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1 **Optimal integration of microalgae production with photovoltaic panels: environmental**
2 **impacts and energy balance**

3

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12

13 **Abstract**

14 **Background:** Microalgae are 10 to 20 times more productive than the current agricultural biodiesel
15 producing oleaginous crops. However, they require larger energy supplies, so that their environmental
16 impacts remain uncertain, as illustrated by the contradictory results in the literature. Besides, during
17 most of the year, solar radiation is too high relative to the photosynthetic capacity of microalgae. This
18 leads to photosaturation, photoinhibition, overheating and eventually induces mortality. Shadowing
19 microalgae with solar panels would therefore be a promising solution for both increasing productivity
20 during hotter periods and producing local electricity for the process. The main objective of this study
21 is to measure, via LCA framework, the energy performance and environmental impact of microalgae
22 biodiesel produced in a solar greenhouse, alternating optimal microalgae species and photovoltaic
23 panel (PV) coverage. A mathematical model is simulated to investigate the microalgae productivity in
24 raceways under meteorological conditions in Sophia Antipolis (south of France) at variable coverture
25 percentages (0% to 90%) of CIGS solar panels on greenhouses constructed with low-emissivity (low-
26 E) glass.

27 **Results:** A trade-off must be met between electricity and biomass production, as a larger photovoltaic
28 coverage would limit microalgae production. From an energetic point of view, the optimal
29 configuration lies between 10% and 20% of PV coverage. Nevertheless, from an environmental point
30 of view, the best option is 50% PV coverage. However, the difference between impact assessments
31 obtained for 20% and 50% PV is negligible, while the NER is 48% higher for 20% PV than for 50%
32 PV coverage. Hence, A 20% coverage of photovoltaic panels is the best scenario from an energetic
33 and environmental point of view.

34 **Conclusions:** In comparison with the cultivation of microalgae without PV, the use of photovoltaic
35 panels triggers a synergetic effect, acting both as a source of electricity and in reducing climate
36 change impacts. Considering an economic approach, low photovoltaic panel coverage would probably
37 be more attractive. However, even with a 10% area of photovoltaic panels, the environmental
38 footprint would already significantly decrease. It is expected that significant improvements in
39 microalgae productivity or more advanced production processes should rapidly enhance these
40 performances.

41 **Keywords:** Biodiesel; *Chlorococcum sp.*; *Desmodesmus sp.*; Life cycle assessment; Raceway;
42 Renewable energy.

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54 **Background**

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56 Renewable liquid fuels are expected to play an essential role in reaching targets to replace petroleum-
57 derived transportation fuels with a viable alternative, and to contribute to the reduction of GHG
58 emissions. Although biodiesel from oleaginous crops and bioethanol from sugarcane are being
59 produced in increasing amounts as renewable liquid fuels, their production cannot sustainably address
60 the demand [1]. Hence, alternative sources of biomass are required to supply this increasing demand.
61 Microalgae-based oil is currently being considered as a promising alternative raw material for
62 biodiesel [2].

63 Microalgae are photosynthetic microorganisms that transform sunlight, water and carbon dioxide into
64 chemical energy. This energy is stored as chemical bound energy, especially into lipids, carbohydrates
65 and proteins. Oil extracted from microalgae species can then be converted into biodiesel [3]. In turn,
66 biodiesel is a form of solar energy. Conventional agricultural oil crops are widely used to produce
67 biodiesel; however, the oil fraction is very low (around 5% of total biomass basis) compared with
68 certain species of microalgae whose oil content can exceed 60% of dry weight [1].

69 Microalgae has several advantages over land-based crops in terms of oil production: high biomass
70 productivity, no competition with feed crops, possibility to uptake industrial sources of CO₂ and
71 reduced competition for land [2]. Microalgae has the possibility to grow on marginal land by using
72 brackish or seawater avoiding its competition for resources with conventional agriculture. Their
73 simple unicellular structure and high photosynthetic efficiency allow for a potentially higher oil yield
74 per area than the best oilseed crops [4] and its culture do not require herbicides nor pesticides [5].

75 Despite these advantages, microalgae-based fuels are still not widely produced, mainly due to their
76 current cost of production [4]. Simultaneous algae biomass production and lipid accumulation is one
77 of the main economic and technological bottlenecks [6]. Productive microalgae species and optimized
78 culture conditions allowing for the production of strains with a simultaneously high growth rate and
79 lipid content are necessary. The high cost and energy demand of harvesting diluted algae cells also
80 remain a major challenge.

81 The use of microalgae for generating energy requires large-scale, low-cost production. This implies
82 cheap, scalable reactor designs with high algal productivity. Many different algal cultivation systems
83 have been developed, which can be divided into two main categories, open and closed. Closed
84 systems, consist of containers, tubes or transparent plastic bags of various sizes closed to the
85 atmosphere [7], while open systems consist of natural or agitated artificial ponds and containers open
86 to the atmosphere.

87 To date, most commercial **production** have taken place in open ponds, thanks to their low cost and
88 ease of construction and operation [7]. The most common technical design is the raceway pond: an
89 oblong, looped pond mixed with a paddlewheel. However, some disadvantages of open systems have
90 been detected, such as high evaporation rates, diffusion of CO₂ to the atmosphere, contamination with
91 competing species and low control of solar radiation and temperature [7]. Ponds enclosed in glass
92 houses or plastic-covered greenhouses which allow a better control of the growth environment [8].
93 Climate control in greenhouses contributes to maintain a better-adapted temperature for growth and
94 therefore enhances the productivity. In addition, it reduces water losses through evaporation as well as
95 the risk of contamination by other algal species or grazers [9].

96 Light and temperature influence algal biomass productivity and lipid cell content [10-12]. High
97 irradiance and high temperature generate an increase in triglyceride synthesis, with a more saturated
98 fatty acid composition compared to conditions at low irradiance and/or temperature [13]. Since light
99 and temperature vary seasonally, these factors are crucial for learning the lipid composition and
100 accumulation in outdoor cultivation systems. Microalgae species should be alternated during the year
101 to best adapt to the season, and thus improve yearly production. Hence, the seasonal variation of lipid
102 productivity results from several processes, which need to be accounted for in order to accurately
103 estimate the algal oil yield

104 Moreover, solar radiation is, for most of the year, too high relative to the photosynthetic capacity of
105 microalgae, thus leading to photosaturation, photoinhibition, also leading to overwarming eventually
106 significantly increasing mortality [9]. Shadowing the microalgae with solar panels therefore turns out
107 to be a promising solution for both increasing productivity during hotter periods and producing local
108 electricity for the process. Jez, Fierro [14] demonstrated an increase in economic competitiveness for

109 microalgae biofuels when photovoltaic panels were used as a source of electricity in the facility. It is
110 also a noteworthy option for producing algal biofuel in remote areas (typically deserts) that are long-
111 distance or difficult access to the electric grid.

112 Solar photovoltaic panels (PV) provide energy security, reduce medium temperature and avoid
113 photoinhibition in microalgae cultures [15]. However, building PV also produces greenhouse gas
114 emissions due to energy consumption during the manufacturing processes. Investment costs on PV
115 technology are still relatively high [16] but they are constantly decreasing due to both technology
116 improvements and increases in production scales [17]. The most common PV technology is
117 Crystalline silicon (single-crystalline sc-Si and multi-crystalline mc-Si), followed by Cadmium-
118 Telluride (CdTe) and Copper Indium Gallium (di) Selenide (CIGS) [17]. Therefore, the viability of PV
119 panels combined with biomass production strongly depends on the geographical location, on local
120 sunlight radiation and on electricity costs.

121 Coupling biomass production with photovoltaic electricity represents an ideal opportunity for
122 significantly reducing environmental impacts and electrical demands for biodiesel production systems.

123 Although this solution is technologically appealing, its sustainability can be questionable as there is a
124 clear trade-off between electricity and biomass production, as a larger photovoltaic panels coverage
125 would limit microalgae production. The large seasonal variations in biomass production alter the value
126 chain as well as its environmental impacts. Quantification of the environmental impacts of algal oil
127 production is therefore necessary. Life cycle assessment (LCA) is a standardized tool that provides a
128 quantitative and scientific analysis of the environmental impacts of products and their industrial
129 systems [18]. The functional unit (FU) considered is 1 MJ of algal methyl ester (biodiesel), used in a
130 conventional internal combustion automobile engine. The system boundary is defined as a set of
131 criteria specifying which unit processes are part of a product system, while the life cycle inventory is a
132 list of input and output components at each step of the production process [19].

133 The main objective of this study is to measure, via LCA framework, the energy performance and
134 environmental impacts of microalgae-based biodiesel produced in a solar greenhouse, alternating
135 optimal microalgae species and photovoltaic panel coverage percentages, to determine the optimal
136 energetic environmental configuration. This prospective assessment is carried out with an eco-design

137 approach to tackle the main features of the system. In addition, four references cases complying with
138 similar system boundaries and allocation approaches have been provided, only as benchmarking
139 systems and not for purposes of comparative assertion. A mathematical model is simulated to
140 investigate the microalgae productivity in raceways under meteorological conditions in Sophia
141 Antipolis (south of France) at variable coverture percentages (0% to 90%) of CIGS solar panels on
142 greenhouses. Biomass productivity and electricity production results are used as input in a process
143 sequence of a virtual facility for biodiesel production over 145 ha, and thereafter, as input to a life
144 cycle inventory implemented into SimaPro 8 software [20]. Three aspects of microalgae production
145 were analyzed: potential environmental impacts, energy and carbon balance.

146

147 **Methods**

148

149 **System description**

150 From a ‘pond to wheel’ point of view, the scope of the system encompasses the production of
151 biomass, process conversion and its combustion in a middle-sized car. The construction, dismantling
152 and final disposal of the infrastructure and machinery were also included, as well as the production of
153 chemicals and their transport. The process is divided into six main areas, also called sub-systems.

154 **Figure 1** illustrates the general schematic of the system boundaries and subsystems.

155 Subsystem 1 considers raceway systems for microalgae biomass production coupled with upstream
156 inoculum production operations. Subsystem 2 includes harvesting and dewatering steps, which help to
157 increase the biomass solid content for processing through subsequent conversion operations to obtain
158 biodiesel: oil extraction (Subsystem 3) and oil conversion (Subsystem 4). The design also includes the
159 combustion of microalgae biodiesel (Subsystem 6) and photovoltaic electricity production (Subsystem
160 5). The infrastructure construction and machinery production and dismantling are also considered.

161

162 **Figure 1** around here

163

164 The size of the facility is assessed for a total production area of 145 ha (including inoculum ponds and
165 downstream processes). The overall site layout assumes that ponds are grouped into unit “modules” of
166 about 5 ha (50 868 m²) each. Each module represents a standard greenhouse, constructed with low-
167 emissivity (low E) glass (KGlass™ from Pilkington: thickness=4 mm, transmittance=82%, density=
168 10 kg·m⁻², lifespan= 30 years) [21] for walls and roof, supported by a steel frame. Low E is an
169 essential contributor to energy conservation, since it reflects energy back into the greenhouse,
170 achieving much lower heat loss than ordinary glass [21], and eventually extending the production
171 period. The greenhouse structure also includes a climate control system through ventilation. It allows
172 for medium temperatures to be maintained close to the optimal growth temperature of the microalgae.
173 The ventilation system consists in favoring air flow by opening and closing the windows (flow rates
174 fixed to 50 m³·s⁻¹·greenhouse⁻¹ and 500 m³·s⁻¹·greenhouse⁻¹, windows are closed and open,
175 respectively).

176 The layout of the greenhouses within the overall facility footprint along with the pipelines and roads
177 required for on-site circulation and transport of materials is detailed in the **Additional material 2.1**.
178 The full facility contains 122 ha of biomass production raceways grouped into 24 individual
179 greenhouses (including 2 for inoculum ponds) connected via a network of pipelines and roadways.
180 The greenhouses form a uniform grid of four columns by six rows. The rows comprise the raceway
181 pond modules as well as the inoculum ponds. The facility also includes a dewatering section, a
182 nutrient and freshwater storage section, and algal biomass conversion sections. Roads with access to
183 all modules are 2 m wide between columns and 2 m wide between rows. The module dimensions
184 include spacing for piping, electricity and roads on the border for access to the ponds. The nutrient
185 and freshwater storage section provides bulk storage for water and nutrient inputs, while biodiesel is
186 stored in the esterification section.

187 The production facility is located in Southern Europe (Sophia Antipolis - France, 43°36'56"N,
188 7°03'18"E), close enough to the Mediterranean coast to allow access to seawater. The geographic
189 location of facility has the highest impact on biomass productivity. The climatic conditions of the
190 chosen location should allow for high biomass productivity throughout the year. The main factors
191 affecting biomass productivity are the average annual irradiance level and temperature. Ideally, the

192 temperature should be around 25°C with minimum diurnal and seasonal variations [8]. Other
 193 considerations also have to be taken into account, such as humidity and rainfall, the possibility of
 194 storms and flood events and the presence of dust and other atmospheric pollutants [8]. Meteorological
 195 data were collected at INRA PACA, Sophia Antipolis in 2015. These data were used to simulate the
 196 dynamics of temperature and light in the cultivation medium, for the various tested designs.
 197 Access to carbon dioxide and water of suitable quality are important. The algae culture and its
 198 transformation should both take place at the same site. The facility is assumed to be established on an
 199 initially shrub land and is modelled as an industrial area with vegetation.

200

201 **Co-product consideration in the assessment**

202 If more than one product is delivered from the system processes, all system flows must be weighted
 203 and divided proportionally to the energy content of the products, and to the mass or market value.
 204 This division is called allocation. Another approach consists in substitution, which takes into account
 205 all products that can be replaced by the co-products; the system therefore receives credits for having
 206 cut down on the use of the initial product. The choice of performing co-product management
 207 approaches is a fundamental step in LCA and can lead to completely different results [22]. Several co-
 208 products can be generated in the system during three steps: i) oil extraction, ii) transesterification and
 209 iii) photovoltaic shading. The oil extraction process produces high value lipids (algal oil) and residual
 210 dry biomass (oilcake). Transesterification yields glycerine as a co-product while photovoltaic panels
 211 obviously produce electricity.

212 The impacts of co-products are based on an allocation approach according to their energy content
 213 [23], which is measured by their lower heating values (LHV). The co-products include surplus
 214 electricity, extraction residue (oilcake) and glycerine. Oilcake and glycerine have an energetic content
 215 (**Table 1**) and can be valorised as a source of energy, animal feed for oilcake and as heat source for
 216 glycerine [9]. Crude oil and oil cake differ in their carbon and energetic content, similarly to
 217 glycerine and biodiesel.

218

Table 1. Lower heating value (LHV) for co-products

Compound	Heating value (MJ/kg)	Ref.
-----------------	------------------------------	-------------

Biodiesel	37.2	[9]
Algal oil	38.3	[3]
Oil cake	0.77*	[9]
Glycerine	18.1	[9]

* Composed by 95% water, 5% biomass (content around 70% carbohydrates and 30% protein), LHV based in composition.

219

220

221 A three-stage allocation scheme is carried out: First the impacts on electricity production, from a
 222 photovoltaic system (Subsystem-5) to electricity injected into the facility and exported electricity
 223 (surplus electricity). Secondly, the impacts incurred due to the production of oilcake and algae oil in
 224 the oil extraction subsystem (Subsystem-3) and thirdly the apportioned impacts of glycerine
 225 production in the oil conversion subsystem (Subsystem-4). **Table 2** presents the average annual
 226 allocations for different photovoltaic coverage ratios and consumption/production of electricity (see
 227 seasonal variations in the **Additional file 8**).

228

229

Table 2. Allocation factors used for biodiesel and co-products

		Percentage of coverage of photovoltaic panels									
		0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
Allocation S5	Electricity from PV panels into facility	0%	84%	55%	36%	26%	20%	17%	14%	11%	9%
	Electricity exported (surplus)	0%	16%	45%	64%	74%	80%	83%	86%	89%	91%
Allocation S3	Algal oil	65%	65%	64%	64%	64%	63%	63%	63%	63%	63%
	Oilcake	35%	35%	36%	36%	36%	37%	37%	37%	37%	37%
Allocation S4	Biodiesel	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%
	Glycerine	9%	9%	9%	9%	9%	9%	9%	9%	9%	9%

230

231 Substitution is also proposed as an alternative allocation method. Produced oilcake can be employed
 232 as animal feed in the same manner as soymeal can be used as a co-product from biodiesel. The protein
 233 content of soymeal is 48% [24], while it is around 30% in oilcake. Thus, 1 kg oilcake from algae
 234 replaces 0.6 kg of soybean for animal feed. The credits for not having to produce 0.6 kg soymeal for
 235 every kg algae oilcake produced are subtracted from the total upstream processes and emissions
 236 associated with the algal biodiesel production. **Algal oilcake co-product replaces the soymeal
 237 production from a soybean crude oil production plant located in United States.** Glycerine and surplus
 238 electricity co-products are respectively assumed to replace petroleum glycerine from an
 239 epichlorohydrine European plant and electricity production from a European mix, respectively.

240

241 **Microalgae specification**

242 The analysis considers *Chlorococcum* sp. and *Desmodesmus* sp, since both species can achieve
243 efficient trade-off between growth rate, lipid accumulation and ease of cultivation [25, 26]. Data are
244 not consistent enough in the literature to accurately describe the variations in lipid profiles due to
245 seasonal light and temperature variations. As a consequence, a constant TAG rate for each species is
246 assumed according to nitrogen starvation conditions [27]. **Additional file 1** provides general
247 information on the biomass as well as compositional details. The analysis considers a 47% and 53.8%
248 lipid content (of dry basis content biomass), for *Chlorococcum* sp. and *Desmodesmus* sp.,
249 respectively.

250

251 **Cultivation**

252 Microalgae cultivation in a module consists of 5 raceways of 8348 m² (2504.5 m³ total volume) mixed
253 with a paddlewheel (more information in **Additional file 2.2**). The 5 raceways are grouped into 1
254 greenhouse; each greenhouse contains feed and harvest pipes between individual raceways and
255 common headers, with the harvest lines drawn off raceways controlled by slide gates and valves and
256 delivered to primary de-watering (in –ground gravity settlers). Paddlewheel mixing is considered in
257 each raceway, which may be viewed as a standard basis for commercial scale facilities [28] (more
258 information in **Additional file 2.3**). The inoculum generally represents around 10% of the operating
259 volume of the raceway. The inoculum grows in the same medium as the production raceway (see
260 more information in **Additional file 2.4**). It is produced after an exponential phase prior to
261 inoculation, within a small-sized raceway [29].

262 The process begins with algal biomass growth and harvesting from the raceways. Biomass is
263 harvested at a seasonally variable culture density for processing through primary settling. The
264 plumbing is a critical factor as it covers a large land footprint. Each pipeline is equipped with a valve
265 for opening or closing the circulation of water, nutrients and/or inoculum in each raceway and
266 inoculum pond. The piping and pumping systems involve five independent pipelines, detailed in the
267 **Additional file 3.1**.

268 The residence time is 10 days, harvesting is performed once a day for each raceway, representing 10%
269 of the total volume (volume extracted by raceway is 218.4 m³·d⁻¹) [1]. The raceway is fed with fresh

270 medium at a specified flow rate. The feed point is typically located just before the paddlewheel.
271 During feeding, the algal culture is either withdrawn or harvested from the raceway at a rate equal to
272 the feed flow rate. Feeding and harvesting only occur during daylight and stop at night; otherwise the
273 biomass could flush out the raceway overnight.

274 CO₂ is supplied from a nearby fossil fuel power plant by direct injection of flue gas. Distribution is
275 ensured thanks to a blower system, under moderate pressure using sufficiently thick HDPE pipes.
276 Carbon requirements depend on biomass growth rate and concentration. The efficiency of the
277 microalgae inorganic carbon uptake was assumed to be 75% [30], while, the percentage of C in the
278 biomass can vary according to the microalgae species (see **Additional file 6.2**).

279 In addition to carbon dioxide, algal growth requires nitrogen (N) and phosphorous (P) as principal
280 nutrients [31]. Nutrient requirements for the inoculum ponds and raceways are assumed to be met
281 using diammonium phosphate (DAP, 18% N, 20.2% P) for phosphorous requirements, and
282 ammonium nitrate (NH₄NO₃, 35%N) for nitrogen requirements at 20% w/w each. Percentages of N
283 and P in biomass vary depending on the species of microalgae. In the case of N, a fraction of the
284 element is also provided by DAP.

285 The fertilizer requirements in the inoculum ponds and raceways were calculated according to the
286 species. For *Chlorococcum sp.* the nitrogen and phosphorous fertilizers are 0.0093 kg NH₄NO₃/kg
287 algae biomass DW (0.026 kg N/kg algae biomass dry weight) and 0.0030 kg DAP/kg algae biomass
288 DW (0.0053 kg P/ kg algae biomass dry weight). For *Desmodesmus sp.* 0.0066 kg NH₄NO₃/kg algae
289 biomass DW (0.018 kg N/kg algae biomass dry weight) was assumed and 0.0022 kg DAP/kg algae
290 biomass DW (0.0038 kg P/ kg algae biomass dry weight). These values (0.026 and 0.018 kg N/kg
291 algae biomass dry weight), for *Chlorococcum sp.* and *Desmodesmus sp.*, respectively are similar to
292 those reported by Collet, Lardon [9] for biodiesel production using *Nannochloropsis oculata* at
293 nitrogen starvation (0.04 kg N/kg algae biomass dry weight). The areal fertilizer requirements in the
294 raceways fluctuate according to the biomass productivity, and thus to the season (detailed in
295 **Additional file 6.1**).

296 Whatever the location, the freshwater supply is insufficient to support any substantial scale production
297 of algal fuels anywhere. The supply in brackish water is also relatively limited. Therefore, the use of

298 seawater and marine algae would be a convenient option for producing algal fuels. Unfortunately, the
299 use of seawater for algae culture, does not totally eliminate the need for freshwater. Freshwater is still
300 necessary for compensating evaporative losses and the consequent increase in culture salinity.
301 Evaporative loss depends on the local climatic conditions, particularly on the irradiance levels, air
302 temperature, wind velocity and absolute humidity [8]. Water is transported to the facility by pipeline
303 from a nearby local marine water resource, while freshwater originates outside of the facility
304 boundaries. The transport of water used in the facility has been ignored in the study. Seawater is used
305 in the cultivation and inoculum ponds, while freshwater is used for fertilizer dilution and for
306 compensating water losses (mainly via pond evaporation). The blowdown volume was assumed to be
307 equal to the water requirement. For inoculum ponds, there is no blowdown; however dilution water in
308 the fertilizer varies according to biomass productivity, while the evaporation volume is seasonally
309 variable (see **Additional file 6.1**).

310

311 **Pond emissions**

312 The volatile compounds emitted by raceways and inoculum ponds are CO₂, N₂O and NH₃. These
313 emissions highly depend on operating conditions, such as dissolved oxygen concentration, pH, mixing
314 rate, gas transfer coefficient, nitrate concentrations, etc. [9]. Further experimental data are required to
315 provide reliable emission factors. Nevertheless, due to lack of information, an average loss emission
316 for each compound was inferred. These are correlated with other LCA studies [9].

317 The efficiency of the CO₂ injection system is low in raceways, resulting in re-emission of a large
318 fraction of flue gas. A 25% emission of injected CO₂ was considered (250 g CO₂ kg⁻¹ CO₂ injected).
319 Nitrogen emissions (N₂O and NH₃) to the environment have been scarcely taken into account in the
320 literature, even though these emissions present harmful effects (causing, amongst others, acidification,
321 eutrophication and global warming). Indeed, N₂O is a greenhouse gas with a much higher GWP
322 (Global Warming Potential) than CO₂ (298 kg CO_{2eq}·kg⁻¹ at a temporal horizon of 100 years).
323 Especially during nighttime anoxic conditions, microalgae cultures have proved to generate both
324 direct and indirect N₂O emissions. Direct N₂O emissions are related to the denitrification process,
325 which reduces nitrate (NO₃⁻) to nitrogen gas through a multistep process, with N₂O as an intermediate

326 product [32]. Complete denitrification involves the production and consumption of N_2O which can be
327 partially released into the atmosphere. N_2O emissions represent 0.003% of the nitrogen fertilizer
328 applied to a fully oxic culture (raceway case) and 0.4% for a microalgae culture that is anoxic during
329 dark periods (photobioreactor case) [32]. In the present study a 0.003% emission ($0.0298 \text{ g } N_2O \cdot \text{kg}^{-1}$
330 N) was considered.

331 Indirect N_2O emissions are the long-term fate of nitrogen fertilizers [33]. Indeed, by providing
332 substrate for microbial nitrification and denitrification after application in the soil, fertilizers indirectly
333 generate N_2O which then volatilizes [33]. In the present study, an emission of $1.6 \text{ g } N_2O \cdot \text{kg}^{-1} \text{ N}$ [33]
334 and $120 \text{ g } NH_3 \cdot \text{kg}^{-1} \text{ N}$ was considered [9].

335

336 **Algae harvesting**

337 Harvesting refers to the removal of algal biomass from the pond, as well as, occasionally, to the
338 primary concentration step. Dewatering is a secondary concentration step [28]. As algal biomass
339 dewatering technologies are still under investigation and development, the best strategy is still
340 difficult to assess. The present model is based on the technology analysed by NREL [28], offering an
341 advantageous trade-off between dewatering performance (power demand, retention efficiency, etc.)
342 and cost (capital and operating costs). Furthermore, this process avoids the addition of chemicals (i.e.
343 flocculants or metal ions), thus maintaining biomass purity for downstream flexibility.

344 Biomass is harvested from the ponds and concentrated through three dewatering steps comprising
345 gravity settlers, membranes and centrifugation to a final concentration of $200 \text{ g} \cdot \text{L}^{-1}$. Clarified water
346 from each step is recycled towards the cultivation raceways, excluding a small fraction that is
347 removed as blowdown to mitigate the build-up of salts and other inorganics.

348 The dewatering process begins with the primary settling ponds, for which energy demand is low since
349 only pumps are required. The settler trenches have a trapezoidal profile with a volume of 364.1 m^3 (50
350 m in length, 1.7 m deep, 8.5 m wide at the top and 0.34 m wide in the bottom). There are a total of 22
351 settler ponds with a 4 h residence time. The biomass is removed from these trenches by positive
352 displacement pumps (assuming a negligible energy demand). The material harvested from gravity
353 settling is transferred to membranes, while clarified effluent is redirected back towards the raceways

354 through feed pipes, along with additional recycled water from membranes and centrifuges through 3-
 355 inch diameter DI pipelines. The settler ponds concentrate the algal biomass from 0.5 to 10 kg·m⁻³,
 356 with 90% efficiency (i.e. 10% of the biomass returns to the ponds in the clarified water stream) and
 357 reduce the volume of water by a factor of 20.

358 The second dewatering process uses hollow fibre membranes. This technology was selected for its
 359 favourable performance and costs at a commercial scales, such as high reliability, direct scalability
 360 and simple thermal, mechanical and chemical management [28]. Maintenance and fouling are not
 361 problematic or costly, based on a daily cleaning protocol for the membrane modules. The hollow fibre
 362 membrane units received biomass at 10 kg·m⁻³ from the settling ponds and concentrate the biomass to
 363 130 kg·m⁻³, with an efficiency of biomass retention close to 100% (assumed here at 99.5%).

364 Centrifugation takes place after the hollow fibre membranes, during the final dewatering step. It leads
 365 to a high biomass concentration [28]. The centrifuge concentrates biomass between 130 kg/m³ and
 366 200 kg/m³, with a dewatering efficiency of 97% (3% of biomass is removed with the clarified water).
 367 The 99.8% of the total water inlet in the subsystem is dewatered during all three steps. **Table 3**
 368 summarizes the parameters of the selected technologies.

369
 370 **Table 3.** Various parameters considered for study.

Unit process	Assumptions	Ref.
Algae cultivation	Algae strains: <i>Chlorococcum sp.</i> and <i>Desmodesmus F2 sp.</i> : 47% and 53.8% lipid content for <i>Chlorococcum sp.</i> and <i>Desmodesmus sp.</i>	[26]; [25]; [34]; [35]; [36]
Algae growth	<p>Velocity culture: 0.3 m·s⁻¹ for raceways and 0.25 m·s⁻¹ for inoculum ponds.</p> <p>HRT: 10 days. Raceways: 110 units of 310 m long x 30 m width x 0.3 m height (2,184.3 m³ volume medium). Inoculum ponds: 40 units of raceways of 160 m long x 15 m width x 0.35 m height (656 m³ volume medium).</p> <p>Facility: 145 ha area. Operating time facility: 330 days · year⁻¹ (90%).</p> <p>Paddlewheels: 0.11 W/m², time functioning: 12 h·d⁻¹. One unit per raceways and inoculum pond.</p> <p>Blower system: 22.2 Wh·kg⁻¹ CO₂, time functioning: 12 h·d⁻¹. One unit per raceways and inoculum pond. 14% v/v CO₂ concentration in flue gas.</p> <p>Water loss (evaporation): daily variable (ranging between 0.01 and 0.34 cm·d⁻¹).</p> <p>Inoculum input Pumping system: Power: 10 kW, 22 units, time functioning: 0.8 h h·d⁻¹. Electricity consumption: around 0.07 kWh·m⁻³</p> <p>Nutrients/water loss pumping system: 24 units (22 for raceways and 2 for inoculum ponds), time functioning: 12 h·d⁻¹. Electricity consumption: negligible.</p>	
Algae Harvesting (De-	<p>Settlers ponds: 22 units, Energy demand: negligible, Efficiency: 90%, Outlet concentration: 10 g/L. Capacity: 364.1 m³. Residence time: 4</p>	[28]; [36]

watering)	<p>hours.</p> <p>Membranes: 22 units, Power: 2 kW, Energy demand (variable): 0.03 to 0.2 kWh·m⁻³, Efficiency: 99.5%, Outlet concentration: 130 g/L. Capacity: 2.3 m³·h⁻¹, Time functioning: 12 h·d⁻¹.</p> <p>Centrifuges: 22 units, Power: 6 kW, Energy demand (variable): 0.9 to 5.05 kWh·m⁻³, Efficiency: 97%, Outlet concentration: 200 g/L. Time functioning: 12 h·d⁻¹.</p> <p>Overall harvesting process: 20% wt outlet concentration. Efficiency: 86.9%. Percentage of water volume reduced: 99.9%.</p> <p>Harvesting Pumping system: 22 units, Power: 7.7 kW, Energy demand: 0.08 kWh·m⁻³, time functioning: 12 h/day.</p> <p>Recirculation pumping system: 22 units, Power: 7.7 kW, Energy demand: 0.08 kWh·m⁻³, time functioning: 12 h/day.</p>
Oil extraction	<p>Sonication: 2 units, Power: 16 kW, Energy demand: 0.013 kWh·kg⁻¹ algae-DW, Capacity: 12 m³·h⁻¹, Time functioning (variable): 1.5 to 8.8 h/day. [30]</p> <p>Static mixer: 1 unit, Power: 6 kW, Energy demand: negligible, Efficiency lipid extraction: 90%, Capacity: 12 m³·h⁻¹, time functioning: 1.5 to 8.8 h/day. Hexane input: 10:1 mass ratio, 0.05% hexane losses.</p> <p>Biomass solvent separator: 1 unit, Power: 6 kW, Energy demand: 0.005 kWh·kg⁻¹ algae-DW, Efficiency: 99.9%. Capacity: 5.7 m³·h⁻¹ time functioning (variable): 3 to 19 h/day.</p> <p>Distillation column: 2 units, Energy demand (variable): 0.09 to 0.55 kWh·kg⁻¹ oil, Capacity: 15.2 m³·h⁻¹ time functioning (variable): 2.7 to 16 h/day.</p>
Oil conversion	<p>Transesterification reactor: 1 unit, Power: 15 kW, Energy demand: 0.03 kWh·kg⁻¹ biodiesel, Time functioning (variable): 2.7 to 16 h/day. [37]</p> <p>Chemical consumption: methanol 1.1 kg·kg⁻¹ biodiesel, Sodium methoxide 0.11 kg·kg⁻¹ biodiesel, HCl 0.014 kg·kg⁻¹ biodiesel, NaOH 0.008 kg·kg⁻¹ biodiesel, Natural gas 0.063 L·kg⁻¹ biodiesel.</p>

371

372 Algae transformation

373 The extraction step involves addition of hexane that dissolves the oil and strips it from the algae. The

374 solvent recovery phase recovers the hexane from the oil. The current model is based on the oil

375 extraction processes documented by Rogers, Rosemberg [30] for a biodiesel plant production at

376 commercial scale. Yield extraction, hexane volume and associated heat and electricity consumptions

377 have been adapted to match the data of this analysis. A 16 kW sonicator was used for cell disruption,

378 processing up to 12 m³/h. The lipid extraction was then performed on the 20% wt slurry in a static

379 mixer. The static mixer combines the solvent and algal biomass during lipid extraction. A solvent to

380 algae-DW mass ratio of 10:1 was assumed, with an 80% extraction efficiency and without any

381 electricity requirement. A daily solvent loss of 0.005% was assumed. In order to separate the oil cake

382 (biomass + water) from the hexane-oil mix, the current model uses a biomass-solvent separator. This

383 separator operates at 6 kW, processing 5.7 m³·h⁻¹. In order to recover the solvent, a distillation column

384 with a maximal capacity of 15.2 m³·h⁻¹ was used. The recovered hexane is re-circulated towards the

385 static mixer and is mixed with the new hexane flux to compensate for hexane emission losses, while
386 the oil continues onwards to the next transesterification subsystem.

387 Algal oil with higher phospholipid contents are less suitable for biofuel, since phosphorous reduces
388 the efficiency of the alkaline catalysts used in the transesterification process [37]. Phospholipids are of
389 primary concern within the polar lipid fraction for their propensity to form gums and deactivate
390 catalysts. For this reason, it is prudent to include a lipid clean up step to remove these impurities. The
391 following two assumptions were made for the oil obtained from the distillation column: the
392 phospholipid and free fatty acid contents are negligible in the algal oil [37], and the oil contains
393 traces of water and hexane [38].

394 Transesterification is assumed for the conversion of algal oil into biodiesel. The current model is
395 inspired from the process proposed by Haas, McAloon [37], for a production of 37854.1 m³
396 biodiesel·y⁻¹ (52158.8 ton·y⁻¹). This design was based on the use of crude, degummed soybean oil
397 with negligible phospholipid and free fatty acid content as feedstock. The process involves three
398 processing sections: i) transesterification unit where the vegetable oil is subjected to chemical
399 transesterification to produce fatty acid methyl esters (biodiesel) and co-product glycerol, ii) a
400 biodiesel purification section where the methyl esters were refined to meet biodiesel specifications
401 and iii) a glycerol recovery section. The final product obtained is biodiesel with a lower than 0.005%
402 (v/v) water content.

403

404 **Combustion emissions**

405 The emissions associated with combustion are assumed to be equivalent to rapeseed-based biodiesel
406 emissions. The emission factors refer to a EURO-3 middle-sized vehicle. They are extracted from the
407 Ecoinvent database [39], assuming a fuel consumption of 0.42 km per MJ of biodiesel. Conventional
408 diesel engines are considered to have the same consumption (see combustion emissions factors in
409 **Additional file 9**).

410

411 **Photovoltaic system**

412 The core of a photovoltaic system is the solar cells converting light energy into electricity. Electricity
413 then generates an electromotive force when the radiation reaches a semiconductor plate presenting a
414 potential gap [40]. Copper indium gallium diselenide (Cu(In,Ga)Se_2 , CIGS) is a mixed alloy of copper
415 indium diselenide (CuInSe_2 , CIS) and copper gallium diselenide (CuGaSe_2 , CGS) semiconductors [41].
416 In comparison to traditional silicon-based technologies, CIGS is appealing because of its competitive
417 cell efficiency and performance in diverse environments [42]. Furthermore, although current
418 efficiencies for CIGS cells average 14%, technological advancements presently contribute to the
419 improvement of cell efficiencies with records up to 23% [42], potentially rendering CIGS increasingly
420 competitive compared with current silicone-based cells. This study considers a conservative
421 efficiency of 15% and a 30-year lifespan for 1 m² area module. The PV production inventory
422 considers mass and energy flows over the whole production process starting from material extraction
423 to the final panel assemblage, use and end of life. The CIGS technology data from Würth Solar
424 (Germany) was used [43]. Different layers of CIGS thin film cells are necessary. The required
425 sequence layers are deposited in a number of subsequent production steps. The active layer consists of
426 a specific copper-indium-selenium configuration deposited by a vaporization process directly over a
427 large area of window glass (substrate material). It is usually airtight sealed with a second glass plate.
428 The modules have a size of 1.2 m by 0.6 m and a weight of 12.6 kg [43]. In **Additional file 16**, the
429 monthly electricity production is plotted as a function of the percentage coverage of photovoltaic.
430 These data have been obtained from the Sophia Antipolis meteorological database (France).

431

432 **Energy assessment**

433 A cradle-to-gate life cycle energy analysis was performed, including the production of raw materials
434 and the production process of biodiesel. The Fossil Energy Ratio (FER) and Net Energy Ratio (NER)
435 were estimated according to the input and output energy for 1 MJ of biodiesel. There are no
436 allocations in energy balance. FER is defined as:

437

$$438 \quad FER = \frac{\text{Renewable energy output}}{\text{fossil energy input}} = \frac{LHV}{CED}$$

439

440 The FER only included fossil (non-renewable) energy in the denominator. NER includes total energy
441 input in the denominator, including renewable sources of energy, such as wind and solar. NER, rather
442 than FER, is used as an indicator of energy efficiency [44].

443 LHV (low heating value) is the life cycle energy output (MJ), determined using the following
444 equation:

445

$$446 \quad LHV = EP_{biodiesel} + EP_{oilcake} + EP_{glycerin} + EP_{surplus\ electricity}$$

447

448 EP represents the Energy for each co-product (MJ), each being defined as:

449

$$450 \quad EP_{biodiesel} = 1 \text{ (Functional unit)}$$

451

$$452 \quad EP_{glycerine} = Mass\ glycerine \left(\frac{kg}{MJ\ biodiesel} \right) \cdot LHV_{glycerine} \left(\frac{MJ}{kg} \right)$$

453

$$454 \quad EP_{oilcake} = \sum_i P_{oilcake,n} \cdot LHV_n$$

455

$$456 \quad EP_{surplus\ electricity} = surplus\ electricity\ (exported)\ from\ photovoltaic\ panels\ (MJ)$$

457

458 Where, $P_{oilcake,n}$ is the percentage of component n in the oilcake (% , e.g. carbohydrates, lipids,
459 proteins, etc.) and LHV_n is the lower heating value of component n (MJ/kg).

460 Cumulative energy demand (CED) represents the life cycle total energy consumption (in MJ), which
461 is represented by the following equation:

462

$$463 \quad CED = \sum_i \sum_j EE_{i,j} \cdot PE_j + \sum_i \sum_n M_{i,n} \cdot PE_n$$

464

465 Where, $EE_{i,j}$ is the j^{th} process energy consumption during stage i (MJ), PE_j is the total energy use for
466 process j production (MJ/MJ) (renewable and non-renewable for NER and non-renewable for FER)
467 $M_{i,n}$ is the n^{th} material consumption during stage i (kg). PE_n is the life cycle total (renewable and
468 non-renewable for NER and non-renewable for FER) energy use for material n production
469 (kg/MJ). Values of CED for material and energy used in the various processes are obtained from the
470 CED method v1.09 (see **Additional file 7**).

471

472 **Environmental assessment**

473 The standard framework of Life Cycle Assessment (LCA) described by ISO 14040:2006 was selected
474 to assess the ecological burdens and energy balance. An attributional LCA is used in the analysis,
475 which considers only physical relationships between each process, different to a consequential LCA
476 where economic relations are also assessed [9]. LCA software SimaPro v8.3 [18] was used for
477 modelling the data, by using the characterization factors from the midpoint (H) ReCiPe 2008 method
478 v1.3 [44]. Full LCI data source are available as supplemental information (**Additional file 7**) [45].
479 The impact categories considered were: Climate Change (CC), Ozone Depletion (OD), Human
480 Toxicity (HT), Photochemical Oxidation formation (POF), Particulate matter formation (PMF),
481 Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME),
482 Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET), Ionising
483 radiation (IR), Natural land transformation (NLT), Urban Land Occupation (Urban LO), Agricultural
484 Land Occupation (Agri LO), Water Depletion (WD), Metal depletion (MD) and Fossil Depletion
485 (FD). The endpoint (H) ReCiPe 2008 method is also used to assess the system at a more aggregated
486 level through the three areas of protection (AoP): Human Health, Ecosystems and Resources.

487

488 **Mathematical model for predicting monthly productivities**

489 The model predicting temperature in the raceway ponds was based on the heat balance presented by
490 B chet, Shilton [46], which was initially developed for an open raceway pond and validated at a large
491 scale [49]. In the B chet model, a total of eight heat fluxes were considered:

- 492 - Solar radiation;
- 493 - Long-wave air radiation;
- 494 - Long-wave pond radiation; Convection with the air flowing at the pond top surface;
- 495 - Evaporation from the pond surface;
- 496 - Conduction with the soil beneath the pond;
- 497 - Heat flux associated with the water inflow; and
- 498 - Heat flux associated with rain.

499 The model developed by Béchet, Shilton [46], still needed to be significantly modified as the presence
500 of the greenhouse significantly impacts the expression of most of these heat fluxes:

- 501 - Solar and air radiation are partly shaded by the greenhouse;
- 502 - Pond radiation is partly reflected back towards the pond by the greenhouse.
- 503 - Convection and evaporation are "natural" in a greenhouse as there is no wind to force these
504 transfer mechanisms;
- 505 - Rain heat flux is obviously inexistent in a closed greenhouse;
- 506 - Conduction and inflow heat fluxes were, however, expressed similarly to the case of an open
507 pond.

508 The greenhouse is assumed to be of rectangular shape and condensation on the greenhouse walls was
509 neglected. All opaque surfaces were considered as diffuse grey, except for the greenhouse walls that
510 were considered as partly transparent. For the reflected radiative heat fluxes, only single reflection
511 was accounted for. Finally, the temperature and relative humidity in the greenhouse are considered
512 homogenous.

513 The air temperatures inside and outside the greenhouse are different. As the air temperature above the
514 pond impacts both evaporation and convection at the pond surface, the air temperature inside the
515 greenhouse needs to be assessed in parallel to the pond temperature. A heat balance on the air in the
516 greenhouse was therefore computed to determine the air temperature at each time step of the
517 simulation. The greenhouse walls emit inward long-wave radiation, a fraction of each being absorbed
518 by the pond. The temperature of the greenhouse walls was therefore evaluated at each simulation time
519 step through a heat balance on the greenhouse walls.

520 This heat balance is relatively complex due to the high number of radiative interactions between the
521 greenhouse and its surrounding environment. Indeed, the pond, the ground inside the greenhouse and
522 the ground outside the greenhouse emit long-wave radiations that are partly absorbed by the
523 greenhouse. The long-wave radiation emitted by a grey body depends on its temperature and as a
524 result, the temperatures of the inside and outside ground surfaces were determined simultaneously
525 through two additional heat balances. It is not straightforward to determine the ground surface
526 temperature as it depends on the conductive properties of the soil. Indeed, ground surface temperature
527 decreases when the ability of the soil to conduct heat in deeper ground layers increases. This
528 conductive heat flux is a function of the soil thermal properties but also of the temperature gradient
529 within the soil. Therefore, to determine the internal and external ground surface temperatures, the
530 temperature profiles in the soil first need to be assessed. In summary, to determine the pond
531 temperature in the greenhouse, a total of five different heat balances were solved simultaneously
532 during the simulations.

533

534 **Results and discussion**

535

536 Dynamic seasonal growth modeling is an important step that critically impacts results. Monthly
537 variations in the life cycle inventory depend on the monthly biomass productivity, which in turn
538 affects lipid and biodiesel productivity. Large differences in assumptions on the productivity potential
539 have directly contributed to the large variance in LCA results from various studies [47]. The high lipid
540 yields reported in literature are typically the result of speculation for future productivity potentials
541 based on the linear scaling of laboratory data [47]. This highlights the importance in developing
542 realistic dynamic productivity models based on experimentally validated biological models integrated
543 with local and seasonal meteorological data [48]. **Table 4** shows the evolution of the microalgae
544 biomass productivity, respectively, for each species, obtained from the mathematical model based on
545 Mediterranean conditions (Sophia Antipolis, France). According to simulation results, *Chlorococcum*
546 *sp.* was chosen for the cold months and *Desmodesmus sp.* for the warm months, depending on the

547 coverture fraction of photovoltaic panels. When the coverture is greater than 60%, only
 548 *Chlorococcum sp.* was chosen because *Desmodesmus sp.* had a very low productivity at low light (< 1
 549 g·m⁻²·d⁻¹).

550 Ten conditions are detailed in this interpretation: absence of photovoltaic panel (0% coverture), and
 551 greenhouse roof coverage from 10% to 90%. 100% coverture was not considered since it would
 552 hinder any biological productivity.

553

554 **Table 4.** Monthly biomass productivity (g·m⁻²·d⁻¹). *Chlorococcum* and *Desmodesmus sp.* (**bold text**).

% PV panel	January	February	March	April	May	Jun	July	August	September	October	November	December
0%	9.79	16.52	26.74	20.59	19.69	22.34	19.40	20.98	15.19	18.49	12.45	9.12
10%	8.88	15.42	24.79	26.20	18.29	21.14	18.40	19.50	14.18	17.18	11.65	8.26
20%	7.93	14.08	22.65	26.33	15.94	19.73	17.23	17.87	18.23	15.67	10.81	7.38
30%	6.83	12.40	19.99	25.11	26.35	17.94	15.76	16.26	18.01	13.96	9.58	6.36
40%	5.84	10.80	17.46	23.08	26.14	16.16	14.29	18.58	17.66	12.37	8.40	5.44
50%	4.81	9.12	14.86	20.42	24.21	18.35	12.62	17.25	18.88	10.69	7.16	4.51
60%	3.74	7.38	15.78	17.31	21.10	20.76	15.61	21.19	16.21	9.41	5.86	3.52
70%	2.59	5.52	12.53	14.73	17.21	19.02	15.77	17.81	13.25	7.94	4.50	2.54
80%	1.32	1.85	8.51	10.78	12.20	14.29	12.21	12.10	9.29	5.17	2.80	1.24
90%	1.00	1.00	3.04	4.85	7.48	8.12	6.99	5.26	4.97	2.41	1.02	1.05

555

556 Energy flows

557 The use of energy for each step of the process was derived from algal productivity, dewatering, oil
 558 extraction and transesterification (see Table 3). Figure 2 illustrates the energy requirements in the
 559 different case studies. The main energy requirement is issued from water pumps used for harvesting
 560 and recirculating flows from de-watering processes, followed by paddlewheel engines (more details in
 561 Additional file 2.3, 3.2, 4.2 and 4.3). The biomass productivity decreases when the coverture fraction
 562 of photovoltaic panels increases at a variation rate below 5% and between 0% and 30% photovoltaic
 563 coverture; however, at 70% photovoltaic coverture this variation rate increases to more than 15%
 564 (reaching almost 50% less biomass productivity at 90% with a 80% photovoltaic coverture).

565

566 **Figure 2 around here**

567

568 The NER and FER results are depicted in **Additional file 17**. Allocation issues do not affect this
569 evaluation, i.e. all production processes are considered as a whole. The total set of products represents
570 an amount of energy (in terms of LHV) ranging from 1.70 MJ_{LHV} without PV up to 9.82 MJ_{LHV} with
571 90% photovoltaic coverage. The total energy investment, CED (renewable + non-renewable energy),
572 ranges from 0.90 (without PV) up to 9.93 for 90% PV. This implies a favourable NER over the whole
573 year, i.e. even in the absence of photovoltaic panels: 1.99 and FER: 2.92. Without PV panels, the
574 electricity should be supplied by the European electricity matrix. In comparison with other similar
575 LCA studies on algal biodiesel, the NER for biodiesel from microalgae using fossil fuel electricity
576 sources are usually slightly greater than 1 [3, 49, 50], although some cases can be lesser than 1, as
577 reported by Lardon, Hélias [3] and Yang, Xiang [51].

578 With photovoltaic panels, the highest NER (larger than 5.0) are obtained during the hottest months
579 (April to September) (see **Additional file 10**). Indeed, during the summer period, the electricity
580 production is higher (large electricity production in comparison to the facility requirements).
581 However, despite optimal energetic performance resulting from the use of photovoltaic panels, the
582 relevance of renewable biofuels rather becomes a matter of producing storable and renewable energy.
583 The production of biodiesel from microalgae is an efficient way to store a fraction of renewable
584 energy. The optimal percentage of photovoltaic panels depends on the month: i.e. during the cold
585 months (October to March), the optimal coverage is 10%, while for hot months (April to September)
586 the optimum is 20% coverage.

587 Comparison of NER and FER between the case studies, first generation biodiesel and conventional
588 diesel, is illustrated in **Figure 3**. The reference cases are obtained from the Ecoinvent database for
589 biodiesel [39] and conventional fossil diesel [52], complying with similar limits for the system and for
590 the allocation of this study. The biodiesel reference scenarios are soybean diesel (US), palm tree
591 diesel (Malaysia) and rapeseed diesel (European average) (more details about comparative cases can
592 be found in **Additional file 15**). A 10% and 20% coverage fraction of photovoltaic panels are the
593 most optimal configurations that obtain highest FER and NER, respectively. The presence of 10% and
594 20% photovoltaic panel favors a higher NER than for first generation and fossil diesel. However, FER

595 presents better results in the cases of soybean and palm tree biodiesel, despite the use of photovoltaic
596 panels to improve the energy balance.

597

598 **Figure 3 around here**

599

600 **Environmental impacts**

601 First generation biodiesels and fossil diesel are compared in **Additional file 18**, which illustrates the
602 endpoint characterization results for the combustion of 1 MJ of biodiesel in a medium-sized car for
603 various fractions of photovoltaic panel coerture. The lowest impact is obtained for a 50% coerture,
604 with equivalent performances from 30% to 60%. The main subsystem contributors are the culture,
605 followed by the photovoltaic subsystem, in the case of human health and resources, or combustion in
606 the case of ecosystem category. Biodiesel from microalgae has the following characteristics:

- 607 - Algal biofuel leads to significant reductions in the Human Health and Ecosystem categories
608 compared to other biodiesels, but is still higher than conventional diesel.
- 609 - Significant reductions in the Resources impact category are obtained relative to conventional
610 diesel; however, the impact is higher than for soybean diesel and palm tree diesel.

611 **Additional file 19** presents the contribution of each process to climate change, accounting for
612 production of electricity using PV panels. Results for midpoint categories are detailed in the
613 **Additional file 12**. The data in **Table 5** make it possible to compare the impact results of algae
614 biodiesel to those obtained by fossil diesel and first generation biodiesels. These overall results on
615 comparisons with others scenarios are coherent with the study by Collet, Lardon [9]. It is important to
616 note that some categories increase for a large coverage of photovoltaic panels (> 80% coerture), such
617 as POF, PMF, TA, ME, or FET. However, the absence of photovoltaic panels either increases or
618 reduces certain impacts, such as IR, mainly due to the electricity requirement or MD due to the
619 production of photovoltaic panels, respectively.

620

621 **Table 5.** Comparison of LCA results between algae biodiesel and conventional or first-generation biodiesels

Impact category	Algae biodiesel in comparison to:			
	Conventional fossil Diesel	Palmtree Biodiesel	Rapeseed Biodiesel	Soybean Biodiesel

Ozone depletion	-	+	-	-/+
Human Toxicity	+	+	-/+	+
Photochemical Oxidation Formation	-	-/+	-	-/+
Particulate Matter Formation	-/+	-/+	-/+	+
Terrestrial Acidification	-/+	-/+	-	+
Freshwater Eutrophication	+	+	-/+	-/+
Marine Eutrophication	-/+	-	-	-
Ionizing Radiation	-/+	+	-/+	-/+
Water Depletion	+	+	+	+
Metal Resources Depletion	+	+	-/+	+
Fossil Resources Depletion	-	+	-/+	+
Natural Land Transformation	-	-	-	-
Agricultural Land Occupation	+	-	-	-
Urban Land Occupation	-/+	-/+	-	-/+
Terrestrial Ecotoxicity	+	-	-	-
Freshwater Ecotoxicity	+	-/+	-	+
Marine Ecotoxicity	+	+	-/+	+

622 - Impact reduction for algae biodiesel; + Impact increase for algae biodiesel

623 -/+ Impact reduction or increase for algae biodiesel, depending of percentage of photovoltaic panel coerture

624

625 The overall results highlight the contribution of the culture, infrastructure production and use. This is
626 coherent with results from contribution analyses in others studies [3, 9]. Culture (Subsystem-1) is the
627 main contribution for most of the assessed impacts (CC, PMF, TET, TA, OD, FD, HT, Nat LO, Agri
628 LO and Urban LO). For the remaining categories, culture is classified as a second contributor,
629 preceded by the photovoltaic system (Subsystem-5) in the case of FET, MET, IR, FE and MD, or
630 combustion (Subsystem-6) in POF and ME.

631 The infrastructure in the culture (Subsystem-1) has a significant effect in terms of CC, PMF, OD, FD,
632 HT, Nat LO, Agri LO and Urban LO, due to the production of materials (mainly steel, PVC, HDPE,
633 aluminium and concrete) used in the greenhouse, and to machinery and pipe productions. In addition,
634 pond emissions from culture mainly contribute to TA and TET through volatilized ammonium and
635 N₂O. Although nitrogen fertilizer requirements are reduced (the culture system works under nitrogen-
636 limiting conditions to improve the lipid contents in microalgae), nitrogen-based fertilizer production
637 remains the main contributor in these categories.

638 The different metals and energy used to build the CIGS system highly contribute to the impacts of the
639 photovoltaic system (Subsystem-5). Silver used for screen manufacturing contributes to MD, CC, TA,
640 PMF and HT. This is mainly due to the impacts generated by the extraction and processing of silver,
641 including also its high requirement in fossil energy (which strongly contributes to IR). In addition,
642 extraction/manufacturing of stainless silver (substrate) essentially impacts OD, while water used for

643 washing the substrate affects WD and eutrophication categories. Other metals, such as copper,
644 indium, gallium and selenium used in the CIGS layer and cabling contribute to eco-toxicity and
645 eutrophication categories.

646 Combustion emissions mainly affect POF and ME; and in a lower extend to CC, PMF, TET and TA.
647 The carbon burned during the biodiesel combustion is biogenic as it originates from photosynthetic
648 fixation, i.e. zero greenhouse emissions in the form of CO₂ is assumed. Hence, the environmental
649 impacts are due to other compounds and/or fossil carbons that are related to the production of
650 chemicals, such as methanol for esterification.

651 The electricity required for the transformation sub-systems (de-watering, oil extraction and oil
652 transformation) at low percentage of photovoltaic panel coverture has an important impact for most of
653 the categories. Nevertheless, the presence of photovoltaic panels at a larger percentage of covertures
654 turns out less important at an environmental impact level. It also becomes a secondary source of
655 impact for some categories, such as OD, FD and Nat LO, mainly due to chemical production (used in
656 the esterification) and transports. The considered processing system does not exist at industrial scales.
657 Hence, this part of the analysis has the most uncertainties and can be subject to errors in the
658 calculation of energy consumption or waste production. Nevertheless, alternative choices have already
659 been tested individually in different studies [28, 30, 37]. This represents a reasonable projection of the
660 processes and avoids over-optimistic or unrealistic assumptions.

661 One of the main objectives of this study is to scale the expected gains on microalgae biodiesel
662 production with respect to the reduction of GHG emissions, when a renewable energy source is
663 considered. In comparison with the cultivation of microalgae without PV, the use of photovoltaic
664 panels triggers a synergetic effect, acting both as a source of electricity and in reducing climate
665 change impacts (**Additional file 19**). Similarly to endpoint category results, the scenario with a 50%
666 PV coverture points to lower impacts on climate change. From a 0% to 80% coverture, climate
667 change emissions are lower for algae diesel in comparison to biodiesel (except for soybean biodiesel)
668 and diesel. A 90% PV coverture leads to highest values in climate change due to the numerous
669 photovoltaic modules and to the strong decrease in biomass productivity. **Additional file 11**
670 comprises monthly GHG emissions for a 50% PV coverture. From April to September, values remain

671 below $0.03 \text{ kg CO}_{2\text{eq}} \cdot \text{MJ}_{\text{biodiesel}}^{-1}$, while during the rest of the year, GHG emissions are higher, with
672 values greater than $0.07 \text{ kg CO}_{2\text{eq}} \cdot \text{MJ}_{\text{biodiesel}}^{-1}$ in winter (December, January). The percentage of
673 decrease depends on the quantity of electricity produced. The higher electricity production during the
674 summer months contributes to the strongest decrease in GHG emissions (In the case of a 50%
675 coverture, emissions reach about 40% less than for the case without PV panels). Nonetheless, the
676 reduction in GHG emissions is lower in winter (November to February), varying between 4% and
677 24% (for a 50% PV coverture) compared to the nominal case excluding PV. **Figure 4** illustrates the
678 effect of biomass productivity on GHG emissions. The decrease in GHG emissions is directly
679 connected to increasing microalgae productivity. Without photovoltaic panels, when biomass
680 productivities are higher than $20 \text{ g}_{\text{biomass}} \cdot \text{m}^{-2} \text{ d}^{-1}$, GHG emissions remain within the range of 0.05 to
681 $0.045 \text{ kg CO}_{2\text{eq}} \cdot \text{MJ}_{\text{biodiesel}}^{-1}$. With a 50% PV coverture, the contribution to Climate Change emissions
682 varies around $0.03 \text{ kg CO}_{2\text{eq}} \cdot \text{MJ}_{\text{biodiesel}}^{-1}$ when the productivity is higher than $12 \text{ g}_{\text{biomass}} \cdot \text{m}^{-2} \text{ d}^{-1}$.

683

684 **Figure 4 around here**

685

686 **Reaching an optimal trade-off**

687 In addition to trying to identify processes with limited energy requirements, the combination of
688 biomass production with PV electricity represents an ideal opportunity for significantly reducing
689 environmental impacts by almost 50% of GHG emissions. However, there is a clear trade-off between
690 electricity and biomass production, as a larger PV coverture would limit microalgae production. This
691 trade-off is associated to a series of optimal process designs and operating strategies that are
692 correlated.

693 Higher biomass productivity, related to higher biodiesel productivity could be achieved in the absence
694 of PV panels. Adding photovoltaic panels can enhance productivity for the hottest months, but
695 reduces biomass productivity on a yearly basis (each 10% PV coverage leads to a decrease of about
696 5% in the biomass productivity, but the decrease rate is higher for a PV coverage greater than 70%).
697 However, at low PV coverage, consumption of electricity from the grid affects the energetic ratio
698 (NER). A 10% coverage of PV increases NER by 48% (1.91 MJ/MJ for 0% PV and 2.83 MJ/MJ for

699 10 PV), with a peak value at 20% PV coverage (For a PV coverage > 20% NER decreases due to
700 lower biomass productivities and higher energetic demands in the infrastructure construction). Thus,
701 from an energetic point of view, the optimal configuration lies between 10% and 20% of PV
702 coverage. Nevertheless, from a human health, ecosystem, resources and climate change point of view,
703 the best option is 50% PV coverage. However, the difference between impact values obtained for 20%
704 and 50% PV is negligible (difference of 7%; $0.044 \text{ kg CO}_{2\text{eq}} \cdot \text{MJ}_{\text{biodiesel}}^{-1}$ and $0.040 \text{ kg CO}_{2\text{eq}} \cdot \text{MJ}_{\text{biodiesel}}^{-1}$
705 $\text{kg CO}_{2\text{eq}} \cdot \text{MJ}_{\text{biodiesel}}^{-1}$ for 20% and 50% PV coverage, respectively), while the NER is 48% higher for 20% PV than
706 for 50% PV coverage. Hence, 20% coverage of photovoltaic panels can be considered as a sound and
707 optimal energetic environmental configuration.

708 In addition, two high potential species have been studied with a monthly-optimized strategy. As
709 ventilation controls the greenhouse climate, medium temperatures are maintained close to the optimal
710 growth temperature. The thermal properties depend upon the PV coverage, thus the succession in
711 cultivated species can vary. The trade-off that needs to be reached is constrained by the local climate
712 and should therefore strongly depend on the location of the plant. Even though a 20% PV coverage
713 has been defined as the best option from an energetic and environmental point of view, the complex
714 and dynamical optimization problems still need to be revisited for any new climate conditions, while
715 the solutions would depend upon the targeted species, which must be chosen according to these
716 light/temperature conditions.

717 The objectives of this study are to reduce environmental impacts, however a techno-economic
718 analysis should also be undertaken in order to identify the trade-off from an economical point of view.
719 Microalgal biofuel, which can be stored, has a higher value than PV electricity. It is also associated to
720 valuable co-products that have a higher economic value. PV contributes to reduce biomass
721 productivity at a yearly scale, and thus a trade-off at a lower PV coverage can be expected when focus
722 is put on economic aspects. The photovoltaic greenhouse has another advantage compared to classical
723 raceways, since it lengthens the production season by modulating the greenhouse climate, hence
724 favoring a better return on investment.

725

726 **Allocation method selection**

727 The allocation methods, which are, in this case, based on energy, cover the co-products, the emissions
728 as well as their impact on the functional unit. Allocation factors of co-products strongly reduce the
729 impacts of biodiesel (see allocations factors in **Table 2**). Their values reflect each upstream chain
730 phase benefit from all downstream co-products in the allocation process [53]. In this case, oil
731 extraction (sub-system 3), oil conversion (sub-system 4) and photovoltaic covertures (sub-system 5)
732 benefit from seed meals, glycerin and electricity, respectively. However, the energetic allocation does
733 not highlight the actual use of co-products derived from the biodiesel production chain. The
734 substitution method highlights the importance of co-product valorization, in which co-products are
735 considered as amendments. The saved emissions, resulting from the substitution of conventional
736 products by co-products are reported with a negative value since they tend to reduce the impact.
737 Even though an energetic substitution method is accepted for biofuel sustainability certification, the
738 results also need to be evaluated by a substitution method, while “estimates would change if co-
739 products were accounted for using the substitution approach” [54]. To highlight the importance of
740 considering co-products on the impact of a functional unit, the environmental performance of the
741 substitution method was evaluated and compared with results produced by the energetic allocation
742 method (**Additional file 20**). It is noteworthy that when co-products are taken into account, the
743 environmental balance is reversed and results are dramatically affected. A 90% PV coverage is
744 associated to lower environmental impacts on human health, ecosystems, resources and climate
745 change categories. This is essentially related to the higher surplus electricity production, which
746 reduces the electricity demand from the European electricity grid. Surplus electricity arises from the
747 large percentage of photovoltaic panels, while electricity consumption is reduced within the facility
748 (due to extremely low biomass productivity). Regrettably, the lower environmental impacts assessed
749 with the substitution method, under conditions of negligible biomass productivity and high
750 photovoltaic electricity, is not compatible with the production of microalgae biodiesel. The
751 representation of a co-product by substitution also implies a modification of the addressed question.
752 The allocation approach (using the energetic content as criterion for partitioning) focuses the study
753 towards the relevance of microalgae biodiesel as an alternative fuel. However, substitution answers a
754 much broader issue. Co-product management practice ends up with a choice between fuel and

755 electricity productions. Results point out that although electricity production is the main issue, it is
756 misleading for the eco-design of an efficient alternative fuel production system.

757 It is crucial to manage co-products appropriately if the energy balance and environmental
758 performance of the overall system are to be enhanced. Substantial energy is also stored as organic
759 matter in the oilcake (obtained from oil extraction), and the energetic allocation assumes an energetic
760 potential for the oilcake. This illustrates how complicated it can be to assess the energy balance and
761 environmental impact in algal systems. Certain processes developed to extract this energy include
762 anaerobic digestion and co-digestion, whose digestate can provide the necessary nutrients, thus
763 reducing the incorporation of external fertilizers. Anaerobic digestion also contributes to recover a
764 fraction of the energy content in oilcake [9] in the form of biogas. However, most of the studies
765 dedicated to anaerobic digestion in microalgae point out that external energy is necessary to run the
766 digester [55-57].

767

768 The sustainability-turn between both allocation methods highlights first the importance of considering
769 the actual uses of co-products, and secondly how the consequences of substituting conventional
770 products can strongly modify the sustainability assessment of biofuel. The oil yield and biomass
771 productivity are therefore not the only parameters that must be taken into account for selecting a
772 sustainable biodiesel production, since co-products also have a significant role. More details about
773 substitution method results and comparison with rapeseed, palm tree, soybean and conventional diesel
774 are described in the **Additional file 13**, **Additional file 14** and **Additional file 15**.

775

776 **Improvement paths**

777 High production costs are the major limitation for the commercialization of algae-based biofuel. It is
778 expected that the price of algal biofuels drops when the biomass and lipid productivity are improved
779 [58]. More recent strategies to enhance biomass and lipid productivity in microalgae include genetic
780 and metabolic engineering [59, 60], addition of phytohormones [61], and co-cultivation of microalgae
781 with fungi [62], yeasts [63, 64] and bacteria [65]. By enhancing the performance of microalgae,
782 which, nowadays, are still wild species, productivity should also increase. Bonnefond, Grimaud [66]

783 have proposed a promising strategy for improving algae efficiency with a lower sensitivity to
784 temperature fluctuations. Their approach resulted in extending the thermal niche with an enhancement
785 of the maximal growth rate and lipid content. In addition, the use of additional species all along the
786 year could probably further improve the process. However, this would also involve more sophisticated
787 logistics, as well as the capacity to simultaneously maintain the different species destined to be
788 successively exploited.

789 This study focuses on classical raceway systems, even though more productive systems could be used,
790 such as biofilm-based processes [67], which are likely to considerably reduce energy and harvesting
791 and dewatering costs. Another strategy to optimize algal biomass and lipid production would be to
792 combine open ponds and photobioreactors (hybrid system) [68, 69]. This hybrid system would first
793 maximize biomass production in photobioreactors under nutrient-sufficient conditions. The biomass
794 would then undergo nutrient-depleted conditions in open ponds to enhance lipid accumulation.

795 Significant PV shadowing could be very beneficial during the hottest periods, although it penalizes
796 growth during the cold season. The combination of effective light collection for electricity production
797 with light distribution strategies for microalgae would be an important design criterion. The
798 adjustment of the PV panels using solar flux tracking mechanisms, are options that could dynamically
799 adapt the shadows to the needs of the microalgae. In addition, the LCA was based on the conservative
800 assumption of a 15% PV yield. Improvement of the PV efficiency should mechanically contribute to
801 reduce the PV coverage for a same electricity production, and thus increase microalgae productivity.

802 These improvements should lead to an additional reduction in the resources and climate change
803 impacts. Based on these same criteria, it however remains challenging to reach a better performance
804 than soybean and palm tree biodiesel. Despite this issue, it should be emphasized that a fair
805 comparison between the two approaches ought to be carried out under the same climate. The
806 reference scenario is assessed for hotter climates, under which significantly higher photovoltaic and
807 biomass productions are expected. A comparison with European rapeseed biodiesel is probably more
808 relevant for an appropriate assessment of photovoltaic greenhouses that produce algal biofuel.

809

810 **Conclusions**

811

812 The combination of microalgae production with photovoltaic panels offers several advantages,
813 the main one is to utilize the excess energy from sunlight to feed the large energy demand for
814 biodiesel microalgae. This could therefore counteract the strong external energy requirement of
815 microalgae. Coupling biomass production with photovoltaic electricity represents an ideal opportunity
816 for significantly reducing environmental impacts by a factor close to 50% of GHG emissions.
817 However, there is a clear trade-off between electricity and biomass production, as a larger
818 photovoltaic panels coverage would limit microalgae production. Thus, from an energetic point of
819 view, the optimal configuration lies between 10% and 20% of photovoltaic panel coverage.
820 Nevertheless, from an environmental point of view, the best option is 50% photovoltaic panel
821 coverage. However, the difference between impact values obtained for 20% and 50% PV is
822 negligible, while the Net Energy Ratio is 48% higher for 20% PV than for 50% PV coverage. Hence,
823 20% coverage of photovoltaic panels is a sound and optimal energetic environmental configuration.
824 Taking economics into account, low photovoltaic panel coverage would probably be more attractive.
825 However, even with a 10% area of photovoltaic panels, the environmental footprint would already
826 significantly decrease. This study was carried out with state of the art technologies, but significant
827 improvements in microalgae productivity or more advanced production processes should rapidly
828 enhance the performances. The challenge is now to maintain a profitable production from an
829 economical point of view, despite the increased technicality of the processes.

830

831 **Declarations**

832

833 **Ethics approval and consent to participate**

834 Not applicable

835 **Consent for publication**

836 Not applicable

837 **Availability of data and material**

838 Not applicable

839 **Competing interest**

840 The authors declare that they have no competing interests

841 **Founding**

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843 **Authors` contributions**

844 All authors read and approved the final manuscript

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848

849 **References**

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1022 **Figure titles**

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1024 **Figure 1.** System boundaries for LCA of biodiesel production

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1026 **Figure 2.** Annual average net electricity input and biomass productivity depending on PV coverage.

1027 *Note: Monthly biomass productivity average values are indicated above bars.*

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1029 **Figure 3.** NER and FER comparison *pond-to-wheels* life cycle microalgae-based biodiesel with first-
1030 generation biodiesel and conventional diesel.

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1032 **Figure 4.** Climate change according to areal productivity and PV coverture.

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