

On Energy Balance and Production Costs in Tubular and Flat Panel Photobioreactors

Niels-Henrik Norsker¹, Maria J. Barbosa²,
Marian H. Vermuë³, and René H. Wijffels³

Reducing mixing in both flat panel and tubular photobioreactors can result in a positive net energy balance with state-of-the-art technology and Dutch weather conditions. In the tubular photobioreactor, the net energy balance becomes positive at velocities $< 0.3 \text{ ms}^{-1}$, at which point the biomass production cost is 3.2 €/kg dry weight. In flat panel reactors, this point is at an air supply rate $< 0.25 \text{ vol vol}^{-1} \text{ min}^{-1}$, at which the biomass production cost is 2.39 €/kg dry weight. To achieve these values in flat panel reactors, cheap low pressure blowers must be used, which limits the panel height to a maximum of 0.5 m, and in tubular reactors the tubes must be hydraulically smooth. For tubular reactors, it is important to prevent the formation of wall growth in order to keep the tubes hydraulically smooth. This paper shows how current production costs and energy requirement could be decreased.

1 Introduction

Electrical power is used for mechanical mixing in both open and closed photobioreactors and is necessary

- to keep the algae suspended,
- to provide sufficient mass transfer which denotes the exchange of oxygen and carbon dioxide,
- to obtain a certain level of light integration.

Light integration means shifting the algae between dark and light zones in the light path whereby the resulting productivity increases towards that of a homogeneously illuminated culture, illuminated by the time-averaged light intensity. Full light integration implies high frequency of flashing. For the microalga *Chlamydomonas reinhardtii*, for example, full light integration implies light flashes of only millisecond duration (Vejrazka et al. 2011), which in practical photobioreactors requires a high and energetically costly level of turbulence.

Optimizing a photobioreactor in terms of cost or energy is hence a complicated process requiring functional relationships between, on the one hand, oxygen, carbon dioxide and irradiation and, on the other, productivity. Furthermore, it should be kept in mind that these processes are overlaid by daily and seasonal cycles of light and temperature. Until these functional relationships have been developed, optimization remains a trial-and-error process. Some guidance can be obtained by identifying the energy-sensitive parameters in the two cultivation systems. The energy requirements for circulation in the tubular and flat panel reactors are normally given as the specific power supply in watt per m^3 (W m^{-3}) of reactor volume and is reasonably comparable since the volumetric productivity of the two systems is rather similar.

1.1 Power Requirements for Mixing in Photobioreactors

Many recent papers have assumed that a specific power supply in the range of 2,000–3,400 W m^{-3} is characteristic of tubular photobioreactors (Siererra et al. 2008; Lehr, Posten 2009; Posten 2009; Xu et al. 2009; Jorquera et al. 2010; Morweiser et al. 2010; Brentner et al. 2011; Gilbert et al. 2011; Hulatt, Thomas 2011; Pegallapati, Nirmalakhandan 2011; Singh, Olsen 2011), but even 6,000 W m^{-3} has been assumed to be typical (Brentner et al. 2011). These figures seem to originate from a single experimental study with a small, airlift-driven helical tubular photobioreactor (Hall et al. 2003), in which a power supply of 2,000–3,400 W m^{-3} was given along with a power efficiency of 1–2 %. This power calculation is probably not correct and the value is certainly not characteristic of tubular photobioreactors in general. For example, in a tubular photobioreactor with 6 cm tubes, a velocity of 1.0 m s^{-1} corresponds to a specific power supply of 170 W m^{-3} (Acién Fernández et al. 2001), and in a recent paper on a tubular pilot reactor, the actual specific circulation power was about 300 W m^{-3} at a fluid velocity of 0.9 m s^{-1} in 9 cm (d) tubing (Acién et al. 2012/in press). Burgess and Fernandez-Velasco (2008), using standard hydraulic estimates for smooth tubes at low Reynolds numbers, obtained much lower specific power requirements for circulation. Their calculation, however, did not

account for the friction caused by flow elements in the system such as bends, T-pieces and restrictions or for that due to biofilm-induced roughness.

As the power requirement for circulation is very dependent on culture velocity, minimizing velocity will reduce power consumption. But what is the minimum velocity? The velocity is needed partly to create sufficient turbulence for light integration and partly to avoid detrimental concentrations of dissolved oxygen in the tubes (to minimize growth inhibition caused by photorespiration). This inhibitory effect of oxygen can be reduced by establishing a maximum level of dissolved oxygen permitted in the medium. At subsaturating light intensities, *Neochloris oleoabundans*, for example, had nearly the same growth rate at dissolved oxygen saturation and at three times the saturation level, but at four times the saturation level the growth rates were reduced, although it was possible to reverse the reduction by operating at a high CO₂ partial pressure (Sousa et al. 2012). A velocity of 0.5 m s⁻¹ was sufficient to keep the oxygen level under 300 % saturation during a passage through a 100 m tube under high irradiation conditions (Ación Fernández et al. 2001). A velocity of 0.5 m s⁻¹ with *Neochloris* would thus be a safe, no-oxygen-effect velocity in that system, but the cost-optimized velocity is probably much lower.

With regard to flat panel reactors or bubble columns, the necessary specific aeration power supply can be calculated as the product of the superficial gas velocity, the gravity acceleration and the liquid density (Sierra et al. 2008). While the preferred value of 53 W m⁻³ emerging from that study has been cited frequently as typical for flat panel reactors, this value does not take the pressure drop over sparger holes or the energy efficiency in the production of compressed air into account and is therefore not a useful indication.

The superficial gas velocity is the most rational basis for discussing mixing in flat panels but the aeration rate is more relevant in relation to compressor economy (superficial gas velocity is equal to the aeration rate divided by the aerated cross-sectional area of the reactor). Very large differences in the aeration rate are employed in different reactor studies. For small flat plate reactors, an aeration rate of 1 liter of air per liter reactor volume per minute is commonly used (Sierra et al.

2008). Whereas this value may be unnecessarily large for mass transfer purposes alone, high aeration rates normally enhance growth. For example, in Zhang et al. (2002), for a 55 cm tall flat panel reactor gassed with 10 % CO₂, an aeration rate of 0.05 vol vol⁻¹ min⁻¹ was defined as optimum, although growth increased with aeration rates up to 1 vol vol⁻¹ min⁻¹. References can also be found to the beneficial effect of applying much larger aeration rates, for example 1-6 vol vol⁻¹ min⁻¹ with high productivity *Spirulina* culture (Qiang, Richmond 1996). For economic modelling purposes, we have been using an aeration rate of 1 vol vol⁻¹ min⁻¹ as a base level and consider that reductions down to 0.05 vol vol⁻¹ min⁻¹ may be optimal in some cases for energy consumption reasons. The energy efficiency of photobioreactors cannot be viewed sensibly without also considering the cost of the mixing. It is important to note that the cost of mixing is composed of power consumption and depreciation of equipment and that the selection of technology (instrumentation) and mixing requirements (process design) can change the magnitude and proportions of the two components considerably.

1.2 Mixing Costs in Photobioreactors

The mixing costs for flat panel reactors consist of the value of the depreciation and cost of the energy consumption of the blowers or compressors delivering the compressed air for sparging, the pressure of which has a dramatic effect on these factors. Roots-type and screw-type blowers produce compressed air at a high energy efficiency over a wide pressure range but are high precision mechanical instruments and very costly. The very commonly used side channel blowers are cheap but energy efficient only at low pressures. Radial blowers (the equivalent of a centrifugal liquid pump) are cheap and energy efficient, generally up to higher pressure levels, but this is strongly influenced by *scale*: large scale radial blowers can be both cheap and energy efficient at higher pressures but also pose an engineering challenge even at a large algal cultivation installation.

The mixing costs for tubular reactors are entirely dominated by the circulation pump costs, which are the sum of the depreciation of the circulation pump and the costs of the pump's energy

consumption. It is possible to get widely varying results depending on the process layout and instrumentation, the type of circulation pump being very important to the circulation economy. Large-turbine wheel centrifugal pumps can be very energy efficient but are costly, while small-turbine wheel centrifugal pumps are cheap but less energy efficient and dissipate the energy deficit as shear stress. Airlift pumps have frequently been preferred to avoid possible shear stress damage, but it is necessary to operate them at a large immersion depth to generate the necessary head to circulate the culture. This excludes the use of cheap and energy-efficient, low-pressure blowers. In order to realize the promises of producing cost-efficient microalgal feedstock for biofuel production, it is essential not to spend more energy on agitation than absolutely necessary.

In 2011, we published a desk study on the cost of producing microalgal biomass with a base case at a north European site (Netherlands), comparing three different cultivation methodologies (open ponds, one-layer tubular photobioreactors, and closely spaced flat panel photobioreactors) at a 100 ha scale (Norsker et al. 2011). The current cost of producing 1 kg of biomass dry weight (DW) was calculated to be 4.95, 4.15 and 5.96 € respectively. These base case results were obtained for a velocity in the tubular reactor of 0.5 m s^{-1} and an aeration rate of $1 \text{ vol vol}^{-1} \text{ min}^{-1}$ for the flat panel reactor. In the tubular reactor, mixing cost constituted 1.27 €/kg DW or 30 % of the total biomass production costs. The cost of the air sparging in flat panel photobioreactor systems was even larger, namely 3.04 € per kg DW or 52 % of the biomass production costs. So there is good reason for looking further into the details of these processes and examining if more economical process layouts can be obtained. We therefore believe that a study of energy optimization of closed photobioreactors in the context of classical hydraulics would be useful.

2 Economic Model

A techno-economic model was established for producing microalgae under Dutch conditions using open ponds, tubular photobioreactors or flat panel reactors as described in Norsker et al.

(2011), and we refer to that paper and the accompanying information for all the details about the calculations. Here, we can briefly state that the microalgal productivity is calculated on the basis of assumptions about reactor-specific typical photosynthetic efficiency (justified in the accompanying information) of ponds, tubular and flat plate photobioreactors. Applying the average monthly irradiation values to different sites then will result in typical biomass productivities for algae with a given caloric value. The individual contributions to the cost of the algal production can then be expressed as the cost per kg algal biomass produced. Here, we perform the calculation with modified input data on mixing costs.

For tubular reactors, a significant amount of energy is required to circulate the culture in the tubes. This energy consumption is necessary to perform the equivalent of mixing in the flat panel reactors and to recycle the culture between the degasser and the solar collector. The energy consumption is usually indicated as the specific power supply, that is the power (in watt) per m^3 solar collector. The specific power supply for circulation depends strongly on the culture velocity and the pump efficiency, which are important process design factors.

Calculating the power needed for circulating the culture in a circuit (a path from degasser tank through manifold and tube and back again) is done by calculating the power associated with tube wall friction and other power absorbing elements in the circuit separately. The power was calculated using the Darcy-Weisbach equation and estimating the friction factor with the Moody approximation to the Blasius equation, setting the sand-equivalent biofilm roughness to either 0 or 1.5 mm and using an overall (pump + motor) energy efficiency of 0.5.

In the economic model for the tubular plant, we operated with variably sized reactor units, each provided with one circulation pump with a flow of $1,000 \text{ m}^3 \text{ h}^{-1}$. In the present case, 100–300 tubes in each direction per pump were necessary. Larger pumps can be found, but units larger than 300 tubes are not practical. The cost of each pump was 29,000 €. The effect of varying the velocity with tubular reactors and varying the air supply rate with the flat panel reactors does not imply

any functional relationship between velocity/air supply and the productivity of the systems but is merely an analysis of the cost effect of these parameters.

For the flat panel reactors, the panel height was lower (0.5 m) than in the previous layout and the distance between reactors was shorter, while the volume of the reactors was kept approximately constant. The height of the panels was set to 0.5 m as that would be the largest possible height with a total pressure drop over the panels of 100 mbar. The purpose of this choice will become obvious later.

In flat panel photobioreactors, compressed air is used for mixing and mass transfer directly in the reactor and constitutes a significant part of the energy consumption. The power supply for sparging depends strongly on the discharge pressure of the compressor, and efficiency as function of the discharge pressure varies strongly between the different types of compressors, so the pressure of the gas used for sparging is an important design factor. It is the sum of the pressure drop over the sparger system and the static height of the reactor. To evaluate the compressor efficiency, it is reasonable to compare it with the energy requirements for isothermal compression, as the compressed air is cooled before injection and the energy represented by compression heat is inevitably lost. For the three actual compressor types for which we managed to acquire data, the total power consumption per volume compressed air delivered was depicted against the discharge pressure, but expressed at standard conditions (1 bar, 20°C) and compared with the power for isothermal compression.

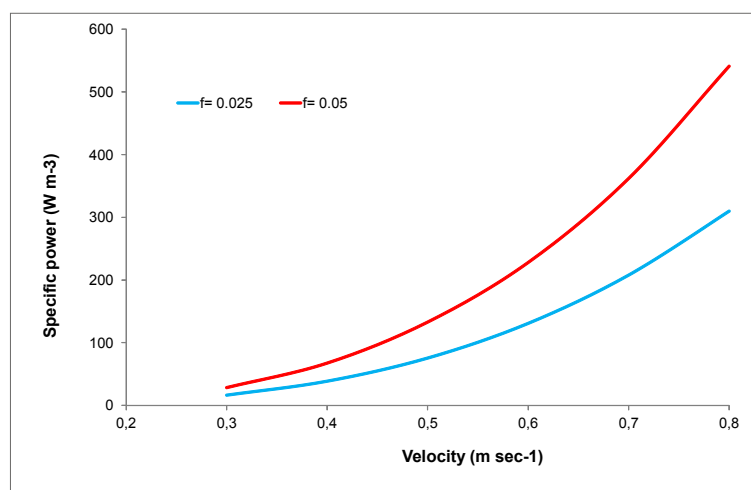
The data were fitted with various regression formula. The efficiency at a given pressure was directly calculated by dividing the power supply for isothermal compression with the actual requirements of the different compressors.

3 Results

3.1 Tubular Photobioreactors

To minimize the mixing costs for tubular photobioreactors, we examined the effect of flow resistance in the tubes as a function of tube wall friction. Figure 1 shows the specific power needed to circulate the algal culture in the tubular photobioreactor plant manifold constructions. Tubes 6 cm in diameter and 100 m long were used. The specific power was calculated using two different friction factors (0.025 for smooth tubes and 0.05 for tubes with an assumed sand-equivalent roughness of 1.5 mm). The sand-equivalent roughness of 1.5 mm is chosen rather arbitrarily, and there is no information available on the hydraulic resistance from biofilm in microalgal bioreactors. Barton et al. (2008), however, estimated that the biofilm sand-equivalent roughness would build up to 2.17 mm before cleaning in a number of sewers. Yet it is hard to say to what extent this can be seen as a parallel to the situation in a tubular photobioreactor. In comparison, the sand-equivalent roughness of 1.5 mm is probably a worst case scenario for tubular photobioreactors. The pump power efficiency was chosen as 0.5; with large-turbine wheel pumps, this is probably at the low side.

Fig. 1: Specific circulation power depicted against tube flow velocity in a tubular reactor



Source: Own compilation

At a velocity of 0.5 m s⁻¹, the resulting specific power is 76 W m⁻³ in smooth tubes and 133 W m⁻³ in rough ones.

The net energy balance (the amount of energy produced minus the amount of energy used) per kg DW produced is indicated in table 1 for a velocity of 0.5 m s⁻¹. At 0.5 m s⁻¹, the circulation pump uses about the same energy as the algae produce.

Table 1: Net energy balance in tubular photobioreactor systems at a velocity of 0.5 m s⁻¹

Energy used	MJ kg DW ⁻¹ algal biomass
Pumps	0.75
Centrifuge	3.01
Circulation pump	27.20
Air blower (degasser)	4.40
LDPE 1Y (low density polyethylene film)	9.96
Energy produced	26.20
Net balance	-19.12

Source: Own compilation

The effect of velocity on the net energy balance is shown in figure 2. If the productivity of the culture is maintained at a velocity of about 0.35 m s⁻¹, the energy balance will be positive. Reducing the velocity carries the risk that there will be an increased concentration of dissolved oxygen at the outlet of the loop and that reduced turbulence may reduce the productivity or the desired product formation at a high level of irradiation as a result of the mechanisms mentioned in the introduction, but virtually no empirical information exists to evaluate this effect. It should be kept in mind that the concentration of dissolved oxygen in the tubes is highly dynamic. At constant irradiation, it increases linearly over the length of the tubes, and the irradiation is furthermore highly dynamic. In all circumstances, therefore, velocity control would be an important tool for reducing power consumption in tubular reactors.

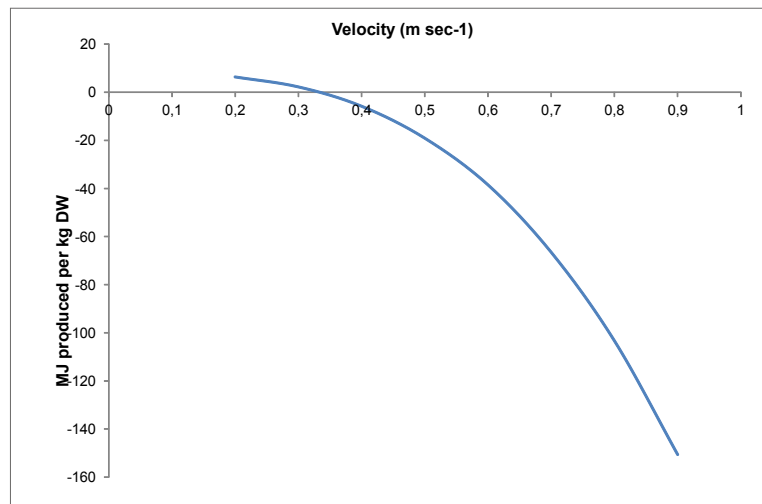
The power supply data were entered in the economic model; the electricity rate used was 5 €ct per kWh. The number and cost of each pump was selected by varying the number of tubes connected to each pump so that the flow provided by each pump was roughly the same – 1,000 m³ h⁻¹. At 0.5 m s⁻¹, the cost of producing biomass at f = 0.025 is 3.97 €/kg⁻¹ and at f = 0.05 is 4.26 €/kg⁻¹. At higher velocities, the effect of the friction becomes more pronounced.

3.2 Flat Panel Reactors

To minimize mixing costs for flat panel reactors, supplier data for power consumption at varying back pressures and flows for three relevant blower types were compared with isothermal compression. The isothermal compression may be considered a theoretical zero-energy loss reference for the blowers as it would imply the compression heat is removed by cooling and not considered conserved in the system.

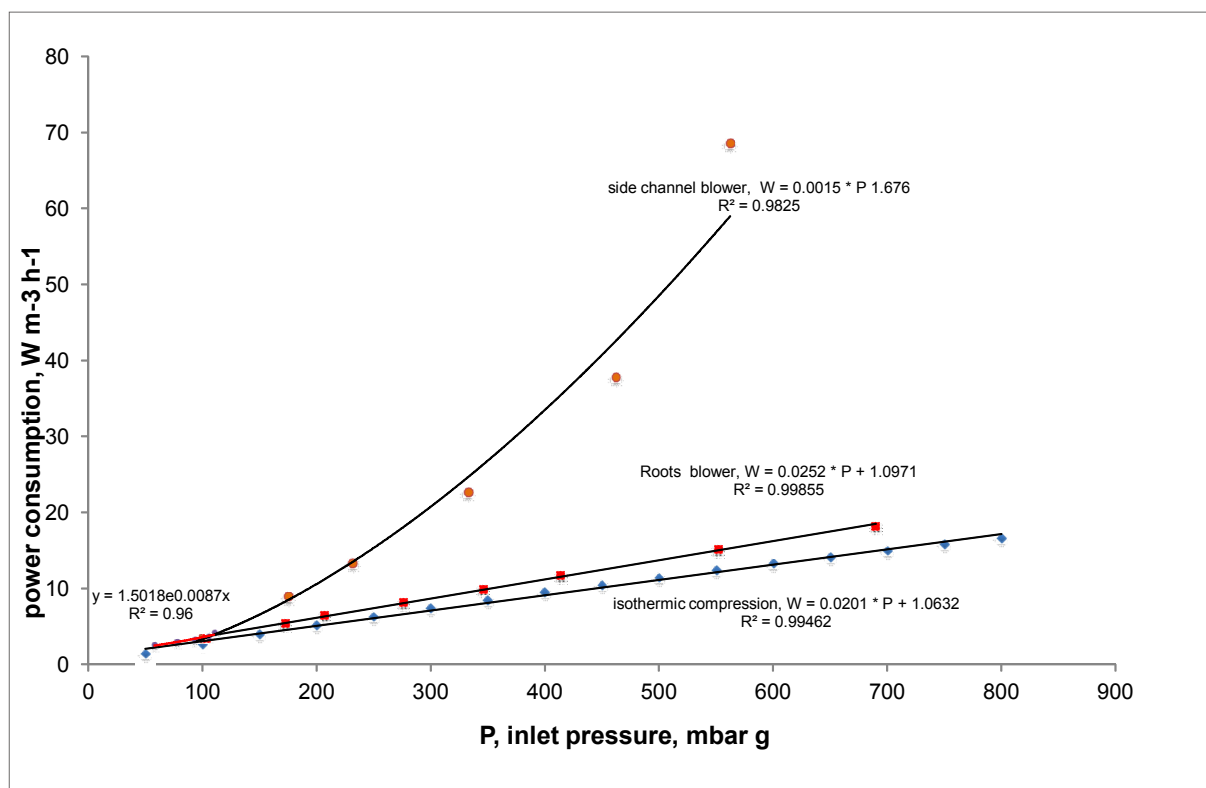
The energy used by a Roots blower (Omega Industries, model 1012), a side channel blower (Elmo-Rietchle, model 2GH1620) and a radial blower (Elektror, model CFXH 280 B) were also compared. The capacities of these blowers are roughly in the same range (about 10,000 m³/h

Fig. 2: Effect of culture velocity on net energy balance in a tubular photobioreactor



Source: Own compilation

Fig. 3: Power supply of different blowers: a Roots blower, a side channel blower, and a radial blower*



* These three blowers have a similar capacity. The performance is expressed in terms of kW per m³ per h and depicted against discharge pressure. The same representation of the power input for an isothermal compression is included, represented by the black line, allowing a direct evaluation of the performance of the blowers.

Source: Own compilation

at 100 mbar). They were chosen as suitable to supply the rather large aeration rates of the flat panel reactors. Each blower thus meets the requirements of flat panel reactors occupying a horizontal area of 3,000 m². Conventional piston compressors are considerably less energy efficient and were a priori not considered.

The power supply per m³ h⁻¹ flow for the three blowers and for isothermal compression is given in figure 3 along with regression lines fitted to the data. The Roots blower data were well approximated by a linear regression, and when comparing with the isothermal compression data, the efficiency over the range from 100 to 800 mbar varied from 79.4 to 84.6 %. The side channel blower efficiency drops from 80.2 % at 100 mbar to 20 % at 600 mbar. Although no data were available below 100 mbar, it is evident from figure 3 that if the pressure is below 100 mbar the side channel blower is as efficient as the

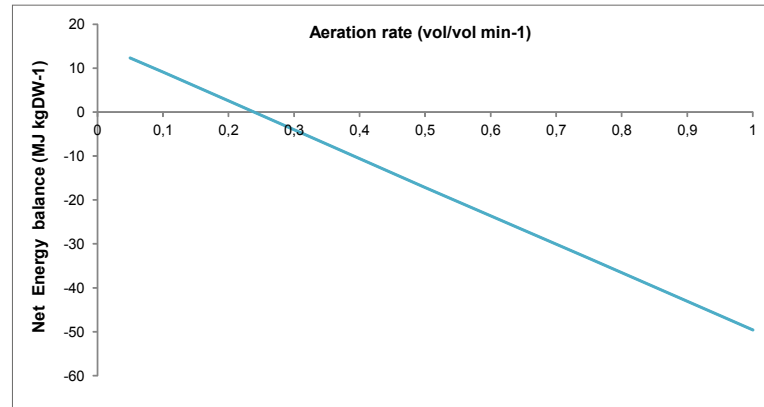
Roots blower. The last type, the radial blower, has a power efficiency of 82 % at 100 mbar, but its pressure range does not exceed 100 mbar.

The blowers were dimensioned to be sufficient for a ground area of 3,000 m². If, however, it were possible to operate with blowers covering a larger area, it would be possible to obtain a pressure higher than 100 mbar while maintaining high efficiency and low cost.

The characteristics for the different blower types were incorporated in the economic model, and the resulting total cost per kg algal biomass produced at an air supply rate of 1 and 0.05 vol vol⁻¹ min⁻¹ is indicated in table 2. Using a radial blower that is four times larger (CFHX 710) only resulted in marginal savings. The conclusion from table 2 is that if the back pressure from the flat panel reactors is kept below 100 mbar, either radial or side channel blowers can be used with the same result on the economics of production.

The Roots blower, however, is significantly more expensive due to the high depreciation. Reducing the aeration rate to the low value of 0.05 vol vol⁻¹ min⁻¹ as suggested in a number of recent papers has a significant effect on the economics of production, resulting in biomass production costs of about 2.2 €/kg⁻¹ (table 2). The net energy balance is positive at an aeration rate < 0.25 vol vol⁻¹ min⁻¹, at which point the biomass production cost is 2.4 €.

Fig. 4: Net energy balance for biomass produced in flat panel reactors (energy produced – energy spent) for Electror CFHX 280B as function of aeration rate at a Dutch site



Source: Own compilation

Table 2: Calculated cost of algal biomass cultivation as influenced by type of blower*

Air supply rate	Microalgae cultivation cost	
	€/kg DW ⁻¹ algal biomass	
	1 vol vol ⁻¹ min ⁻¹	0.05 vol vol ⁻¹ min ⁻¹
Type of blower		
Roots	4.32	2.27
Radial blower, CFHX 280	3.02	2.21
Radial blower, CFHX 710	2.99	2.18
Side channel blower	3.13	2.21

* All blowers operating at full capacity at 100 mbar. Air flow rate was 1 volume of air per volume reactor per min.

Source: The costs for the Roots blower was estimated based on DACE 2002

Figure 4 demonstrates that a positive energy balance can be obtained for a flat panel reactor if the aeration rate in a low profile flat panel reactor is limited to 0.25 vol vol⁻¹ min⁻¹ and the productivity of the reactor is maintained.

4 Discussion

In the literature, the value given for the required circulation power of tubular reactors is up to 3,400 W m⁻³, but this high energy demand appears to be

based on a misunderstanding of work done on small airlift-driven helical tubular photobioreactors. The calculations in this paper show that given a suitable design for tubular photobioreactors with smooth tubes, it should be possible to reduce the specific energy demand for microalgae cultivation to 75 W m⁻³ tube volume. Nevertheless, maintaining circulation is still the dominant cost factor in tubular reactors, so it is important to minimize the velocity in tubular reactors. Positive energy balances can result just from reducing the energy spent on mixing in tubular reactors (but also in flat panel reactors). In our calculations, a rather high cost is employed for the pumps, corresponding to the cost associated with slowly turning centrifugal pumps with large impellers which have been selected to avoid shear stress damage, but the worry about shear stress damage of the microalgae in centrifugal pumps is probably out of proportion, and more research into shear stress damage of commercially applicable microalgae is needed. If larger pumps were utilized, pumping costs would also be reduced, but using large pumps also increases the size of each bioreactor unit, which makes contamination more troublesome. In the present case, it was necessary to use 100–300 tubes in each direction connected to a single pump in order to use a 1,000 m³ h⁻¹ pump. Larger units are not practical. Reducing the flow velocity to the minimum would require looking carefully into the maximum permissible level of dissolved oxygen,

which is an area of microalgal biotechnology that has been investigated very little. The biomass production costs could be reduced below 2 € per kg biomass by reducing the velocity to 0.3 m s⁻¹ and sourcing a circulation pump for 1,000 m³ h⁻¹ at a head of 0.2 m s⁻¹. Further reductions will involve separation technology, operating at more sunny sites, optimizing reactor photosynthetic efficiency, and reducing costs for nutrients and CO₂ supply.

In a recent tubular pilot reactor study, the actual specific circulation energy was about 300 W m⁻³, but a fluid velocity of 0.9 m s⁻¹ was used in 9 cm (d) tubing (Acién et al. 2012/in press).

An average photosynthetic efficiency (solar) of 3.6 % was reported with an equivalent productivity of 90 t ha⁻¹ year⁻¹. The actual production costs in the 428 m² pilot plant were 69.2 € kg⁻¹. A scale up study of the technology was calculated to result in biomass production costs of 12.6 € kg⁻¹, and the authors concluded that a further reduction could be achieved by simplifying technology and materials and by reducing power consumption, man power and raw materials.

It thus seems that “simple” engineering is the way to achieve significant cost reductions with the tubular system since the photosynthetic efficiency is probably as good as it gets under a natural day cycle. But it should be emphasized that the necessary biological knowledge to do so is still lacking.

If, in a flat panel reactor, the pressure drop over the panels is maximum 100 mbar, it is possible to obtain an aeration solution that is economic in both depreciation and power consumption. More than 80 % energy efficiency is readily obtainable with radial and side channel blowers.

Direct displacement pumps such as the Roots blowers can produce compressed air very efficiently at higher pressures but are costly and result in high production costs. One possible solution to high profile panels are very large units – with radial blowers – but the channelling and lack of isolation is a serious drawback of this option. If a flat panel reactor has no more than 100 mbar of available sparging pressure, the maximum panel height is probably no more than 50 cm to allow for pressure drop over sparger holes and in tubing. This raises the problem of air filtration, which probably very few microalgal biotechnologists are prepared to sacrifice. So what is the solution to this

problem? One answer is recirculation of part of the sparger gas, so only a minor part of the sparger gas has to be pressed through filters. Obviously, oxygen levels will rise in the recirculated gas, raising again the question of the maximum amount of dissolved oxygen permitted in photobioreactors.

5 Conclusion

The energy costs for mixing have a strong influence on the economics of microalgal biomass production in photobioreactors, but simple hydrodynamic engineering combined with knowledge of the effect of dynamic oxygen and irradiation conditions on microalgal productivity can potentially turn microalgal photobioreactors into net producers of energy. For tubular photobioreactors, this may be accomplished by keeping tube wall friction and circulation velocity at a minimum, and for flat panel reactors, by minimizing the aeration rate and using highly energy-efficient blowers. This, in turn, requires that either a low panel profile or very large reactor units be employed, served by single large blowers.

Notes

- 1) Niels-Henrik Norsker is associated with the bio-engineering Grupu at Wageningen University. His current contact is bioTOPIC, Kildegårdsvej 75, 2900 Hellerup, Denmark
- 2) Food and Biobased Research, Bornse Weiland 9, 6708 WG, Wageningen, The Netherlands
- 3) Bioprocess Engineering, Wageningen University, P.O. Box 8129, 6700 EV Wageningen, The Netherlands

References

- Acién Fernández, F.G.; Fernández Sevilla, J.M.; Sánchez Pérez, J.A. et al., 2001: Airlift-driven External-loop Tubular Photobioreactors for Outdoor Production of Microalgae: Assessment of Design and Performance. In: Chemical Engineering Science 56/8 (2001), pp. 2721–2732
- Acién, F.G.; Fernández, J.M.; Magán, J.J. et al., 2012/in press: Production Cost of a Real Microalgae Production Plant and Strategies to Reduce it. In: Biotechnology Advances

- Alias, C.B.; Lopez, M.C.G.-M.; Fernandez, F.G.A. et al.*, 2004: Influence of Power Supply in the Feasibility of *Phaeodactylum tricornutum* Cultures. In: *Biotechnology and Bioengineering* 87/6 (2004), pp. 723–733
- Barton, A.F.; Wallis, M.R.; Sargison, J.E. et al.*, 2008: Hydraulic Roughness of Biofouled pipes, Biofilm Character, and Measured Improvements from Cleaning. In: *Journal of Hydraulic Engineering* 134/6 (2008), pp. 852–857
- Brentner, L.B.; Eckelman, M.J.; Zimmerman, J.B.*, 2011: Combinatorial Life Cycle Assessment to Inform Process Design of Industrial Production of Algal Biodiesel. In: *Environmental Science & Technology* 45/16 (2011), pp. 7060–7067
- Burgess, G.; Fernandez-Velasco, J.G.*, 2008: Materials, Operational Energy Inputs, and Net Energy Ratio for Photobiological Hydrogen Production. In: *International Journal of Hydrogen Energy* 32/9 (2008), pp. 1225–1234
- DACE – Dutch Association of Cost Engineers*, 2002: *Prijzenboekje*. Leidschendam
- Gilbert, J.J.; Ray, S.; Das, D.*, 2011: Hydrogen Production Using *Rhodobacter Sphaeroides* (O.U. 001) in a Flat Panel Rocking Photobioreactor. In: *International Journal of Hydrogen Energy* 36/5 (2011), pp. 3434–3441
- Hall, D.O.; Fernandez, G.A.; Canizares Guerrero, E. et al.*, 2003: Outdoor Helical Tubular Photobioreactors for Microalgal Production: Modeling of Fluid dynamics and Mass Transfer and Assessment of Biomass Productivity. In: *Biotechnology and Bioengineering* 82/1 (2003), pp. 62–73
- Hulatt, C.J.; Thomas, D.N.*, 2011: Energy Efficiency of an Outdoor Microalgal Photobioreactor Sited at Mid-temperate Latitude. In: *Bioresource Technology* 102/12 (2011), pp. 6687–6695
- Jorquera, O.; Kiperstok, A.; Sales, E.A. et al.*, 2010: Comparative Energy Life-cycle Analyses of Microalgal Biomass Production in Open Ponds and Photobioreactors. In: *Bioresource Technology* 101/4 (2010), pp. 1406–1413
- Lehr, F.; Posten, C.*, 2009: Closed Photo-bioreactors as Tools for Biofuel Production. In: *Current Opinion in Biotechnology* 20/3 (2009), pp. 280–285
- Morweiser, M.; Kruse, O.; Hankamer, B. et al.*, 2010: Developments and Perspectives of Photobioreactors for Biofuel Production. In: *Applied Microbiology and Biotechnology* 87/4 (2010), pp. 1291–1301
- Norsker, N.-H.; Barbosa, M.J.; Vermuë, M.H. et al.*, 2011: Microalgal Production – A close Look at the Economics. In: *Biotechnology Advances* 29 (2011), pp. 24–27
- Pegallapati, A.; Nirmalakhandan, N.*, 2011: Energetic Evaluation of an Internally Illuminated Photobioreactor for Algal Cultivation. In: *Biotechnology Letters* 33/11 (2011), pp. 2161–2167
- Posten, C.*, 2009: Design Principles of Photobioreactors for Cultivation of Microalgae. In: *Engineering in Life Sciences* 9/3 (2009), pp. 165–177
- Qiang, H.; Richmond, A.*, 1996: Productivity and Photosynthetic Efficiency of *Spirulina Platensis* as Affected by Light Intensity, Algal Density and Rate of Mixing in a Flat Plate Photobioreactor. In: *Journal of Applied Phycology* 8/2 (1996), pp. 139–145
- Sierra, E.; Ación, F.G.; Fernández, J.M. et al.*, 2008: Characterization of a Flat Plate Photobioreactor for the Production of Microalgae. In: *Chemical Engineering Journal* 138/1–3 (2008), pp. 136–147
- Singh, A.; Olsen, S.I.*, 2011: A Critical Review of Biochemical Conversion, Sustainability and Life Cycle Assessment of Algal Biofuels. In: *Applied Energy* 88/10 (2011), pp. 3548–3555
- Sousa, C.; de Winter, L.; Janssen, M. et al.*, 2012: Growth of the Microalgae *Neochloris Oleoabundans* at High Partial Oxygen Pressures and Subsaturating Light Intensity. In: *Bioresource Technology* 104 (2012), pp. 565–570
- Vejraska, C.; Janssen, M.; Streefland, M. et al.*, 2011: Photosynthetic Efficiency of *Chlamydomonas Reinhardtii* in Flashing Light. In: *Biotechnology and bioengineering* 108/12 (2011), pp. 2905–2913
- Xu, L.; Weathers, P.J.; Xiong, X.-R. et al.*, 2009: Microalgal Bioreactors: Challenges and Opportunities. In: *Engineering in Life Sciences* 9/3 (2009), pp. 178–189
- Zhang, K.; Kurano, N.; Miyachi, S.*, 2002: Optimized Aeration by Carbon Dioxide Gas for Microalgal Production and Mass Transfer Characterization in a Vertical Flat-plate Photobioreactor. In: *Bioprocess and Biosystems Engineering* 25/2 (2002), pp. 97–101

Contact

Niels-Henrik Norsker
 bioTOPIC
 Kildegårdsvej 75, 2900 Hellerup, Denmark
 E-mail: niels-henrik-norsker@wur.nl

