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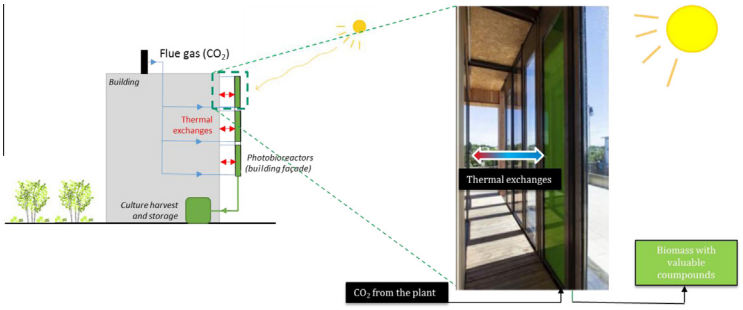
HIGHLIGHTS

- Vertical photobioreactor (PBR) integration in building facade was investigated.
- Results were compared to conventional systems (raceways, stand-alone PBR).
- The conditions then induced could benefit to the yearly PBR operation.
- Optimization of thermal exchanges between culture and building was critical.

GRAPHICAL ABSTRACT



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ABSTRACT

Vertical flat-panel photobioreactors for microalgae culture can be integrated into building facades. On top of providing the large solar illuminated surfaces needed for microalgae production, this original combination opens various optimization opportunities, such as the possibility to create mutual benefits for both systems with appropriate and efficient integration. For example, microalgal photosynthesis can be used to fix the CO_2 contained in flue gas emitted from the building (in a factory set-up) or to significantly reduce energy consumption for thermal regulation of both photobioreactors and building.

Here we report the results of a theoretical modelling-based investigation designed to define how the specific building integration conditions affect photobioreactor operation. Expected biomass production and light attenuation conditions encountered in the culture volume were determined for the green microalgae *Chlorella vulgaris* for a location based in Nantes (France). Results were compared to figures from the more conventional systems such as horizontal or ideally-inclined microalgal culture systems. We conclude with an energetic analysis that underlines the relevance of optimizing thermal exchanges between microalgal culture and building.

1. Introduction

Microalgae are emerging as a valuable new organic feedstock for an array of applications ranging from foods and feeds to cosmetics, pharmaceutical and biofuels [1,2]. Microalgae can be cultured in various systems, from open ponds to closed photobioreactors (PBR). Open ponds are cheap and easy to scale up, whereas closed-systems PBRs are notoriously expensive, which limits their use for mass-scale solar cultivation [3–9]. As a result, around 90% of current biomass production worldwide is obtained in open systems, despite the fact that PBR technologies offer greater potential in terms of productivity, control of culture conditions and applicability to cultivate various strains.

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The main objective in the industrial-scale deployment of this new technology today is to decrease PBR costs without compromising system performances. In this context, symbiosis with buildings appears a promising way to reduce the capital and operating costs of PBR technologies while at the same time bringing added-value benefits to the building, such as a partial reduction of its energy consumption or even effluent emissions. The large-scale illuminated areas are available, some costs like glazing can be shared, and the integration into a building facade allows fluid exchanges between building and PBRs to reduce thermal regulation and nutrient demands (especially if CO_2 sources are available in the building).

Optimization of exchanges (i.e. symbiosis) between the two systems is critical, as the ultimate utility of the concept here will result from mutual benefits between building needs and microalgae needs. A facade without PBR or a stand-alone vertical PBR will obviously be cheaper than an integrated solution, so only an optimized integration maximizing symbiosis between the two systems will result in a solution of interest.

Considering the PBR only, its installation on a building facade hinges on resolving a number of technical challenges. System geometry has to respond to architecture constraints, light capture has to be optimized to guarantee maximal performances, and the process has to be robust with ideally a continuous automated operation running for several months at a time. Relevant factors are system design and the mixing conditions applied or material used to avoid biomass fouling on glazed surfaces. The vertical-plane installation that on-facade integration entails adds a further major constraint. Although vertical installation is commonly encountered in PBR technologies like air-lift systems, it creates specific irradiation conditions that in turn create specific culturing conditions. Indeed, Pruvost et al. [6,10,11] showed a direct and strong correlation between light collected, photosynthetic growth, and resulting process response which is especially relevant for PBR technologies that are controllable enough to overcome any growth limitation other than light (the so-called "light-limited regime"). For a given microalgal strain, the process is then fully driven by light collected onto the cultivation system.

Appropriate consideration of the influence of sunlight on the cultivation system makes it possible to determine information of primary relevance like time-course of biomass concentration or biomass productivity. Modelling is especially useful here as it can relate the many complex phenomena involved in the conditions of solar culture, such as (1) time variations in sunlight in terms of intensity, beam–diffuse radiation partitioning, or collimated angle onto the PBR surface, and their effects on (2) radiative transfer in the culture volume and (3) the resulting photosynthetic conversion and biomass growth. This kind of approach has already been used, but only for standalone production units such as horizontally-fixed and solar-tracking systems, and mainly to investigate production limits or the effect of PBR location [10].

This work will extend our modelling approach to the particular case of flat-panel PBR integration in a building facade. More specifically, we investigate the case of integrating airlift PBR into the south-facing facade of a flue gas-emitting plant for simultaneous biomass production and CO_2 biofixation (SymBIO2 project). Maximal biomass productivity achievable (discussed here for the microalga *Chlorella vulgaris*) in such systems will be determined, and the resulting CO_2 biofixation capacity will be defined. The constraint of vertical installation will also be addressed by comparing results with standard cultivation systems (horizontal and inclined systems). The investigation will round up with an energetic analysis with special focus on energy requirements for thermal regulation to investigate the potential benefit of inducing thermal symbiosis with the supporting building. All these results will help characterize the utility, potential and limits of vertical building-integrated PBR.

2. Photobioreactor integration into the building facade

2.1. Context of the study

Symbio2 is an industrial R&D project with a brief to develop advanced hybrid facade systems that optimize the concept of symbiosis between building and microalgal cultivation by integrating flat-panel microalgae PBRs enabling optimized exchanges with the support building so as to decrease thermal needs and enable CO_2 biofixation for a flue-gas-emitting building—in this case a waste processing plant.

Given the lack of relevant literature, a set of preliminary investigations was planned to address the most relevant aspects of this complex process, i.e. (1) culture conditions induced by installing a PBR on a vertical facade, (2) conservative estimates of achievable biomass productivity, (3) interest of inducing thermal exchanges with the support building, (4) hydrodynamic optimization of the flat-panel PBR to prevent fouling on optical glass surfaces, and (5) validation of the concept in real outdoor operating conditions. This paper reports the results of these preliminary investigations, except for the hydrodynamics and real-outdoor investigations which are currently in progress.

2.2. Thermal regulation of solar PBRs: how to benefit from building integration

Like with any biological process, temperature directly influences photosynthesis and microorganism growth. Under high solar illumination, closed PBRs tend to overheat while open systems can suffer water evaporation issues, both of which can be attributed to culture confinement and to the strongly exoenergetic photosynthetic growth [12–15]. In fact, the thermodynamic efficiency over the PAR region of systems working with the low light regimes typical of artificial illumination (100–300 $\mu mole_{h\nu}\, m^{-2}\, s^{-1}$) is generally below 5% [16], decreasing to 2% under large solar irradiance (>500 $\mu mole_{h\nu}\, g^{-2}\, s^{-1}$). In addition, under outdoor conditions, around 50% of the energy in the solar radiation is contained in the near- and mid-infrared above 750 nm and directly participates in heating up the culture [15,17–19]. As a result, around 95% of the captured total light spectrum energy is converted into heat.

Thermal regulation of PBRs has been widely investigated as a major issue of solar microalgal cultivation [15,18,20,21]. The appropriate temperature window is strongly dependent on species cultivated, but typically ranges between 10 and 30 °C. Unfortunately, without proper thermoregulation, temperatures lethal to living microorganisms can easily be reached inside the PBR when exposed to solar light. On the other hand, in temperate climates, excessively low temperatures during winter can result in loss of biomass growth and productivity, in which case culture heat-up becomes can be beneficial [17]. Year-round operation can create then a need for both cooling and heating.

Various solutions have been developed for heating or cooling PBRs depending on PBR technology, size, and location. Cooling and/or heating by spraying water on the PBR's outer surfaces or by direct immersion in a pool are often used [20]. In temperate regions, microalgae culture systems can also be placed in greenhouses. Although efficient, those methods can increase the construction and operating costs and negatively impact the environmental footprint through excessive energy and water consumption.

Although technical solutions currently exist, PBR temperature control remains a challenge under solar conditions, especially if the aim is to find cost-effective, low-energy-demand, year-round-operable solutions. The engineering of the cultivation system is equally relevant. For example, Goetz et al. [19] experimentally

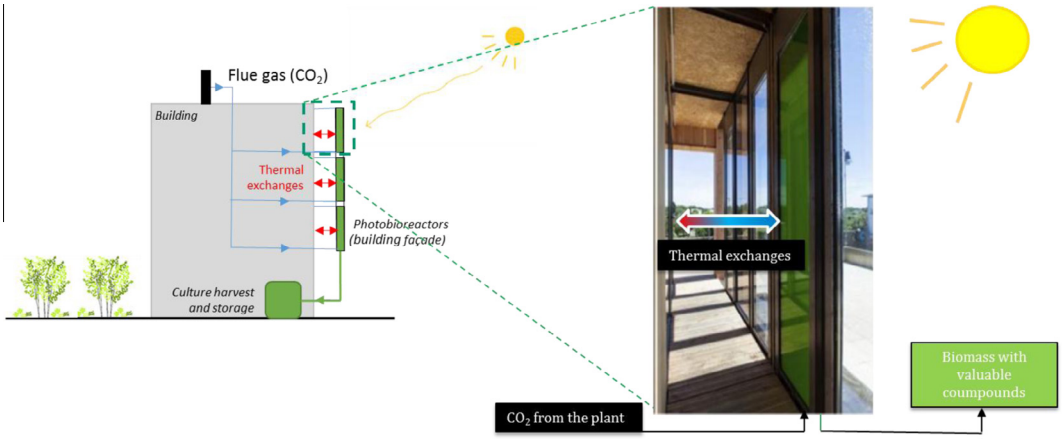

Fig. 1. Sketch-up of the building-integrated photobioreactor and its fluid exchanges.

and theoretically investigated the effect of various flat-panel PBR designs and found that depending on configuration, PBR energy consumption could be decreased by up to one order of magnitude. IR filtering, for example, was found to be especially effective at reducing culture over-heat.

The specific case of facade integration offers various benefits for thermal management of both PBR and host building by exploiting the host-building support (Fig. 1). Energy exchanges between building and PBRs can be designed to cool or warm each one's subsystem. For example, in summer, PBRs can filter sunlight to reduce thermal load on the building, while in winter, excess thermal energy in the cultivation system can be used to warm the building. The added thermal mass of the building can also be used to facilitate PBR thermal regulation regardless of season. All these aspects could contribute positively to the energetic balance of the process over a year of exploitation.

2.3. Achieving maximal biomass productivity: the major role of light supply

The growth of photosynthetic microorganisms is dependent on various parameters. Culture conditions (pH and temperature) can be kept optimal by appropriate regulation, although at large scale and in external solar conditions this can prove very difficult (as for regulation of culture temperature). Chemical nutrients such as dissolved inorganic carbon and mineral nutrients can be supplied while avoiding limiting or toxic concentrations. If all parameters are kept at their optimal value and nutrients are supplied in adequate quantities, light-limited conditions where light alone limits growth will be achieved. By definition, this will allow maximal biomass performance which will be fixed by the collected light and its use by the culture [22,23].

As recently discussed and clarified elsewhere, the light-limited regime is not sufficient to obtain maximal biomass productivities, which also hinge on controlling radiative transfer conditions inside the culture [6,24,25]. If biomass concentration is too low, some of the light is transmitted through the culture. Conversely, if biomass concentration is too high, a dark zone appears deep in the culture. For eukaryotic cells like microalgae that demonstrate respiration, a dark zone in the culture volume where respiration is predominant will result in a loss of productivity due to respiratory activity. Maximal productivity will then require the exact condition of full absorption of all light received but without a dark zone in the culture volume. This is the so-called luminostat regime, extensively described elsewhere [23,25]. As a result, unlike processes based only on surface conversion (e.g. photovoltaic panels), optimizing the amount of light collected on the microalgal cultivation system surface is still not sufficient. As light conversion by photosynthetic microorganisms occurs within the culture bulk, transfer of the collected light flux inside the bulk has to be factored in.

In continuous mode, light attenuation conditions can be controlled by adjusting biomass concentration in the cultivation system, which can be done by modifying the residence time τ_p applied to the system (or dilution rate $D = 1/\tau_p$). In practice, maintaining optimal light attenuation conditions is no easy task, especially in the case of solar production which adds a degree of complexity to the optimization and control of the cultivation system compared to artificial illumination. The process is fully dynamic and driven by an uncontrolled input, i.e. solar incident flux.

All these aspects recently prompted the development of a generic model to represent light-limited growth in solar PBRs [11,26]. This model could be associated with a solar database to predict surface biomass productivity as a function of system location or its ability to intercept solar radiation (which is influenced by factors such as system inclination, geometry, orientation or season). As shown next, this model forms a good basis to predict performances of building-integrated vertical PBRs.

2.4. Theoretical considerations

2.4.1. Modelling solar cultivation systems

Recent research has brought a model for simulating PBR operated in solar conditions [10,11,23,27]. The main features are given in Appendix A, and the interested reader can refer to the relevant literature. The model is able to predict biomass growth represented by time-course of biomass concentration as a function of light collected by the system.

Irradiation conditions were determined using Meteonorm software (www.meteonorm.com) for the Nantes location and for the various cases investigated here, i.e. horizontal ($\theta = 0°$), inclined at optimal angle for France (45°), and vertical inclination (90°). The model was applied on the green microalgae *C. vulgaris* with the growth model borrowed from Takache et al. [28] and reviewed by Soulies [29]. The depth of the facade PBR was fixed to $L_z = 0.05$ m, and all facade PBRs were south-facing.

2.4.2. CO_2 biofixation

The kinetic model predicting biomass growth was completed with the stoichiometric equation of photosynthetic growth of *C. vulgaris* [30]:

$$HCO_3^- + 0.495H_2O + 0.159NH_4^+ + 0.006SO_4^{2-} + 0.007PO_4^{3-} \rightarrow CH_{1.750}O_{0.413}N_{0.159}S_{0.006}P_{0.007} + 1.129O_2 + 0.874OH^- \quad (1)$$

This equation shows phosphate (P source) and nitrate (N source) demands. These minerals can be found in liquid effluents of a given building. With appropriate coupling, a partial depollution of building effluent can thus be set. But this equation emphasizes that the most important biological demand is in the need of CO_2 supply during photosynthetic growth, which is around 1.4–1.8 kg of CO_2 fixed per kg of dry microalgal biomass. Availability of a CO_2 source close to the microalgal production unit thus appears of interest. CO_2 biofixation was deduced from the stoichiometric equation combined with biomass production predictions to estimate the relevant potential of facade PBRs.

2.4.3. Energetic analysis

As PBR integration into building facades is expected to decrease energy requirements, we led an energetic analysis of the system. This analysis was restricted to the energy requirement for mixing and thermal regulation of microalgal cultures as the two main drivers of energy consumption [4,31–33].

Thermal regulation requirement should ideally be determined from a complete thermal balance of the cultivation system so as to predict temperature time-course as a function of operating conditions, including energy used for either cooling or heating the microalgal culture. This was proposed in the case of a solar PBR (single production unit) by Goetz et al. [19], but the approach implies a detailed description of the process and its geometry. In addition, a thermal regulation strategy should be related to the impact of temperature on growth (for example, no thermal regulation could be assumed, as it is usually the case in open systems such as raceway, but this will could be then highly detrimental to microalgae growth). At this preliminary stage of the study, all these informations being impossible available (PBR geometry, temperature time-course prediction, and relation to microalgae growth), the analysis of energy requirements was thus conducted at macro-scale.

As shown in Goetz et al. [19], the infrared part mostly contributes to water and then culture heating, while the visible part which is absorbed by cells for photosynthetic conversion results in around 95% in heat (the counterpart of the thermodynamic efficiency of photosynthetic conversion, which is around 5%). As a result, as a first approximation, a microalgal culture can be considered as a black body. This assumption obviously greatly simplifies the determination of heat flux absorbed by the system, which is then roughly equal to irradiation collected by the PBR. Calculating energy requirements for thermal regulation entails considering thermal exchanges with the surroundings. This part greatly depends on PBR geometry, operating conditions (i.e. culture temperature to maintain), and immediate-environmental conditions such as wind, ambient temperature or rain. At this stage of our study, all those exchanges were summarized as a thermal exchange yield, where 0% corresponds to an adiabatic PBR (i.e. no exchange with the surrounding) and 100% to a complete regulation of culture temperature by only exchanging with the surroundings (i.e. the process does not consume energy for its thermal regulation). As an example of realistic values, Goetz et al. [19] showed that optimized PBR design and thermal control made it possible to cut energy requirement for thermal regulation down to 0.5% of the solar energy collected (i.e. thermal exchange yield of 99.5%). This was obtained by optimizing exchange with ambient air, by allowing temperature variation up to 35 °C and by using glasses filtering the infrared part of the solar spectrum. Without optimization, energy requirement for thermal regulation was found 10-fold higher.

Energy for mixing can also contribute significantly to the total energy need of the cultivation system, and again is highly dependent on the process, its design and operating conditions. In a general manner, mixing energy is related to culture volume [4,31]. For mechanical mixing devices such as paddle wheels used in raceway systems, this energy is estimated at around 0.1–0.3 kW h m^{-3}. For aeration, as commonly used in PBRs (i.e. air-lift systems, as in facade PBRs), mixing energy is found to be higher, in the range 0.35–0.5 kW h m^{-3}. These values were used in our energetic analysis (i.e. 0.1 kW h m^{-3} for raceway and 0.35 kW h m^{-3} for PBR).

3. Results and discussion

3.1. Effect of vertical inclination on intercepted light for a south-facing system

Table 1 and Fig. 2 show the effect of PBR inclination in light intercepted. For a location in France (47°12N, 01°33W), light intercepted by a vertically-inclined PBR is around 1000 kW h m^{-2} (corresponding to an averaged PFD value in the PAR range of around 220 μmole m^{-2} s^{-1}), which is lower than for horizontal (1220 kW h m^{-2}, −22%) and 45° inclined (1440 kW h m^{-2}, −44%) systems, where a 45° inclination angle corresponds roughly to the inclination maximizing the yearly amount of light energy intercepted for a fixed system in France. A 45° inclination also offers a better orientation towards the sun, as represented by yearly-averaged values of incident angle θ cosine (yearly-averaged values of $\cos(\theta)$ are 0.64 and 0.42 for vertical and 45° inclinations, respectively).

Yearly evolution of Fig. 2 shows that vertical installation leads to very specific irradiation conditions, especially in summer due to the higher altitude angle of the sun that results in a big decrease in light collected during this period compared to any other inclination angles. As summer also corresponds to the year period with higher irradiation values, this explains the significant difference thus obtained in yearly-round light collected. For a standalone PBR, vertical inclination emerges as the less favourable case for locations like France (especially for summer production). However, for facade PBRs, vertical installation remains a major integration constraint that cannot reasonably be avoided, as practically all building facades are vertically-inclined.

3.2. Prediction of expected biomass productivity in facade-integrated PBRs

The biomass productivity of a given cultivation system is highly influenced by in-process light attenuation conditions. Maximum biomass productivity can easily be achieved in PBRs exposed to constant artificial illumination by setting the biomass concentra-

Table 1
Summary of yearly irradiation conditions and areal productivities obtained for the different cases investigated (see text for details).

Areal productivity (g m^{-2} day^{-1})	Light intercepted (kW h m^{-2})	Collimated distribution (%)	Light interception yield (%)	Average $\cos(\theta)$	τ_p^{opt} (days)	Expected maximal productivity in real running conditions (g m^{-2} day^{-1}/t_x ha^{-1} $year^{-1}$)
Nantes, $\beta = 0°$ (horizontal system)	1220	47	72	0.49	1.05	8.84/32.3
Nantes, $\beta = 45°$ (optimally inclined system)	1423	50	82	0.64	1.16	9.43/34.4
Nantes, $\beta = 90°$ (vertical system)	1003	45	63	0.42	1.30	7.68/28

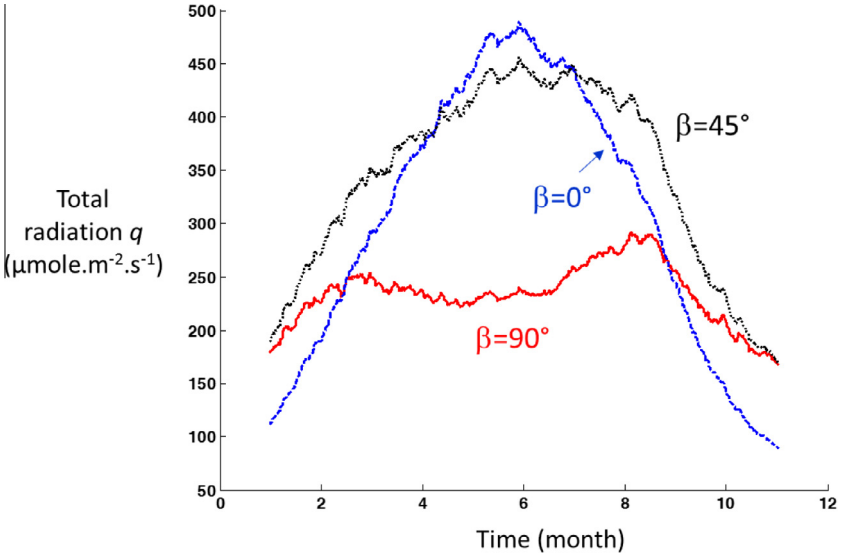

Fig. 2. Effect of PBR inclination on light intercepted (month-averaged values).

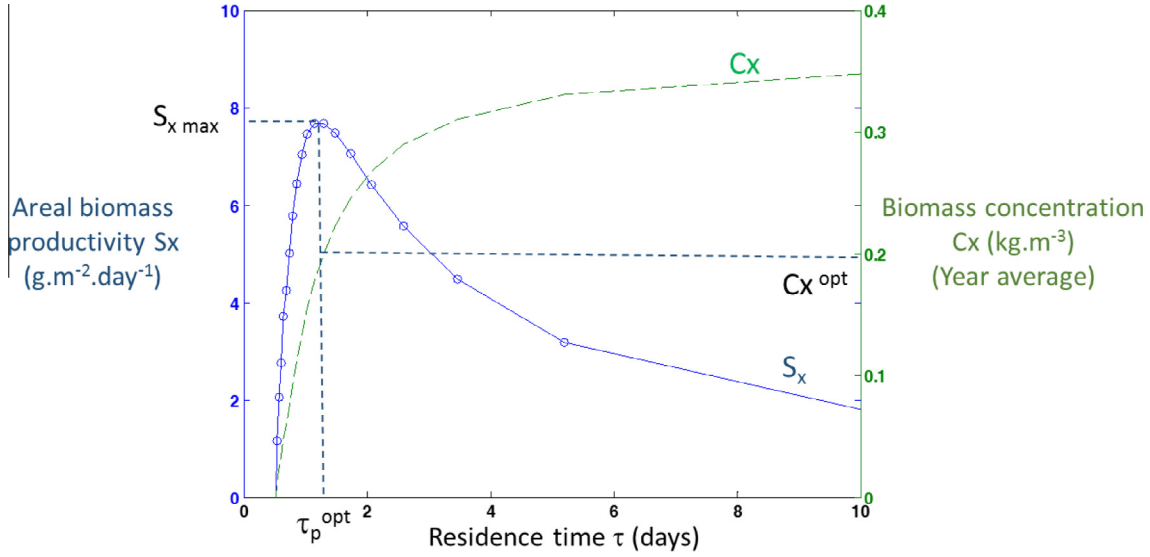

Fig. 3. Year-round biomass productivity as a function of residence time applied in the microalgal culture system.

tion corresponding to optimal light attenuation conditions, i.e. luminostat regime [22]. Under sunlight, biomass growth rate is insufficient to compensate for the rapid changes in sunlight intensity. Consequently, light attenuation conditions that are fixed by biomass concentration are never optimal. A compromise has to be found on the conditions thus applied, for example by defining a residence value that will maximize biomass productivity over the year of operation by acting on biomass concentration time-course and the related light attenuation conditions.

Fig. 3 reports yearly biomass productivity as a function of residence time for facade PBRs. An optimal value of $\tau_p = 1.3$ day is obtained, leading to a year-averaged biomass productivity of 7.68 g m^{-2} day^{-1}. The same calculation was applied to other cultivation systems, and results are given in Table 1. Compared to other cases, vertical inclination has a clear-cut effect. As expected, due to the decrease in light collected during summer, vertical PBRs offer 20% lower productivity than the optimal 45° inclination. For the facade PBR run on a whole-year basis, this results in an expected yearly production of around 25–30 tons biomass per ha with *C. vulgaris* (i.e. average daily productivity of 7.68 g m^{-2} day^{-1}), which corresponds to around 40–50 tons of CO_2 fixed per year per ha.

As already observed in Pruvost et al. [11] comparing microalgae versus cyanobacteria culture, the residence time values maximizing biomass productivities are found in a narrow range for microalgae. This is again confirmed in the present study, with maximal productivity obtained for a specific value of residence time $\tau_p^{opt} = 1.3$ day, leading to an operating biomass concentration in the range of $C_X = 0.2$ kg m^{-3} (year average value). If residence time is shorter than τ_p^{opt}, light transmission occurs, resulting in a loss of biomass productivity. Conversely, if residence time is longer, high biomass concentration and thus high absorption conditions are obtained, which creates dark volumes in the cultivation system. In the case of eukaryotic cells like microalgae, dark volumes promotes respiration activity which decreases the resulting biomass productivity.

Fig. 4 charts the year-long time-course of biomass productivity of *C. vulgaris* at optimal residence time. For a 45° inclination where

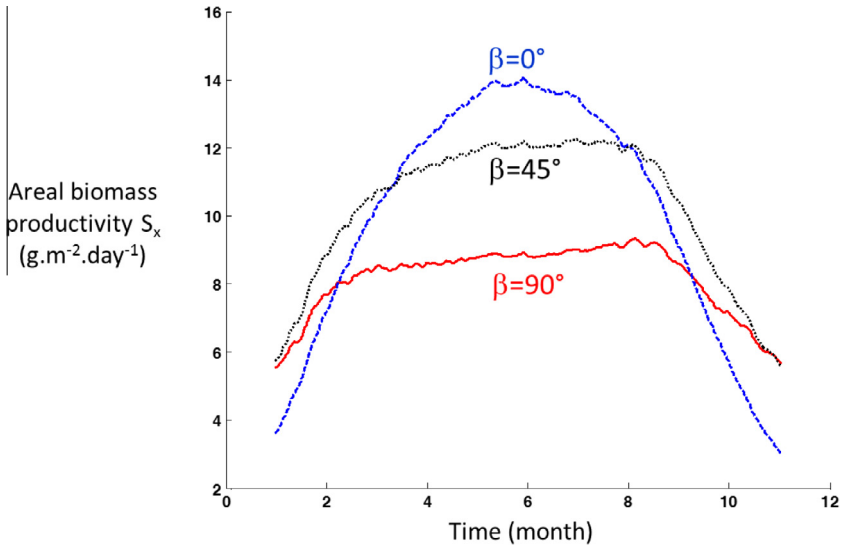

Fig. 4. 12-month time-course of the areal biomass productivity of a PBR located in Nantes, for various inclination angles.

highly different conditions are encountered between summer and winter, there is a 4-fold swing in biomass productivity, whereas the facade PBR demonstrates almost constant biomass productivity due to its vertical implementation. From a practical standpoint, this can facilitate system design and operation for a year-round production period, typically by making it easy to scale downstream processing units like harvesting capacity in centrifuges or other devices. In general, these systems are defined to fit production needs over year-round cycles. As vertical installation is expected to offer almost constant biomass productivity year-round, scaling of the system is simplified.

Looking at biomass productivity optimization, residence time can be defined on a whole-year basis (previous case) or for shorter periods, for example by setting different values for low (winter) and high (summer) irradiation conditions. Modelling proves useful here as it enables optimal value to be calculated for any set of irradiation conditions. The time-course of optimal residence time value can then be easily determined over the year of operation. The model does this by calculating for each irradiation value (one per hour in our case) the biomass concentration leading to luminostat regime and then the residence time to apply to obtain this concentration set-point [11]. Note however that maintaining luminostat regime over the year has no interest in practice as it cannot be applied in actual operating conditions due to the disconnect between the dynamics of irradiation conditions (below 1 h) and biomass concentration changes (on timescales of several days). The luminostat assumption thus corresponds to a theoretical functional limit that is unachievable in real-world conditions. Note too that by definition, this also gives the threshold capping maximum biomass productivity (see Pruvost et al. [10]).

The ideal time-course of optimal residence values along the year is given in Fig. 5. There is a relatively small degree of variation along the year (i.e. values comprised between 1 and 1.8 day). Applying this ideal time-course of residence time over the year leads to a year-averaged biomass productivity of 9.6 g m^{-2} day^{-1} (35 t ha^{-1} year^{-1}). Surprisingly, this figure is not so far from the value achieved when applying a constant residence time value all year long (productivity of 7.68 g m^{-2} day^{-1}, 28 t ha^{-1} year^{-1}). This shows that there is little utility in time-optimizing residence time over the year (i.e. less than 20% increase), which again is fully explained by the fact that vertical inclination leads to less variation in irradiation conditions. Applying constant operating parameters (like residence time) is sufficient to achieve good process efficiency.

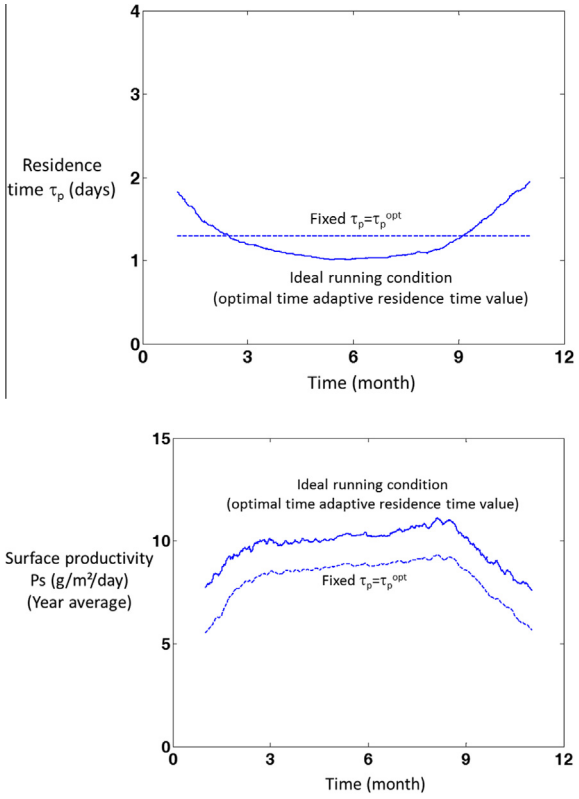

Fig. 5. Prediction of ideal values of residence time (solid line) for optimal light attenuations in the PBR (luminostat regime) and comparison to the predicted fixed value maximizing biomass productivity on a whole-year basis (dashed line). Figures (a) and (b) give time evolution of residence time τ and biomass productivity respectively.

3.3. Analysis of light attenuation conditions encountered over the year in a facade PBR

Variations in incident irradiation mean that a wide range of light attenuation conditions can be encountered inside the culture volume during the course of a day. This can affect process stability as described in Pruvost et al. [11]. For example, promoting a short residence time to reduce the extent of dark zones leads to low biomass concentrations. It also reduces light attenuation and may

even impair process stability for periods where oversaturating light is encountered, such as at noon in summer. A practical advice consists of relying on large biomass concentration to promote light attenuation. For example, Hindersin et al. [15] recommended a minimum biomass concentration value for a given incident PFD on a solar PBR with sun-tracking capabilities to maintain sufficient light attenuation. However, this approach results in a decrease in biomass productivity, particularly for species with large respiration activity under illumination, as previously discussed. Again, a compromise has to be found between process productivity and stability and robustness.

Similarly to our previous work [11], we considered light transmission through the PBR as a sign of insufficient PFD attenuation, as complete light extinction in the culture is known to reduce photoinhibition effects and culture drift [9,12,34]. Based on simulations of process operation, we calculated then the number of hours during which light transmission through the PBR occurs over a year of operation for vertical and horizontal inclinations. Results are given in Fig. 6a which gives the fraction of time when light transmission is non-zero as a function of residence time imposed on the culture system. Obviously this criterion can only be considered as a first estimate of light attenuation regimes encountered in the PBR volume which could impaired culture growth, as the photosynthetic apparatus is also sensitive to the intensify of light energy absorption. We added then in this study the calculation of the specific rate of light energy absorption, noted $\mathcal{A}$. As already discussed in Kandilian et al. [35], this value is indeed useful as it represents the rate of light energy absorbed by the growing biomass. As for light transmission, results were expressed in terms of the number of hours when oversaturating rate of light energy absorption is encountered over a year of operation (Fig. 6b). Oversaturating rate was here defined by setting a value of $\mathcal{A}$ equal to 100 $\text{mole}_{h\nu}$ per kg of biomass and hour. This value was set arbitrarily and its exact determination should request further investigation. It must however be noticed that this value seems in line with Pruvost et al. [36], where optimal growth conditions were estimated in the range of 40 $\text{mole}_{h\nu}$ per kg of biomass and hour.

Fig. 6a illustrates that number of hours when light transmission occurs is strongly influenced by residence time due to its direct dependence on biomass concentration. For example, a long residence time results in large biomass concentration and strong PFD attenuation. Comparing vertical against horizontal inclinations,

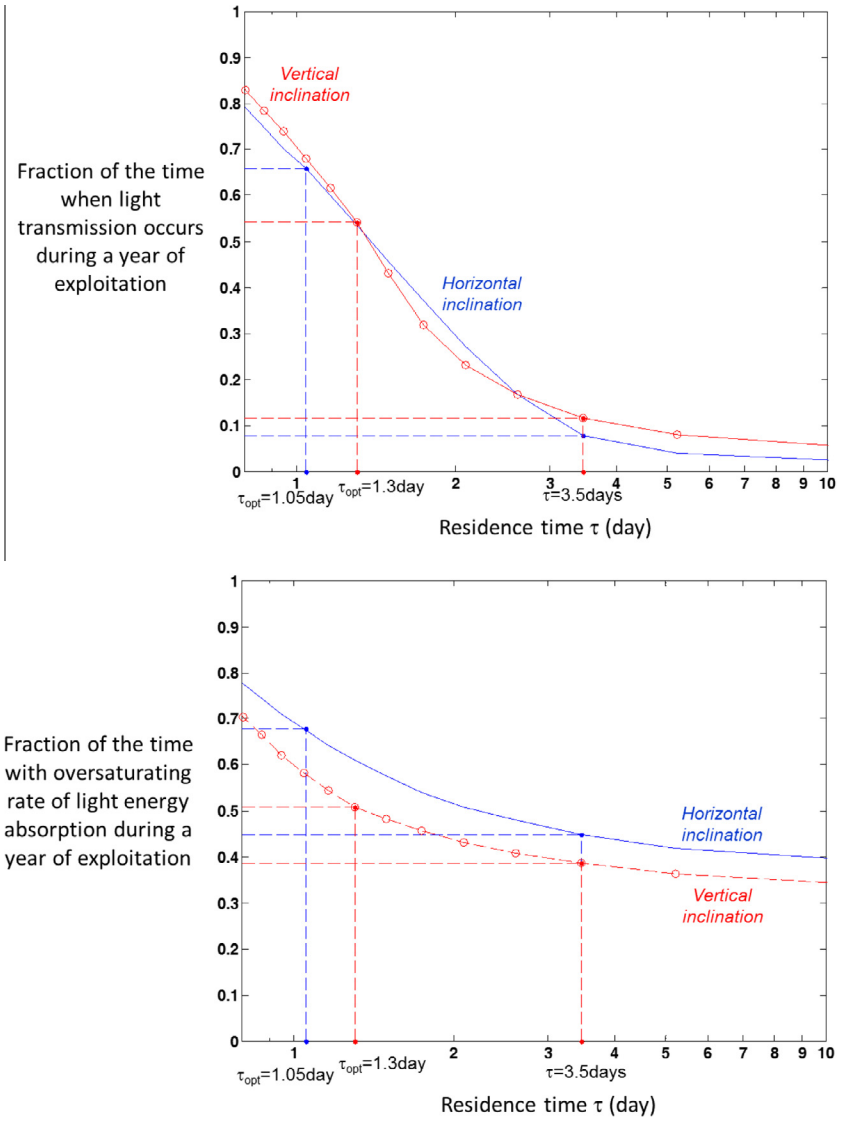

Fig. 6. Distribution of the number of light-transmissive (a) and light-oversaturating (b) hours per year and as a function of residence time applied in the cultivation system, for vertical and horizontal inclination angles. Values are normalized to total number of light hours in the year, i.e. 4355 h for the Nantes location.

the lower year-round variation in irradiation due to vertical inclination is again found to influence the light attenuation conditions encountered in the PBR. When the system is operated at optimal residence time, the light transmission regime prevails 55% of the time when the cultivation system is illuminated (*vs* 65% for a horizontal system). This relatively large fraction would certainly generate a significant risk of photoinhibition and culture drift, and potentially process instability and loss of efficiency. Indeed, as shown in Fig.6b, this corresponds to more than 50% of the time (around 70% for a horizontal system) when culture received oversaturating rates of light energy absorption $\mathcal{A} > 100\ mole_{hv}\ kg^{-1}\ h^{-1}$).

Those results are fully explained by the optimization procedure which maximizes biomass productivity, thus tending to limit periods with high light absorption conditions and consequently promoting light transmission regimes and then culture periods subjected to receive oversaturating light. This risk can be reduced by increasing the residence time to obtain a larger biomass concentration. For example, applying a residence time of 3.5 days (in line with common practice) results in a loss of productivity (about 40%, i.e. 4.5 g m^{-2} day^{-1}) but also in a big drop in light transmission regimes and periods of oversaturating rates of light energy absorption, with less than 12% and 40% of the lightened hours of the year respectively. A horizontal system reproduces the similar effect. It must be noticed that, as vertical inclination collects less light in the summer period, the main effect is in the rates of light energy absorption. Horizontal inclination is indeed found to present a longer operating time with oversaturating rates of light energy absorption, with values achieved systematically higher than for vertical implantation (Fig. 6a). This can be expected to make production more robust in vertical facade-integrated PBRs than other configurations.

3.4. Facade-integrated PBRs vs other microalgal culture systems for biomass production

The predicted biomass productivities from the previous section were used to compare facade PBRs to other common culture systems. The comparator retained was an arbitrary production goal of one ton of biomass per year. In addition to the horizontal PBR and 45°-inclined systems presented in the previous section, the widely-used raceway technology was also considered. As an open system, the raceway technology is expected to yield lower productivity, mainly due to its lower controllability in culture conditions and possible growth limitation by carbon supply.

Values of productivities and energy requirements for raceway technology were obtained from literature and adjusted based on the experience of AlphaBiotech Ltd (AlgoSource group), a industrial microalgae producer using raceways in the Nantes region (Asserac, France). A productivity of 5.5 g m^{-2} day^{-1} (20 t ha^{-1} $year^{-1}$) was then retained (9.5 g m^{-2} day^{-1} or 35 t ha^{-1} $year^{-1}$ for the horizontal configuration). The raceway was mixed by paddlewheel, with an energy requirement for mixing estimated at 0.1 kW h m^{-3}. Energy of thermal regulation was set to 150 kW h m^{-2}, which is lower than in closed systems (which usually work in the range 200–500 kW h m^{-2}) as open systems are less sensitive to overheating due to their higher volume (thermal inertia), natural exchange with surrounding air, and water evaporation. This value of 150 kW h m^{-2} was obtained for a thermal regulation maintaining culture temperature near optimal value for *C. vulgaris* (25 °C). This is a yearly averaged value which was calculated for Nantes location (France).

3.4.1. Surface, volume and energy requirements

Fig. 7a and b shows the surface and volume required to produce 1 ton of biomass per year. For a given biomass production objec-

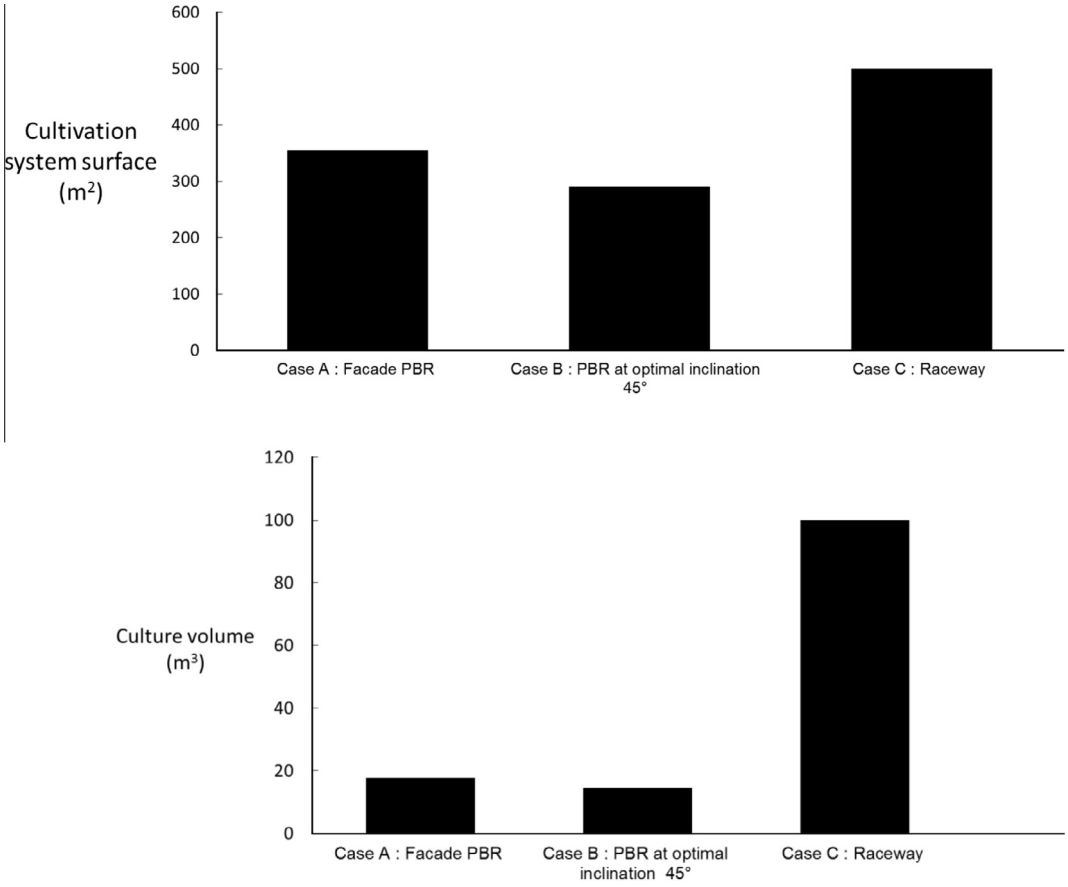

Fig. 7. Surface (a) and volume (b) required to produce one ton of biomass per year.

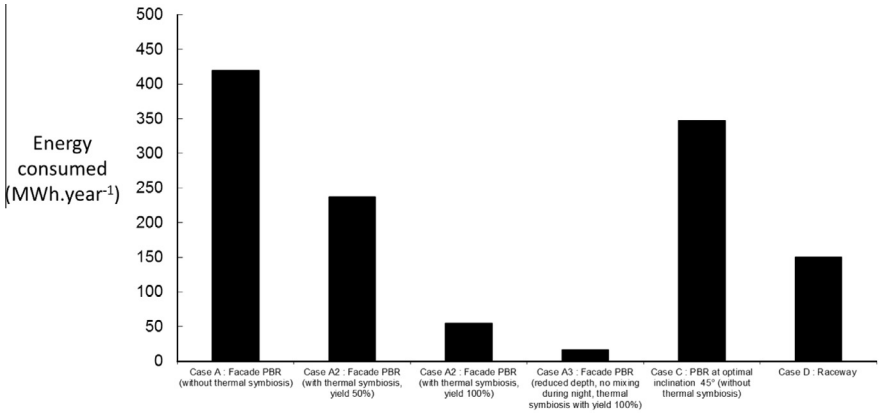

Fig. 8. Energy required to produce one ton of biomass per year.

tive, facade PBR require 30% less illuminated surface than raceways and more than 5-fold lower culture volumes. A 45°-inclined PBR has the lowest surface and volume requirements for a given biomass production target due to its better inclination for light conditions found in France (−20% compared to facade PBR). Note that in this case surfaces are expressed in terms of illumination surface and not on a ground basis. It is obvious that vertical installation has a very small footprint compared to other systems.

Fig. 8 gives the energy requirements for the production goal. Various cases were simulated to investigate the interest of inducing thermal symbiosis with the building to decrease energy needs for thermal regulation of the culture volume. This was represented by thermal exchange yields ranging from 0% (no exchange) to 100% (full thermal regulation provided by optimal symbiosis with the building). The results show that thermal regulation requirements are a critical factor in total energy demand, accounting for around 80–90% of total energy consumption in standalone PBR technologies (45° case, same trend for facade PBRs without thermal interaction with the building). For raceway systems, energy requirements also turned out high, due to the significant volume needed to achieve the production target. Energy for thermal regulation was found to be around 50% of total energy, the remaining part being explained by mixing energy. Regarding facade PBRs, without inducing thermal symbiosis with the building (full thermal regulation requirement), energy demand for the facade PBR was of the same order of magnitude as with other PBRs. The lower irradiation thus intercepted tends to reduce need for thermal regulation, but a higher production surface was needed to achieve the production target of 1 ton biomass per year.

3.4.2. Influence of thermal symbiosis

Increasing thermal exchange yield significantly influenced the results. When assuming thermal exchange yields of 50% and 100% (full thermal symbiosis), energy requirements were around 2–8-fold lower than with a standard PBR. This is fully explained by the high impact of thermal regulation on total energy needs in closed solar PBRs. Because of our black body assumption for the thermal behaviour of PBR, the yearly energy requirement per unit of PBR surface for thermal regulation only is, without symbiosis, in the range of 1000 kW h m^{-2}. This can be considered high, regarding values usually reported in literature (200–500 kW h m^{-2}) which are explained by the fact that PBR generally present thermal exchange with their surroundings. So, a thermal exchange yields of 50% or below could be reached in practice with an adequate integration of the facade PBR in its building support. As shown by our results, this will significantly impact the process.

A final case (Case A3, Fig. 8) was simulated in order to investigate whether energy requirements could be further reduced. As energy was found to be highly related to culture volume, a thin facade PBR (0.02 m) was simulated. Mixing was also limited to day periods. As expected, this led to a lower energy consumption, with an additional decrease of 70% in energy consumed (total energy consumption of 17 MW h/year). However, this configuration was still outperformed by a thermal symbiosis set-up which enabled a decrease of more than 300 MW h/year.

Finally, as microalgal culture is being touted as a potential source of biofuel [37,38], we made a first estimate of the energy balance for such application. Note that downstream processing which would require additional energy, was not considered. By assuming an energy content of 5.56 kW h per kg of microalgal biomass (20 MJ kg^{-1}), the facade PBR can be expected to yield a maximum of 5.56 MW h per year from biomass production. Even in the best-case scenario (Case A3 with full thermal symbiosis, thin PBR and without mixing during the night), a positive energy balance was still not obtained (minimum energy requirement of 17 MW h per year). Facade-integrated PBRs do not therefore appear suitable for a sustainable biofuel production with a positive energy balance, whatever the case and optimization conditions.

4. Conclusions

A theoretical study was conducted to investigate the interest of building facade-integrated PBR technologies. A vertical installation was found to induce specific operating conditions, notably including a significant decrease in light collected in the summer period due to the higher sunlight path in France. This drawback, which facade-based integration cannot reasonably avoid, was however found to lead to the most constant year-round operating conditions, which does bring the benefit of greatly facilitated process management.

A comparison to standalone microalgal culture units showed that CO_2 feeding and thermal regulation were two key aspects that can be optimized to significantly decrease operational costs. This was especially the case for thermal symbiosis, which emerged as a critical factor as it could significantly decrease the energy demands for microalgal culture compared to solar standalone units where overheating is a major issue.

These theoretical studies are currently being completed by an extensive set of indoor and outdoor characterization trials, including investigations into the thermal behaviour of building facade-integrated PBRs and the hydrodynamics optimization of the culture unit, with the aim of defining an optimized PBR geometry and related operating procedure adapted specifically to on-building integration.

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The process described in the work is patented (X-TU, patent no. EP2367926; X-TU and CNRS, University of Nantes, patent no. FR2012/051704).

This project was also a part of R&D activities conducted on AlgoSolis R&D facility (www.algosolis.com).

Appendix A

In the specific case of outdoor biomass production, numerous features can impair process production, such as mineral or carbon limitation, non-ideal temperature or pH control, non-optimized harvesting strategies, and contamination. Our model is voluntarily restricted to the case of the so-called light-limited regime, where only light limits growth. This makes process productivity solely dependent on light capture and use in the culture volume. As light is the only limiting factor, the maximal performances of a given PBR can be calculated at a given location and for a given species. Based on this assumption, we had already proposed a model for solar PBR which can be directly applied in this study. Please note that this model is the result of numerous years of development, and was proved efficient in several cases like artificial and sunlight conditions [10,11,24,27,28], scaling and optimization of PBR of various shapes [16,39], and biomass optimization of different microalga and cyanobacteria strains [22,40–45]. As it is already described elsewhere [10,11,23,27], only main features are reported here.

The model applies to cultivation systems presenting a flat illuminated surface (ponds, rectangular PBR, etc.). The one-dimensional and azimuth-independence assumptions can then be used to describe the irradiance field in the culture bulk, making it possible to apply the two-flux radiative model with its corresponding analytical solutions [46]. Application to the solar case implies taking into account non-normal incidence (thus introducing the incident angle θ) with a separate treatment of the direct and diffuse components of the radiation due to their difference in angular distribution on the PBR surface [27]. The total hemispherical incident light flux density (or PFD, see next section) q is divided into the direct $q_{//}$ and diffuse $q_{\cap}$ components ($q = q_{//} + q_{\cap}$). Total irradiance (representing the amount of light received in the culture bulk) is given by summing the resulting contribution of collimated and diffuse radiation:

$$G(z) = G_{\mathrm{col}}(z) + G_{\mathrm{dif}}(z) \tag{A1}$$

where G_{col} is the irradiance field for collimated radiation, as given by:

$$\frac{G_{\mathrm{col}}(z)}{q_{//}} = \frac{2}{\cos\theta}\frac{(1+\alpha)\exp[-\delta_{\mathrm{col}}(z-L)] - (1-\alpha)\exp[\delta_{\mathrm{col}}(z-L)]}{(1+\alpha)^2\exp[\delta_{\mathrm{col}}L] - (1-\alpha)^2\exp[-\delta_{\mathrm{col}}L]} \tag{A2}$$

and G_{dif} the irradiance field for diffuse radiation:

$$\frac{G_{\mathrm{dif}}(z)}{q_{\cap}} = 4\frac{(1+\alpha)\exp[-\delta_{\mathrm{dif}}(z-L)] - (1-\alpha)\exp[\delta_{\mathrm{dif}}(z-L)]}{(1+\alpha)^2\exp[\delta_{\mathrm{dif}}L] - (1-\alpha)^2\exp[-\delta_{\mathrm{dif}}L]} \tag{A3}$$

In these equations, $\alpha = \sqrt{\frac{E_a}{(E_a+2bE_s)}}$ is the linear scattering modulus, and $\delta_{\mathrm{col}} = \frac{\alpha C_X}{\cos\theta}(E_a + 2bE_s)$ and $\delta_{\mathrm{dif}} = 2\alpha C_X(E_a + 2bE_s)$ are the two-flux collimated and diffuse extinction coefficients, respectively. θ is the incident angle (defined from the outward normal of the PBR surface), E_a is mass absorption coefficient and E_s mass scattering coefficient for the cultivated photosynthetic microorganism, b the back-scattered fraction, and C_X the biomass concentration in the culture medium. Here, radiative properties (E_a, E_s, b) were spectrally averaged over the PAR. Values are given in Table A1.

Determining the irradiance field makes it possible to determine the corresponding local photosynthetic growth rate in the culture volume. In light-limited conditions, this rate is linked only to available light as represented by the irradiance field (Eq. (A1)). We recently proposed a growth kinetic relation giving local photosynthetic specific oxygen evolution rate for microalgae [11,29]:

$$\begin{aligned} J_{O_2} &= \left[\rho\bar{\phi}'_{O_2}\mathcal{A} - \frac{J_{\mathrm{NADH_2}}}{\upsilon_{\mathrm{NADH_2-O_2}}}\times\frac{K_r}{K_r+G}\right] \\ &= \left[\rho_M\frac{K}{K+G}\bar{\phi}'_{O_2}\mathcal{A} - \frac{J_{\mathrm{NADH_2}}}{\upsilon_{\mathrm{NADH_2-O_2}}}\times\frac{K_r}{K_r+G}\right] \end{aligned} \tag{A4}$$

where ρ is energy yield for photon conversion and ρ_M its maximum value, $\bar{\phi}'$ is the mole O_2 quantum yield for the Z scheme of photosynthesis, K the half-saturation constant for photosynthesis, $J_{\mathrm{NADH_2}}$ the specific rate of cofactor regeneration on the respiratory chain, linked to oxygen consumption by the stoichiometric coefficient $\upsilon_{\mathrm{NADH_2}} - O_2$ (the stoichiometric coefficient of cofactor regeneration on the respiratory chain), and K_r is a saturation constant describing the inhibition of respiration in light.

The mass volumetric biomass growth rate is simply given from Eq. (A5) by the mole-to-mass conversion:

$$r_X = \frac{J_{O_2}C_X M_X}{\upsilon_{O_2-X}} \tag{A5}$$

with M_X the C-molar mass for the biomass and υ_{O_2-X} the stoichiometric coefficient of the oxygen production.

Eqs. (A4) and (A5) are valid insofar as the culture is illuminated (i.e. during daytime). At night, long dark periods of several hours trigger a switch to respiratory metabolism with a resulting biomass catabolism [47,48]. This can be taken into account by introducing a negative biomass decay rate of production for night periods. Same value as considered for *C. reinhardtii* in Pruvost et al. [11] was here applied, with $\langle r_X\rangle/C_X = \mu = 0.004\ \mathrm{h^{-1}}$, for *C. reinhardtii* [49,50].

Finally, the determination of the mean growth rate allows the mass balance equation, here for biomass, to be solved [6,44,51]. For a continuous system assuming perfectly mixed conditions, this equation is:

$$\frac{dC_X}{dt} = \langle r_X\rangle - \frac{C_X}{\tau_p} \tag{A6}$$

where $\langle r_X\rangle$ is the mean biomass volumetric growth rate in the system, and τ_p the residence time resulting from the liquid flow rate of the feed (fresh medium).

The mean biomass volumetric growth rate in Eq. (A6) is obtained by averaging the local formulation of the volumetric growth rate over the culture volume (Eq. (A5)). For a cultivation system with one-dimensional light attenuation, this consists in a simple integration along the depth of culture z (with L the total depth of the PBR):

$$\langle r_X\rangle = \frac{1}{L}\int_{z=0}^{z=L} r_X\,dz \tag{A7}$$

Table A1
Summary of the growth model parameters for *Chlorella vulgaris*.

Parameter	Value	Unit
ρ_M	0.8	–
J_{NADH_2}	1.8×10^{-3}	$mol_{NADH_2}\ kg_X^{-1}\ s^{-1}$
υ_{O_2-X}	1.13	–
$\bar{\phi}'$	1.1×10^{-7}	$mol_{O_2}\ \mu mol_{hv}^{-1}$
M_X	0.024	$kg_X\ C\text{-}\ mol^{-1}$
$\upsilon_{NADH_2-O_2}$	2	–
K_A	30,000	$\mu mol_{hv}\ kg^{-1}\ s^{-1}$
K_r	150	$\mu mol_{hv}\ kg^{-1}\ s^{-1}$
$\mathcal{A}$	1500	$\mu mol_{hv}\ kg^{-1}\ s^{-1}$
Ea	200	$m^2\ kg^{-1}$
Es	2870	$m^2\ kg^{-1}$
b	0.002	–

The variable PFD in sunlight conditions means that the irradiance field inside the culture bulk and the resulting local and mean volumetric growth rates vary continuously, and hence steady-state cannot be assumed in Eq. (A7). This implies solving the transient form of the mass balance equation (using for example the *ode23tb* routine in Matlab software).

Finally, having determined the time-course of biomass concentration, we can now calculate the corresponding biomass productivity. Areal productivity P_S ($g\ m^{-2}\ day^{-1}$) will be used here as a useful variable to extrapolate to land area production, as given by:

$$P_S = \frac{C_X V_r}{\tau_p S_{light}} = \frac{C_X}{\tau_p a_{light}} \quad (A8)$$

with V_r and S_{light} the volume and illuminated surface of the PBR respectively.

All parameters used in the growth model are given in Table A1.

References

[1] C. Posten, C. Walter, Microalgal Biotechnology: Potential and Production, Walter de Gruyter & Co, 2012.
[2] A. Richmond, Handbook of Microalgal Culture: Biotechnology and Applied Phycology, Blackwell Sciences Ltd, Oxford, UK, 2004.
[3] A.P. Carvalho, L.A. Meireles, F.X. Malcata, Microalgal reactors: a review of enclosed system designs and performances, Biotechnol. Prog. 22 (2006) 1490–1506.
[4] F. Lehr, C. Posten, Closed photo-bioreactors as tools for biofuel production, Curr. Opin. Biotechnol. 20 (2009) 280–285.
[5] M. Morweiser, O. Kruse, B. Hankamer, C. Posten, Developments and perspectives of photobioreactors for biofuel production, Appl. Microbiol. Biotechnol. 87 (2010) 1291–1301.
[6] J. Pruvost, Cultivation of algae in photobioreactors for biodiesel production, in: A. Pandey, C. Larroche, S.C. Ricke, C.G, Dussap (Eds.), Biofuels: Alternative Feedstocks and Conversion Processes, E.I. USA, 2011, pp. 439–464.
[7] C.U. Ugwu, H. Aoyagia, H. Uchiyamaa, Photobioreactors for mass cultivation of algae, Bioresour. Technol. 99 (2008) 4021–4028.
[8] O. Pulz, Photobioreactors: production systems for phototrophic microorganisms, Appl. Microbiol. Biotechnol. 57 (2001) 287–293.
[9] M.E. Grima, A.F.G. Fernandez, G.F. Camacho, Y. Chisti, Photobioreactors: light regime, mass transfer, and scaleup, J. Biotechnol. 70 (1999) 231–247.
[10] J. Pruvost, J.F. Cornet, V. Goetz, J. Legrand, Theoretical investigation of biomass productivities achievable in solar rectangular photobioreactors for the cyanobacterium *Arthrospira platensis*, Biotechnol. Prog. 28 (2012) 699–714.
[11] J. Pruvost, J.F. Cornet, F. Le Borgne, V. Goetz, J. Legrand, Theoretical investigation of microalgae culture in the light changing conditions of solar photobioreactor production and comparison with cyanobacteria, Algal Res. 10 (2015) 87–99.
[12] A.P. Carvalho, S.O. Silva, J.M. Baptista, F.X. Malcata, Light requirements in microalgal photobioreactors: an overview of biophotonic aspects, Appl. Microbiol. Biotechnol. 89 (2011) 1275–1288.
[13] G. Torzillo, P. Accolla, E. Pinzani, J. Masojidek, In situ monitoring of chlorophyll fluorescence to assess the synergistic effect of low temperature and high irradiance stresses inSpirulina cultures grown outdoors in photobioreactors, J. Appl. Phycol. 8 (1996).
[14] C. Wilhelm, D. Selmar, Energy dissipation is an essential mechanism to sustain the viability of plants: the physiological limits of improved photosynthesis, J. Plant Physiol. 168 (2011) 79–87.
[15] S. Hindersin, M. Leupold, M. Kerner, D. Hanelt, Irradiance optimization of outdoor microalgal cultures using solar tracked photobioreactors, Bioprocess Biosyst. Eng. 36 (2013) 345–355.
[16] J.-F. Cornet, Calculation of optimal design and ideal productivities of volumetrically lightened photobioreactors using the constructal approach, Chem. Eng. Sci. 65 (2010) 985–998.
[17] S. Hindersin, Photosynthetic efficiency of microalgae and optimization of biomass production in photobioreactors, in: U. Hamburg (Ed.), 2013.
[18] S. Hindersin, M. Leupold, M. Kerner, D. Hanelt, Key parameters for outdoor biomass production of Scenedesmus obliquus in solar tracked photobioreactors, J. Appl. Phycol. (2014).
[19] V. Goetz, F. Le Borgne, J. Pruvost, G. Plantard, J. Legrand, A generic temperature model for solar photobioreactors, Chem. Eng. J. 175 (2011) 443–449.
[20] M.A. Borowitzka, Commercial production of microalgae: ponds, tanks, and fermenters, Prog. Ind. Microbiol. 35 (1999) 313–321.
[21] J.U. Grobbelaar, Factors governing algal growth in photobioreactors: the "open" versus "closed" debate, J. Appl. Phycol. 21 (2008) 489–492.
[22] H. Takache, G. Christophe, J.F. Cornet, J. Pruvost, Experimental and theoretical assessment of maximum productivities for the microalgae Chlamydomonas reinhardtii in two different geometries of photobioreactors, Biotechnol. Prog. 26 (2010) 431–440.
[23] J. Pruvost, J.F. Cornet, Knowledge models for engineering and optimization of photobioreactors, in: C.P.a.C. Walter (Ed.), Microalgal Biotechnology, De Gruyter GmbH & Co. KG, 2012, pp. 181–224.
[24] J.F. Cornet, C.G. Dussap, A simple and reliable formula for assessment of maximum volumetric productivities in photobioreactors, Biotechnol. Prog. 25 (2009) 424–435.
[25] H. Takache, G. Christophe, J.F. Cornet, J. Pruvost, Experimental and theoretical assessment of maximum productivities for the micro-algae Chlamydomonas reinhardtii in two different geometries of photobioreactors, Biotechnol. Prog. 26 (2010) 431–440.
[26] E. Lee, J. Pruvost, X. He, R. Munipalli, L. Pilon, Design tool and guidelines for outdoor photobioreactors, Chem. Eng. Sci. 106 (2014) 18–29.
[27] J. Pruvost, J.F. Cornet, V. Goetz, J. Legrand, Modeling dynamic functioning of rectangular photobioreactors in solar conditions, AIChE J. 57 (2011) 1947–1960.
[28] H. Takache, J. Pruvost, J.F. Cornet, Kinetic modeling of the photosynthetic growth of Chlamydomonas reinhardtii in a photobioreactor, Biotechnol. Prog. 28 (2012) 681–692.
[29] A. Soulies, Contribution à l'étude hydrodynamique et à la modélisation des photobioréacteurs à haute productivité volumique, PhD Thesis, University of Nantes, 2014.
[30] F. Hadj-Romdhane, P. Jaouen, J. Pruvost, D. Grizeau, G. Van Vooren, P. Bourseau, Development and validation of a minimal growth medium for recycling *Chlorella vulgaris* culture, Bioresour. Technol. 123 (2012) 366–374.
[31] J.R. Benemann, W.J. Oswald, Systems and economics analysis of microalgae ponds for conversion of CO_2 to biomass, Technical Report, US DOE (1996).
[32] P.M. Slegers, M.B. Lösing, R.H. Wijffels, G. van Straten, A.J.B. van Boxtel, Scenario evaluation of open pond microalgae production, Algal Res. 2 (2013) 358–368.
[33] O. Jorquera, A. Kiperstok, E.A. Sales, M. Embirucu, M.L. Ghirardi, Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors, Bioresour. Technol. 101 (2010) 1406–1413.
[34] A. Richmond, Principles for attaining maximal microalgal productivity in photobioreactors: an overview, Hydrobiologia 512 (2004) 33–37.
[35] R. Kandilian, J. Pruvost, J. Legrand, L. Pilon, Influence of light absorption rate by Nannochloropsis oculata on triglyceride production during nitrogen starvation, Bioresour. Technol. 163 (2014) 308–319.
[36] J. Pruvost, J.F. Cornet, L. Pilon, Large scale production of algal biomass: photobioreactors, in: U. Springer (Ed.), Algae Biotechnology: Products and Processes, 2015, in press.
[37] Y. Li, M. Horsman, N. Wu, Q. Lan, N. Dubois-Calero, Biofuel from microalgae, Biotechnol. Prog. 24 (2008) 815–820.
[38] M.K. Weschler, W.J. Barr, W.F. Harper, A.E. Landis, Process energy comparison for the production and harvesting of algal biomass as a biofuel feedstock, Bioresour. Technol. 153 (2014) 108–115.
[39] K. Loubiere, J. Pruvost, F. Aloui, J. Legrand, Investigations in an external-loop airlift photobioreactor with annular light chambers and swirling flow, Chem. Eng. Res. Des. 89 (2011) 164–171.
[40] J. Pruvost, G. Van Vooren, B. Le Gouic, A. Couzinet-Mossion, J. Legrand, Systematic investigation of biomass and lipid productivity by microalgae in photobioreactors for biodiesel application, Bioresour. Technol. 102 (2011) 150–158.
[41] J.F. Cornet, J. Albiol, Modeling photoheterotrophic growth kinetics of Rhodospirillum rubrum in rectangular photobioreactors, Biotechnol. Prog. 16 (2000) 199–207.
[42] J.F. Cornet, C.G. Dussap, P. Cluzel, G. Dubertret, A structured model for simulation of cultures of the cyanobacterium Spirulina platensis in photobioreactors. 2. Identification of kinetic parameters under light and mineral limitations, Biotechnol. Bioeng. 40 (1992) 826–834.
[43] J.F. Cornet, C.G. Dussap, J.B. Gros, Kinetics and energetics of photosynthetic micro-organisms in photobioreactors: application to Spirulina growth, Adv. Biochem. Eng. Biotechnol. 59 (1998) 155–224.
[44] J.F. Cornet, L. Favier, C.G. Dussap, Modeling stability of photoheterotrophic continuous cultures in photobioreactors, Biotechnol. Prog. 19 (2003) 1216–1227.

[45] B. Farges, C. Laroche, J.-F. Cornet, C.-G. Dussap, Spectral kinetic modeling and long-term behavior assessment of Arthrospira platensis growth in photobioreactor under red (620 nm) light illumination, Biotechnol. Prog. 25 (2009) 151–162.
[46] L. Pottier, J. Pruvost, J. Deremetz, J.F. Cornet, J. Legrand, C.G. Dussap, A fully predictive model for one-dimensional light attenuation by *Chlamydomonas reinhardtii* in a torus reactor, Biotechnol. Bioeng. 91 (2005) 569–582.
[47] J.C. Ogbonna, H. Tanaka, Night biomass loss and changes in biochemical composition of cells during light/dark cyclic culture of Chlorella pyrenoidosa, J. Ferment. Bioeng. 82 (1996) 558–564.
[48] F. Le Borgne, J. Pruvost, Investigation and modeling of biomass decay rate in the dark and its potential influence on net productivity of solar photobioreactors for microalga *Chlamydomonas reinhardtii* and cyanobacterium *Arthrospira platensis*, Bioresour. Technol. 138 (2013) 271–276.
[49] J.F. Cornet, Etude cinétique et énergétique d'un photobioréacteur. Etablissement d'un modèle structuré. Applications à un écosystème clos artificiel., PhD Thesis, Université Paris XI Orsay, 1992.
[50] F. Le Borgne, Développement d'un photobioréacteur solaire intensifié en vue de la production à grande échelle de biomasse microalgale, in, Université de Nantes, Saint-Nazaire, 2011.
[51] J. Pruvost, J.F. Cornet, J. Legrand, Hydrodynamics influence on light conversion in photobioreactors: an energetically consistent analysis, Chem. Eng. Sci. 63 (2008) 3679–3694.