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# Coupling semi-transparent PV PANELS with thin-film PBRs for sustainable microalgal biomass production

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## ABSTRACT

The development of sustainable microalgal cultivation systems for large scale biomass production is a challenge. Working with closed thin film culture systems (< 0.01 m) is of interest as it allows decreasing the culture volume for a given biomass production resulting in significant reduction in use of water and energy for mixing and pumping. However, as a direct consequence, it results in a lower thermal inertia, raising difficulties in the temperature regulation, which is also known as one of the most energy consuming part of microalgae culture process. The use of passive solution is a promising mean to reduce this cost. As microalgae only need a small portion of the solar spectrum (the Photosynthetic Active Range: PAR), the unnecessary wavelengths can be removed to limit overheating of the culture. As a further solution, it can be proposed hybrid processes combining photobioreactors (PBRs) associated to semi-transparent solar panels (PVs) that are able to convert some specific wavelengths into electricity, while letting PAR wavelengths pass through for microalgae photosynthetic growth. This would allow a more optimal use of the solar spectrum. Here, the potential use of such a solution was investigated in a thin film closed PBR (AlgoFilm® PBR) through simulation. A dynamic model able to compute the hourly evolution of various parameters (i.e. energy needs for culture thermal regulation, biomass and electricity production) as a function of outdoor conditions was developed. The simulation was used to investigate various configurations of light filtering for a whole year of operation. The use of light filters helped to prevent overheating during the day, however, temperatures at nighttime were lower which is a possible significant drawback. One potential way to overcome the low temperature at night, is storing the excess of heat produced during the day (using, for example, phase changing materials) to redistribute it at night.

## 1. Introduction

Microalgae are photosynthetic microorganisms that can convert light and nutrients into various valuable molecules such as lipids and proteins. Industrial scale microalgal production is therefore promising for a large number of fields including food, feed, health and energy (Milledge, 2011). However, establishing large scale algal production processes ensuring optimal growth with limited energy footprint is a challenge (Gifuni et al., 2019; Lam et al., 2012; Zhang et al., 2016). This is especially critical when biofuels applications is targeted because a positive energy balance is expected for sustainable production (Maranduba et al., 2016).

Among the various possible solutions, operating the culture at low depth (i.e. thin film photobioreactor) has certain advantages (Chen et al., 2011). Indeed, it has been shown that areal biomass productivity

(i.e. the relevant quantity when looking for large scale solar culture) of a given algal species is determined, in optimal conditions, by the light collected by the culture system surface (Pruvost et al., 2015). On the other hand, volumetric biomass productivity is related to the depth of culture: the thinner it is, the higher the volumetric productivity will be. Thin-film culture systems (depth below 0.01 m) are then interesting concepts, as they allow to significantly increase volumetric biomass productivity when compared to usual systems (with depths ranging from 0.05 m to 0.2 m). In thin film reactors, the culture volume is decreased and biomass concentration is increased (both being related) while same areal productivity is achieved as other systems. Then, there is a direct benefit to the energy demand for a given biomass production as most energy needs are related to the culture volume (i.e. mixing, pumping, thermal regulation, harvesting, etc).

Thin-film culture can be obtained from different means (Doucha

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et al., 2005; Yoo et al., 2013). For instance, Pruvost et al. (2017) proposed such a system based on the falling film principle named Algo-Film©. This photobioreactor (PBR) enables to obtain a culture depth of around 0.003–0.005 m corresponding to a surface to volume ratio of 200–500 m<sup>-1</sup> (i.e. 2–5 L of culture medium per m<sup>2</sup> of illuminated surface). In simulated solar conditions, a biomass volumetric productivity of 5.7 kg.m<sup>-3</sup>.day<sup>-1</sup> (12.1 g.m<sup>-2</sup>.day<sup>-1</sup>) was obtained with *Chlorella vulgaris* (Le Borgne, 2011). This correspond to an operating biomass concentration of 16 g.L<sup>-1</sup> in continuous mode which is much higher than conventional PBR cultivation systems where productivity range from 0.5 to 1.5 g.L<sup>-1</sup>.day<sup>-1</sup> (Le Borgne, 2011).

One of the major challenges of thin-film culture is directly related to their low culture volume which resulted in a highly dynamic system when operated under outdoor conditions. For instance, the low thermal inertia induces rapid changes in temperature over the day, and a temperature build-up larger than 30–40 °C can be observed for few hours around noon. Microalgal growth is strongly dependent of the temperature and optimum growth temperature is species specific with 10–30 °C range being commonly admitted (Ras et al., 2013).

In solar conditions, photons which wavelengths are outside of the Photosynthetic Active Range (PAR) combined to the exothermic biochemical reactions of the photosynthetic growth contribute to the culture medium heating. Hence, only around 5% of the light belonging to the PAR contribute efficiently to microalgal growth. The remaining 95% are converted into heat (Cornet, 2010). As a consequence, in summer, and even in temperate climates, open cultivation systems will suffer from water evaporation while closed systems without cooling means may easily reach lethal temperature for microalgae (> 40 °C) (Goetz et al., 2011; Ras et al., 2013). On the other hand, the temperature may drop during the night, leading to significant biomass productivity loss in the early hours of the morning (Michels et al., 2014; Torzillo et al., 1991). A temperature regulation unit is then, in most cases, mandatory for optimal growth.

While various technical solutions exist to heat up or cool down microalgal closed cultivation systems (water spray, immersion in a pool, double water jacket, etc), active temperature regulation is however one of the most resources consuming part of the process (Mehlitz, 2009; Torzillo et al., 1986). The development of passive solutions is a promising way to reduce this energy cost and footprint. Different approaches have already been investigated: integration to a building facade (Pruvost et al., 2016), exchanges with the ground (Pruvost et al., 2019), use of phase changing materials (Le Borgne, 2011; Uyar and Kapucu, 2015) or light filtering (Nwoba et al., 2019; Vadiveloo et al., 2016). The latter can use, for example, the hot mirror principle to selectively reflect ultraviolet (UVs) and infrareds (IRs) which represents roughly 50% of the solar energy (ASTM, 2012). As they do not belong to the PAR, they only contribute to the system's heating, hence their removal is an efficient way to prevent overheating. This solution however results in a poor utilization of the solar spectrum as 50 % of the energy collected by the system is directly wasted.

A novel approach to light filtering has been proposed by (Parlevliet and Moheimani, 2014). It consists on placing semi-transparent photovoltaic (PV) panels on top of the optical surface of a flat panel PBR. Semi-transparent PV panels are able to absorb and convert into electricity some specific wavelengths while letting the other pass through for photosynthetic microalgae growth. The benefit when compared to hot mirrors solutions (i.e. which only reflects light) is the additional production of electricity from the conversion of UVs and IRs which is a valuable output for such an hybrid system (Morales et al., 2019). The global efficiency of solar light conversion is improved with the biomass and electricity coproduction while reducing the energy needs for thermal regulation of the culture volume.

Here the potential of such solar hybrid system was numerically investigated, combining thin film PBR (AlgoFilm©) with semi-transparent PV panels. The aim is to develop a solar bioprocess for sustainable biomass production. A dynamic model able to predict the

time evolution of various outputs of the process (energy required for thermal regulation, biomass and electricity production) as a function of dynamic outdoor conditions is proposed. The model developed in Pruvost et al. (2016a) predicting biomass growth in AlgoFilm© was combined to the thermal model presented in Goetz et al. (2011) and then extended to the case of PBR coupling to semi-transparent PV panels, as described in Parlevliet and Moheimani (2014). Different configurations were also simulated to determine the optimal settings of such association.

## 2. Material and methods

### 2.1. Process description

The thin film PBR AlgoFilm© was previously described in Pruvost et al. (2017). It is based on the falling film principle which enables very thin culture depth (around 2–5 mm), leading to a high specific illuminated surface area (200–500 m<sup>2</sup>.m<sup>-3</sup>). The culture medium is injected at the top of a tilted surface, flows down it, and is then pumped back to the top by a peristaltic pump through a tube forming a closed loop. A glass plate covers the surface (with a gas headspace between the glass and the falling film) giving a full enclosed geometry. This also limits CO<sub>2</sub> degassing from the cultivation system. CO<sub>2</sub> being supplied by automatic injection in the gas phase through pH measurements (Pruvost et al., 2017).

In this study, coupling with a semi-transparent PV panels was considered by placing such panel on top of the covering glass. Two cases were considered: with and without a separation gap between the PV and the covering glass. In the first case, the gap is large enough to allow sufficient air flow. Because of this air flow and the low thermal conductivity of air, it was assumed that heat produced by the photovoltaic panel was not transferred to the PBR. This case was named hereafter as "uncoupled". In the second case, the two subsystems are in contact and the heat produced by the photovoltaic panel is transferred to the covering glass of the PBR. This case was noted "coupled".

The process is schematized by the Fig. 1.

### 2.2. Modeling

#### 2.2.1. Overview of the modeling approach

The present model was built on several interacting models which are depicted in Fig. 2. It relates the influence of light on growth, temperature and electrical energy production as a function of characteristics of the various components of the culture system. Each sub-model are experimentally validated models from the literature. Their equations and relations are described hereafter.

#### 2.2.2. Photovoltaic model

The model for the PV panel to compute the power generated by the PV was adapted from Parlevliet and Moheimani (2014). The only dynamic input of this model is the hemispherical incident spectral light flux density  $q(\lambda)$  (here given in W.m<sup>-2</sup>.nm<sup>-1</sup>) which is dependent of the weather conditions:

$$P = FF \cdot I_{sc} \cdot V_{oc} \quad (1)$$

$$I_{sc} = \int_0^{\infty} EQE(\lambda) \cdot AF(\lambda) \cdot q(\lambda) d\lambda \quad (2)$$

$$V_{oc} = \frac{k \cdot T_{stc}}{e} \cdot \ln \left( \frac{I_{sc} + I_0}{I_0} \right) \quad (3)$$

where P [W] is the electrical output power, I<sub>sc</sub> [A] the short circuit current, V<sub>oc</sub> [V] the open circuit voltage, k [m<sup>2</sup>.kg.s<sup>-2</sup>.K<sup>-1</sup>] the Boltzmann constant, e [A.s] the elementary charge, and AF [-] the spectral absorbance. FF [-], EQE [-] and I<sub>0</sub> [A] are the fill factor, the external

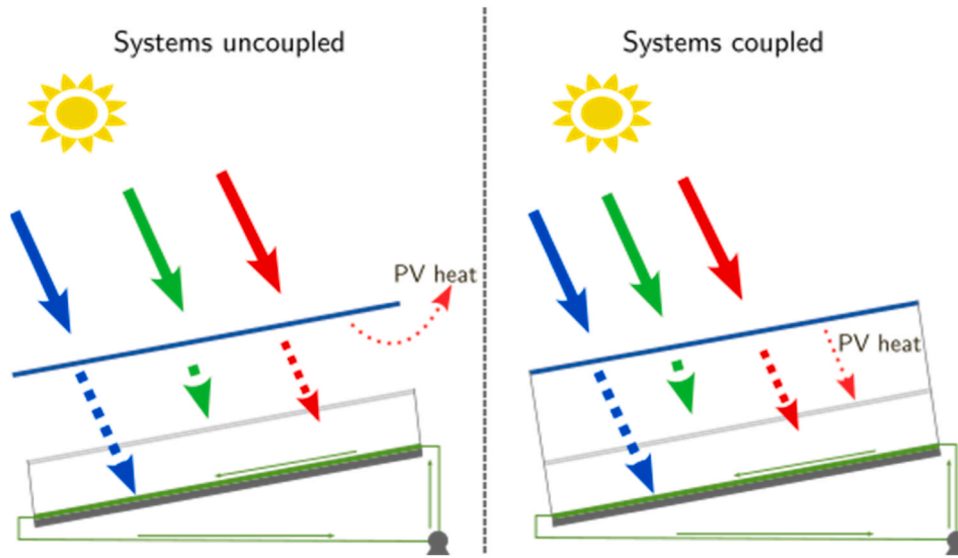


Fig. 1. Schema of the process with the PBR and the PV panel being coupled or uncoupled.

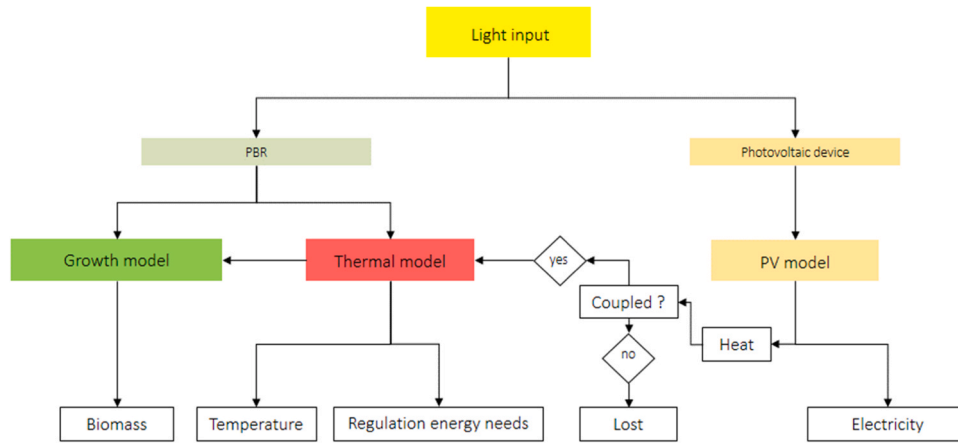


Fig. 2. Overview of the modeling approach.

quantum efficiency and the dark saturation current respectively (obtained from PV panel constructor data).  $T_{stc}$  [K] is the standard test temperature (25 °C).

The photovoltaic panel does not convert all the light into electricity and most of it is transformed into heat. Furthermore, PV panel efficiency is known to decrease as its temperature rises. The most common way to model this is to linearly correct the electrical output power as a function of the difference between the operating temperature and the standard test temperature (Skoplaki and Palyvos, 2009):

$$\eta_{real} = \eta_{stc} \cdot (1 - \beta \cdot (T_{pv} - T_{stc})) \quad (4)$$

where  $\eta_{stc}$  [-] is the PV panel efficiency in standard test conditions and  $\eta_{real}$  [-] is the PV panel efficiency in operating conditions.  $\beta$  is the temperature coefficient of the PV panel. Literature reports that it differs as a function of the technology used but  $0.0045 \text{ } ^\circ\text{C}^{-1}$  is common across multiple technologies (Skoplaki and Palyvos, 2009).

Ideally, temperature effect on the PV panel should be considered. This implies using a thermal model to determine its temperature which would need data that was not available at the time of the study. Hence this aspect was not considered. The impact of this hypothesis on simulation results will be discussed later.

### 2.2.3. Thermal modeling of the microalgal culture system

The model proposed by Goetz et al. (2011) was used to predict the thermal behavior of the studied PBR. The PBR was divided into two sub-systems, namely the culture volume and the covering glass. By applying thermal balance on those sub-systems equations related to the evolution of the temperature of the culture ( $T_s$ ) and glass ( $T_g$ ) as a function of PBR characteristics and weather condition (solar irradiation, ambient temperature and wind speed) were obtained. As the weather conditions are constantly changing, the equations were solved in transient regime:

$$m_g \cdot C_p \frac{dT_g}{dt} = q \cdot S_g \cdot \alpha_g + \epsilon_g \cdot \sigma \cdot S_g (T_{sky}^4 - T_g^4) + h_{g-amb} \cdot S_g \cdot (T_{amb} - T_g) + \dot{Q}_{pv} \quad (5)$$

$$(m_s \cdot C_p + m_u \cdot C_p) \frac{dT_s}{dt} = q \cdot S_s \cdot \alpha_s \cdot \tau_g + h_{g-s} \cdot S_s \cdot (T_g - T_s) + h_{u-amb} \cdot S_u \cdot (T_{amb} - T_s) + \dot{Q}_{reg} \quad (6)$$

where  $m_x$  [kg] are the mass of the considered subsystem (g stands for glass, s for solution and u for underside),  $C_p$  [ $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ] the specific heat capacities,  $S_x$  [ $\text{m}^2$ ] the surface,  $\epsilon$  [-] the emissivity,  $\sigma$  [ $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$ ] the Stephen-Boltzmann constant,  $\alpha_x$  [-] the absorptivity,  $q$  [W] the

incident light flux,  $T_{sky}$  [K] the sky temperature,  $T_{amb}$  [K] the ambient temperature and  $h_{x-y}$  [ $W \cdot m^{-2} \cdot K^{-1}$ ] the convective exchange coefficient between  $x$  and  $y$ .

The convection coefficients and sky temperature for radiative heat transfer are given (Goetz et al., 2011):

$$h_{g-amb} = h_{u-amb} = 5.7 + 3.8 \cdot v \quad (7)$$

$$T_{sky} = 0.0552 \cdot T_{amb}^{1.5} \quad (8)$$

Eq. (6) introduces the power provided by the thermal regulation unit ( $\dot{Q}_{reg}$ ). In this study, the thermal regulation system was assumed perfect (with output power sufficiently high to consider any amount of heat or cold to be provided instantaneously). Thus the power needed to regulate the reactor ( $\dot{Q}_{reg}$ ) is the power required to nullify Eq. (6) when the temperature of the culture exceeds the defined temperature range. This leads to:

$$\dot{Q}_{reg} = - (q \cdot S_s \cdot \alpha_s \cdot \tau_g + h_{g-s} \cdot S_s \cdot (T_g - T_s) + h_{u-amb} \cdot S_u \cdot (T_{amb} - T_s)) \quad (9)$$

Eq. (5) introduces the coupling between the thermal and photovoltaic models with the term  $\dot{Q}_{pv}$ , the heat power transmitted from the PV panel to the PBR's glass. It is considered that  $\dot{Q}_{pv}$  is the net difference between light flux absorbed by the PV panel (depending of the spectral panel's absorptivity  $AF$ ) and its conversion into electrical power ( $P$ ):

$$\dot{Q}_{pv} = \int_0^\infty AF(\lambda) \cdot q(\lambda) d\lambda - P \quad (10)$$

#### 2.2.4. Kinetic growth model

The growth model developed by Pruvost et al. (2016a) is able to predict microalgal growth in solar PBR which are light limited (i.e. no growth limitation other than light occurs). This model relates the light attenuation field (represented by rate of photons absorption  $A$ ) inside the culture volume to the local photosynthetic growth rate. The culture volume was modeled as a unidirectional system of depth  $L$  (i.e. the culture thickness), with light attenuation only occurring along the culture depth  $z$ . To model the radiation field in solar conditions, both direct ( $q_{0c}$ ) and diffuse ( $q_{0d}$ ) lights were considered as their penetration in the culture broth were different. Their respective contribution on the fluence rate ( $G$ ) along the culture depth ( $z$ ) was represented by the following equations:

$$G_c(z) = q_{0c} \cdot \frac{2 \cdot (1 + \alpha) \cdot \exp(-\delta_c \cdot (z - L)) - (1 - \alpha) \cdot \exp(\delta_c \cdot (z - L))}{\cos(\theta) \cdot ((1 + \alpha)^2 \cdot \exp(\delta_c \cdot L) - (1 - \alpha)^2 \cdot \exp(-\delta_c \cdot L))} \quad (11)$$

$$G_d(z) = q_{0d} \cdot 4 \cdot \frac{(1 + \alpha) \cdot \exp(-\delta_d \cdot (z - L)) - (1 - \alpha) \cdot \exp(\delta_d \cdot (z - L))}{(1 + \alpha)^2 \cdot \exp(\delta_d \cdot L) - (1 - \alpha)^2 \cdot \exp(-\delta_d \cdot L)} \quad (12)$$

with  $\alpha = \sqrt{\frac{E_a}{E_a + 2 \cdot E_s \cdot b}}$ ,  $\delta_c = \frac{\alpha \cdot C_x}{\cos(\theta)} \cdot (E_a + 2 \cdot E_s \cdot b)$  and  $\delta_d = 2 \cdot \alpha \cdot C_x \cdot (E_a + 2 \cdot E_s \cdot b)$

Eqs. (11) and (12) are related to the radiative properties of the cultivated strain, with  $E_a$  [ $m^2 \cdot kg^{-1}$ ] the mass absorption cross section,  $E_s$  [ $m^2 \cdot kg^{-1}$ ] the mass scattering cross section and  $b$  [-] the backward scattering fraction (Pruvost et al. 2016).  $\theta$  [rad] is the direct light incidence angle onto the PBR surface (i.e. the covering glass) and  $C_x$  [ $kg \cdot m^{-3}$ ] the dry biomass concentration. The  $c$  subscript stands for collimated light and the  $d$  stands for the diffuse light.

Eqs. (11) and (12) enable us to calculate the fluence rate by summing direct and diffuse light contributions ( $G(z) = G_c(z) + G_d(z)$ ), and then the local rate of photons absorption  $A(z)$ :

$$A(z) = E_a \cdot G(z) = E_a \cdot (G_c(z) + G_d(z)) \quad (13)$$

The local rate of photons absorption allow us to relate absorbed light to the photosynthetic growth rate, here expressed as the net specific rate of oxygen production  $J_{O_2}$ :

$$J_{O_2}(z) = \rho_M \cdot \frac{K_a}{K_a + A(z)} \cdot \Phi_{O_2} \cdot A(z) - \frac{J_{nadh_2-O_2}}{\nu_{nadh_2-O_2}} \cdot \frac{K_r}{K_r + A(z)} \quad (14)$$

Corresponding volumetric growth rate ( $r_x(z)$ ) and average growth rate  $\langle r_x \rangle$  can then be deduced:

$$r_x(z) = \frac{J_{O_2}(z) \cdot C_x \cdot M_x}{\nu_{O_2-x}} \quad (15)$$

$$\langle r_x \rangle = \frac{1}{L} \cdot \int_{z=0}^{z=L} r_x(z) dz \quad (16)$$

Eq. (15) relates to day periods (i.e. photosynthetic growth). During the night, only respiration occurs (i.e. no light), and the growth rate is then related to a specific rate of biomass decay  $\mu_{night}$ :

$$\langle r_{x-night} \rangle = -C_x \cdot \mu_{night} \quad (17)$$

A mass balance equation on the biomass enables to relate biomass concentration time evolution with the volumetric growth rate  $\langle r_x \rangle$ . In the case of a continuous culture, this leads to:

$$\frac{dC_x}{dt} = \langle r_x \rangle - C_x \cdot D \quad (18)$$

with  $D$  [ $s^{-1}$ ] the dilution rate applied to the culture. It is the inverse of  $\tau_p$  the residence time ( $D = \frac{1}{\tau_p}$ ).

As for the thermal model, due to light changing conditions during the day, Eq. (18) was solved in transient mode.

Once the dry weight biomass concentration was obtained, PBR's biomass productivity was deduced in terms of volumetric ( $P_x = C_x \cdot D$  in  $kg \cdot m^{-3} \cdot s^{-1}$ ) and areal ( $S_x$  in  $kg \cdot m^{-2} \cdot s^{-1}$ ) productivities. The two productivities are related by:

$$S_x = P_x \cdot \frac{V_r}{S_{light}} = \frac{C_x \cdot \tau_p}{a_{light}} \quad (19)$$

where  $a_{light}$  [ $m^{-1}$ ] is the specific illuminated area which represents the ratio of the illuminated surface ( $S_{light}$ ) to the culture volume ( $V_r$ ). Eq. (19) clearly shows that the volumetric productivity increase with the specific area, then, for a given illuminated surface, it decreases with the culture thickness  $L$  ( $a_{light} = \frac{S_{light}}{V_r} = \frac{1}{L}$ ) of the culture system. It can be outlined that in light limited conditions, the areal productivity is independent of the cultivation system design (Cornet, 2010; Pruvost et al., 2011).

### 2.3. Method of resolution

#### 2.3.1. Numerical consideration and models parameters

The models used where implemented in Python (CPython 3.10.5) with the use of numeric (Numpy 1.23.1) and scientific (Scipy 1.8.1) packages (Millman and Aivazis, 2011; Oliphant, 2007; van der Walt et al., 2011). Differential equations were solved with the 4(5) order Runge-Kutta method (Hairer et al., 1987).

The weather data required for the models were extracted from a weather database (Meteonorm) for the city of Nantes (France, 47°12'N, 01°33'W). The dataset was obtained from the average of ten years of measurements. This input gives hourly data all over the year for light (both global, collimated and diffuse), light incidence angle, ambient temperature and wind speed. The light spectrum used was the AM 1.5 (ASTM G-173) (ASTM, 2012) (Fig. 3a) which is widely used as a reference spectrum for photovoltaic simulations. The simulated photovoltaic panel was type crystalline. Its EQE curve (Eq. (2)) and properties are reported in Fig. 3b (Green et al., 2012).

*Chlorella vulgaris* was used here as a reference case for this study. Kinetic growth model parameters and radiative properties are reported in Table 1 and Fig. 4. They were issued from Kandilian et al. (2016) and Pruvost et al. (2016).

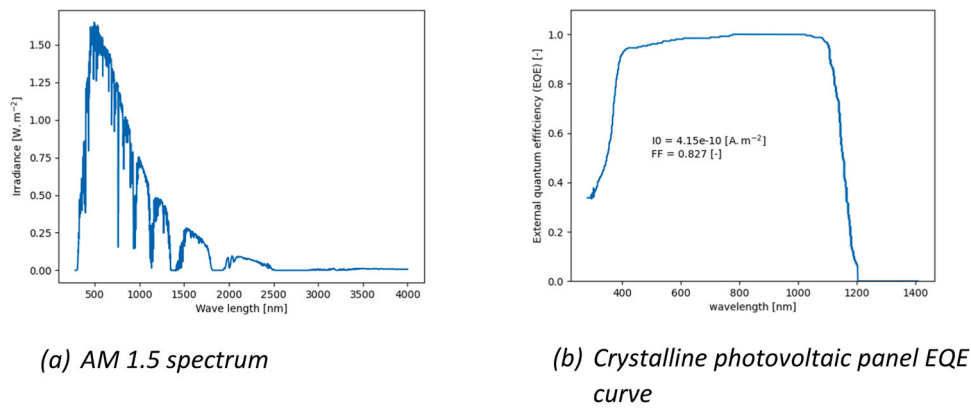


Fig. 3. AM 1.5 spectrum and crystalline photovoltaic panel properties.

**Table 1**  
Parameters of the kinetic growth model of *Chlorella vulgaris*.

Ac	$\mu\text{mol}_w \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$	2800
$J_{\text{NADH2-o2}}$	$\text{mol}_{\text{NADH2}} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$	$1.84 \cdot 10^{-3}$
$K_a$	$\mu\text{mol}_w \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$	$4 \cdot 10^4$
$K_r$	$\mu\text{mol}_w \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$	932
$M_x$	$\text{kg} \cdot \text{mol}^{-1}$	0.024
$\nu_{\text{NADH2-o2}}$	$\text{mol}_{\text{NADH2}} \cdot \text{mol}_{\text{o2}}^{-1}$	2
$\phi_{\text{o2}}$	$\text{kg}_x \cdot \mu\text{mol}_w^{-1}$	$1.1 \cdot 10^{-7}$
$\nu_{\text{o2-x}}$	$\text{mol}_{\text{o2}} \cdot \text{mol}_x^{-1}$	2
$\rho_M$	-	0.8
$\mu_{\text{dark}}$	$\text{s}^{-1}$	$1.1 \cdot 10^{-6}$

The residence time applied to the culture system was set to a constant value of  $\tau_p=25$  h (i.e. chemostat mode). Such value was found to give almost maximal biomass productivity in Nantes (France) location. This could be further optimized by adjusting it for example as a function of the weather conditions and time of the day, but such fine optimization was not the aim of this study. The thermal and physical properties of AlgoFilm© PBR are summarized in Table 2 (Goetz et al., 2011).

In the context of this study, two types of simulations were run. First, the impact of light filters on the temperature of the PBR was examined. Here the temperature control was disabled ( $\dot{Q}_{\text{reg}} = 0$ ). The second set of simulations was run based on the energy needs. The PBR was then regulated in the range of optimum growth temperature [ $15^\circ\text{C}$ – $35^\circ\text{C}$ ] which was assumed to result in a negligible impact on *Chlorella vulgaris* growth (Todisco, 2019). Hence the coupling between the thermal and growth model was neglected.

### 2.3.2. Light filtering scenarios

One key element in the design of the semi-transparent PV panel is its spectral absorbance AF. To assess the effect of light filtering on the

**Table 2**  
Physical properties of AlgoFilm© PBR.

	m [kg]	Cp [ $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ]	S [ $\text{m}^2$ ]	$\alpha$ [-]	$\epsilon$ [-]	$\tau$ [-]
Glass	7.8	720	1	0.05	0.92	0.9
Solution	2	4180	1	1	0	0
Underside	36	500	1.5	1	0.58	0

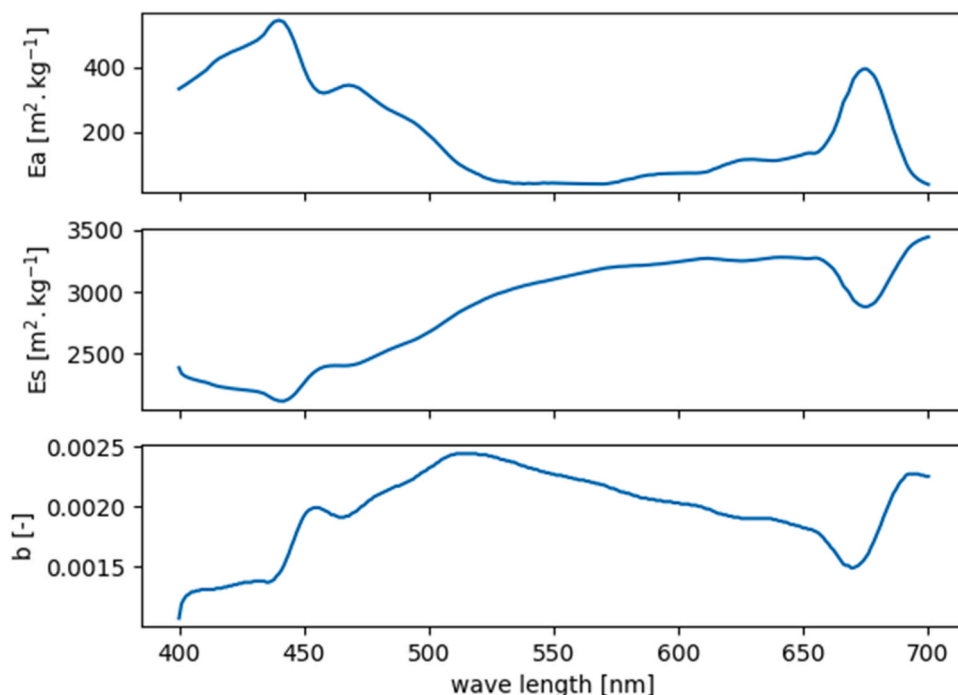


Fig. 4. Radiative properties of *Chlorella vulgaris* (Kandilian et al. 2016).

system, different light filters were tested.

- a reference scenario representing a system without any light filtering was setup (noted Scenario #0).
- an ideal scenario (Scenario #1) where all the visible light was provided to the culture for optimal microalgae growth with combined full use of the UV/IR by the PV panel for electricity production.
- a third scenario (scenario #2) investigating the impact on a selective green light removal by the PV panel (as shown on Fig. 4, a large part of the green light is indeed not absorbed by the microalgae and is mainly diffused).
- two imperfect scenarios which are closer to actual light filters properties as given by Nwoba et al. (2020). Scenario #3 is obtained with 75 % of the PAR and 10 % of the UV/IR are transmitted to the culture. Scenario #4 let 50 % of the PAR light to be transmitted to the microalgae culture.

Table 3 summarized the light fractions absorbed by the PV panel as a function of the wavelength ranges. The complementary fraction is transmitted to the PBR, contributing then to both microalgae growth ( $q_0$  in Eqs. (11) and (12)) and culture volume heating ( $q$  in Eqs. (5) and (6)). Photosynthesis being sensitive to the photon flux density ( $\mu\text{mol}_{\text{ph}}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) and heat transfer to the light energy flux density ( $\text{W}\cdot\text{m}^{-2}$ ), light flux were converted according to their light spectrum (AM 1.5 for incoming sunlight or light spectrum modified by PV filtering).

### 3. Results and discussion

#### 3.1. Thermal behavior of the hybrid system

The thermal behavior of AlgoFilm© PBR was firstly assessed by simulating the case without thermal regulation system and without semi-transparent PV panel. Fig. 5 shows a typical time evolution achieved with corresponding ambient temperature and light input during late summer period (one week starting the 1st of September).

A large temperature evolution was obtained with temperature ranged from 10 °C in the night to more than 40 °C during the day with some peaks over 55 °C for some sunny days at noon. The temperature dynamics were also found fully related to the sunlight profile with high temperature during the day mostly incompatible with *Chlorella vulgaris* growth and temperatures close to the ambient temperature during the night. Such behavior emphasizes the very low thermal inertia of thin film culture systems and the great influence the weather conditions have on them.

Fig. 6 represents the temperature profiles obtained at the same outdoor conditions and period without thermal regulation unit, but with the filtering system (both coupled and uncoupled cases) as described in scenario #1.

Applying a light filter significantly lowers the temperature of the culture broth. In the coupled case (i.e. with the PV panel transferring heat to the culture system), the culture volume is 5 °C lower than the reference case (without filter). When the heat absorbed by the PV panel is not transferred to the PBR (i.e. uncoupled case), the PBR is even colder (up to 20 °C cooler for the hottest day). As expected, there is no impact of light filtering on the PBR thermal behavior during the night period. As

a consequence of the very low thermal inertia of AlgoFilm© PBR, the minimum temperature accepted (15 °C) is then reached quickly. When adding light filters to the system, this temperature is reached later in the morning and earlier in the evening when compared to the reference case. This demonstrates a potential drawback of light filtering solution: the decrease of the build-up temperature during the day combined with the low thermal inertia of AlgoFilm© PBR results in too low temperature during the night that could have detrimental effects on the microalgae growth during the day-night cycles. When conducting the analysis over a broader set of simulated data, the efficiency of light filter dependence toward light conditions is confirmed, with a larger efficiency on sunny days with clear sky.

Table 4 summarizes the average temperature reduction over a complete year compared to the reference scenario (with no filter) as a function of the type of light filter. As the light filter are only efficient during light periods, two cases were considered. First, a simple average over the whole year (including the night) was performed. Then, a second analysis where the data was limited to the daily periods (10 h - 16 h) excluding morning, evening and night was done.

The most efficient temperature reduction from light filtering was found when the PV and PBR are uncoupled, with a reduction of the average daily temperature of the culture temperature between 4.3 °C and 5.4 °C depending on the filter characteristics. When the two systems are coupled, as some energy absorbed by the PV panel is transmitted to the PBR, the cooling efficiency is decreased with average temperature reduction between 1.6 °C and 2.1 °C.

As mentioned previously, the presented model lacks a prediction of the temperature of the PV panel, then its efficiency was not corrected by its temperature. However, as the modelled photovoltaic device exchanges heat similarly to the covering glass of the PBR (i.e. absorbing light and converting it to heat then exchanging it with ambient air) it was assumed in first instance to follow similar temperature evolution. To assess the hypothesis of temperature independent PV panel efficiency, a sensitivity analysis was then conducted on the PBR glass characteristics (assuming it is representative of the temperature of a PV panel). Eq. (4) was used to estimate the error made by this hypothesis. The temperature coefficient of the PV ( $\beta$ ) which represents the decay of efficiency with PV panel temperature, was set to  $0.0045\text{ }^{\circ}\text{C}^{-1}$ , which is common value for PV panels (Skoplaki and Palyvos, 2009). Only data for day periods were taken into account (i.e. the periods with light, when the PV panel is productive).

On average, the temperature of the glass was 18.4 °C. This would indicate that the model underestimated by 3 % the production of the PV panel (according to Eq. 4). By considering minimum (percentile 5 % corresponding to 4.1 °C) and maximum (percentile 95% corresponding to 39.8 °C) values of PV panel temperatures predicted over the year, an underestimation of 9.9% and an overestimation of 5.5 % of the produced electricity were found respectively. Therefore, the electrical production model accuracy could be estimated at  $\pm 7.7\%$ , 90% of the time. The hypothesis of temperature independent photovoltaic production could be considered fair in this paper as this does not significantly affect its conclusions.

**Table 3**  
Summary of studied scenarios.

Scenario	UV (<400 nm)	blue ([400–500nm])	green ([500–600 nm])	Red ([600–700] nm)	IR (>700 nm)
0	0%	0%	0%	0%	0%
1	100%	0%	0%	0%	100%
2	100%	0%	100%	0%	100%
3	90%	25%	25%	25%	90%
4	90%	50%	50%	50%	90%

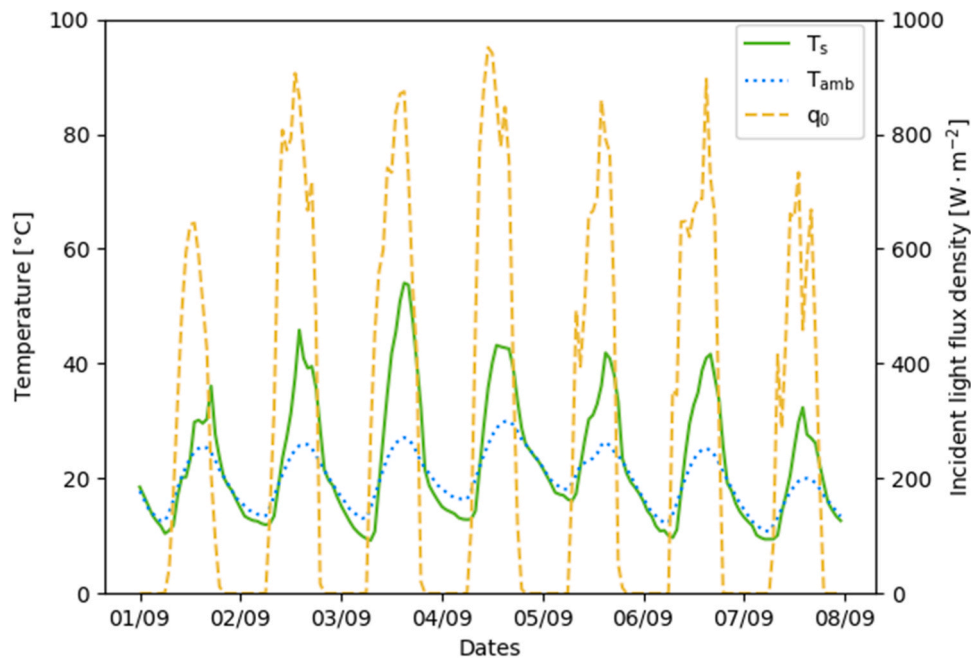


Fig. 5. Typical time evolution of the temperature of the PBR as a function of weather conditions (no thermal regulation and semi-transparent PV panel).

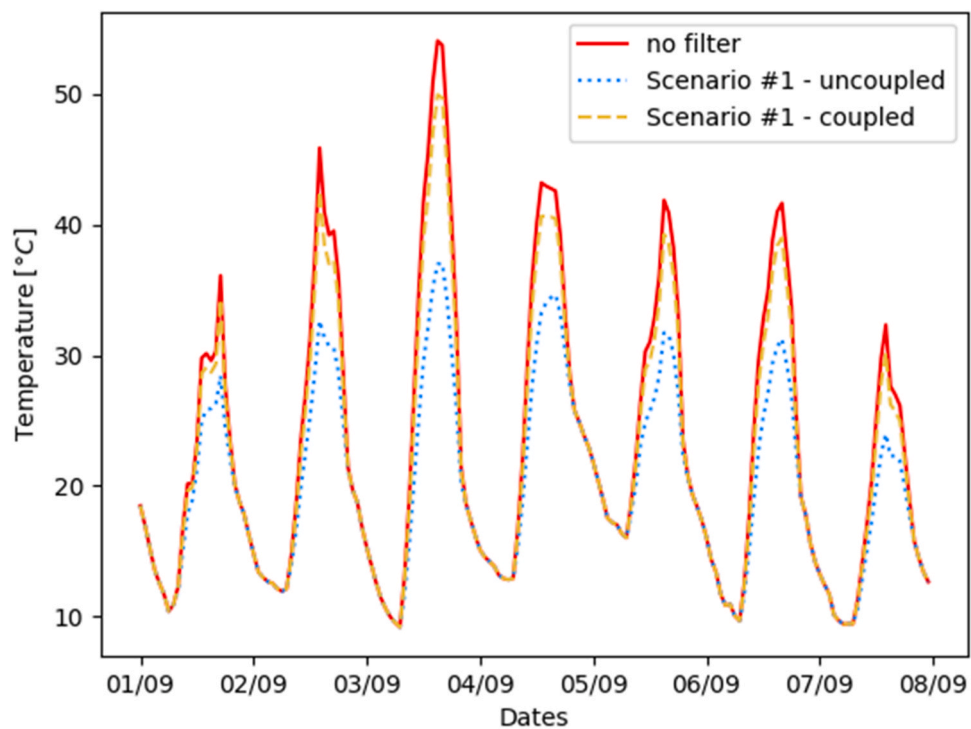


Fig. 6. Time evolution of the culture volume temperature with and without light filtering by the semi-transparent PV panel.

Table 4

Average temperature reduction for each type of filtering applied (Scenario #1 to #4) by comparison to the reference case (no filter), calculated here on a full year of operation.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uncoupled	yearly	-2.6 C	-3.3 C	-2.9 C	-3.4 C
	10 h - 16 h	-7 C	-8.9 C	-7.6 C	-8.9 C
Coupled	yearly	-0.7 C	-0.9 C	-0.7 C	-0.9 C
	10 h - 16 h	-1.8 C	-2.3 C	-2.0 C	-2.3 C

### 3.2. Benefits on energy consumption for thermal regulation

The effect on the energy needs for thermal regulation was determined from Eq. (9) enabling to calculate  $\dot{Q}_{reg}$  to maintain a given temperature range, here fixed between 15 °C and 35 °C. Fig. 7 shows an example of the time evolution (one week in September) of the PBR temperature with the thermal regulation activated (no light filter applied).

When the culture temperature moved outside of the optimum temperature range, thermal regulation was activated. The amount of energy

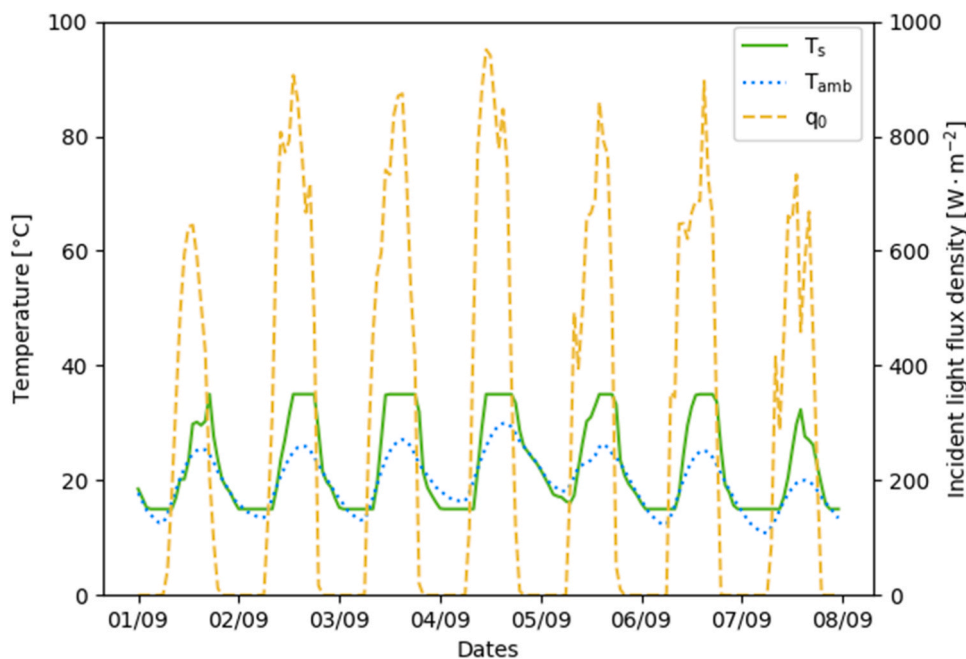
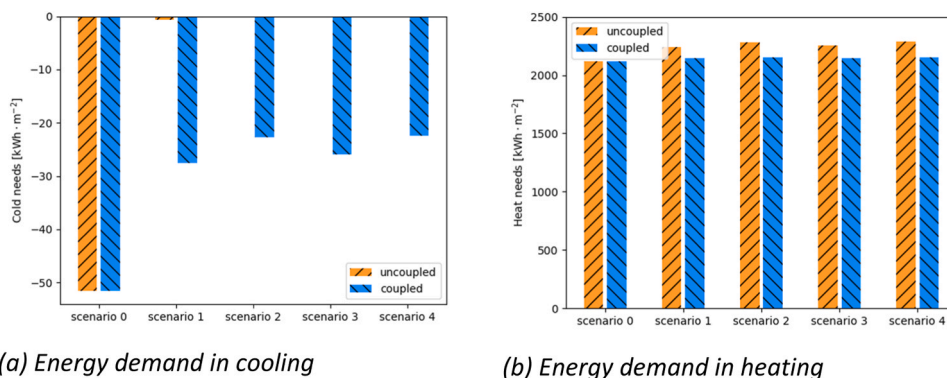


Fig. 7. Thermal behavior of AlgoFilm© PBR with thermal regulation and without semi-transparent PV panel (no light filtering).



(a) Energy demand in cooling

(b) Energy demand in heating

Fig. 8. Energy demands in cooling (a) and heating (b) for the thermo-regulated AlgoFilm© PBR for the different scenarios of semi-transparent PV panels (coupled and uncoupled).

required to maintain the temperature was calculated by integrating  $\dot{Q}_{reg}$  over the time. Results in terms of energy demands are summarized in Fig. 8a and Fig. 8b for each studied scenario.

Efficiency of light filtering to decrease the energy required for cooling down the culture is confirmed (Fig. 8a). When the PBR and the PV panel are uncoupled, light filtering is so efficient that there is almost no need to cool down the PBR whatever the semi-transparent PV panel characteristics. When the two systems are coupled, as some of the energy received by the PV panel is still transmitted to the PBR, the energy needs increase significantly to reach value comprised between reference scenario (largest energy need) and the uncoupled version (lowest energy needs). However, whatever the semi-transparent PV characteristics, the energy demand is almost halved when compared to the reference case (no filter). Thus, even when coupled, the combination of semi-transparent PV panel and PBR appears as a solution of great interest to reduce energy demand for thermal regulation.

Fig. 8b emphasizes the main drawback of such strategy with the demand in heating being increased in all cases. As reported in the literature, the main limitation of PBR in solar conditions is the need of cooling because of the tendency of closed geometries (i.e. no water evaporation) to overheat (Pruvost et al., 2011). Surprisingly, in the case

of AlgoFilm© PBR, even without light filtering (i.e. reference case) the demand in heating is 10.4 times greater than the one for cooling. This is clearly explained by the low thermal inertia of thin film PBR. During the night, the PBR temperature cools down to the ambient air temperature (see Fig. 5). In the region of Nantes (France), where night temperature can be close or below 0 °C (in winter), maintaining the PBR’s temperature up to 15 °C during the whole night would require a large amount of energy. When a light filter is applied, as the light, hence energy, received and accumulated in the PBR is decreased, the need in heating energy is further increased. When considering the total energy (cooling and heating), uncoupling the PV panel and the PBR is detrimental in all cases. The raise in heat demand is indeed superior to the energy saved for cooling. On the other hand, simulations with coupled systems show an overall decrease in energy demand. However, this remain negligible (a few kWh over the year) compared to the energy required to heat up the culture volume.

The outcome of simulations conducted in this study clearly illustrates the need to propose adequate engineering solutions for thin film culture systems such as AlgoFilm© PBR. The low thermal inertia of such a concept reveals a major issue to reach efficient passive thermal regulation. Increasing the thermal mass of the culture would require increasing

the culture depth, which would obviously be against the intensification principle of reaching high volumetric biomass productivity and would lead to negative consequences on energy demands of other parts of the process (i.e. mixing, harvesting, etc). As a possible solution, materials could be integrated in the PBR framework to reduce temperature variations between day (heat accumulation) and night (heat release). The use of phase changing materials (PCM) for this purpose appears as a promising solution (Le Borgne, 2011). By inducing PCM melting, the time of the day where cooling is necessary could be delayed, hence reducing the energy needed. Further, thanks to the latent heat release during the night, the time when heating is needed would also be delayed. In overall, this could help maintain passively the culture broth at a temperature closer to the optimal range.

As illustrated in Pruvost et al. (2019) the operating range of culture temperature has a large impact on the energy needs for thermal regulation. To emphasize this possible strategy in the case of thin-film PBR, the lower temperature set-point for thermal regulation was dropped to 10 °C instead of 15 °C. As shown on Fig. 9, the energy required for heating up the culture is then halved, confirming the relevance of culture temperature range adjustment strategy to reduce the global energy demand. Such a conclusion is obviously dependent of outdoor conditions. In the used weather dataset, the average ambient air temperature at night over the year is indeed 9.4 °C. Hence the temperature difference between the PBR minimum set-point and the ambient air is reduced, lowering the thermal losses of the PBR. Changing temperature operating range of the culture system may certainly reduce microalgae growth rate (Michels et al., 2014; Torzillo et al., 1991). Such effect was not included in the simulation, which should request appropriate formulation of temperature effect on kinetic growth.

### 3.3. Analysis of yearly biomass and electrical production

In addition to decreased energy needs for thermal regulation, the semi-transparent PV panel produces electricity from absorbed light. Because there is a possible overlap between spectral region absorbed by the PV panel used in photosynthesis (i.e. depending on the PV panel characteristics), both electrical and biomass productions were predicted for the different scenarios of combination. Results are shown in Fig. 10.

As expected, removing only the UV and IR did not affect the microalgae productivity (scenario #1). Using those wavelengths to produce electricity is then obviously of interest and can be considered as the ideal case to maximize biomass production. Scenario #2 shows that removing the green light ([500–600 nm]) reduced the microalgae production by 30 %. The explanation lies in how the light is diffused into the culture volume. As already described in Kandilian et al. (2016), blue and red wavelengths are quickly absorbed along the depth of the culture because of the light spectra of green algae, with chlorophyll absorption peaks in those regions. As a consequence, blue and red light poorly contribute to the growth of the microalgae in the depth of the culture, while green light penetrates deeper and contributes then more to the growth of the microalgae by reducing the negative effects of dark volume on resulting photosynthesis growth. So removing the green light with filter is interesting for cooling as these wavelengths represent a large part of the solar spectrum (15 % as defined by (ASTM, 2012)) but with a non-negligible negative impact on the biomass production. However, it allows to produce a large amount of electricity (+26.9 % compared to the scenario #1). In fact, the semi-transparent PV panel is designed to be efficient to convert these wavelengths (see Fig. 3b). Therefore, this option could be of interest in the perspective of setting a compromise between biomass and electricity production, and energy needs for cooling the system.

### 3.4. Analysis of production period along one year of exploitation

The presented model can be used as a decision tool, for example, to determine when it's worth to produce microalgae, depending on the period and weather conditions. The simulations showed indeed that the energy needs and biomass productivity are not constant through the year because of the large variation of outdoor conditions in a location such as France. The biomass production is then larger in summer than in winter. The latter period also implies colder days where the PBR will need to be heated to be kept in the targeted temperature range suitable for optimized culture growth (15 °C – 35 °C).

Fig. 11 shows the cumulated percentage of the biomass and electricity production and energy needed to keep the PBR in the targeted temperature range (15 °C – 35 °C). Only the scenario #1 was used as all

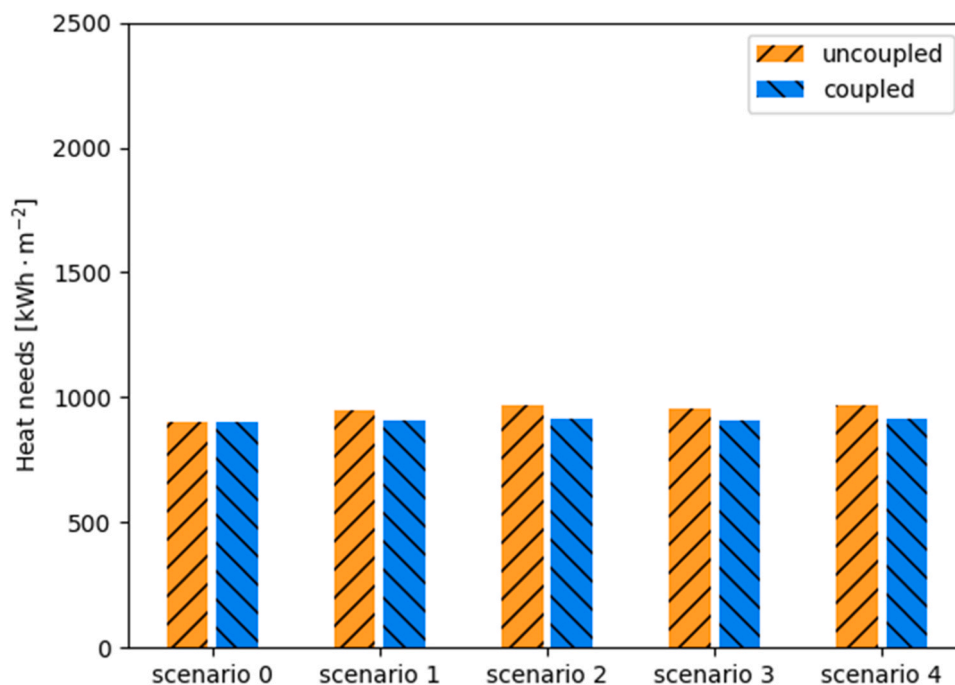


Fig. 9. Heat energy demand for AlgoFilm© PBR with temperature regulation between 10 °C and 35 °C.

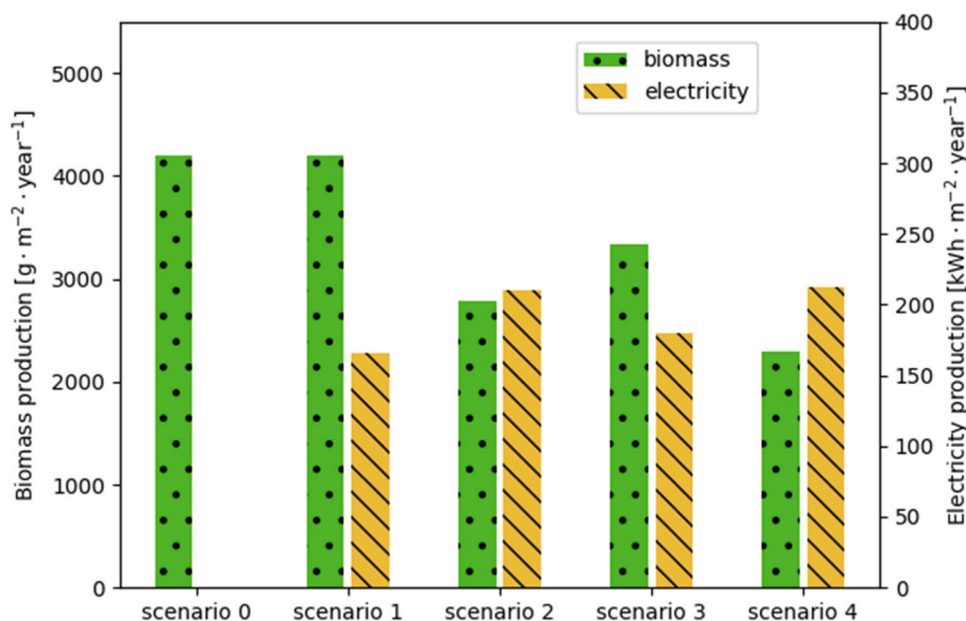


Fig. 10. Biomass and electricity production by AlgoFilm© PBR combined with semi-transparent PV panel for each scenario.

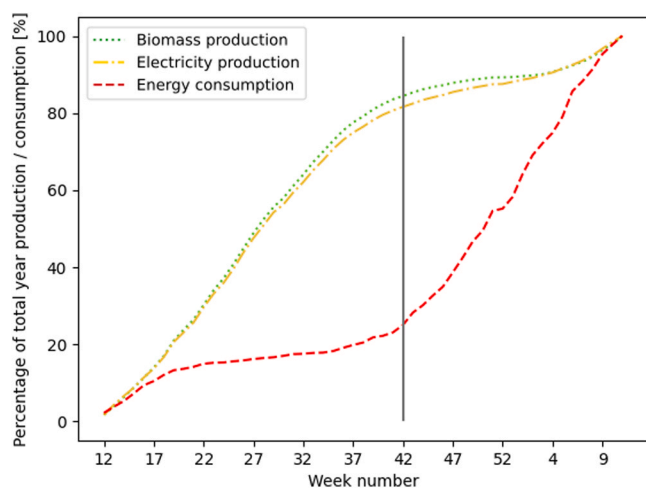


Fig. 11. Evolution over the year of cumulated percentage of biomass and electricity production and energy needs of the PBR.

scenario showed very similar evolutions. Note that time axis has been shifted to start at the end of the least productive season for France (i.e. winter) for readability purpose.

Energy needs and biomass productivity of the hybrid system were found to follow different trends. Two periods can be distinguished: on the first one (between week 12 and week 42), around 80 % of the biomass and electricity has been produced with only about 20 % of the yearly energy required for thermal regulation. On the contrary, the second period (from week 42 to week 12) will need 80 % of the energy consumed by the PBR to produce the remaining 20 % of yearly biomass and electricity production. Such analysis appears then useful to optimize the operation of the system over the year of exploitation. For example, by combining it to an economic analysis, it could be decided to stop during a given period. It could also help defining strategies for a sustainable production by relating, for example, energy needed (i.e. energy consumed minus energy produced by PV panel) to produce a given amount of biomass so as to define suitable culture periods.

#### 4. Conclusion

Three models from the literature were combined to assess the potential of the coupling between the thin-film AlgoFilm© PBR and a semi-transparent PV panel. The resulting model was found useful to explore such a coupling in terms of energy needs to regulate the temperature of the culture as well as in terms of biomass and electricity produced over a year of exploitation.

The result shows that, whatever the case, light filtering alone provided by semi-transparent PV panel allows significant reduction of energy needs for thermal regulation in a system such as AlgoFilm© PBR. Overheating and energy needs for cooling were significantly reduced. However, simulations also show that AlgoFilm© PBR could be further improved in terms of engineering by storing exceeding energy for the night. This was a direct consequence of the low thermal inertia of thin-film PBR. Surprisingly the energy needed to heat up the culture volume was indeed found highly superior to the energy needed for cooling. The use of materials like PCM could be an attractive solution as they allow both passive cooling during the day and passive heating during the night. The impact of the minimum temperature set point was also found relevant, as it halved the energy needs for heating. The model should however be further improved to take into account effects of non-optimal temperature on microalgal growth-rate, to be able to find the compromise between biomass production and energy demand for thermal regulation.

As an additional benefit of using semi-transparent PV panel, the impact on simultaneous biomass and electricity production was also simulated. Various spectral filtering were tested to investigate the compromise between microalgae growth, electricity production, and decrease in energy for thermal regulation. Filtering green light which is only poorly absorbed by microalgae cells was found of interest to increase electricity production while reducing energy for thermal regulation. But, because of their deeper penetration in the culture depth, it resulted also in a decrease of growth rate because of a larger influence of the respiration activity in the dark zone as induced by dense culture. Whatever the case, the model was found useful as a decision tool. It could be associated to techno-economic or life-cycle analysis to determine when it is worth growing microalgae over the year for optimizing the economics or sustainability of such system. As demonstrated in this study, combining thin-film culture system with semi-transparent PV panel could lead to a very interesting hybrid solution in the context of

setting microalgae culture systems with low-energy demands.

### CRedit authorship contribution statement

**Mariana Titica:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Jérémy Pruvost:** Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition, Conceptualization. **Navid Moheimani:** Validation, Supervision, Funding acquisition, Conceptualization. **Julien Louveau:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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