Energy balance of algal biomass production in a 1-ha "Green Wall Panel" plant: How to produce algal biomass in a closed reactor achieving a high Net Energy Ratio

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Energy balance of algal biomass production in a 1-ha "Green Wall Panel" plant: How to produce algal biomass in a closed reactor achieving a high Net Energy Ratio ☆

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HIGHLIGHTS

- *Tetraselmis suecica* production in a 1-ha GWP plant in Tuscany (Italy) has a NER < 1.
- Major energy costs are embodied energy of GWP and mixing.
- In a suitable location (North Africa) the NER increases by 40%.
- Integration of photovoltaic in the GWP allows to achieve a NER of 1.7.
- *T. suecica* cultivated in a GWP plant can yield up to 30 t of protein ha^{-1} $year^{-1}$.

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ABSTRACT

The annual productivity of *Tetraselmis suecica* in a 1-ha Green Wall Panel-II (GWP-II) plant in Tuscany (Italy) is 36 t (dry weight) ha^{-1} $year^{-1}$, which corresponds to an energy output of 799 GJ ha^{-1} $year^{-1}$. The energy inputs necessary to attain that productivity amount to 1362 GJ ha^{-1} $year^{-1}$, mainly given by the embodied energy of the reactor (about 30%), mixing (about 40%), fertilizers (11%) and harvesting (10%). The Net Energy Ratio (NER) of *T. suecica* production is thus 0.6. In a more suitable location (North Africa) productivity nearly doubles, reaching 66 t ha^{-1} $year^{-1}$, but the NER increases only by 40% and the gain (difference between output and inputs) remains negative. In a GWP-II integrated with photovoltaics (PV), the NER becomes 1.7 and the gain surpasses 600 GJ ha^{-1} $year^{-1}$. Marine microalgae cultivation in a GWP plant, in a suitable location, can attain high biomass productivities and protein yields 30 times higher than those achievable with traditional crops (soya). When the GWP reactor is integrated with PV, the process attains a positive energy balance, which substantially enhances its sustainability.

1. Introduction

In the recent period, algae have been the object of increasing interest due to the attractive perspectives that they offer in the current scenario of dwindling energy and food resources. The main advantage of algae as renewable fuel sources is that they can be grown in non-arable land areas without using freshwater and, thus, do not directly compete with crop-based food commodities. Besides, microalgae cultures are flexible systems, which permit to obtain many different products ranging from biodiesel and other kinds of fuels [1] to algal meal as alternative protein source, to omega-3 fatty acids and other molecules with commercial interest in the health-food [2,3], pharmaceutical and cosmetic markets [4].

The limitation to the development of algae culture technologies at commercial scale is associated to their relatively high cost and negative energy balance [5], that is still object of discussion, but generally is much less favorable than that of fossil fuels and traditional renewable energy resources [6,7]. A high energy efficiency of the process, usually reported as Net Energy Ratio (NER) or Energy Return On Investment (EROI), is crucial when these

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Nomenclature

NER	Net Energy Ratio
GWP	Green Wall Panel
LDPE	low-density polyethylene
PAR	Photosynthetic Active Radiation
PVC	poly-vinyl-chloride
PV	photovoltaic
E.E.	embodied energy
P_e	electrical power (W)
ΔP	pressure drop (Pa)
Q	flow rate ($m^3 s^{-1}$)
η	efficiency
P_{cool}	thermal power to be dissipated ($W m^{-2}$)
P_{net_in}	irradiance on the panel surfaces ($W m^{-2}$)
P_{conv}	power dissipated (or gained) due to convective exchange with ambient ($W m^{-2}$)
P_{evap}	power dissipated by water evaporation ($W m^{-2}$)
P_{rad}	power dissipated by radiative effect toward ambient ($W m^{-2}$)
P_w	power requirement (kW)
w	gas mass flow rate ($kg s^{-1}$)
R	universal gas constant (8.314 $kJ kmol^{-1} K^{-1}$)
T_1	absolute inlet temperature (K)
p_1	absolute inlet pressure (atm)
p_2	absolute outlet pressure (atm)
n	$(k-1)/k = 0.23$ for air (adopted also for flue-gas)
k	C_p/C_v
C_v	specific heat at constant volume ($J kg^{-1} K^{-1}$)
P_G	power input (W)
V_L	volume unit (m^3)
ρ_L	density of liquid ($kg m^{-3}$)
g	gravitational acceleration ($m s^{-2}$)
U_G	superficial gas velocity ($m s^{-1}$)

microorganisms are cultivated for biofuels or as sources of food and feed. The sustainability of the process, in fact, strongly depends on the ratio between the energy produced and the fossil energy required in the production process and it implies a NER significantly higher than one [6,7].

The cultivation of algae in controlled and confined systems requires significant amounts of energy and matter inputs, mainly in form of electrical power, fertilizers, water and materials for plant construction. The energy consumption and the amount and type of materials employed strongly depend on the type of plant considered: the more significant differences are between open systems and photobioreactors (PBRs). Open ponds are attractive systems because they present lower investment and management costs, which permit to obtain biomass at lower costs. However, they are limited by disadvantages such as low volumetric productivity, high risk of contamination and high consumption of water [8,9]. Photobioreactors offer a partial solution to contamination and show higher productivities, but at higher installation and operation costs [9]. A relatively cheap system for the cultivation of microalgae in photobioreactors was ideated by Tredici and Rodolfi [10] with the realization of the Green Wall Panel (GWP), a flat PBR constituted by a disposable transparent LDPE film enclosed within a metal or wooden frame.

In recent years several research groups have carried out energy analyses of biofuels production from algae in open ponds to assess the sustainability of the process [11–17], but the results are not in agreement or are not always directly comparable [18]. Fewer analyses have been done on closed reactors, and particularly on flat PBRs. An estimation was carried out by Jorquera et al. [13], who calculated a NER for flat reactors of 4.5 for biomass production and 1.65 for oil production and a NER < 1 for tubular reactors for both applications. Hulatt and Thomas [19] calculated the NER of a flat plate PBR at temperate latitudes, finding variable results (from 0.39 to 7.81) in function of reactor light-path and sparging power input. Other important works related to flat PBRs have been published, for example about the energy costs for mixing [20,21] and on general energy and economics [22], but these studies do not allow to reach a conclusion on the efficiency in terms of energy employed by closed systems for algae cultivation.

The objective of this study was to provide an estimation of the NER of *Tetraselmis suecica* biomass production in a 1-ha plant made of flat panel (GWP-II) reactors. The choice of the plant location and the source of the data have large influence on the results of the energy analysis. The analysis here developed is mostly based on experimental data obtained with GWP pilot installations at the Fotosintetica & Microbiologica S.r.l. (F&M) research area of Sesto Fiorentino (Florence, Italy). The use of longtime, year-round experimental data to perform the analysis represents a highlight of this paper, being most of the analyses performed up to now based on productivity (and biomass composition) data derived from short-term experiments. The authors aim to provide realistic values of energetic efficiency of algal cultures in closed reactors, upon which future development of the technology could be based. It is necessary to point out that the present analysis is valid within the boundary limits adopted and only for the type of cultivation system here considered (the GWP-II).

2. Material and methods

2.1. NER of the 1-ha GWP plant: functional unit, system boundaries, data sources

The NER is commonly used as a monetary-independent index to evaluate the efficiency of any energy generation process and represents *"The ratio of the total energy production to the primary non-renewable energy requirements associated with the system life cycle"* [23]. In every energy analysis final results are strongly affected by the definition of the system boundaries and by the functional unit chosen. The comparison between different systems, processes or products can be only carried out if similar conditions are applied [24].

A 1-ha GWP-II plant has been chosen as the *functional unit* for the present analysis. This is a convenient size for many industrial applications of algae, although not representative of an algae-fuel or algae-food production plant. Much larger scales are necessary to evaluate the energy efficiency of the production of these commodities, and the large scale may affect the final result in an unpredictable way (e.g., not necessarily with a reduction of costs). Our choice was dictated by the decision to use experimental data collected in many years of field trials with systems of comparable size to that of the modules comprising the 1-ha GWP-II plant here described. The present analysis ends with the production of wet algal biomass (70–80% moisture). Thus, it is worth mentioning that, very likely, more energy would have to be spent in a real process aimed at obtaining a drop-in fuel or food from the algal biomass. See Fig. 1 for a scheme of biomass production and downstream processes, where the boundary limits of the analysis are also shown.

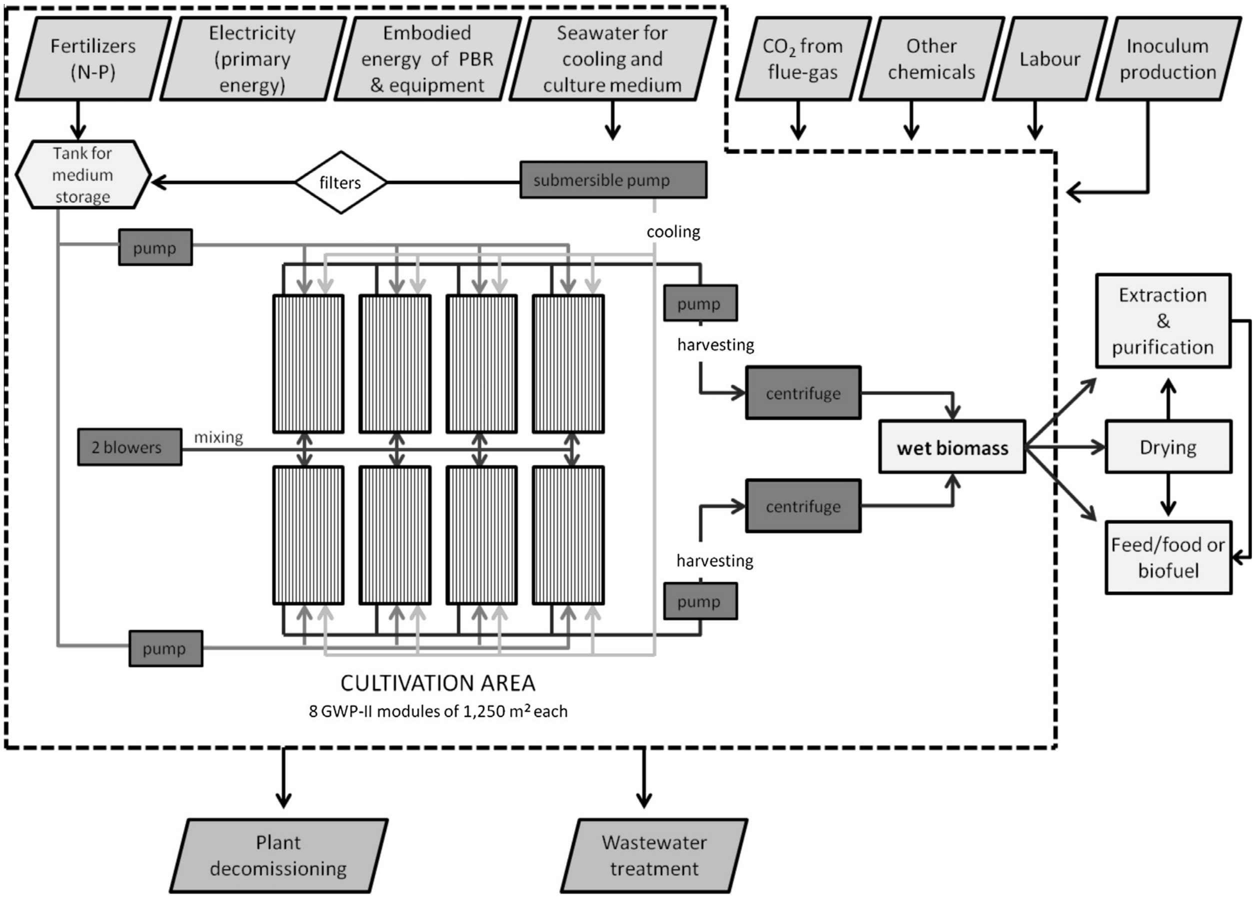

Fig. 1. Scheme of algal biomass production and downstream processes. Boundary limits (dotted box) for the energy analysis are shown.

An area close to Livorno (latitude 43°24′N; longitude 10°28′E) was chosen for the plant location given its proximity to the sea that permits to use seawater for the preparation of the growth medium and for cooling. Moreover, the climatic conditions of the chosen area are similar to those found in Sesto Fiorentino (Florence), where pilot-scale GWPs have been operated by our group for several years, allowing to build a large database (algae areal productivity, CO_2 uptake efficiency, nutrients requirement, energy consumption for mixing, etc.). Other data were obtained from the experimental facilities of F&M at Rosignano Solvay (Livorno, Italy) and from the Microalghe Camporosso S.r.l. plant (Camporosso, Italy), which, with 1500 m^2 of GWP-I reactors currently in operation, represents the biggest commercial installation for microalgae production in Italy.

The total energy obtained (*energy output*) is represented by the energy chemically stored in the algal biomass annually produced in the 1-ha plant. Average monthly productivities of *T. suecica* have been obtained after analyzing the available data, that enabled us to establish a reliable relationship between productivity (in gram per unit of occupied land) and solar radiation. The total energy requirement (*energy input*) to run the plant was divided in three main inputs: (i) embodied energy of materials, which includes the reactors and ancillary equipment (blowers, pumps, centrifuges, etc.); (ii) energy of fertilizers used as nutrients; (iii) energy for operations. The energy supplied by manpower and that associated to plant decommissioning are marginal and, thus, were not included.

2.2. Description of the GWP-II reactor and of the 1-ha GWP-II plant

The GWP is a flat photobioreactor with a disposable culture chamber, designed and patented in 2004 [10] and currently used by F&M in FP7 EU projects (BIOFAT and FUEL4ME) and for the commercial production of microalgae biomass at Microalghe Camporosso S.r.l. It is also used by companies in several R&D projects (in Chile, Portugal, Sweden, Saudi Arabia, Italy). The original GWP design, the GWP-I [10], has been improved in order to reduce its embodied energy and cost [25]. In the new design (GWP-II) (Fig. 2) the plastic culture chamber is contained by a number of vertical stainless-steel uprights directly driven into a wooden base and connected at the top by a horizontal stainless-steel bar so as to form a unique frame [25]. The removal of the grids and the reduction of the culture chamber height from 1 to 0.7 m have allowed the construction of a much lighter metal frame, decreasing in this way the energy associated with reactor materials and reactor cost. The culture chamber is made of a flexible, PAR-transparent (>90%),

Fig. 2. GWP-II photobioreactor at the F&M facility in Sesto Fiorentino (Italy).

LDPE film (0.3 mm thickness). When in a vertical position and filled up to the top, the culture chamber has an average thickness (light path) of 4.5 cm. Thus 1 m of panel contains on average 31.5 L of culture. Mixing, gas/liquid mass-transfer and carbon supply are achieved by bubbling CO_2 and air or flue-gas through a perforated pipe, which runs at the bottom of the culture chamber. Thermoregulation is provided by an internal stainless steel serpentine in which a cooling/heating fluid is circulated; alternatively the culture can be circulated by a pump through an external heat exchanger.

The main advantages of the GWP are the low construction cost (compared to other, especially tubular, closed systems), easiness of operation, flexibility and the capacity to be scaled-up. The main limitations are the energy expenditures for mixing and cooling, and the relatively high embodied energy [26,27]. GWP (GWP-II and GWP-III) reactors are commercialized by Fotosintetica & Microbiologica S.r.l., a spin-off of the University of Florence (http://www.femonline.it).

The 1-ha plant considered in our analysis is made of eight identical GWP-II modules, each comprising twenty-five 50-m-long vertical panels that occupy a land area of 1250 m^2. The panels are placed in parallel rows spaced by one meter and are E-W oriented (i.e., a wall of the panel is facing east and the other west) in order to maximize solar radiation capture during the cultivation season and reduce solar heating (and thus cooling needs) in the middle of the day. The total area occupied by the plant is 10,000 m^2 (1 ha), the total length of the panels is 10,000 m, the total volume of culture is 315 m^3, the total surface area of panels is 7000 m^2 and the total illuminated (photosynthetic) surface is 14,000 m^2 considering both panel faces. The ratio of surface area of panels to occupied land surface area is 0.7; the ratio of photosynthetic surface to occupied land surface area is 1.4.

The analysis includes the following ancillary equipment: two blowers for culture bubbling, one submersible pump for circulation of seawater, four centrifugal pumps for culture transfer and fresh medium preparation/distribution, two centrifugal separators for culture harvesting (Fig. 1). Both the embodied and the operational energy costs of equipment have been included.

2.3. Calculation of the NER

2.3.1. Energy output

The energy output was assumed to be equal to the biomass productivity (g m^{-2} occupied land day^{-1}) multiplied by the energy content (specific enthalpy) of biomass (kJ g^{-1}), and was given as kJ m^{-2} day^{-1} or GJ ha^{-1} $year^{-1}$. For *T. suecica* cultivated in nutrient replete conditions an energy content of 22.2 kJ g^{-1} was assumed. For the location chosen the useful cultivation season was assumed to be limited to the eight sunniest months of the year (from March to October). According to experimental data gathered in previous years, the average productivity in the chosen period was assumed to be 21.5 g m^{-2} of panel day^{-1}. Since there are 0.7 m^2 of panel per square meter of land, the average land areal productivity of the plant is 15 g m^{-2} day^{-1}, corresponding to an annual productivity of 36 tonnes of dry *T. suecica* biomass per hectare.

2.3.2. Energy inputs

2.3.2.1. Embodied energy of materials, machinery and other equipment. The embodied energy (E.E.) is here defined as "*The total primary non-renewable energy consumed during the whole life time of a product*" [28]. Embodied energy values can differ widely according to the boundaries conditions and data sources. The values used in this work were collected from reviewed literature, technical reports and open-access databases and refer mainly to the "*Cradle to Gate*" approach [28–30]. Only the energy related with raw materials extraction and processing was considered, excluding the cost for transportation to the plant site. Some materials, as plastic or timber, extensively used within the plant, might be recycled or burnt as fuel at the end of their useful life, thus producing heat (energy) that might be subtracted from the total energy requirements [31]. Energy recovery of materials at the end of their life was not considered in this analysis. However, we assumed using recycled PVC for piping and recycled steel for the containment frame. The total E.E. of an assembled machine is mainly given by the contribution of three distinct inputs: (i) the E.E. of the materials that constitute the machine; (ii) the energy necessary for its production; (iii) the energy for its maintenance [32]. In our analysis we have only considered the energy content of materials and the energy for machine production. Lifespan (the period for which the machines and plant components are functional) data were collected from the literature [23] and adjusted to the specific operational and environmental conditions of our plant. For the materials and components for which references were not available, lifespan values were obtained through enquiries with local producers. Lifespan for assembled machines were assumed to be 5 (for pumps), 20 (for blowers), and 25 (for centrifuges) years.

2.3.2.2. Fertilizers and other chemicals. The contribution of fertilizers to the overall energy input was calculated from their annual consumption and their unitary energy cost (MJ kg^{-1}). Chemicals for reactor cleaning and disinfection were not considered. The amount of fertilizers used in the process (kg ha^{-1} $year^{-1}$) was calculated from the biomass productivity (g m^{-2} day^{-1} or t ha^{-1} $year^{-1}$) considering an average biomass content of 7% for nitrogen and 0.7% for phosphorus. Only nitrogen (supplied as sodium nitrate) and phosphorus (supplied as sodium dihydrogen phosphate) were considered, since the requirement of iron is low and the remaining nutrients (including microelements) can be obtained from seawater.

2.3.2.3. Primary energy input for operations. The electricity consumption of the electromechanical equipment (blowers, pumps, centrifuges) was calculated from its power requirement multiplied by the time needed to accomplish each operation (water pumping, nutrient supply, bubbling, cooling, harvesting, etc.). In order to define the primary energy consumed by machinery, an overall electrical energy production efficiency (η_{pe}) must be assumed. The η_{pe} depends on the mix of fuels used for electricity generation. An overall conversion efficiency of 46% is reported for Italy [33], but in this analysis a higher value (58%), achievable with the best conversion technologies (e.g., with a modern combined cycle plant) [34], was adopted.

2.3.2.3.1. Energy for growth medium and culture pumping. A specific energy consumption of 0.058 kWh m^{-3} was considered for growth medium and culture pumping. This includes pumping of the culture from the reactors to the centrifuge and refilling of the reactor with fresh growth medium. A daily dilution rate of 25% (78.8 out of 315 m^3) was assumed. Since the plant is placed next to the sea, the water necessary for daily dilution and evaporation replenishment can be directly pumped from the sea by means of a submersible pump and sent, after filtration, to the tank where the growth medium is prepared. Specific consumption of the submersible pump was 0.077 kWh m^{-3}. The specific energy consumption of the pumps was calculated according to Eq. (1):

$$P_e = \frac{\Delta PQ}{\mu} \tag{1}$$

where P_e = electrical power (W); ΔP = pressure drop (Pa); Q = flow rate (m^3 s^{-1}); η = pump efficiency, considered to be 70%.

2.3.2.3.2. Energy for cooling. In the present study it was assumed to start cooling at 30 °C, that is the temperature value above which the growth of *T. suecica* is reduced. Cooling is attained by circulating seawater at 20 °C through the internal serpentine. The energy required for cooling is a function of three main variables: solar irradiance on the panel surfaces, ambient temperature, and heat exchange between panel and ambient. Hourly global irradiance ($W\,m^{-2}$) for each day during the chosen period on vertical east and west facing surfaces and hourly air temperature values were collected from http://re.jrc.ec.europa.eu/pvgis/ and www.lamma.rete.toscana.it. The hourly energy cooling demand was evaluated by means of Eq. (2):

$$P_{cool} = P_{net\_in} - P_{conv} - P_{evap} - P_{rad} \tag{2}$$

where P_{cool} = thermal power to be dissipated ($W\,m^{-2}$); P_{net_in} = irradiance ($W\,m^{-2}$) on the panel surfaces, considering hourly direct and diffuse radiation, shadow effects among the GWP rows and reflection from the ground; P_{conv} = power dissipated (or gained) due to convective exchange with ambient ($W\,m^{-2}$); P_{evap} = power dissipated by water evaporation ($W\,m^{-2}$); P_{rad} = power dissipated by radiative effect toward ambient ($W\,m^{-2}$).

Due to its small contribution during daylight, the radiative effect was neglected. Assuming a constant difference of the cooling water temperature of about 10 °C between the inlet and the outlet of the cooling serpentine, the necessary seawater flow was calculated as follows (Eq. (3)):

$$M_{cool} = \frac{P_{cool}}{C_p \Delta T} \tag{3}$$

where M_{cool} = mass flow-rate ($kg\,s^{-1}$); P_{cool} = thermal power ($W\,m^{-2}$); C_p = specific heat capacity ($J\,kg^{-1}\,K^{-1}$); ΔT = temperature difference between inlet and outlet of cooling water (K).

Considering a standard centrifugal pump, controlled by an inverter, with a global net efficiency of 70%, the electrical input for cooling can be evaluated. This model was validated with experimental data available in the F&M database.

2.3.2.3.3. Energy for mixing. Mixing (bubbling) is necessary to avoid culture sedimentation, to ensure a desired light-dark cycle and a suitable gas–liquid mass transfer. The energy consumption for mixing contributes significantly to the total primary energy input in bubbled as well as in pump-mixed reactors. In the GWP mixing is provided by bubbling. In this specific study two blowers are employed to supply compressed air or flue-gas to the 1-ha plant. The power consumption for mixing was estimated by the formula of adiabatic compression of Metcalf and Eddy [35] (Eq. (4)), that is commonly used to calculate power for bubbling in wastewater treatment plants:

$$P_w = \frac{wRT_1}{29.7n\eta}\left[\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right] \tag{4}$$

where P_w, the power requirement (kW), is a function of gas mass flow rate w ($kg\,s^{-1}$), universal gas constant R (8.314 $kJ\,kmol^{-1}\,K^{-1}$), absolute inlet temperature T_1 (K), absolute inlet pressure p_1 (atm), absolute outlet pressure p_2 (atm), compressor efficiency η and n that is $(k-1)/k$ = 0.23 for air, that was adopted also for flue-gas, where $k = C_p/C_v$, with C_p = specific heat at constant pressure ($kJ\,kg^{-1}\,K^{-1}$) and C_v = specific heat at constant volume ($kJ\,kg^{-1}\,K^{-1}$).

The optimal flow rate was determined experimentally both for daylight hours and the night. The pressure drop ($p_2 - p_1$) was measured experimentally in a GWP-II reactor by a pressure gauge at different flow rates and the P_w value was calculated for an efficiency of the blowers of 60%. The power values thus calculated were compared with those derived with the formula of Chisti [36] (Eq. (5)) using the same flow rates and hydraulic head:

$$\frac{P_G}{V_L} = \rho_L g U_G \tag{5}$$

According to Eq. (5) the power input (P_G, W) per volume unit (V_L, m^3) is correlated to the density of liquid ρ_L ($kg\,m^{-3}$), the gravitational acceleration g ($m\,s^{-2}$) and the superficial gas velocity U_G ($m\,s^{-1}$).

2.3.2.3.4. CO_2 supply. Flue gas with a CO_2 content of 12.5% was assumed to be used as carbon source and for pH control. The facility was assumed to be located next to a flue-gas generator (anaerobic digester, fermenter or power plant), so power input for flue-gas supply to the blowers was considered negligible.

2.3.2.3.5. Energy for harvesting. The culture concentration at harvesting is on average 1.9 $g\,L^{-1}$. This allows to avoid the pre-concentration step and to use directly a centrifuge. Based on data available in the literature [37] and on the experiments carried out, we have used a specific energy consumption of 1.2 $kWh\,m^{-3}$ for centrifuge operation.

3. Results and discussion

3.1. Energy output

Considering, on the basis of real productivity data collected during several seasons in Tuscany, that an average land areal biomass productivity of 15 $g\,m^{-2}\,day^{-1}$ can be achieved for eight months (240 days), the annual productivity in the chosen location is 36 tonnes of dry algae per hectare. Given an energy content of *T. suecica* biomass of 22.2 $MJ\,kg^{-1}$, this biomass yield corresponds to an energy output of 799 $GJ\,ha^{-1}\,year^{-1}$.

3.2. Energy inputs

3.2.1. Embodied energy of reactor, piping and machinery

The embodied energy of the GWP-II reactors, piping, fittings and machinery was calculated. The embodied energy of materials needed to build the plant amounts to about 410 $GJ\,ha^{-1}\,year^{-1}$, the major energy cost being associated with the materials required to build the eight GWP-II modules (390 $GJ\,ha^{-1}\,year^{-1}$ when recycled material is used for the chamber containment framework and PVC piping) (Table 1), despite the fact that the GWP design has been recently improved in order to reduce the energy demand associated with its construction [25].

The plastic chamber is the more expensive component of the reactor. The LDPE film used for the culture chamber has a high E.E. (89.3 $MJ\,kg^{-1}$) and, being necessary to change the film every year, this leads to an energy expense of 268 $GJ\,ha^{-1}\,year^{-1}$. Part of this energy might be recovered by recycling the discharged plastic, but this possibility was not considered here. The annual energy expenditure for the metal uprights and the horizontal bars that form the containment framework would amount to 221 $GJ\,ha^{-1}$, but decreases to 60 $GJ\,ha^{-1}$ when recycled material, as in this case, is used. The embodied energy of other materials used within the plant (PVC piping, fittings and machinery) is less influential (Table 1).

3.2.2. Fertilizers

Only *N* and *P* requirements were considered. The energy consumption for fertilizers required to produce 36 tonnes of *T. suecica* biomass amounts to 152 $GJ\,ha^{-1}\,year^{-1}$ (Table 2). It is worth mentioning that the process needs to be regulated so as to keep the efficiency of nutrient use close to 100%.

3.2.3. Energy for operations

3.2.3.1. Mixing (bubbling). An air flow-rate of 0.22 $L\,L^{-1}\,min^{-1}$ adopted for 10 daylight hours has been shown to be suitable to

Table 1
Embodied energy of the materials used to build the 1-ha GWP-II plant.

Material	Unitary E.E. ($MJ\ kg^{-1}$)		Total amount used ($t\ ha^{-1}$)	Life Span (years)	Annual E.E. used ($GJ\ ha^{-11}\ year^{-11}$)	
	Virgin	Recycled			Virgin	Recycled
GWP					**560.2**	**389.7**
Timber beam for GWP-II base	8.5[a]		36	10	30.6[a]	
Stainless steel for chamber framework	56.7	15.3[b]	78	20	221.1	59.6
PVC bubbling pipe and fittings	67.5	52.6[c]	3	5	40.5	31.5
LDPE film for culture chamber	89.3[a]		3	1	268.0[a]	
PVC – GENERAL PIPING	**67.5**	**52.6**	**1.8**	**9**[d]	**13.5**	**10.5**
MACHINERIES					**9.6**[a]	
Centrifuges	56.7[a]		2	25	4.5[a]	
Blowers	56.7[a]		1	20	2.8[a]	
Pumps	56.7[a]		0.2	5	2.3[a]	
TOTAL E.E.					**583.3**	**409.8**

[a] Value for virgin material used for both (virgin and recycled) calculations.
[b] [28].
[c] [38].
[d] [23].

Table 2
Energy consumption for fertilizers (N and P) to sustain a productivity of 36 $t\ ha^{-1}\ year^{-1}$ of *Tetraselmis suecica* in the 1-ha GWP-II plant.

	Nutrient content in biomass (%)	Nutrient unit energy cost[a] ($MJ\ kg^{-1}$)	Daily amount used ($kg\ ha^{-1}\ day^{-1}$)	Daily energy cost ($MJ\ ha^{-1}\ day^{-1}$)	Annual energy cost[b] ($GJ\ ha^{-1}\ year^{-1}$)
N	7	56.8	10.5	596.4	143.1
P	0.7	33.3	1.05	35.0	8.4
TOTAL				**631.4**	**151.5**

[a] Sodium nitrate (16.5% N) and sodium dihydrogen phosphate (25.8% P) have an energy content of 9.38 and 8.6 $MJ\ kg^{-1}$, respectively [7].
[b] Assuming a 240-day cultivation season.

Table 3
Energy consumption for operation (240 days) of the 1-ha GWP-II plant producing 36 $t\ ha^{-1}\ year^{-1}$ of *Tetraselmis suecica*.

Device or equipment	Function	Electrical energy consumption		Incidence %
		$kWh\ day^{-1}$	$GJ\ ha^{-1}\ year^{-1}$	
Blowers (N.2)	Culture bubbling	**367.0**	**317.1**	68.3
Submersible Pump (N.1)[a]	Water pumping for cooling	**60.6**	**52.4**	11.3
	Water pumping for growth medium preparation[b]	**6.1**	**5.3**	1.1
Pumps (N.4)	Culture and growth medium pumping	**9.2**	**7.9**	1.7
Centrifuges (N.2)	Culture harvesting (78.8 $m^3\ day^{-1}$)	**94.5**	**81.6**	17.6
TOTAL ENERGY CONSUMPTION[c]		**537.4**	**464.3**	100.0

[a] Used for two functions.
[b] The specific energy consumption increases as water passes through the filters before entering the tank.
[c] Human labor is not considered.

avoid oxygen build-up in the culture and maintain high productivity. Experiments done in Sesto Fiorentino (Florence, Italy) have also shown that during the night, the air flow-rate can be reduced without negative consequences as far as it is sufficient to avoid sedimentation and to provide the oxygen required for algal respiration. Thus, during the remaining 14 h, the air flow-rate is lowered to 0.12 $L\ L^{-1}\ min^{-1}$. The power consumption for the blowers (Table 3) was calculated with the formula of Metcalf and Eddy [35]. The formula of Chisti [36], that is often used [13,20] to calculate the power input for bubbling, gives a power consumption that is 19% lower with respect to that calculated with the formula of Metcalf and Eddy [35]. In the context of an energy analysis, the formula of the adiabatic compression [35] is preferable since it provides a more realistic evaluation of the required power for bubbling, as the pressure drop due to friction losses at the sparger, and the efficiency of gas compression are included. In our case (0.7 m high panels) the power consumption by the blowers is about 73 $W\ m^{-3}$ for daytime and 31 $W\ m^{-3}$ during the night. The annual electrical energy cost due to mixing is thus 317 $GJ\ ha^{-1}\ year^{-1}$ (Table 3), that corresponds to a primary energy input of about 547 $GJ\ ha^{-1}\ year^{-1}$ (68% of the total for operations).

3.2.3.2. Cooling. Based on experiments carried out in Florence with the GWP-II and *T. suecica*, cooling is necessary for 5–6 months a year. The pump used to circulate the cooling water through the serpentines or the heat exchanger consumes 52.4 $GJ\ ha^{-1}\ year^{-1}$ (Table 3), that corresponds to a primary energy input of 90.3 $GJ\ ha^{-1}\ year^{-1}$, and represents 11% of the total.

3.2.3.3. Culture harvesting. Electrical consumption of self-cleaning disk centrifuges, used to harvest the culture, was assumed to be 1.2 $kWh\ m^{-3}$ for a continuous daily use of 6–7 h. Hence, centrifuges consume 81.6 $GJ\ ha^{-1}\ year^{-1}$ (Table 3), corresponding to a primary energy input of about 141 $GJ\ ha^{-1}\ year^{-1}$ (18% of the total operational costs).

Since a 100% nutrient uptake efficiency is the goal, the clarified medium will be clean and devoid of nutrients and thus able to be disposed without further treatment. This will be possible only if nutrients are daily integrated according to productivity and their relative content into the biomass, and never given in excess. Based on experimental measurements, water daily lost by evaporation averages 0.14 L per meter of panel, which amounts to 1.4 m^3 of water for the whole plant. This loss is replenished with seawater. Since we use a dilution rate of 25% and the medium after centrifugation is discharged, the increase of salinity over the season is negligible and does not affect productivity of *T. suecica*.

The total consumption of electric energy for operations amounts to 537 kWh day^{-1} (Table 3) which corresponds to 464 GJ ha^{-1} $year^{-1}$ and, at a 58% conversion efficiency, to 800 GJ ha^{-1} $year^{-1}$ of primary energy. The major operation costs are mixing (68% of total), harvesting (18% of total) and cooling (11% of total). The electric energy consumption for growth medium preparation, and culture and growth medium pumping is a minor input (about 3% of total).

3.3. The NER

The scenario considered in this study leads to a NER value for algal biomass production in the 1-ha GWP-II plant of 0.59 (Table 4). This means that the amount of non-renewable energy consumed in the process is 70% higher than the chemical energy stored in biomass by algal photosynthesis. The energy balance shows that about 60% of the non-renewable energy input is due to the primary energy (associated to electricity consumption) needed for the cultivation phase and for harvesting, 30% of the energy consumed is due to the embodied energy of the materials employed (reactor, machinery, etc.), while fertilizers contribute for about 10% of the total energy consumption.

The NER value found in this work is much lower than that reported in previous studies for analogous culture systems. For example, the study of Jorquera et al. [13], in which a compared energy analysis for raceway ponds, tubular reactors and flat panels based on the GWP design was carried out, found, for a GWP-plant of comparable size to that proposed here, a NER of 4.5. This high value is the result of a very high productivity (100 t ha^{-1} $year^{-1}$) and the fact that important energy inputs (cooling, harvesting, nutrients) and conversion of electric energy input to primary energy were not considered. Besides that, in the Jorquera et al. [13] analysis, a biomass with a 30 MJ kg^{-1} caloric content is attained as output product, which will require a relatively high lipid content. A productivity of 100 t ha^{-1} $year^{-1}$ of a lipid-rich biomass is unlikely, even at the small scale.

3.3.1. Implementation of the NER and future perspectives

The NER of a process can be improved by increasing the energy output and/or decreasing the energy inputs. With *T. suecica* cultivated in the GWP-II, monthly averaged productivities surpassing 30 g m^{-2} of panel surface day^{-1}, corresponding to about 20 g m^{-2} of occupied land day^{-1}, have been achieved by our group in different years and with different reactor configurations (Chini Zittelli et al., unpublished; Sampietro and Tredici, unpublished). We believe that, in a more favorable location (for example in a Mediterranean African country), these productivities could be maintained for at least 11 months a year, leading to an annual output of 66 t ha^{-1}. Further improvements of productivity per land unit would be attainable by placing the panels at a closer distance so as to intercept more light. This is the approach adopted, for example, by Solix and Algenol [9; http://www.algenol.com/direct-to-ethanol/direct-to-ethanol]. Even if successful in providing higher areal outputs, the final energy balance of this close arrangement will be much worsened, due to the much increased energy requirements (both embodied and operational) of closely spaced panels. For example, at the latitude of Florence the 0.7-m high, E-W facing panels placed at a distance of 1 m intercept on average from 54 (albedo of 0.2) to 60 (albedo of 0.5)% of the solar radiation falling on the horizontal. Reducing the distance between panel rows from 1 to 0.5 m (which requires a doubling of panel rows) increases the fraction of radiation intercepted by the plant per unit occupied land (and therefore plant areal productivity) of less than 40% (with an albedo of 0.2). In this packed configuration, however, the embodied and operational energy inputs nearly double, and thus the NER decreases significantly.

The calculation of the NER of the 1-ha GWP-II plant located in climatic conditions able to provide an annual output of 66 t ha^{-1} is reported in Table 5. Since, together with the longer cultivation season, also some inputs increase significantly (e.g., energy consumption for operations and fertilizers), the almost doubling of productivity only leads to an about 40% increase of the NER.

Decreasing the energy inputs is also possible, although it is difficult to significantly reduce some of them without decreasing productivity. A possibility would be reducing the culture thickness so as to reduce the total culture volume and thus the expenses for mixing, harvesting, medium preparation and pumping. This strategy will be applied in the next generation of the GWP series, in which we aim at decreasing the average culture thickness to less than 3 cm. Energy for cooling could be significantly reduced if a thermo-tolerant strain were used. For example growing an alga with a temperature optimum between 40 and 45 °C could save the operational energy cost for cooling and the E.E. associated with

Table 4
NER of *Tetraselmis suecica* biomass production in the 1-ha GWP-II plant producing 36 t ha^{-1} $year^{-1}$ (240 operation days).

Energy output	**GJ ha^{-1}**	**799**
Productivity	t ha^{-1} $year^{-1}$	36.0
Biomass energy content	MJ kg^{-1}	22.2
Energy inputs	**GJ ha^{-1}**	**1362**
$E_{operations}$	GJ ha^{-1}	800
$E_{fertilizers}$	GJ ha^{-1}	152
$E_{embodied}$	GJ ha^{-1}	410
NER		**0.59**

Table 5
NER of *Tetraselmis suecica* biomass production in the 1-ha GWP-II plant in a suitable location producing 66 t ha^{-1} $year^{-1}$ (330 operation days).

Energy output	**GJ ha^{-1}**	**1465**
Productivity	t ha^{-1} $year^{-1}$	66.0
Biomass energy content	MJ kg^{-1}	22.2
Energy inputs	**GJ ha^{-1}**	**1781**
$E_{operations}$	GJ ha^{-1}	1093
$E_{fertilizers}$	GJ ha^{-1}	278
$E_{embodied}$	GJ ha^{-1}	410
NER		**0.82**

Table 6
NER of *Tetraselmis suecica* biomass production in the 1-ha PV-integrated GWP-II plant in a suitable location producing 66 t ha^{-1} $year^{-1}$ (330 operation days).

Energy output	**GJ ha^{-1}**	**1465**
Productivity	t ha^{-1} $year^{-1}$	66.0
Biomass energy content	MJ kg^{-1}	22.2
Energy inputs	**GJ ha^{-1}**	**848**
$E_{operations}$	GJ ha^{-1}	0
$E_{fertilizers}$	GJ ha^{-1}	278
$E_{embodied}$	GJ ha^{-1}	570[a]
NER		**1.73**

[a] 410 GJ ha^{-1} $year^{-1}$ E.E. of the plant + 160 GJ ha^{-1} $year^{-1}$ E.E. of PV.

Table 7
Comparison between soya and *Tetraselmis suecica* production in terms of annual biomass and protein yield, annual energy gain and NER.

Crop	Yield ($t\ ha^{-1}\ year^{-1}$)	Energy output ($GJ\ ha^{-1}\ year^{-1}$)	Energy input ($GJ\ ha^{-1}\ year^{-1}$)	NER	Gain ($GJ\ ha^{-1}\ year^{-1}$)	Protein yield ($t\ ha^{-1}\ year^{-1}$)
soya (USA)[a]	2.6	39.2	10.6	3.7	28.6	0.91
Tetraselmis suecica (Tuscany, Italy)	36.0	799	1362	0.6	−563	16.2
Tetraselmis suecica (Africa)	66.0	1465	1781	0.8	−316	29.7
Tetraselmis suecica (Africa)[b]	66.0	1465	848	1.7	617	29.7

[a] [44].
[b] In a PV-GWP-II integrated system.

the cooling device. Finally, when the target is a biomass rich in lipid and/or carbohydrate, the culture could be grown under nitrogen and/or phosphorus limitation or starvation, thus reducing by more than 50% the energy input for fertilizers.

To achieve a higher NER, we have recently proposed [39–41] to integrate the GWP with a photovoltaic (PV) system. The rationale for this is that by covering about 15% of the surface area of the panels with PV elements able to achieve 15% efficiency of light energy conversion into electricity, the whole energy needs for operations can be supplied. Of course, PV application on the GWP surface should be done without reducing plant productivity, and will increase the E.E. of the plant.

Experiments carried out in Florence during two consecutive years (2012–2013) with 45°-inclined N-S oriented GWP-II have shown that a *T. suecica* culture can be shaded up to 20% of its surface exposed to beam radiation by PV strips without any decrease of productivity (Sampietro and Tredici, unpublished).

If we integrate a PV system in the photobioreactor, the energy costs associated with the construction, operation and decommissioning of the PV elements must be considered. By far the largest fossil fuel inputs for PV are associated with their production and installation, while energy costs for operation and decommissioning are marginal. Thanks to the rapid growth of PV industry and continuous improvement of technologies, the energy requirement per unit area of crystalline silicon cell has gradually decreased to less than 3 GJ per square meter [42]. In this study we have assumed a cost for silicon purification, cell fabrication, panel assembly, wiring power electronics, support frame, transport and installation of about $3.8\ GJ\ m^{-2}$ [42,43] that, assuming a lifespan of 25 years, increases the E.E. of our integrated PV-GWP system of $160\ GJ\ ha^{-1}\ year^{-1}$ (Table 6), bringing the total E.E. of the plant from 410 to $570\ GJ\ ha^{-1} year^{-1}$. However, since the energy requirements for operations ($1093\ GJ\ ha^{-1}\ year^{-1}$) are now supplied by PV, the NER increases up to more than 1.7. The calculation of the NER of a PV integrated GWP-II plant is shown in Table 6.

A NER value of 1.7 is not sufficient to compete with traditional crops as source of food or biofuels, especially since our energy analysis ends with wet biomass as the final product, and does not consider the downstream processing (Fig. 1). However, some considerations that here follow show that, even with a relatively low NER, algae cultivation in the GWP can compete with traditional crops for food/fuel, when the gain per unit land area and the nutritional value of the biomass produced are taken into consideration.

In the United States soya yields average $2.6\ t\ ha^{-1}\ year^{-1}$ providing an energy output of $39.2\ GJ\ ha^{-1}\ year^{-1}$ [44]. Energy inputs amount on average to $10.6\ GJ\ ha^{-1}\ year^{-1}$ thus allowing to attain a NER of 3.7 and a gain of $28.6\ GJ\ ha^{-1}\ year^{-1}$ [44] (Table 7). Because of its high protein content (35%), soya is the most important protein crop in the world. With a grain yield of $3\ t\ ha^{-1}\ year^{-1}$ (achievable under optimal climatic conditions) the protein yield of soya reaches about $1\ t\ ha^{-1}\ year^{-1}$.

With *T. suecica* the energy output in a suitable location can reach $1465\ GJ\ ha^{-1}\ year^{-1}$ (Table 7). Since, thanks to integration with PV, the energy inputs have been decreased to less than $850\ GJ\ ha^{-1}\ year^{-1}$, even at the relatively low NER of 1.7, *T. suecica* cultivation in GWPs will allow high gains (20 times those of soya) per unit of occupied land, which is particularly important in reducing the soil footprint of food or biofuel production. Besides, it is necessary to mention again that marine algae cultivation may be carried out without using freshwater on marginal lands, or even in desert areas, that will never sustain high soya (or any other traditional crop) productivities. Finally, under nutrient sufficient conditions, the protein content of *T. suecica* biomass typically reaches 45% [45], thus its culture has the potential for a protein yield of 16 (Tuscany) to 30 (Mediterranean Africa) tonnes per hectare against the 1 tonne per hectare of soya (Table 7).

4. Conclusions

The NER of *T. suecica* production in a 1-ha GWP-II plant located in Tuscany is much less than 1, thus this technology cannot be proposed for biofuel, and even feed or food production with this system will be limited by low efficiency of energy conversion and low sustainability. In a more suitable location, where the cultivation is carried out the whole year and higher productivities are achieved, the NER increases up to 0.8, a value that can be more than doubled adopting a GWP system integrated with photovoltaics. Despite the relatively low NER compared to traditional crops (e.g., soya) the cultivation of this microalga shows high potential for the production of biofuel and/or food, especially when the high energy gains and protein yields attainable per unit land area are taken into consideration. *T. suecica* grown under nutrient replete conditions typically contains about 45% protein, thus its cultivation in suitable areas could provide annually up to 30 tonnes of protein per hectare. This is thirty times the protein yield of soya in good soils and suitable climates. Marine microalgae can attain high areal yields in biomass, lipid, carbohydrate and protein, without impacting on freshwater and arable land. The day we will be able to cultivate a marine nitrogen-fixing cyanobacterium at large scale with productivities and gains similar to those of green microalgae, we will be able to attain these outcomes without using nitrogen fertilizers, which are a main concern for their adverse impact on watercourses and the atmosphere.

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