perspective concerning technical, economic, social and policy aspects. A summary of the recommended actions is presented in Table G.4.1.

The plan considers the three important fields “Priority”, “Duration” and “Cost”, ranging from a score of 1 to 3 depending on effort connected to the respective solution:

- provided that all the recommendations have high priority because all the mentioned barriers significantly contribute to the creation of the big gap with the conventional fuels to be reduced, the priority score can be high (score 3) if the solution must be implemented as soon as possible otherwise the intervention is not viable, medium (score 2) if the recommendation has high impact but a short delay in implementation can be accepted and low (score 1) if the benefit is relevant but there are many other issues to fix before;
- the duration scores (meant as 3-long, 2-medium and 1-short) indicate the duration requested by the proposed action to achieve a significant result;

- the cost scores (3-high, 2-medium and 1-low cost) are indicative of the investments to be done by the scientific community (i.e.: the EC, national institutions, research centers) for the successful realization of the mentioned actions over the expected duration.

Table G.4.1: Barriers-Recommendations Matrix

Context	Barrier	1st class	2nd class	Solution (recommendation)	Priority	Duration	Cost
Technical	Conversion Efficiency Algae-Biofuel: oil extraction and biofuel production rates are very low if compared to the input raw materials.	▲		Selection of the most efficient technology. Research for the development of highly innovative technologies. Research for biological advancement toward more efficient algal strains	⚠⚠⚠	🕒🕒	€€€
Technical	High amount of water needed per functional unit.		▲	Selection of the most efficient technology. Research for the development of highly innovative technologies.	⚠⚠⚠	🕒🕒	€€€
Technical	The use of wastewater: although promising for the environmental benefits, it raises O&M issues and it is a barrier to the production of some valuable co-products.		▲	Incentives for the investors in plants using WW to solve the technical barriers. Research for improvements in O&M issues to overcome the biological barriers.	⚠⚠	🕒🕒	€€
Technical	Large cultivation fields are needed		▲	Research for the development of highly innovative technologies.	⚠⚠⚠	🕒🕒	€€€
Technical	Low biomass productivity	▲		Research for the development of highly innovative technologies and more efficient algal strains.	⚠⚠⚠	🕒🕒	€€€
Technical	Low compatibility of valuable co-products and algal biofuel		▲	Accurate design to decide the most applicable combinations of product/co-products.	⚠⚠	🕒	€€

Context	Barrier	1st class	2nd class	Solution (recommendation)	Priority	Duration	Cost
Technical	Use of bioengineering is necessary for the achievement of the optimal algae strains. This is linked to the barrier of public acceptance.		▲	Research in the biological field of laboratory tests, technological innovation, etc.	⚠⚠	◷◷	€€
Technical	No multiproduct plants exist or promise to be valuable	▲		Demonstrative tests are needed to prove the technical and economical viability	⚠	◷◷	€€€
Economic	Production costs not competitive with other biofuel production chains (wood, crops) or in reference to the fossil fuel sector.	▲		The solution will be mainly a consequence of the technical improvements and of additional public incentives	⚠⚠⚠	◷◷	€€€
Economic	Fiscal and economic incentives not favorable to the development of algae production chains		▲	Put higher incentives on biofuel production, transformation and distribution processes. Incentives might be allocated under the form of grants or low-cost loans (to investments in bio fuel algae production chains), tax concession, feed-in-tariffs or premium (which guarantee a minimum price to biofuel from algae supplied on the market) or quotas (e.g., green certificates).	⚠⚠⚠	◷	€€€

Context	Barrier	1st class	2nd class	Solution (recommendation)	Priority	Duration	Cost
Economic	Demand only for high volume of biofuels, which requires important investments in equipment in the start-up phase of the business.		▲	Higher economic incentives to investments in biofuel from algae production chain at the start-up stage of plant development.	⚠⚠	🕒🕒	€€
Policy and normative background	Uncertain/undefined legal and policy frameworks. Patents and authorizations to start a business are not well defined or are provided at a very high cost for investors.		▲	Strengthen the legal framework at European and national levels (defining responsibilities, bodies involved and public authorizations required).	⚠⚠	🕒	€
Public acceptance	Skepticism of the population towards unknown technologies, use of bioengineering and towards highly impacting systems in terms of land occupancy. Diffidence towards land occupancy for industrial purposes vs. agricultural scopes.		▲	Consensus building campaigns. Demonstrative projects to prove the reliability and the effectiveness.	⚠⚠⚠	🕒🕒🕒	€
Public acceptance	Odors in Open Pond are an issue that can cause “NIMBY” phenomena along with the general skepticism.		▲	Stress on research activities. Consensus building campaigns.	⚠⚠⚠	🕒🕒🕒	€

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glassforeurope.com

IEA World Energy Outlook 2013

APPENDIX H

QUESTIONNAIRE FOR DATA COLLECTION TO FP7 PROJECTS

CATEGORIES	NOTES	DESCRIPTION/VALUE
Microalgae species		
Taxonomic group		
Metabolism type	Photoautotrophic, heterotrophic, etc.	
Chemical composition	Lipid content	
Photosynthetic efficiency [%]		
Growth rate [g/m2/d]		
CO2, nutrients, light and water uptake and sources		
Specific growth requirements	CO2, nutrient, PH, solar radiation, temperature, mixing, etc.	
Cultivation technologies		
Type and description	Open ponds, tubular PBR, flat plate PBR, fermenters, etc.	
Size [m2]		

CATEGORIES	NOTES	DESCRIPTION/VALUE
Operability conditions and technical parameters	Batch/continuous cultivation, algal concentration [g/l]	
Energy input [kWh/m3]		
Cultivation environments		
Type and description	Sewage/waste water plant, power plant, marine/fresh water, etc.	
Water/nutrient savings [%]		
Distance between nutrient/CO2/water sources and cultivation systems [m]		
Harvesting and dewatering technologies		
Type and description	Centrifugation, flocculation, gravity sedimentation, etc.	
Final slurry [% total solids]		
Retention time [h]		
Energy input [kWh/m3]		

CATEGORIES	NOTES	DESCRIPTION/VALUE
Extraction techniques		
Type and description	Chemical solvents extraction, mechanical methods, etc.	
Percentage of oil extraction [%]		
Chemicals [ml/g of dried algae]		
Retention time [h]		
Energy input [kWh/m3]		
Transesterification		
Description of process		
Chemical quantity		
Operative conditions	T, p, retention time	
Percentage of oil converted to biodiesel [%]		

CATEGORIES	NOTES	DESCRIPTION/VALUE
Residual biomass [g]		
Energy input [kWh/m3]		
Other steps involved in biodiesel production		
Description of process	Distillation and/or other additional processes	
Retention time [h]		
Energy input [kWh/m3]		
Process output		
Energy product and main features (energy density, carbon number, etc.)	Biodiesel for engine testing, aviation, etc.	
Daily and annual average algal biomass production [dry t /ha/d or dry t/ha/y]		
Daily, monthly and annual peak values [dry t/ha/d]		
Daily and annual biodiesel production [l/ha/d or l/ha/y]		

CATEGORIES	NOTES	DESCRIPTION/VALUE
Operating days [d]		
Co-products 1		
Type		
Quantity		
Application	Biogas plant, product wholesale	
Additional information		
Co-products 2		
Type		
Quantity		
Application	Biogas plant, product wholesale	
Additional information		

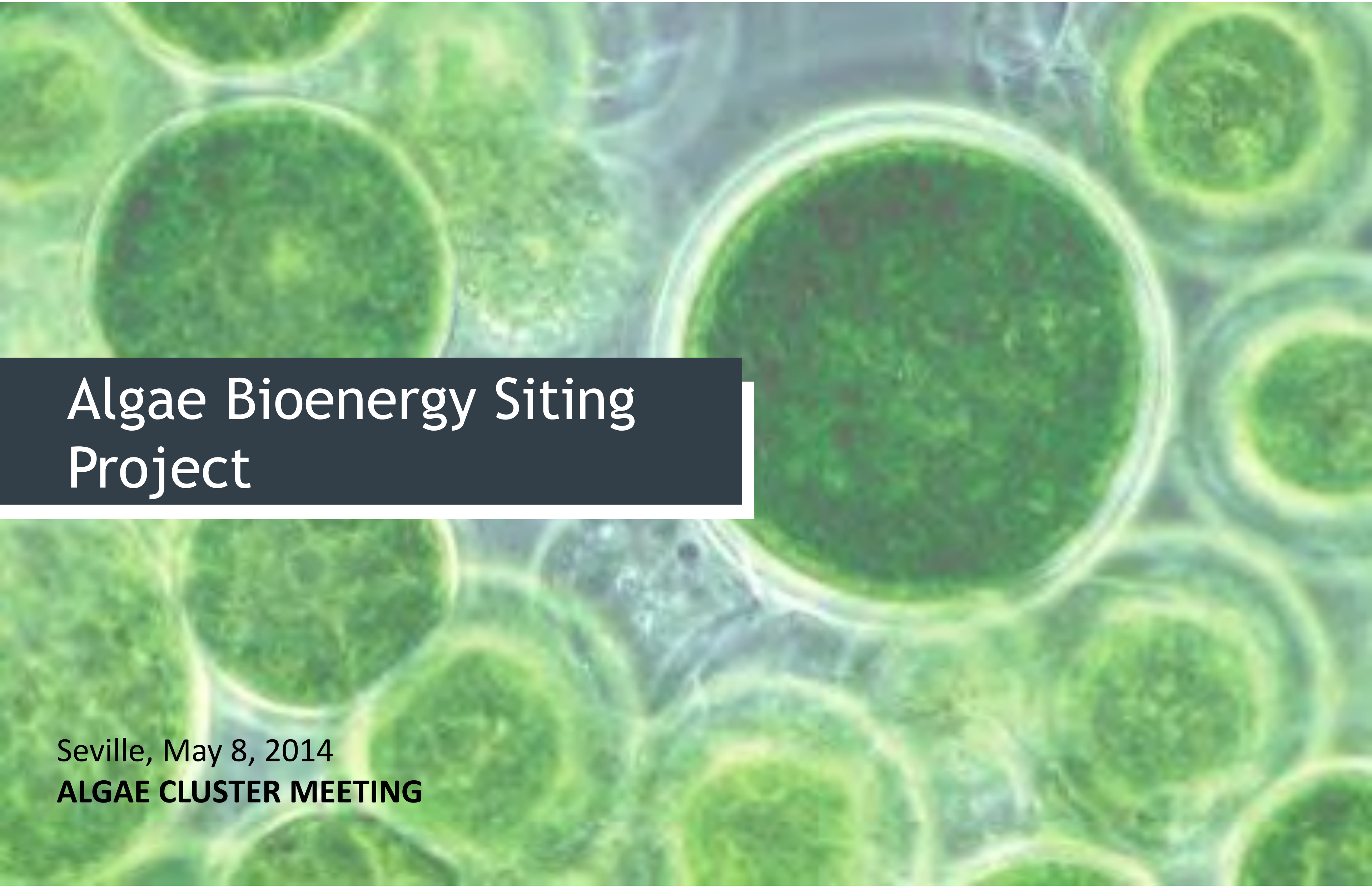
CATEGORIES	NOTES	DESCRIPTION/VALUE
Cost performance		
Capital Costs (equipment) [€]	Cultivation technologies	
	Harvesting and dewatering technologies	
	Extraction techniques	
	Transesterification	
	Other processes	
Operating Costs (Labor and supervision, furniture, raw materials and energy input) [€/dry t]	Cultivation technologies	
	Harvesting and dewatering technologies	
	Extraction techniques	
	Transesterification	
	Other processes	

CATEGORIES	NOTES	DESCRIPTION/VALUE
Geographical location and site description		
Land use		
Slope [%]		
Solar radiation [kWh/m2/d]		
Monthly temperature [°C]		
Net annual evaporation rate [m]		
Rainfall [mm/y]		
Distance from CO_2, nutrient, water sources [m]		
Ancillary infrastructures for biofuel system access and operability	Access road, electrical substation, pipelines, etc.	
Environmental impact		

CATEGORIES	NOTES	DESCRIPTION/VALUE
Description of environmental impacts	Water use, landscape quality and ecosystem damage, etc.	
Involved stakeholders		
Stakeholders		
Land coverage constraints		
Permitting/licenses	Environmental (national parks, nature reserves, etc.), territorial planning and safety constraints	

APPENDIX I

SLIDES FROM THE EVENT IN SEVILLE



Algae Bioenergy Siting Project

Seville, May 8, 2014

ALGAE CLUSTER MEETING

SELC biologia e geologia applicate

Università degli Studi di Padova

D'APPOLONIA consulting, design, operation & maintenance engineering

The Project

Technical Assistance to the European Commission Directorate General (DG) for Energy:

"Siting, Commercial Deployment and Development Analysis of Algae Cultivation Systems"

Duration:

15 months (Feb 2014 – May 2015)

Project Consortium:

D'Appolonia

SELC – Applied biology and geology

University of Padova – Department of Biology

The Consortium

D'APPOLONIA

engineering firm providing qualified technical consultancy services to industry, governmental bodies and public administrations at regional, national and international level with over 50 years experience in energy, civil, geotechnical, environmental and structural engineering, risk assessment, health and safety, system engineering

SELC biologia e geologia applicate

For fifteen years of work SELC has developed a comprehensive and growing range of operational and research activities in the environmental field, with specific attention to applied biology and geology, including the conduction of monitoring, surveys and studies on land, lagoon, river and sea, the implementation of measures of morphological requalification, environmental recovery, environmental enginery

Università degli Studi di Padova

The scientific objectives of the Department of Biology encompass most of the fields of modern biology, from the study of the different levels of organisations, to the evolutionary ecology themes. The main areas of investigation active in the department are: Biophysics, Biochemistry, Molecular Biology, Cellular Biology, Genetics, Botany, Microbiology, Zoology, Comparative Anatomy, Physiology, Anthropology, Ecotoxicology, Ecology, Evolutionary Biology and Information and Communication Technology.

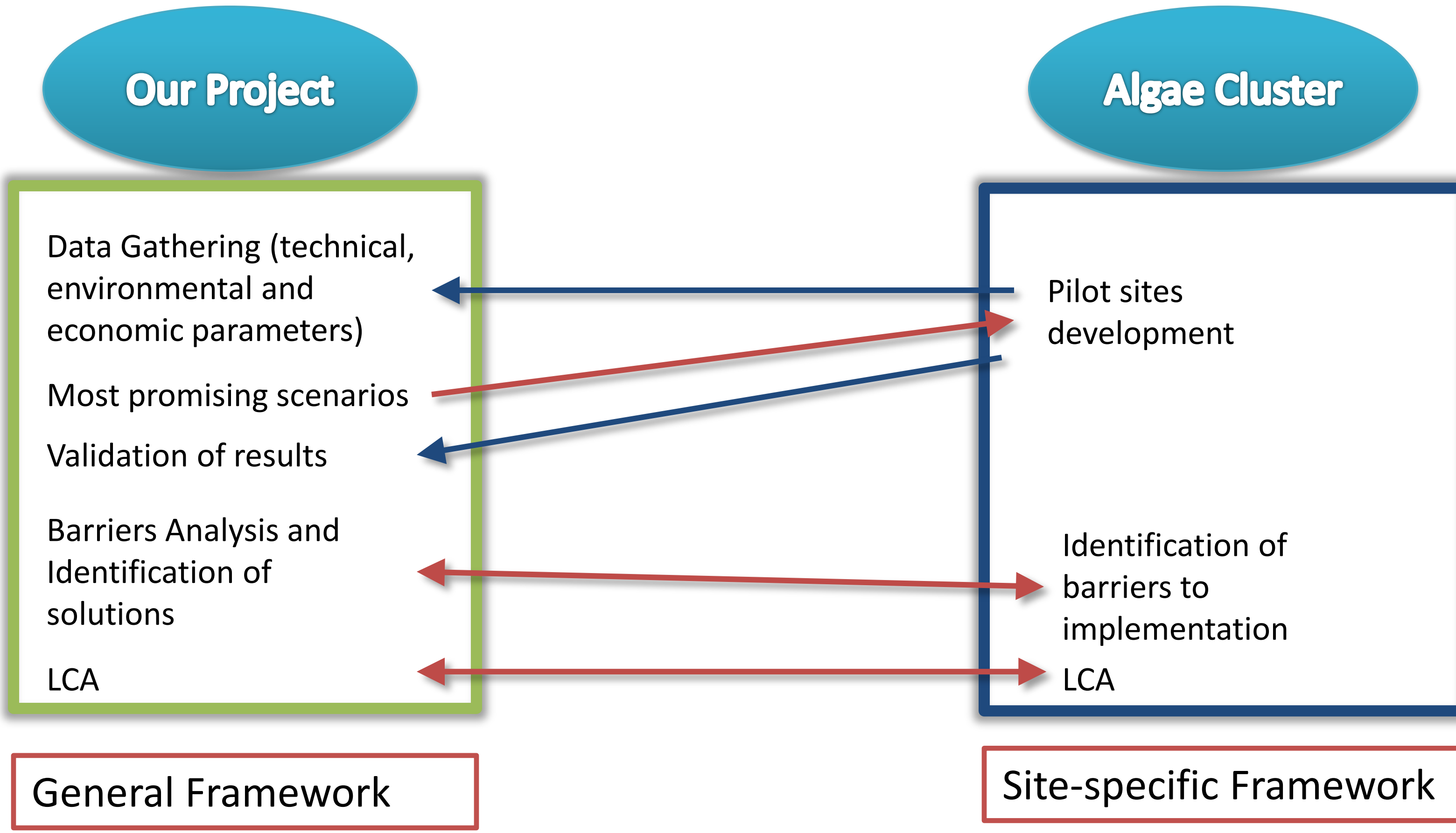
The Project: objectives

General Objective
Scaling up of Algal bioenergy and co-product chains in EU market

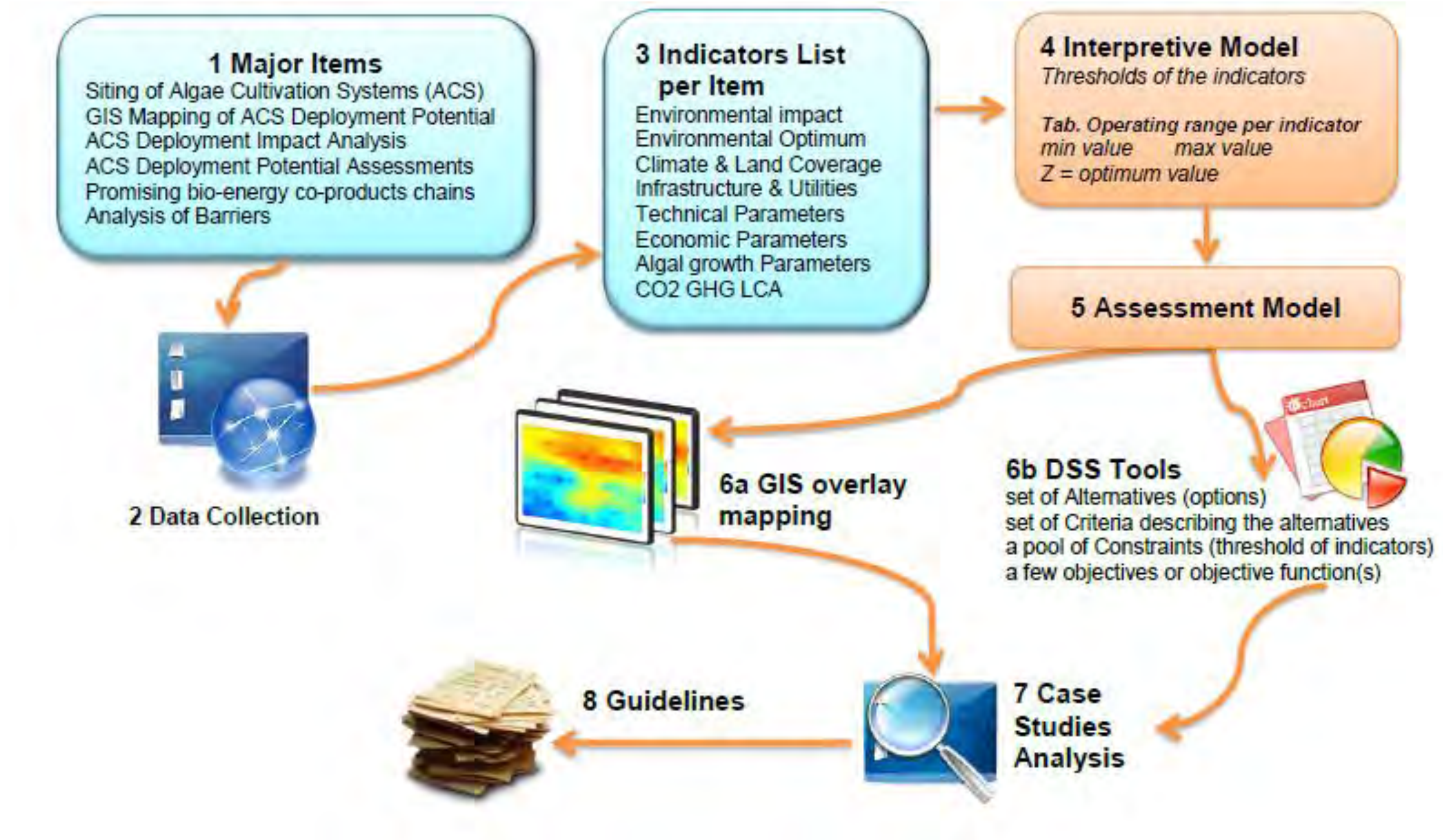
Expected Results
Technical Manual including:

- description and analysis of Algae cultivation systems siting constraints and implications
- technical, environmental & economic analysis of the most promising bio energy production and co-product chains
- identification and analysis of the existing barriers to the deployment
- guidelines addressed to EU, institutions, authorities and private sector
- GIS based Spatial Decision Support System (S-DSS)
- FP7 Pilot Cases Comparative analysis

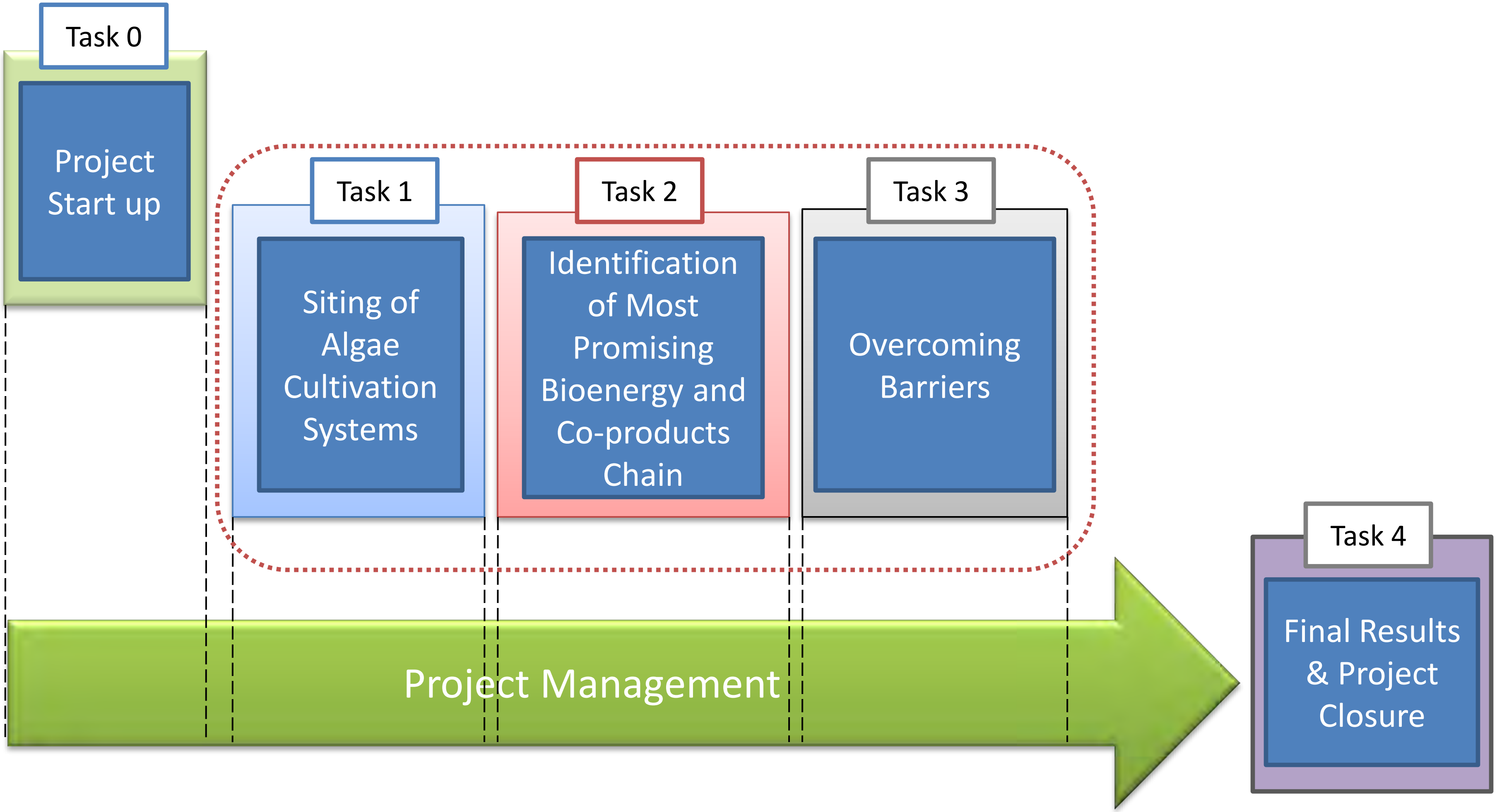
Project & Algae Cluster



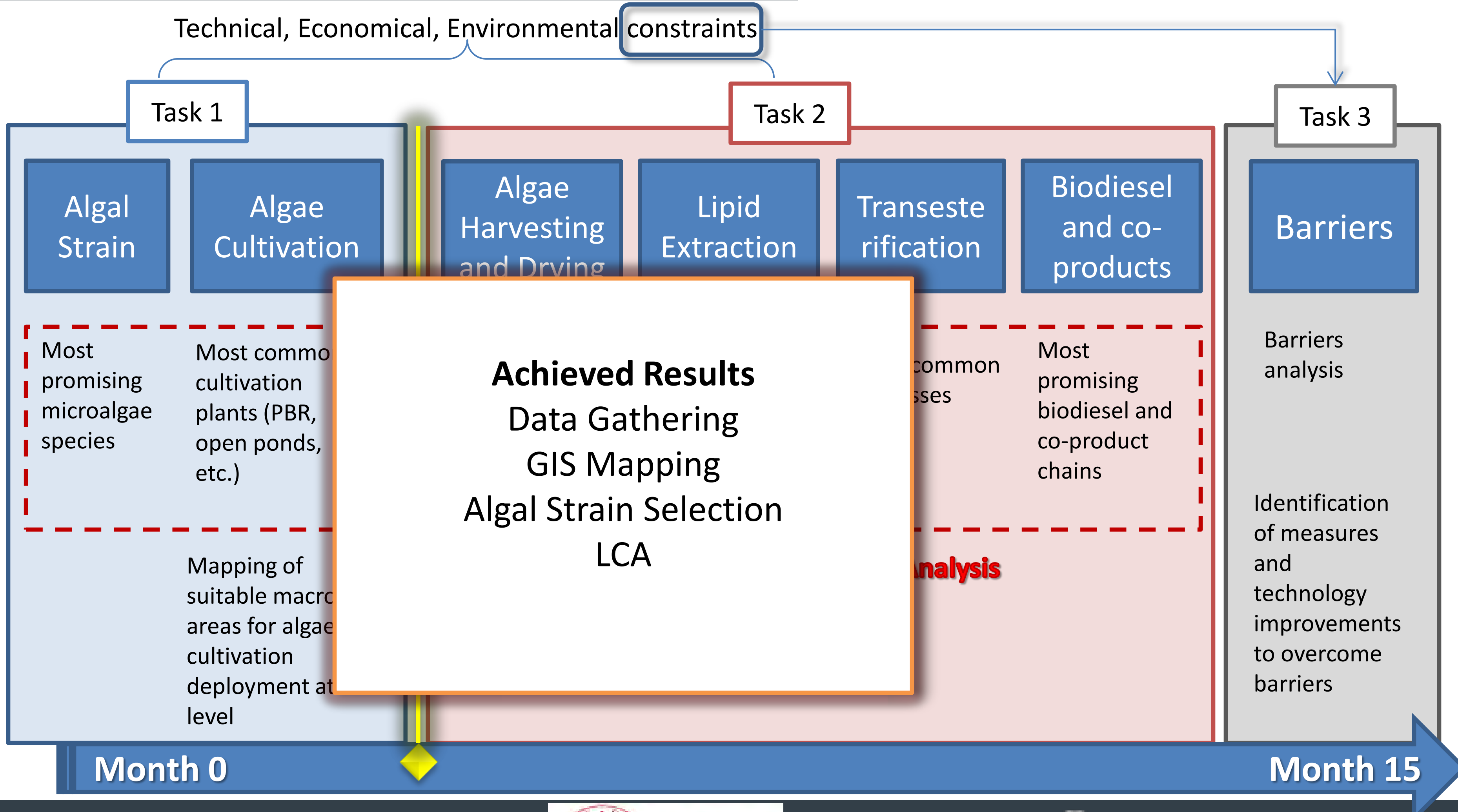
The Project: Methodology Scheme



The Project: Action Plan



Project Layout



SELC biologia e geologia applicate
Università degli Studi di Padova
D'APPOLONIA consulting, design, operation & maintenance engineering

Achieved Results: Data Gathering

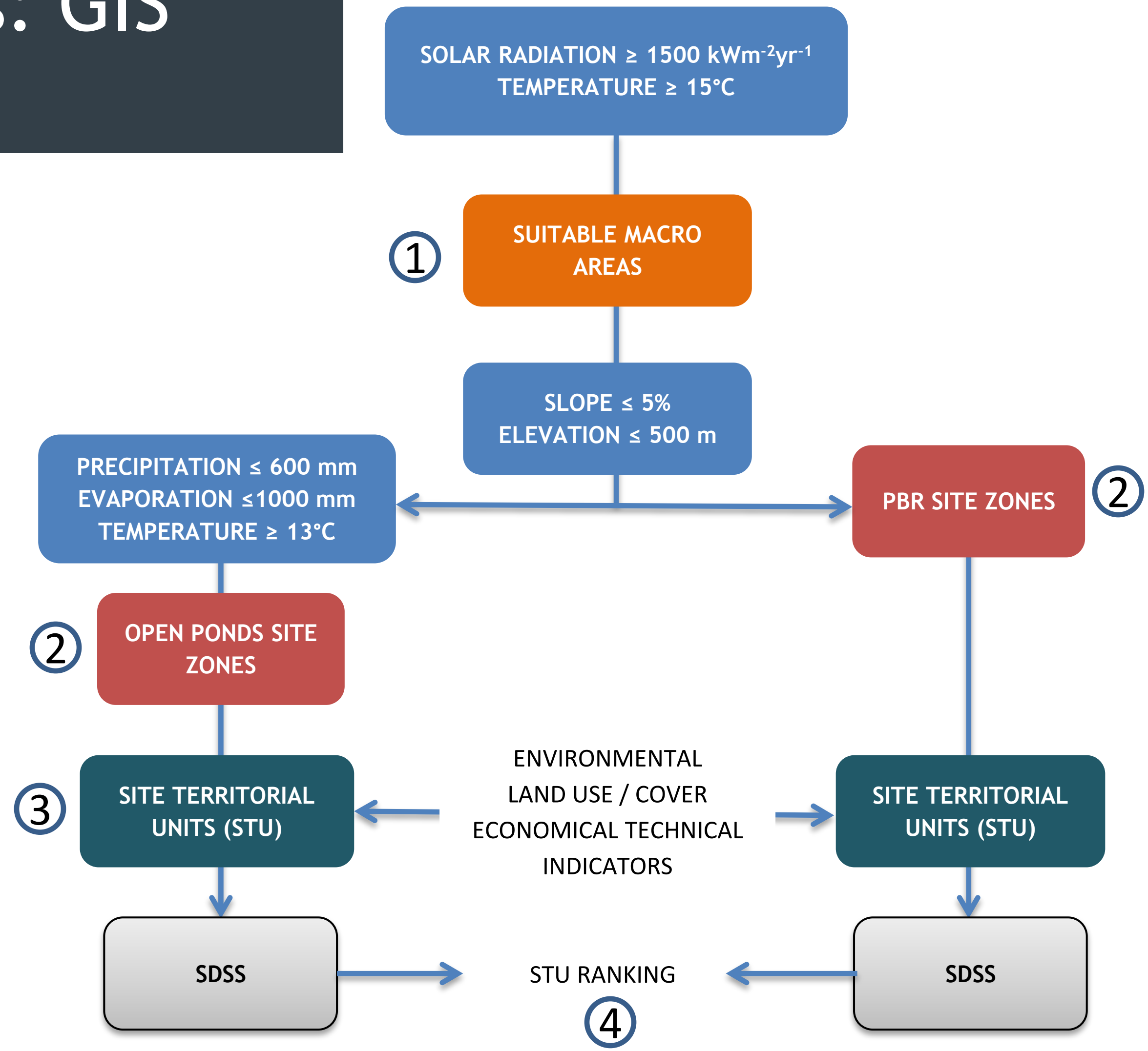
Submission of Checklist to relevant stakeholders and implementers involved in both existing case studies and specific FP7 projects

- *Microalgae Species*
- *Cultivation technologies*
- *Cultivation Environments*
- *Harvesting and dewatering technologies*
- *Extraction techniques*
- *Transesterification*
- *Other steps*
- *Process output*
- *Co-products*
- *Cost performance*
- *Geographical location*
- *Environmental impact*
- *Involved stakeholders*
- *Land coverage constraints*

CATEGORIES	NOTES	DESCRIPTION/VALUE
Microalgae species		Nannochloropsis / Tetraselmis
Taxonomic group		Eustigmatophyte (Nannochloropsis) / Prasinophyceae (Tetraselmis)
Metabolism type	Photoautotrophic, heterotrophic, etc.	Photoautotrophic, heterotrophic
Chemical composition	Lipid content	Lipid content / carbohydrate content
Photosynthetic efficiency [%]		-
Growth rate [g/m2/d]		Project goal:100 ton/ha/year; Comfortable scenario: 80 ton/ha/year
CO2, nutrients, light and water uptake and sources		CO_2 from non-fossil origin
Specific growth requirements	CO2, nutrient, PH, solar radiation, temperature, mixing, etc.	Seawater / low shear stress technologies
Cultivation technologies		
Type and description	Open ponds, tubular PBR, flat plate PBR, fermenters, etc.	Cascade raceways, tubular PBRs and Green Wall panels
Size [m2]		10.000 m^2 total area; 7.000 m^2 production area
Operability conditions and technical parameters	Batch/continuous cultivation, algal concentration [g/l]	2 step cultivation: continuous growth + batch induction
Energy input [kWh/m3]		Estimate: 5,9 kWh/kg dry weight (only for algae production and concentration process), considering project goal productivity

Achieved Results: GIS Mapping

Process for suitable macro-areas, site zones, site territorial units (STU) identification and SDSS application



Achieved Results: GIS Mapping

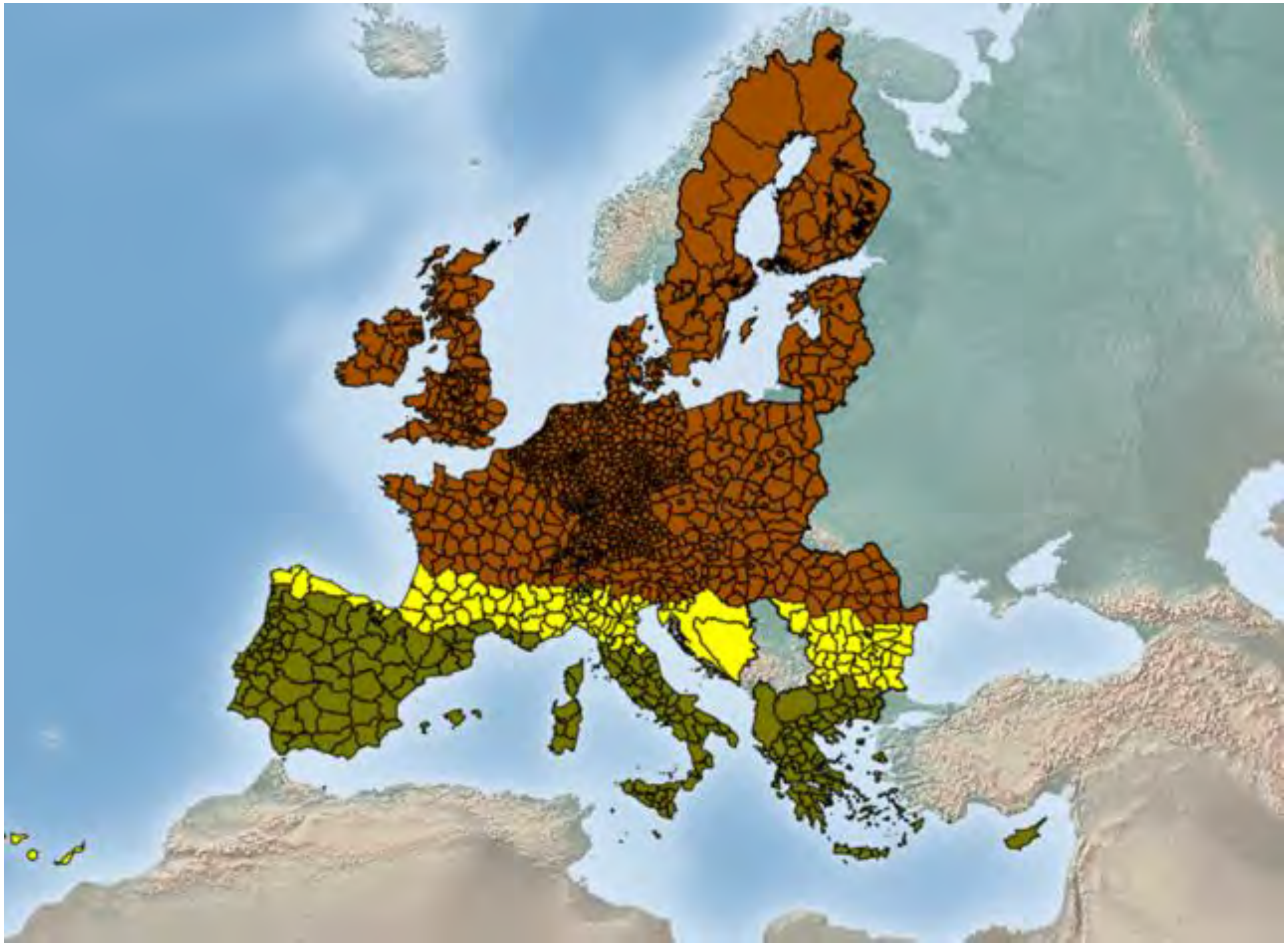
① Macro Areas Suitability Map

- ✓ Solar Radiation ≥ 1500 kW m-2 yr-1
- ✓ Mean annual Air Temperature ≥ 15° C

Suitable

Buffer zone

Non suitable



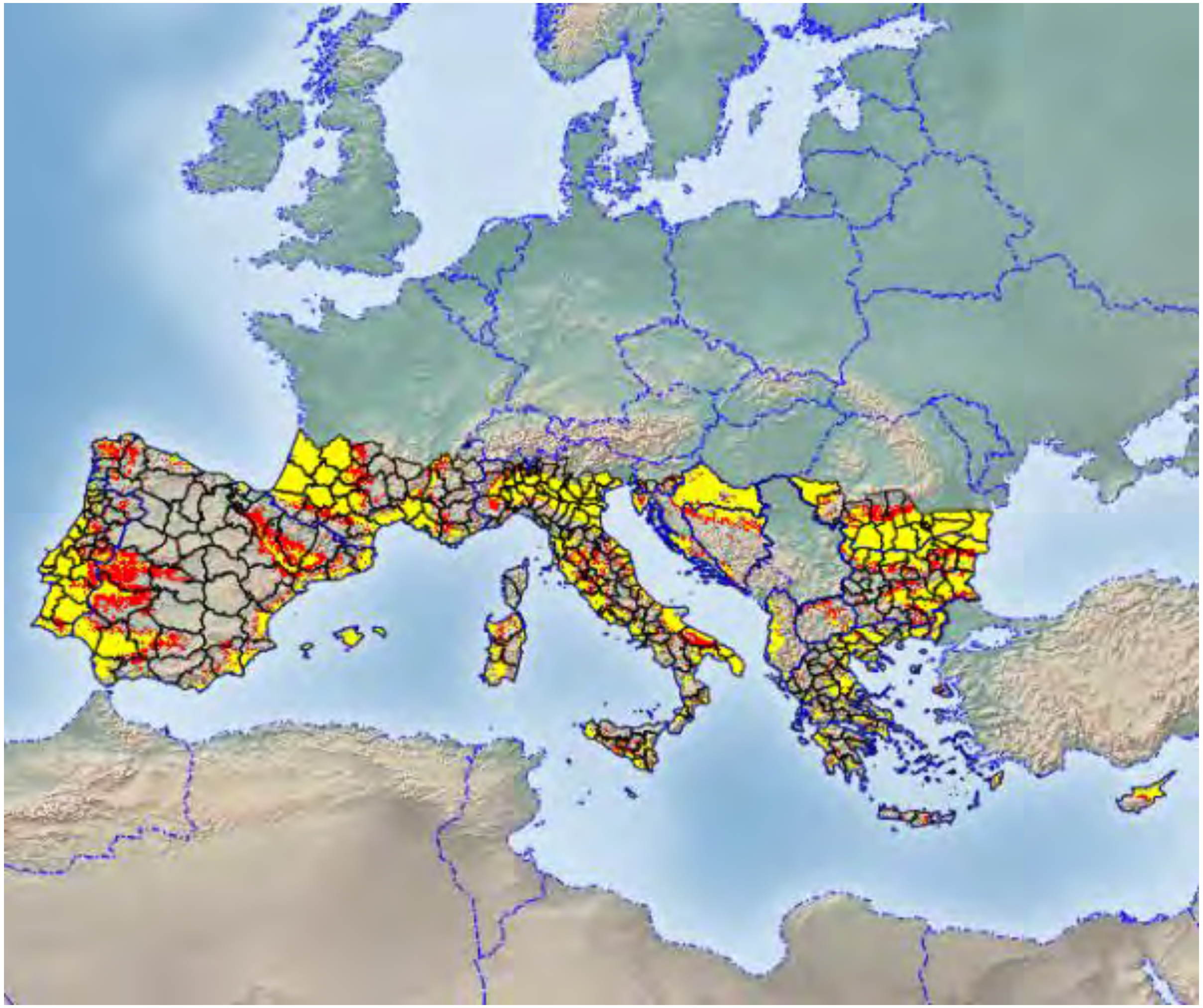
Achieved Results: GIS Mapping

② Suitable Site Zones for PBR plants

- ✓ Slope ≤ 5%
- ✓ Elevation ≤ 500 m

Elevation 300 m – 500 m

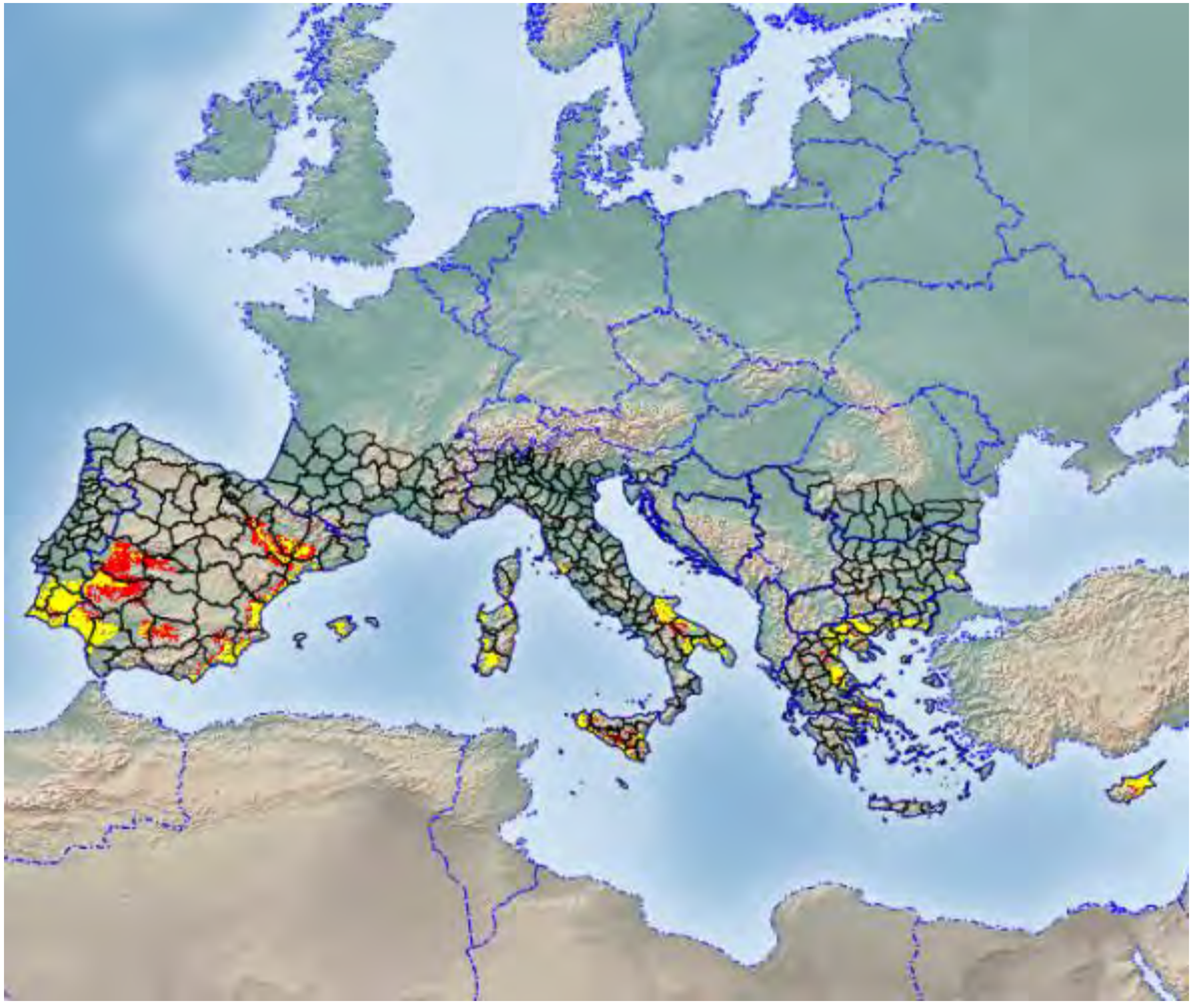
Elevation ≤ 300 m



Achieved Results: GIS Mapping

② Suitable Site Zones for Open Ponds plants

- ✓ Slope ≤ 5%
- ✓ Elevation ≤ 500 m
- ✓ Precipitation ≤ 600 mm
- ✓ Evapotranspiration ≤ 1000 mm
- ✓ Temperature ≥ 13° C

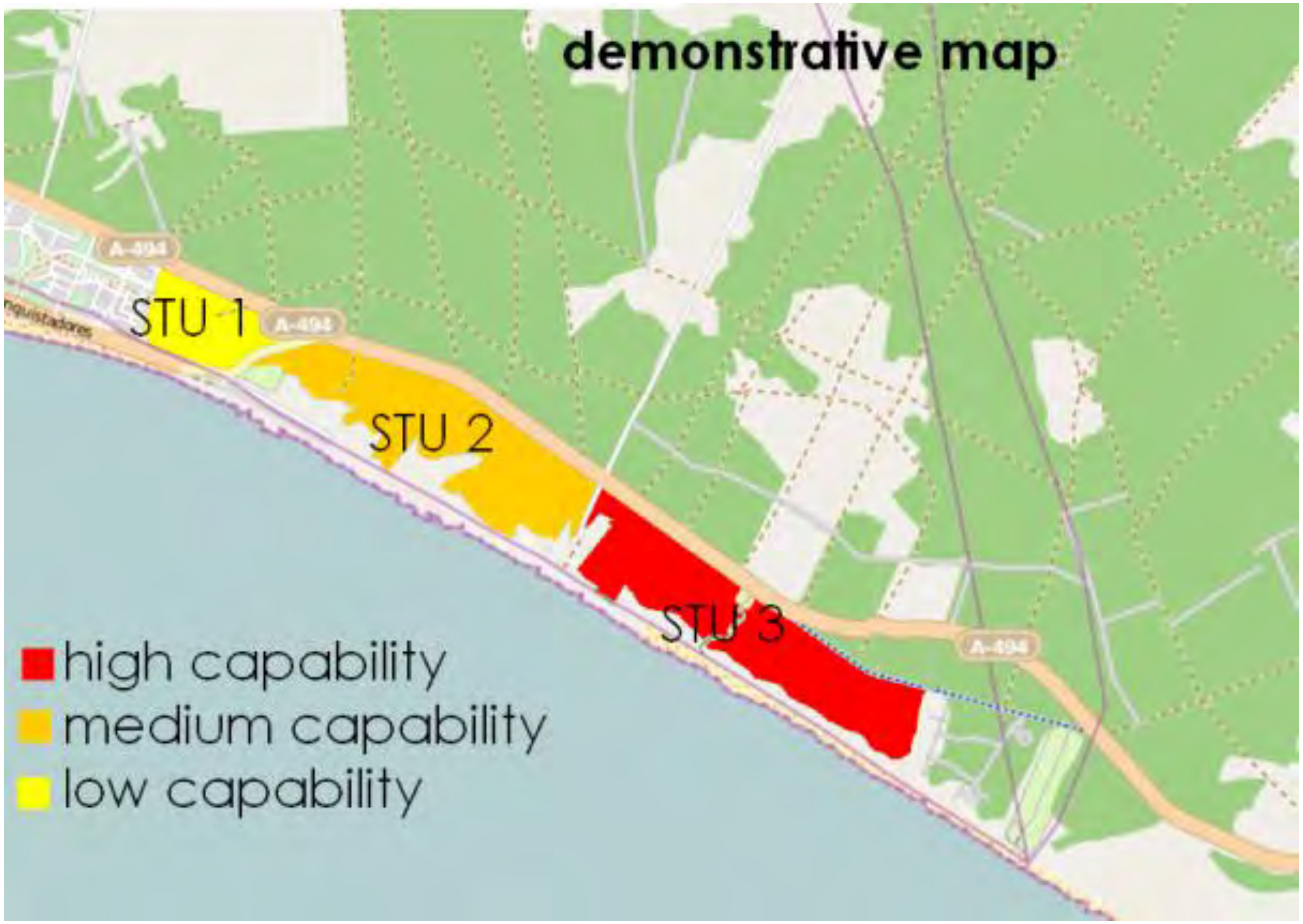


- Elevation 300 m – 500 m (red)
- Elevation ≤ 300 m (yellow)

Next Steps

③ Detection of STU

④ Ranking



Achieved Results: Algal Strains

SPECIES SELECTION - METHODOLOGICAL APPROACH

Data collection:

- available literature (e.g.: media, web, etc.)
- experience of Consortium and the outcomes of already funded completed and ongoing projects (e.g.: FP7 AquaFUELs framework)

Data elaboration:

In the first phase of the project, biological aspects of algae have been considered for species selection, such as:

- Productivity/Growth rate
- Biomass composition
- Resistance to environmental conditions changes (e.g.: Temperature, salinity, pH)
- Co-products
- Different water sources for cultivation (freshwater, seawater and wastewater)

Achieved Results: Algal Strains

SPECIES SELECTION

Data elaboration → about a dozen species have been selected

Some examples:

- Chlorophyta

Neochloris oleoabundans → high lipid content

Scenedesmus spp. → among the faster growing and highest oil producing algae

- Bacillariophyta

Phaeodactylum tricornutum → ease of cultivation and rich oil content

Biological criteria

	Biomass Productivity/ Growth rate	Temperature pH - Salinity	Lipid content	Co-products
Species 1	+	+	-/+	+
Species 2	+	+	+	+
Species 3	+	-/+	+	+
Species 4	+	+	+	+
Species 5	-	-/+	+	+
Species 6	-/+	-	+	+
Species 7	-/+	+	+	+
Species 8	+	+	+	+
Species 9	+	+	+	+
Species 10	+	+	+	+
Species 11	+	+	+	+

Cultivation environments

		Seawater	Seawater + Wastewater	Freshwater	Freshwater + Wastewater
Species 1	S/F	5 [a]	5 [a]	5 [a]	5 [a]
Species 2	S/F	5	5 [f]	5	5 [f]
Species 3	F	-	-	3	(?)
Species 4	F	-	-	5	5 [b]
Species 5	F	-	-	3 [c,d]	3
Species 6	F	-	-	5	(?)
Species 7	S	5	3 [e]	-	-
Species 8	S/F	-	-	5	5 [a]
Species 9	S/F	(?)	(?)	5 [g]	5 [g]
Species 10	S	5	5	-	-
Species 11	S	5	5	-	-

Achieved Results: Algal Strains

SPECIES SELECTION

Barriers:
- Difficulties in obtaining a complete set of data about some species
- Different measure units (e.g.: different methods of productivity measurement)
- Conflicting opinions regarding the suitability of some species for biofuel production

Next Steps:

Practical aspects of biofuel production will be considered, such as:
- Open ponds vs closed photobioreactors
- Harvesting, thickening, dewatering, extraction and purification of microalgae biomass for biofuel production
- Weaknesses of biofuel production (e.g.: contamination with unwanted species)
- Environmental impacts from microalgae cultivation

Life Cycle Assessment

Goal of our LCA
To verify the energy and GHG balance of the process chains

Specific goals
LCA will focus on energy and global warming aspects: IPCC Global Warming Potentials (global warming aspects); Cumulative Energy Demand (energy aspects).
Consistency with the AlgaeCluster approach:
- Overall Methodology
- Functional unit (e.g.: MJ biofuel - kg of dry algae stream)
- Impact categories

Life Cycle Assessment

When LCA in the Project?

- WP 1.3 Cultivation System Deployment Potential Analysis
- WP 2.2 Comparison with Case Studies
- WP 2.3 Bioenergy and Co-Product Chain Deployment Potential Analysis

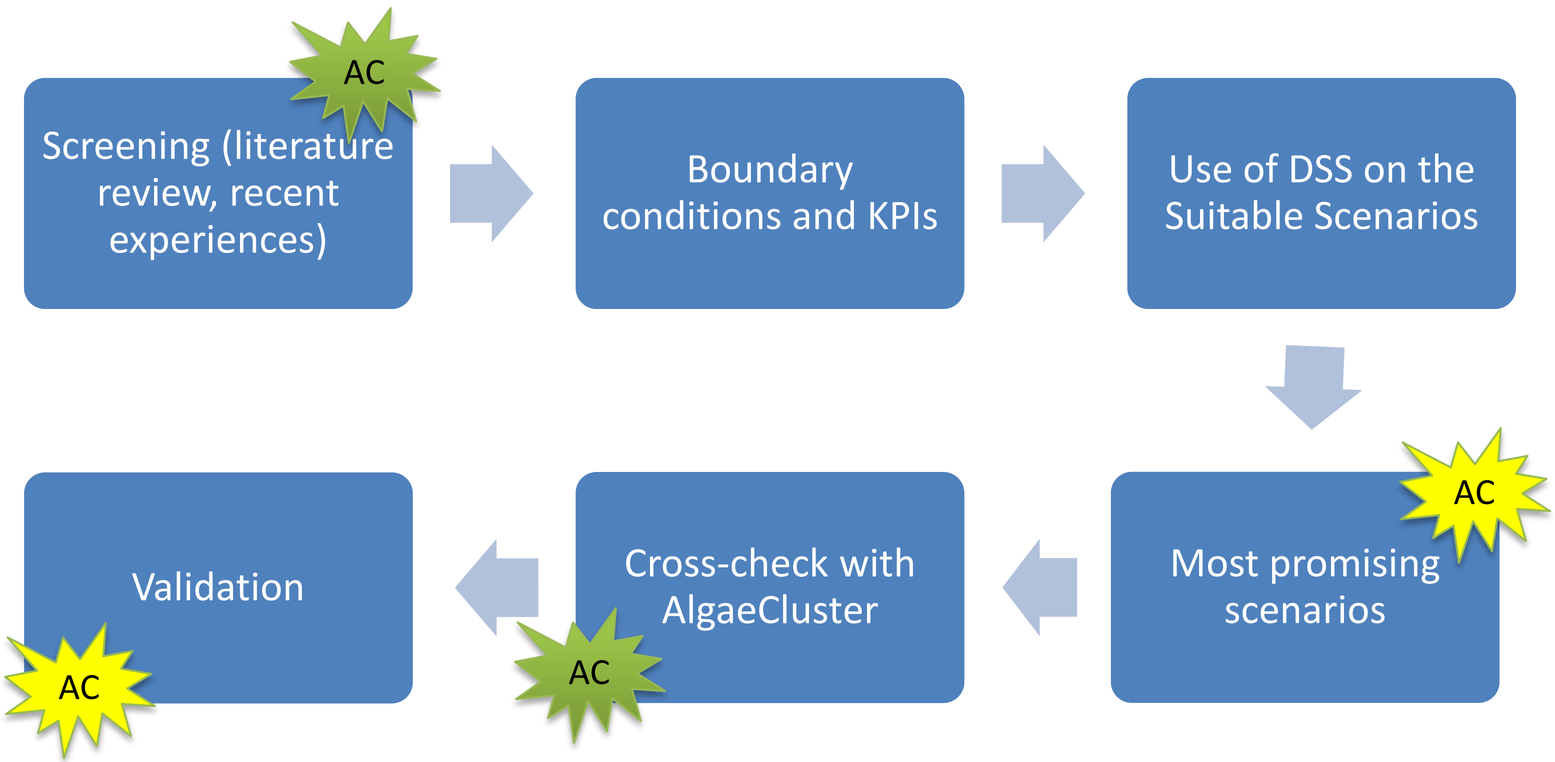
General approach

ISO standards and of JRC methodology and guidelines
EcoInvent database

Interconnections with AlgaeCluster

AC Input from AC

AC Output to AC



Acknowledgements

Thanks to:

SELC – Mr. Daniele Curiel, Mr. Daniele Mion, Mr. François Levarlet, Ms. Chiara Miotti, Mr. Marco Montanari, Mr. Andrea Rismondo

University of Padova – Prof. Fabrizio Bezzo, Prof. Giorgio Giacometti, Ms. Barbara Gris

D'Appolonia – Mr. Lorenzo Facco, Mr. Alessandro Venturin, Ms. Nicoletta Robertelli

Any questions?

Thanks for your attention

RINA 1861 D'APPOLONIA

consulting, design, operation & maintenance engineering

D'APPOLONIA
consulting, design, operation & maintenance engineering

APPENDIX J
ABSTRACT FOR LCA WORKSHOP IN BRUSSELS

Lorenzo Facco, Alessandro Venturin, Giorgio Bonvicini – D'Appolonia (Italy)

Marco Montanari – SELC (Italy)

Fabrizio Bezzo, Barbara Gris – University of Padua, Department of Industrial Engineering (Italy)

3rd European Workshop on LCA for Algal Biofuels and Biomaterials, Brussels, 11 May 2015

"LCA of micro algae production chains from cultivation to biofuel"

Abstract

The European Union (EU) is strongly dependent on fossil fuels for its transport needs and is a net importer of crude oil. At the same time, concerns are increasing about climate change and the potential economic and political impact of peak oil production. To radically cut GHG emissions and reduce dependency on fossil fuels, the EU has adopted measures to encourage the production and use of sustainable biofuels.

Algae-based biofuels are expected to contribute largely to the overall biofuel category, but the production of microalgae has not reached industrial scale development, despite a considerable number of bench scale experiments and relatively small demonstration plants.

The EC is particularly interested in the specific topic and the DG Energy has awarded the Consortium constituted by D'Appolonia, SELC – Biologia e geologia applicate and University of Padua a service contract (ENER/C2/2012/421-1) for a technical assistance on "Algae bioenergy siting, commercial deployment and development analysis", with a duration of 15 months.

In this framework, the experts are assessing the most suitable siting for algae cultivation, the technologies that could lead to commercial algae biofuel production, the deployment potential of bioenergy and co-product chains as well as the overall economic, social and environmental impacts. The target is to identify barriers to the development of algae-based biofuels and a set of guidelines to overcome those barriers, which will be collected in a dedicated technical manual.

After a first data collection including technical, environmental and economic aspects, a GIS based Spatial Decision Support System (S-DSS) was realized to create a high definition suitability map in digital format for optimal site planning of the selected algal cultivation systems in different cultivation environments.

In parallel, the most promising biofuel and co-product chains were identified and analysed. Within this task, production chains were analysed under a Life Cycle Assessment (LCA) perspective, in addition to a technical and an economic assessment.

More in detail, the first round of the analysis focused on the assessment of algae siting, cultivation and harvesting, whereas the second part concerned the assessment of processes bringing from algae to biofuel and co-products. The analysis is concerned with five production chains, from biomass to biofuel and co-products in several combinations of technological choices.

Within the first phase, different cultivation, harvesting, thickening technologies, as well as different sources of water for the cultivation plant were considered. Later, the technologies identified as more promising during the previous phase were considered to build representative case studies for the production chains, by analyzing different technologies for algae cultivation and thickening, bio-oil extraction and biodiesel production.

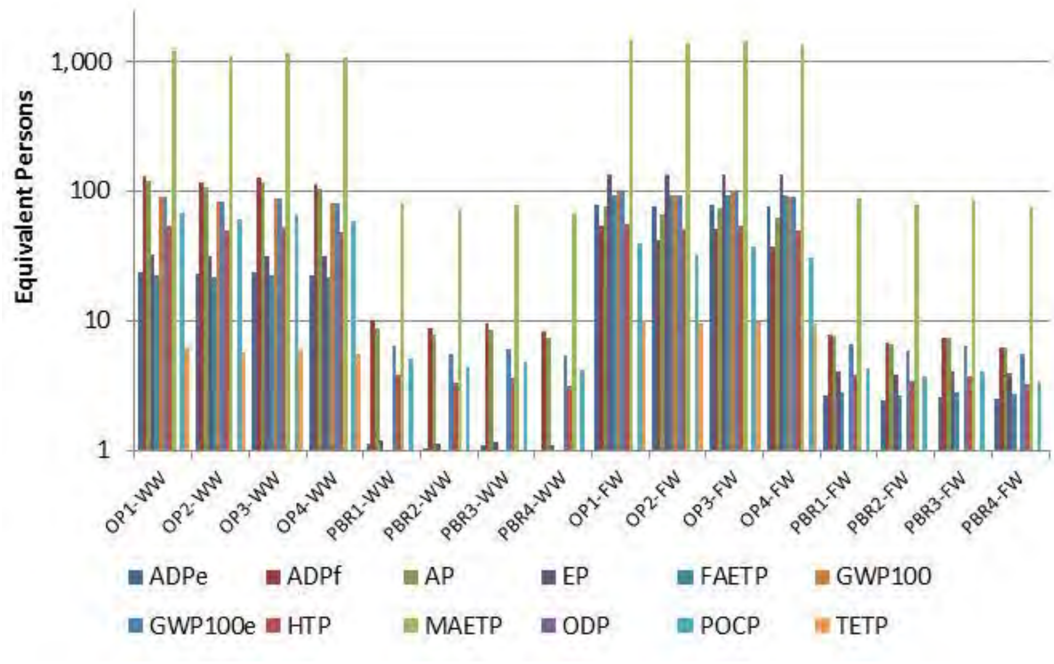
The LCA on the selected case studies was performed using GaBi® software according to a Cradle-to-Grave approach on some of the sub-processes and to a Cradle-to-Gate approach on the remaining ones.

The comparison among the results of the LCAs allowed to identify the main differences among the selected technologies. Thus, different functional units were used: for the first phase, the unit of mass of produced algae was considered, whereas for the second phase the unit of mass of produced biodiesel was considered.

The main results emerging from the LCA are:

- PROs and CONs of PBR and OP,
- identification of the low-impact techniques for harvesting and thickening,
- positive impacts of wastewater in the processes.

An example of our results is the chart below, with of the Comparison of LCA Indicators for OP/PBR Cultivation Systems.



Example of LCA Results

APPENDIX K
SLIDES FROM THE LCA WORKSHOP IN BRUSSELS

LCA of micro algae production chains from cultivation to biofuel

L. Facco, A. Venturin, G. Bonvicini, M. Montanari, F. Bezzo, B. Gris

3rd European Workshop on LCA for Algal Biofuels and Biomaterials,
Brussels, May 11th, 2015

D'APPOLONIA

consulting, design, operation & maintenance engineering

Project Description

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

General Objectives

- Technical Assistance to European Commission – DG Energy
- Scaling up of algal bioenergy and co-product chains in the EU market
- Link to FP7 Projects of the AlgaeCluster

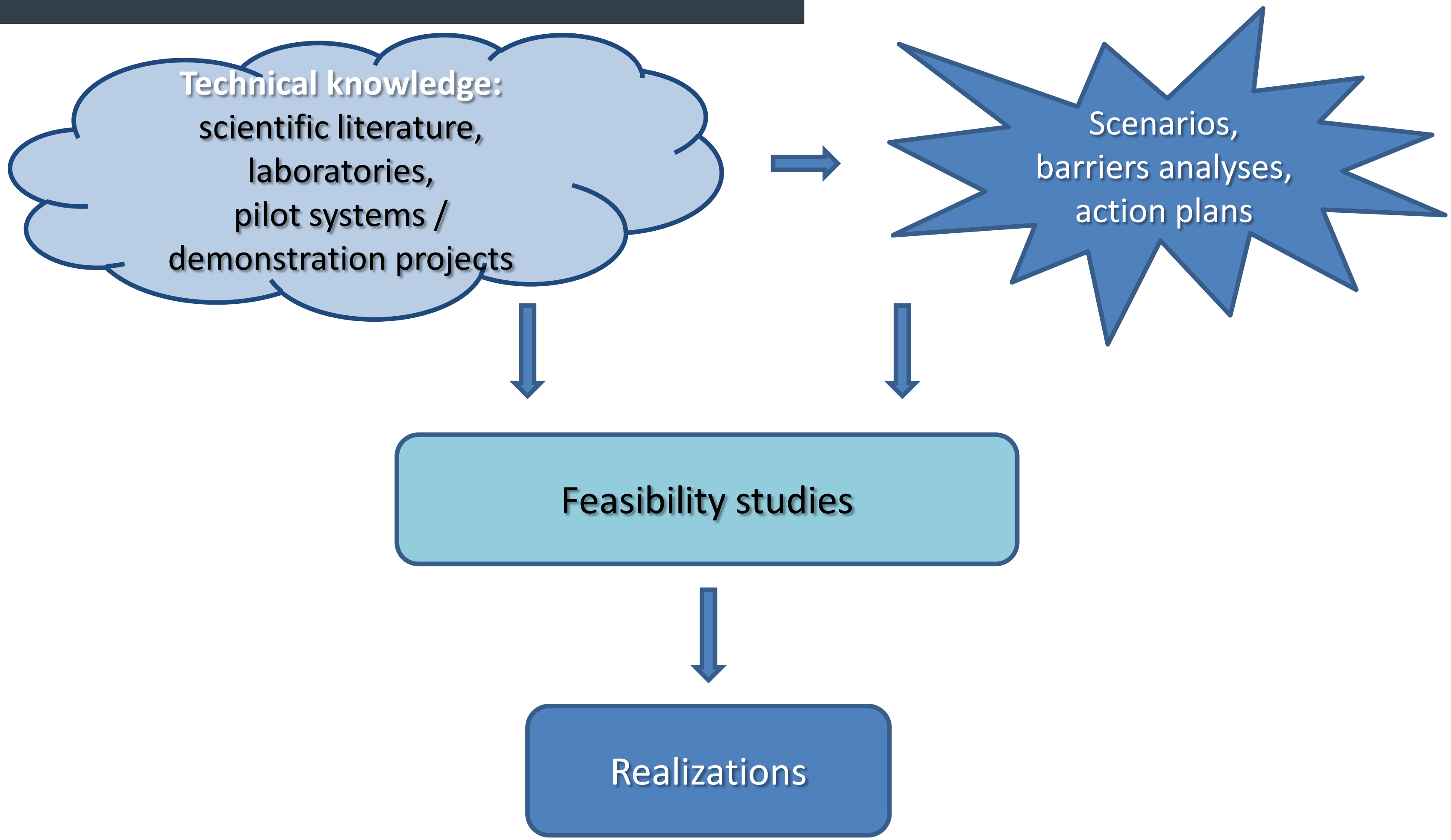
Duration

- 15 months, from January 2014 to April 2015

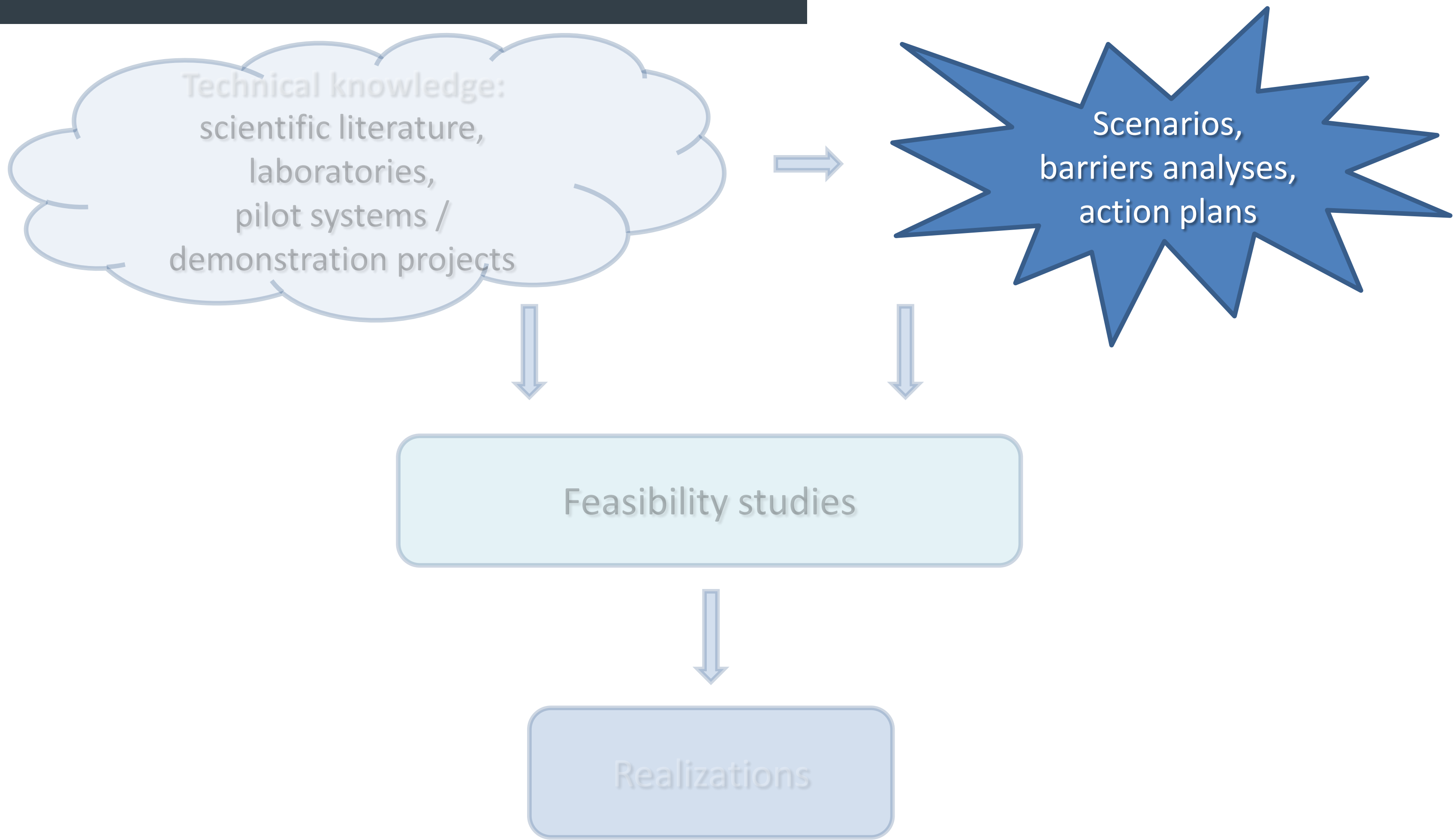
Project Developers

- D'Appolonia
- SELC
- Università degli Studi di Padova

Knowledge Chain



Knowledge Chain



Project Outcome

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

Outcome

Technical Manual including:

- technical, environmental, biologic and economic analysis of the most promising algae cultivation systems and bioenergy/co-product chains
- GIS mapping of algae cultivation systems deployment potential
- analysis of relevant case studies, including pilots being realized within the research projects of the AlgaeCluster
- identification and analysis of the existing barriers
- guidelines to overcome the barriers, addressed to EU, institutions, authorities and private sector

Project Development

Data Collection

- Literature Review
- Data Gathering
- Source of Information

Siting

- Identification of Constraints
- Deployment Potential GIS Mapping
- Cultivation Systems Impacts and Deployment Potential Assessment

Bio Energy & Co Product

- State of the Art
- Indicators and Bio-energy & Co-Products Ranking
- FP7 Case Studies Analysis

Barriers Analysis

- Identification and Analysis of Barriers to Deployment
- Recommendations

Project Development

LCA

Data Collection
- Literature Review
- Data Gathering
- Source of Information

Siting
- Identification of Constraints
- Deployment Potential GIS Mapping
- Cultivation Systems Impacts and Deployment Potential Assessment

Bio Energy & Co Product
- State of the Art
- Indicators and Bio-energy & Co-Products Ranking
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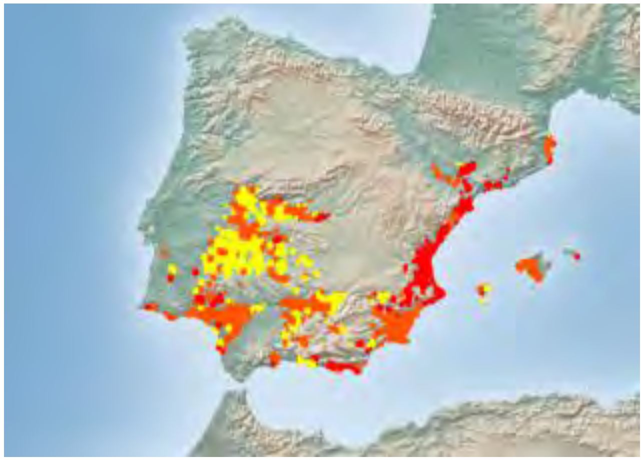
Barriers Analysis
- Identification and Analysis of Barriers to Deployment
- Recommendations

Project Development



GIS siting of algae cultivation systems based on climate, geography, socio-economic indicators:
- Macro Areas – Suitability Maps
- Site Zones
- Site Territorial Units

SWOT analyses of algae cultivation and biofuel / co-product chains based on:
- biology
- technology
- economy
- LCA

PROs and CONs of PBR and OP and of the related biofuel production chains

Project Development

Analysis of Barriers and Recommendations

- cruces for access to market of a specific technology
- barriers to development of algae-based system
- recommendations to overcome the barriers
- action plan

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Technical	Conversion Efficiency Algae-Biofuel: oil extraction and biofuel production rates are very low if compared to the input raw materials.	▲		Selection of the most efficient technology Research for the development of highly innovative technologies. Research for biological advancement toward more efficient algal strains	⚠⚠⚠	◷◷	€€€
Technical	High amount of water needed per functional unit.		▲	Selection of the most efficient technology. Research for the development of highly innovative technologies.	⚠⚠⚠	◷◷	€€€
Technical	The use of wastewater: although promising for the environmental benefits, it raises O&M issues and it is a barrier to the production of some valuable co-products.		▲	Incentives for the investors in plants using WW to solve the technical barriers. Research for improvements in O&M issues to overcome the biological barriers.	⚠⚠	◷◷	€€
Technical	Large cultivation fields are needed		▲	Research for the development of highly innovative technologies.	⚠⚠⚠	◷◷	€€€
Technical	Low biomass productivity	▲		Research for the development of highly innovative technologies and more efficient algal strains.	⚠⚠⚠	◷◷	€€€
Technical	Low compatibility of valuable co-products and algal biofuel		▲	Accurate design to decide the most applicable combinations of product/co-products	⚠⚠	◷	€€

Project Development

Analysis of Barriers and Recommendations

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Technical	The use of wastewater: although promising for the environmental benefits, it raises O&M issues and it is a barrier to the production of some valuable co-products.		▲				
Technical	Large cultivation fields are needed		▲				
Technical	Low biomass productivity	▲					
Technical	Low compatibility of valuable co-products and algal biofuel		▲				

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Technical	Use of bioengineering is necessary for the achievement of the optimal algae strains. This is linked to the barrier of public acceptance.		▲	Research in the biological field of laboratory tests, technological innovation, etc.	⚠⚠	🕒🕒	€€
Technical	No multiproduct plants exist or promise to be valuable	▲		Demonstrative tests are needed to prove the technical and economical viability	⚠	🕒🕒	€€€
Economic	Production costs not competitive with other biofuel production chains (wood, crops) or in reference to the fossil fuel sector	▲		The solution will be mainly a consequence of the technical improvements and of additional public incentives	⚠⚠⚠	🕒🕒	€€€
Economic	Fiscal and economic incentives not favorable to the development of algae production chains		▲	Put higher incentives on biofuel production, transformation and distribution processes. Incentives might be allocated under the form of grants or low-cost loans (to investments in bio fuel algae production chains), tax concession, feed-in-tariffs or premium (which guarantee a minimum price to biofuel from algae supplied on the market) or quotas (e.g., green certificates)	⚠⚠⚠	🕒	€€€

Project Development

Analysis of Barriers and Recommendations

- cruces for access to market of a specific technology
- barriers to development of algae-based system
- recommendations to overcome the barriers
- action plan

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Technical	Large cultivation fields are needed		▲				
Technical	Low biomass productivity	▲					
Technical	Low compatibility of valuable co-products and algal biofuel		▲				

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Economic	Fiscal and economic incentives not favorable to the development of algae production chains		▲				

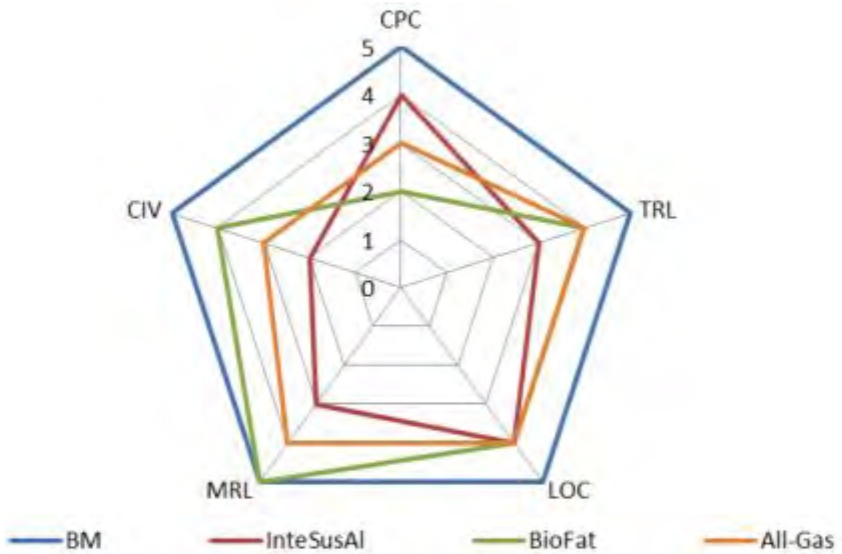
Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Economic	Demand only for high volume of biofuels, which requires important investments in equipment in the start-up phase of the business		▲	Higher economic incentives to investments in biofuel from algae production chain at the start-up stage of plant development	⚠⚠	🕒🕒	€€
Policy and normative background	Uncertain/undefined legal and policy frameworks. Patents and authorizations to start a business are not well defined or are provided at a very high cost for investors		▲	Strengthen the legal framework at European and national levels (defining responsibilities, bodies involved and public authorizations required)	⚠⚠	🕒	€
Public acceptance	Skepticism of the population towards unknown technologies, use of bioengineering and towards highly impacting systems in terms of land occupancy. Diffidence towards land occupancy for industrial purposes vs. agricultural scopes		▲	Consensus building campaigns. Demonstrative projects to prove the reliability and the effectiveness	⚠⚠⚠	🕒🕒🕒	€
Public acceptance	Odors in Open Pond are an issue that can cause "NIMBY" phenomena along with the general skepticism		▲	Stress on research activities. Consensus building campaigns	⚠⚠⚠	🕒🕒🕒	€

Interaction with FP7

Continuous interaction with FP7 projects of the AlgaeCluster

- questionnaire for input data
- review of interim documents
- comparison of LCA approaches
- gap analysis and rating

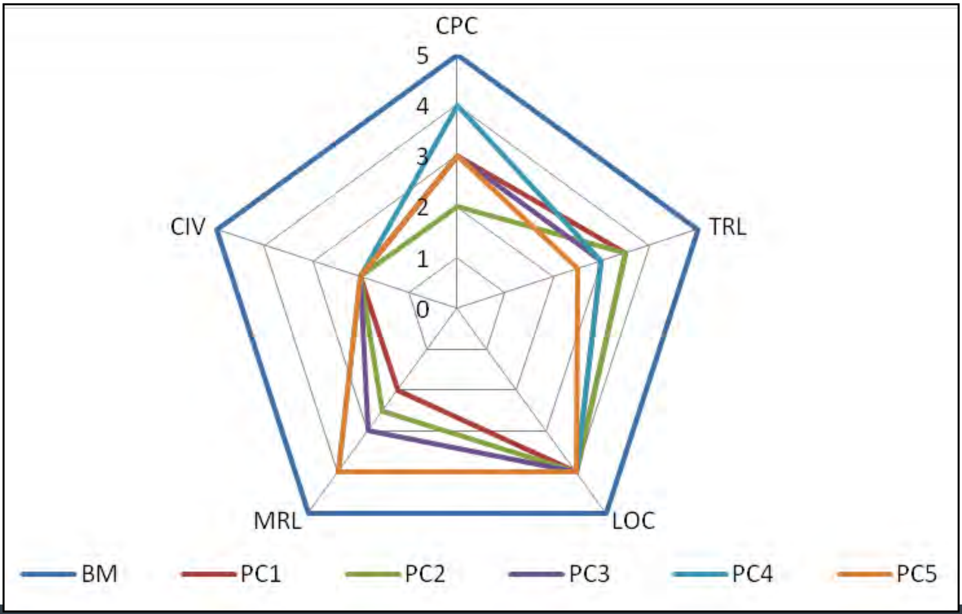
CATEGORIES	NOTES	DESCRIPTION/VALUE
Microalgae species		Fresh water
Taxonomic group		Natural bloom... it means that any mono species culture is promoted in our Raceway ponds.
Metabolism type	Photoautotrophic, heterotrophic, etc.	Photoautotrophic
Chemical composition	Lipid content	Less than 10%
Photosynthetic efficiency [%]		N.A.
Growth rate [g/m2/d]		Average: 25 gr/m2/d (After 18 months of operation)
CO2, nutrients, light and water uptake and sources		Pure CO2, waste water as nutrients source.
Specific growth requirements	CO2, nutrient, PH, solar radiation, temperature, mixing, etc.	
Cultivation technologies		
Type and description	Open ponds, tubular PBR, flat plate PBR, fermenters, etc.	Conventional ponds
Size [m2]		32 m2/unit
Operability conditions and technical parameters	Batch/continuous cultivation, algal concentration [g/l]	Continuous, algal concentration, NA
Energy input [kWh/m3]		To be confirmed



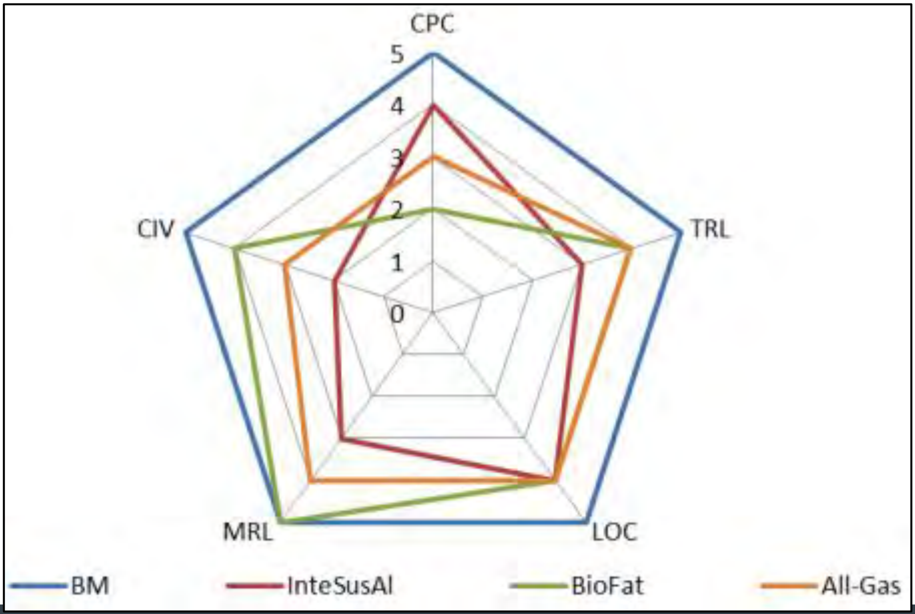
Interaction with FP7

Distance from the market – Gap analysis and rating
Scores assigned to our Production Chains and to FP7 pilot plants

- technologies readiness level and availability (TRL);
- location suitability (LOC);
- competitiveness in production costs (CPC);
- achievement of critical industrial volumes (CIV);
- market readiness level (MRL).



Ratings for the Production Chains



Ratings FP7

LCA approach

Cradle to grave only where possible

- plant construction was not considered
- plants were considered to be installed in a suitable location
- wastewater treatment was included in the analysis
- **input materials at gate**

LCA approach

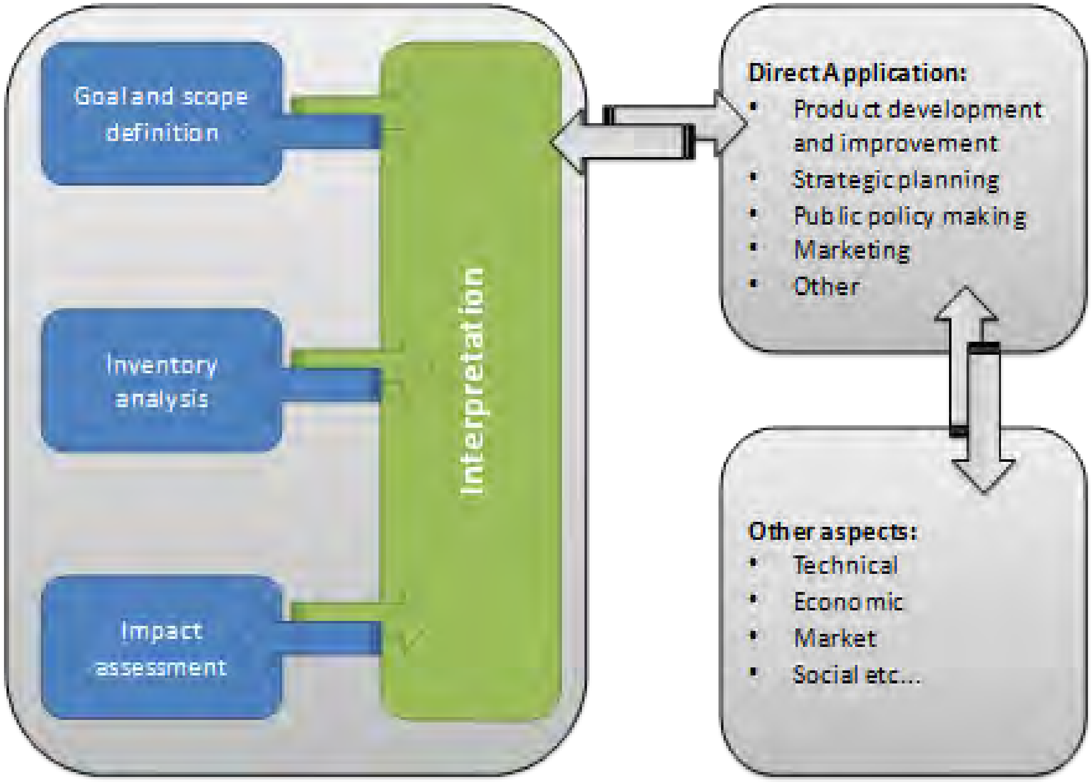
Boundary conditions - IN

- energy consumptions, heat and electricity
- processing of materials
- electricity generation from the mix
- waste
- wastewater treatment

Boundary conditions - OUT

- construction of the facility
- internal transportation
- end users' vehicle engines
- anything after the initial production of the biofuel

LCA Methodology



LCA as much as possible consistent with AlgaeCluster:

- Data from PE International Database (now Thinkstep) analyzed using GaBi®
- Functional unit

1 kg of wet algae - cultivation
1 kg biodiesel – biofuel production

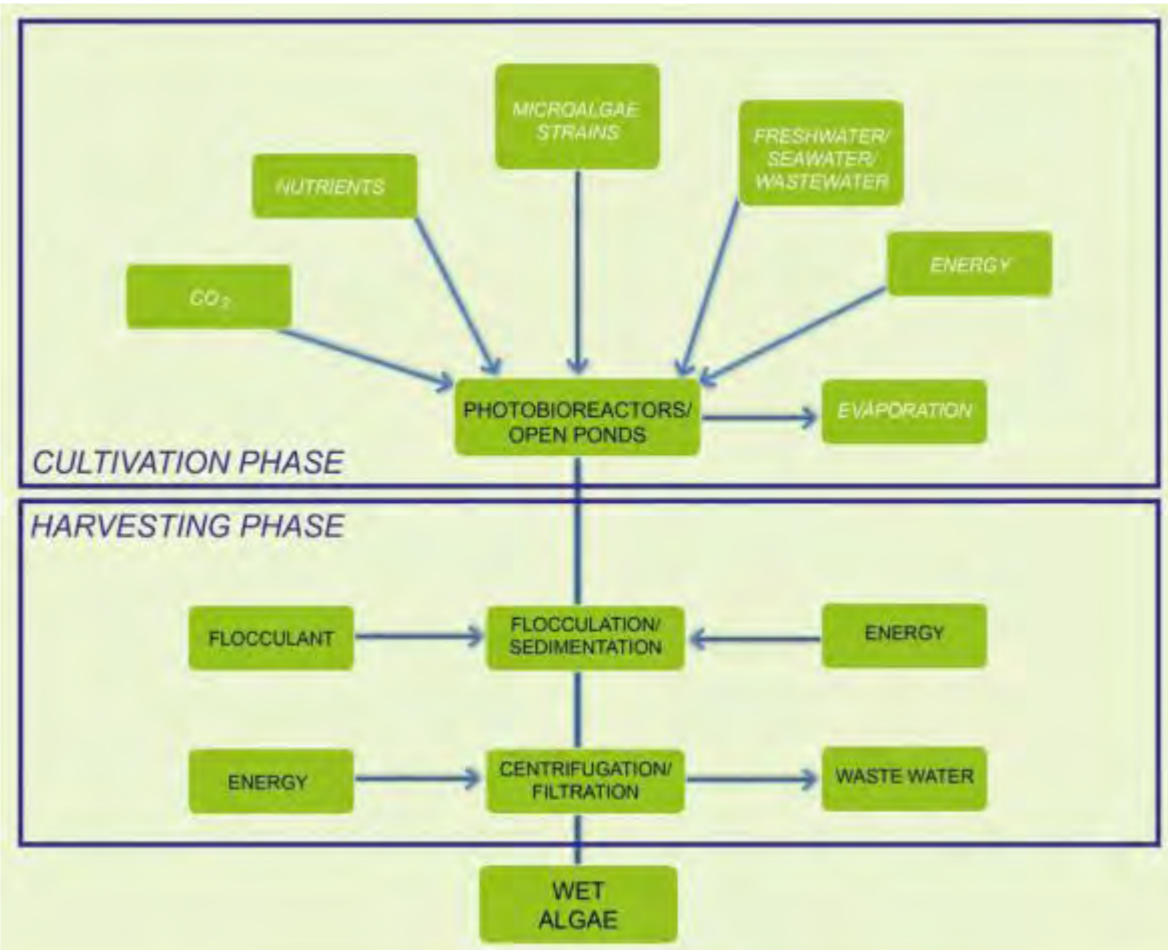
- System boundaries

From cultivation to biofuel

- Impact Assessment Methodologies

CML 2001 + IPCC AR5

LCA of Algae Cultivation



Cultivation phase:
16 case studies

- cultivation: open ponds / photobioreactors
- cultivation medium: freshwater / seawater / wastewater
- harvesting: flocculation / sedimentation
- thickening: centrifugation / filtration
- output: wet algae

LCA Case Studies

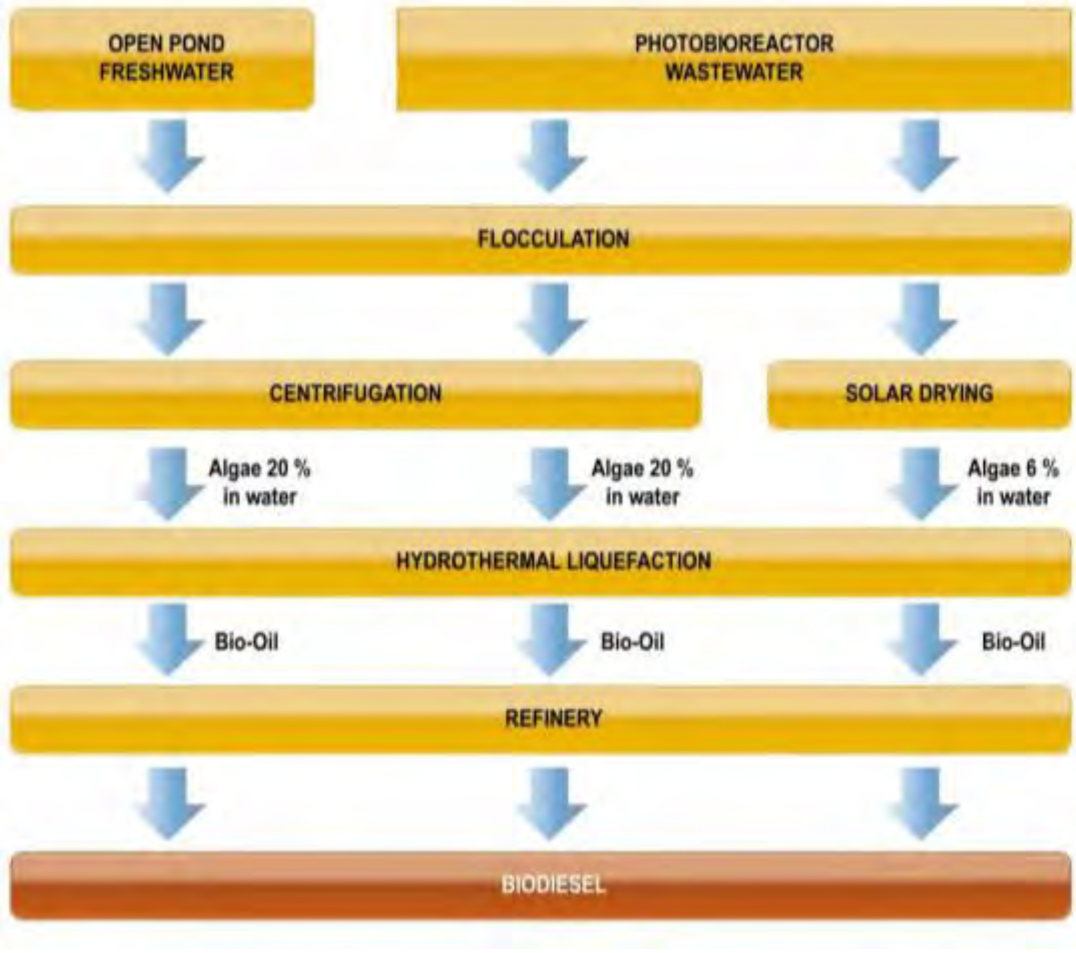
Identification of five production chains:

- PC1 – Biomass Production
- PC2 – Biofuel Production without Co-Products
- PC3 – Biofuel Production without Co-Products but with Environmental Benefits
- PC4 – Biofuel Production with Valuable Co-Products
- PC5 – Multi-Product Approach

It is worth noting that:

- for some PC, several sub-cases exist;
- different PC have different functional units;
- on some PC LCA was not performed due to tangled layout of processes.

LCA of Production Chains



Biofuel / Co-Products Chains

- same approach as cultivation
- alternative use of freshwater or wastewater
- flocculation for harvesting
- centrifugation / solar drying for thickening
- hydrothermal liquefaction and biodiesel production
- output: biodiesel

LCA Reference Data

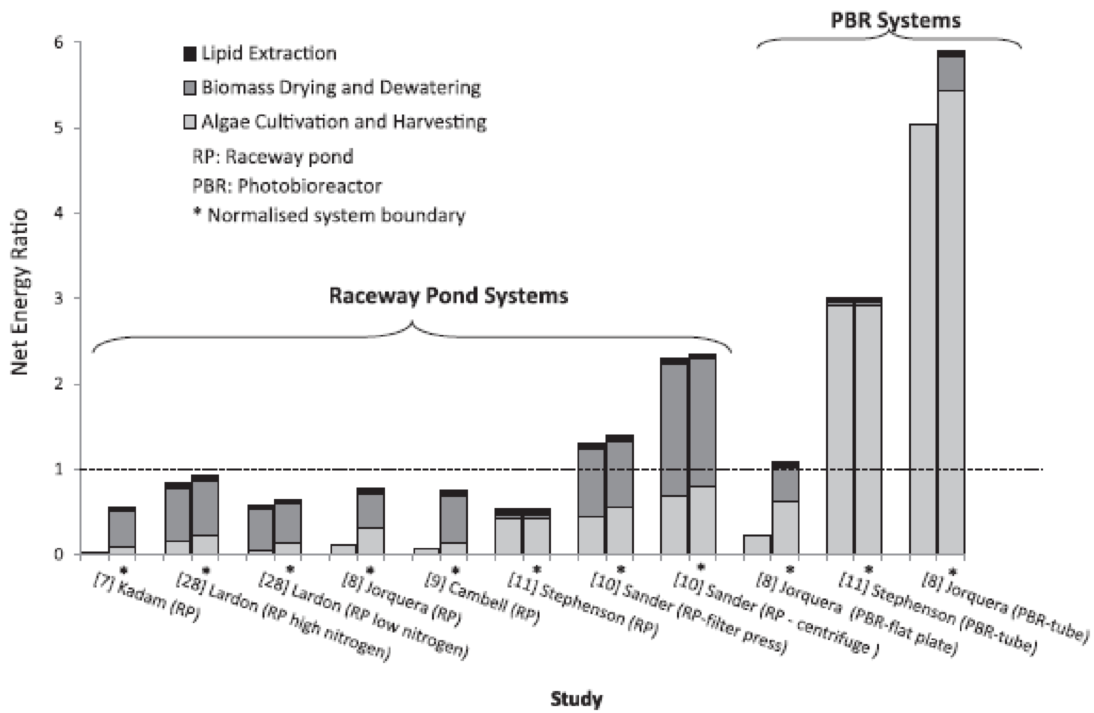
Parameter	1 A	1 B	1 C	2	3 A	3 B
Mass flows [kg]						
Water	900	22.5	22.5	900	22.5	22.5
Carbon dioxide	8.75	2.62	2.62	8.75	2.62	2.62
Fertilizer	0.31	0.31	0.31	0.31	0.31	0.31
Flocculant	0.35	0.35	0.35	0.35	0.35	0.35
Natural gas	-	-	-	0.028	0.028	0.028
Energy flows [kWh]						
Water feeding	0.875	0.025	0.025	0.875	0.025	0.025
Cultivation	0.49	0.015	0.015	0.49	0.015	0.015
Carbon dioxide feeding	0.175	0.050	0.050	0.175	0.050	0.050
Water-algae pumping	0.218	0.025	0.025	0.218	0.025	0.025
Bulk harvesting	0.006	0.006	0.006	0.006	0.006	0.006
Thickening	0.27	0.027	-	0.27	0.027	-
Hydrothermal liquefaction	-	-	-	0.069	0.069	0.069

Uncertainty on real data

- literature studies based on pilot plants
- energy consumption strongly depends on cooling need
- reported net energy ratios (energy consumption / biofuel energy content) range from 0.5 to 6.0

LCA Reference Data

Parameter	1 A	1 B	1 C	2	3 A	3 B
Mass flows [kg]						

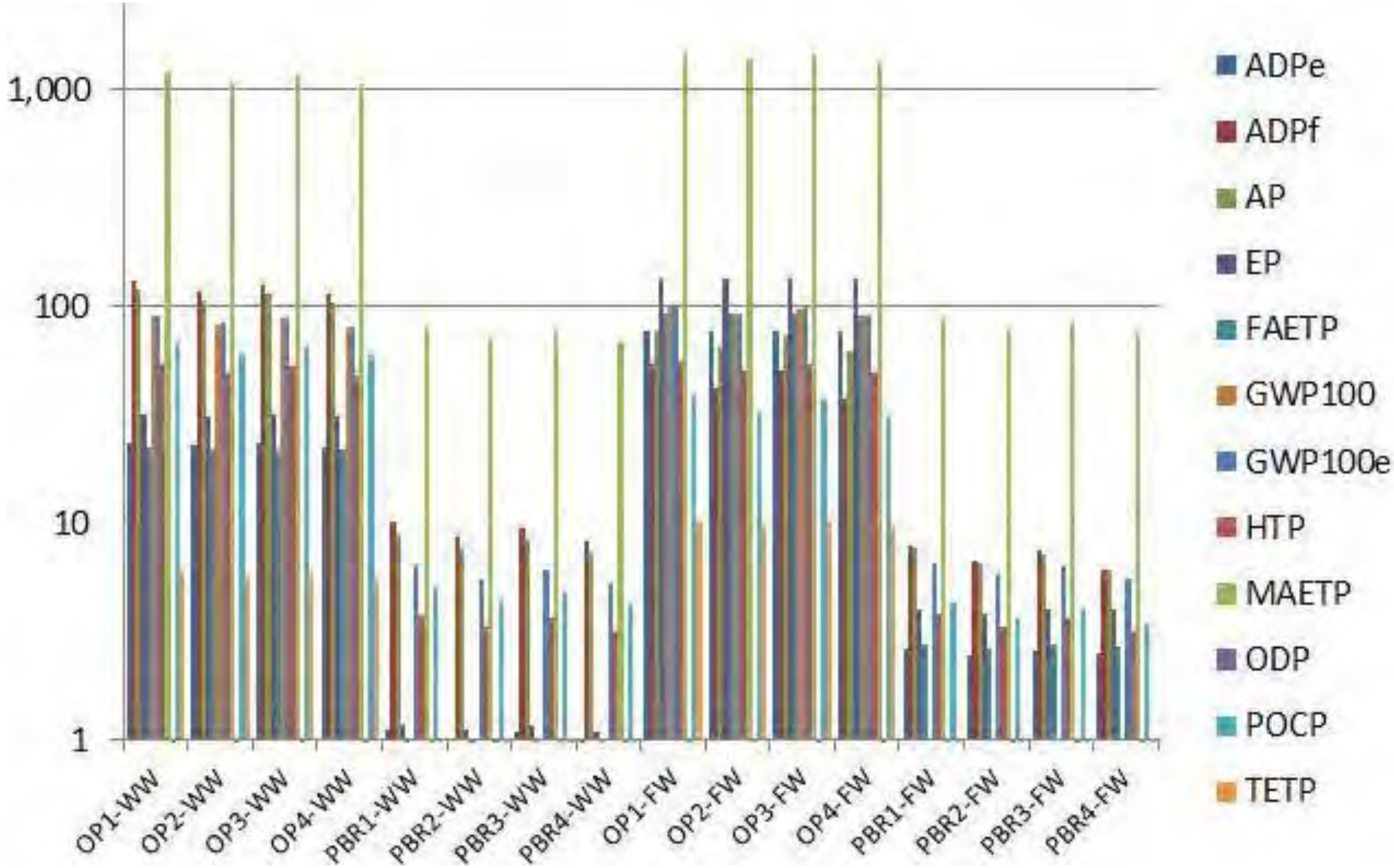


Uncertainty on real data

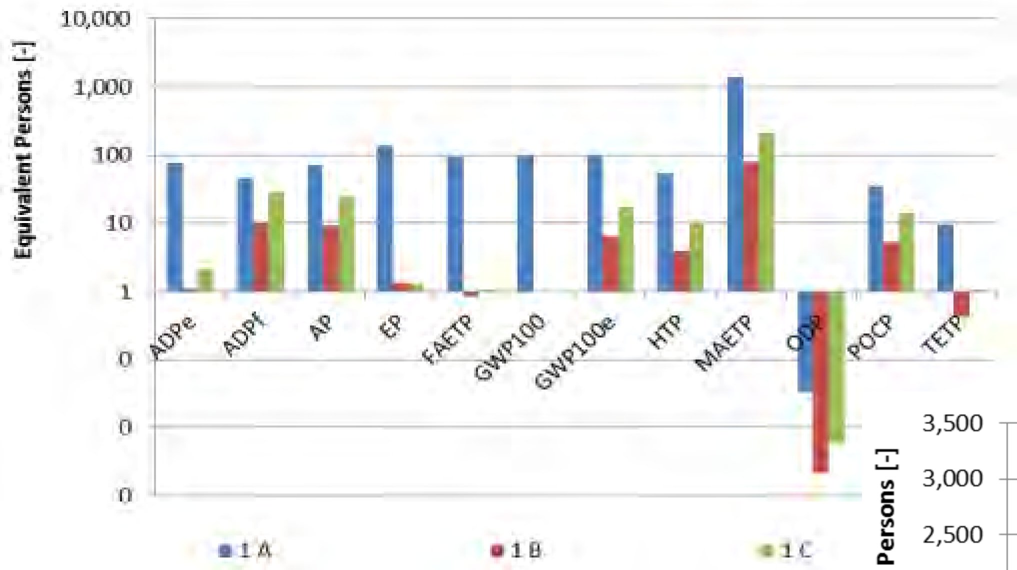
- literature studies based on pilot plants
- energy consumption strongly depends on cooling need
- reported net energy ratios (energy consumption / biofuel energy content) range from 0.5 to 6.0

LCA Results - Cultivation

Figures from the 16 Case Studies



LCA Results - Biofuel



Production Chain 1 - biomass only

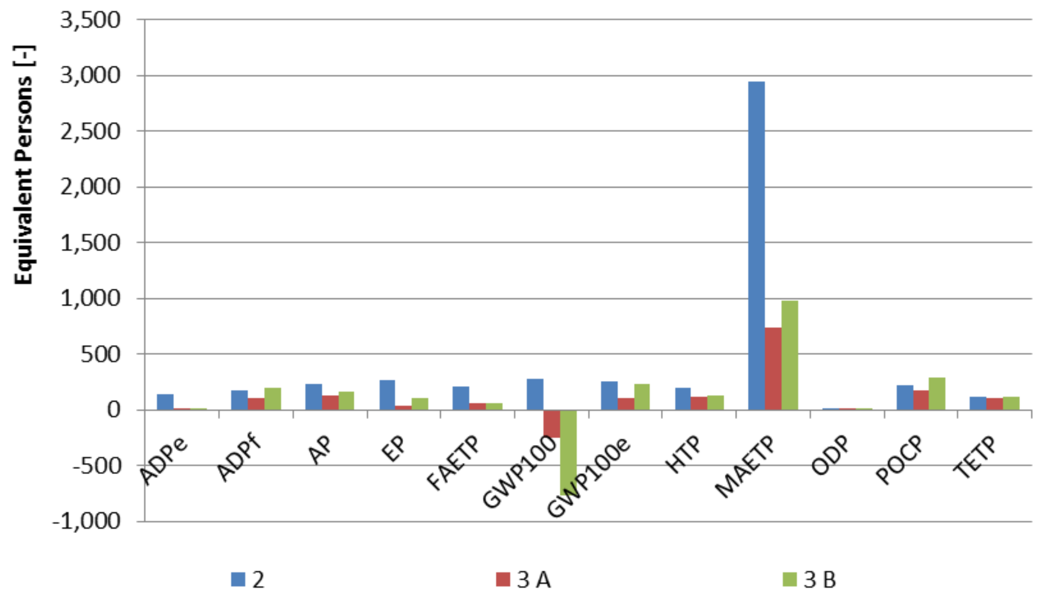
- 1A: OP, FW, Flocc, Centr,
- 1B: PBR, WW, Flocc, Centr
- 1C: PBR, WW, Flocc, Solar Dr

- functional unit: 1 kg of wet algae

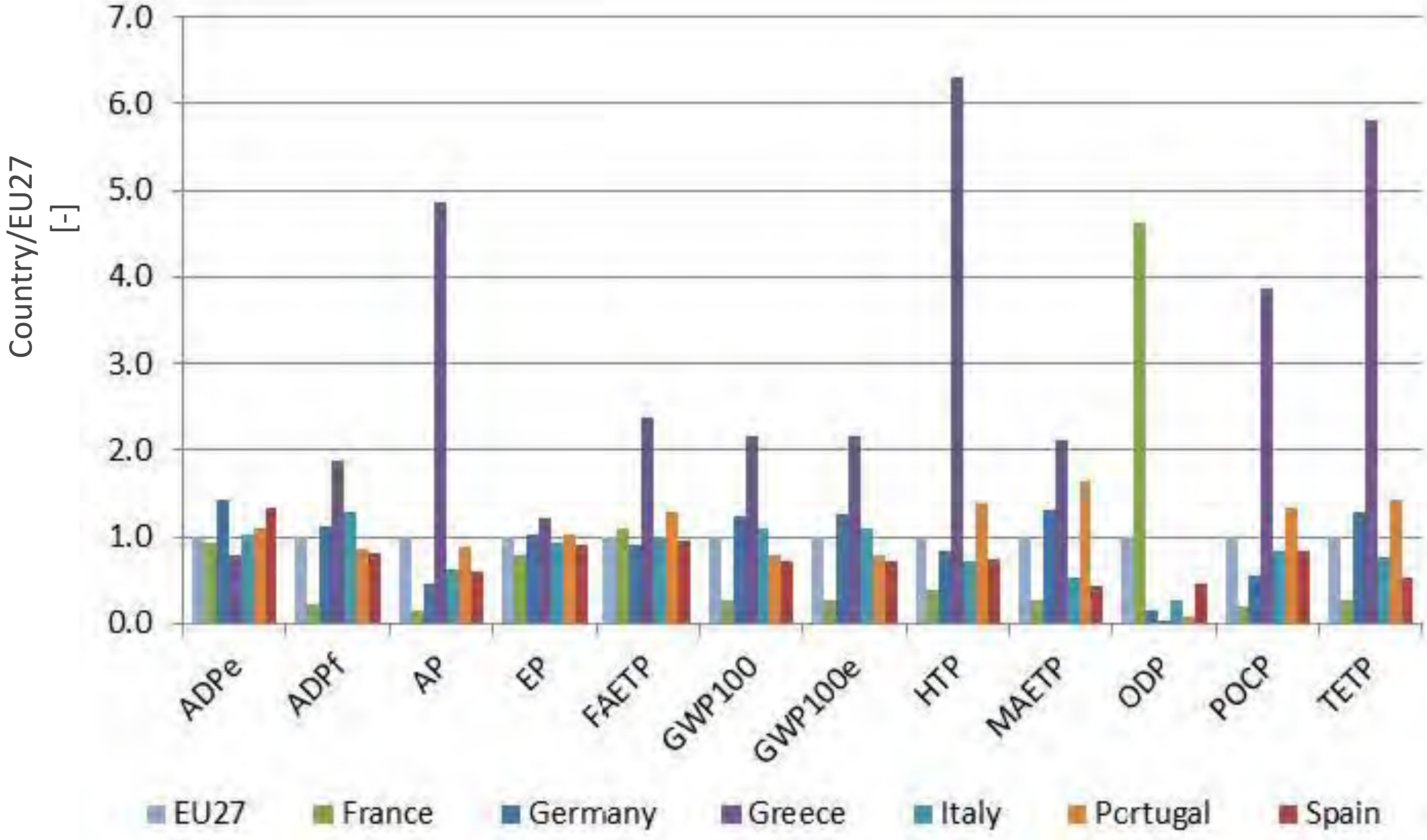
Production Chains 2-3 - biodiesel

- 2: 1A, HTL, biorefinery
- 3A: 1B, HTL, biorefinery
- 3B: 1C, HTL, biorefinery

- functional unit: 1 kg of biodiesel



Sensitivity Analysis



LCA Results

The main results of the LCA study are:

- large uncertainties exist in the input data on resources use
- **real measured data** in demo plants are strongly required
- strong differences from Country to Country, even in the EU
- PBRs seem to have a lower impact than OPs (issue with **cooling**? ☺)
- **economic and energy distance** among different solutions is much larger than the environmental – LCA one
- possible solutions to reduce impact:
    - **optimal siting** of the cultivation plant
    - choice of low-energy harvesting / thickening techniques
    - maximum **wastewater recycling** and use of CO_2 from industry

Conclusions

Besides LCA results, the study allowed to provide useful data to the scientific panorama about:

- suitable algae strains and cultivation plants
- biologic, technologic, economic and environmental aspects of algae cultivation and subsequent biofuel production
- identification of **best suitable areas** for algae-based plants
- gap analysis to assess the **distance from the market** of each production technology
- identification of **barriers**
- **recommendations** and **action plan**

- **The project deliverables are available on the website http://www.algaetofuel.eu**

ALGAE TO FUEL

Thanks for your attention
Any questions?

consulting, design, operation & maintenance engineering

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APPENDIX L
SLIDES FROM THE FINAL EVENT IN BRUSSELS

Algae Bioenergy siting, commercial deployment and development analysis

Project Overview

Final Meeting

Brussels

May 12, 2015

D'Appolonia S.p.A.
AN ISO 9001 AND ISO 14001 CERTIFIED COMPANY
www.dappolonia.it

Algae Bioenergy Siting, Commercial Deployment and Development Analysis

General Objectives

- Technical Assistance to European Commission – DG Energy
- Scaling up of algal bioenergy and co-product chains in the EU market
- Link to FP7 Projects of the AlgaeCluster

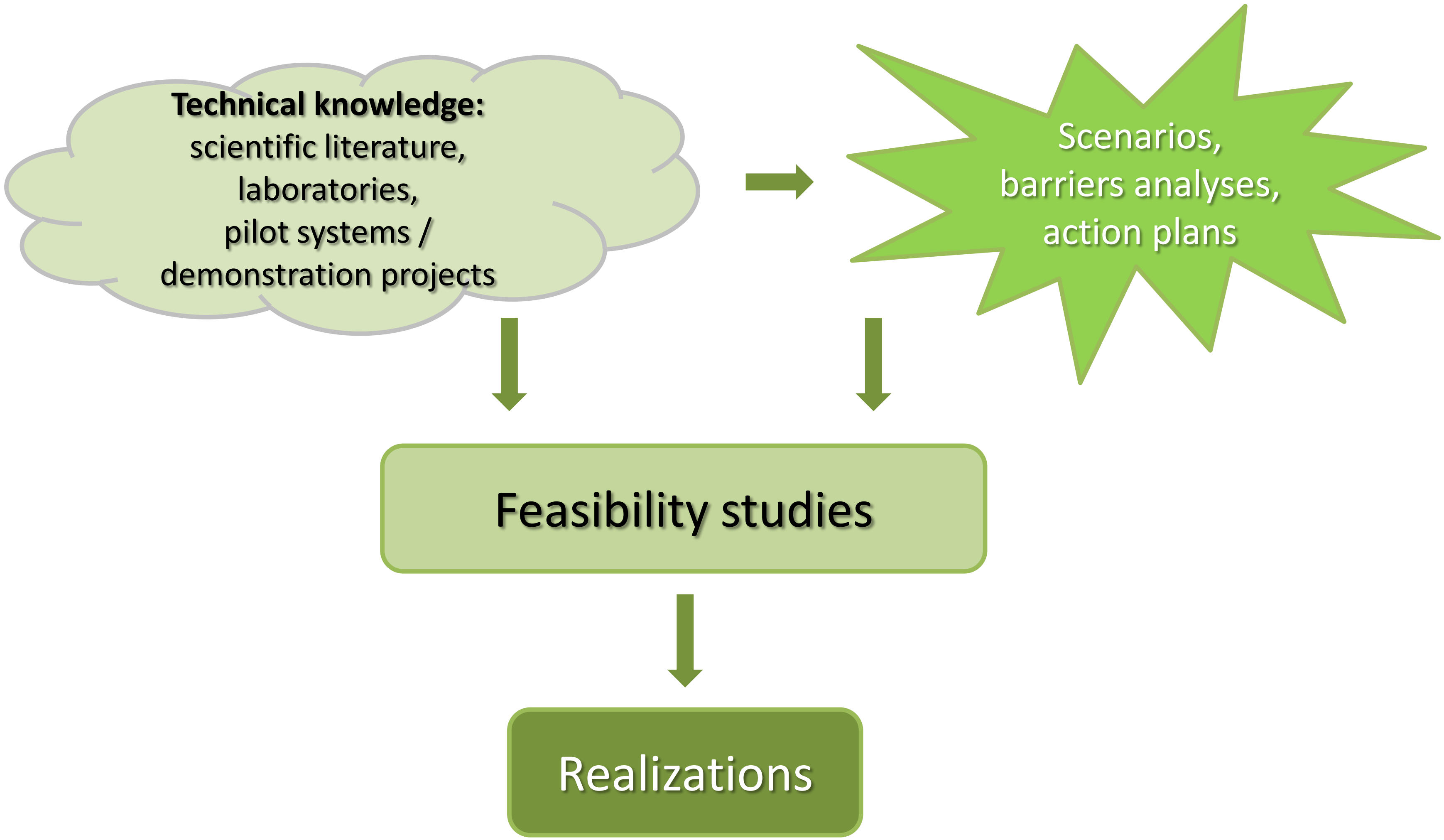
Duration

- 15 months, from January 2014 to April 2015

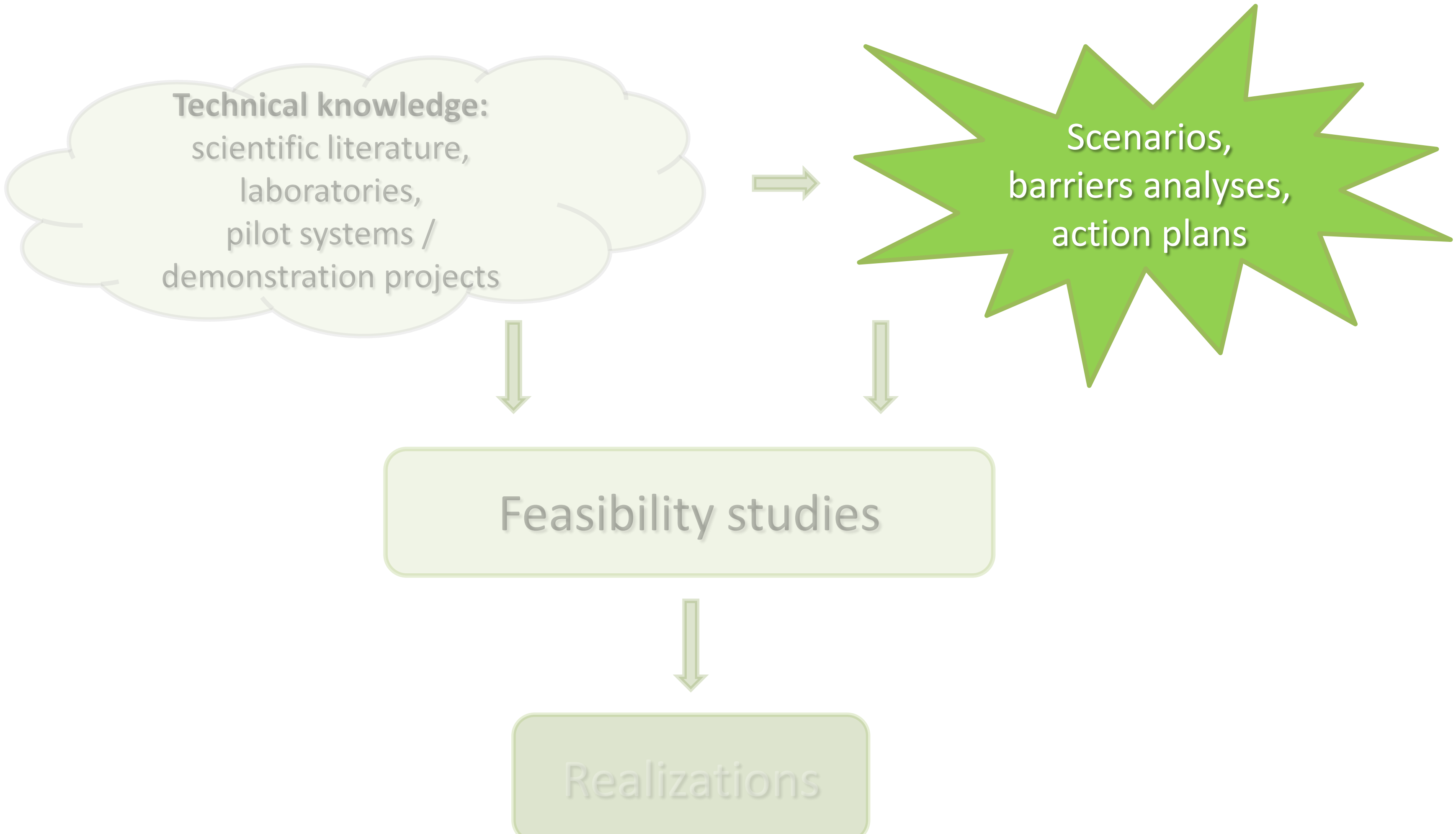
Project Developers

- D'Appolonia
- SELC
- Università degli Studi di Padova

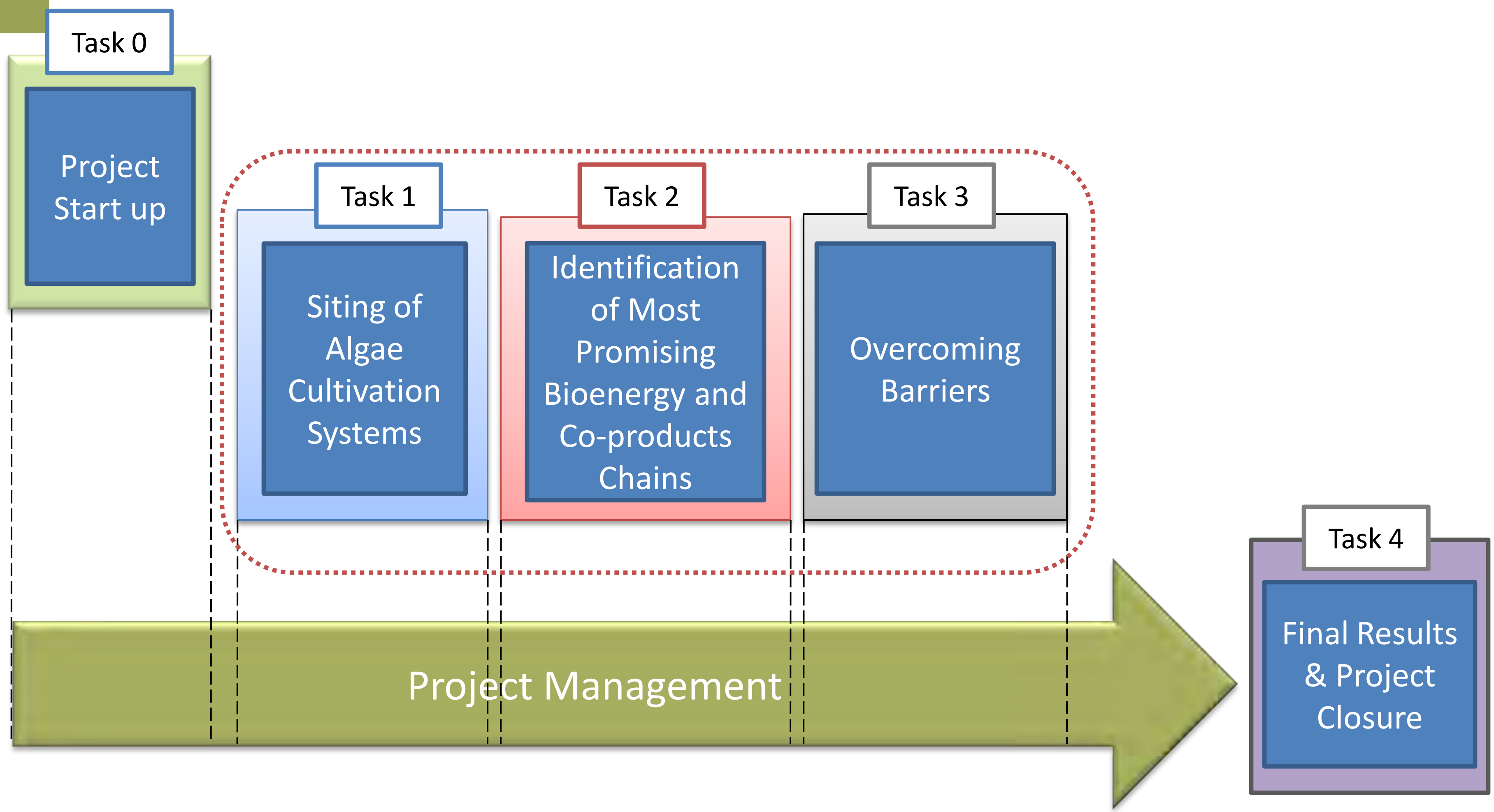
Knowledge Chain



Knowledge Chain



Project Implementation Plan



D'APPOLONIA
consulting, design, operation & maintenance engineering

SELC biologia e geologia applicate

Università degli Studi di Padova

Project Implementation Plan

Technical, Economical, Environmental constraints

Task 1

Siting

Mapping of suitable macro-areas for algae cultivation deployment at EU level

Algae Cultivation

Most promising microalgae species and plants (PBR, open ponds).
SWOT
LCA

Task 2

Production Chains

Most common production chains from cultivation to biofuel and co-products.
SWOT
LCA

Gap Analysis

Distance from the market of our production chains and the pilot plants

Cruces

Most promising biodiesel and co-product chains

Literature Review and Case Studies Analysis

Task 3

Barriers

Barriers analysis

Action Plan

Identification of measures and technology improvements to overcome barriers

Month 0 → Month 15

TASKS IN SHORT

Task 0 – Project Start-up

Establishing the operational work team including representatives of the Consortium members, set the procedures for the internal and external communication and the rules governing the Steering Committee

Task 1 – Siting of Algae Cultivation Systems

Analysis of the most update sectoral literature and the outcomes of the algae cluster FP7 projects to provide in depth assessment of the deployment potential of algae cultivation systems

Task 2 – Identification of Most Promising Bioenergy and Co-product Chains

Benchmark and Multicriteria analysis of the Most promising bioenergy and co-product chains already available as case with focus on economic parameters in the assessment of best practices

Task 3 – Overcoming the Barriers

Analysis of the existing barriers to the development of algal cultivation systems and product and co-product chain, elaboration and assessment of different scenarios to address better solutions for overcoming barriers and setting of the measures, actions and recommendations for the deployment of Algae Cultivation and Bioenergy

Task 4 – Final Wrap Up and Awareness Raising

Organize in a report and present the final outputs and results of the project. Prepare brochure and other promotional material to present to the general public possibility and advantages of Algae Bioenergy and needed steps for implementation

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SELC biologia e geologia applicate
Università degli Studi di Padova

REAL TIME SCHEDULE

TASK Workpackage	Months															
	gen-14	feb-14	mar-14	apr-14	mag-14	giu-14	lug-14	ago-14	set-14	ott-14	nov-14	dic-14	gen-15	feb-15	mar-15	apr-15
Task 0 – Project Start Up																
WP 0.1: Team Mobilization and Organization	M1 09/01/20	D 0.1 D.0.2														
WP 0.2: Stakeholders' Engagement		D.0.3														
WP 0.3 Data Collection			D.0.4													
Task 1 – Siting of Algae Cultivation Systems																
WP 1.1: GIS Mapping of Algae Cultivation Systems Deployment Potential						D.1.1-1.3 D.1.4										
WP 1.2: Algae Cultivation System Deployment Impact Analysis									D.1.5 D.1.6 D.1.7							
WP 1.3 Algae Cultivation System Deployment Potential Analysis										D.1.8						
Task 2 – Identification of Most Promising Bioenergy and Co-Product Chain																
WP 2.1: Bioenergy and Co-Product Chain Analysis										D.2.1						
WP 2.2: Case Studies										D.2.2						
WP2.3: Bioenergy and Co-Product Chain Deployment Potential Analysis												D.2.3				
Task 3 – Overcoming the Barriers																
WP 3.1: Barriers Analysis													D.3.1			
WP 3.2: Algae Cultivation and Bioenergy Deployment Action Plan															D.3.2	
Task 4 – Final Wrap Up And Awareness Raising																
WP 4.1: Final Report																D.4.1
WP 4.2: Final Workshop																D.4.2
WP 4.3: Dissemination Activities				D.4.3				D.4.4				D.4.5				D.4.6
Task 5 – Project Management																
Report		R.1					R.2							R.3		
Meeting	M1 09/01/20			M2?										M3		M4
Steering Committe				SC.1			SC2					SC.3				SC.4

PILLARS

Technical analyses of four domains:

- technologies
- environment
- biology
- economics

Key Experts for the domains:

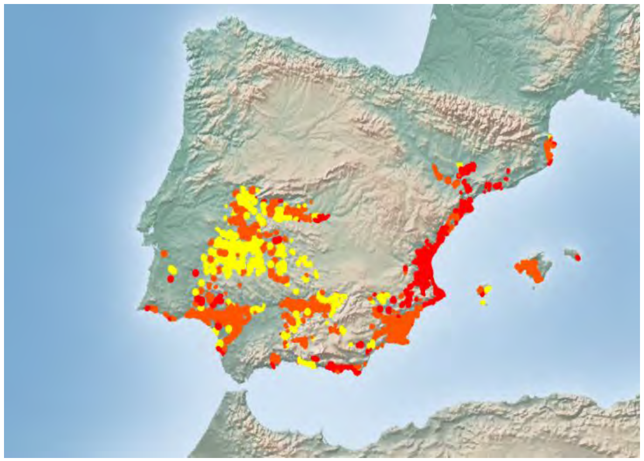
- GIS Mapping and Analysis Expert – Daniele Mion
- Bioenergy Process Expert – Fabrizio Bezzo
- Algae Cultivation Experts – Daniele Curiel and Chiara Miotti
- Environmental Economics Expert – François Levarlet
- Life Cycle Assessment – Alessandro Venturin

PROJECT OUTCOME

Technical Manual including:

- technical, environmental, biologic and economic analysis of the most promising algae cultivation systems and bioenergy/co-product chains
- GIS mapping of algae cultivation systems deployment potential
- analysis of relevant case studies, including pilots being realized within the research projects of the AlgaeCluster
- identification and analysis of the existing barriers
- guidelines to overcome the barriers, addressed to EU, institutions, authorities and private sector

TASK 1 and 2

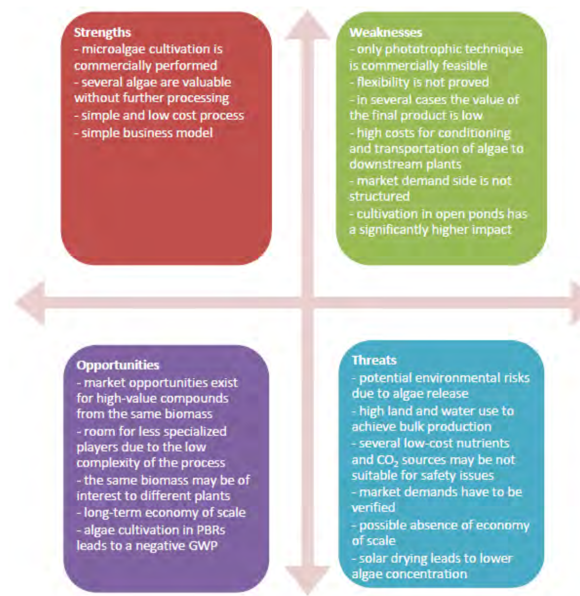


GIS siting of algae cultivation systems based on climate, geography, socio-economic indicators:

- Macro Areas – Suitability Maps
- Site Zones
- Site Territorial Units

SWOT analyses of algae cultivation and biofuel / co-product chains based on:

- biology
- technology
- economy
- LCA



PROs and CONs of PBR and OP

OP

Relatively low investment and operational costs (low energy consumptions and easy maintenance).

The use of wastewater is of interest: reduces the consumption of carbon dioxide and fertilizers, and allows a recycle of water leading to lower water consumptions and to a lower LCA impact.

The most critical points identified during the study are:

- large surface required for the plant;
- cultivation system applicable only to some microalgae species;
- low final density and biomass productivity;
- poor mixing and low efficient use of carbon dioxide and light;
- significant water and consequent energy consumption for pumping, mixing, harvesting;
- difficulty in controlling temperature;
- high risk of contamination.

PROs and CONs of PBR and OP

PBR

Photobioreactors are closed systems, more flexible, their size can be significantly small and the main parameters are easily controllable.
Productivity is higher because of their good mixing and efficient use of light and carbon dioxide.
The system is suitable for high-value products, and algae harvesting is quite easy. Also in this case, using wastewater as water source, the supply of carbon dioxide and fertilizers is reduced and consequently the costs and the LCA impact are lower.

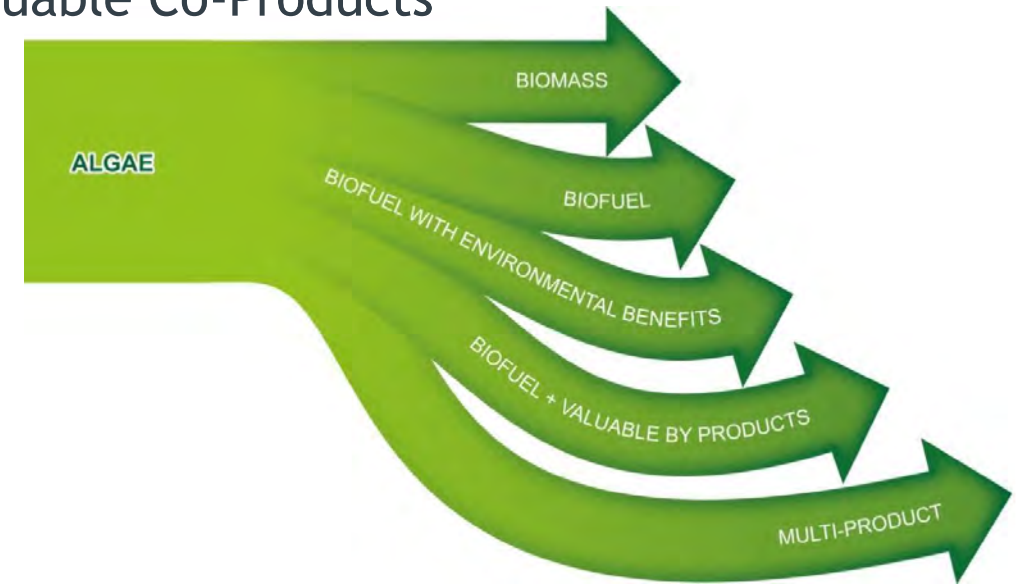
On the other hand:

- expensive installation due to material costs;
- expensive operation due to high energy consumptions for cooling;
- possible overheating of the reactor or additional costs for thermoregulation;
- toxic accumulation of oxygen, adverse pH and carbon dioxide gradients.

FROM ALGAE TO BIOFUEL AND CO-PRODUCTS

Identification of five production chains:

- PC1 – Biomass Production
- PC2 – Biofuel Production without Co-Products
- PC3 – Biofuel Production without Co-Products but with Environmental Benefits
- PC4 – Biofuel Production with Valuable Co-Products
- PC5 – Multi-Product Approach



TASK 3

Analysis of Barriers and Recommendations

- cruces for access to market of a specific technology
- barriers to development of algae-based systems
- recommendations to overcome the barriers
- action plan

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Technical	Conversion Efficiency Algae-Biofuel: oil extraction and biofuel production rates are very low if compared to the input raw materials.	▲		Selection of the most efficient technology. Research for the development of highly innovative technologies. Research for biological advancement toward more efficient algal strains	⚠⚠⚠	🕒🕒	€€€
Technical	High amount of water needed per functional unit.		▲	Selection of the most efficient technology. Research for the development of highly innovative technologies.	⚠⚠⚠	🕒🕒	€€€
Technical	The use of wastewater: although promising for the environmental benefits, it raises O&M issues and it is a barrier to the production of some valuable co-products.		▲	Incentives for the investors in plants using WW to solve the technical barriers. Research for improvements in O&M issues to overcome the biological barriers.	⚠⚠	🕒🕒	€€
Technical	Large cultivation fields are needed		▲	Research for the development of highly innovative technologies.	⚠⚠⚠	🕒🕒	€€€
Technical	Low biomass productivity	▲		Research for the development of highly innovative technologies and more efficient algal strains.	⚠⚠⚠	🕒🕒	€€€
Technical	Low compatibility of valuable co-products and algal biofuel		▲	Accurate design to decide the most applicable combinations of product/co-products.	⚠⚠	🕒	€€

TASK 3

Analysis of Barriers and Recommendations

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Technical	Large cultivation fields are needed						
Technical	Low biomass productivity	▲					
Technical	Low compatibility of valuable co-products and algal biofuel						

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Technical	Use of bioengineering is necessary for the achievement of the optimal algae strains. This is linked to the barrier of public acceptance.		▲	Research in the biological field of laboratory tests, technological innovation, etc.	⚠⚠	◷◷	€€
Technical	No multiproduct plants exist or promise to be valuable	▲		Demonstrative tests are needed to prove the technical and economical viability	⚠	◷◷	€€€
Economic	Production costs not competitive with other biofuel production chains (wood, crops) or in reference to the fossil fuel sector.	▲		The solution will be mainly a consequence of the technical improvements and of additional public incentives	⚠⚠⚠	◷◷	€€€
Economic	Fiscal and economic incentives not favorable to the development of algae production chains		▲	Put higher incentives on biofuel production, transformation and distribution processes. Incentives might be allocated under the form of grants or low-cost loans (to investments in bio fuel algae production chains), tax concession, feed-in-tariffs or premium (which guarantee a minimum price to biofuel from algae supplied on the market) or quotas (e.g., green certificates).	⚠⚠⚠	◷	€€€

TASK 3

Analysis of Barriers and Recommendations

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Technical	Large cultivation fields are needed						
Technical	Low biomass productivity	▲					
Technical	Low compatibility of valuable co-products and algal biofuel						

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Economic	Fiscal and economic incentives not favorable to the development of algae production chains						

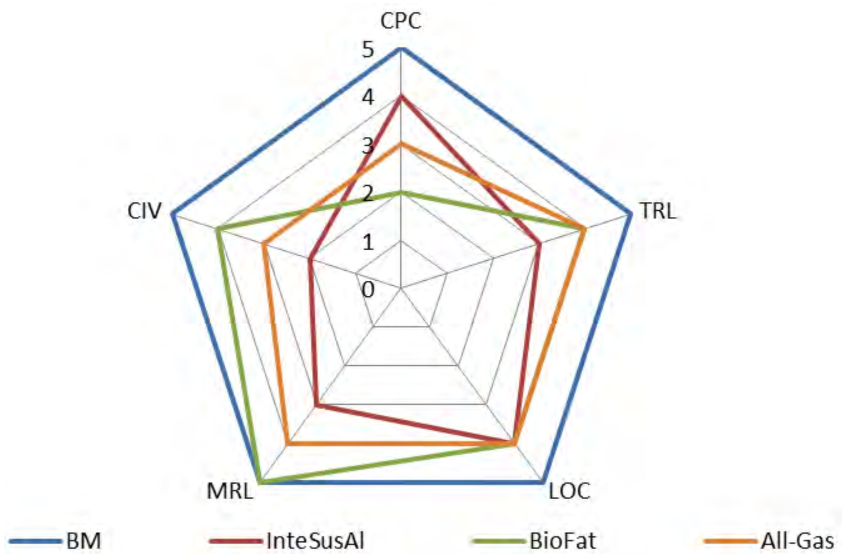
Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Economic	Demand only for high volume of biofuels, which requires important investments in equipment in the start-up phase of the business.		▲	Higher economic incentives to investments in biofuel from algae production chain at the start-up stage of plant development.	⚠⚠	◷◷	€€
Policy and normative background	Uncertain/undefined legal and policy frameworks. Patents and authorizations to start a business are not well defined or are provided at a very high cost for investors.		▲	Strengthen the legal framework at European and national levels (defining responsibilities, bodies involved and public authorizations required).	⚠⚠	◷	€
Public acceptance	Skepticism of the population towards unknown technologies, use of bioengineering and towards highly impacting systems in terms of land occupancy. Diffidence towards land occupancy for industrial purposes vs. agricultural scopes.		▲	Consensus building campaigns. Demonstrative projects to prove the reliability and the effectiveness.	⚠⚠⚠	◷◷◷	€
Public acceptance	Odors in Open Pond are an issue that can cause "NIMBY" phenomena along with the general skepticism.		▲	Stress on research activities. Consensus building campaigns.	⚠⚠⚠	◷◷◷	€

OUR PROJECT AND FP7

Continuous interaction with FP7 projects of the AlgaeCluster

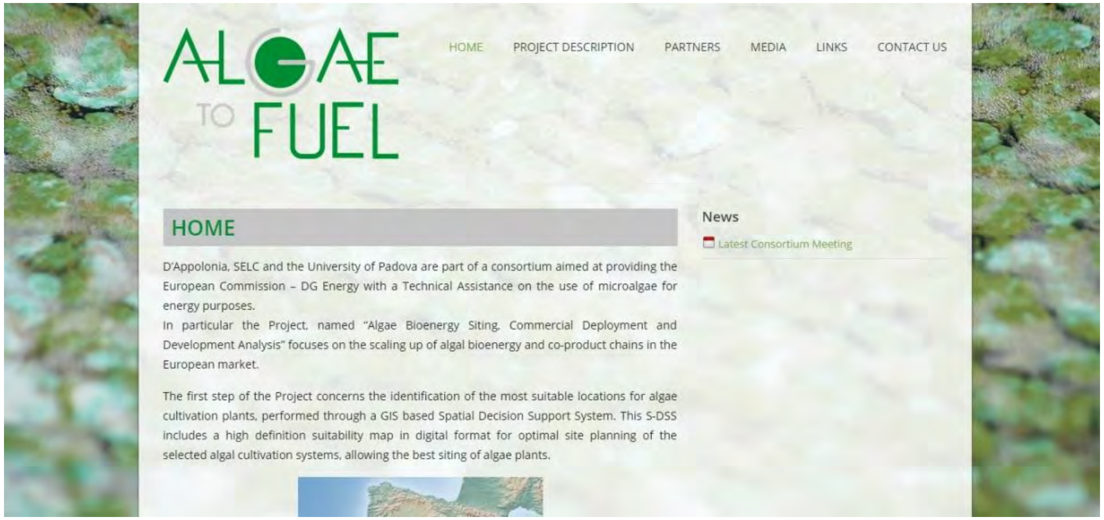
- questionnaire for input data
- review of interim documents
- comparison of LCA approaches
- gap analysis and rating

CATEGORIES	NOTES	DESCRIPTION/VALUE
Microalgae species		Fresh water
Taxonomic group		Natural bloom… it means that any mono species culture is promoted in our Raceway ponds.
Metabolism type	Photoautotrophic, heterotrophic, etc.	Photoautotrophic
Chemical composition	Lipid content	Less than 10%
Photosynthetic efficiency [%]		N.A.
Growth rate [g/m2/d]		Average: 25 gr/m2/d (After 18 months of operation)
CO2, nutrients, light and water uptake and sources		Pure CO2, waste water as nutrients source.
Specific growth requirements	CO2, nutrient, PH, solar radiation, temperature, mixing, etc.	
Cultivation technologies		
Type and description	Open ponds, tubular PBR, flat plate PBR, fermenters, etc.	Conventional ponds
Size [m2]		32 m2/unit
Operability conditions and technical parameters	Batch/continuous cultivation, algal concentration [g/l]	Continuous, algal concentration, NA
Energy input [kWh/m3]		To be confirmed



WEBSITE AND PROMOTION

- Project website http://www.algaetofuel.eu



- Logo

WEBSITE AND PROMOTION

- individual promotion;
- participation in dedicated seminars specifically devoted to biofuels and algae:
  - ✓ the European Workshop on LCA for Algal Biofuels and Biomaterials (2nd edition as attendees, April 2014 – 3rd edition as speakers, May 2015),
  - ✓ the side-event of the Algae Cluster Meeting in Seville (May 8, 2014),
  - ✓ the event of the European Algae Biomass Association (EABA) and of the Directorates General for Energy and Research & Innovation of the European Commission in Florence, (December 2014).

AGENDA

- 09:30 Chiara **Miotti** - Biologic Component for Siting and Cultivation
- 09:50 Daniele **Mion** - Siting and GIS tool
- 10:10 Fabrizio **Bezzo** - Technology aspects and related barriers
- 10:30 Alessandro **Venturin** - LCA
- 10:50 Coffee Break
- 11:10 François **Levarlet** - Economic assessment, barriers and scenarios
- 11:30 Lorenzo **Facco** - Recommendations and Conclusions
- 11:50 Discussion Q&A

Algae Bioenergy siting, commercial deployment and development analysis

Biologic Component for Siting and Cultivation

Final Meeting

Brussels

May 12, 2015

SUMMARY OF PRESENTATION

OBJECTIVE: Selection of promising microalgae species for biofuel production.

Steps in the Analysis Process:

1) data collection;

2) qualitative data analysis;

3) division of species into groups having similar characteristics;

4) SWOT analysis of algal groups.

LIMITATIONS and ASSUMPTIONS

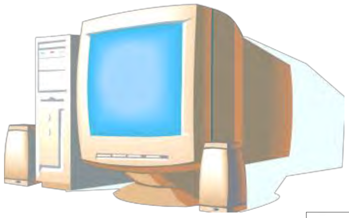
LIMITATIONS

- Literature data availability
  (e.g. difficulties in obtaining a complete set of data about some species).
- Different measure units
  (e.g. different methods of productivity measurement).
- Conflicting opinions regarding the suitability of some species for biofuel production.

ASSUMPTIONS

- Selected Microalgae: it is important to consider them as examples of promising species for biofuel production.
- SWOT analysis: a groups-based approach is deemed appropriate for the purposes of the analysis (to express a general opinion on algae cultivation plants).

DATA COLLECTION



- using the available literature
  (e.g. media, web, etc.)

- analysis of the species used
  in FP7 pilot projects

- the experience of Consortium

DATA COLLECTION FOCUSING ON:

BIOLOGICAL ASPECTS

-Biomass productivity/growth rate.
- Growth conditions (e.g. autotrophic cultivation).
- Resistance to environmental conditions variations (temperature/pH/salinity).
- Cell composition (lipid, protein, carbohydrate content).
- Co-products and application areas.

PRACTICAL ASPECTS

- Cultivation systems (open pond/photobioreactor).
- General cultivation aspects (e.g. use of different water sources).

DATA COLLECTION – AN EXAMPLE

Chlorella spp. (*Chlorella vulgaris*)

N20 | Chlorella spp.

	A	B	C	D
1	**Group (class)**	**Species**	**Lipid content (% dry weight biomass)**	**Lipid productivity (mg/L/day)**
2	Chlorophyceae	Ankistrodesmus sp.	24,0–31,0	–
3	Chlorophyceae/Trebouxiophyceae	Botryococcus braunii	25,0–75,0	–
4	Bacillariophyceae/Coscinodiscophyceae	Chaetoceros muelleri	33,6	21,8
5	Bacillariophyceae/Coscinodiscophyceae	Chaetoceros calcitrans	14,6–16,4/39,8	17,6
6	Chlorophyceae/Trebouxiophyceae	Chlorella emersonii	25,0–63,0	10,3–50,0
7	Chlorophyceae/Trebouxiophyceae	Chlorella protothecoides	14,6–57,8	1214
8	Chlorophyceae/Trebouxiophyceae	Chlorella sorokiniana	19,0–22,0	44,7
9	Chlorophyceae/Trebouxiophyceae	Chlorella vulgaris	5,0–58,0	11,2–40,0
10	Chlorophyceae/Trebouxiophyceae	Chlorella spp.	10,0–48,0	42,1
11	Chlorophyceae/Trebouxiophyceae	Chlorella pyrenoidosa	2	–

Appunti | Carattere | Allineamento

E7

	A
1	Mata T.M., Martins A.A., Caetano N.S., 2010. Microalgae for biodiesel production and other applications: A review. Sust. Energ. Rev., 14: 217-232.
2	Chlorella vulgaris, Haematococcus pluvialis, Arthrospira (Spirulina) platensis are examples of strains found to grow under photoautotrophic, heterotrophic,
3	A major handicap in the large-scale cultivation of algae is our inability to grow selected species in substantial volumes of hundreds of cubic meters.
4	The reduction in nitrogen in the medium increases the lipid content in all five investigated Chlorella strains, among which C. emersonii, C. minutissima and C.
5	
6	Huang G., F. Chen, D. Wei, X. Zhang, G. Chen, 2010. Biodiesel production by microalgal biotechnology. Applied energy, 87:38-46.
7	Enclosed photobioreactor system is more suitable for some microalgae which are readily contaminated by other microbes, except for some special
8	
9	Ahmad A.L., Mat Yasin N.H., Derek C.J.C., Lim J.K., 2011. Microalgae as a sustainable energy source for biodiesel production: A review. Renewable and Sustainable Energy Reviews 15: 584–593.
10	Several researchers have focused on the Chlorella sp., which appears to be a good option for biodiesel production because they are readily available and easily cultured in the laboratory. Converti et al. (2009) attempted to increase the lipid content in microalgae by varying the temperature and nitrogen concentration during the culture of Nannochloropsis oculata and Chlorella vulgaris and concluded that variation of temperature and nitrogen concentration strongly influenced the lipid content of the microalgae.
	Converti A, Casazza AA, Ortiz EY, Perego P, Borghi MD., 2009. Effect of

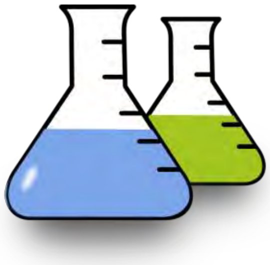
Dati alghe | Chlorella | Spirulina | Dunaliella | Nannochloropsis | Botryoco

Pronto

DATA ELABORATION

METHODOLOGICAL APPROACH:

1) Qualitative analysis to evaluate species suitability (considering biological aspects).



2) Qualitative analysis of the identified species cultivation in open ponds and photobioreactors (considering practical aspects).

MICROALGAE SPECIES

According to biological and practical aspects, ten taxa (genera/species) have been selected:

Chlorophyta	*Botryococcus braunii*
	Chlorella spp. (*Chlorella vulgaris*)
	Chlorococcum spp.
	Dunaliella spp. (*Dunaliella salina*)
	Haematococcus pluvialis
	Neochloris oleoabundans
	Scenedesmus spp.
	Tetraselmis spp. (*Tetraselmis suecica*)
Ochrophyta	*Nannochloropsis* spp.
	Phaeodactylum tricornutum

MICROALGAE SPECIES – QUALITATIVE ANALYSIS

1) QUALITATIVE ANALYSIS TO EVALUATE SPECIES SUITABILITY

Scientific Literature data

+

Experts assessment

→

BIOLOGICAL Parameters

General indications for the suitability of species for biofuels production.

MICROALGAE SPECIES – QUALITATIVE ANALYSIS

Species suitability for biofuels production

green (+): positive aspects

red (-): negative aspects

yellow (-/+): negative and positive aspects

	Biomass Productivity/ Growth rate	Temperature pH - Salinity	Cell composition (Lipid content)	Co-products
Botryococcus braunii	-	-/+	+	+
Chlorella spp. (*Chlorella vulgaris*)	+	+	+	+
Chlorococcum spp.	+	+	+	+
Dunaliella spp. (*Dunaliella salina*)	-/+	+	+	+
Haematococcus pluvialis	-/+	-	+	+
Neochloris oleoabundans	+	-/+	+	+
Scenedesmus spp.	+	+	+	+
Tetraselmis spp. (*Tetraselmis suecica*)	+	+	+	+
Nannochloropsis spp.	+	+	+	+
Phaeodactylum tricornutum	+	+	+	+

MICROALGAE SPECIES – QUALITATIVE ANALYSIS

Species suitability for biofuels production

green (+): positive aspects

red (-): negative aspects

yellow (-/+): negative and positive aspects

	Biomass Productivity/ Growth rate	Temperature pH - Salinity	Cell composition (Lipid content)	Co-products
Botryococcus braunii	-	-/+	+	+
Chlorella spp. *(Chlorella vulgaris)*	+	+	+	+
Chlorococcum spp.	+	+	+	+
Dunaliella spp. *(Dunaliella salina)*	-/+	+	+	+
Haematococcus pluvialis	-/+	-	+	+
Neochloris oleoabundans	+	-/+	+	+
Scenedesmus spp.	+	+	+	+
Tetraselmis spp. *(Tetraselmis suecica)*	+	+	+	+
Nannochloropsis spp.	+	+	+	+
Phaeodactylum tricornutum	+	+	+	+

MICROALGAE SPECIES – QUALITATIVE ANALYSIS

Possible areas of application and co-products

	Biomass Productivity/ Growth rate	Temperature pH - Salinity	Lipid content	Co-products
Botryococcus braunii	-	-/+	+	+
Chlorella spp. *(Chlorella vulgaris)*	+	+	+	+
Chlorococcum spp.	+	+	+	+
Dunaliella spp. *(Dunaliella salina)*	-/+	+	+	+
Haematococcus pluvialis	-/+	-	+	+
Neochloris oleoabundans	+	-/+	+	+
Scenedesmus spp.	+	+	+	+
Tetraselmis spp. *(Tetraselmis suecica)*	+	+	+	+
Nannochloropsis spp.	+	+	+	+
Phaeodactylum tricornutum	+	+	+	+

Application Areas	MICROALGAE *Tetraselmis* spp. *(Tetraselmis suecica)*	*Neochloris oleoabundans*	*Scenedesmus* spp.	*Botryococcus braunii*	*Haematococcus pluvialis*
Human Feed (probiotic, nutraceuticals and supplements)	probiotic	source of carotenoids	carotenoids and lutein (nutraceutical)	source of carotenoids and lutein	astaxanthin and carotenoids (nutraceuticals), nutritional supplement
Aquaculture Feed	food for larval bivalves	food in aquaculture	food in aquaculture		food in aquaculture and pigmenter (for salmons)
Animal Feed	feed additive		carotenoids and lutein (nutraceutical)		feed additive
Cosmetics	sunscreen (source of vitamin E) active ingredients influencing growth of hair, pigmentation of skin	active ingredients (slimming effects)			
Pharmaceutical				extracts used as bacteriostatic agents	astaxanthin is an antioxidant

Application Areas	MICROALGAE *Dunaliella* spp. *(Dunaliella salina)*	*Chlorella* spp. *(Chlorella vulgaris)*	*Chlorococcum* spp.	*Nannochloropsis* spp.	*Phaeodactylum tricornutum*
Human Feed (probiotic, nutraceuticals and supplements)	health food, nutritional supplement and colourant, β-carotene (a precursor to vitamin A) and vitamin C	health food, food supplement and feed surrogates, carotenoids - canthaxanthin and astaxanthin	potential sources of astaxanthin	source of eicosapentaenoic acid (EPA, 20:5ω3) (nutritional supplement), antioxidants (feed additive)	source of eicosapentaenoic acid (EPA, 20:5ω3) (nutritional supplement)
Aquaculture Feed	food in aquaculture and pigmenter (for fishes)	food in aquaculture	food source for fish larvae and rotifers	food in aquaculture	food in aquaculture (EPA source)
Animal Feed	feed additive	feed additive			
Cosmetics	β-Carotene as additive to cosmetics	extracts used in cosmetics		extracts (antioxidants) used in cosmetics	extracts used in cosmetics
Pharmaceutical	β-carotene (a precursor to vitamin A) is antioxidant, anticarcinogen and antiheart disease agent, glycerol	health benefits, skin care, sun protection and hair care products, antibacterial extracts		extracts (antioxidants) used in pharmaceutical preparations	polysaccharides (antibacterial and antiinflammatory activities)

MICROALGAE SPECIES – QUALITATIVE ANALYSIS

Application Areas	MICROALGAE: *Tetraselmis* spp. (*Tetraselmis suecica*)	*Neochloris oleoabundans*	*Scenedesmus* spp.	*Botryococcus braunii*	*Haematococcus pluvialis*
Human Feed (probiotic, nutraceuticals and supplements)	probiotic	source of carotenoids	carotenoids and lutein (nutraceutical)	source of carotenoids and lutein	astaxanthin and carotenoids (nutraceuticals), nutritional supplement
Aquaculture Feed	food for larval bivalves	food in aquaculture	food in aquaculture		food in aquaculture and pigmenter (for salmons)
Animal Feed	feed additive		carotenoids and lutein (nutraceutical)		feed additive
Cosmetics	sunscreen (source of vitamin E) active ingredients influencing growth of hair, pigmentation of skin	active ingredients (slimming effects)			
Pharmaceutical				extracts used as bacteriostatic agents	astaxanthin is an antioxidant

Application Areas	MICROALGAE: *Dunaliella* spp. (*Dunaliella salina*)	*Chlorella* spp. (*Chlorella vulgaris*)	*Chlorococcum* spp.	*Nannochloropsis* spp.	*Phaeodactylum tricornutum*
Human Feed (probiotic, nutraceuticals and supplements)	health food, nutritional supplement and colourant, β-carotene (a precursor to vitamin A) and vitamin C	health food, food supplement and feed surrogates, carotenoids - canthaxanthin and astaxanthin	potential sources of astaxanthin	source of eicosapentaenoic acid (EPA, 20:5ω3) (nutritional supplement), antioxidants (feed additive)	source of eicosapentaenoic acid (EPA, 20:5ω3) (nutritional supplement)
Aquaculture Feed	food in aquaculture and pigmenter (for fishes)	food in aquaculture	food source for fish larvae and rotifers	food in aquaculture	food in aquaculture (EPA source)
Animal Feed	feed additive	feed additive			
Cosmetics	β-Carotene as additive to cosmetics	extracts used in cosmetics		extracts (antioxidants) used in cosmetics	extracts used in cosmetics
Pharmaceutical	β-carotene (a precursor to vitamin A) is antioxidant, anticarcinogen and antiheart disease agent, glycerol	health benefits, skin care, skin protection and hair care products, antibacterial extracts		extracts (antioxidants) used in pharmaceutical preparations	polysaccharides (antibacterial and antiinflammatory activities)

Application Areas	***Dunaliella* spp. (*Dunaliella salina*)**
Human Feed (probiotic, nutraceuticals and supplements)	health food, nutritional supplement and colourant, β-carotene (a precursor to vitamin A) and vitamin C
Aquaculture Feed	food in aquaculture and pigmenter (for fishes)
Animal Feed	feed additive
Cosmetics	β-Carotene as additive to cosmetics
Pharmaceutical	β-carotene (a precursor to vitamin A) is antioxidant, anticarcinogen and antiheart disease agent, glycerol

Dunaliella spp. (*Dunaliella salina*)

MICROALGAE SPECIES – QUALITATIVE ANALYSIS

2) QUALITATIVE ANALYSIS OF THE IDENTIFIED SPECIES CULTIVATION IN OPEN PONDS AND PHOTOBIOREACTORS

Selected taxa

- evaluation of general cultivation aspects (e.g. biomass productivity and growth rate)

- in open ponds and PBRs

- different water sources (freshwater, seawater and wastewater).

		Water sources			
OPEN SYSTEM (raceway ponds)		Seawater	Seawater + wastewater	Freshwater	Freshwater + wastewater
Botryococcus braunii	Freshwater	-	-	3	3
Chlorella spp. *(Chlorella vulgaris)*	Seawater/ Freshwater	-	-	5	5
Chlorococcum spp.	Seawater/ Freshwater	-	-	5	5
Dunaliella spp. *(Dunaliella salina)*	Seawater	5	3	-	-
Haematococcus pluvialis	Freshwater	-	-	5	-
Neochloris oleoabundans	Freshwater	-	-	3	-
Scenedesmus spp.	Freshwater	-	-	5	5
Tetraselmis spp. *(Tetraselmis suecica)*	Seawater/ Freshwater	5	5	5	5
Nannochloropsis spp.	Seawater	5	5	-	-
Phaeodactylum tricornutum	Seawater	5	5	-	-

5 = positive aspects,
3 = coexistence of negative and positive aspects,
1 = negative aspects.

MICROALGAE SPECIES – QUALITATIVE ANALYSIS

OPEN SYSTEM (raceway ponds)		Water sources: Seawater	Seawater + wastewater	Freshwater	Freshwater + wastewater
Botryococcus braunii	Freshwater	-	-	3	3
Chlorella spp. (*Chlorella vulgaris*)	Seawater/ Freshwater	-	-	5	5
Chlorococcum spp.	Seawater/ Freshwater	-	-	5	5
Dunaliella spp. (*Dunaliella salina*)	Seawater	5	3	-	-
Haematococcus pluvialis	Freshwater	-	-	5	-
Neochloris oleoabundans	Freshwater	-	-	3	-
~~*Scenedesmus* spp.~~	Freshwater	-	-	5	5
Tetraselmis spp. (*Tetraselmis suecica*)	Seawater/ Freshwater	5	5	5	5
Nannochloropsis spp.	Seawater	5	5	-	-
Phaeodactylum tricornutum	Seawater	5	5	-	-

Species	Productivity (mg/L/day)
Botryococcus braunii	2,6-24
Chlorella spp. (Chlorella vulgaris)	40
Chlorococcum spp.	53
Dunaliella spp. (Dunaliella salina)	33-116
Haematococcus pluvialis	12
Neochloris oleoabundans	90-134
~~*Scenedesmus spp.*~~	35
Tetraselmis spp. (Tetraselmis suecica)	27-36
Nannochloropsis spp.	37-90
Phaeodactylum tricornutum	45

Most of these microalgae present a good level of biomass productivity, both in OP and PBR and seem to be able to grow using different water sources.

MICROALGAE SPECIES – SWOT ANALYSIS

MICROALGAE SELECTION

↓

Next step: Identifying groups of species having similar characteristics.

↓

SWOT ANALYSIS ON MICROALGAE GROUPS

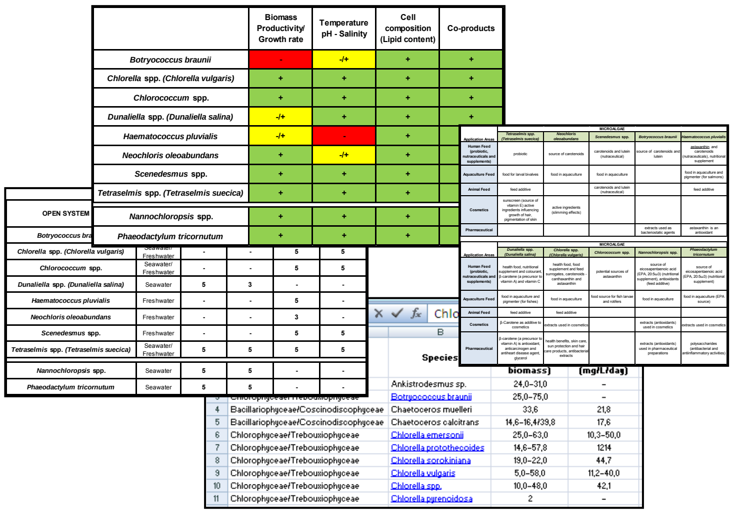
(strengths, weaknesses, opportunities and threats of algae cultivation systems)

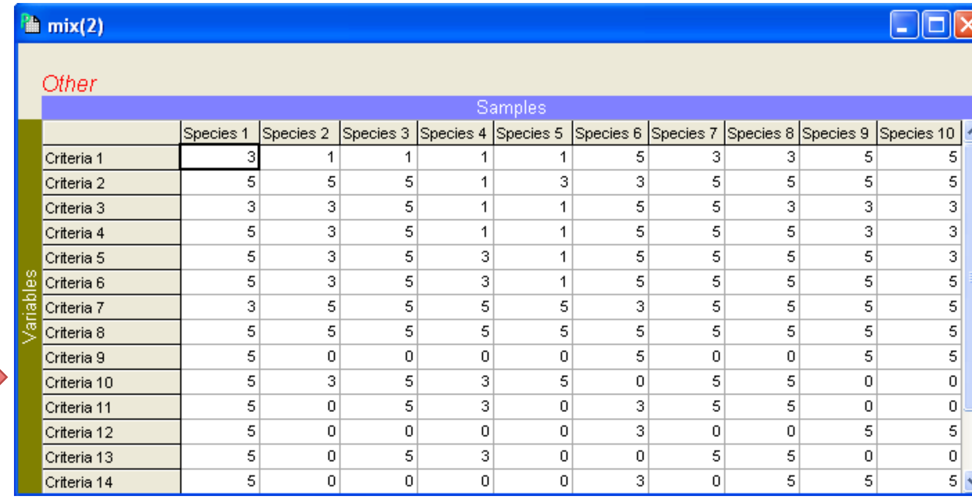
MICROALGAE GROUPS

Species were grouped according to a set of criteria, related to:

1) Biological aspects relevant to biofuels production.
2) General indications concerning their cultivation in open ponds and photobioreactors.
3) Processing of microalgal biomass.
4) Environmental impacts.

MICROALGAE GROUPS





	Species 1	Species 2	Species 3	Species 4	Species 5	Species 6	Species 7	Species 8	Species 9	Species 10
Criteria 1	3	1	1	1	1	5	3	3	5	5
Criteria 2	5	5	5	1	3	3	5	5	5	5
Criteria 3	3	3	5	1	1	5	5	3	3	3
Criteria 4	5	3	5	1	1	5	5	5	3	3
Criteria 5	5	3	5	3	1	5	5	5	5	3
Criteria 6	5	3	5	3	1	5	5	5	5	5
Criteria 7	3	5	5	5	5	3	5	5	5	5
Criteria 8	5	5	5	5	5	5	5	5	5	5
Criteria 9	5	0	0	0	0	5	0	0	5	5
Criteria 10	5	3	5	3	5	0	5	5	0	0
Criteria 11	5	0	5	3	0	3	5	5	0	0
Criteria 12	5	0	0	0	0	3	0	0	5	5
Criteria 13	5	0	5	3	0	0	5	5	0	0
Criteria 14	5	0	0	0	0	3	0	5	5	5

A total of 27 Parameters/Criteria

Biological aspects: 7
Cultivation in OP and PBR: 9
Biomass Processing: 9
Environmental impacts: 2

Data matrix
assessments of criteria expressed in terms of a score

5 = positive aspects
3 = coexistence of negative and positive aspects
1 = negative aspects

MICROALGAE GROUPS

mix(2)

Other

Data matrix

Variables	Species 1	Species 2	Species 3	Species 4	Species 5	Species 6	Species 7	Species 8	Species 9	Species 10
Criteria 1	3	1	1	1	1	5	3	3	5	5
Criteria 2	5	5	5	1	3	3	5	5	5	5
Criteria 3	3	3	5	1	1	5	5	3	3	3
Criteria 4	5	3	5	1	1	5	5	5	3	3
Criteria 5	5	3	5	3	1	5	5	5	5	3
Criteria 6	5	3	[illegible]	3	1	[illegible]	5	5	5	5
Criteria 7	3	5	3	5	5	3	5	5	5	5
Criteria 8	5	5	5	5	5	5	5	5	5	5
Criteria 9	5	0	0	0	0	5	0	0	5	5
Criteria 10	5	3	5	3	5	0	5	5	0	0
Criteria 11	5	0	5	3	0	3	5	5	0	0
Criteria 12	5	0	0	0	0	3	0	0	5	5
Criteria 13	5	0	5	[illegible]	0	0	5	5	0	0
Criteria 14	5	0	0	[illegible]	0	3	0	5	5	5

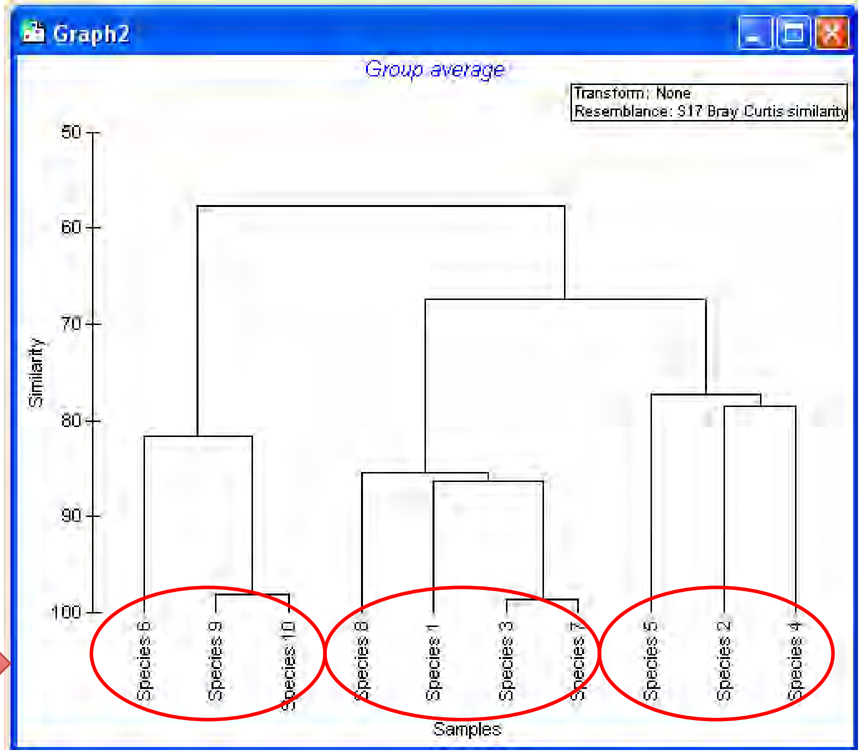
Resem2

Similarity (0 to 100)

Similarity matrix

	Species 1	Species 2	Species 3	Species 4	Species 5	Species 6	Species 7	Species 8	Species 9	S
Species 1										
Species 2	66,116									
Species 3	85,517	77,778								
Species 4	60,345	78,481	71,845							
Species 5	55,357	77,333	66,667	77,143						
Species 6	74,242	56,842	63,866	46,667	37,209					
Species 7	87,075	76,364	98,507	70,476	65,347	66,116				
Species 8	84,286	69,903	85,039	69,388	59,574	66,667	86,822			
Species 9	72,308	60,215	54,701	45,455	42,857	82,692	57,143	69,643		
Species 10	70,313	61,538	52,174	46,512	43,902	80,392	54,701	67,273	98	

Cluster analysis



MICROALGAE GROUPS

Three main groups were identified:

Group 1 → 1 Chlorophyta *Dunaliella* spp. (*Dunaliella salina*), 2 Ochrophyta *Nannochloropsis* spp. and *Phaeodactylum tricornutum*.

Group 2 → 4 Chlorophyta *Chlorella* spp. (*Chlorella vulgaris*), *Scenedesmus* spp., *Chlorococcum* spp. and *Tetraselmis* spp. (*Tetraselmis suecica*).

Group 3 → 3 Chlorophyta *Botryococcus braunii*, *Haematococcus pluvialis* and *Neochloris oleoabundans*.

SWOT ANALYSIS ON MICROALGAE – GROUP 1

Chlorophyta

Dunaliella spp. (*Dunaliella salina*)

Ochrophyta

Nannochloropsis spp.

Phaeodactylum tricornutum

SWOT ANALYSIS ON MICROALGAE – GROUP 2

Chlorophyta

Chlorella spp.
(*Chlorella vulgaris*)

Scenedesmus spp.

Chlorococcum spp.

Tetraselmis spp.
(*Tetraselmis suecica*)

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SWOT ANALYSIS ON MICROALGAL – GROUP 3

Strengths

- can grow in both OP and PBR

Weaknesses

- generally good lipid content but slow growth rate
- some suffer of environmental fluctuations and can be contaminated by other species
- some are less controlled in OP than in PBR

Opportunities

- can grow using wastewater
- can be used for bioremediation
- widely used in other industries

Threats

- some are toxic for micro-organisms and fishes
- cultivated algae may escape in the environment

Chlorophyta

Botryococcus braunii

Haematococcus pluvialis

Neochloris oleoabundans

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CONCLUSIONS AND RECOMMENDATIONS

- Selected Microalgae are examples of promising species for biofuel production.
- Nowadays: no known algal strain capable of fulfilling all the requirements of biofuel production.
- Local Feasibility Study: essential tool to identify algal species and the related biofuels production plants.

Thank you for your attention

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Algae Bioenergy siting, commercial deployment and development analysis

Siting of Algae Cultivation Systems
GIS Mapping of Algae Cultivation Systems Deployment Potential
Best Siting Suitability Maps

Final Meeting

Brussels

May 12, 2015

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INTRODUCTION

OBJECTIVE
Selection of optimal sites for the deployment of algae cultivation plants at EU-28 scale

STEPS OF ANALYSIS

1. Selection of Macro-Areas
2. Selection of Site Zones (SZ)
3. Selection of Site Territorial Units (STU) within the Site Zones
4. Classification of the Site Territorial Units into classes of suitability to host algae cultivation plants by means of spatial decision support system (S-DSS)

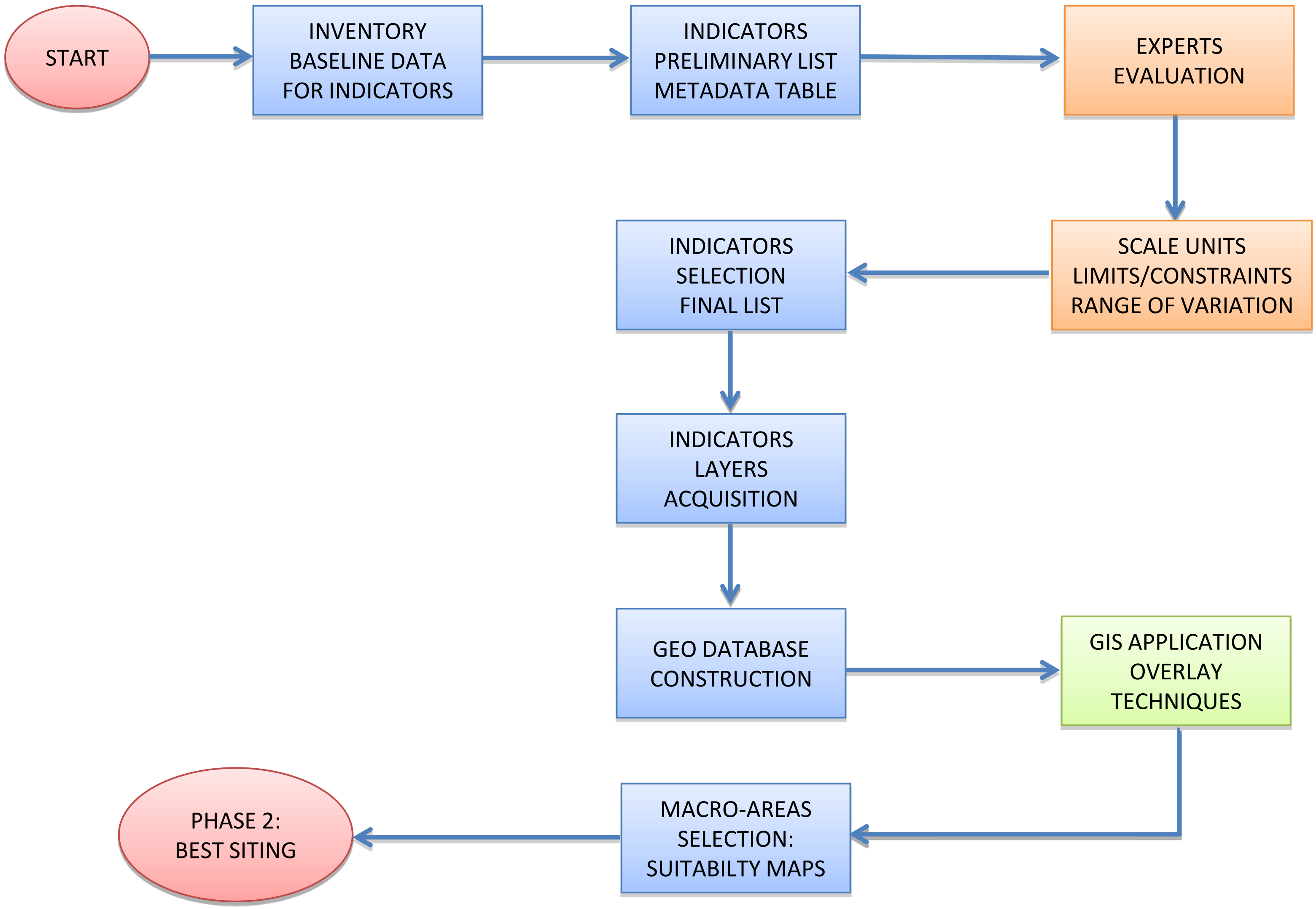
MAIN ASSUMPTIONS

- **Focus of the analysis: only on autotrophic cultivation** of microalgae. Heterotrophic cultivation seems not a suitable solution because of long-term objectives of security and sustainability
- **Thresholds for each indicator should be not considered as constraints**, instead as recommendations to be verified at local scale
- **Indicators and thresholds:** acquired from **public available data**, approved by the project experts after consultation

LIMITS AND RECOMMENDATIONS

- The criteria and thresholds used should be intended as **indicative values** in view of the actual technology
- The classification of areas is based on **public available data** which could be **not very precise at local scale**
- Care should be taken especially analysing those areas **having few km^2 in size**, which require deeper data acquisition **at local scale**
- This analysis should be carried out on the STU which are of interest for stakeholders during the **stage of feasibility analysis**

Macro-areas methodological approach



SELECTION OF MACRO-AREAS

DEFINITION OF MACRO-AREAS

Wider trans-national regional areas at European scale where algae cultivation is most favourable on the basis of environmental conditions

FACTORS FOR SUITABILITY

The suitable (most favourable) areas for algae cultivation are defined as those ones falling in the conditions:

Solar Radiation	≥ 1500 kWh m^{-2} yr^{-1}
Mean Annual Air Temperature	≥ 15° C

«Buffer Zones» are defined those with conditions near suitability, with high variability:

Solar Radiation	1300 - 1500 kWh m^{-2} yr^{-1}
Mean Annual Air Temperature	13° - 15° C

RESULTING AREAS

Three macro-areas are detected:

•The **suitable areas** range as a whole below 43° N, including almost all the Mediterranean area

•The **buffer zones** range in the belt between about 43° and 45° N, including all the N-coast of Spain, the S-Atlantic coast of France, the coast of N-Italy and the W-coasts of the Black Sea

•The **non-suitable areas** extend about above 45° N

•The **Mediterranean Sea** shows most of the suitable macro-areas

•No account was taken of **different cultivation systems** at this step

SELECTION OF SITE ZONES

DEFINITION OF SITE ZONES (SZ)

Zones at regional scale, within the macro areas and the buffer zone, where to detect suitable sites for algae cultivation plants.

SZ are separately detected for the two major groups of algae cultivation systems:

- **Photobioreactors (PBR)**
- **Open Ponds (OP)**

INDICATORS AND THRESHOLDS FOR SZ SELECTION

Indicator	Threshold	Notes
Solar Radiation	≥ 1500 kWh^{-2} year^{-1}	Annual cumulative
Air temperature	≥ 15° C	Annual average
Precipitation	≤ 600 mm year^{-1}	Annual cumulative (Open Ponds only)
Evapotranspiration	≤ 1000 mm year^{-1}	Annual cumulative (Open Ponds only)
Slope	≤ 2% (Open Ponds) ≤ 5 % (PBR)	
Air temperature (*)	<0° C	average min of the coldest month
Air temperature (*)	>40° C	average max of the hottest month (PBR only)

(*) Control parameters used after the selection of the Site Zones to verify the exclusion of areas having those values.

INDICATORS AND THRESHOLDS FOR SZ SELECTION

REMARKS ON INDICATORS AND THRESHOLDS

•**Elevation** is important as difference from water sources, having relevance on pumping costs (that can be detected only at local scale), so it was **neglected at SZ selection process**

•Annual **precipitation** and **evapotranspiration** are not considered for selecting **SZ for PBR**

•Different thresholds are applied on **slope** for Open Ponds e PBR

•**Extreme temperatures:** control made on SZ after the selection for:

1)continuous avg. min temperature < 0° C for at least 1 month

2)continuous avg. max temperature > 40° C for at least 1 month (PBR only); **no areas resulted to fall in both these conditions**

RESULTING SITE ZONES

OPEN PONDS:

- South Portugal, S-W Spain (coast and internal regions), S-E coast of Spain
- In Italy: parts of Sardinia, Sicily, Apulia
- Some parts of the East coast of Greece and of Cyprus.

PHOTOBIOREACTORS:

- South Portugal, whole S-W Spain, almost all the Mediterranean coast of Spain
- In Italy: wide areas of Sardinia, Sicily, Apulia; some coastal Tyrrhenian areas and Calabria
- Greater part of East Greece, Ionian coasts of Greece and Crete
- Almost all areas in Cyprus

MAP OF SZ FOR OPEN PONDS

Fig.2 Open Ponds suitable SZ (yellow). EU-28 Administrative Units at NUTS 3 belonging to suitable macro-areas and buffer zone are overlaid

MAP OF SZ FOR PBR

Fig.3 Open Ponds suitable SZ (red). EU-28 Administrative Units at NUTS 3 belonging to suitable macro-areas and buffer zone are overlaid

SELECTION OF SITE TERRITORIAL UNITS

DEFINITION OF TERRITORIAL UNITS (STU)

Areas, within the Site Zones, where it is possible to build one or more algae cultivation plants, at different classes of capability

STU are separately detected for 9 cultivation systems selected by the experts:

Open Ponds (Raceway Ponds)	Photobioreactors (PBR)
Sea water (OP SW)	Sea water (PBR SW)
Fresh water (OP FW)	Fresh water (PBR FW)
Waste water (OP WW)	Waste water (PBR WW)
Sea water – Waste water (OP SW-WW)	Fresh water – Waste water (PBR FW-WW)
Fresh water – Waste water (OP FW-WW)	

INDICATORS AND THRESHOLDS FOR STU SELECTION

- STU are extracted from SZ using indicators layers from **CORINE Land Cover 2006**
- A buffer of **5 km from the urban centres** was set for selection criteria regarding proximity to urban areas
- The **elevation threshold was set at 100 m** only for sea water plants, to exclude unsuitable situations in the coastal areas (e.g. flat lands on high cliffs)
- Assuming the **minimum size of 100 ha** for a single plant, all the STU **less than 2 km^2** in size were discarded

RESULTING STU

Plant Type	N of STU
OP SW	230
OP FW	409
OP WW	566
OP SW-WW	109
OP FW-WW	246
PBR SW	496
PBR FW	651
PBR WW	619
PBR FW-WW	343
Total	**3669**

- A total of **3669 STU** were detected
- The number of STU per type of plant ranges **from 109** (OP sea water – waste water) **to 651** (PBR fresh water)
- The size of a single STU ranges **from 2 km²** (constraint) to a **maximum of 11200 km²**
- The **average size** of a single STU is **52.8 km²**, but more of the half of STU (55.5%) is from 2 to 10 km² in size.

SPATIAL DECISION SUPPORT SYSTEM (S-DSS)

S-DSS methods were applied for classifying the STU in **classes of suitability (capability classes)**

- A matrix was built for each type of plant, composed by **indicators x STU**
- **Four indicators** were calculated for each STU from CORINE Land Cover and existing databases
- **Threshold values** were assigned to each indicator
- A **score** (0 to 100) was given to each STU for every indicator, based on the **distance of the indicator to the threshold** (utility functions)
- The sum of all scores per each STU gave the **total capability score** per STU
- **Capability maps** of the STU were produced per each type of plants

INDICATORS AND THRESHOLDS FOR S-DSS

Plant Type	S-DSS Indicator	Threshold
All	Proximity to industrial plants	Within 5 km from industrial areas Score (100 to 0) for proximity from 0 to 15 km
All	Proximity to road networks	Within 0.5 km from the road network Score (100 to 0) for proximity from 0 to 1.5 km
All	Share of agricultural area	30% of the STU area (optimal) Score 0 to 100 for area from 0% to 30% Score 100 to 0 for area to 30% to 60%
All	Economic Index	Calculated combining 5 socio-economic indicators (no threshold) Score 0 to 100 for index from 1 to 5

STU CAPABILITY CLASSES

- The **suitability score** ranges from 0 to 334.3 over all the STU (mean = 78.8, standard deviation = 57.3)
- The STU are classified into **3 classes of suitability** (capability classes) based on the score:

  Low suitability < 50.1

  Mid suitability 50.1 - 107.4 (limits included)

  High suitability > 107.4

- The classes limits are given by the average value of all the scores plus/minus 1/2 standard deviation

RESULTS OF STU CLASSIFICATION

Plant Type	Low	Mid	High	Total
OP SW	80	88	62	230
OP FW	179	167	63	409
OP WW	162	210	194	566
OP SW-WW	17	32	60	109
OP FW-WW	81	81	84	246
PBR SW	195	180	121	496
PBR FW	276	248	127	651
PBR WW	180	214	225	619
PBR FW-WW	117	116	110	343
Total	**1287**	**1336**	**1046**	**3669**

- **1046 STU** out of 3669 (28.5%) result **highly capable** to host cultivation plants
- The most frequent high-suitable STU are for PBR-waste water and Open Ponds-waste water plants

BEST SITING MAPS

- A total of 27 maps were produced, i.e. 3 maps for each of the 9 plant types centred respectively for better visualization on:
  1) Spain-Portugal
  2) Italy
  3) Greece-Cyprus
- At higher detailed scale, it is possible to produce such maps for each of the 3669 STU detected

STU CAPABILITY MAPS

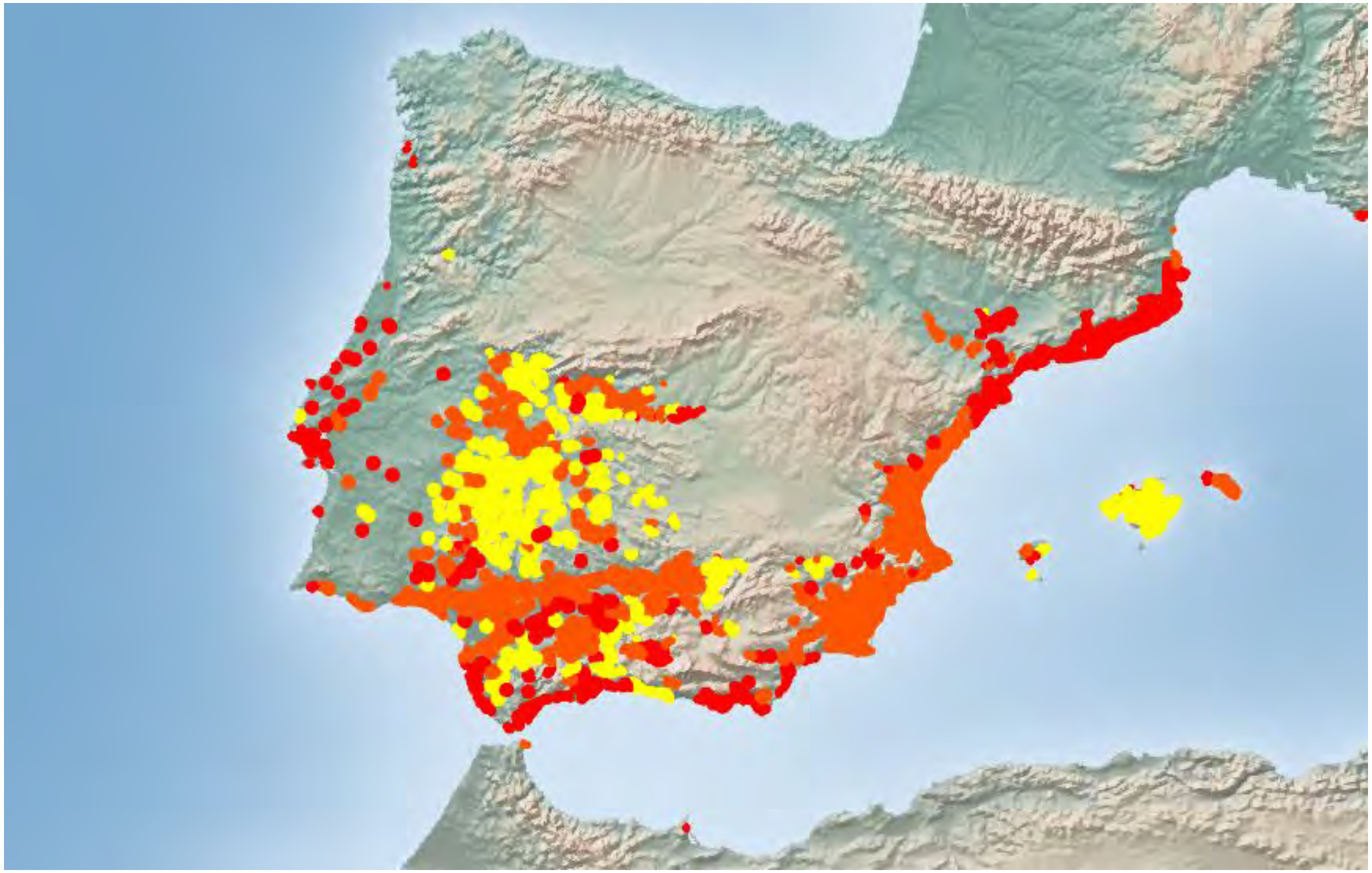


Fig.8 Example of STU classified into capability classes for PBR-waste water systems, Spain and Portugal area. Red: high capability; orange: mid capability; yellow: low capability

STU CAPABILITY MAPS

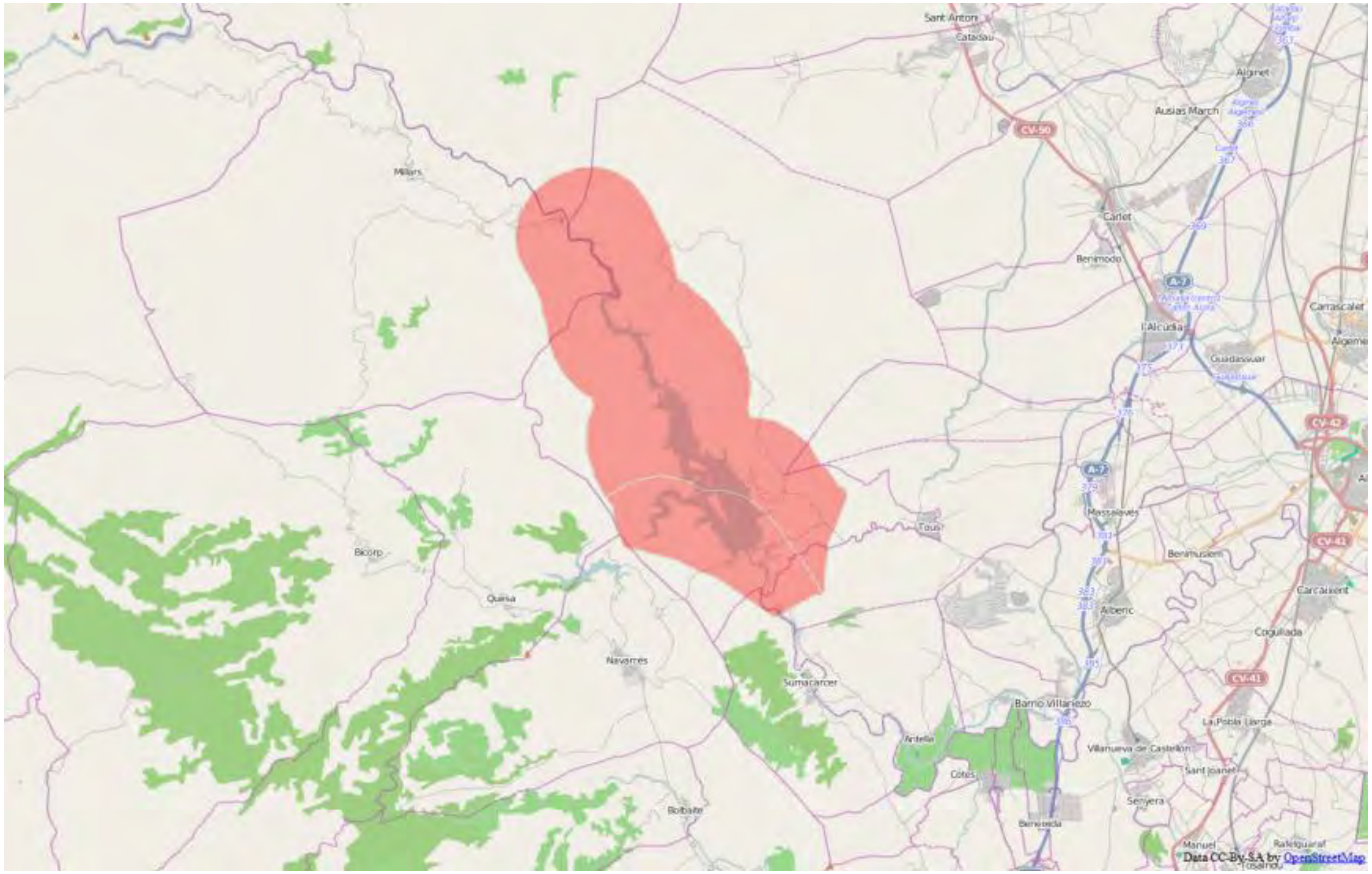


Fig. 9 Example of detail map of STU for Open Ponds-fresh water, high capability class, Spain (scale 1:125,000 approx.).

Algae Bioenergy siting, commercial deployment and development analysis

Technology aspects and related barriers

Final Meeting

Brussels

May 12, 2015

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OUTLINE

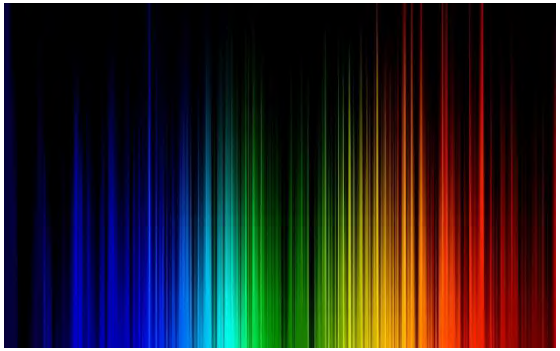
- Technologies
- Issues
- Increasing the added value
- Perspectives and final remarks

AVAILABLE TECHNOLOGIES

open ponds

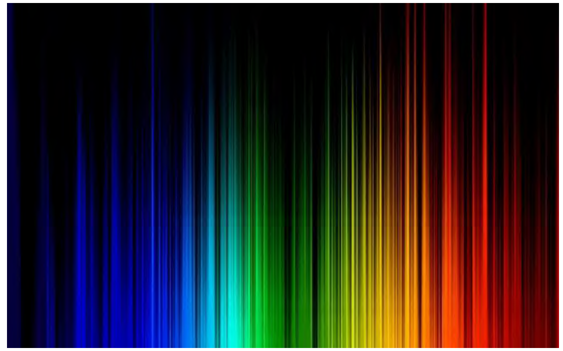
photobioreactors

THE FIRST ISSUE

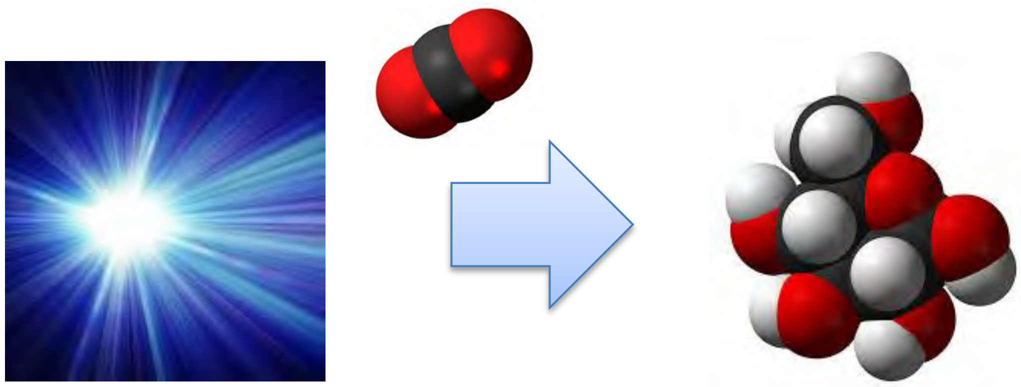


Visible light (PAR) is the only radiation exploited for photosynthesis: **46%**

THE FIRST ISSUE

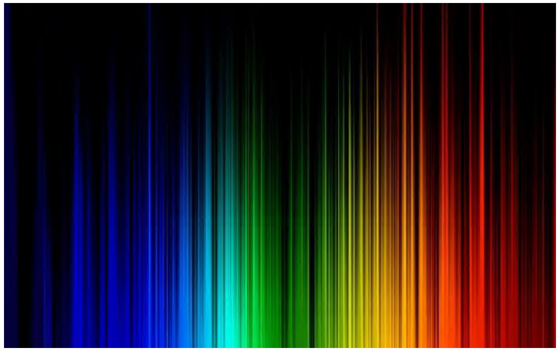


Visible light (PAR) is the only radiation exploited for photosynthesis: **46%**



Theoretical efficiency in the PAR conversion into chemical energy: **26%**

THE FIRST ISSUE



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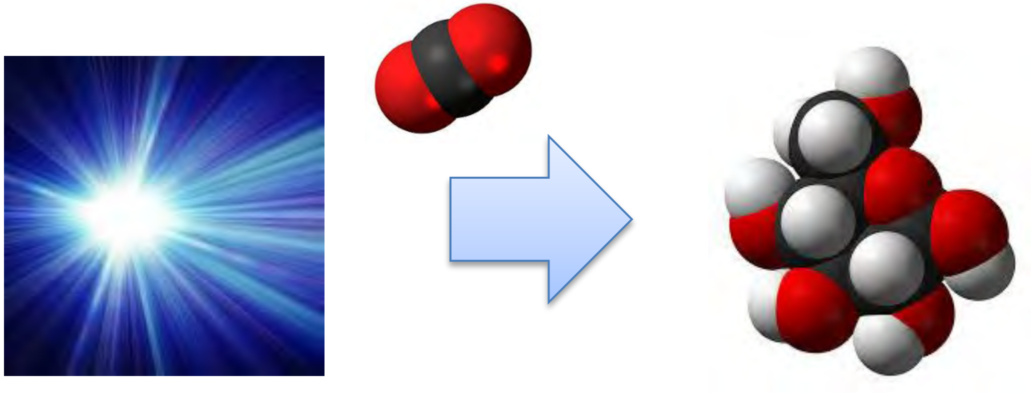
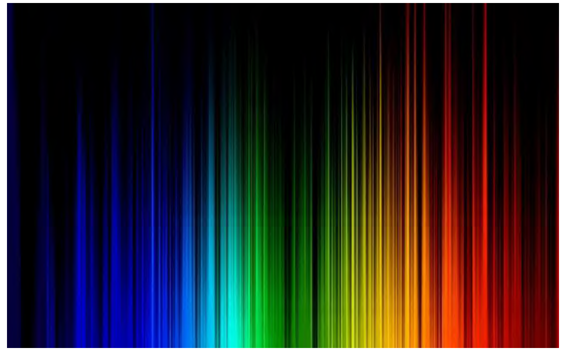


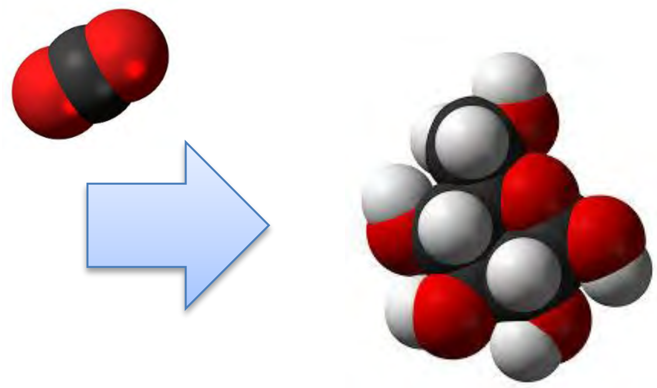
Theoretical efficiency in the PAR conversion into chemical energy: **26%**

Light theoretical efficiency is about **13%**

THE FIRST ISSUE



Visible light (PAR) is the only radiation exploited for photosynthesis: **46%**



Theoretical efficiency in the PAR conversion into chemical energy: **26%**

Light theoretical efficiency is about **13%** → **>350 t/ha/year**

THE FIRST ISSUE

Conversion efficiency in real large scale cultivation systems:
1-2% open ponds
3-5% photobioreactors

THE FIRST ISSUE

Conversion efficiency in real large scale cultivation systems:
1-2% open ponds
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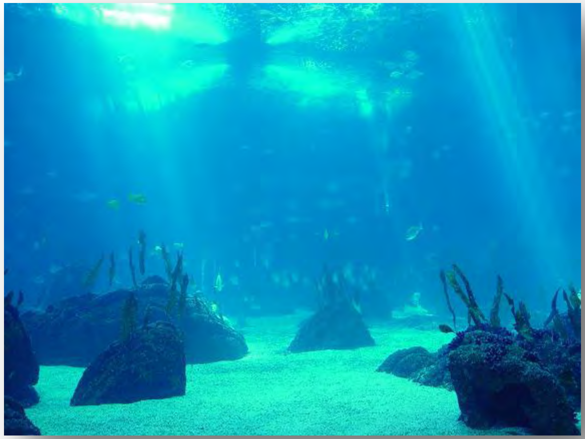
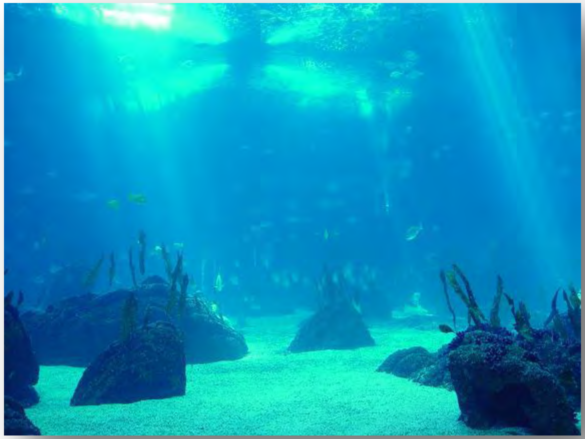


vs.

THE FIRST ISSUE

Conversion efficiency in real large scale cultivation systems:
1-2% open ponds
3-5% photobioreactors



vs.

- Intensive production still difficult
- large surface requirements
- CAPEX per surface unit is still high

OPEN PONDS

- Possibly the **most mature** technology for microalgae growth
- **Lower CAPEX** and easier operation (e.g. no need for temperature control)

OPEN PONDS

- Possibly the **most mature** technology for microalgae growth
- **Lower CAPEX** and easier operation (e.g. no need for temperature control)
- But
  - **Lower yield** (→ large surface requirements) and lower biomass concentration
  - **Subject to environmental conditions** (atmospheric events, external temperature…)
  - Significant **water footprint**
  - Prone to **exogenous contamination** (and viceversa)
  - Process optimisation and **intensification non-trivial**

PHOTOBIOREACTORS

- **Good productivity** (more efficient light conversion) and **higher biomass concentration**
- Possibility to guarantee **stable growth conditions** and more room for process optimisation

PHOTOBIOREACTORS

- **Good productivity** (more efficient light conversion) and **higher biomass concentration**
- Possibility to guarantee **stable growth conditions** and more room for process optimisation
- But:
  - **Large CAPEX and OPEX** (e.g. need for temperature control)
  - **Fouling** and maintenance costs
  - **No mature design** and configuration

WATER RESOURSES

WATER RESOURSES

- **Seawater**
  - no water footprint
  - unlimited and cheap water resources
  - fouling is higher (especially for PBRs)
  - siting must be along coasts

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WATER RESOURSES

- **Seawater**
  - no water footprint
  - unlimited and cheap water resources
  - fouling is higher (especially for PBRs)
  - siting must be along coasts

- **Freshwater**
  - water footprint may be an issue (especially for OPs)
  - water may become a significant cost
  - higher flexibility for siting
  - usually poorer in micronutrients

WATER RESOURSES

- **Wastewater**
  - cheap (a cost may be turned into a profit source)
  - nutrients (especially nitrogen) do not need adding
  - mixotrophy could be a sensible choice, too
  - in general dilution is still needed
  - limitations on suitable microalgae species
  - fouling may be a severe issue (especially for PBRs)
  - contamination issues may appear
  - limited wastewater resources

THE SECOND ISSUE

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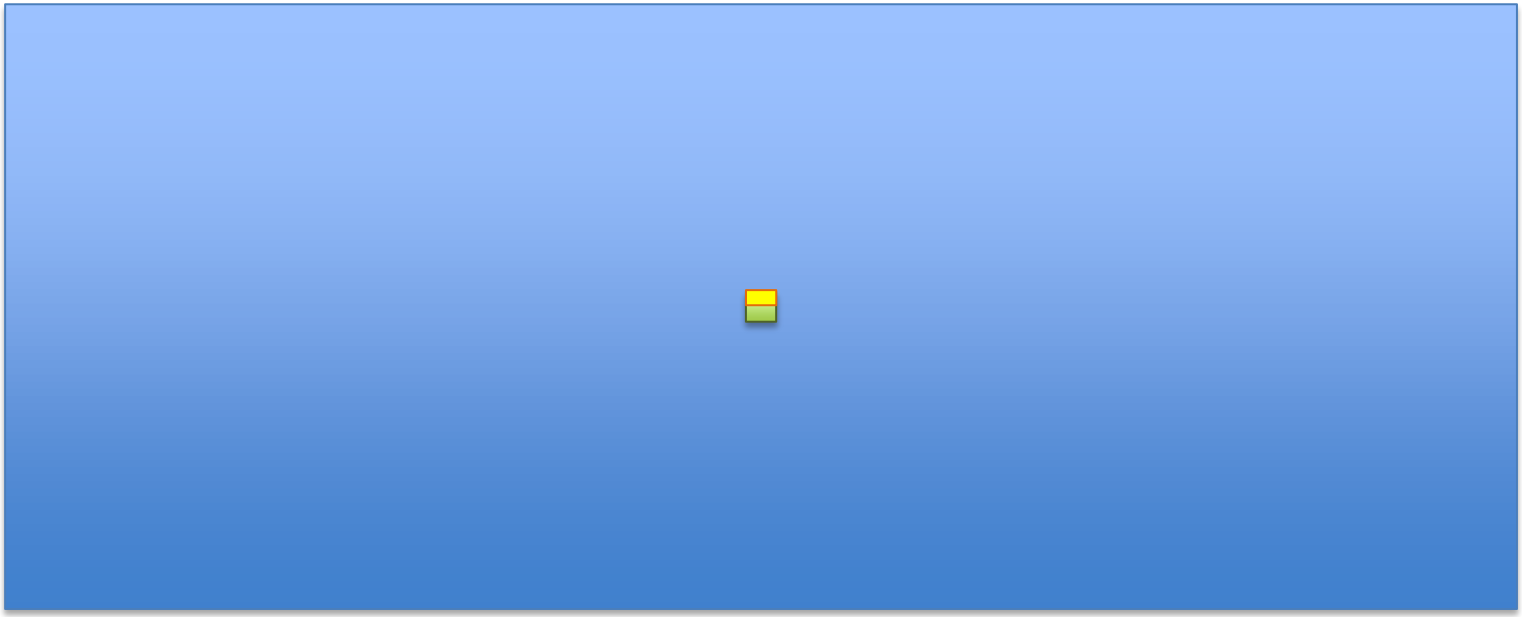
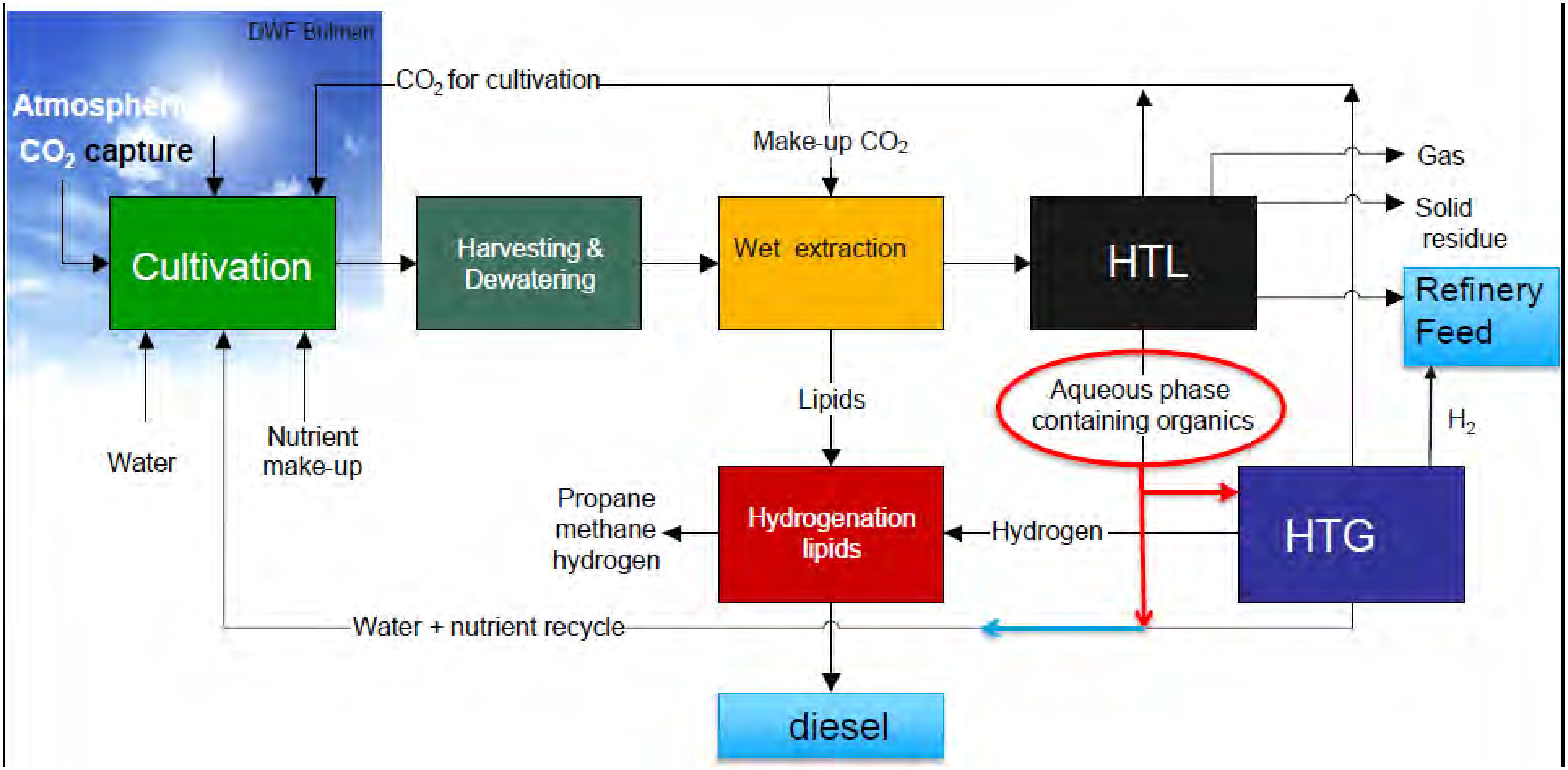


HARVESTING

- Microalgae cultivation is **not an intensive process**
  - light is a diffuse source of energy and conversion efficiency is limited
- **99.9%** of the cultivation system outlet is something we are not interested in (i.e. water)
  - harvesting the product is an issue and technologies can be **costly and energy intensive**; if the final product is oil and not biomass, then an additional degree of complexity is added
  - technology: combination of sedimentation, flotation, centrifugation, drying (with/without addition of chemicals)
  - **HTL** of algae seems interesting perspective (minor requirement of water removal and no need to extract oil from biomass)

HARVESTING



(Brilman, 2013)

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  - solid sources of CO_2 (e.g. carbonates) may represent an interesting perspectives (costs and biological drawbacks to be evaluated)
  - Perhaps opportunities from CCS and CO_2 pipelines

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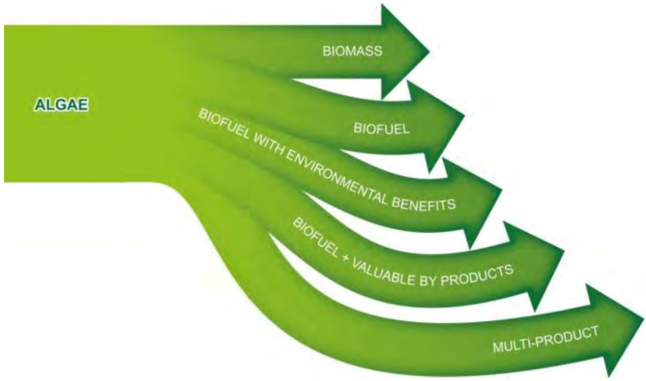
  - Perhaps opportunities from CCS and CO_2 pipelines
- **Fouling and maintenance** costs often underestimated
- **Usage of chemicals** (from coagulants to ionic liquids) not properly evaluated
  - may increase costs and cause issues on water recycle (inhibition on algae growth)

INCREASING THE CHAIN VALUE



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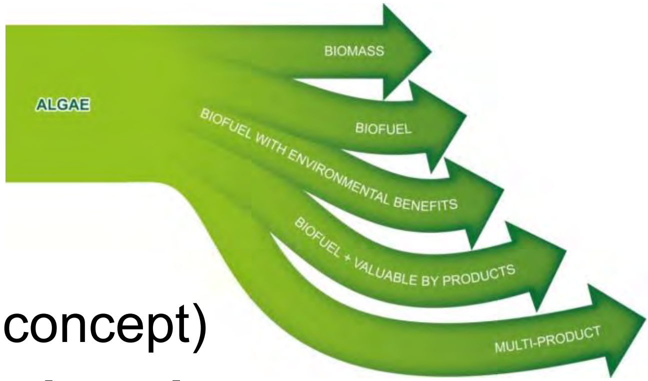
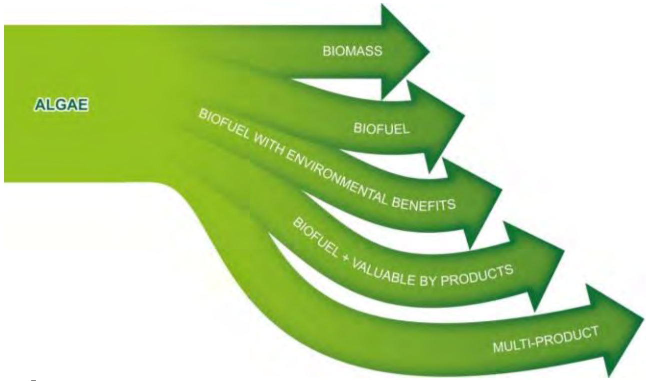


- Biofuels + valuable co-products
  - Highly interesting perspective (biorefinery concept)
  - Nowadays most valuable **products from microalgae are alternative to biofuels** (not complementary)
  - "Easy" bioproducts from residual biomass are low value-added products (compost, biogas, heat & power)
  - High value-added products require **high-tech separation systems and processes**
    - technical maturity is questionable
    - capex and opex can be very high
    - energy actor interested at entering value-added market?
    - new constraints on production technology (wastewater usage may not be allowed)

INCREASING THE CHAIN VALUE



- Multi-products
  - The biorefinery concept is strengthened
  - Fuel production cannot be given for granted
    - the objective is to make the chain profitable
  - Autotrophy is not a necessary requirement
  - **Focus on high-value added products**
    - technical maturity is questionable
    - new constraints on production technology (wastewater usage may not be allowed)
  - HTL may represent an interesting perspective
    - but it delegates to current petroleum and petrochemical industry the issue of developing and choosing the right technologies
    - algae producers deliver one product, i.e. the biocrude (and possibly an organic stream); other players decide the eventual products

PERSPECTIVES

- **Process intensification** and **cost reduction** are the key issues to be solved
  - **biological advances** required: new strains needed (selection or mutation) for more efficient light exploitation and biomass concentration
  - **tighter integration** between engineering design and biological know-how
    - design cultivation systems still based on experience and trial and error approach
    - lack of reliable quantitative models and **process simulation tools** hinder process understanding and optimisation
  - **downstream processes to be consolidated**
    - HTL promising but many issues still to be solves (e.g. biocrude stability)

PERSPECTIVES

- Co-product or multi-product based technologies still at their infancy
  - very interesting potential, but technical feasibility, large-scale yields, actual costs to be demonstrated
  - Need for tight process integration
  - Supply chain needs optimising and petrochemical industry may become key partner

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  - Need for tight process integration
  - Supply chain needs optimising and petrochemical industry may become key partner
- "The devil is in the detail"
  - nutrient and CO_2 supply (and costs) to be better assessed
  - maintenance costs and culture growth stability to be properly evaluated

FINAL REMARKS

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- The bet of obtaining fuels from algae has not been won yet, but still is a Pascal’s wager, i.e. the award is worth the gamble (still for a while at least)

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  - large investment on pilot plants or preindustrial facilities should be evaluated carefully

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  - large investment on pilot plants or preindustrial facilities should be evaluated carefully
- Technologies for high value-added products may give stimulus to technology advancements and investments on riskier investments
- Economic levers are as important as technology advancement

THANK YOU FOR YOUR ATTENTION

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Department of Industrial Engineering
University of Padova

Algae Bioenergy siting, commercial deployment and development analysis

Life Cycle Assessment

Final Meeting

Brussels

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PROJECT LAYOUT

Data Collection
- Literature Review
- Data Gathering
- Source of Information

Siting
- Identification of Constraints
- Deployment Potential GIS Mapping
- Cultivation Systems Impacts and Deployment Potential Assessment

Bio Energy & Co Product
- State of the Art
- Indicators and Bio-energy & Co-Products Ranking
- FP7 Case Studies Analysis

Barriers Analysis
- Identification and Analysis of Barriers to Deployment
- Recommendations

D'APPOLONIA
consulting, design, operation & maintenance engineering

SELC
biologia e geologia applicata

Università degli Studi di Padova

PROJECT LAYOUT

LCA

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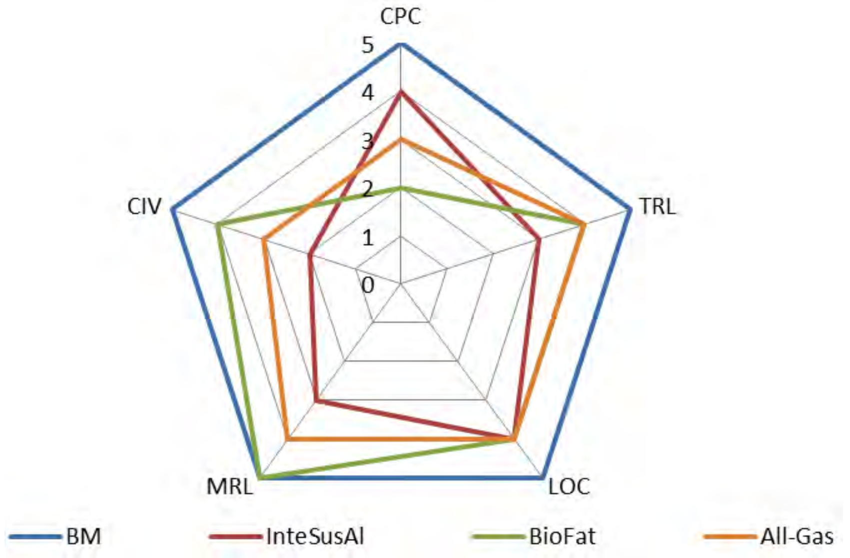
INTERACTION WITH FP7

Continuous interaction with FP7 projects of the AlgaeCluster

- questionnaire for input data
- review of interim documents
- comparison of LCA approaches
- gap analysis and rating

CATEGORIES	NOTES	DESCRIPTION/VALUE
Microalgae species		Fresh water
Taxonomic group		Natural bloom… it means that any mono species culture is promoted in our Raceway ponds.
Metabolism type	Photoautotrophic, heterotrophic, etc.	Photoautotrophic
Chemical composition	Lipid content	Less than 10%
Photosynthetic efficiency [%]		N.A.
Growth rate [g/m2/d]		Average: 25 gr/m2/d (After 18 months of operation)
CO2, nutrients, light and water uptake and sources		Pure CO2, waste water as nutrients source.
Specific growth requirements	CO2, nutrient, PH, solar radiation, temperature, mixing, etc.	
Cultivation technologies		
Type and description	Open ponds, tubular PBR, flat plate PBR, fermenters, etc.	Conventional ponds
Size [m2]		32 m2/unit
Operability conditions and technical parameters	Batch/continuous cultivation, algal concentration [g/l]	Continuous, algal concentration, NA
Energy input [kWh/m3]		To be confirmed



APPROACH TO LCA

Cradle to grave only where possible

- plant construction was not considered
- plants were considered to be installed in a suitable location
- wastewater treatment was included in the analysis
- input materials at gate

APPROACH TO LCA

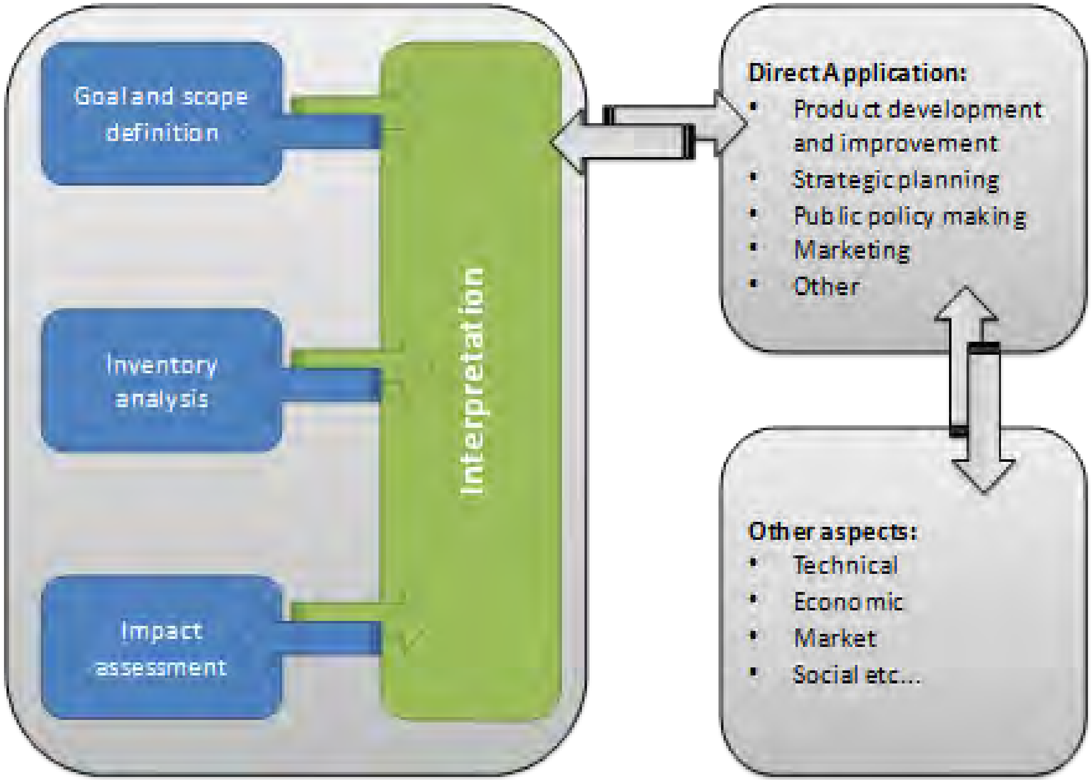
Boundary conditions - IN

- energy consumptions, heat and electricity
- processing of materials
- electricity generation from the mix
- waste
- wastewater treatment

Boundary conditions - OUT

- construction of the facility
- internal transportation
- end users' vehicle engines
- anything after the initial production of the biofuel

METHODOLOGY



LCA as much as possible consistent with AlgaeCluster:

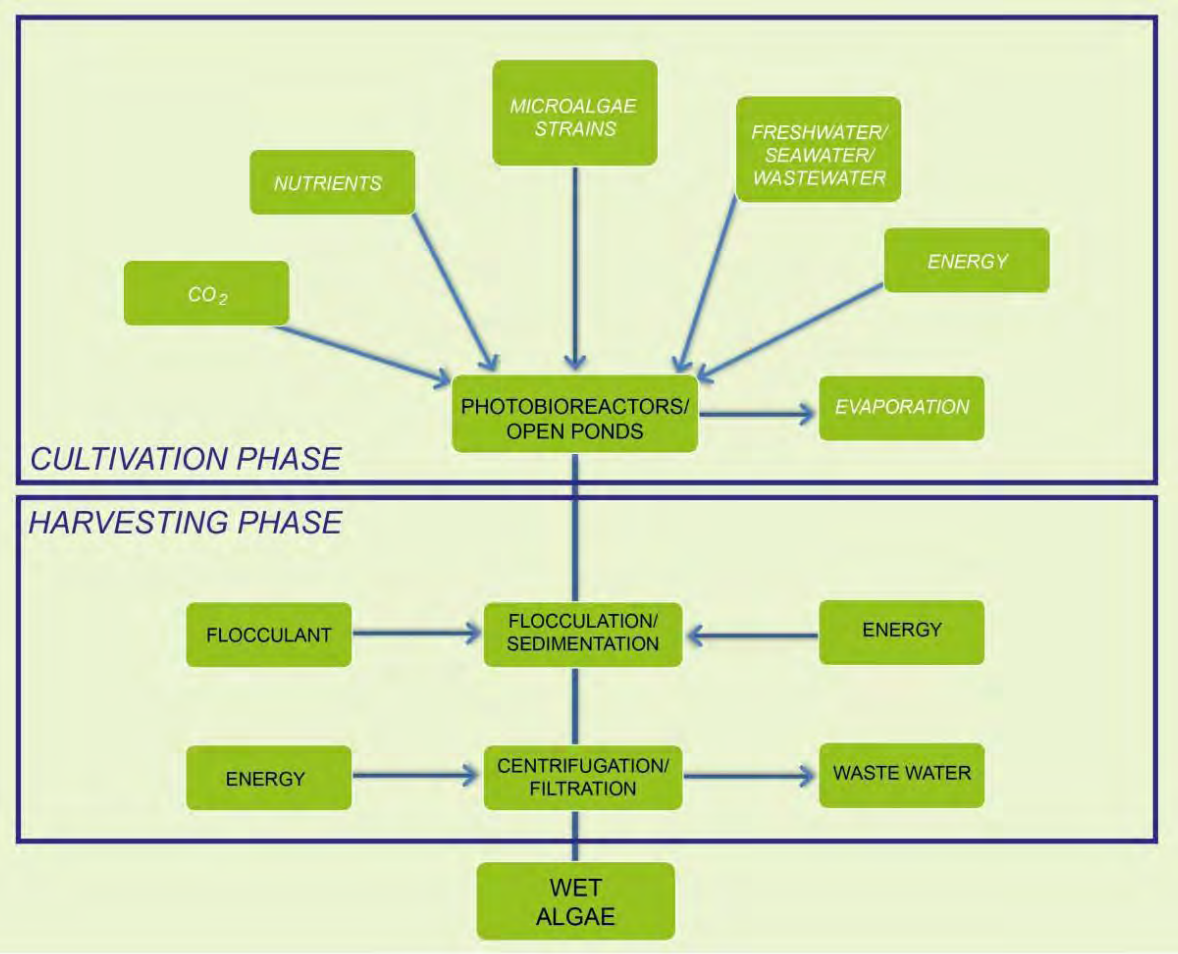
- Data from PE International Database (now Thinkstep) analyzed using GaBi□

- Functional unit
1 kg of wet algae - cultivation
1 kg biodiesel – biofuel production

- System boundaries
From cultivation to biofuel

- Impact Assessment Methodologies
CML 2001 + IPCC AR5

LCA OF ALGAE CULTIVATION



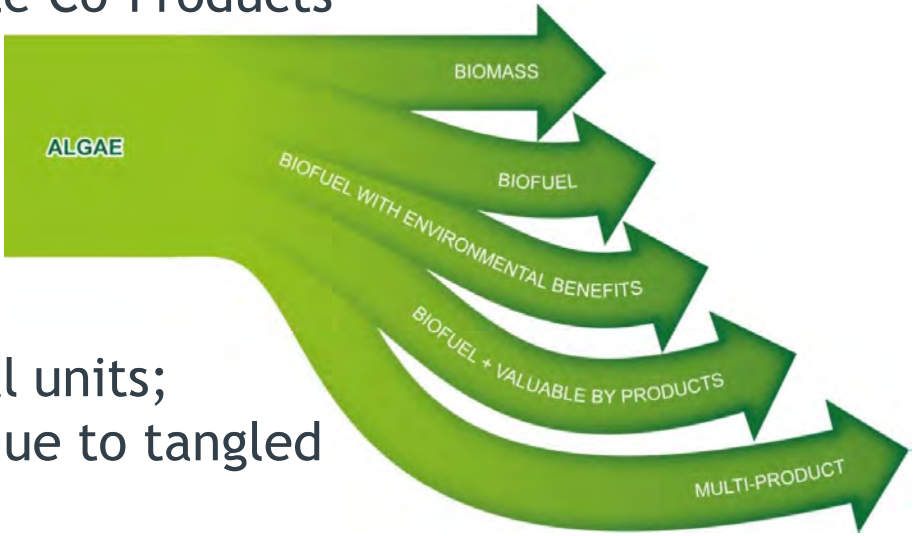
Cultivation phase:
16 case studies

- cultivation: open ponds / photobioreactors
- cultivation medium: freshwater / seawater / wastewater
- harvesting: flocculation / sedimentation
- thickening: centrifugation / filtration
- output: wet algae

CASE STUDIES

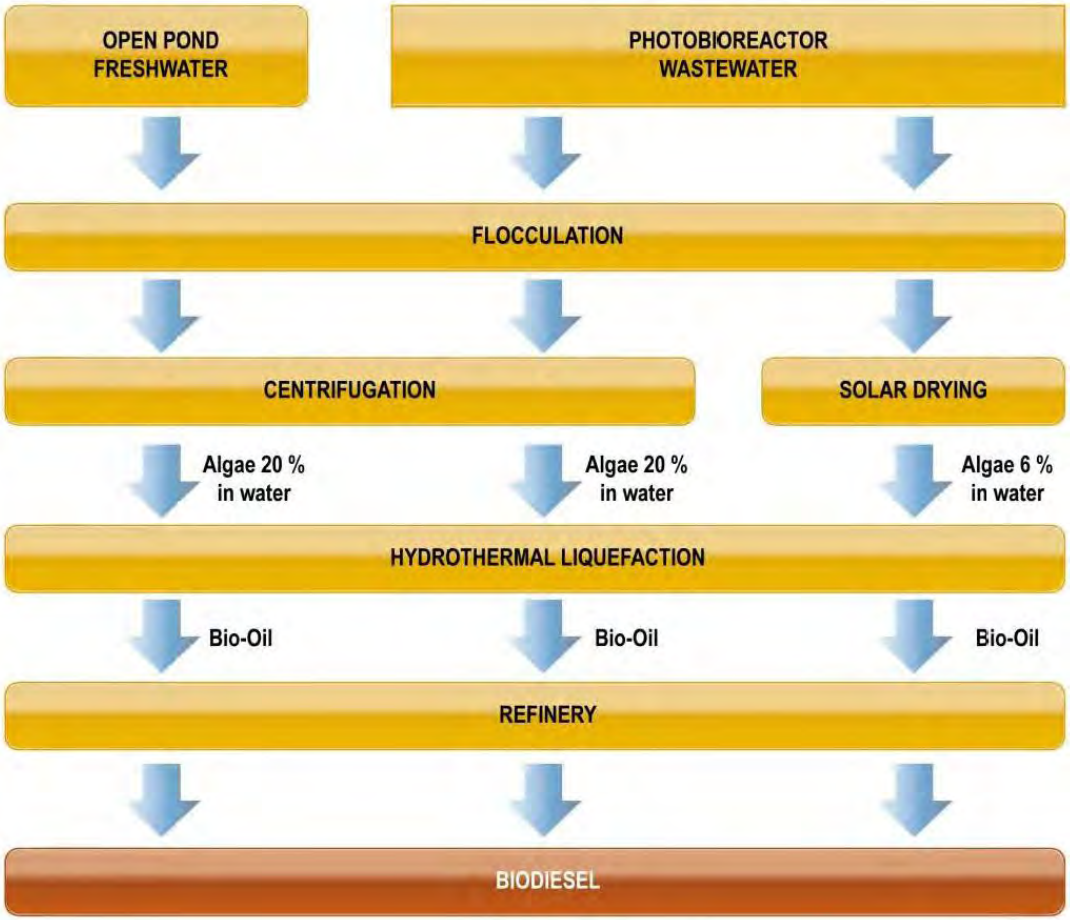
Identification of five production chains:

- PC1 – Biomass Production
- PC2 – Biofuel Production without Co-Products
- PC3 – Biofuel Production without Co-Products but with Environmental Benefits
- PC4 – Biofuel Production with Valuable Co-Products
- PC5 – Multi-Product Approach



It is worth noting that:
- for some PC, several sub-cases exist;
- different PC have different functional units;
- on some PC LCA was not performed due to tangled layout of processes.

PRODUCTION CHAINS



Biofuel / Co-Products Chains

- same approach as cultivation
- alternative use of freshwater or wastewater
- flocculation for harvesting
- centrifugation / solar drying for thickening
- hydrothermal liquefaction and biodiesel production
- output: biodiesel

REFERENCE DATA

Parameter	1 A	1 B	1 C	2	3 A	3 B
Mass flows [kg]						
Water	900	22.5	22.5	900	22.5	22.5
Carbon dioxide	8.75	2.62	2.62	8.75	2.62	2.62
Fertilizer	0.31	0.31	0.31	0.31	0.31	0.31
Flocculant	0.35	0.35	0.35	0.35	0.35	0.35
Natural gas	-	-	-	0.028	0.028	0.028
Energy flows [kWh]						
Water feeding	0.875	0.025	0.025	0.875	0.025	0.025
Cultivation	0.49	0.015	0.015	0.49	0.015	0.015
Carbon dioxide feeding	0.175	0.050	0.050	0.175	0.050	0.050
Water-algae pumping	0.218	0.025	0.025	0.218	0.025	0.025
Bulk harvesting	0.006	0.006	0.006	0.006	0.006	0.006
Thickening	0.27	0.027	-	0.27	0.027	-
Hydrothermal liquefaction	-	-	-	0.069	0.069	0.069

Uncertainty on real data

- literature studies based on pilot plants
- energy consumption strongly depends on cooling need
- reported net energy ratios (energy consumption / biofuel energy content) range from 0.5 to 6.0

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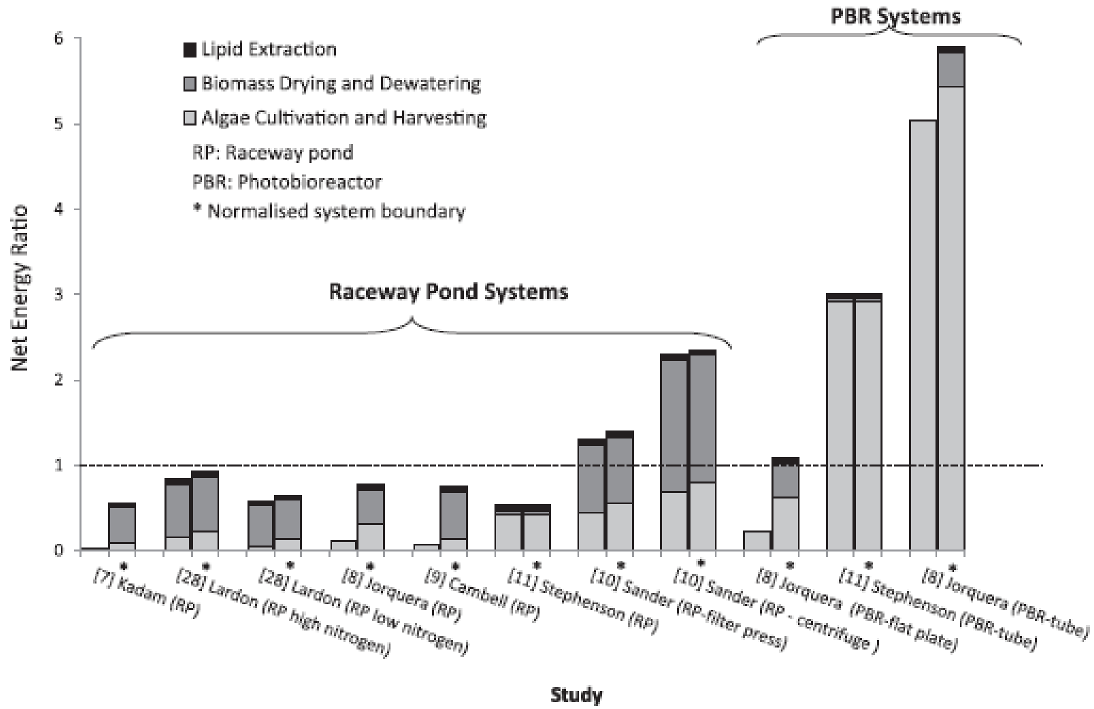

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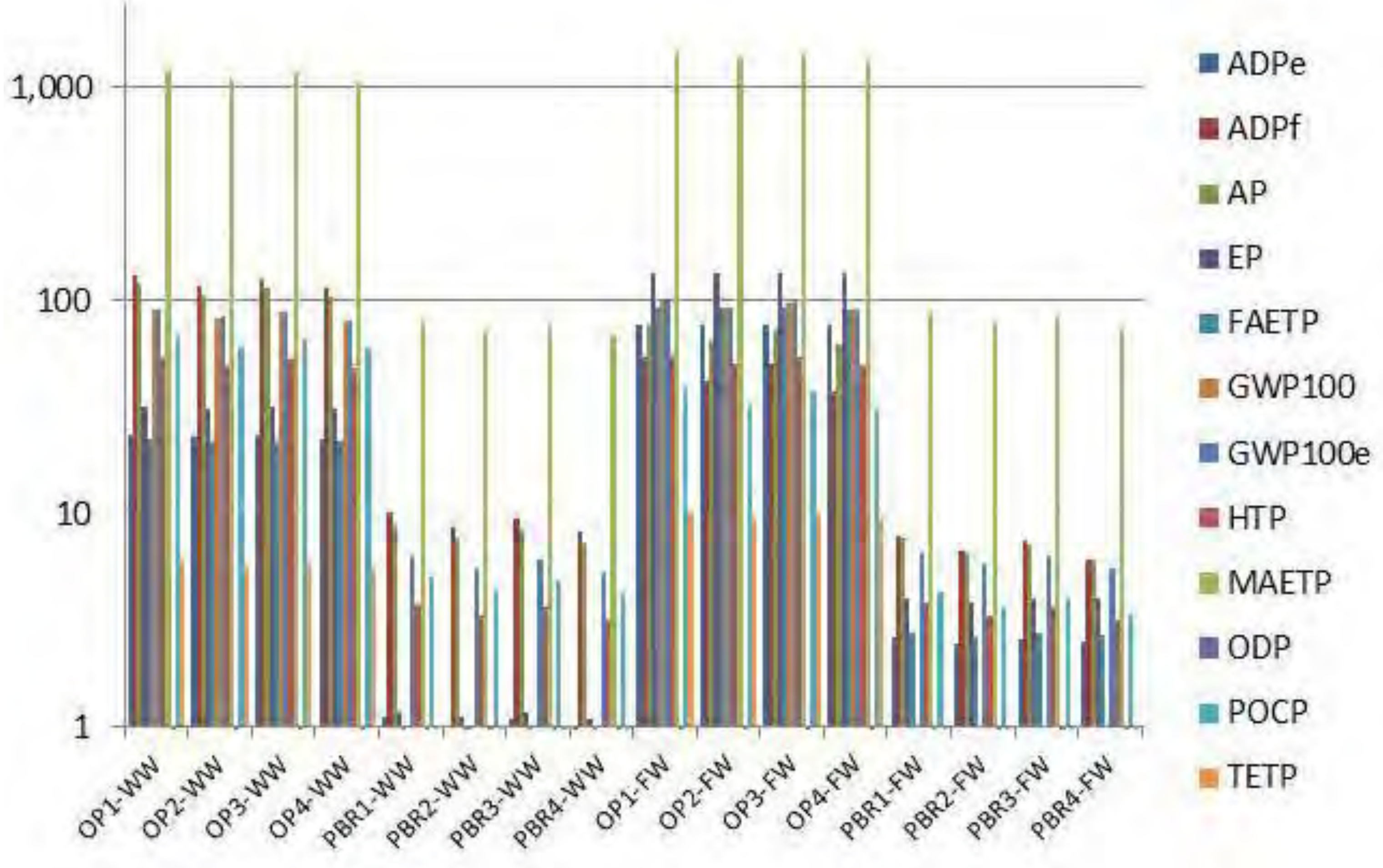
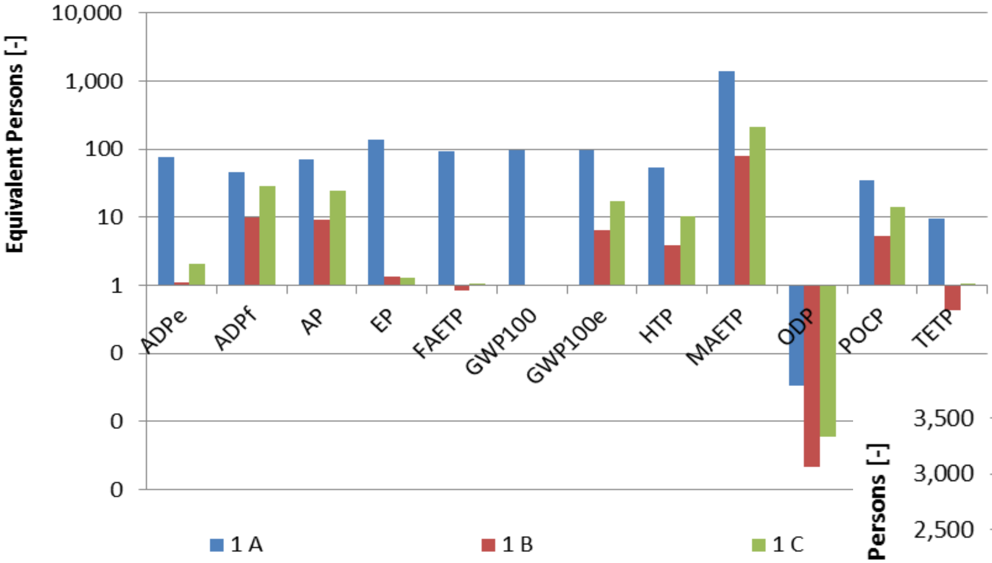
FIGURES FOR CULTIVATION

Figures from the 16 Case Studies



FIGURES FOR BIOFUEL PRODUCTION



Production Chain 1 – biomass only

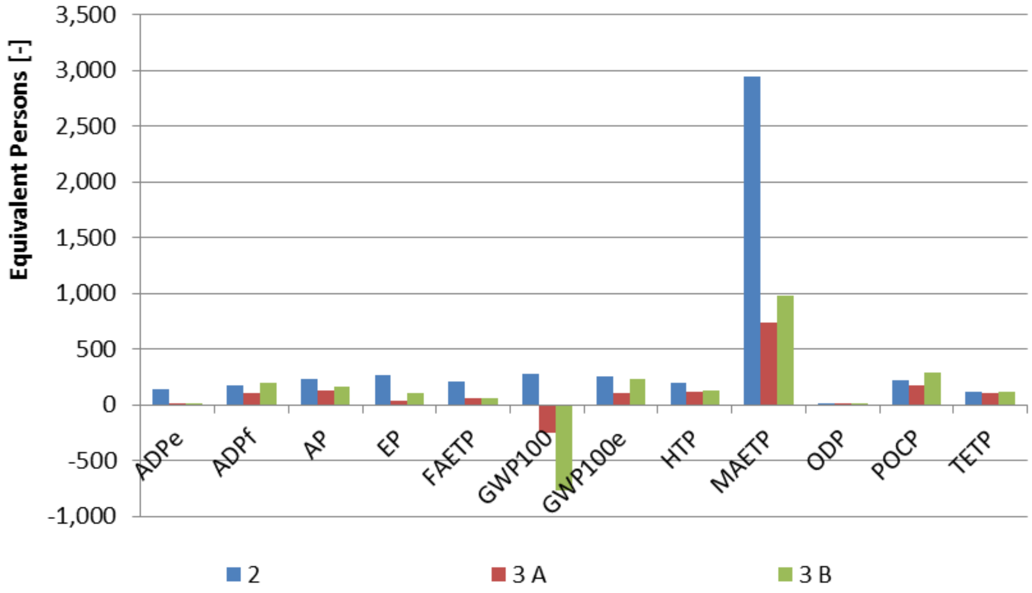
- 1A: OP, FW, Flocc, Centr,
- 1B: PBR, WW, Flocc, Centr
- 1C: PBR, WW, Flocc, Solar Dr

- functional unit: 1 kg of wet algae

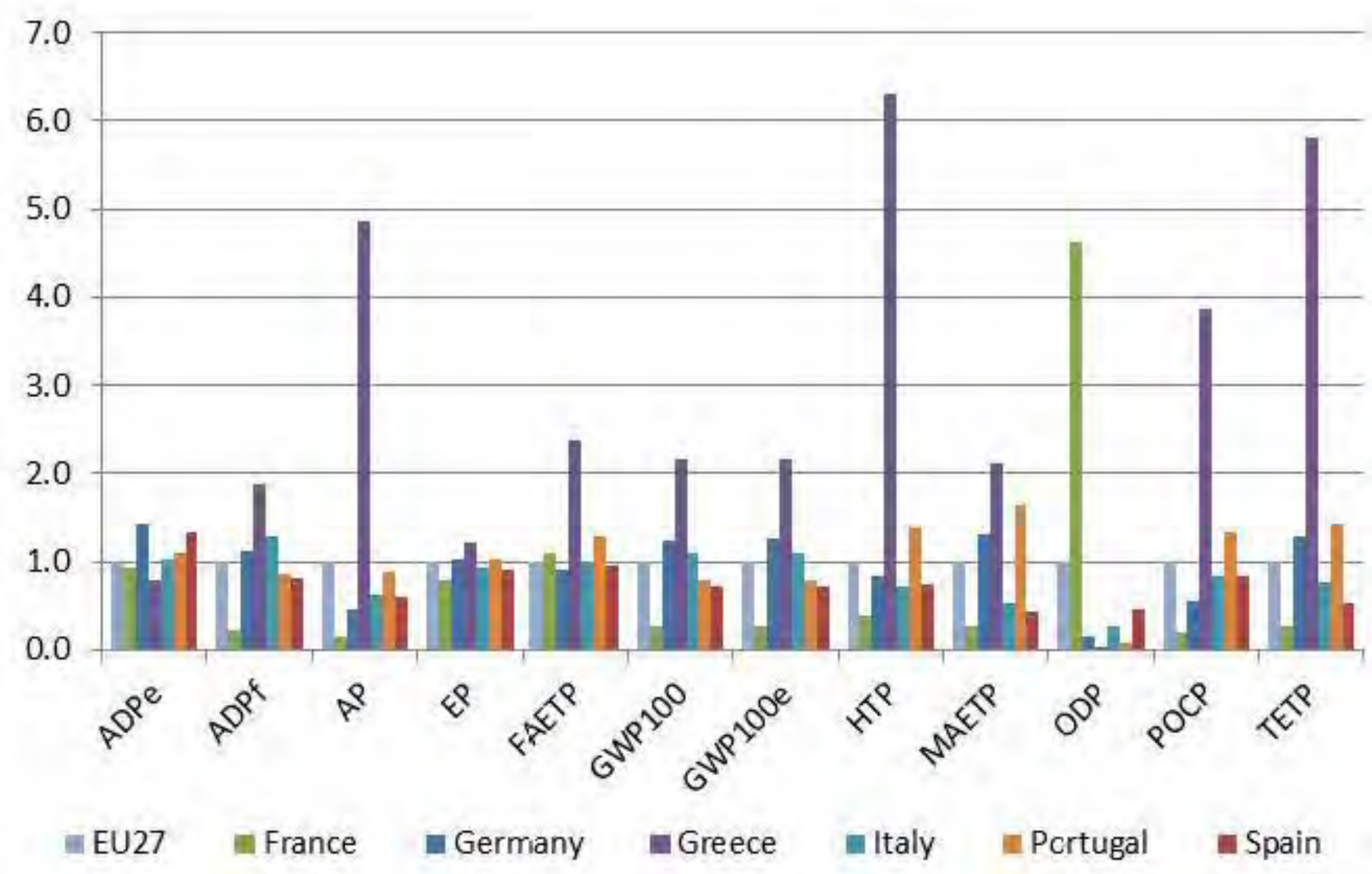
Production Chains 2-3 - biodiesel

- 2: 1A, HTL, biorefinery
- 3A: 1B, HTL, biorefinery
- 3B: 1C, HTL, biorefinery

- functional unit: 1 kg of biodiesel



SENSITIVITY ANALYSIS



LCA RESULTS

The main results of the LCA study are:

- large uncertainties exist in the input data on resources use
- real measured data in demo plants are strongly required
- strong differences from Country to Country, even in the EU
- PBRs seem to have a lower impact than OPs (issue with cooling? ☺)
- economic and energetic distance among different solutions is much larger than the environmental – LCA one
- possible solutions to reduce impact:
  - optimal siting of the cultivation plant
  - choice of low-energy harvesting / thickening techniques
  - maximum wastewater recycling and use of CO_2 from industry

CONCLUSIONS

Besides LCA results, the study allowed to provide useful data to the scientific panorama about:

- most suitable algae strains and cultivation plants
- biologic, technologic, economic and environmental aspects of algae cultivation and subsequent biofuel production
- identification of best suitable areas for algae-based plants
- gap analysis to assess distance from the market of each production technology
- identification of barriers
- recommendations and action plan

- the project deliverables are available on the website **http://www.algaetofuel.eu**

Algae Bioenergy siting, commercial deployment and development analysis

Economic assessment, barriers and scenario

Final Meeting

Brussels

May 12, 2015

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What have we done ?

- Draw a list of indicators to address socio-economic issues for siting (task 1)
- contribute to the SWOT analysis : economic strengthens and weaknesses of technologies and production chains (task 2)
- Identify economic barriers and scenario (task 3)

Socio-economic indicators for siting (task 1)

- **Objective** : Rank suitable sites based on socio-economic parameters (identify situation/areas favorable for siting)
- **Hypothesis** : Need capital, skills, inputs and infrastructures to invest and operate in biofuel sectors (plants). Not all areas in Europe are suitable for this (or not at the same degree);
- **Selection criteria :** be quantified at nuts 3 or 2 levels with a good European coverage (databases : Eurostats and ESPON project)

Socio-economic indicators for siting (task 1)

- List of **indicators** proposed (some of them are proxy):
  - ‘Population density’ (proxy for waste water collection systems)
  - ‘Share of industrial, commercial and transport units’ (proxy for land and inputs supply)
  - ‘Potential accessibility to road’ (concentration in transport infrastructure)
  - ‘Gross value added’ (proxy for investment capacity)
  - ‘Share of population by highest level of education’.

Socio-economic indicators for siting (task 1)

Table 3.4: European EU28 Average Values

Variables	EU28 Average	% of STU under EU average - Open pond	% of STU under EU average - PBR
Population density (Inhabitants per square kilometre)	**117**	65%	68%
Share of industrial, commercial and transport units (hectares per total hectares area)	**1.9%**	94%	93%
Potential accessibility by road (Composite value)	**19191791**	100%	100%
Gross Value Added (EUR Millions)	**9373**	48%	56%
Share of population by highest level of education (population with highest level of education per total population)	**12.3%**	58%	68%

Source: Eurostat; Espon

Socio-economic indicators for siting (task 1)

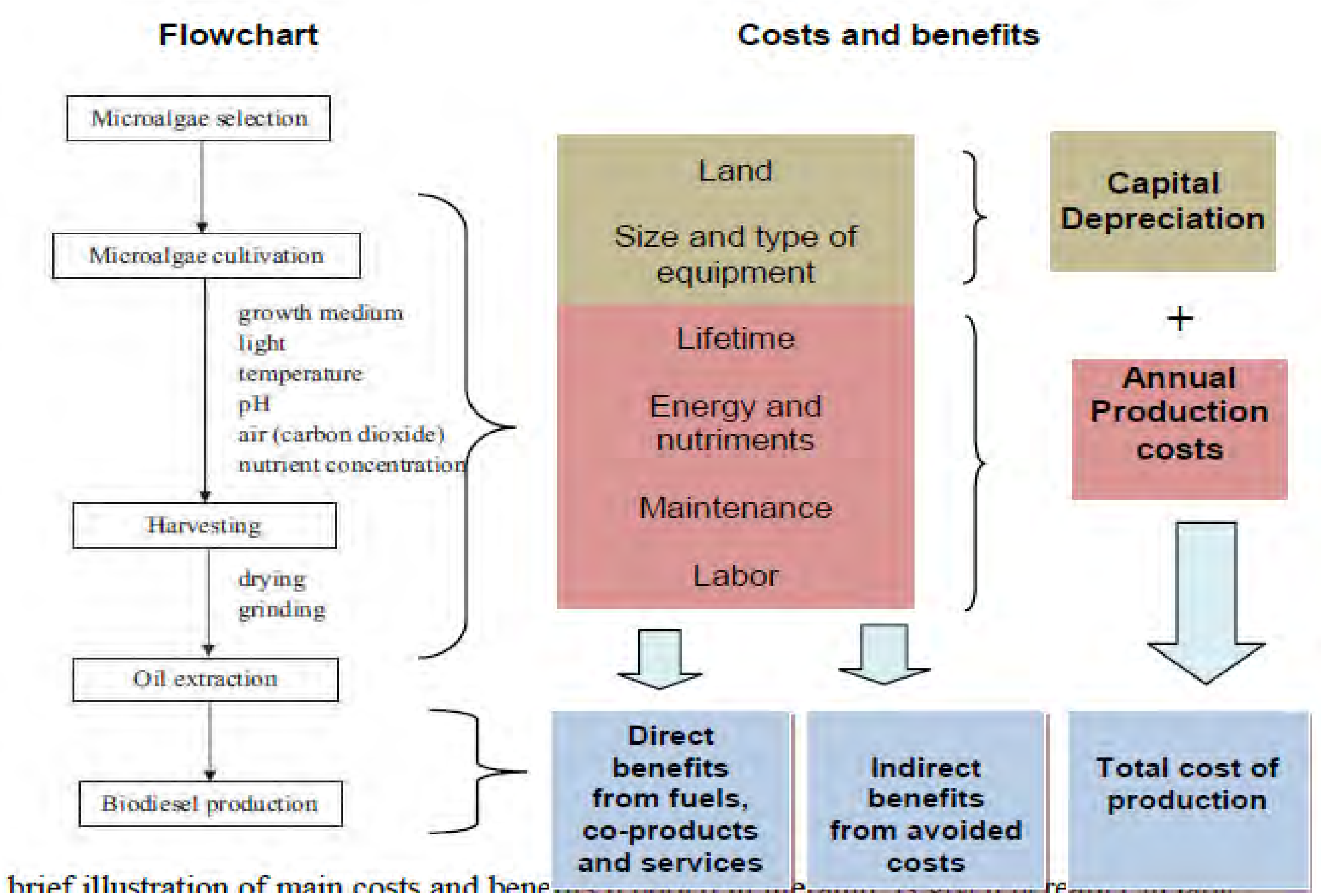
- **Few sites are favourable** (considering the average EU value): many of them are in the ‘middle of the bush’
- **But … paradox (?) :** the Southern regions in Europe (the less developed one) enjoy more subsidies for investment in infrastructures than the Northern regions (through the ESI funds).

Economic SWOT analysis (Task 2)

- **Objectives** : Better understand what are the main sources of costs and benefits all along the biofuel production chains (or technologies)

Typology of costs	Direct and indirect Benefits
- Land requirement (surface); - Size and type of equipment - Investments - Maintenance costs - Energy and nutriments - Labour and engineering costs	- Biofuels - Co-products (biomass, feed for animals, fertilizer, pigments, chemicals) - External benefits (storage of CO_2, waste water recycling, ..)

Economic SWOT analysis (Task 2)



Economic SWOT analysis (Task 2)

Economic SWOT for PBRs

Strengths
- low land requirements
- low water use
- can use CO_2 from combustion
- high-value by-products
- low costs for some harvesting techniques

Weaknesses
- high equipment costs
- high energy consumptions
- high staff cost
- high costs for some harvesting techniques

Opportunities
- possible circular and close production systems recycling water, nutrients, by products
- costs are dropping with technology improvement
- high fossil fuel energy prices

Threats
- limited market for by-products
- costs are still high compared to other biofuels or fossil fuels
- low economy of scale

Economic SWOT for Open Ponds

Strengths
- low investment costs
- strongly variable land costs
- generally low energy needs
- can use CO_2 from combustion
- high-value by-products
- low costs for some harvesting techniques

Weaknesses
- land surface not below 100 ha
- infrastructures are required
- significant fertilizer costs
- significant water consumption and energy for pumping
- high costs for some harvesting techniques

Opportunities
- possible circular and close production systems recycling water, nutrients, by products
- costs are dropping with technology improvement
- high fossil fuel energy prices

Threats
- limited market for by-products
- costs are still high compared to other biofuels or fossil fuels
- low economy of scale

Economic SWOT analysis (Task 2)

- How to improve the cost-benefit balance of algae biofuel production systems (i.e. fostering benefits and reducing costs) ?
  - Minimizing energy demand from the production process (re-use biomass as energy source) or used external energy sources at low cost (heat or electricity from co-generation plants);
  - water recycling (on site)
  - Access to low cost nutriments and CO2 sources (from industrials processes);
  - Delivering by-product able to compete with (and substitute) market products at a reasonable high level of demand.
  - Reused brownfields' areas (for siting);
  - Invest in place which are as close as possible to infrastructures and public facilities (roads, water supply systems, waste treatments systems, …)

Economic barriers and scenario (task 3)

- **Objective** : identify economic barriers at short-medium terms and solutions.
- **Main barriers :**
  - Production not competitive with standard fuels (ratio 1/10 reported in the literature);
  - Significant investments needed to reach economy of scale (large volume of biofuel are probably required to optimized production/distribution costs)
  - Fiscal and economic incentives not (still) favourable to the development of algae production chains (at least not enough to boost production and distribution at EU/national levels).

Economic barriers and scenario (task 3)

- **Scenario on energy prices**: Scenarios on energy prices – based on supply and demand analysis in fossil fuels - are not favourable at medium and also - according simulation from Europe Commission - at long term (2010-2050). Confirmed the ‘factor 10’ over the next decade (at least) in a scenario with no-technological progress ? Other possible scenario: where the price of the permits to emit CO_2 increased in a dramatic way – due to stronger climate mitigation policies - pushing the fossil energy prices up ?

Economic barriers and scenario (task 3)

- Solutions to overcome economic barriers:
  - Fill the normative gap at EU and Member levels, identifying a clear financial and normative mechanism to support the development of the sector over the next five years ? What are the last development in this field …
  - Propose some financial supports (grants or Financial instruments) to investments in the development phase of bio-algae production process (From ESI Funds ?); taking also into account the funding of public infrastructures needed for plants development;
  - Enhance tax concession, or financials incentives, or enlarge the biofuel obligation approach (quota) to biofuel production from algae.

We probably need angels (Business-) to overcome the Pascal's wager !

Thanks for your attention

François Levarlet

D'APPOLONIA

SELC biologia e geologia applicate

Università degli Studi di Padova

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Recommendations and Conclusions

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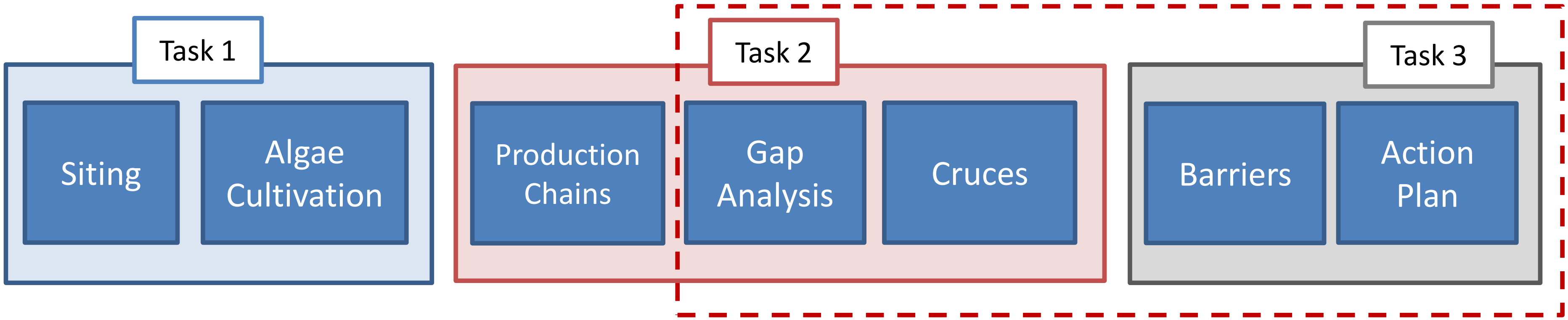
RECOMMENDATIONS AND CONCLUSIONS
AREAS OF THE PROJECT



Main activities:

- Gap Analysis
- Cruces
- Barriers
- Action Plan

Recommendations and Conclusions

METHODOLOGICAL APPROACH

«The Barrier»:

- a big distance still exists between conventional fossil fuels and the algae-based biofuels in terms of competitiveness on the market.

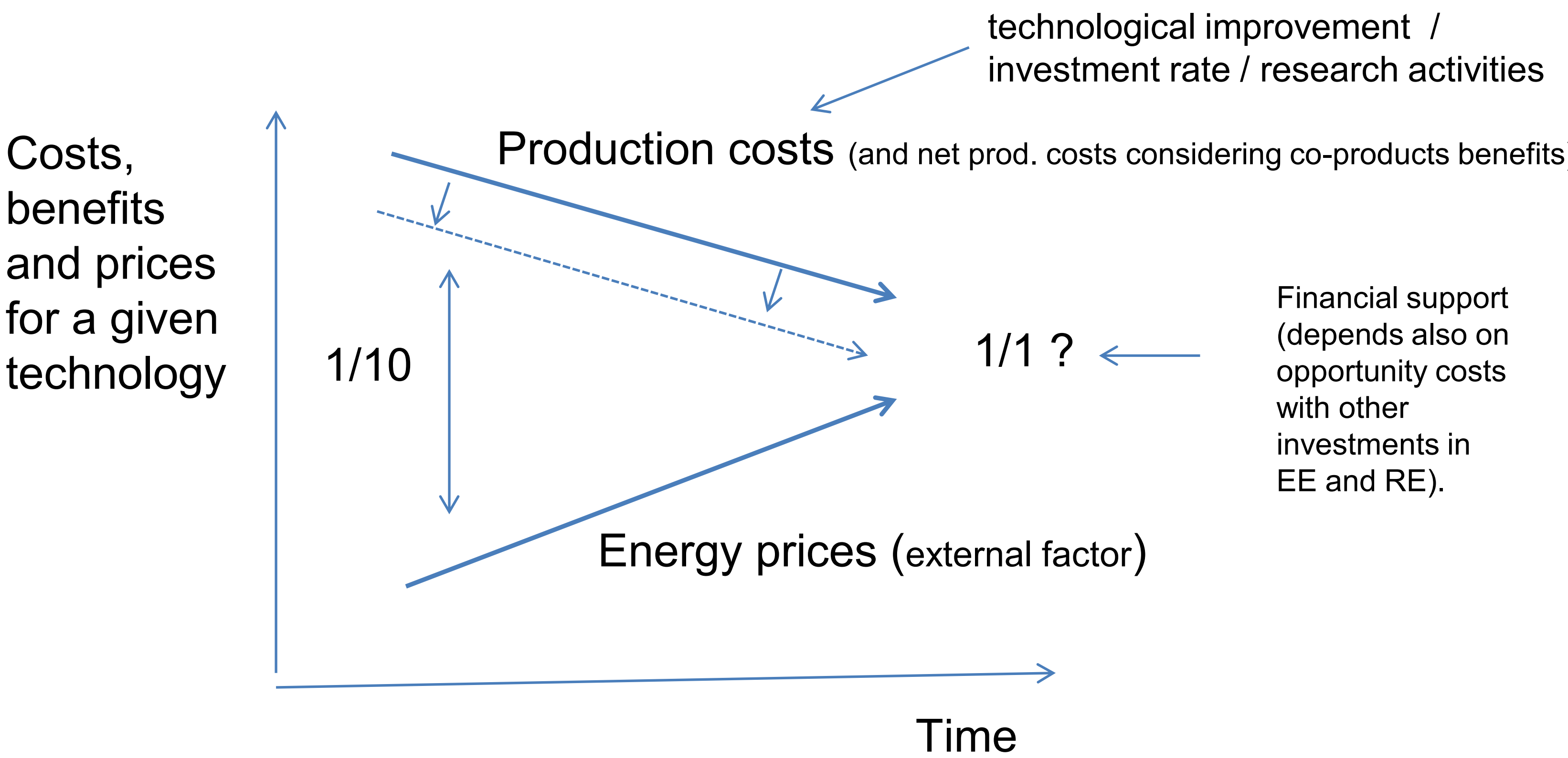
Cruces:

- necessary conditions to achieve before entering the process of access to the market. After the overcoming of a crux, further barriers may exist.

Barriers:

- issues that generate a negative consequence on the chain
- according to the severity of their effects, barriers are classified as:
    - first class (hinder the development of a process)
    - second class (reduce the performances of a process)
- the following aspects are considered:
    - technical
    - economic
    - policy and normative background
    - public acceptance
- can be overcome

"THE BARRIER"


technological improvement / investment rate / research activities
Costs, benefits and prices for a given technology
Production costs (and net prod. costs considering co-products benefits)
1/10
1/1 ?
Financial support (depends also on opportunity costs with other investments in EE and RE).
Energy prices (external factor)
Time

CRUCES

Five main cruces to market development of algae-based plants:

- Competitiveness of Production Costs
- Technology Availability and Readiness
- Location
- Market Readiness for Products and Operators
- Achievement of Critical Industrial Volumes

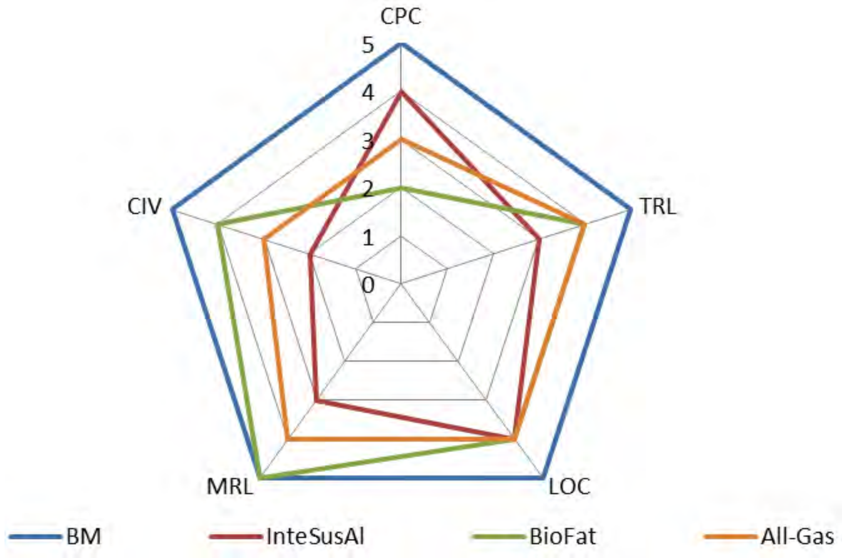
score / meaning	Competitiveness of Production Costs	Technologies Availability and Readiness	Location	Market Readiness for Products and Operators	Achievement of Critical Industrial Volumes
1	Production chain with absolute lack of competitiveness in production costs compared to other fuel and biofuel production chains.	The technology is at extremely low TRL. The concept is available but no prove of implementation in working environment is available.	The site is not suitable for the installation of an algae cultivation plant, due to geographical issues and lack of availability of water, carbon dioxide, nutrients and other materials.	Production chain with almost no possibility to generate revenues and to acquire shares of any market.	This production chain is in a pilot phase, thus very far from the achievement of a consistent industrial diffusion.
2	Production chain still not competitive in production costs compared to other fuel and biofuel production technologies. The gap from a viable solution can be reduced in the medium term.	Technology with poor availability, non solid and with relevant lackings in terms of real scale application. Basic components and constituents are not yet available or are immature, and strongly limit its implementation.	Location showing a sufficient degree of suitability for the installation of an algae cultivation plant only on some of the geographical characteristics. In addition, the supply of most of the required materials is difficult.	Production chain with limited and non-proven capacity to acquire shares of the market and no possibility of transfer to different markets.	The production chain is in a pre-industrial diffusion scale and a critical industrial volume is not reachable at the moment.
3	Production chain having a sufficient degree of competitiveness in production costs with respect to the current state of the art in the sector.	Technology having a good degree of maturity, with ancillary items yet to be developed or adapted, or some adaptation missing (e.g.: to make it work autonomously, to make it robust or operated autonomously,	The site is suitable under a geographical perspective, but its location leads to difficult supply of at least one among water and other required materials.	Production chain facing the limitations and barriers to access within a specified field technological domain, is expected to generate revenues and to be able to conquer a niche.	The production chain is developed and is starting to be implemented; a consistent industrial diffusion of the final product is foreseen in the medium term, at least in specific areas.
4	Production chain having a good competitiveness in production costs compared to other fuel and biofuel production chains.	Technology totally assessed, perfectly working and at high degree of maturity. Minimum adaptations are required to improve the performances.	Location that meets the minimum requirements in terms of both geographical characteristics and availability of water, carbon dioxide, nutrients and other necessary	Production chain with recognised capacity to generate revenues and whose products will positively be received from markets.	Production chain that is widely applicated in only a few countries. Critical industrial volume is reached only in some areas.
5	Production chain having outstanding cost competitiveness with respect to the current state of the art in the sector.	Technology at the highest level of TRL. Completely assessed, scalable and ready for the installation. No limitations and need for adaptation of the technology in the different cases of installation.	Location characterized by excellent features on geographical parameters and availability of water, carbon dioxide, nutrients and other necessary material.	Optimal production chain, capable of fast assessment and rapid growth in differentiated markets and whose products are easily sold on the market.	Fully developed production chain, having a wide diffusion in different countries, thus achieving a critical industrial volume.

OUR PROJECT AND FP7

Continuous interaction with FP7 projects of the AlgaeCluster

- questionnaire for input data
- review of interim documents
- comparison of LCA approaches
- gap analysis and rating

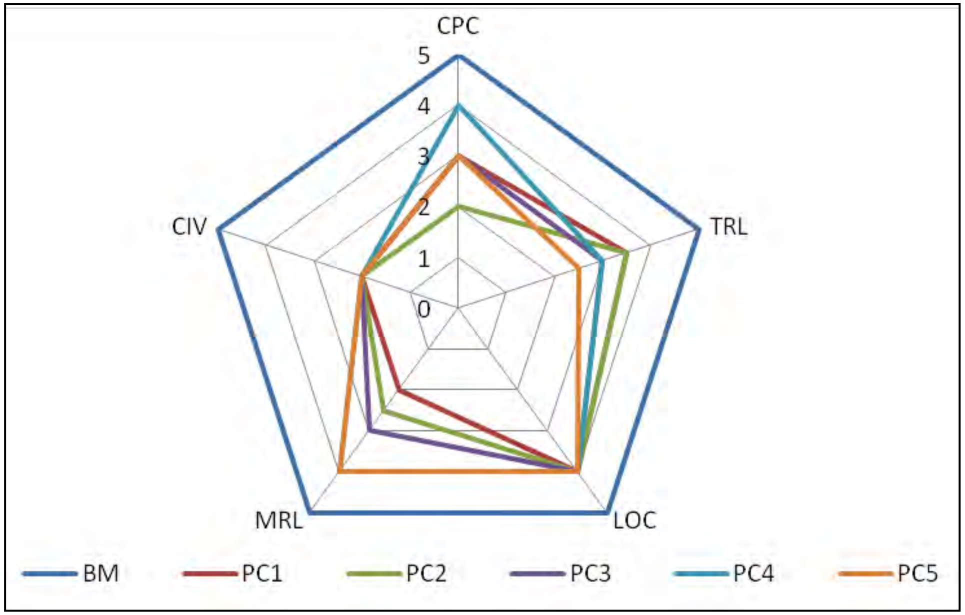
CATEGORIES	NOTES	DESCRIPTION/VALUE
Microalgae species		Fresh water
Taxonomic group		Natural bloom… it means that any mono species culture is promoted in our Raceway ponds.
Metabolism type	Photoautotrophic, heterotrophic, etc.	Photoautotrophic
Chemical composition	Lipid content	Less than 10%
Photosynthetic efficiency [%]		N.A.
Growth rate [g/m2/d]		Average: 25 gr/m2/d (After 18 months of operation)
CO2, nutrients, light and water uptake and sources		Pure CO2, waste water as nutrients source.
Specific growth requirements	CO2, nutrient, PH, solar radiation, temperature, mixing, etc.	
Cultivation technologies		
Type and description	Open ponds, tubular PBR, flat plate PBR, fermenters, etc.	Conventional ponds
Size [m2]		32 m2/unit
Operability conditions and technical parameters	Batch/continuous cultivation, algal concentration [g/l]	Continuous, algal concentration, NA
Energy input [kWh/m3]		To be confirmed

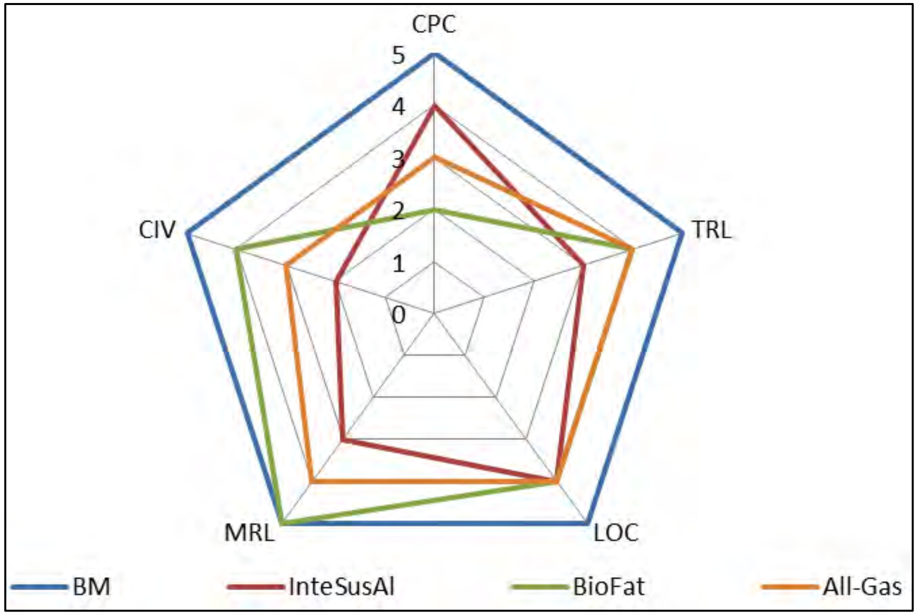


GAP ANALYSIS AND RATING

Based on the identified cruces:

- gap analysis for
  - production chains
  - pilot plants under realization within FP7 Projects (AlgaeCluster)
- comparison with a benchmark (existing biofuel production plant, commercially operational and not necessarily perfect)





Ratings for the Production Chains

Ratings FP7

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BARRIERS IDENTIFICATION

Based on weaknesses and threats identified in the SWOT analysis:

- identification of barriers affecting the development of algae-based systems
- recommendations aimed at overcoming the barriers
- action plan in terms of
  - priority
  - duration
  - costs

BARRIERS AND RECOMMENDATIONS

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Technical	Conversion Efficiency Algae-Biofuel: oil extraction and biofuel production rates are very low if compared to the input raw materials.	▲		Selection of the most efficient technology. Research for the development of highly innovative technologies. Research for biological advancement toward more efficient algal strains	⚠⚠⚠	🕒🕒	€€€
Technical	High amount of water needed per functional unit.		▲	Selection of the most efficient technology. Research for the development of highly innovative technologies.	⚠⚠⚠	🕒🕒	€€€
Technical	The use of wastewater: although promising for the environmental benefits, it raises O&M issues and it is a barrier to the production of some valuable co-products.		▲	Incentives for the investors in plants using WW to solve the technical barriers. Research for improvements in O&M issues to overcome the biological barriers.	⚠⚠	🕒🕒	€€
Technical	Large cultivation fields are needed		▲	Research for the development of highly innovative technologies.	⚠⚠⚠	🕒🕒	€€€
Technical	Low biomass productivity	▲		Research for the development of highly innovative technologies and more efficient algal strains.	⚠⚠⚠	🕒🕒	€€€
Technical	Low compatibility of valuable co-products and algal biofuel		▲	Accurate design to decide the most applicable combinations of product/co-products.	⚠⚠	🕒	€€

BARRIERS AND RECOMMENDATIONS

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Technical	Use of bioengineering is necessary for the achievement of the optimal algae strains. This is linked to the barrier of public acceptance.		▲	Research in the biological field of laboratory tests, technological innovation, etc.	⚠⚠	🕒🕒	€€
Technical	No multiproduct plants exist or promise to be valuable	▲		Demonstrative tests are needed to prove the technical and economical viability	⚠	🕒🕒	€€€
Economic	Production costs not competitive with other biofuel production chains (wood, crops) or in reference to the fossil fuel sector.	▲		The solution will be mainly a consequence of the technical improvements and of additional public incentives	⚠⚠⚠	🕒🕒	€€€
Economic	Fiscal and economic incentives not favorable to the development of algae production chains		▲	Put higher incentives on biofuel production, transformation and distribution processes. Incentives might be allocated under the form of grants or low-cost loans (to investments in bio fuel algae production chains), tax concession, feed-in-tariffs or premium (which guarantee a minimum price to biofuel from algae supplied on the market) or quotas (e.g., green certificates).	⚠⚠⚠	🕒	€€€

BARRIERS AND RECOMMENDATIONS

Context	Barrier	1st class	2nd class	Solution (Recommendation)	Priority	Duration	Cost
Economic	Demand only for high volume of biofuels, which requires important investments in equipment in the start-up phase of the business.		▲	Higher economic incentives to investments in biofuel from algae production chain at the start-up stage of plant development.	⚠⚠	🕒🕒	€€
Policy and normative background	Uncertain/undefined legal and policy frameworks. Patents and authorizations to start a business are not well defined or are provided at a very high cost for investors.		▲	Strengthen the legal framework at European and national levels (defining responsibilities, bodies involved and public authorizations required).	⚠⚠	🕒	€
Public acceptance	Skepticism of the population towards unknown technologies, use of bioengineering and towards highly impacting systems in terms of land occupancy. Diffidence towards land occupancy for industrial purposes vs. agricultural scopes.		▲	Consensus building campaigns. Demonstrative projects to prove the reliability and the effectiveness.	⚠⚠⚠	🕒🕒🕒	€
Public acceptance	Odors in Open Pond are an issue that can cause "NIMBY" phenomena along with the general skepticism.		▲	Stress on research activities. Consensus building campaigns.	⚠⚠⚠	🕒🕒🕒	€

CONCLUSIONS

Many barriers affect the path to reduce the distance and make biofuels from algae attractive as primary driver for an investment.

An action plan was outlined by using the conclusions drawn from our analysis, basing on the most relevant sectors identified.

Nevertheless…
The gap between algae based biofuels and conventional fuels is still wide.

Technologies maturity is not achieved by all the blocks of the process diagram at industrial scale.

The recent fluctuations of price for the barrel have had negative impact on the alternative chains & most of the optimistic scenarios are based on oil barrel prices that double the current values.

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