

Thesis Systems and Control

Modelling of energy consumption for algae photo bioreactors in various scenarios

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19 December 2011

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WAGENINGEN UNIVERSITY
AGROTECHNOLOGY AND
FOOD SCIENCES

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Name course : Thesis project Systems and Control
Number : SCO-80436
Study load : 36 ects
Date : 19 December 2011

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Study programme : MBT (Biotechnology)

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Abstract

In 2015 the demand for fuels is expected to exceed the supply. In order to prevent depletion, alternatives have been found in biofuels, which are fuels from a renewable sources[1, 2]. The main disadvantage of the first and second generation of biofuels is that the fuel production has to compete with the world food production. A more sustainable and carbon efficient alternative has been found in micro algae, which are relatively fast growing and utilize CO₂ and sunlight for the production of biofuels in photo bioreactors[3]. Algae production can take place as well in areas where no crops can grow. Models to evaluate algae production in photo bioreactors have been developed [4-6], but do not yet include the energy demand and energy efficiency.

This work concerns the development of a mathematical model for the energy demand and production of three photo bioreactors, which are the flat plate, tubular and open pond bioreactor. This model is used to show how the Netto Efficiency Ratio (NER, energy production divided by consumption) and the energy cost to produce algae biomass changes by days, seasons and by adjusting the design parameters such as the concentration of biomass and the lightpath. The model is therefore able to analyse the design of a bioreactor.

A NER higher than 1 implies that the reactor is able to produce more energy than it consumes. a reference scenario for a standard flat plate system gives a NER of 0.36 for the flat plate reactor, 1.3 for the tubular reactor and 6.27 for the open pond reactor. This result has been obtained for environmental conditions in the Netherlands and for the *P. Tricornutum* algae specie. Improvement of the flat plate bioreactor may be achieved by other methods of aeration, such as sparging over multiple reactors. All reactors may see improved NER with a faster growing algae species.

Bioreactors have improved efficiencies in specific seasons with high sunlight intensity. The efficiencies are significantly higher than the yearly average NER suggests. Therefore, the NER can also be improved by producing in specific months rather than year-round production.

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1. Introduction

In 2015 the demand for fuels is expected to exceed the supply[7], which will become a worldwide concern. In order to prevent complete depletion, alternatives have been found in biofuels, which are fuels from a renewable source[1, 2]. The main disadvantage of the first and second generation of biofuels is that the fuel production has to compete with the world food production. A more sustainable and carbon efficient alternative has been found in micro algae, which are relatively fast growing and utilize CO₂ and sunlight for the production of biofuels in a photo bioreactor [3].

The cultivation of algae on large scale happens in different production systems; an open system, such as an open pond (raceway) or in closed systems, such as a flat panel reactor or a tubular reactor. The main difference between the two systems is that an open system has a lower variable (biomass) production cost, but a closed system has a higher yield. Wijffels et al[8]. expects that after optimization of the closed photo bioreactor the production costs can become lower than in an open photo bioreactor[8]. Algae biomass is further processed into biofuel after the cultivation.

The cultivation of algae has some challenges; next to the high costs of biomass production, a sufficient amount of land is required to obtain enough sunlight for production. Only part of the sunlight is used and therefore the reactor in the summer is heated up. On the other hand, in winter the ambient temperature might not be sufficient enough to sustain the optimal growth conditions of the photo bioreactor and needs to be heated.

The energy consumption of a photo bioreactor contributes significantly to the running costs of the cultivation process. Lehr et al.[9] concludes that a high amount of supplied energy during cultivation is one of the reasons that biodiesel from algae currently cannot compete with diesel production. Norsker et al. [10] have investigated the economic outlook for photo bioreactor and concludes that costs should be reduced by approximately 80-90% in order to make the process feasible. However, Cheng-Wu et al [11] states that the energy cost is surmounted by labour costs for an industrial flat plate reactor and therefore not significant.

In order to gain insight of how the energy balance of a photo bioreactor can be optimised a mathematical model is required. It is important to realise the different constructions between the different production systems. An open pond (raceway) system suffers from e.g. evaporation of water from the pond whereas in a closed system this phenomena does not occur. There are already several models for the prediction of production with respect to sunlight. In these models, the sunlight penetration is calculated and the production is estimated by Lambert-Beer equations combined with Geiders[12] cultivation model[4-6]. These models have laid the emphasis on the production of algae biomass, so that the energy production can be estimated. These models have not yet considered the energy balances involved for the reactors, such that the netto energy yield of a reactor cannot be fully shown. Lehr et al [9] argues that the external energy input requirement for a tubular reactor is

considerably large, such that a tubular reactor cannot be profitable for energy production. Energy reducing should therefore be employed before the configuration can be used, but no model exists at this point, to show the change of energy yield, per change in a reactor.

Norsker et al[10], has depicted the most energy cost intensive processes for the different reactor types from general engineering rules. These are the sparging for the flat plate reactor, degassing for the tubular reactor and the paddle wheel for the raceway pond[10]. Next to this the cultivation systems are dependent on other factors, such as the environmental conditions and biological demands of the algae. Although these may not require the largest amount of energy, it is unclear how much they contribute to the total energy demand. Further research is needed to gain more insight in ways to reduce the amount of energy required to produce algae for the production of biodiesel.

This mathematical model is used to evaluate several scenarios for comparison. These scenarios are developed for the Netherlands. For this purpose the model for the energy balances is developed and linked to the production and cultivation models of Slegers, van Beveren and Lösing[4-6]. With this combination it is possible to evaluate the total energy requirements of a photobioreactor under different conditions, such as the design parameters, algae concentration and so on. Various environmental data, such as temperature, humidity and light intensity have been measured over 2009 in a 10 minute interval. The cultivation of algae has been modelled separately for the three different configurations. The production values of such models are added as an external input for the mathematical model. The goal of this model is to provide a method to show how the energy demand and netto energy yield changes on an yearly average.

2. The model

For algae cultivation open and closed photobioreactors are used (figure 1). In open photobioreactors (open pond) the cultivation broth is in direct contact with the environment and exchange of heat and water (vapour) occurs directly. The cultivation broth in closed photobioreactors is not in direct contact with the open air and there is no water (vapour) exchange while heat exchange only occurs through the reactor wall. Among the closed systems the flat plate and tubular systems have the most attention. In this chapter the energy required for a photobioreactor is quantified. For an open pond it concerns the paddle wheel and CO₂ supply. Open systems are mostly not temperature controlled and therefore the energy calculations to keep the system at a required temperature are not considered. For a closed system the energy for CO₂ supply, fluid recirculation, and the energy for controlling the temperature are considered.



Figure 1: from left to right: tubular reactor, flat plate reactor and an open pond reactor

To calculate the energy demand for the system, three different categories of processes are considered: Biological (growth of algae), exchange with the environment (e.g. radiation, sunlight) and physical units for the required conditions (e.g. pumps). Their inner relation is depicted in figure 2.

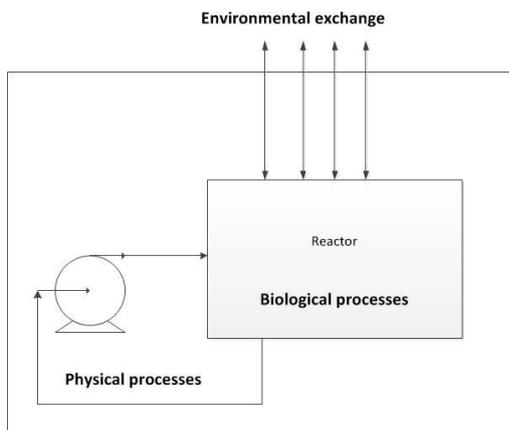


Figure 2: the relation between the biological, environmental and physical processes

Whereas biological processes and environmental exchange show similarities, physical processes differ for each configuration. The biological processes and environmental exchanges will be explained in section 2.1 and physical processes in section 2.2.

2.1 Biological processes and environmental exchange

The biological processes and environmental exchanges contribute to the thermal energy balance, which results in temperature fluctuations in the reactor. A cooling/heating unit is used to keep the temperature constant. The cooling/heating unit requests for electrical energy to provide the cooling/heating medium, together with other physical processes. A schematic overview of biological processes and environmental exchange is given in figure 3.

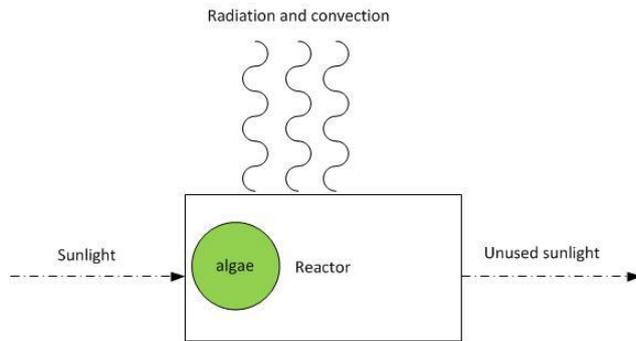


Figure 3: biological processes and environmental exchange in a closed photobioreactor

The biological process of the reactor consists of the cultivation of algae, whereas the environmental exchange consists of the intensity of the sun entering the reactor, radiation and convective energy dissipation of the reactor.

2.1.1 Cultivation of algae

The cultivation of algae concerns growth and maintenance. Slegers[4] and van Beveren[6] have extensively described the algae production and sunlight simulation of a flat plate and a tubular photobioreactor respectively. The energy uptake of the algae, assuming the concentration in the reactor remains constant, is described as,

$$Q_{algae} = H_{comb} \mathcal{P}_r + r_{max} C_x V \Delta H_{algae} \quad (1)$$

Where Q_{algae} is the energy requirement of the algae in $[J s^{-1}]$, ΔH_{algae} is the combustion energy of the algae in $[J kg^{-1}]$, \mathcal{P}_r is the production of the reactor in $[kg s^{-1}]$, r_{max} is the maximum maintenance coefficient in $[s^{-1}]$, C_x is the concentration of the algae in $[kg m^{-3}]$ and V is the volume in $[m^3]$.

The production term follows from the actual growth or algae outflow from the reactor, according to the steady state mass balance,

$$0 = \mu_{growth} V C_x - \phi_{out} C_x \quad (2)$$

$$\mathcal{P}_r = \phi_{out} C_x \quad (3)$$

Where μ_{growth} is the growth rate of the algae in $[s^{-1}]$ and ϕ_{out} is the outflow of the reactor $[m^3 s^{-1}]$.

Constant factors such as the combustion energy are found in annex A.

2.1.2 Sunlight intensity

Energy for the algae to grow is provided by sunlight. However, the algae are not able to fully utilize the sunlight for metabolism and therefore the remaining sunlight is heating up the broth as well. The received intensity of sunlight is;

$$Q_{\text{sunlight}} = I_{\text{sun}}A_r \quad (4)$$

$$I_{\text{sun}} = I_{\text{direct}} + I_{\text{diffuse}} + I_{\text{reflected}} \quad (5)$$

Where Q_{sunlight} is the energy gained from the sun in $[\text{J s}^{-1}]$, I_{sun} is the radiance of the sun on the reactor wall corrected for the reflection in $[\text{J m}^{-2} \text{ s}^{-1}]$ and A_r is the surface of the reactor in $[\text{m}^2]$. I_{sun} has three components; direct sunlight that falls on the reactor and diffuse sunlight which does not fall directly on the reactor. Diffuse sunlight is divided in scattered sunlight which has no distinct pathway and reflected sunlight is direct sunlight, which is reflected via an object onto the reactor. An overview is given in figure 4.

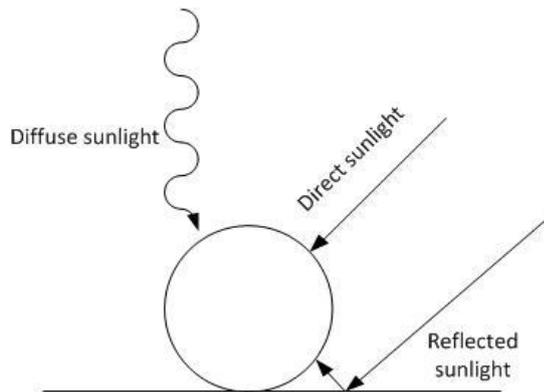


Figure 4: different pathways of light for a tubular reactor

2.1.3 Radiation loss

Radiation energy loss of an object is a natural occurrence as a function of relative humidity (RH) and difference in temperature [5]. Radiation loss is determined as;

$$Q_{\text{radiance}} = A_r \epsilon_w \sigma [(T_r + 273.15)^4 - T_{\text{sky}}^4] \quad (6)$$

Where Q_{radiance} is the radiance energy in $[\text{J s}^{-1}]$, ϵ_w is the emissivity of water in the infrared spectrum, σ is the Stefan-Boltzmann Constant and T_r is the temperature in $[\text{°C}]$ of the reactor and T_{sky} is the sky temperature in $[\text{°K}]$, which is;

$$T_{sky} = (273.15 + T_a) \cdot [0.711 + 5.6 \cdot 10^{-3} T_{dew} + 7.3 \cdot 10^{-5} T_{dew}^2 + 0.013 \cdot \cos(15 \cdot t_{solar})]^{\frac{1}{4}} \quad (7)$$

Where T_a is the air temperature in [$^{\circ}\text{C}$], T_{dew} is the dewpoint temperature and t_{solar} is the elapsed time after midnight in [hr]. The air temperature is assumed to be equal to the ambient temperature as collected in the same dataset of the sunlight. The dewpoint temperature is estimated from;

$$T_{dew} = \frac{240.97 \cdot \ln\left(\frac{e_a}{611.21}\right)}{17.502 - \ln\left(\frac{e_a}{611.21}\right)} \quad (8)$$

Where e_a is the water pressure of the air, which is calculated as;

$$e_a = RH \cdot 611.21 e^{\frac{17.502 T_a}{240.97 + T_a}} \quad (9)$$

The relative humidity (RH) has been measured in the same dataset as sunlight intensity. The cloudiness of the air has not been taken into consideration as such data was not available. This may have an effect on the radiation losses.

2.1.4 Convection

The ambient temperature has an influence on the reactor due to convection. Bird et al[13] gives a resistance based approach to determine this fluctuation which is described as;

$$Q_{env} = \frac{T_a - T_r}{\frac{1}{h_{h_2o}} + resistance + \frac{1}{h_a}} \cdot A_r \quad (\text{for flat surfaces}) \quad (10)$$

$$Q_{env} = \frac{2 \pi L (T_a - T_r)}{\frac{1}{r_2 h_{h_2o}} + resistance + \frac{1}{r_1 h_a}} \quad (\text{for curved surfaces}) \quad (11)$$

Where T_a is the environmental temperature in [$^{\circ}\text{C}$], r is the radius of the tube in [m] and h is the heat transfer coefficient in [$\text{W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$]. The resistance is the path where the convection stream has to go through between the liquid and air. This is shown as;

$$resistance = \frac{L}{k} \quad (\text{for a flat surfaces}) \quad (12)$$

$$resistance = \frac{\ln(r_1/r_2)}{k} \quad (\text{for curved surfaces}) \quad (13)$$

Where k [$\text{W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$] is the heat conductivity of the material, L [m] is the thickness of the wall between the broth and air, r_1 [m] is the outer surface radius and r_2 [m] is the inner surface radius. The heat transfer coefficient h [$\text{W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$] is calculated as following;

$$h = \frac{N_{nu} k}{l} \quad (14)$$

where N_{nu} is the Nusselt, number and l as the specific length [m] which is defined as

$$l = \frac{4(w \cdot d)}{2(w+d)} \quad \text{for water and} \quad (15)$$

$$l = \frac{4(h_e \cdot d)}{2(h_e+d)} \quad \text{for air} \quad (16)$$

In a flat plate reactor and

$$l = 2r \quad \text{for a tubular reactor} \quad (17)$$

Where w is the width [m], z is the depth [m] and h_e is the height of the reactor [m].

The Nusselt number follows from the Prandtl number and the Reynolds number [14];

$$N_{nu} = 0.0366 N_{re}^{0.8} N_{pr}^{1/3} \quad (\text{for a flat plate reactor turbulent flow}) \quad (18)$$

$$N_{nu} = 0.664 N_{re}^{0.5} N_{pr}^{1/3} \quad (\text{for a flat plate reactor laminar flow}) \quad (19)$$

$$N_{nu} = 0.027 N_{re}^{0.8} N_{pr}^{1/3} \quad (\text{for a tubular reactor turbulent flow}) \quad (20)$$

$$N_{nu} = 1.86 \left(N_{re} N_{pr} \frac{D}{L} \right)^{1/3} \quad (\text{for a tubular reactor laminar flow}) \quad (21)$$

Where N_{pr} and N_{re} are the Prandtl and Reynolds number respectively, which follows from,

$$N_{re} = \frac{\rho \nu l}{\mu} \quad (22)$$

$$N_{pr} = \frac{c_p \mu}{k} \quad (23)$$

Where μ is the kinematic viscosity in [Pa s]. For the broth the Reynolds number and Prandtl number calculated found by using the properties of water, see table 1. For the environment the fluctuating temperature and wind velocity have to be taken into account. The properties of air are found by using empirical relations¹ as a function of the ambient temperature, which are described as follows;

$$\mu_{air} = -2 \cdot 10^{-10} \cdot T_a^2 + 5 \cdot 10^{-8} \cdot T_a + 2 \cdot 10^{-5} \quad (24)$$

$$\rho_{air} = 2 \cdot 10^{-7} \cdot T_a^3 + 2 \cdot 10^{-6} \cdot T_a^2 - 0.0045 \cdot T_a + 1.293 \quad (25)$$

$$c_{p_{air}} = 1.005 \cdot 10^3 \quad (26)$$

$$k_{air} = 7 \cdot 10^{-5} \cdot T_a + 0.0243 \quad (27)$$

Where T_a is the ambient temperature in [°C], ρ_{air} is the density of air in [kg m⁻³] and $c_{p_{air}}$ is the specific heat of air in [J kg⁻¹°C⁻¹].

¹ Derived from the engineering toolbox: http://www.engineeringtoolbox.com/air-properties-d_156.html (accessed 13 December 2011)

Table 1: properties of water

Property	Value	Unit
μ_{h2o}	10^{-3}	Pa s
ρ_{h2o}	1000	Kg m ⁻³
c_{ph2o}	4180	J Kg ⁻¹ °C ⁻¹
k_{h2o}	0.58	W m ⁻¹ °C ⁻¹

2.2 Physical processes flat plate reactor

The flat plate photo bioreactor is seen as a geometric cuboid. The distance of the plate between the plates of the flat plate photobioreactor is relatively small compared to the width and height. Therefore the depth of the reactor is neglected for surface and energy dissipation calculations. A schematic overview of a flat plate bioreactor is given in figure 5;

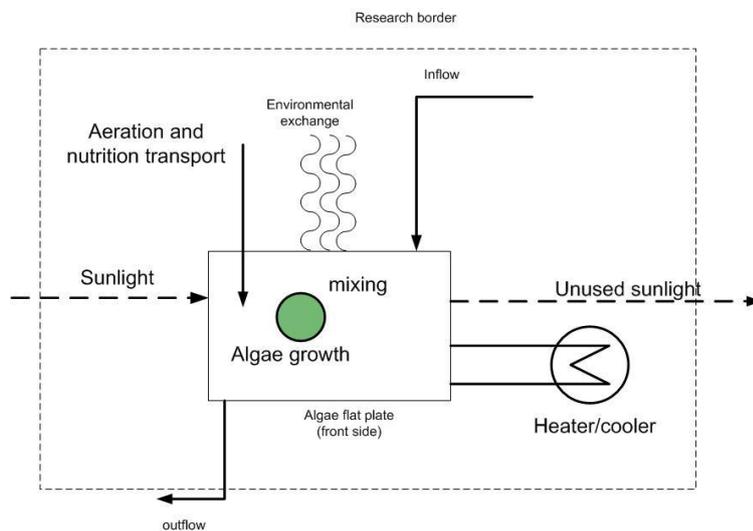


Figure 5: schematic overview of a flat plate bioreactor

In section 2.1 the biological processes and environmental exchange have been discussed. The physical processes occurring in a flat plat photobioreactor are the inflow of fresh medium, the aeration of the reactor and the heating or cooling of the broth.

2.2.1 Inflow of fresh medium

It is assumed that the reactor is running under steady state conditions. From equation 3 follows

$$\phi_{in} = \phi_{out} = \frac{P_r}{C_x} \quad (28)$$

The inflow of fresh medium is entering the reactor at the bottom The pressure difference is determined as;

$$\Delta P = P_{bottom} - P_{atm} \quad (29)$$

Where P is the pressure in [pa]. The energy required to overcome the pressure is equal to;

$$E_{inflow} = \Delta P \phi_{out} \quad (30)$$

A method to determine the energy equivalent cost in ct€ per kg biomass is;

$$cost_{inflow} = \frac{E_{inflow} ct_{kwh}}{3600000 P_r \eta_e} \quad (31)$$

Where $cost_{inflow}$ is the cost for the inflow in [ct€ kg⁻¹], η_e is the pump efficiency and ct_{kwh} is the cost of Kwh in [ct€ kWh⁻¹]. The cost is a rate of consumption over the timespan for the energy requirement and biomass production.

2.2.2 aeration

The aeration is done by bubbling in microbubbles from the bottom of the reactor in order to create enough mixing within the tank in such a way that no mechanical mixing is required. Norsker states that the energy requirement of a cycloblower for a flat plate photobioreactor is

$E_{demand} = 110 [m^3 hr^{-1} Kw^{-1}]$ and the inflow requirement of such reactor is equal to

$\phi_{demand} = 1 [m^3 min^{-1} m^{-3}(\text{volume})]$. The air flow for a specific flat plate photobioreactor is equal to;

$$\phi_{aeration} = \phi_{demand} V dt_{minhr} \quad (32)$$

Where $\phi_{aeration}$ is the aeration requirement in [$m^3 hr^{-1}$], ϕ_{demand} is the aeration demand as proposed by Norsker, V is the volume of the reactor and dt_{minhr} is a correction factor (minutes to hour). The energy requirement is then determined as;

$$E_{blower} = \frac{\phi_{aeration}}{E_{demand}} \quad (33)$$

Where E_{blower} is the energy requirement of the specific reactor in [Kw], E_{demand} is the energy demand as proposed by Norsker and dt_{hrsec} is a conversion factor from (hour to seconds). Finally the cost per kg biomass is determined similar to equation 31;

$$cost_{blower} = \frac{E_{blower} ct_{kwh}}{3600 P_r} \quad (34)$$

2.2.3 Temperature control

The temperature of the broth remains constant to obtain optimal conditions for algae growth. The shortage or excess of heat is determined as;

$$Q_{reactor} = Q_{sunlight} - Q_{env} - Q_{algae} - Q_{radiance} \quad (35)$$

The right-hand side is the sum of the biological processes and environmental exchanges, as explained in section 2.1. If $Q_{reactor}$ is negative the reactor needs to heat up and vice versa if $Q_{reactor}$ is positive it needs to cool down such that;

$$Q_{reactor} = Q_{heat/cool} \quad (36)$$

Cooling of the reactor happens by an evaporative cooling unit. It is assumed that the conditions are good enough to evaporate the water without constraints. This gives an evaporation flow of;

$$\phi_{cool} = \frac{Q_{reactor}}{\Delta H_v} \quad (37)$$

Where ΔH_v is the amount of energy one unit of water can evaporate [kJ Kg]. Heating up the reactor is done by a heat exchanger such that;

$$Q_{reactor} = \phi_{heat} \rho_{h2o} c_{p_{h2o}} (T_r - T_{heater}) \quad (38)$$

Where the temperature of the heater, T_{heater} , is always higher than the temperature of the reactor. Rearrangement yields the water flow required to heat up the reactor. Lumping the cooling and heating flows together gives the temperature fluctuation flow, ϕ_{fluc} . The energy requirements are determined via the extended Bernoulli equation, which is

$$E_{fluc} = \phi_{fluc} \left(4N_{fan} \left(\frac{L_{tube}}{D_{tube}} \right) \left(\frac{1}{2} \right) v_{fluc}^2 + gh_e \right) \quad (39)$$

Where E_{fluc} [J s⁻¹] is the energy requirement, N_{fan} is the fanning friction factor, L_{tube} [m] is the length of the tubing, D_{tube} [m] is the diameter of the tubing, v_{fluc} [m s⁻¹] is the superficial liquid velocity and g is the gravitational constant in [m s⁻²]. The superficial liquid velocity is determined as;

$$v_{fluc} = \frac{\phi_{fluc}}{A_t} \quad (40)$$

$$A_t = \frac{1}{4} \pi D_{tube}^2 \quad (41)$$

Where A_t is the cross sectional area of the cooling/heating tube. The fanning friction factor is dependent of the Reynolds number, which is determined as;

$$N_{fan} = \sqrt{\frac{16}{N_{re}}} \quad (\text{for laminar flows}) \quad (42)$$

$$N_{fan} = 0.079 N_{re}^{-0.25} \quad (\text{for turbulent flows}) \quad (43)$$

Equation 43 is known as the Blasius equation. The cost for cooling and heating is determined similar to equation 31,

$$cost_{fluc} = \frac{E_{fluc} ct_{kwh}}{3600000 P_r \eta_e} \quad (44)$$

Where η_e is the pump efficiency. The total rate of consumption for a flat plate reactor is determined as

$$cost_{total} = cost_{inflow} + cost_{blower} + cost_{fluc} \quad (45)$$

2.3. Physical processes tubular reactor

The tubular reactor is a cylinder with a length L and radius r . A schematic overview of a tubular reactor is given in figure 6,

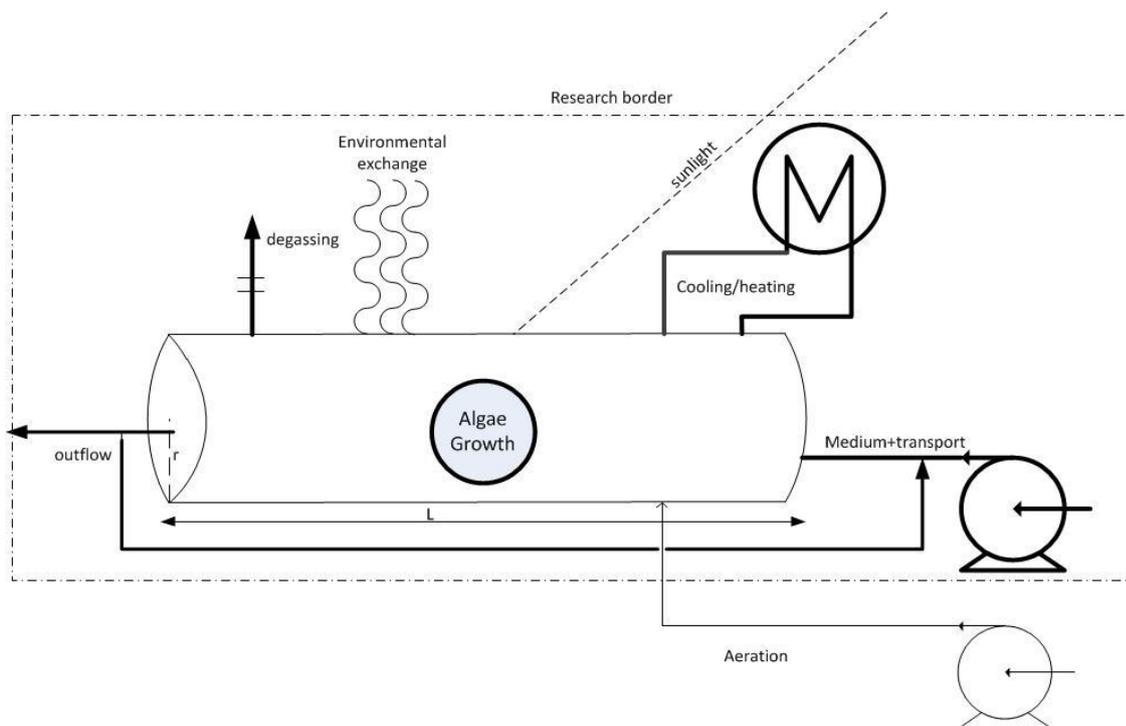


Figure 6: schematic overview tubular reactor

The CO_2 (aeration) entering the tubular reactor is injected directly from a pressured vessel. Therefore no energy is required for CO_2 transport through the pipe. The algae build up higher oxygen levels in the tubular reactor than in a flat plate or pond reactor. These higher oxygen levels are inhibiting the growth, which also limits the length of the tubular reactor. A degasser is required to remove the excess amount of oxygen. Cooling and heating of the tubular reactor is done by an evaporative cooler and a heat exchanger respectively, similar as the flat plate reactor, which is explained in section 2.2.2 and onwards. The biological processes and environmental exchange have been reviewed in section 2.1 and onwards.

2.3.1 Flow

The flow of the reactor is based on the Reynolds number. For minimal turbulent flow around spherical objects the flow requires a Reynolds number of at least 1000. The superficial liquid velocity follows from rearranging equation 22,

$$v_{h2o} = \frac{N_{re}\mu_{h2o}}{(2*r_{tube})\rho_{h2o}} \quad (46)$$

The flow inside the tube is then determined as,

$$\phi_{flow} = v_{h2o}A_t \quad (47)$$

Where A_t is the cross sectional area of the tube similar to equation 41. Friction occurs in the pipe due to recirculation. Two elbow pipes and two T-split piping are used for recirculation in the model. The energy required for the flow in the tube is determined by the extended Bernoulli equation including friction of the pipe for recirculation ,

$$E_{flow} = \frac{\left(4N_{fan}\left(\frac{L_{tube}}{D_{tube}}\right)\frac{1}{2}v_{h2o}^2 + \frac{v_{h2o}^2}{2g} \cdot 2(1.2+1.8)\rho_{h2o}g\right)\phi_{flow}}{\eta_e} \quad (48)$$

Where L_{tube} [m] is in straight part equivalent in meter and 1.8 and 1.2 are friction factors for the elbow pipe and T-split tubing respectively. The costs can be calculated by an equation similar to equation 31

$$cost_{flow} = \frac{E_{flow}ct_{kwh}}{3600000P_r} \quad (49)$$

2.3.2. Degassing

Oxygen can leave a flat plate system easier than a tubular reactor. These higher levels of oxygen in the tubular reactor are inhibiting the algae growth and eventually will decrease the production. A degassing unit is required to remove the excess amount of oxygen. A schematic overview of the degasser is given in figure 7.

Under steady state conditions the equilibrium of the degasser is given as,

$$\phi_{gas}(x_{air, out} - x_{air, in}) = \phi_{h2o}(x_{o2, in} - x_{o2, out}) \quad (50)$$

Where ϕ_{gas} is the gas flow in [m^3s^{-1}], x_{air} is the amount of oxygen in air in [$mol m^{-3}$] for the inflow and outflow of air in the degassing unit, ϕ_{h2o} is the broth flow and x_{o2} is the oxygen concentration in the broth entering and exiting the degasser. Equation 50 is based on certain assumptions, firstly the oxygen concentration in the liquid leaving the degasser ($x_{o2, out}$) is fixed. This is set as 0.3 [$mol m^{-3}$][6],

therefore this condition is always met. Secondly, the oxygen concentration of the air flow entering the degasser is equivalent to atmospheric conditions. Lastly, the outgoing oxygen concentration is considered as;

$$x_{air, out} = n_{max} x_{air, in} \quad (51)$$

Where n_{max} is a pre-specified amplitude of the inflow concentration to determine the maximum oxygen concentration in the outflow, disregarding the design of the degasser. Actual oxygen build-up in the tubular reactor is expressed as[15];

$$x_{O_2, in} = \frac{R_{O_2} L}{v_{h_2O}} + x_{O_2, out} \quad (52)$$

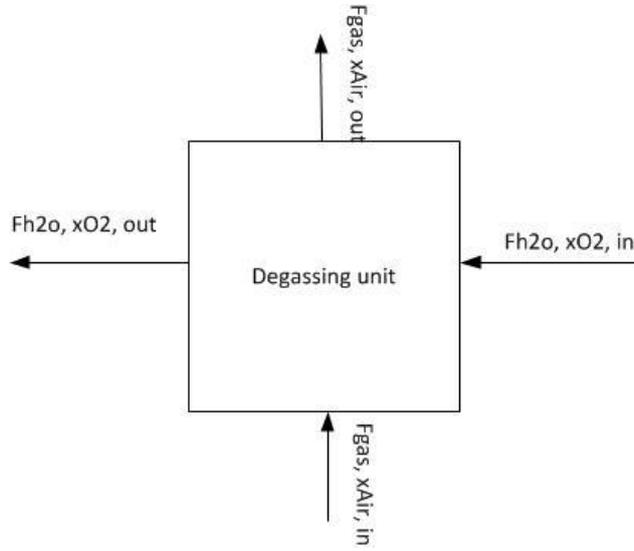


Figure 7: schematic overview of the degassing unit.

Where R_{O_2} is the oxygen generating rate, which is empirically determined as $0.003 \text{ [mol m}^3 \text{ s}^{-1}]$ [16], L_t is the length of the tube in [m] and v_{h_2O} is the superficial broth velocity in $[\text{m s}^{-1}]$. The required gas flow, ϕ_{gas} is determined by rearranging equation 50. The energy requirement is determined by the extended Bernoulli equation similar to equation 39,

$$E_{degas} = \phi_{gas} \left(4N_{fan} \left(\frac{L_{gastube}}{D_{gastube}} \right) \left(\frac{1}{2} \right) v_{gas}^2 + gh_e \right) \quad (53)$$

$$E_{degasnet} = \frac{E_{degas}}{\eta_e} \quad (54)$$

Where η_e is the pump efficiency, $L_{gastube}$ and $D_{gastube}$ are the length and diameter of the gas tubing respectively. The fanning friction factor, N_{fan} , is determined by equation 42 or 43, gh_e is the energy

requirement to overcome the water pressure in the degasser and v_{gas} is the superficial gas velocity of the gas [$m\ s^{-1}$], which is determined as

$$v_{gas} = \frac{\phi_g}{\frac{1}{4}\pi D_{gastube}^2} \quad (55)$$

The cost requirement is analogue to equation 44,

$$cost_{degas} = \frac{E_{degasnet} ct_{kwh}}{3600000 P_r} \quad (56)$$

2.3.3 determining the total energy requirement

The cooling and heating requirement are determined by equation 44 which is,

$$cost_{fluc} = \frac{E_{fluc} ct_{kwh}}{3600000 P_r \eta_e} \quad (57)$$

Together with equation 49 and 56 the total rate of consumption is determined as;

$$cost_{total} = cost_{degas} + cost_{fluc} + cost_{flow} \quad (58)$$

2.4 Physical processes pond reactor

The open pond reactor is the most commonly used type of an open photo bioreactor system, with an area A and a depth d . A schematic overview of an open pond reactor is given in figure 8,

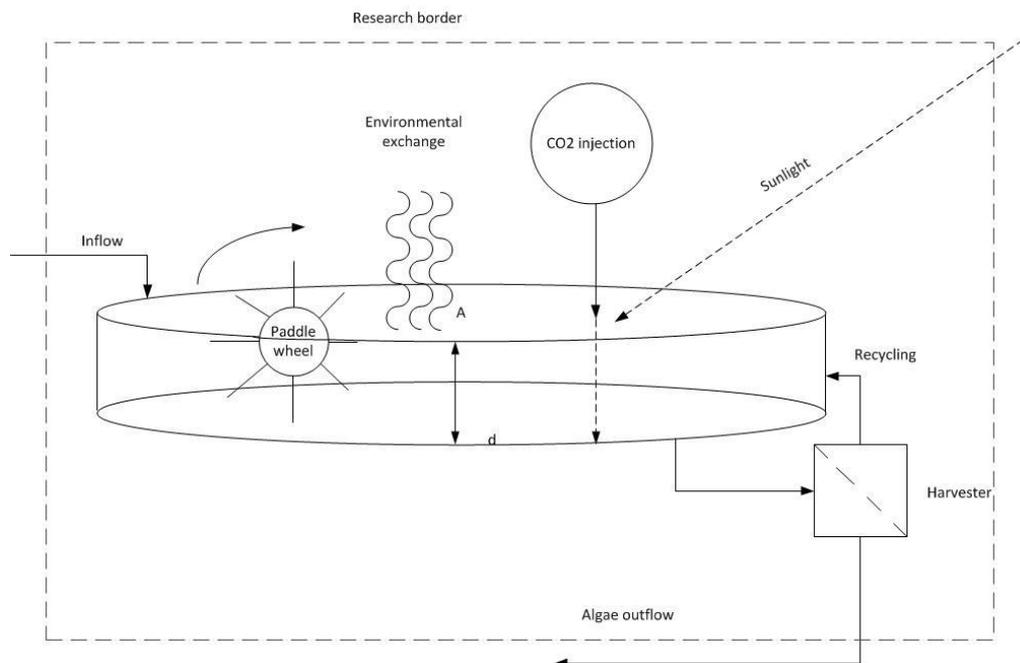


Figure 8: schematic overview of a pond reactor

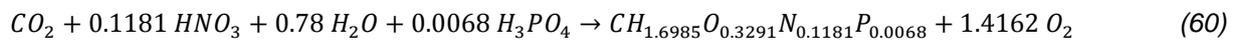
The open pond system has two distinguished geometrical shapes. It is either a man-made or a natural lake or a raceway system. To compensate for the production outflow (equation 3) and the evaporation, an inflow pump is required. After the cultivation step (both open and closed systems), a harvesting step occurs. The algae concentration in pond reactors is significantly lower than in closed systems, to compensate for this in analysis, a harvesting step is included in the pond reactor to compensate the cost requirement for more insight in comparison with the closed system. Finally a paddle wheel is required for stirring and degassing. CO₂ has to be injected to compensate for the CO₂ requirements. The water entering the open pond due disturbances in the weather (rain, snow, etc.) has not been considered as such data was not available.

2.4.1 Energy requirement of the paddle wheel and CO₂ injection

The paddle wheel roughly uses² 5000 W ha⁻¹ or 0.5 W m⁻². The energy cost to run the paddle wheel is therefore,

$$cost_{paddle} = \frac{0.5A_{pond}ct_{kwh}}{3600000 P_r} \quad (59)$$

Where A_{pond} is the surface area of the pond reactor [m²]. The CO₂ requirement is linked to the stoichiometric requirement of the algae, as the aeration is not required for the pond reactor. The stoichiometric growth equation of *P. Tricornutum* is



Where $CH_{1.6985}O_{0.3291}N_{0.1181}P_{0.0068}$ is the representation of the algae. This implies that 1 mol of CO₂ is used for 1 mol of algae.

The CO₂ inflow is determined as;

$$\phi_{CO_2} = \frac{y_{sur}P_rV}{p_{CO_2}} \quad (61)$$

Where y_{sur} is a surplus factor of CO₂ and p_{CO_2} is the density in [kg m⁻³]. The energy requirement for the CO₂ is then determined by the extended Bernoulli equation similar to equation 39;

$$E_{CO_2} = \phi_{CO_2} \left(4N_{fan} \left(\frac{L_{tubeCO_2}}{D_{tubeCO_2}} \right) \left(\frac{1}{2} \right) v_{CO_2}^2 + gd \right) \quad (62)$$

The Fanning friction factor, N_{fan} , is determined by equation 42 or 43, L_{tubeCO_2} and D_{tubeCO_2} are the length and diameter of the supply tube of CO₂ respectively. gd is the term to overcome the water pressure of the reactor. v_{CO_2} is the superficial gas velocity, which is determined similar as equation 55.

²Personal communications Norsker June 2011

The cost equation is applied, which is analogue to equation 46;

$$cost_{CO2} = \frac{E_{CO2}ct_{kwh}}{3600000P_r\eta_e} \quad (63)$$

2.4.2 Energy requirements for the inflow and outflow

The inflow of the reactor is determined by the production and evaporative losses such that,

$$\phi_{inflow,bruto} = \frac{P_r}{C_x} + \frac{Q_{evaporation}}{\Delta H_v} \quad (64)$$

Where $Q_{evaporation}$ is the evaporation energy loss and H_w is the evaporation energy of water in $[J\ m^{-3}]$

Due to the harvester the inflow is reduced as the outflow is concentrated. The removed water from the harvester is returned to the pond, which will decrease the inflow. The reduction ratio is determined as

$$ratio = \frac{C_x_{harvested}}{C_x_{pond}} \quad (65)$$

Which gives the new inflow as

$$\phi_{inflow} = \frac{\phi_{inflow,bruto}}{ratio} \quad (66)$$

The evaporation heat loss is determined by [5]

$$Q_{evaporation} = A_{pond}h_{evaporation}(e_s - e_a) \quad (67)$$

Where $h_{evaporation}$ is the evaporative transfer function, e_s is the saturated water pressure and e_a is the saturated air pressure, which are determined as[5],

$$h_{evaporation} = 0.036 + 0.025v_{air} \quad (68)$$

$$e_a = RH \cdot 611.21e^{\frac{17.502T_a}{240.97+T_a}} \quad (9)$$

$$e_s = RH \cdot 611.21e^{\frac{17.502T_{h_2O}}{240.97+T_{h_2O}}} \quad (69)$$

Where T_a and T_{h_2O} are the ambient and water temperature respectively and v_{air} is the wind velocity in $[m\ s^{-1}]$. The energy requirement for the inflow is determined by the Bernoulli equation similar to equation 62

$$E_{inflow} = \frac{\phi_{inflow} \left(4N_{fan} \left(\frac{L_{tubeinflow}}{D_{tubeinflow}} \right) \left(\frac{1}{2} \right) v_{inflow}^2 \right)}{\eta_e} \quad (70)$$

Where the superficial inflow velocity is determined as equation 55.

Harvesting the algae with the purpose of concentrating the algae outflow stream is done by a separator, which costs 1.1 Kwh m^{-3} [10]. It is assumed that this energy requirement includes recirculation of the excluded water as well. Therefore the cost for the inflow and outflow is determined as,

$$cost_{inflow} = \frac{(E_{inflow})ct_{kwh}}{3600P_r} \quad (71)$$

$$cost_{outflow} = \frac{E_{outflow}ct_{kwh}}{P_r} \quad (72)$$

The total rate of consumption for the pond reactor then

$$cost_{total} = cost_{paddle} + cost_{CO2} + cost_{inflow} + cost_{outflow} \quad (73)$$

2.5 Reference scenarios

In order to compare the energy consumption of the three models with each other, the rate of consumption of energy per kilogram dry weight of algae is determined. A harvesting step is implemented for the open pond reactor, to compensate for the low biomass concentration in comparison with the closed systems. Every ten minutes a weather data point from 2009 was taken [17], to provide the environmental conditions of the model. The data concerned the biomass production, sunlight, wind velocity, relative humidity and the ambient temperature. The models are compared on their efficiency, which is shown as their *Netto Energy Ratio* (NER). The NER is determined as,

$$NER = \frac{P_r \Delta H_{algae}}{E_{total}} \quad (74)$$

Where ΔH_{algae} is the combustion energy of algae and E_{total} is the total energy demand of the reactor. When the NER is smaller than 1, the produced energy from the algae is not enough to sustain the variable energy cost and is therefore not efficient. The simulations run in MatLAB (version 2011A). The program is administered at the system and control group of Wageningen University and Research.

2.5.1 Scenarios for the flat plate photobioreactor

The reactor is located in the Netherlands and is cultivating *P. Tricornutum*. Table 2 describes the input variables for the flat plate photobioreactor. In the reference scenario of the flat plate reactor the volume of the reactor is 30 L and is based on Slegers et al. [4] reference case;

Table 2: Reference scenario flat plate reactor

Variable	Base case value	Unit
Cx	2	Kg m ⁻³
Width	1	m
Height	1	m
Lightpath	0.03	m
T reactor	18	°C
Cooling tube length	100	m
Cooling tube diameter	0.25	m
Pump efficiency	0.4	-

2.5.2 Scenarios for the tubular photobioreactor

The reactor is located in the Netherlands and is cultivating *P. Tricornutum*. Table 3 describes the input variables for the tubular photobioreactor. The volume of the tubular reactor is 300L. The reference scenarios of the tubular reactor is based on van Beveren[6] reference case

Table 3: Reference scenario tubular reactor

Variable	Base case value	Unit
Cx	2	Kg m ⁻³
Reactor radius	0.03	m
Reactor length	100	m
T reactor	18	°C
Degas tube	100	m
Degas diameter	0.06	m
Air out amplitude	2.0	-
Cooling tube length	100	m
Cooling diameter	0.06	m
Pump efficiency	0.4	-

2.5.3 Scenarios for the pond reactor

The reactor is located in the Netherlands and is cultivating *P. Tricornutum*. Table 4 describes the input variables for an open pond reactor. The harvester increases the concentration to 3 [Kg m⁻³] and uses 1.1 [Kwh m⁻³]. The reference scenario of the open pond reactor is based on Lösing[5] reference case

Table 4: Reference scenario pond reactor

Variable	Base case value	Unit
Cx	0.3	Kg m ⁻³
Pond depth	0.3	m
Pond area	5000	m ²
Length CO2 pipe	100	m
CO2 pipe diameter	0.06	m
Surplus CO2	1.4	-
Pump efficiency	0.4	-

3. Results

For the three systems the energy costs per kilogram biomass, the most energy cost intensive process and the netto energy efficiency are calculated. The reference scenarios of section 2.5 have been used to investigate the changes in the energy consumption when changing input variables. The investment costs of the reactor have been disregarded.

3.1 Results flat panel photobioreactor

The production of the flat plate reactor varies with lightpath and the concentration as shown in figure 9[4]. The reactor has an certain optimum production depending on the concentration and lightpath, which is around 11 [Kg panel⁻¹ year⁻¹]. Increasing the concentration results in a decrease of production, due to the algae biomass being too dense to receive enough light. In extreme cases, this respiration may overrule the growth of the algae culture,

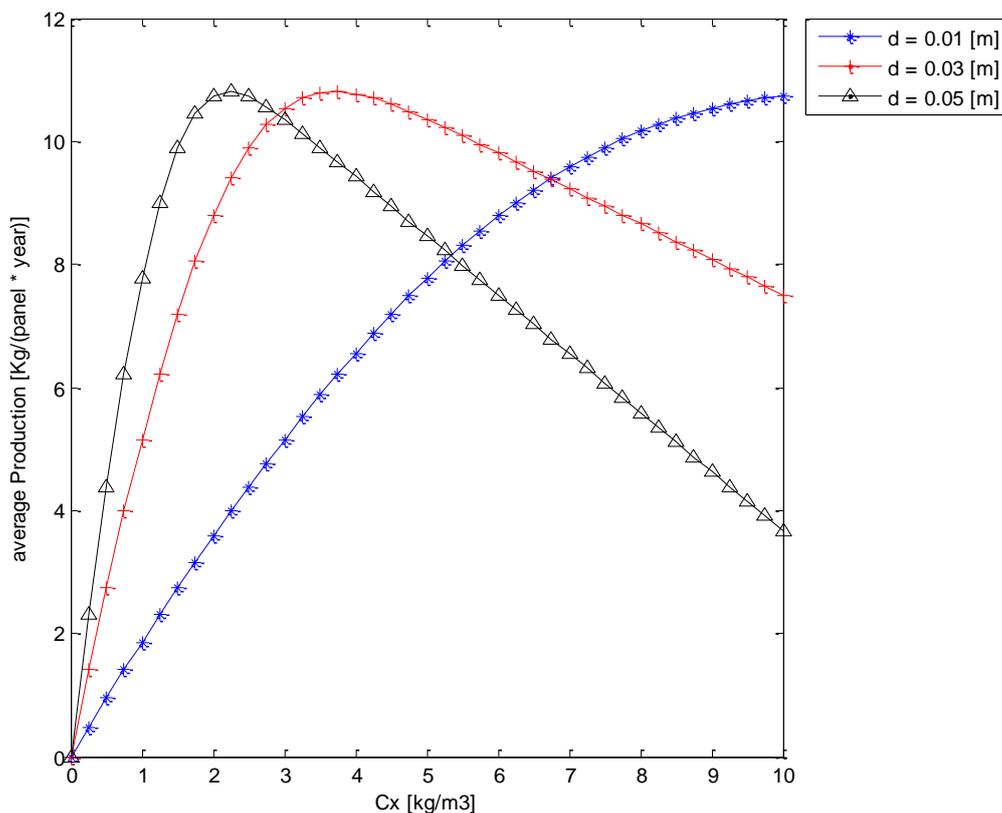


Figure 9: yearly production of biomass in a flat plate reactor with for different distances between the plates based on Slegers[4]
The energy costs for biomass production is independent of the production, but it is influenced by the volume. The energy consumption linearly increases with the volume as shown in figure 10.

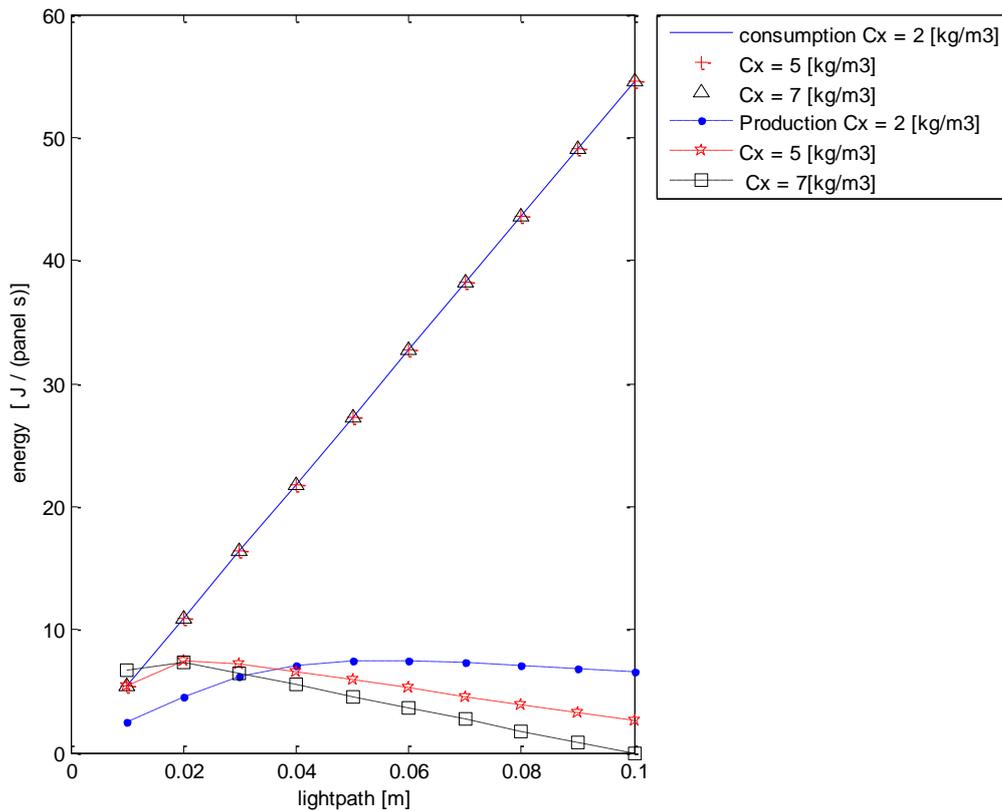


Figure 10 average energy production content of the produced algae and energy consumption per panel per second with different biomass concentration

The produced energy content of the algae does not linearly increase with volume. The increased density of the algae culture and the longer lightpath are decreasing the available light for the algae, shown as well in figure 9. The energy production is not enough to overcome the reactor consumption, which shows that the reactor is not able to run sustainable. Decrease of energy production occurs after the maximum production conditions.

The energy efficiency of the reactor is given by the NER, which is the ratio between the produced energy and consumed energy. For a $NER > 1$ the reactor produces more energy than it consumes. In figure 11 the NER is shown with a fixed lightpath for a varying concentration.

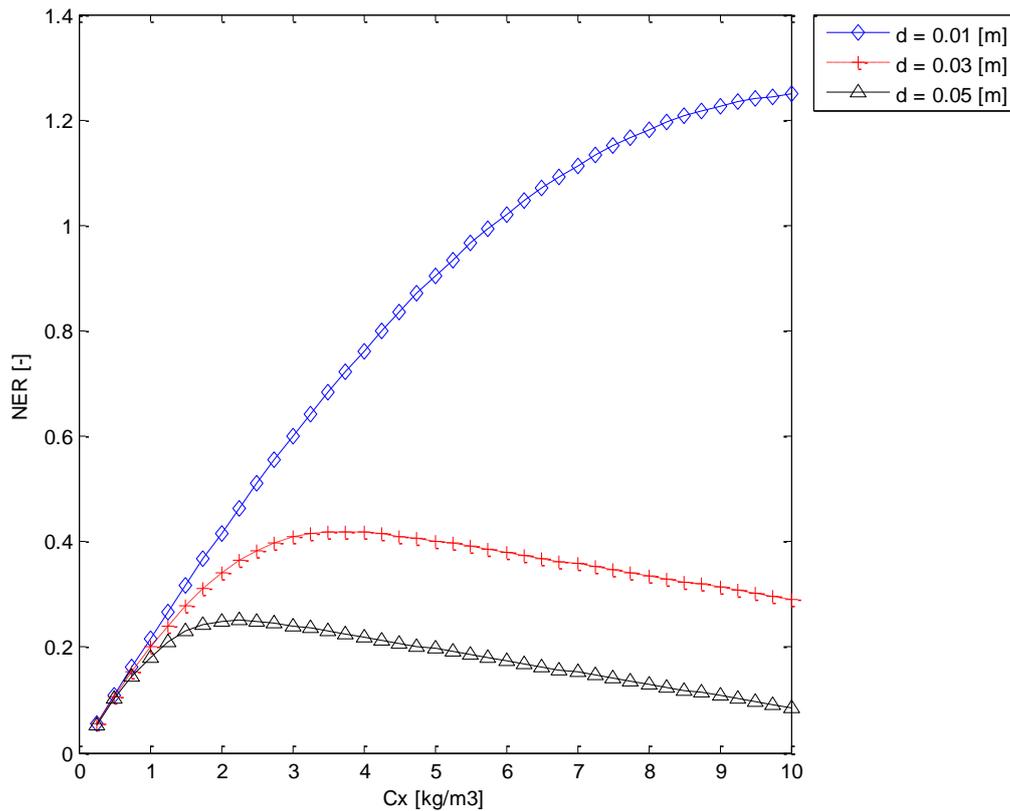


Figure 11: yearly average NER for flat plate configurations for different lightpaths

The efficiency of the reactor increases significantly when the lightpath is small (< 0.01 [m]), in combination with a high biomass concentration. The NER for the reference scenario 0.36. The high NER for small lightpath is due to the low energy consumption, as shown in figure 10, but gains enough light to sustain a high biomass concentration and therefore able to produce enough energy to keep a $NER > 1$. Larger lightpath show a significant in energy consumption, but the maximum biomass production remains constant as shown in figure 9, which is why flat plate reactors with a larger lightpath (> 0.01 [m]), have a significant decrease in NER.

Figure 12 shows the energy costs required to produce a kilogram of algae. By increasing the lightpath, a larger volume has to be mixed (by aeration). The blower is therefore consuming more energy for larger lightpaths. For low lightpaths the inflow of new medium requires the most energy, for the most commonly used lightpaths (0.02 – 0.05 [m]) the blower requires the most energy for the production of biomass.

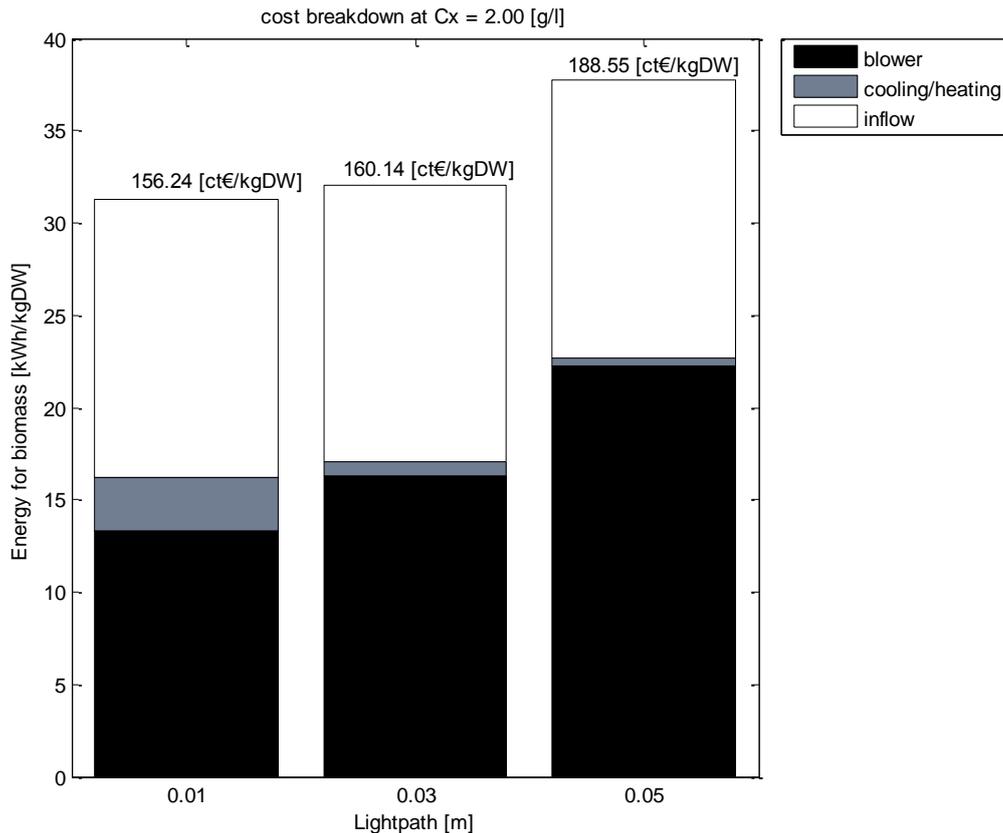


Figure 12: energy cost breakdown by aeration, cooling and inflow of new medium for a panel for the production of one kilogram of algae

The increased effect of cooling/heating for a lightpath 0.01 [m], is due to a discontinuity of determining the fanning friction factor from equation 42 and 43. Due to the transition between laminar and turbulent flow the fanning friction factor can be up to six time higher for laminar flows than for turbulent flows, which causes the elevated contribution.

Figure 13a shows the energy efficiency for producing *P. Tricornutum* as a function of the lightpath and the concentration, whereas figure 13b shows the efficiency for *T.Pseudonana*, another algae species, which grows slower and requires more sunlight for its metabolism. It is shown that choosing a fast growing algae species has a significant effect on the energy efficiency. The growth of *T.Pseudonana* is more affected with the change of lightpath than *P.Tricornutum*. Therefore has a lower energy efficiency as well. The optimum production *T.Pseudonana* is lower as well, which is not able to produce as much energy as the *P.Tricornutum*, which explains the lower efficiency.

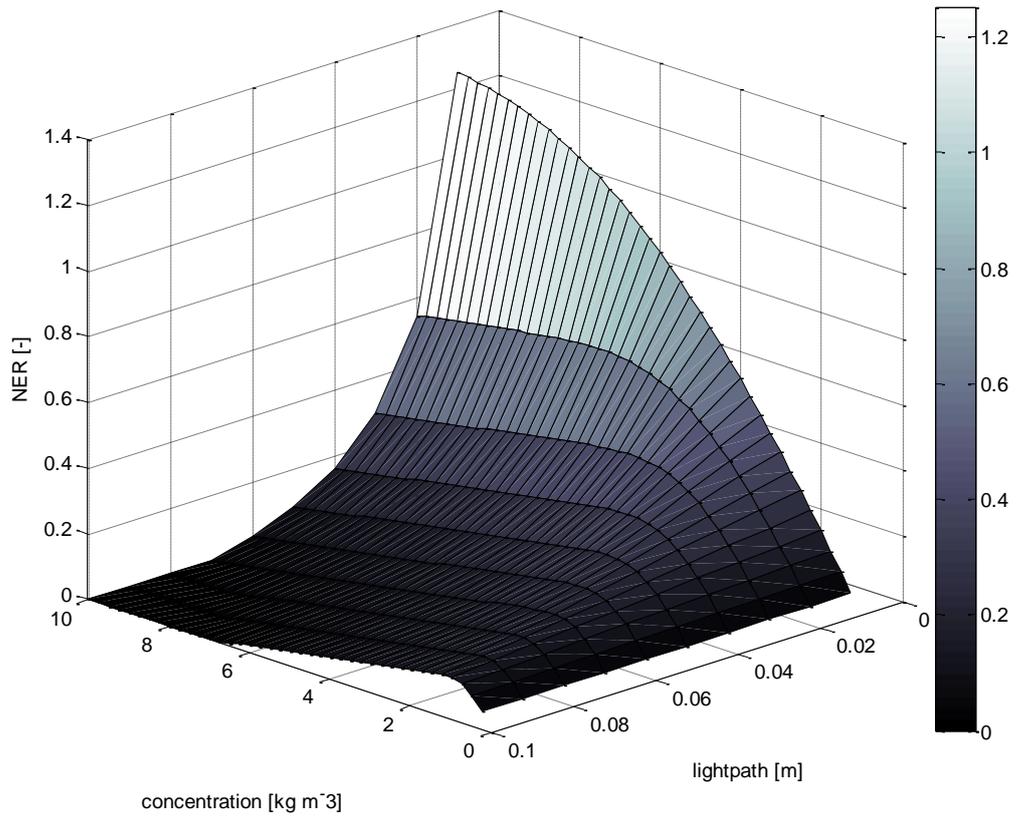


Figure 13a: the efficiency of producing *P.tricornutum* as yearly average.

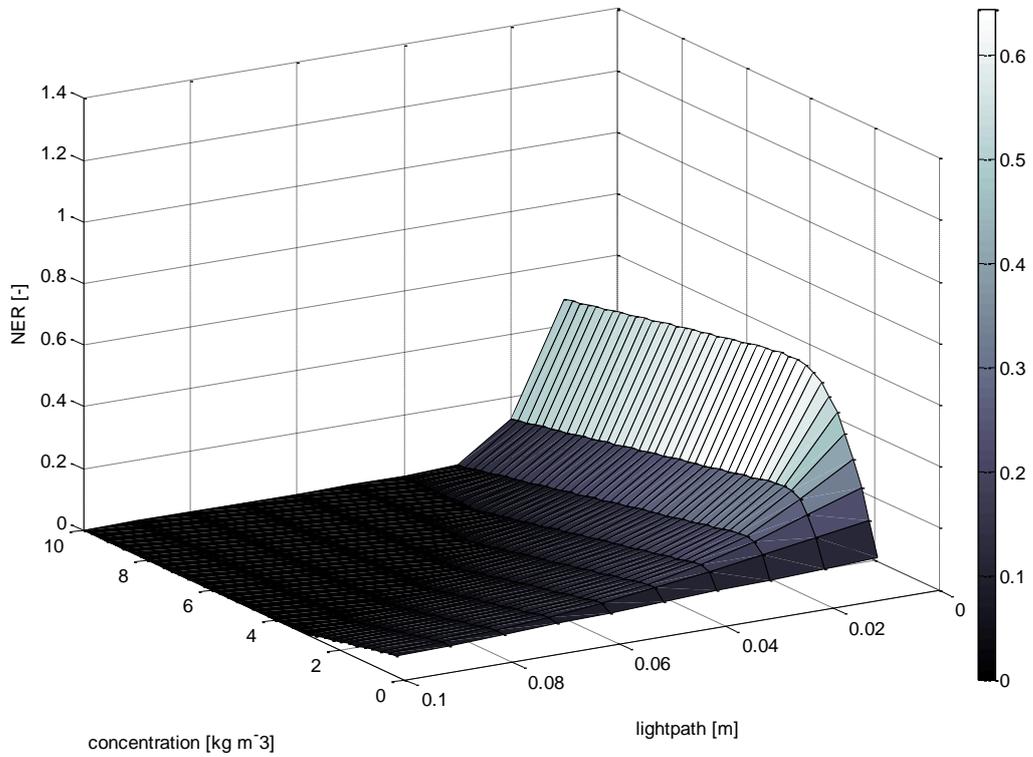


Figure 13b: The efficiency of producing *T.pseudonana* as yearly average.

3.2 Results Tubular reactor

The production of the tubular reactor varies with lightpath (tube radius) and the concentration as shown in figure 14 [6].

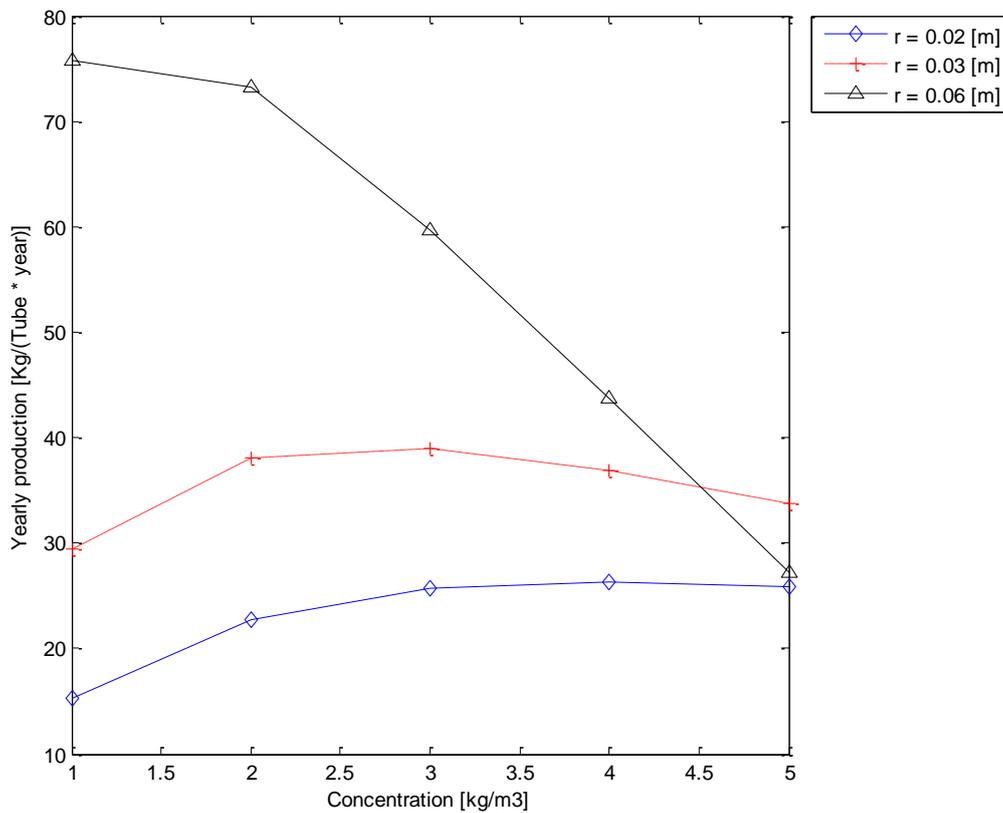


Figure 14: yearly production of algae for a 100 [m] tube with as function of concentration and radius based on van Beveren [6]

The production is increasing with a larger lightpath, due to an increase of production volume. When the culture becomes too dense, the production decreases sharply, due to a shortage of available light . The optimum production of the algae shifts to the right with a decreasing radius.

The energy required to produce algae is dependent on the volume. In figure 15 the energy required for production and the energy contained by the produced algae is shown.

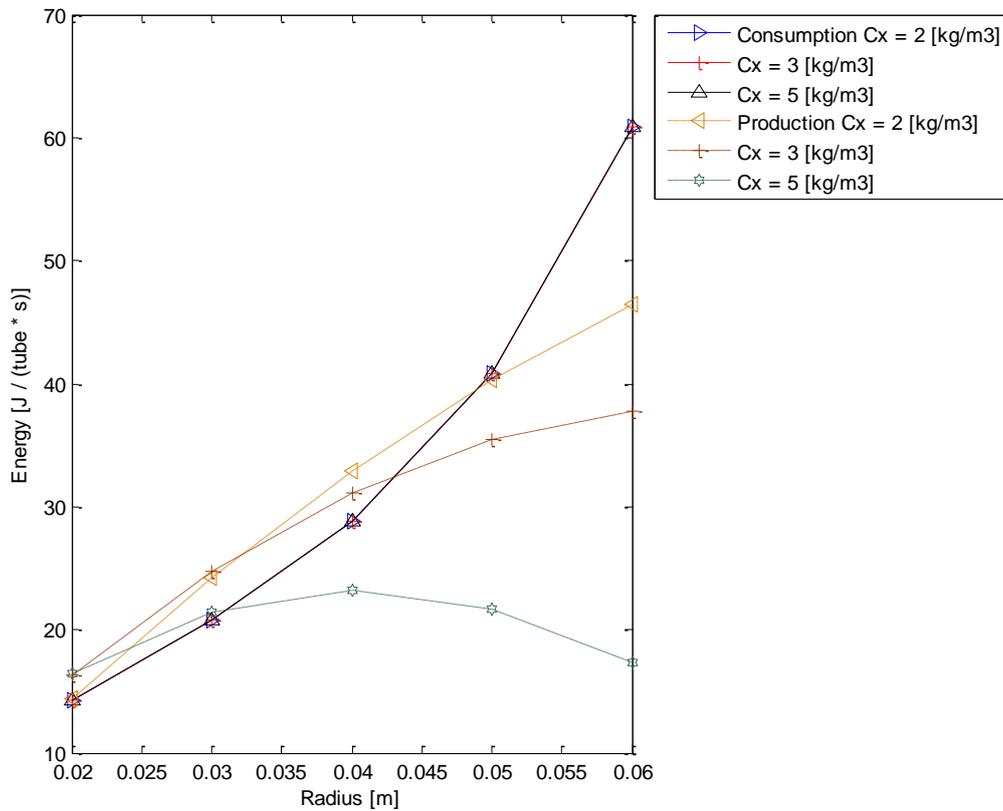


Figure 15: energy consumption and the energy contained by the produced algae for a 100 [m] tube.

The energy consumption of the tubular reactor is increasing exponentially with a larger radius. The increase of the energy consumption is due to the larger volume within the tube, which has to be recirculated, which is simulated with equation 47. The increase of the radius has an exponential effect on the amount of liquid that has to flow through the pipe. A longer radius is extinguishing 'the available light for the algae as well, which decreases the growth of the algae and therefore the produced energy. The concentration of the reference scenario ($Cx = 2 \text{ [kg m}^{-3}\text{]}$), has a breakeven point with a radius of 0.05 [m].

In figure 16 the NER is shown with a fixed lightpath for a varying concentration.

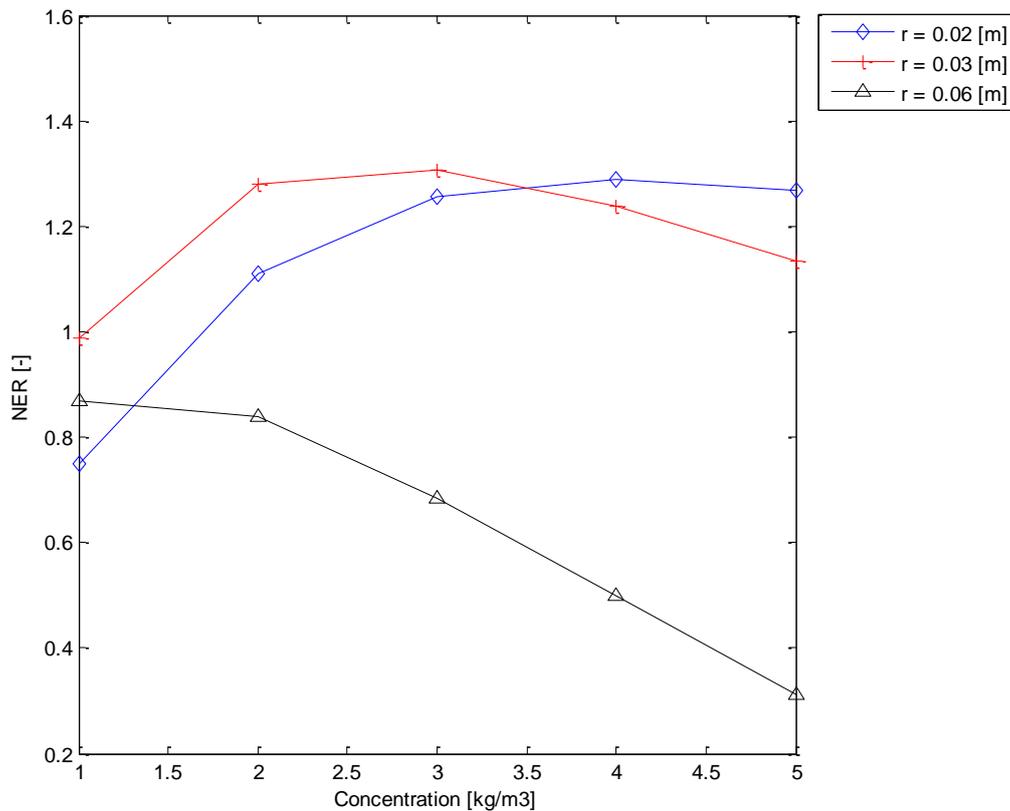


Figure 16: yearly average NER for tubular reactor configurations with different lightpaths for a 100 [m] tube

The tubular reactor with a large lightpath ($r > 0.06$ [m]) has a $NER < 1$, whereas the reactors with smaller lightpath ($r < 0.03$ [m]) do show the potential to run with a $NER > 1$. A larger radius increases the energy consumption of the tubular reactor, as shown in figure 15, but due to light extinction and higher biomass concentration the algae production is decreasing. The reference scenario has a NER of 1.3, which is above the energy neutral point. The length of the tube has an influence on the efficiency as well, which is shown in figure 17.

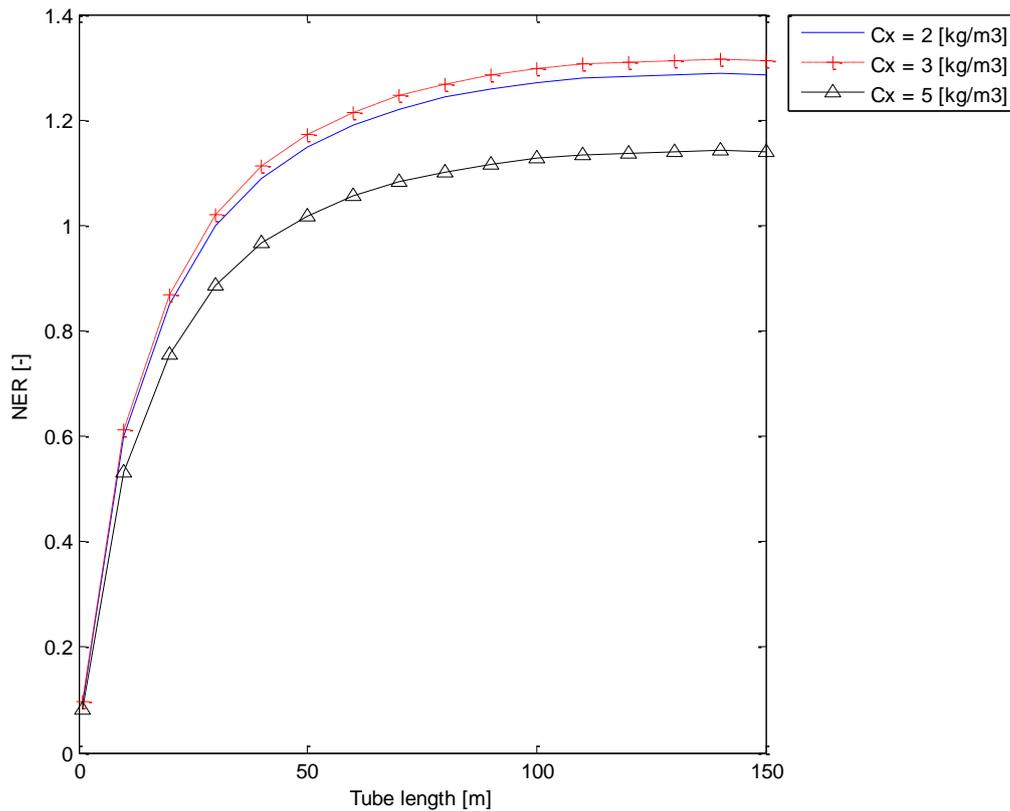


Figure 17: average yearly NER for tubular reactor with a radius of 0.03[m] with varying length

The length has a significant influence on the efficiency. A short tube has a lower algae production than a longer tube, but the energy demand increases as well with increasing tube length. To achieve a $NER > 1$, a tube of at least 40 [m] should be used for the reference scenario. Longer tubes build up more oxygen according to equation 52, which consumes more energy with increasing tube length. In order to determine the most energy intensive process of the tubular reactor, the energy required to produce one kilogram of algae is given in figure 18 for every processing unit.

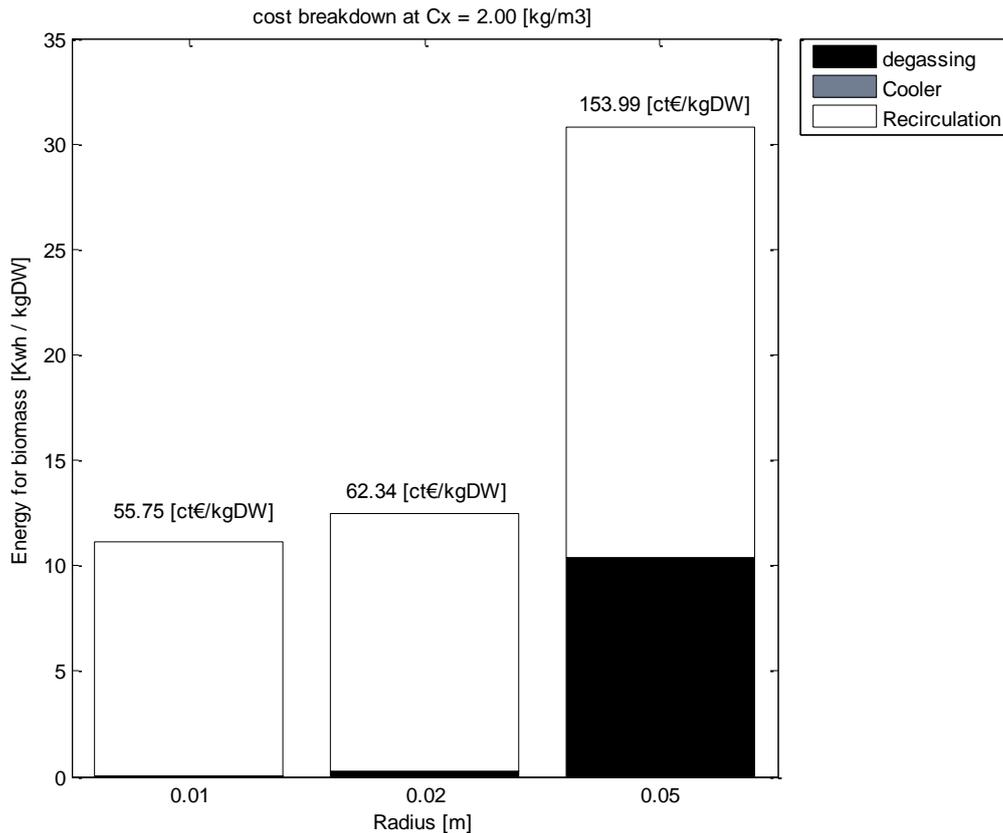


Figure 18: energy requirement for producing a kilogram algae breakdown to degassing cooling/heating processes and liquid recirculation

Recirculation and degassing have the major contribution to the energy requirement. The cooling has little to no influence on the energy consumption per kilogram algae, due to the large surface area the tubular reactor has to cool. The increase of radius increases the volume of the reactor, which increases the demand on the recirculation pump. As shown in figure 14, the production sharply decreases with the increase of the radius, which increases the energy requirement per kilogram algae. The energy demand of the degasser changes with the length of the reactor rather than with a larger radius, due to the longer residence time of the algae in which more oxygen can be build up as explained earlier. The efficiency of the effect of the tube length and the efficiency of the degasser as shown in figure 19;

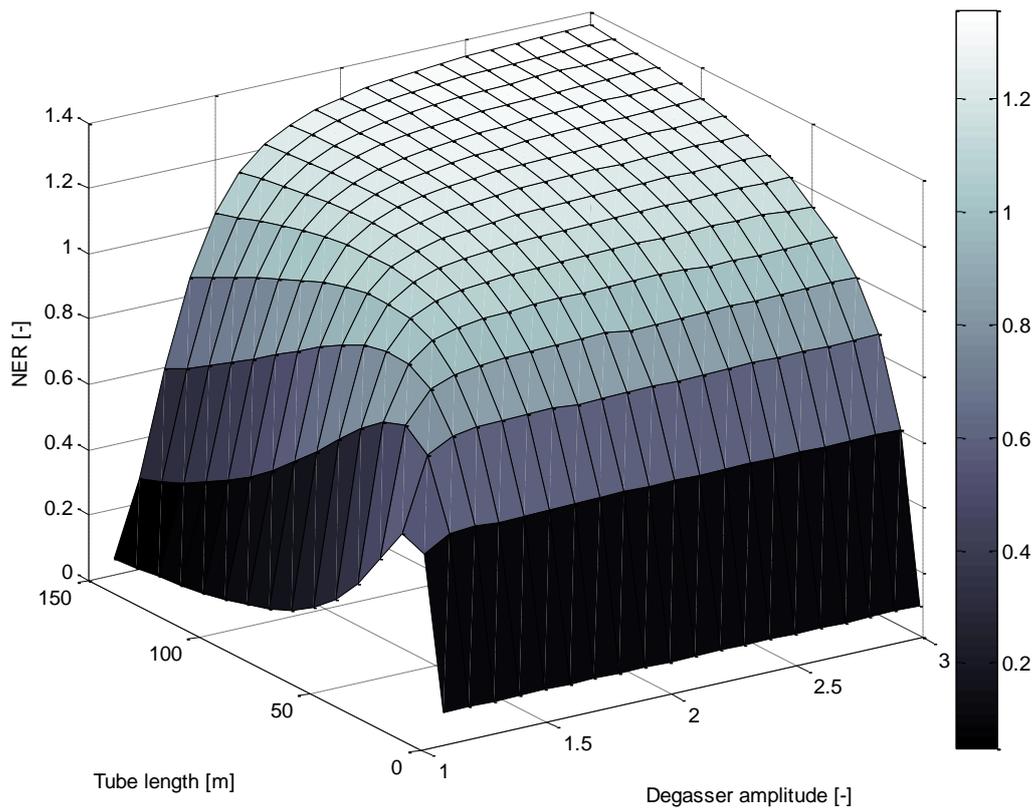


Figure 19: The influence of the degasser on the yearly average NER with radius of 0.03 [m].

The degassing amplitude is the ratio between the oxygen level in the inflowing air and the outflowing air. A degassing amplitude of 2 implies that the oxygen concentration in the outflowing air is twice as high than in the inflowing air, such as is formulated in equation 51. The efficiency of the reactor sharply decreases when the amplitude of the degasser is below 1.4. The degassing energy demand shows no significant change when the amplitude is 2 or higher (which is commonly used). Therefore a good operating (clean) degasser is required to keep the tubular reactor efficient. A tube which is too long, shows a decrease in NER, when the degasser has to remove too much oxygen.

Figure 20a shows the efficiency of the reactor as a function of the concentration and the radius for *P. Tricornutum*. Figure 20b shows the efficiency of the reactor as a function of the concentration and the radius as well, but for *T. Pseudonana*, which is a different algae species. *T. Pseudonana* requires more energy and sunlight to grow. The effect is significant, as the growth rate of *T. Pseudonana* is lower than *P. Tricornutum*. The energy production is therefore lower as well, which influences the efficiency of the reactor.

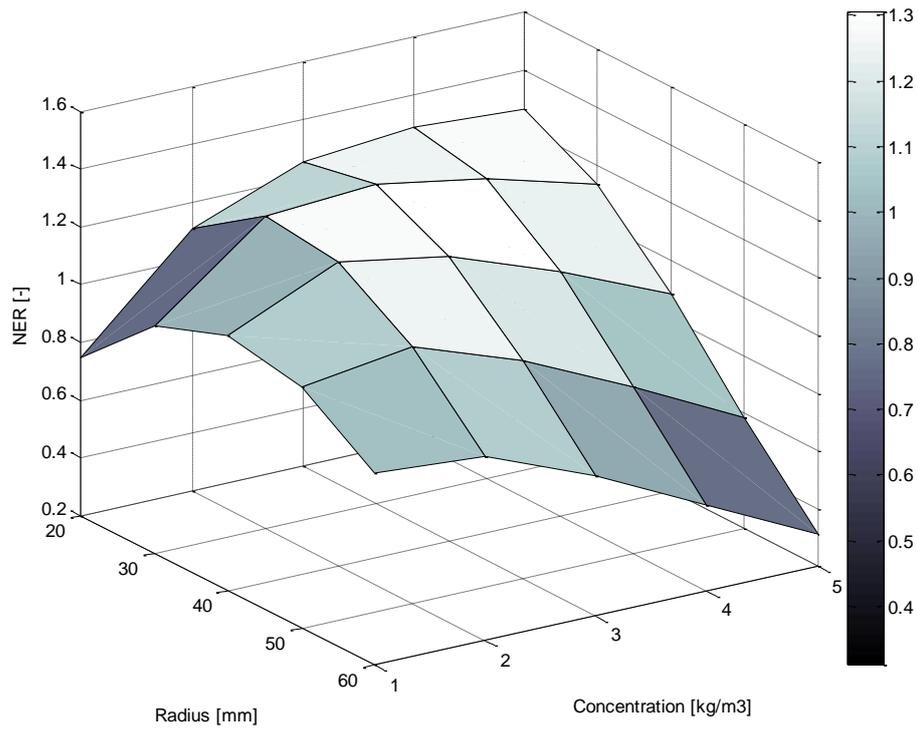


Figure 20a: the efficiency of producing *P.tricornutum* as yearly average.

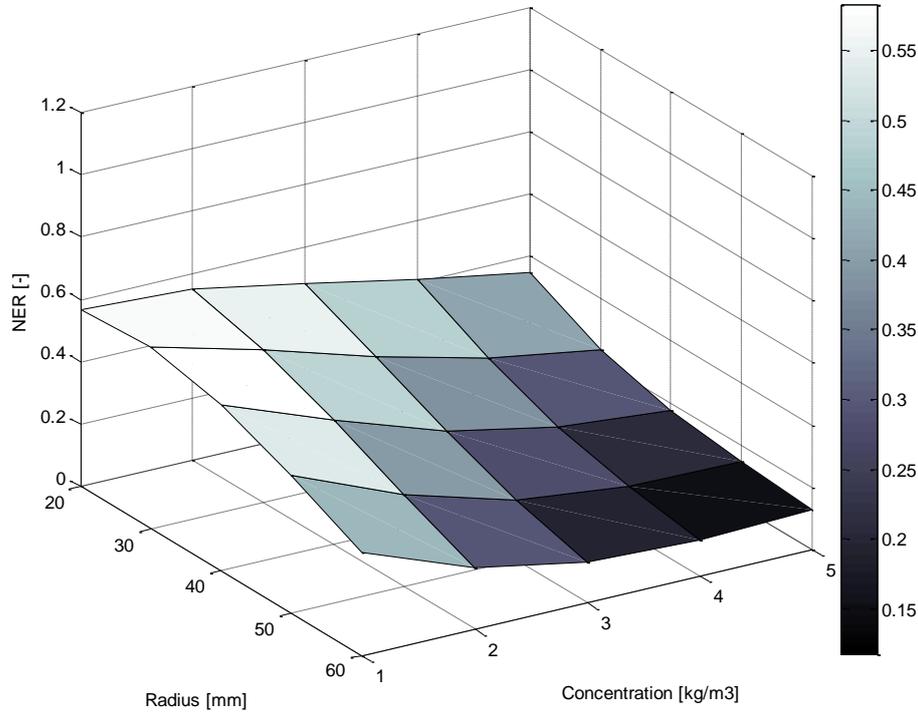


Figure 20b: The efficiency of producing *T.pseudonana* as yearly average.

3.3 Results Open pond reactor

The production of an open pond reactor varies with the concentration and pond depth as shown in figure 21. The growth of algae is according Lösing[5],

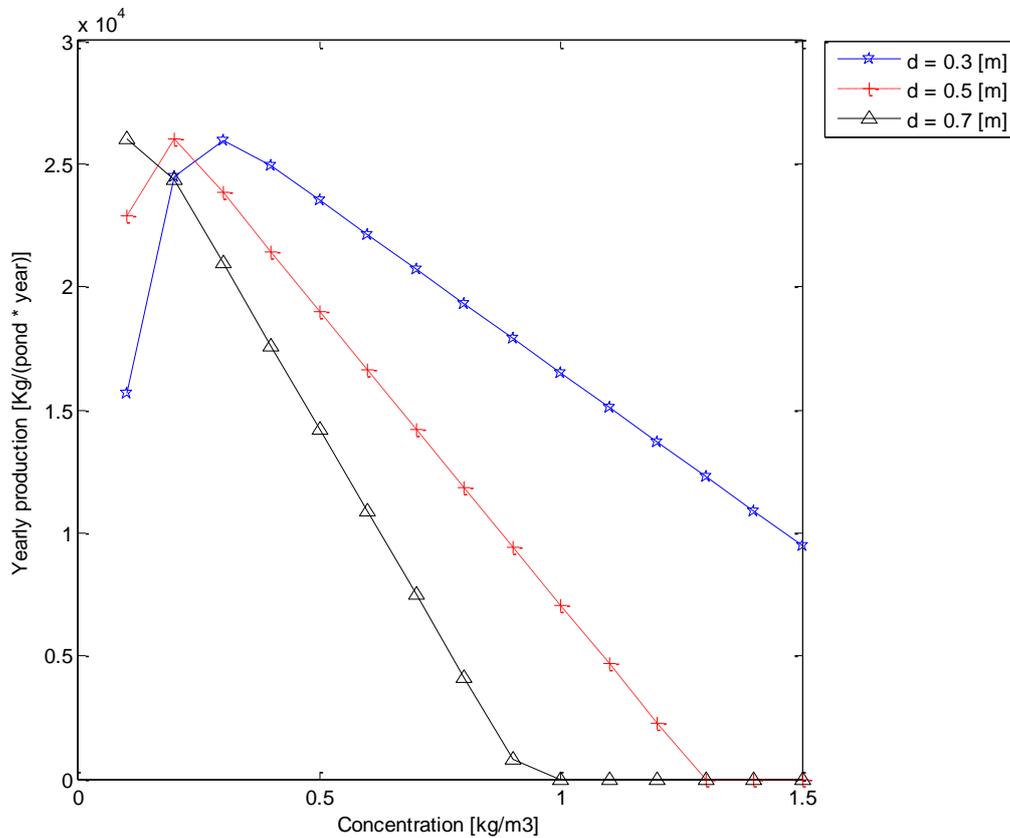


Figure 21: yearly production of the open pond reactor according to Lösing [5] with a 5000 [m²] surface.

The maximum production of an open pond reactor with a surface of 5000 [m²] is 26 tons per year at the optimum configuration. Due to the lower concentration of a pond reactor, the commonly used reactors are significantly larger than a flat plate or a tubular reactor system. The production decreases when the concentration increases in combination with a larger lightpath (depth). In extreme cases the respiration of the algae may overrule the production, which leads to decreased production. The pond reactor has a larger lightpath than the closed photo bioreactors. Norsker [10] discusses that due to size of the paddle wheel the depth of the reactor should be at least 0.2-0.3 [m]. Smaller depths of the reactor are therefore not considered.

The energy requirement of the pond reactor is independent of the concentration and depth of the reactor, but the production of algae is dependent on the concentration and depth, which is shown in figure 22,

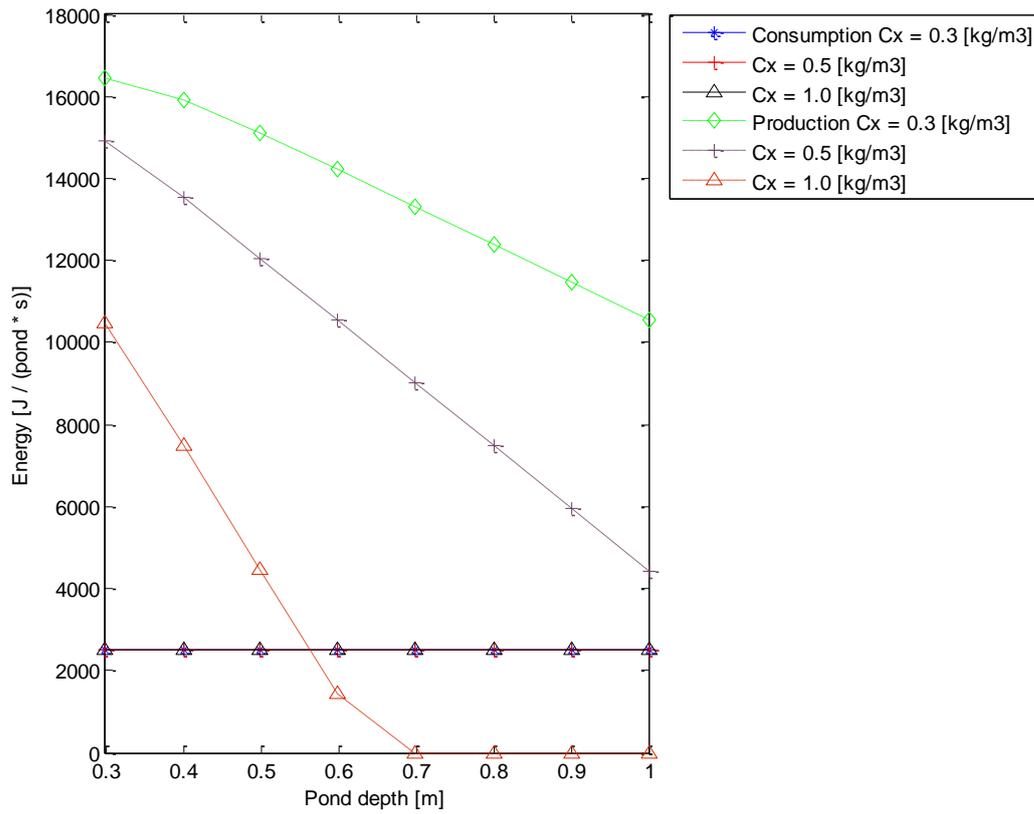


Figure 22: the energy contained by production of algae and the consumption of the algae reactor for a 5000 [m²] surface pond reactor.

While it seems that the energy consumption does not increase in figure 22, the consumption should increase slowly due to increase pressure head due to larger lightpath (pond depth). The pond reactor consumes less energy that the amount of algae can produce, which makes the pond reactor an energy efficient reactor. This is shown better in figure 23, where the NER is shown for different pond depths,

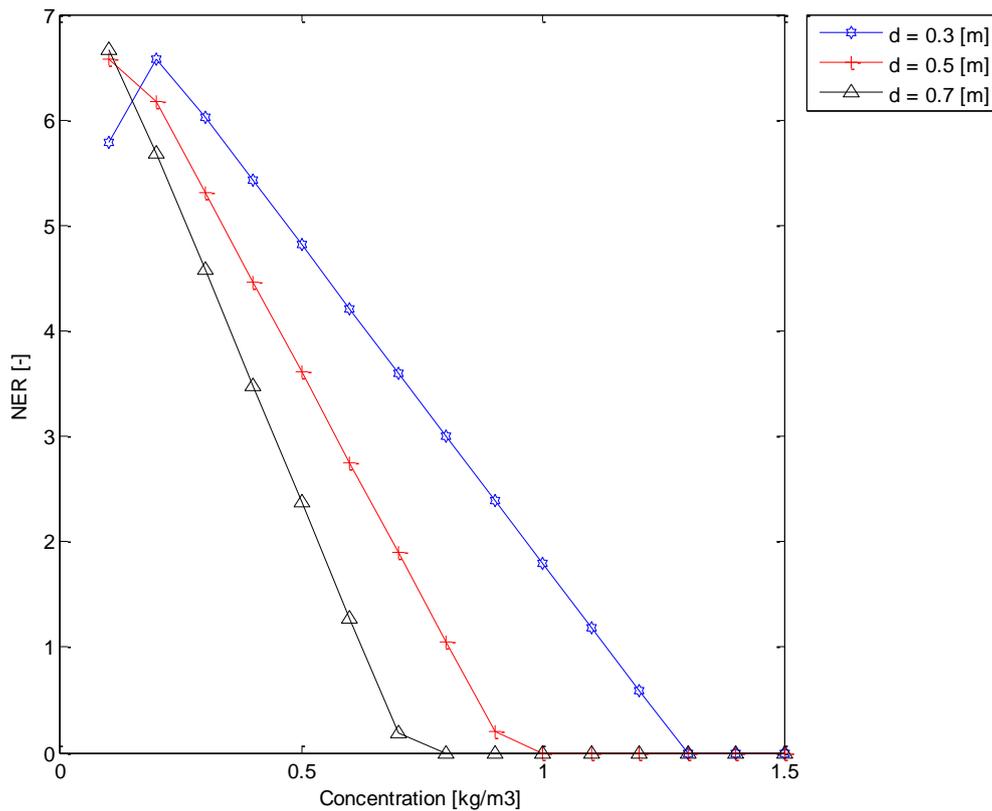


Figure 23: NER with an open pond reactor is a 5000 [m²] surface, for different reactor depth (d)

A reactor with a high lightpath ($d = 0.7$ [m]) in combination with a low concentration still has a $NER > 2$. A lower lightpath ($d = 0.3$ [m]) needs a higher concentration to reach its optimum production as shown in figure 21, but does not necessarily means that its NER can be improved significantly. The lower maximum NER for a pond depth of 0.3 [m] is due to the lower maximum algae production in comparison with the other pond depths. A NER of 6.5 is the highest possible efficiency under these conditions. the NER of the reference scenario is 6.27, which shows that the reactor is able to run efficiently.

The energy cost for the production of a kilogram biomass is shown in figure 24, to determine the most energy intensive process.

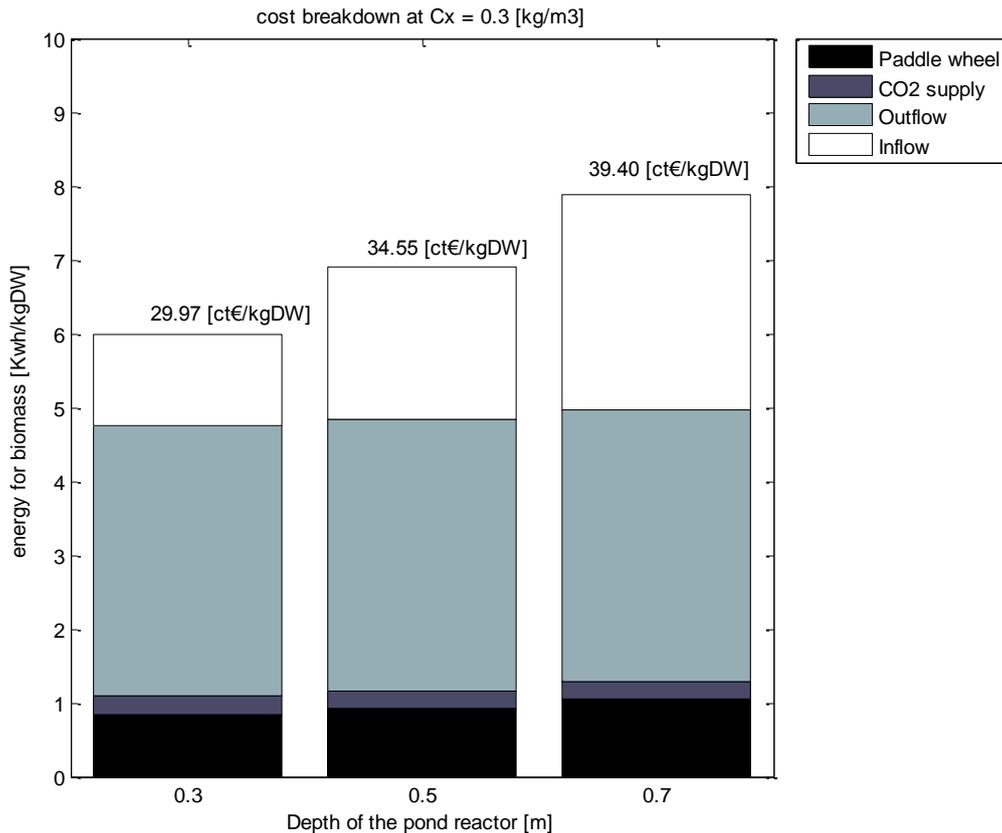


Figure 24: Energy demand for producing a kilogram algae

The outflow and therefore the harvester is using the most energy is therefore the most energy intensive process of the open pond reactor. Increasing the depth of the reactor increases the amount of energy the inflow and CO₂ supply required. This is due to the water head pressure increases, which requires more energy to overcome. All other processes consumes a relative constant amount of energy.

Figure 22 suggests however that the paddle wheel (Which consumes 2500 W in a 5000 [m²] reactor) is dominating. Due to the low concentration the reactor requires the most energy for the paddle wheel, due to the large amount of volume in the reactor, but produces little amount of biomass. Therefore the harvester has to use more energy to produce a kilogram of algae biomass, which increases the amount of energy the harvester requires to thicken the biomass, which is more energy than to keep the medium flowing.

The NER can also be shown for the concentration in combination with the pond depth, which is given in figure 25. The efficiency given in figure 25a is shown for the *P. Tricornutum* algae species. In figure 25b the efficiency is given of *T. Pseudonana* as a function of concentration and pond depth. *T. Pseudonana* is an other algae species with a lower growth rate and requires more sunlight to grow.

The decrease in efficiency in figure 25a for a low pond depth with a low concentration is due to the production of *P. Tricornutum* is before the optimum settings. The difference between the two algae is significant even though both species may be used for an energy efficient algae production. The production of *T.Pseudonana* is lower than that of the *P. Tricornutum*, which is shown as the lower NER in figure 25b.

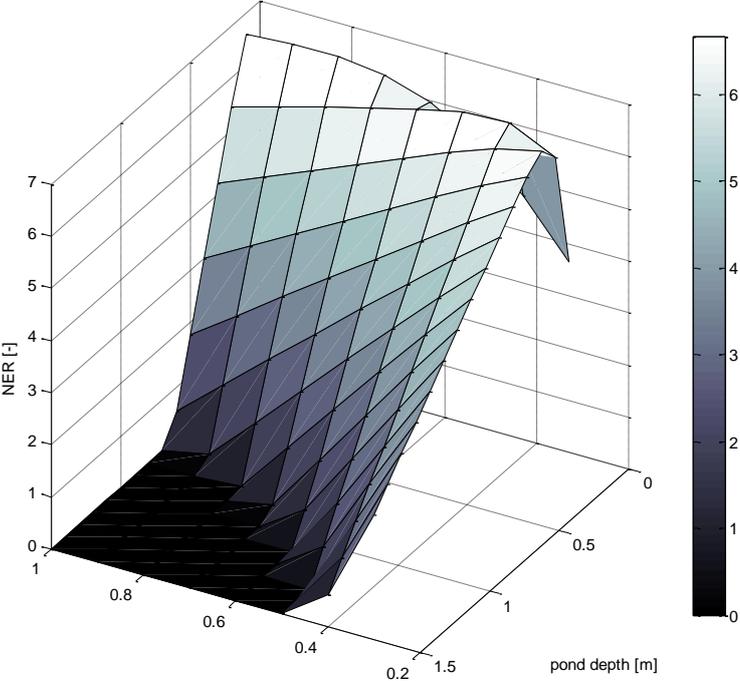


Figure 25a: NER versus concentration and the pond depth of *P. tricornutum*.

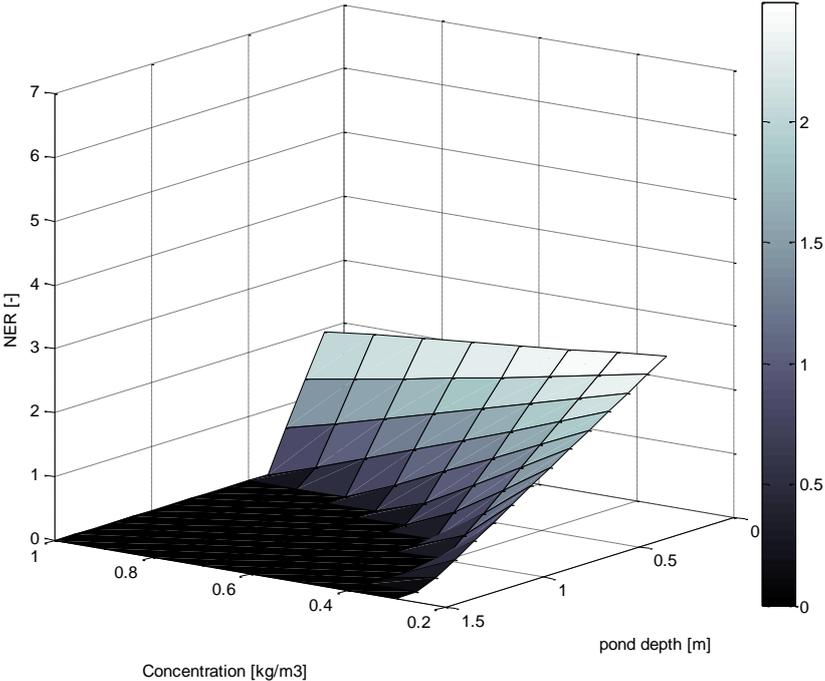


Figure 25b: NER versus concentration and the pond depth of *T. Pseudonana*

4. Discussion

The results have been obtained for yearly averages. On a daily basis the NER of the reactor can differ greatly, based on the temperature, light intensity, relative humidity and so on. To illustrate this effect figure 26 to 28 shows the efficiency of a flat plate, tubular and open pond reactor respectively, in the winter and summer. The configurations of the reference case is shown in section 2.5

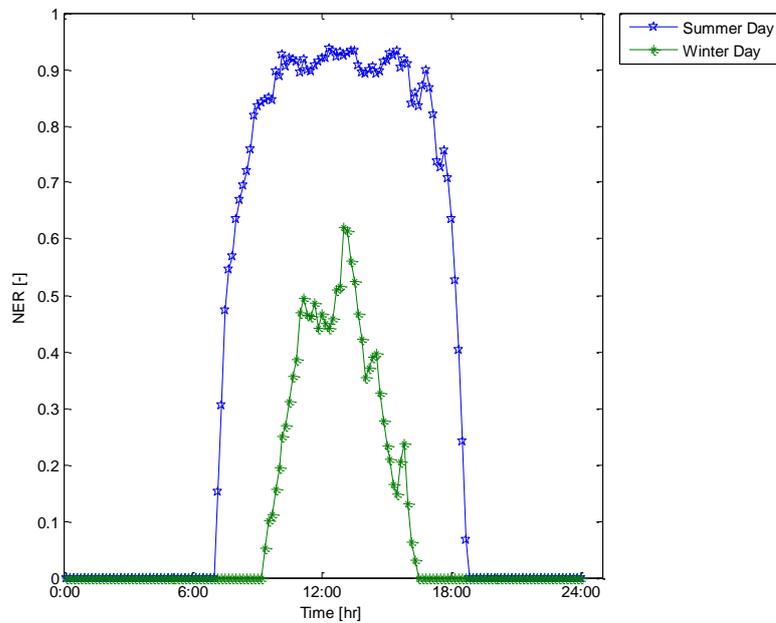


Figure 26: The efficiency of a flat plate reactor on a summer and winter day

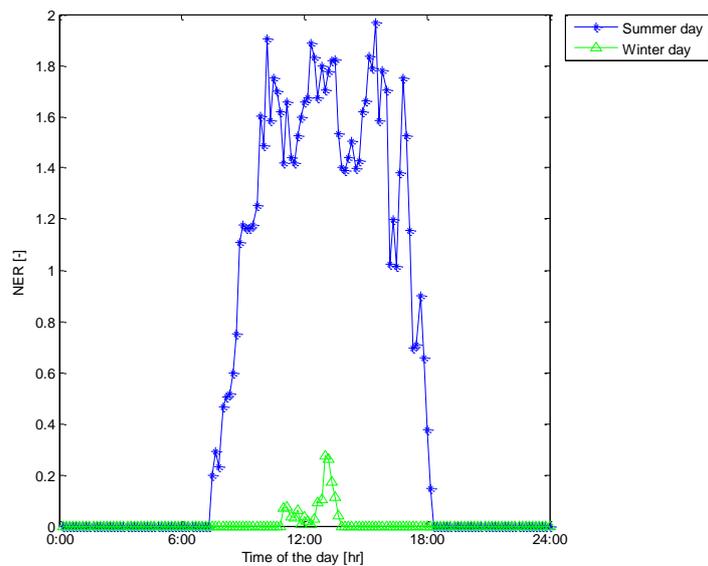


Figure 27: The efficiency of a tubular reactor on a summer and winter day

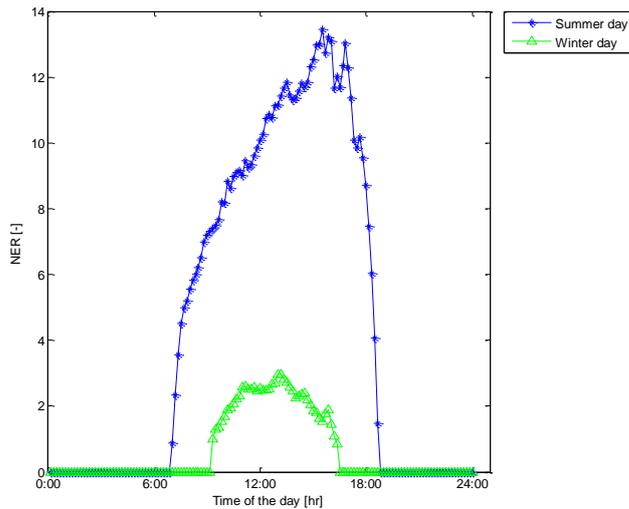


Figure 28: The efficiency of an open pond reactor on a summer and winter day

In the winter there is less light available than in the summer. All scenarios show that the efficiency of the reactor increases when the sun is climbing in the sky. In the summer the flat plate reactor is able to run almost energy neutral, despite the low yearly efficiency ratio. The tubular reactor shows that it is not able to run in the winter, despite it has an yearly NER > 1. The amount of sunlight hours in the summer is higher than in the winter as well, which indicates why the reactor is able to run longer in the summer than in the winter. To increase the efficiency of the reactor, specific operating times may be used in order to omit less efficient days of the year. This model may help to find opportunities to reduce energy consumption of the reactor in the design stage of the reactor. Improvements of the reactor can be established on either the energy consumption side or the energy production side with the model presented in this work.

The three configurations all have the potential to run energy efficient. Out of the three configuration the flat plate reactor needs the most improvement to run energy neutral. The relatively small volume of production in a closed system, which needs to be controlled, requires too much energy in comparison with the open system. Therefore the working area for the operating units should be increased, which may reduce the energy cost per reactor.

The choice of the algae has a large effect on the efficiency of the reactor. While the energy request of the reactor may partially be influenced by the choice of the algae, it is of a lesser concern. The major influence of the algae is on the energy production side of the balance. As algae grow faster or slower per species, it has a direct influence on how much algae is produced therefore increasing the energy efficiency with an increasing growth rate.

The blower of the flat plate reactor is requesting the most amount of energy in the flat plate reactor. The energy consumption may be improved by increasing the efficiency of the blower or by non-continuous aeration, as can be achieved by a sparging system. Such a sparging system may also be

used over multiple plates, which may reduce the energy cost even further. Using the blower only part of the day may also result in improved efficiency. Linear increasing of downtime of the blower will shift the energy consumption line of figure 10 downwards. The NER will then increase, but the algae growth may decrease slightly, due to inhibition by oxygen.

Less energy consumption in a tubular reactor is harder to achieve, as there is not much to gain with a more efficient degasser and the energy consumption is constrained by the recirculation. A faster growing (or genetically modified) algae, gives more space to improve the efficiency ratio. A pond reactor is already energy efficient, but requires much land to run. Energy wise there is no need to improve the pond reactor, although a faster growing algae species may be able to improve the NER to higher levels.

The NER indicates that the flat plate reactor requires more energy than it produces. However, this does not indicate that the flat plate reactor is not feasible. The NER is of great importance to the bulk chemistry sector, such as the production of biodiesel. In the pharmaceutical field, such as the production of ω 3,6 and 9 fatty acids, the selling prices are much higher, which may improve the feasibility of any configuration.

Norsker [10] published energy costs for the production of one kilogram algae in three configurations. His estimates to produce one kilogram algae are € 0.24 , € 0.57 and € 2.43 for an open pond reactor, tubular reactor and a flat plate reactor respectively. These figures represent the energy costs only. This work determines the cost to produce a kilogram algae to be €0.29, €0.62 and €1.60, for an open pond, tubular and a flat plate reactor respectively. The costs presented in this work differ from these figures partly due to a faster growing algae species and due to different estimates for energy consumption. The production of algae in the flat plate reactor is 2.5 times higher in this work, which reduces the running energy cost per algae. Furthermore, the inflow of new medium enters from the bottom of the reactor, which gives an additional energy requirement due to the pressure head of water. Lastly, Norsker uses some processing equipment for multiple reactors. This is not taken into account in this work.

Cheng-Wu et al.[11] shows that for the cultivation of *Nannochloropsis* sp. in a 2000 L flat plate reactor with a lightpath of 10 cm, the energy costs take up to 6.5% of the total costs. In order to achieve this, the process units are only running a specific amount of time per day. In this work all process units that depends on the growth of the algae, such as the degasser, are consuming only energy when there is a positive production. This means that the operating hours are longer in the summer than in the winter and the process units are switched off in the evening. At this point there is no influent as well, as it is assumed that the respiration of algae is small and used to supply nutrients to the remaining algae culture.

For the closed reactor systems it is assumed that the evaporation cooling conditions are optimal. This implies that the air has no water vapour and therefore the relative humidity of the environment is 0. The relative humidity on the reactor itself should (in ideal conditions) be 1, to give the maximum potential to remove the heat. In practise, the relative humidity of air lowers this potential. If the relative humidity of the air is taken into account of the cooling flow, which is formulated in equation 37, the equation may be reformulated as[18],

$$T_{\infty} - T_s = \Delta H_v \left(\frac{h_{mass}}{h_{convect}} \right) [\rho_{a, sat}(T_s) - \rho_{A, \infty}] \quad (75)$$

Where T_{∞} is the ambient temperature, T_s is the required temperature for the reactor, ΔH_v is the evaporation energy per kilogram water, $\left(\frac{h_{mass}}{h_{convect}} \right)$ is the ratio between the evaporative and convective transfer functions, $\rho_{a, sat}(T_s)$ is the density of water on the reactor and $\rho_{A, \infty}$ is the density of air at the specific humidity. When the relative humidity is high re-condensation on the reactor can occur. The cooler is not able to remove the excess heat, which is a limitation for the cooling. Therefore in humid countries, such as in western Europe, evaporative cooling is a particularly inefficient cooling method, especially during relatively wet and cold periods, as spring autumn and winter. The excess amount of heat which would be removed by evaporation would now be removed by convective cooling, which creates an additional layer where sunlight has to go through. The intensity of sunlight may be less when it reaches the algae, therefore reducing the amount of growth, making the closed photobioreactor less efficient.

5. Conclusion

A mathematical model has been made to analyse in the energy efficiency of a flat plate, tubular and an open pond reactor. With this model the netto energy ratio (NER) is calculated for various algae photobioreactor designs. This NER analysis can be done for several time scales, from efficiency on one day to a year round average. It is shown that all the reactor configurations have different performance in NER which depends changes in the concentration and lightpath. The intensity of the sun has a significant effect on the efficiency of the reactors, which gives higher NER in the summer than in the winter and at noon rather than the morning.

The flat plate, tubular and open pond reactor have been simulated to show the effects of changing the input and design variables. For standard photobioreactors NER is 0.36 for a flat plate reactor, 1.3 for a tubular reactor and 6.27 for the open pond reactor. This result has been obtained for environmental conditions in the Netherlands and for the *P.Tricornutum* algae species. The choice of the algae is important as faster growing algae produce more biomass, which directly influence the NER positively.

For the most commonly used lightpaths (0.02 – 0.05 [m]) in flat plate reactors, the aeration uses the most energy, which increases linearly with the increase of volume. A small lightpath (< 0.01 [m]) in combination with a high biomass concentration provides a NER > 1.

P.Tricornutum does not grow fast enough to provide enough energy to sustain an energy neutral configuration for a flat plate reactor, therefore a faster growing algae should be employed. Other methods for aeration, such as sparging, should be investigated in order to reduce the energy consumption. A combination of a faster growing algae species and energy consumption reduction will improve the efficiency of the flat plate reactor, which is currently not able to run energy neutral yet.

A standard tubular reactor is operates with a positive NER. The liquid recirculation demands the most energy. In comparison with the flat plate reactor there are less options in order to reduce the energy and therefore increasing the growth rate of algae has the best opportunity to make this reactor more efficient.

The open pond reactor has an overall efficiency NER > 1, which means that the reactor is able to run energy efficient. The reference scenario has an efficiency of 6.27. The consumption of the open pond reactor is fixed due to the dominating energy cost of the centrifuge. Reduction of the paddle wheel and centrifuge costs may increase the NER, to increase the efficiency even further.

References

Literature

1. Naik, S.N., et al., *Production of first and second generation biofuels: A comprehensive review*. Renewable and Sustainable Energy Reviews. **14**(2): p. 578-597.
2. Nigam, P.S. and A. Singh, *Production of liquid biofuels from renewable resources*. Progress in Energy and Combustion Science, 2011. **37**(1): p. 52-68.
3. Chisti, Y., *Biodiesel from microalgae*. Biotechnology Advances, 2007. **25**: p. 294-306.
4. Slegers, P.M., et al., *Design scenarios for flat panel photobioreactors*. Applied Energy, 2011. **88**(10): p. 3342-3353.
5. Lösing, M.B., *Modelling & Simulating microalgae production in an open pond reactor*, in *System and Control 2011*, Wageningen UR: Wageningen.
6. van Beveren, P.J.M., *Algal growth in horizontal tubular reactor*, in *System and Control 2011*, Wageningen UR: Wageningen.
7. Owen, N.A., O.R. Inderwildi, and D.A. King, *The status of conventional world oil reserves—Hype or cause for concern?* Energy Policy, 2010. **38**(8): p. 4743-4749.
8. Wijffels, R.H. and M.J. Barbosa, *An Outlook on Microalgal biofuels*. Science, 2010. **329**(5993): p. 796-799.
9. Lehr, F. and C. Posten, *Closed photo-bioreactors as tools for biofuel production*. Current Opinion in Biotechnology, 2009. **20**(3): p. 280-285.
10. Norsker, N.H., et al., *Microalgal production - A close look at the economics*. Biotechnology Advances, 2011. **29**(1): p. 24-27.
11. Cheng-Wu, Z., et al., *An industrial-size flat plate glass reactor for mass production of Nannochloropsis sp. (Eustigmatophyceae)*. Aquaculture, 2001. **195**(1-2): p. 35-49.
12. Geider, R.J. and H.L. MacIntyre, *A dynamic model of photoadaptation in phytoplankton*. Limnology and Oceanography, 1996. **41**(1): p. 1-15.
13. Bird, R.B., W.E. Stewart, and E.N. Lightfoot, *Transport Phenomena* 1960: Wiley International.
14. Geankoplis, C.J., *Transport Processes and separation unit principles (includes unit operations)*. 4th ed 2003: Prentice Hall.
15. Acién Fernández, F.G., et al., *Airlift-driven external-loop tubular photobioreactors for outdoor production of microalgae: assessment of design and performance*. Chemical Engineering Science, 2001. **56**(8): p. 2721-2732.
16. Molina, E., et al., *Tubular photobioreactor design for algal cultures*. Journal of Biotechnology, 2001. **92**(2): p. 113-131.
17. Knap, W., *measurements of radiation at station Cabauw.*, KNMI, Editor 2009: De Bilt.
18. Incropera, et al., *Fundamentals of Heat and Mass Transfer*. 6th ed 2007: John Wiley & Sons.
19. Thomas, W.H., et al., *Yields, photosynthetic efficiencies and proximate composition of dense marine microalgal cultures. I. Introduction and Phaeodactylum tricornutum experiments*. Biomass, 1984. **5**(3): p. 181-209.

Acknowledgements

This report is the product of hard work and a lot of stress and would not be completed without the help of various people, which I would like to thank for their contribution.

Ellen Slegers for the opportunity for taking this project and supervision throughout the year. Ton van Boxtel, for his endless patience, correcting this document, supervision and thoughts. The science group SCO for taking me as one of them for almost a year, especially Rachel van Ooteghem, for solving a lot of Matlab problems. The students of SCO, which came and go from my room, specifically Peter van Beveren and Martin Lösing, for their help with the startup of the project and their data from their projects. My numerous friends for dealing with me in desperate times. Last but not the least, my parents for always believing in me.

I would like to extend my gratitude to the AlgaePARC project of Wageningen University for providing the pictures used on the front page and in figure 1 and Marcel Alderlieste for his correctional work on spelling and grammar.

Annex A: Constant factors

Table A.1 Algae specific constant factors

	<i>P. Tricornutum</i>	<i>T. Pseudonana</i>	Unit
Growth constant[4]	1.40	3.29	Day ⁻¹
Maintenance[4]	0.05	0.05	Day ⁻¹
Combustion energy	22990	22990	kJ Kg ⁻¹
Lipid content	20[19]	20[4]	%
Oxygen production[16]	0.003	0.003	molO ₂ m ⁻³ s ⁻¹

Table A.2 Reactor constants

	Value	Unit
Pump efficiency	40	%

Table A.3 Water properties

	Value	Unit
Density	1000	Kg m ⁻³
Viscosity	0.001	Pa s
Evaporation heat	2270	Kj Kg ⁻¹
Emissivity in infrared	0.057	-
Heat capacity	4180	J Kg ⁻¹ °C ⁻¹
Heat conductivity	0.58	W m ⁻¹ °C ⁻¹

Table A.4: Physics constants

	Value	Unit
Stefan-Boltzmann constant	5.67e-8	J °K ⁴ s ⁻¹
Gravity	9.81	m s ⁻²

Table A.5 Material Properties

	Value	Unit
Heat conductivity of glass	1.05	W m ⁻¹ °K ⁻¹

Table A.6 Economical constants

	Value	Unit
Cost of kWh	5	ct€ kWh ⁻¹

Annex B: Nomenclature

Table B.1 main variables

Variable		Unit
\mathcal{P}_r	Production	Kg s^{-1}
η_e	Efficiency factor of pumps	-
μ_{growth}	Growth rate	s^{-1}
ϵ_w	Emissivity of water in infrared spectrum	-
A	Area	m^2
c_p	Specific heat	$\text{J Kg}^{-1}\text{C}^{-1}$
ct_{Kwh}	cost of Kwh	$\text{ct}\text{€ Kwh}^{-1}$
C_x	Concentration	Kg m^{-3}
d	Depth of the reactor	m
D	Diameter	m
E	Electrical energy	J s^{-1}
g	Gravitational force	m s^{-2}
h	Heat transfer coefficient	$\text{W m}^{-2}\text{C}^{-1}$
H_{comb}	Combustion energy	J Kg^{-1}
h_e	Height of the reactor	m
I	Sunlight intensity	$\text{J m}^{-2} \text{s}^{-1}$
k	Heat Conductivity	$\text{W m}^{-1}\text{C}^{-1}$
l	Specific length of the reactor	m
L	Length of the reactor	m
N	Number (dimensionless)	-
n_{max}	Amplitude of potential oxygen removal in degassing	-
P	Pressure	Pa
Q	Heat energy	J s^{-1}
r	Radius	
r_{max}	Maintenance coefficient for algae	s^{-1}
R_{O_2}	Rate of oxygen production	$\text{mol m}^{-3} \text{s}^{-1}$
T	Temperature	$^{\circ}\text{C}$
t_{solar}	Time elapsed after midnight	s
V	Volume	m^3
w	Width of the reactor	m
x	Mol	mol
y_{sur}	surplus factor CO_2 supply	-
ΔH_v	Evaporation constant of water	J m^3
dt_{hrsec}	Correction factor seconds to hours	s hr^{-1}
dt_{minhr}	Correction factor minutes to hours	min hr^{-1}
e	Saturated vapour	-
μ	Dynamic viscosity	Pa s
v	Superficial velocity	m s^{-1}
ρ	Density	Kg m^{-3}
σ	Stefan-Boltzmann constant	$\text{J }^{\circ}\text{K}^4 \text{s}^{-1}$
ϕ	flow	$\text{m}^3 \text{s}^{-1}$

Table B.2: suffixes

suffix	
1	Outer radius
2	Inner radius
a	Ambient
aeration	Aeration flow
air	Air
Algae	<i>P. Tricornutum</i> algae species
blower	Aeration unit
CO₂	CO ₂ supply flow
cool	Cooling
degas	Bruto degassing flow
degasnet	Netto degassing flow
demand	Energy requirement
diffuse	Diffuse sunlight
direct	Direct sunlight
Env	Environment
evaporation	Energy exchange due to temperature
fan	Fanning friction
flow	Recirculation flow
fluc	Cooling water flow
gas	Gas
gastube	Gas tube for degassing
h₂O	Water
harvested	Harvester
heat	Heating
heat/cool	Cooling or heating unit
heater	Heating unit
Inflow	Influent
inflow,bruto	Bruto influent pond reactor
nu	Nusselt
out	Outflow
outflow	Effluent
paddle	Paddle wheel
pond	Pond reactor
pr	Prandtl
r	Reactor
Radiance	Energy loss due emission
re	Reynold
reactor	Photobioreactor
reflected	Reflected sunlight
s	Water saturation
sky	Sky temperature
sun	Total sunlight
Sunlight	Electromagnetic radiation from the sun
t	Tubular
tube	Tubular reactor
tubeCO₂	CO ₂ supply tube
tubeinflow	Influent supply tube of the pond reactor

