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Algae Cultivation Using Geothermal Gas and Heat

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ABSTRACT

Tuscany (Italy) is the most important area for geothermal electrical energy production in continental Europe, with 37 geothermal units for a total net installed power of about 766 MWe. In Tuscany about 32% of the electrical energy requirement is provided by geothermal sources. CO_2 enriched gas and heat represent the two main outputs from geothermal power plants. Large-scale algae facilities require huge amounts of CO_2 for algal growth and heat for culture thermoregulation and biomass drying. Thanks to EGP and COSVIG financial contribution, a 120 m2 pilot algae facility was built by F&M close to one EGP power plant at Chiusdino (Siena, Italy) to evaluate the use of geothermal sources (CO_2, condensed steam (40-45°C) and cold water (25°-28°C) from cooling tower), in the cultivation of microalgae. The pilot plant has been operated since June 2017 with A. platensis F&M-C256 grown outdoors in raceway ponds and Green-Wall Panel (GWP®) reactors to compare performances. The use of geothermal CO_2 did not reduce biomass productivity in both pond and GWP® when compared with food grade CO_2. Detailed analysis of the produced biomass confirmed the possibility to use geothermal CO_2 as source of carbon. Condensed steam and cold water were used for culture temperature control. Warmed cultures, regardless of the culture system used, attained higher (+ 43%) productivity. Mass and energy balances extrapolated to 1 ha size showed that the availability of geothermal heat and CO_2 reduces biomass production cost of more than 50%. As well as demonstrating the technical-economic feasibility of cultivating Spirulina, the project aim is to create new investments and job opportunities at local level, within a circular economy perspective linked to this renewable. Based on the aforementioned results twenty suitable areas for spirulina cultivation have been identified near geothermal plants installed in Tuscany. Moreover, some contacts with potential investors interested in algal cultivation have been started and to date at least two projects for the realization of a full-scale algae production plant integrated with geothermal sources are ongoing.

Regarding the geothermal sources reuse after the production of electric power, EGP is also one of the most important Italian operator in district heating from renewable source. Indeed EGP has some district heating plants in operation for a total net power of about 170 MWt which deliver a yearly heat energy of about 330 GWh-t to over ten thousand users among domestic and enterprises and already contribute to the reduction of CO_2 emitted for heating to over 100,000 tons/year.

Moreover with the aim of realizing a model of circular economy, EGP has also signed an agreement with a company involved in drink and food industry, for using the geothermal CO_2 at the outlet of a power plants for the production of sparkling water and other drinks or for food conservation.

1. INTRODUCTION

Almost all the power plants in operation in Larderello-Travale and Mt. Amiata are based on direct cycle or flash cycle technologies, depending on the nature of available geothermal fluid, in these areas superheated steam, saturated steam or two-phase fluid with a NCG (Non-condensable gases) content of about 2-10% wt, which mainly consists of CO_2.

In the direct cycle technology, the steam (see Figure 1), coming from production wells or flash stage, is fed directly into a steam turbine. After the expansion, where power is produced, the steam is condensed in a mixer condenser through the use of cooling water. After the condensation, the condensed steam and the cooling water are fed to a wet cooling tower (normally three cells are used for a standard 20MWe unit); in the tower the water is cooled and the condensed steam is partially stripped and emitted with the heated air (about 50-70% of the inlet flow). Stripped condensed steam and water drops of various dimensions (the so-called drift) are then released in the atmosphere, and contain components already present in the original geothermal fluid. The newest cooling tower installed at the geothermal plants are equipped with an innovative drift eliminator, which guarantees drift emissions lower than 0.1 m3/h. The remaining part of condensed steam flow (about 30-50%) is injected into the reservoir. In the mixer condenser, the gas is separated from the condensed steam and is fed, through a gas extractor, to the treatment plant (i.e. AMIS® technology), where H2S and Hg are abated and the purified CO_2 is emitted into the atmosphere. Another source largely available in the geothermal areas is the thermal energy.

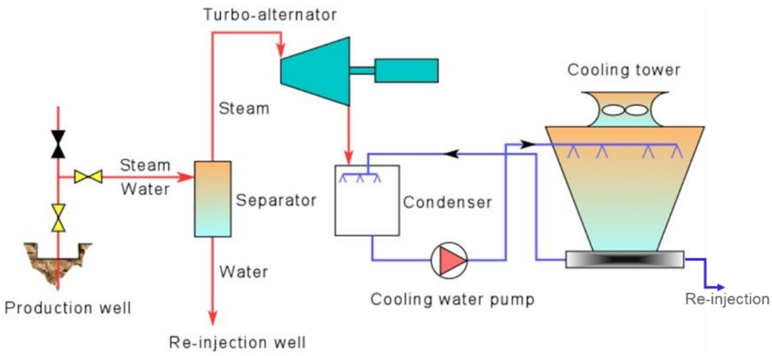

Figure1: Direct cycle technology scheme.

Considering that large-scale algae facilities require huge amounts of CO_2 for algal growth and heat for culture thermoregulation and biomass drying, the aim of this activity is to evaluate the use of geothermal sources (CO_2, hot water for heating (at a temperature of 40-45°C) and cold water for cooling (25°-28°C) coming from a real geothermal plant), in the cultivation of microalgae.

2. EXPERIMENTS IN ALGAL PRODUCTION USING GEOTHERMAL SOURCES

This document summarises the main results obtained over 12 months of experiments with the cultivation of cyanobacteria *Arthrospira platensis* (spirulina) at a test plant. The project, sponsored by EGP and COSVIG, was developed with the

competencies and experience in algal biotechnology provided by F&M S.r.l., which also relied on input from the DISPAA (department of agrifood production and environmental sciences) of the University of Florence for some phases of the project.

The main objective of the project was to demonstrate the technical and economic feasibility OF the production of photosynthetic micro-organisms, specifically *Arthrospira platensis* (spirulina), using geothermal resources (heat and gas) made available by EGP.

The project included the creation of an experimental facility of about 125 m2 for the installation of two different culture systems (reactors and tanks) to compare the different production technologies. Two panel photobioreactors (green wall panels) were installed with a total volume of about 460 litres as well as two raceway ponds with a total volume of about 650 litres. The plant was also equipped with a service area for auxiliary activities, such as: laboratory activities, preparing CULTURE media, collecting and concentrating the algal biomass, storage.

The two main process parameters that can significantly impact the productivity of the culture - pH and temperature - were controlled by managing geothermal FLUIDS (water and gas) received from EGP's geothermal plant in Chiusdino. Over the course of the EXPERIMENT the culture temperature had to be kept between 22 and 37°C, adjusting the temperature by using hot (35-45°C) and cold (22-27°C) geothermal water from the power plants cooling towers.

The other fundamental resource for the growth of the cultures was CO_2, which served as both a source of carbon for photosynthesis and as a means of adjusting the pH of the cultures. The CO_2 was provided using outflow gas from the AMIS® treatment plant, which contained 80-90% CO_2 by weight.

2.1 PILOT PLANT DESCRIPTION

The facility for the cultivation of *Arthospira platensis* (spirulina) was created inside the power plant in Chiusdino (SI) using an area provided by EGP.

The facility was assembled inside a tunnel greenhouse (fig.2) in order to extend the test period as much as possible and limit environmental contamination.

The completed pilot plant covered a total surface of about 130 m2 (6.5x20 m) and was composed of:

1. Process Control Unit + F&M-BCP photobioreactors “bubble columns”.

2. GWP®-II panel reactors and F&M-RWP tanks.

3. System for the storage, preparation and distribution of the culture medium.

4. System for the compression, storage, filtration and distribution of AMIS gas.

5. System for collecting the biomass and storing the spent medium.

6. System for drying the biomass produced.

Figure2: Pilot plant at the EGP power plant in Chiusdino (SI). Culture systems used: F&M-RWP tanks (bottom left); GWP® photobioreactors (bottom right).

Figure3: Close ups of the pilot plant for the cultivation of *A. platensis*.

2.2 EXPERIMENTAL TESTS DESCRIPTION

Various tests were conducted over the course of the year to investigate the aspects listed above (cf. paragraph 2.1). The tests that were most significant in terms of the experiment's overall objective will be described in detail in the following paragraphs. All the experiments used *Arthrospira platensis* strain F&M-C256, originating from the collection of Fotosintetica & Microbiologica S.r.l.

(www.femonline.it). It is a filamentous, non spiralled, cyanobacterium, already widely cultivated and used as a dietary supplement or ingredient in snacks, drinks, cheeses and many other foods.

TEST 1

Objective: Evaluate the use of geothermal gas originating from the AMIS plant (AMIS GAS) as a source of carbon and as a means of correcting the pH of the cultures, instead of food-grade CO_2.

Experimental conditions:

The test was conducted simultaneously in both tanks reactors. A treatment (AMIS GAS) and a control (CO_2 canisters) were set up for each of the two types of culture systems. The AMIS GAS provided by the plant is mainly composed of CO_2 (85% wt), O2 (2% wt), N2 (10% wt) and H2O (3%).

	GWP 1	GWP 2	RWP 1	RWP 2
CO_2 CANISTER		X		X
AMIS GAS	X		X	
HEATING	X	X		
COOLING				

Table1: Experimental conditions for Test 1.

Results:

The figures provided below, which show the trend in biomass concentration over the course of the test (fig.4) and the average productivity for the area (fig.5), clearly demonstrate that:

- reactors provided superior biomass productivity compared to tanks.

- there was no significant difference in terms of productivity between the control supplied with CO_2 from canisters and the cultures supplied with AMIS GAS, in fact, the cultures supplied with AMIS GAS showed slightly superior productivity.

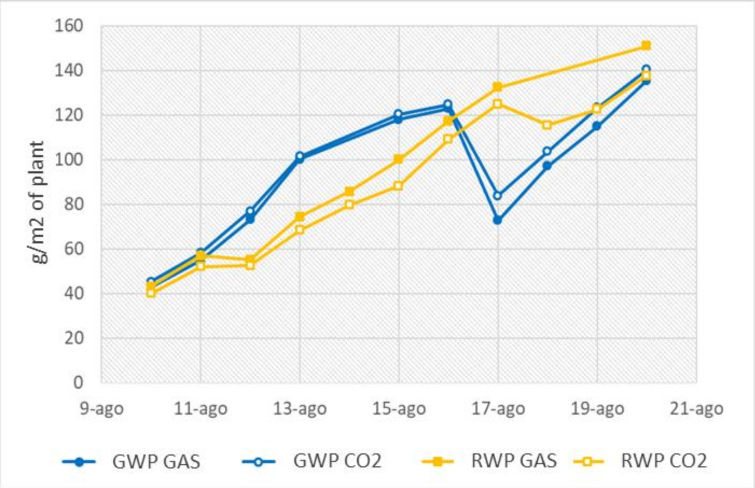

Figure4: Biomass growth trend for A. platensis F&M-C256 in GWP reactors and RWP tanks with two different sources of CO_2.

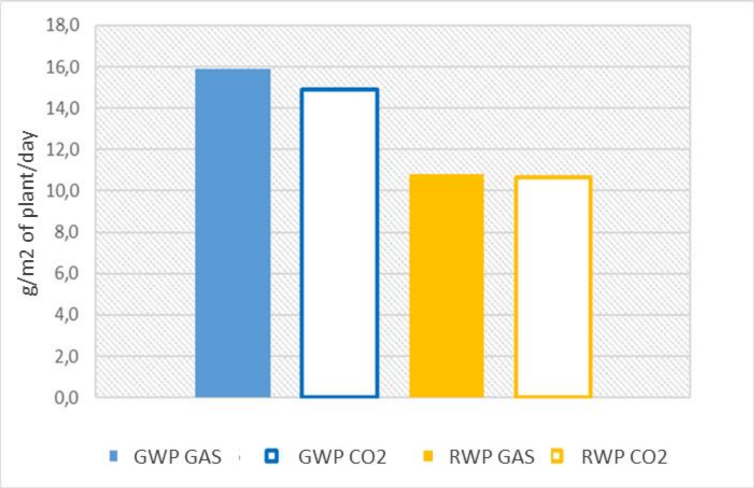

Figure5: Biomass productivity trend for A. platensis F&M-C256 in GWP reactors and tanks supplied with different sources of CO_2.

Given the results obtained during this test, a decision was made to only use AMIS GAS as a source of CO_2 for the subsequent tests.

TEST 2

Objective: To study how biomass productivity is affected by the heating and cooling of the cultures, using GEOTHERMAL water as a thermal vector.

Experimental conditions:

The test was conducted simultaneously in both tanks reactors. A reference (H-) and a tester (H+) were set up for each of the two culture systems. The experimental conditions tested are reported in table 4. As specified in table 4, the reactor and control tank (H+) were heated and cooled using geothermal water provided by the power plant. The cultures were cooled using outflow water from the cooling towers at an average temperature of 24°C, while water at a temperature of about 40°C was used for heating.

The table below provides the intervention settings of the thermostat system for the cultures tested.

	GWP 1 **H+**	**GWP 2** **H-**	**RWP 1** **H+**	**RWP 2** **H-**
HEATING	X		X	
COOLING	X		X	
CO_2 SOURCE	AMIS GAS			

Table2: Experimental conditions for Test 2.

Results:

Biomass productivity data (fig. 6) shows that the cultures needed to receive heating as early as September to keep the temperature within the optimal growth range for the strain: 22-37°C.

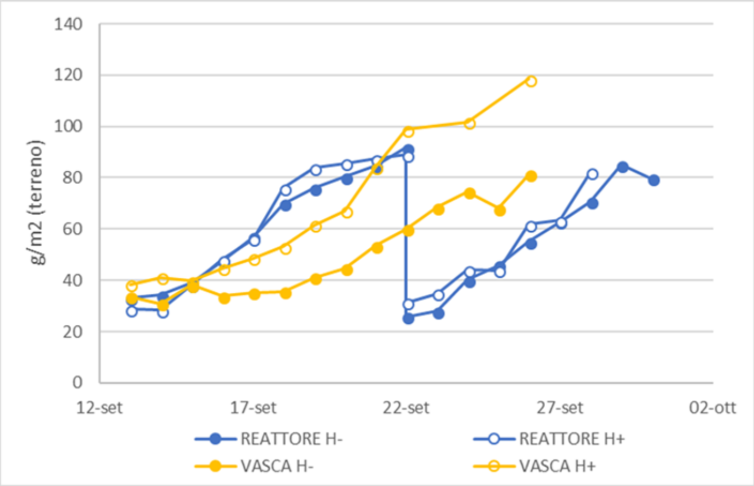

Figure6: Biomass growth trend for A. platensis F&M-C256 in both heated and unheated GWP reactors and tanks

Fiure7: Biomass productivity trend for A. platensis F&M-C256 in both heated and unheated GWP reactors and tanks

In both tests the heated cultures, regardless of the culture system being considered (tank or reactor), showed higher productivity - up to +43% for the tanks (fig.7). The difference in productivity between heated and unheated cultures increased, as one would logically expect, as the seasons progressed. This was particularly evident in the reactors. In TEST 3 the difference in productivity was fairly limited (<10%), while the difference rose to +36% for the heated reactor compared to the unheated reactor in TEST 4. The explanation lies in the nature of the reactors themselves. Unlike tanks, reactors have a much lower thermal inertia, since they constitute a "closed" environment and are not subject to evaporation. It's also worth noting that productivity values tended to decrease as the season progressed, regardless of whether the cultures were heated or not. This is because temperature control is not enough to sustain elevated productivity in the absence of a sufficient quantity of light.

3.3 CHARACTERISATION OF THE BIOMASS PRODUCED

3.1.1 Heavy Metals

Besides studying the effects on biomass productivity, for the purposes of this experiment it was important to establish whether the experimental conditions tested—use of GEO gas and use of GEO water—allowed for the production of "quality" biomass, with heavy metal levels beneath legal limits.

Specifically, heavy metal content (As, Hg, Cd and Pb) was evaluated for eight biomass samples obtained from the following tests:

a) Test 1 - The objective of this test was to compare the use of GEO gas and food-grade CO_2 as carbon sources.

b) Test 2 - The objective of this test was to evaluate the effect of heating on the productivity and biochemical composition of the biomass obtained from the cultures. Analysis of heavy metal content was only conducted on samples originating from heated cultures.

The testing showed practically non-existent levels of mercury (Hg), and of heavy metals in general, for all the biomass samples produced by the experiments.

In order to evaluate the quality of the biomass produced, the values obtained were compared against the following standards:

a) REGULATION (EC) No 629/2008 OF THE COMMISSION dated 2 July 2008 amending regulation (EC) no 1881/2006, which sets the maximum levels for certain contaminants in food products.

b) Technical specifications for A. platensis present on the market.

c) The limits set by the certifying body NATURLAND (www.naturland.de) for the biological certification of A. platensis.

SAMPLE	TEST TYPE	CULTURE TECHNOLOGY	CARBON SOURCE	CADMIUM	MERCURY	ARSENIC	LEAD
				mg/kg dry matter			
1	TEST 1	RWP	AMIS GAS	<0.1	<0.1	<0.1	<0.1
2	TEST 1	RWP	CO_2 CANISTER	<0.1	<0.1	<0.1	<0.1
3	TEST 1	GWP	AMIS GAS	<0.1	<0.1	<0.1	<0.1
4	TEST 1	GWP	CO_2 CANISTER	<0.1	<0.1	<0.1	<0.1
5	TEST 2	GWP	AMIS GAS	<0.1	<0.1	<0.1	<0.1
6	TEST 2	GWP	AMIS GAS	<0.1	<0.1	<0.1	<0.1
7	TEST 2	RWP	CO_2 CANISTER	<0.1	<0.1	<0.1	<0.1
8	TEST 2	RWP	CO_2 CANISTER	<0.1	<0.1	<0.1	<0.1

Table3: Biomass samples that were analysed for heavy metal content

3.1.2 General composition

The biomass samples that were collected and tested for heavy metal content were also analysed to determine their biochemical composition: proteins, lipids, carbohydrates and phycocyanin.

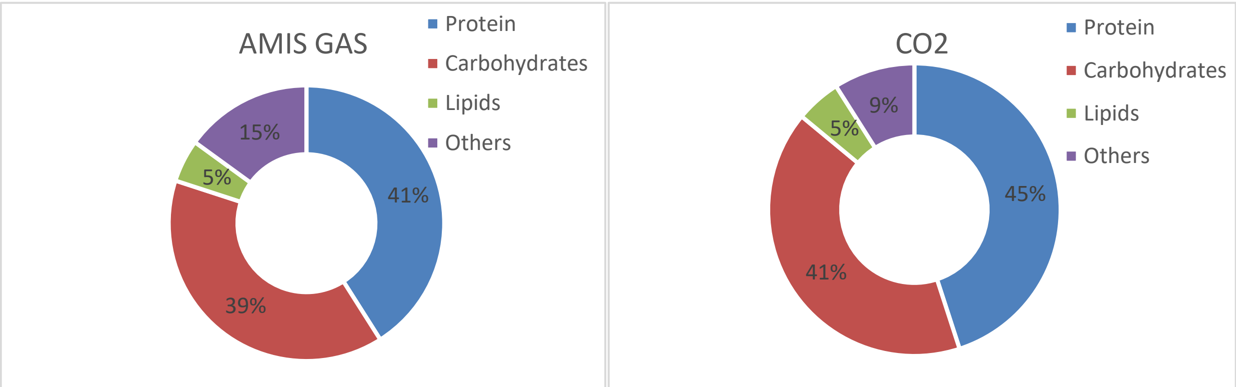

Figure8 :Biochemical composition of the biomass produced in GWP reactors for Test 1.

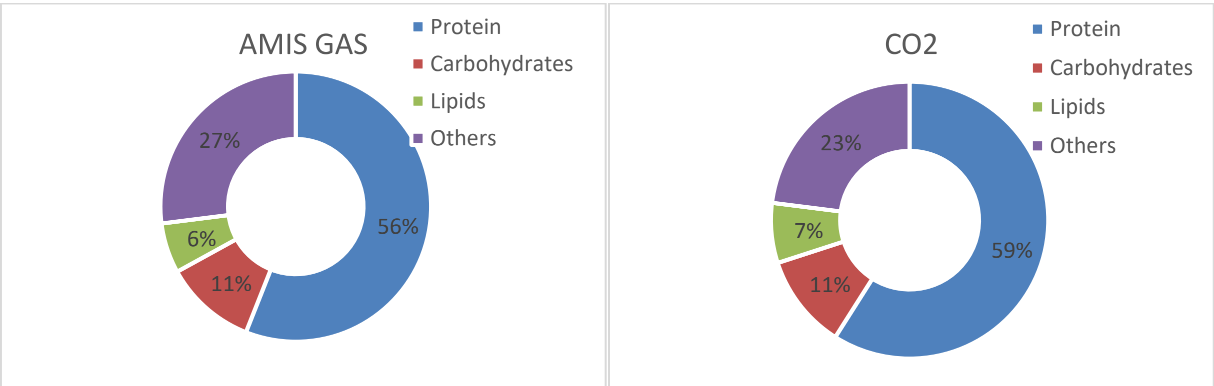

Figure9: Biochemical composition of the biomass produced in RWP tanks for Test 1.

The low protein content of the biomass produced in GWP® reactors (fig.8) was not due to the lack of nutrients, mainly nitrogen, since these were always present and compensated for as the culture grew. It may have been caused by high temperatures instead. This hypothesis cannot be tested since the temperature data is missing for this test, due to software problems.
Meanwhile, the protein content of the biomass produced in the tanks was not particularly high considering the typical levels for the strain (~60-65)%, especially when carbohydrate content is considered. Levels were very high for the component labelled "Other". It may be that the biomass was not washed thoroughly at the moment of collection. Checking "ash" content would be useful.

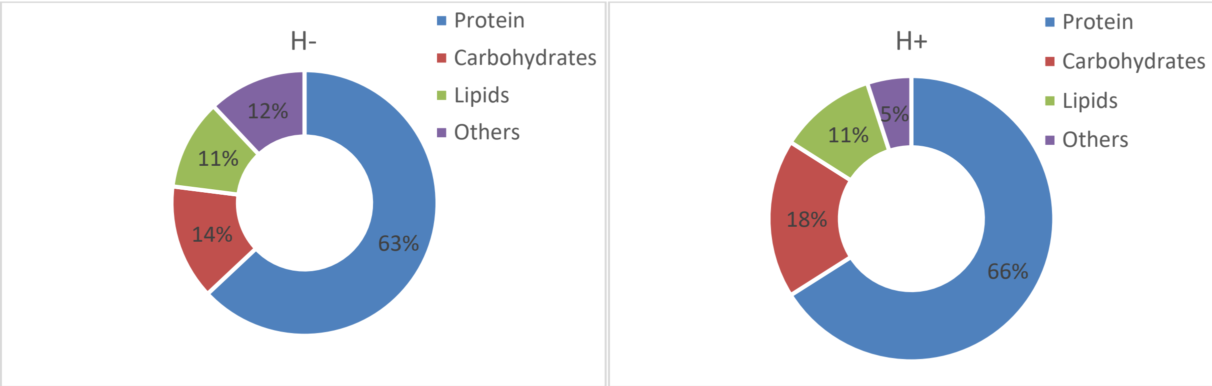

Figure10: Biochemical composition of the biomass produced in heated (H+) and unheated (H-) GWP reactors during Test 2.

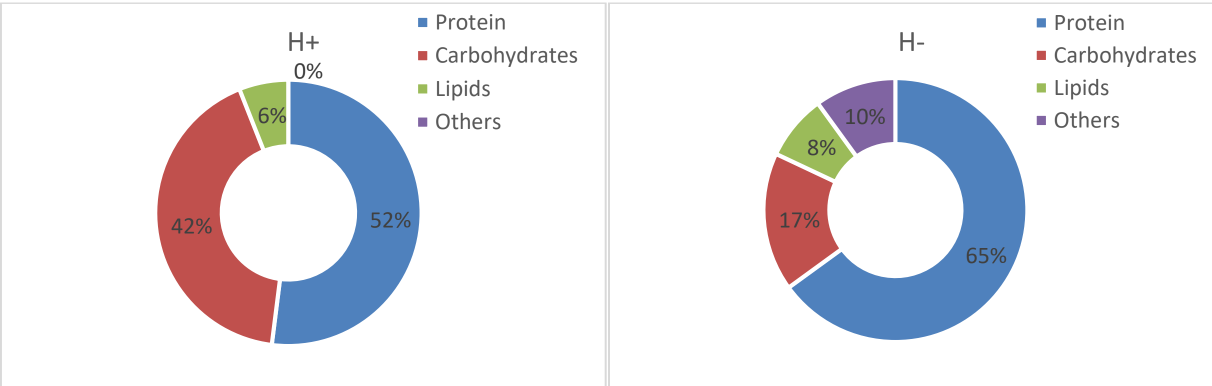

Figure11: Biochemical composition of the biomass produced in heated (H+) and unheated (H-) RWP tanks during Test 2.

There's no substantial difference in biochemical composition for the biomass produced in the reactors (fig.10). Meanwhile, contrary to what might have been expected, biomass produced in tanks showed lower protein content and higher % of carbohydrate content for the heated (H+) culture, as opposed to the unheated culture (H-) (fig.11).

4. TECHNICAL AND ECONOMIC RESULTS OF THE EXPERIMENTS

4.1 TECHNICAL RESULTS

The objectives of the experiment included collecting data (flow rate, temperatures, consumption of CO_2 and GEO gas, etc.) to determine the mass and energy budget (culture system heating/cooling) for the CAPEX-OPEX analysis of a commercial-scale plant: 1 ha. The cultivation systems used for the experiments - tanks and reactors - were therefore equipped with the following instruments:

- Gas flow detector to register the consumption of CO_2 and GEO gas.

- Flow meter to measure and register the consumption of water for temperature control (hot or cold GEO water).

- Temperature sensors to measure/register the temperatures of the cultures.

- Temperature sensors to measure/register the IN/OUT temperatures of the water used for temperature control.

The thermal demand required to heat the tanks, in relation to incident global radiation, was calculated using the data collected. This allowed for an extrapolation of average monthly thermal demand (kWh/m2 day). Only the monthly heating requirement is provided for the tanks, since the cooling of the culture is guaranteed by average daily evaporation. As with the tanks, the average monthly thermal demand for heating and cooling the reactors was extrapolated from the correlation curves provided previously. Unlike tanks, reactors also need to be cooled. The excess water from the EGP power plant tower, supplied at a temperature of 24 to 28°C depending on the season, was used for cooling. The cultures were kept at a maximum temperature of 37°C.

The correlation of CO_2 consumption, geothermal gas and thermal requirements with available radiation, and therefore with the season, was also obtained by processing the data collected.

The consumption of AMIS GAS by the tanks and the reactors was monitored during the experiments. As with the thermal demand, gas consumption was also correlated with available radiation and therefore with biomass productivity. The average monthly consumption of AMIS gas, used to correct the pH of the cultures and as a source of CO_2 for the tanks and GWP® reactors, is provided in fig.17. As shown in the figure, the demand for AMIS gas was lower in the tanks compared to the reactors. This is a consequence of the method used to supply the gas to the two culture systems during the tests. The tanks were, in fact, fitted with a highly efficient diffuser (fig. 33). Also, pure gas was supplied, whereas the reactors were fed a mixture of air and gas (3-5% by volume) using the reactor's bubbling system, which does not guarantee the level of efficiency of the diffuser used for the tanks.

4.1.1 RWP pool Thermal balance

The data collected was used for the correlation provided in figure 12, where the thermal demand for heating the tanks is correlated with the global radiation incident on the horizontal surface. This allowed for an extrapolation of the average monthly thermal demand (kWh/m2 tank day) (fig.13). Only the monthly heating requirement is provided for the tanks, since the cooling of the culture is guaranteed by average daily evaporation.

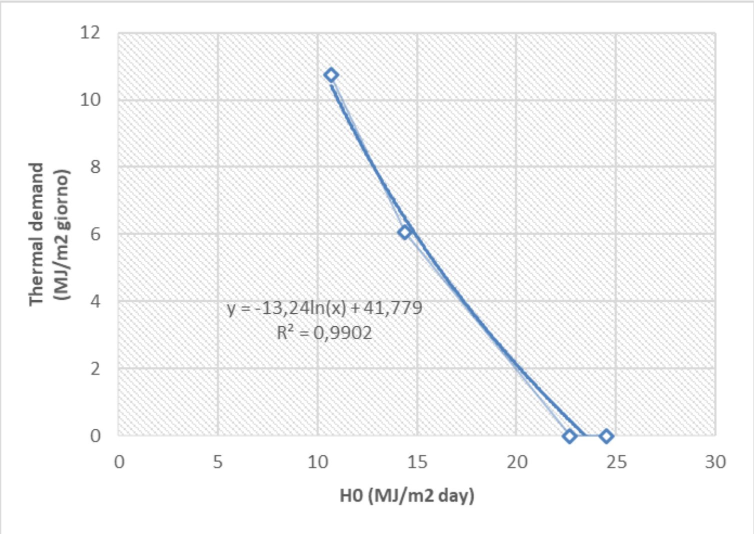

Figure12: Correlation curve showing thermal demand (heating) for RWP tanks.

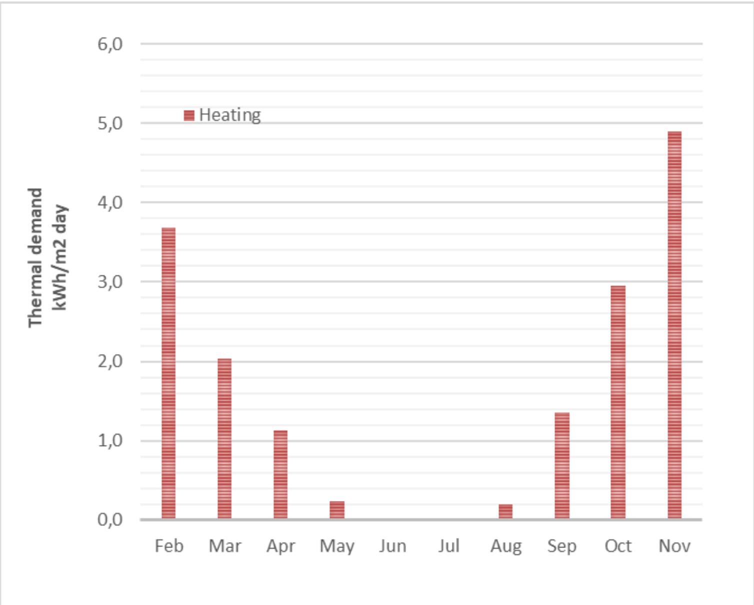

Figure13: Average monthly thermal demand for RWP tanks. Minimum culture temperature 22°C.

4.1.2 GWP reactor Thermal balance

Unlike tanks, reactors need to be cooled. The excess water from the EGP power plant tower, supplied at a temperature of 24 to 28 °C depending on the season, was used for cooling (fig. 14). The cultures were kept at a maximum temperature of 37 °C.

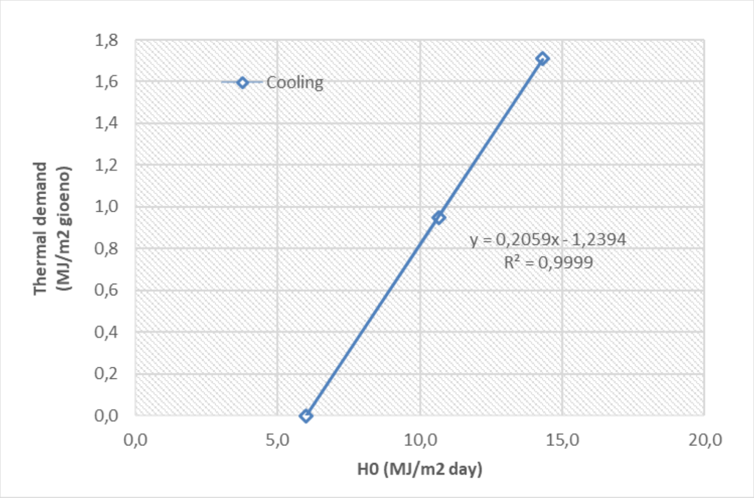

Figure14: Correlation curve showing thermal demand (cooling) GWP.

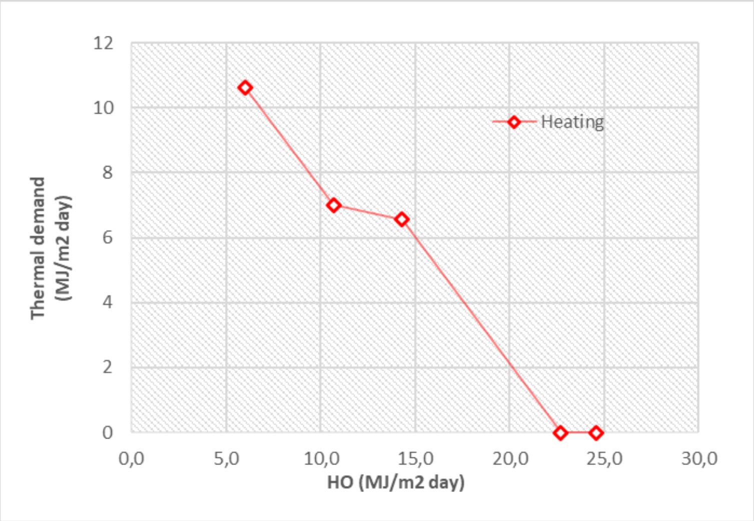

Figure15: Correlation curve showing thermal demand (heating) GWP.

As with the tanks, the average monthly thermal demand for the heating and cooling of the reactors was also extrapolated from the correlation curves provided previously (fig.16).

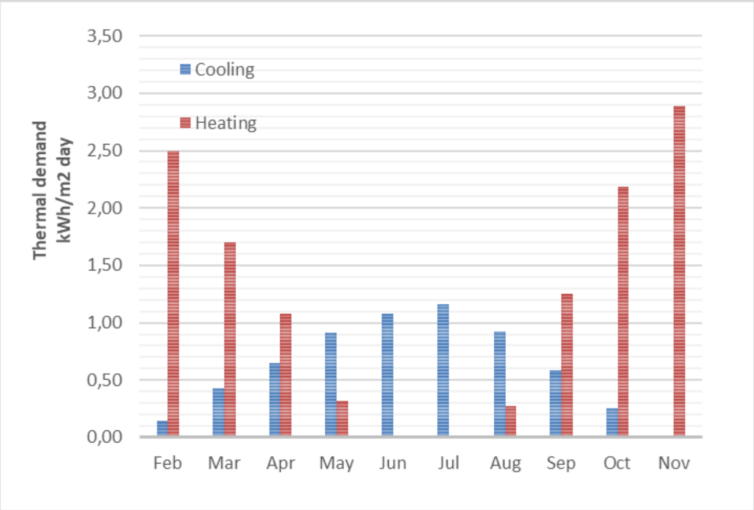

Figure16: Average monthly thermal demand for GWP reactors. Minimum culture temperature 22°C, maximum temperature 37°C.

4.1.3 Geothermal gas mass balance

The consumption of AMIS GAS by the tanks and the reactors was monitored during the experiments. As with the thermal demand, gas consumption was also correlated with available radiation and therefore with biomass productivity. The average monthly consumption of AMIS gas, used to correct the pH of the cultures and as a source of CO_2 for the tanks and GWP® reactors, is provided in fig.17. As shown in the figure, the demand for AMIS gas was lower in the tanks compared to the reactors. This is a consequence of the method used to supply the gas to the two culture systems during the tests. The tanks were, in fact, fitted with a highly efficient diffuser. Also, pure gas was supplied, whereas the reactors were fed a mixture of air and gas (3-5% by volume) using the reactor's bubbling system, which does not guarantee the level of efficiency of the diffuser used for the tanks.

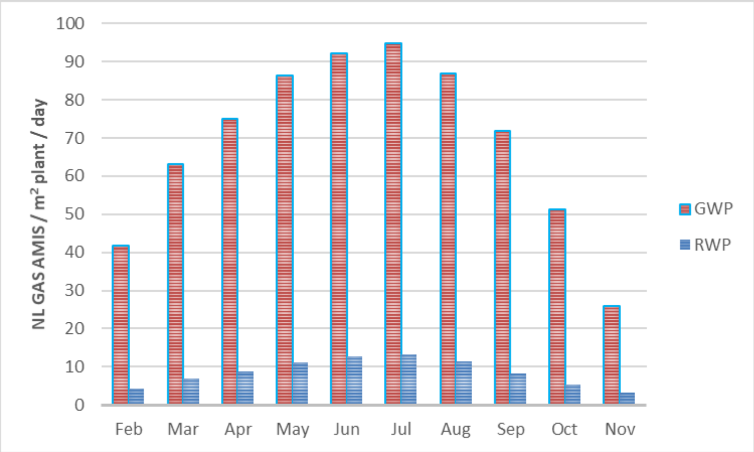

Figure17: Average monthly demand for AMIS gas

4.2 ECONOMIC EVALUATION FOR A FULL-SCALE PLANT

Productivity data; consumption of AMIS gas; thermal demand for heating/cooling the cultures; water consumption to prepare the culture medium, compensate for evaporation, and heat and cool the cultures; nutrient mass results etc. collected over the year of experimentation were used as a basis for the CAPEX-OPEX analysis of a theoretical 1 ha plant to be created at a geothermal area in Tuscany.

The CAPEX-OPEX analysis was developed for three different scenarios:

a) ALGAE+GEOTHERMAL ENERGY (S.1): CO_2 and hot and cold water for temperature control supplied by the geothermal power plant with which the algal plant will be paired. Production season 277/365 days. Annual biomass production: 22.4 tonnes/year.
b) CONVENTIONAL + HEATING (S.2): Food-grade CO_2 purchased, heat for heating the cultures produced using an industrial boiler that runs on methane. Production season 277/365 days. Annual biomass production: 22.4 tonnes/year.
c) CONVENTIONAL – HEATING (S.3): Food-grade CO_2 purchased, cultures not heated. The lack of heating reduces the production season (222/365 days). Annual biomass production: 18.4 tonnes/year.

For each scenario studied (S.1, S.2 and S.3) the following products were considered:

a) Unprocessed biomass: unprocessed spirulina biomass mainly destined for a B2B (Business to Business) market.
b) Processed biomass: pills, capsules, shavings etc. The added value of the biomass produced can be increased significantly through simple physical transformation and packaging. After packaging, the product is mainly destined for a B2C (Business to Consumer) market. The present analysis evaluated the option of entrusting the processing and packaging to a third party.

The plant will need to be located next to one of the EGP geothermal power plants in Tuscany, in order to readily make use of the heat and geothermal gas (AMIS GAS) needed for the cultivation process. To that end, EGP has already located more than 20 sites that are potentially available for the creation of this type of plant with the following specifications:

a) Sufficient surface area: the plant will occupy a total area of 10,000 m2, of which 8,520 are productive. A flat surface that is well exposed to solar radiation will need to be selected.
b) Availability of water sources: the plant will require a daily supply of fresh water for the preparation of the culture medium, for cleaning operations and especially to compensate for evaporation. The average daily demand is estimated at 40-50 m3/day.
c) Sufficient solar radiation: the selection of the site must take into consideration the average amount of solar radiation available each year. The average yearly solar radiation for the geothermal area in Tuscany is 15 MJ/m2 day (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#).
d) Ease of access.

The tables below list the main conditions assumed for the CAPEX-OPEX analysis.

Table4: Assumed conditions for the scenarios being considered

	UNIT	ALGAE + GEOTHERMAL ENERGY	CONVENTIONAL + HEATING	CONVENTIONAL - HEATING
Operative days	days/year	300	300	240
Cleaning days	days/year	23	23	18
Actual days of production	days/year	277	277	222
Annual production	tonnes/year	22.4	22.4	18.4
Production cycles	no./year	185	185	148
Duration individual production cycle	Days/cycle	6	6	6

Table5: Market price assumptions for the two different types of products considered.

	UNIT	VALUE
Unprocessed biomass (powder)	€/kg	70
Processed biomass (pills, capsules, etc.)	€/kg	250

Table6: Unit cost assumptions for OPEX calculations

	UNIT	ALGAE + GEOTHERMAL ENERGY	CONVENTIONAL + HEATING	CONVENTIONAL - HEATING
Electricity	€/kWh	0.22	0.22	0.22
Water supply	€/m3	2.0	2.0	2.0
Nutrients	€/tonne	606	606	606
CO_2	€/tonne	-	450	450
Thermal energy	€/MWth	-	75	75
Personnel costs				
Plant director	€/year	45000	45000	45000
Biologist	€/year	35000	35000	35000
Production specialist	€/year	30000	30000	30000

Table7: General characteristics of the plant

PLANT CONFIGURATION	
Total surface / m^2	10,000
Productive surface / m^2	8,520
Production modules / no.	4

Tank surface / m^2	7,920
Reactor surface / m^2	600
Total volume tanks / m^3	636
Total volume reactors / m^3	59
Total volume of the plant / m^3	695
CONFIGURATION OF THE INDIVIDUAL MODULE	
Area of the individual module /m^2	2130
Area of the reactors / m^2	150
Area of the tanks / m^2	1980
Volume of the individual module / m^3	173

The proposed plant is composed of 4 production modules, to provide continuity for the process and to cultivate multiple algal strains at the same time. Each module is composed of:

- GWP® photobioreactor panels to develop and maintain the inoculation material.
- No. 1 growth tank (TANK A).
- No. 1 production tank (TANK B).

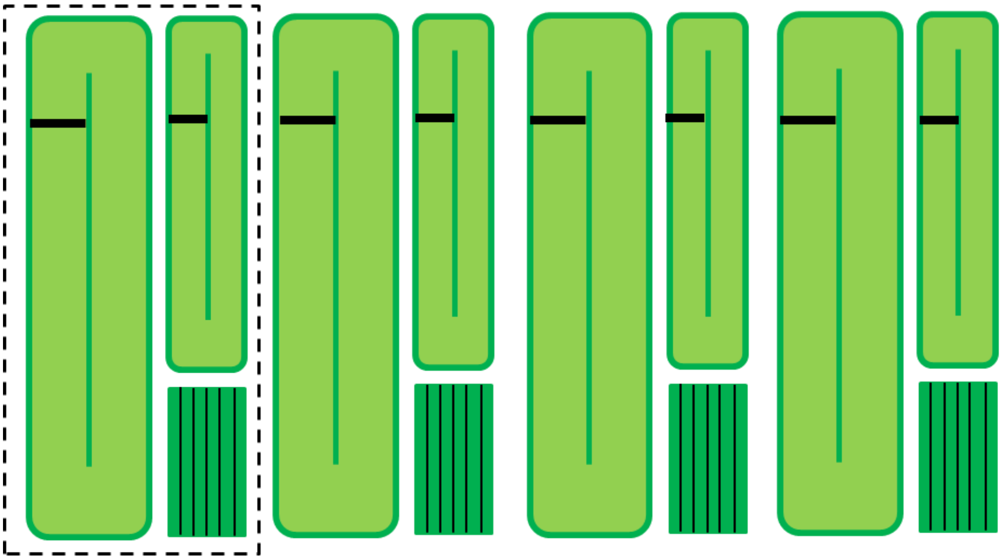

Figure18: General layout of the 1 ha plant

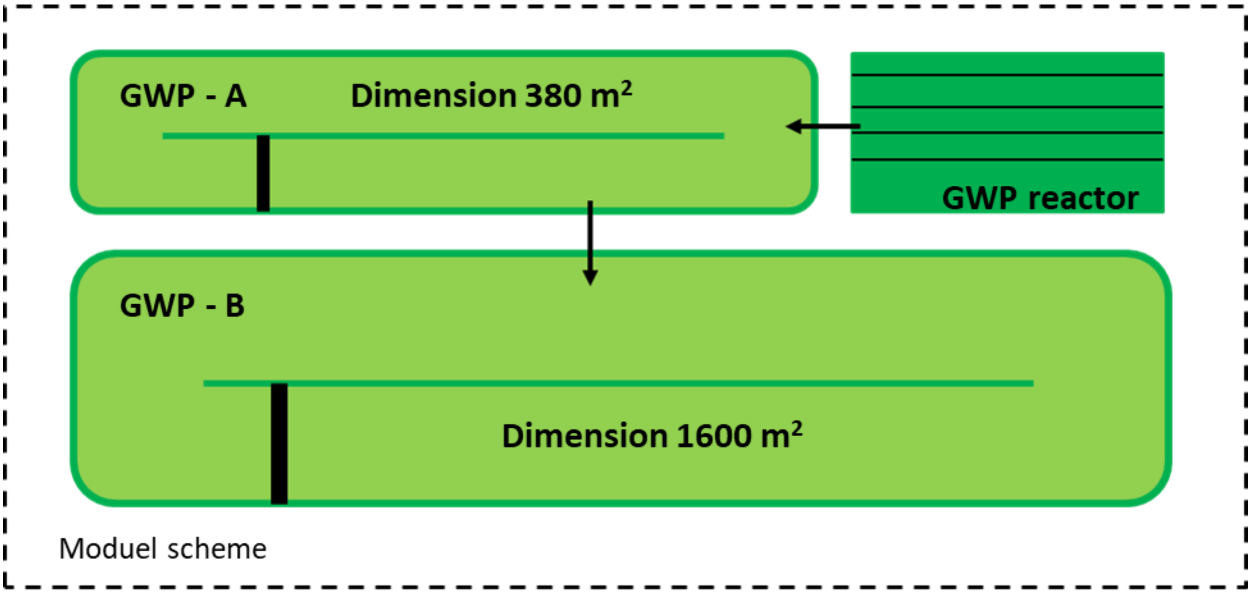

Figure19: Layout of the individual module

The key differences between the three hypothetical scenarios (S.1, S.2 and S.3) are the type of gas supplied and whether heating and cooling are used for the production plant. For the S.1 scenario (ALGAE + GEOTHERMAL ENERGY) the CO_2 source is gas obtained from the AMIS facility, supplied by the EGP power plant, while for the other two scenarios the CO_2 must be purchased at the price listed in table 6.

Meanwhile, each of the three scenarios has its own peculiarities when it comes to the heating/cooling of the plant:

S.1: the cultures are heated and cooled using hot and cold water obtained from the power plant. Therefore, only the cost of pumping the water was considered for regulating the temperature of the cultures.

S.2: the cultures were heated using hot water specifically produced by boilers. The cost of producing the hot water was calculated at 75 €/MWh (cf. tab. 6).

S.3: the cultures are not heated. Besides reducing productivity over the colder months, as demonstrated by the experiments (cf. paragraph 2.2), this also shortens the productive season from 277 days for scenarios S.1 and S.2 to 222 days for scenario S.3.

4.2.1 Economic results (CAPEX-OPEX)

The tests conducted as part of the experiments at the pilot plant in Chiusdino allowed for the collection of productivity data that was used to extrapolate the production capacity of the proposed plant. Fig. 37 lists the yearly production for the three scenarios considered.

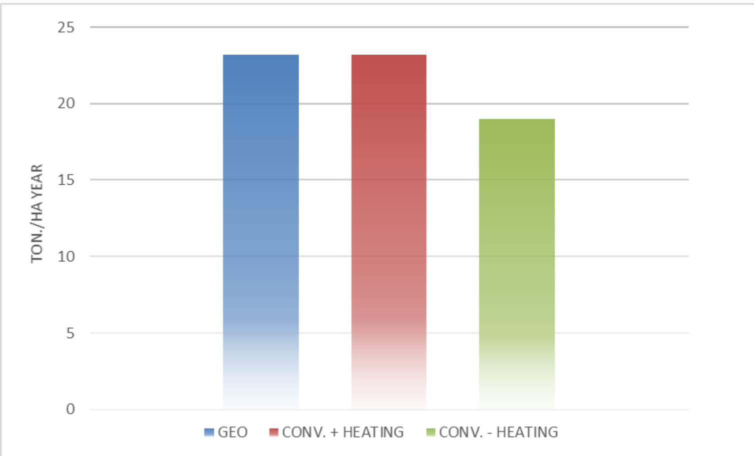

Figure20: Annual production (dry matter) for the three scenarios considered.

Table 8 lists the direct and indirect costs that would be incurred for the creation of the 1 hectare plant described in the paragraphs above. The greater cost of scenario S.2 (CONVENTIONAL + HEATING) stems from the cost of purchasing the boilers used to produce hot water for heating the cultures.

Table8: Investment cost (CAPEX) for the creation of the 1 hectare plant

		ALGAE + GEOTHERMAL ENERGY	CONVENTIONAL + HEATING	CONVENTIONAL - HEATING
DIRECT COSTS (DC)	**€**	**	**	**
PLANNING + WORK MANAGEMENT (7% DC)	**€**	**	**	**
PLUMBING FACILITIES and PROCESS INSTRUMENTATION (7% DC)	**€**	**	**	**
ELECTRICAL FACILITIES and AUTOMATION (5% DC)	**€**	**	**	**
TOTAL CAPEX	**€**	**2,212,305**	**2,486,814**	**2,283,705**

The tables and graphs below show the main operating costs for the three scenarios being considered: S.1, S.2 and S.3 and for the two possible products: a) unprocessed biomass; b) processed biomass.

<u>a) UNprocessed biomass</u>

Table9: OPEX for the production of unprocessed spirulina biomass at a 1 hectare plant

	ALGAE + GEOTHERMAL ENERGY	CONVENTIONAL + HEATING	CONVENTIONAL - HEATING
PERSONNEL	**	**	**
ELECTRICITY	**	**	**
CO_2	No cost	**	**
NUTRIENTS	**	**	**
WATER	**	**	**
HEAT	No cost	**	**
PACKAGING	**	**	**
BIOMASS PROCESSING	--	--	--
CONSUMABLES	**	**	**
MAINTENANCE (3 % plants)	**	**	**
ADMINISTRATIVE EXPENDITURES	**	**	**
GENERAL EXPENDITURES	**	**	**
Subtotal	**	**	**
CONSULTING FEES	**	**	**
OPEX TOTAL	**396,534**	**718,472**	**396,726**

The final production costs of the biomass produced under the three scenarios was calculated considering a 10 year amortisation period for CAPEX. (fig. 21). It's obvious that scenario S.1 (ALGAE + GEOTHERMAL ENERGY) is economically advantageous allowing for the production of biomass at less than 30 €/kg compared to 42 €/kg for scenario S.2. The difference is mainly due to the cost of generating hot water to heat the cultures (tab.9). The greater cost of scenario S.3 (CONV. – H) compared to S.1 mainly stems from the fact that CAPEX and OPEX are largely unchanged while the quantity of biomass produced each year drops from 23.2 to 19 tonnes/ha year (fig.20)

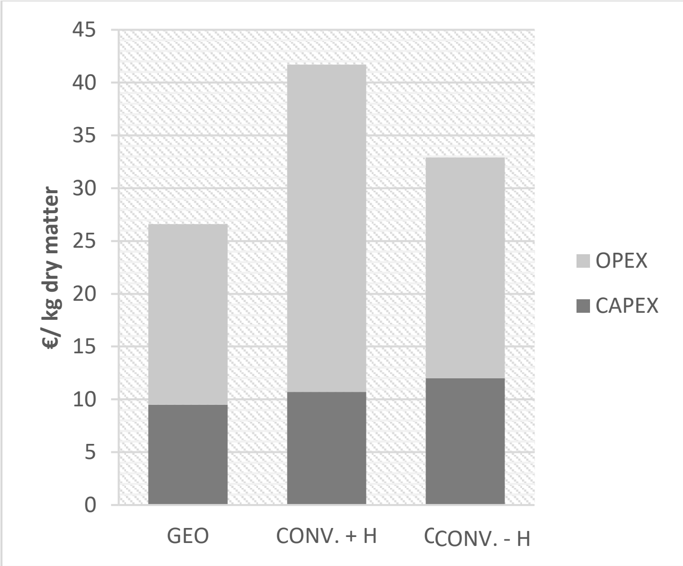

Figure21: Production cost of unprocessed biomass

<u>a) Processed biomass</u>

Table10: OPEX for the production of processed spirulina biomass at a 1 hectare plant

	**ALGAE + GEOTHERMAL ENERGY**	**CONVENTIONAL + HEATING**	**CONVENTIONAL - HEATING**
PERSONNEL	**	**	**
ELECTRICITY	**	**	**
CO_2	No cost	**	**
NUTRIENTS	**	**	**
WATER	**	**	**
HEAT	No cost	**	**
PROCESSING AND PACKAGING*	**	**	**
CONSUMABLES	**	**	**
MAINTENANCE (3 % plants)	**	**	**
ADMINISTRATIVE EXPENDITURES	**	**	**
GENERAL EXPENDITURES	**	**	**
Subtotal	**	**	**
CONSULTING FEES	**	**	**
OPEX TOTAL	**1,424,802**	**2,486,814**	**2,283,705**
*By a third party **			

In the event that the value of the biomass produced were increased through physical processing for the production of products such as pills, tablets or spirulina shavings, the operating costs would be those listed in tab. 10. It was assumed that processing and packaging would be entrusted to a third party at a cost of 45 €/kg.

As shown in fig.40, processing and packaging have the highest cost (tab 10) and significantly increased the operating costs. However, they also raised the value of the end product considerably. In fact, for this analysis the market price of the unprocessed biomass was assumed to be 70 €/kg while the price of processed biomass was assumed to be 250 €/kg (tab.5).

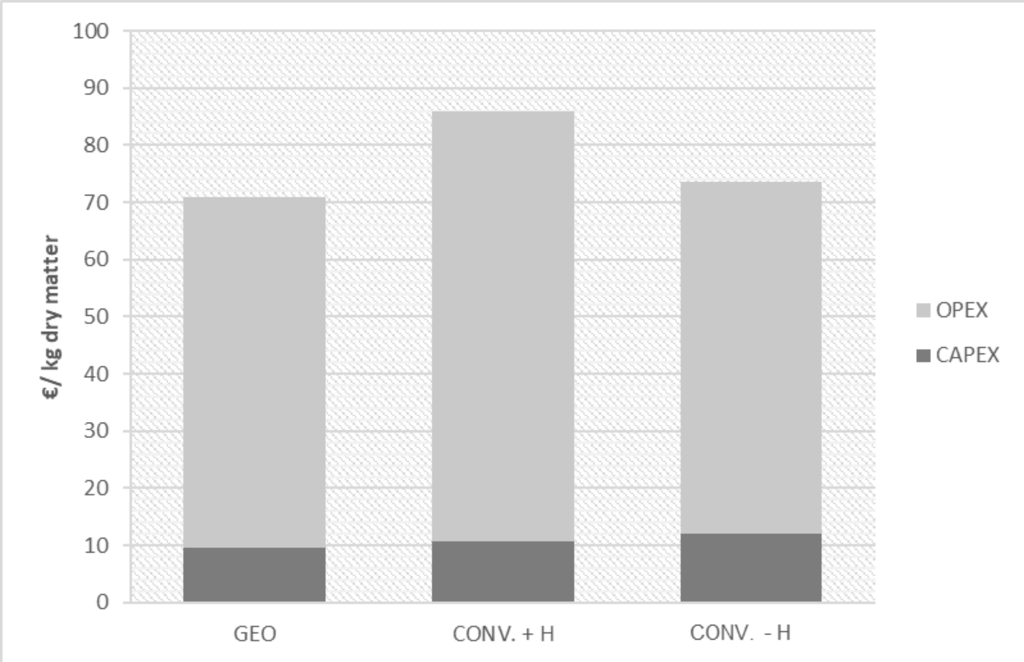

Figure22: Production cost of processed biomass

5. CONCLUSIONS

We can summarise the main results of the experiments with the following points:

- the use of AMIS GAS as a source of CO_2 doesn't decrease productivity nor does it negatively impact the quality of the biomass; no increase in heavy metals was detected, nor was there any change to the biochemical composition of the biomass;
- heating the cultures was shown to have a positive effect on biomass productivity; and, as one would logically expect, these differences were greater for tanks compared to reactors.
- A comparison of the operating costs (OPEX) for the three scenarios revealed that the availability of heat, specifically of hot water at 40-45°C, is the determinant element for the economic sustainability of the production of algal biomass.
- The production cost (€/kg dry matter) of algal biomass (raw unprocessed biomass) is lower (-56%) if production is integrated with geothermal energy, compared to the scenario in which hot water must first be produced to then heat the cultures. In the event that the biomass were subsequently processed to produce pills, tablets, etc. the advantage offered by integration with a geothermal power plant drops by -20%. This is due to the fact that the cost of processing and packaging, entrusted to external companies operating as third parties, is the highest of all operating costs, which reduces the entity of the expenditure needed to heat the cultures.