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ENERGY BALANCE OF MICROALGAE BIOFUELS

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Abstract

Microalgae are small organisms that live in the water and use solar energy to grow. Like plants, they can be used to produce biofuels. Since the Second World War there have been repeated attempts to produce biofuels from microalgae. The idea has recently received a boost due to one specific feature of microalgae: unlike other biofuel feedstock, microalgae do not compete with food production for arable land.

Biofuel production with microalgae is only sensible when less energy is required to produce the fuel than is stored in the fuel. The ratio of energy demand to energy output, the 'Net Energy Ratio' (NER), should be smaller than one. Previous studies have shown that the NER depends significantly on (a) the assumed operation energy, and (b) the expected biomass productivities. Although it is well-known that these two parameters are inherently linked, this dependency has not been considered when calculating the NER.

In this dissertation, for the first time biomass productivity is calculated based on operation energy. For this purpose, a correlation between the key parameters to model operation energy and biomass productivity (aeration rate, light intensity and photosynthetic efficiency (PE)) is derived and validated based on a systematic analysis of published experimental data. Based on this correlation, the NER of microalgae biofuels production is calculated. Aerated flat plate photobioreactors are investigated as a method of microalgae cultivation. These have previously been examined as promising systems for outdoor cultivation. As a biofuel, biomethane production is investigated since its production requires the least energy compared to other biofuels.

The results of this dissertation show that operation energy and biomass productivities are related non-linearly: to achieve high productivities, disproportionately more energy is required than to achieve low productivities. Consequently, the aim of energy-efficient microalgae cultivation is not to achieve the highest possible biomass yield but to find a good balance between operation energy and biomass yield. Furthermore, due to these interactions, the lowest possible NER is not achieved with the maximum biomass yield. The optimum NER depends on the interaction of all model parameters. The effect of parameter changes on the NER depends also on the aeration rate.

The NER calculated in this dissertation for aerated flat plate photobioreactors is around 1.8. This value is achieved at an aeration rate of 0.25 vvm (gas volume gas per liquid volume and minute). This corresponds, when coupled with the further findings and assumptions of this study, to an operation power of 54 W m^{-3} or 2.2 W m^{-2} and a biomass productivity of 50 t ha^{-1} y^{-1}. A NER below one could not be achieved even though expected technological improvement is considered in the calculation. The calculated NER is compared to the NER results in previous studies which were partially below one. The analysis of previous studies showed that there are two main reasons for a NER < 1: one is incomplete system boundaries; the other is that the relation between energy demand and productivity is not considered.

With the systematic approach presented in this dissertation, the potential development of microalgae biofuel production can be predicted more reliably. Expected technological

development could improve the relation between operation energy and biomass productivities, but it cannot uncouple these parameters. Their correlation is based on the fundamental principles of microalgae growth, which apply to all cultivation systems and all types of algae.

The method developed in this thesis can also be applied to quantify the best possible NER for other cultivation systems, based on the relation between operation energy and biomass productivity. The approach to correlating important model parameters based on the underlying scientific mechanisms can be transferred to other systems as well. It can thus also be applied to estimate the potential development of other technologies.

Zusammenfassung

Mikroalgen sind im Wasser lebende Mikroorganismen, die mit Hilfe von Sonnenlicht wachsen. Bereits seit dem Zweiten Weltkrieg wird versucht, aus Algen Biotreibstoff herzustellen. Dieser Ansatz wird derzeit wieder verstärkt diskutiert, da Mikroalgen – im Gegensatz zu Landpflanzen – nicht mit Nahrungsmittelproduktion um fruchtbaren Boden konkurrieren.

Sinnvoll ist die Gewinnung von Biotreibstoff aus Mikroalgen nur dann, wenn weniger Energie benötigt wird, um den Treibstoff zu produzieren, als im gewonnenen Treibstoff gespeichert ist: Der Quotient dieser beiden Werte (Energieaufwand und Energiegehalt des Treibstoffes), der ‚Net Energy Ratio' (NER) muss kleiner eins sein. Bisherige Studien zeigen, dass im Wesentlichen zwei Parameter den NER bestimmen: Kultivierungsenergie und Biomasse-Ertrag. Obwohl diese beiden Parameter offensichtlich voneinander abhängen, wurde diese Abhängigkeit bisher nicht berücksichtigt, um den NER zu berechnen.

In dieser Dissertation wird erstmalig der Biomasse-Ertrag abhängig von der Kultivierungsenergie modelliert. Dazu wird eine Korrelation zwischen wichtigen Modellparametern (Begasungsrate, Lichtintensität und photosynthetischer Effizient (PE)) aus Experimentaldaten hergeleitet und anhand weiterer Literatur validiert. Diese Korrelation wird zugrunde gelegt, um den NER der Biotreibstoffproduktion aus Mikroalgen zu berechnen. Als Methode der Algenkultivierung werden begaste flache Photobioreaktoren untersucht. Diese wurden bisher als vielversprechende Systeme für die Freilandkultivierung intensiv erforscht. Als gewonnener Treibstoff wird beispielhaft Biomethan untersucht, da seine Produktion den geringsten Energiebedarf im Vergleich zur Produktion anderer Treibstoffe aufweist.

Die Ergebnisse dieser Arbeit zeigen, dass Kultivierungsenergie und Biomasse-Ertrag nichtlinear voneinander abhängen: um hohe Erträge zu erzielen, wird überproportional mehr Energie benötigt, als für niedrige Erträge. Um Mikroalgen möglichst energie-effizient zu kultivieren, sollte daher nicht der höchstmögliche Biomasse-Ertrag angestrebt werden, sondern vielmehr ein ausgewogenes Verhältnis zwischen Energiebedarf und Biomasse-Ertrag. Aus diesem Zusammenhang folgt weiterhin, dass ein niedriger NER nicht mit dem höchstmöglichen Biomasse-Ertrag zu erreichen ist. Der bestmögliche NER hängt von weiteren Modellparametern ab, die sich wechselseitig beeinflussen. Parameteränderungen wirken sich je nach Begasungsrate unterschiedlich stark auf den NER aus.

Der in der vorliegenden Arbeit berechnete NER für begaste Photobioreaktoren liegt bei etwa 1,8. Dieser Wert wird bei einer Begasungsrate von 0,25 vvm (Gasvolumen per Flüssigkeitsvolumen und Minute) erreicht. Das entspricht, zusammen mit den weiteren Ergebnissen und Annahmen und dieser Arbeit, einem Leistungseintrag von 54 W m^{-3} oder 2,2 W m^{-2} und einem Biomasse-Ertrag von 50 t ha^{-1} y^{-1}. Ein NER unter eins kann nicht erreicht werden, obwohl zu erwartende Technologieentwicklung in die Berechnung miteinbezogen wurde.

Der berechnete NER wird mit anderen Studien verglichen, die teilweise auf deutlich niedrigere NER kommen. Eine Analyse dieser Studien zeigt zwei Ursachen für einen NER < 1: Einerseits sind die Systemgrenzen zum Teil unvollständig, anderseits wird der Zusammenhang zwischen Energiebedarf und Biomasse-Ertrag nicht berücksichtigt.

Mit dem hier vorgestellten systematischen Ansatz lassen sich verlässliche Aussagen zum Entwicklungspotential der Biotreibstoffproduktion aus Mikroalgen treffen. Erwartete Fortschritte in der Technologieentwicklung können das Verhältnis von Kultivierungsenergie und Ertrag verbessern. Es ist jedoch nicht möglich, diese beiden Parameter zu entkoppeln, da ihre Abhängigkeit auf den fundamentalen Mechanismen des Algenwachstums basiert. Diese treffen auf alle Algenkultivierungssysteme und alle Arten von Mikroalgen zu.

Die Methodik kann angewendet werden, um den Zusammenhang zwischen Kultivierungsenergie und Biomasse-Ertrag auch für andere Mikroalgen-Kultivierungssysteme zu bestimmen und so ihren bestmöglichen NER zu berechnen. Der Ansatz, der die Zusammenhänge wichtiger Modellparameter aufgrund der zugrundeliegenden Mechanismen berücksichtigt, ist systemübergreifend einsetzbar. Er kann daher auch genutzt werden, um das Entwicklungspotential anderer Technologien einzuschätzen.

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List of acronyms

CED	Cumulative Energy Demand
CHP	Combined heat power plant
DW	Dry weight
EROI	Energy return on investment (inverse of NER)
FU	Functional unit
GHG	Greenhouse gasses
GJeq	Gigajoule-equivalents
GMA	Genetically modified algae
HDPE	High density polyethylene
HHV	Higher heating value
HVP	High value product
KA	Karlsruhe
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact analysis
LDPE	Low density polyethylene
LHV	Lower heating value
MA	Madrid
MJeq	Megajoule-equivalents
n.a.	Not available
NER	Net Energy Ratio
PAR	Photosynthetically active radiation
PBR	Photobioreactor
PE	Photosynthetic efficiency

PETG	Polyethylene terephthalate granulate
PFD	Photon flux density
VS	Volatile solids

List of parameters

Symbol	Name, description	Units
a	Land area occupied by a cultivation system	[m^2]
A	Flow cross-section, also A_g flow cross-section gas, A_l flow cross-section liquid	[m^2]
b_1, b_2	Variables to determine the relation between PE and aeration rate, *PE(vvm)*	[-]
$biom_{DW}$	Dry weight of the produced biomass	[kg] or [t]
c	Biomass concentration	[kg m^{-3}] or [g L^{-1}]
c_{inoc}	Correction factor for inoculation	[-]
c_{resp}	Correction factor for respiration	[-]
c_T	Correction factor for temperature, also $c_{T,KA}$ for Karlsruhe, $c_{T,MA}$ for Madrid	[-]
CED_n	Cumulative Energy Demand of an LCI flow	[MJeq $unit^{-1}$]
$cred_{mat}$	Energy credit for material combustion	[MJ kg^{-1}]
d_y	Cultivation days per year	[d]
d_{ex}	Batch time, days between culture exchange	[d]
$energy_{DW}$	Energy content of biomass (dry weight)	[MJ kg^{-1}] or [kWh kg^{-1}]
E	Energy, also E_{op} operation energy E_{harv} energy for harvesting, E_{tr} energy for culture transport (filling and emptying)	[kWh] or [MJ]
exc_{mat}	Material excess for production	[-]
g	Gravitational constant: 9.81 m s^{-2}	[m s^{-2}]
h	Height of PBR (wall)	[m]
Δh	Hydraulic height of the water column	[m]
h_{prod}	Productive hours, also $h_{prod,d}$ per day, $h_{prod,y}$ per year	[h]
I_0	Solar irradiation, also $I_{0,h}$ irradiation per hour, $I_{0,y}$ irradiation per year	[W m^{-2}] or [µmol m^{-2} s^{-1}]
l	Length of PBR (wall)	[m]
l/D_h	Length/hydraulic diameter	[-]
lt_n	Lifetime of an LCI flow	[y]
n	Dummy variable for energetic relevant LCI flows	[-]

$\dot{n}_{gas}$	Mol flux gas	[mol s^{-1}]
P	Power, also P_g power for gassing, P_l power for liquid pumping	[W]
p	Pressure or pressure drop, also p_g pressure for for gassing p_l pressure for liquid pumping, p_a ambient pressure	[N m^{-2}], [mbar]
Δp	Pressure drop, also Δp_f friction loss, Δp_h water head, Δp_v velocity head, Δp_{other} other pressure drop	[N m^{-2}], [mbar]
PE	Photosynthetic efficiency; determines how efficient algae turn photons into biomass, also *PE(vvm)* depending on the aeration rate	[%]
PFD	Photon flux density (unit to measure light)	[µmol m^{-2} s^{-1}]
$prod_{area}$	Areal productivity, also $prod_{area,h}$ per hour, $prod_{area,d}$ per day, $prod_{area,y}$ per year	[g m^{-2} h^{-1}], [g m^{-2} d^{-1}], [kg m^{-2} y^{-1}]
$prod_{vol}$	Volumetric productivity, also $prod_{vol,\,h}$ per hour, $prod_{vol,\,d}$ per day; usually determined from the average growth rate and cell concentration during a certain time $\overline{\mu c}$	[g L^{-1} h^{-1}], [g m^{-3} d^{-1}]
r_{op}	Night-time operation rate	[-]
sup_{biom}	Energy or supplies related to the produced biomass	[unit kg^{-1}]
T	Temperature	[K] or [°C]
th_{mat}	Thickness of a material, e.g. PBR walls	[m]
v	Flow velocity, also v_g flow velocity gas (superficial flow velocity), v_l flow velocity liquid	[m s^{-1}]
$\dot{V}_g$	Delivered gas volume	[m^3 s^{-1}] or [m^3 min^{-1}]
$\dot{V}_g/V_c$	Aeration rate, see also *vvm*	[m^3 m^{-3} s^{-1}], [m^3 m^{-3} min^{-1}]
V_c	Culture volume	[m^3]
V_c/a	Culture volume per area, characteristic parameter of a cultivation system	[m^3 m^{-2}]
vvm	Aeration rate, see also $\frac{\dot{V}_g}{V_c}$	[m^3 m^{-3} min^{-1}]
w	Width of a PBR (in flat plates also called 'light path length')	[m]
x_n	Required amount of an LCI flow, also $x_{n,\,biom}$ supplies related to biomass, $x_{n,cred}$ credited amount of LCI flow	[unit]
X_{fuel}	Amount of produced biofuel (within considered time period)	[unit]

$Y_{ha,y}$	Biomass yield per hectare and year, see also $prod_{area}$	[t ha^{-1} y^{-1}]
y	Year	[y]
α	Angle of PBR inclination	[°]
ζ	Friction factor	[-]
η	Pump efficiency	[-]
μ	Growth rate of microalgae	[h^{-1}] or [d^{-1}]
ρ	Density	[kg m^{-3}]

Subscripts

h	per hour	[h^{-1}]
d	per day	[d^{-1}]
y	per year	[y^{-1}]
$area$	per area	[m^{-2}] or [ha^{-1}]
vol	per volume	[m^{-3}] or [L^{-1}]
DW	per biomass dry weight	[kg^{-1}] or [t^{-1}]

1 Introduction

1.1 Why microalgae biofuels?

Microalgae are small organisms that live in the water and use solar energy to grow. They have been cultivated for a long time to produce food, feed and other substances. Microalgae biomass can also be used to produce biofuels, such as (bio-) ethanol, diesel, hydrogen or methane. Since the Second World War there have been repeated attempts to produce biofuels from microalgae (Borowitzka 2013). Initial motivation was the independence of external fuel supply and/or saving fossil resources. The idea has recently received a boost due to a specific feature of microalgae: unlike other biofuel feedstock, microalgae do not compete with food production for arable land. Like plants, microalgae grow quickly with concentrated CO_2 and can thus re-use CO_2 from other resources.

To produce biofuels from microalgae, microalgae must be cultivated on large scale in technical systems (with nutrients and CO_2). The biomass must be harvested and converted into a fuel. The energy needed to provide electricity and materials for all processes along the biofuel production chain can be assessed with the so-called 'cumulative energy demand' (CED), a method of life cycle assessment (LCA). The total energy demand of all processes and materials related to the biofuel energy content is called net energy ratio (NER).

Prerequisite to produce microalgae biofuels is a NER less than one: Less energy should be required to produce the fuel than energy is provided with the fuel. However, microalgae cultivation requires much energy so that a NER<1 is not possible today (Morweiser *et al.* 2011). Despite intensive research, no commercial microalgae biofuel production plant exists and many previous attempts to produce microalgae biofuels on large scale have failed (Tredici 2003, Borowitzka 2013).

1.2 Problem definition

LCA studies about microalgae biofuels production calculated NER results above and below one (Sills *et al.* 2011). Almost all studies about microalgae biofuels production emphasise the need for technology development "to make algae biofuels a sustainable, commercial reality" (Sander and Murthy 2010).

The NER is the result of a model and, as such, depends on assumptions about system boundaries, input parameters and underlying functions. Different NER results and therefore different expectations regarding the potential development of the technology can be due to all three aspects:

The first and most obvious reason for different NER results are incomplete system boundaries. For example, some studies assessed only the operation energy to cultivate

microalgae, others included energy demand for harvesting and processing the biomass but omit energy for supplies and materials. Not surprisingly, Slade *et al.* (2011a) found that "the most optimistic results [of the NER] come from the systems which are least complete". Second, the variety of cultivation methods, harvesting methods and processes to produce biofuels results in different NERs.

The third and maybe most important reason for different NER results are the underlying functions or more precisely, whether a correlation between core model parameters has been considered or not.

Regarding the last aspect, previous studies found that the NER depends strongly on the operation energy demand (Stephenson *et al.* 2010, Weinberg *et al.* 2012). They also found that the expected biomass yield strongly influences the NER result (Zamolla *et al.* 2011, Slade *et al.* 2011b). Further information connects these findings: it is "well-established and clearly evident" (Hu and Richmond 1996) that the operation energy determines the cultivation conditions and therefore the biomass yield. This dependency has not yet been considered to calculate and predict the NER of microalgae biofuels production.

In summary, no previous LCA study calculated the NER of microalgae biofuels production considering that the biomass yield depends on the operation energy – even though (a) both parameters considerably determine the NER and (b) a correlation between these parameters is evident.

1.3 Objectives and scope

The aim of this study is to investigate dependencies between key parameters of microalgae cultivation and model the net energy ratio (NER) of microalgae biofuel production based on these dependencies.

This aim can be expressed in the following research questions:

1.) Why and how do important model parameters depend on each other?
2.) What are the consequences for the NER with regard to the dependencies?
3.) What are the consequences regarding technology development?

The approach shall help to better understand important interactions regarding microalgae cultivation. It shall also allow calculating more reliable NERs of microalgae biofuels production. The results of this dissertation shall help decision makers in policy, society and industry to better evaluate the potential of microalgae biofuels production.

This thesis focusses on the energy balance of biofuels production from microalgae mass cultivation in closed photobioreactors. These terms are defined in the following in order to set the scope of this dissertation:

Microalgae mass cultivation involves – in contrary to harvesting microalgae from their natural environment – the provision of a cultivation system, nutrients and CO_2 supply on a large scale. Furthermore, it implies changing light, temperature and weather conditions.

The focus of this study lies on microalgae cultivation in **closed photobioreactors (PBRs)** since it is expected that improved PBR technology can contribute to a better net energy

ratio (NER). A lower NER is also expected from genetically modified or specially selected algae – those should not be cultivated in open systems to avoid contamination. Therefore, open cultivation systems which are in contact with the surrounding environment are not examined in this thesis.

Last but not least, this study investigates **biofuel production** as the **main purpose** and function of microalgae cultivation. Biofuels as a by-product of another main product is not considered. Apart from methodological issues (about how to assess the NER of a system with several outputs), this has practical reasons: very few microalgae products leave residual biomass. For example, the whole algae cell is used to produce food and feed. Furthermore, markets for extracted substances (e.g. antioxidants or pigments) are small.

1.4 Thesis outline

In this dissertation it is analysed why and how most important model parameters to determine biomass yield and operation energy are related. For this purpose, a 'core model' is developed describing the dependencies. This model is used to calculate the net energy ratio (NER) of microalgae biofuels production.

The thesis is structured as follows (Figure 1.1): Chapter 2 provides the methodological background to assess the net energy ratio of microalgae biofuels production and the literature review highlighting the research gaps.

Chapter 3 explains the fundamental principles, requirements and limitations of microalgae growth and cultivation. Those are essential to understand why and how core model parameters are related. The most important equations to calculate biomass yield and operation energy are introduced.

In chapter 4, the 'core model' is developed which describes a correlation between important parameters to calculate operation energy and biomass yield. The model is validated with further laboratory and outdoor data.

Chapter 5 defines all other upstream and downstream assumptions and parameters to calculate the NER of microalgae biofuels production. Scenarios and parameter variations are introduced.

Chapter 6 shows the NER results under different assumptions. A best case NER is defined and compared to the NER results of previous LCA studies. The reasons for different results are analysed. Limitations of this thesis are discussed and the transferability of method to other systems is described.

Finally, chapter 7 summarises the answers to the research questions and gives suggestions for further research.

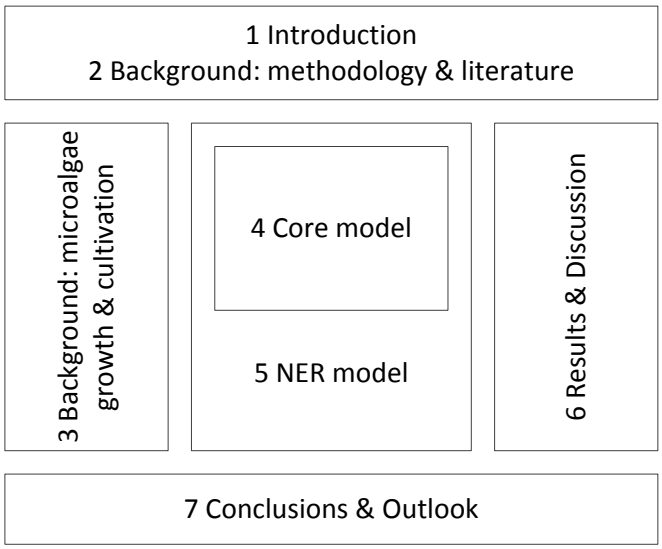


Figure 1.1: Thesis framework

2 Methodological background and literature review

This chapter describes the methodological and literature background of the study.

Section 2.1 presents the methodology to calculate the NER of microalgae biofuels production based on the LCA approach. Section 2.2 gives a review about the most important literature about the NER of microalgae biofuels production with a focus on the research gaps.

2.1 Methodology

This section explains the method of Life Cycle Assessment (LCA), the Cumulative Energy Demand (CED) as a method within LCA and the net energy ratio (NER) as characteristic quotient which can be calculated with the above definitions.

2.1.1 Life cycle assessment (LCA)

The net energy ratio of microalgae biofuels production should include all direct and indirect energy inputs and outputs along the production chain. These apply for: providing the resources for cultivation, harvesting and processing the biomass and, if applicable, disposal or recycling processes. Those can be assessed with the method of Life Cycle Assessment (LCA). LCA principles and framework, requirements and guidelines are described in the ISO guidelines 14040 and 14044 respectively (DIN Deutsches Institut für Normung e.V. 2006, 2006). The four interdependent stages of an LCA are:

1.) Goal and scope definition
2.) Live cycle inventory (LCI)
3.) Live cycle impact assessment (LCIA)
4.) Interpretation of results

Goal and scope define the purpose and recipient of the LCA: What question should be answered and who wants to know the answer? For example, an LCA for industry can identify weak points along the microalgae production chain or trade-offs between different processes. The goal and scope determines also the main function of the investigated process: the functional unit (FU). All inputs and outputs are usually related to the FU.

The life cycle inventory (LCI) describes the mass and energy flows of the processes (e.g. cultivating microalgae and producing biofuels) and how they are related; it is the core of the LCA. The assumptions taken in the LCI: boundary conditions, parameters and their dependencies determine the LCA result. Therefore, the LCI should – as any model – reflect the reality as good as possible.

LCIA methods linearly assign one or several 'environmental impacts' of different 'categories' to each mass or energy flow of the LCI. For example, a process can require resources (energy, land, water, …), cause emissions (CO_2, SO_2, …), or have other effects on

the environment. Data for relations between flows and impacts ('characterisation factors') result from physical, toxicological and other measurements. For a variety of processes (e.g. the production of 1 kg of steel) the 'environmental impacts' have already been calculated in previous LCAs. Results are stored in large databases like the German *GaBi* or the Suisse *ecoinvent* and can be used for further calculations. The data can be evaluated, combined and modified with LCA software, such as umberto, openLCA or SimaPro.

The result of the LCA depends on the data and decisions of the previous steps. Are they adequate to fulfill the purpose of the study? If not they must be verified or changed. The process of LCA is thus iterative (Figure 2.1).

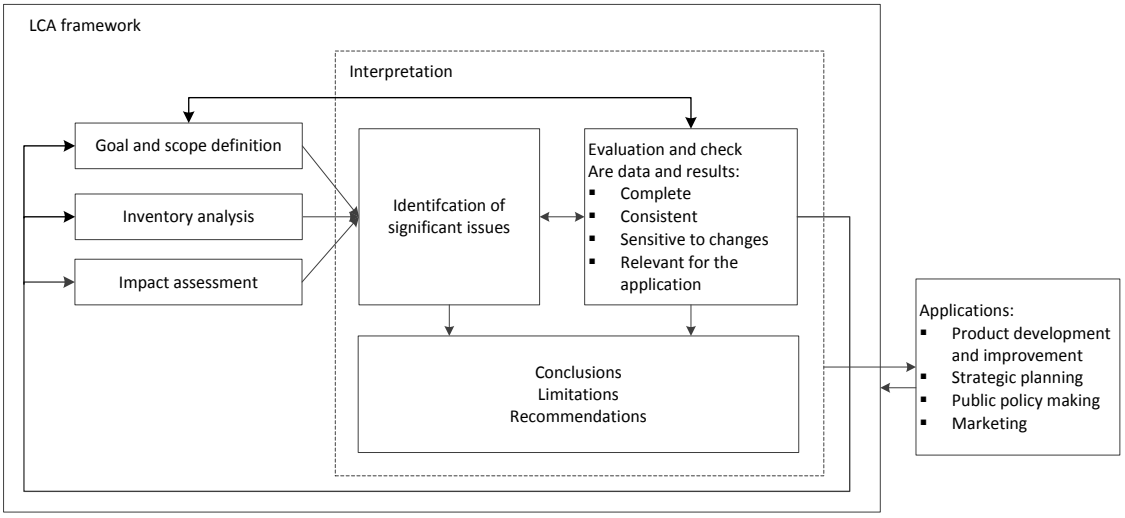


Figure 2.1: Iterative process during the interpretation of the LCA result (adapted from ISO 14044 DIN Deutsches Institut für Normung e.V. 2006)

2.1.2 Cumulative Energy Demand (CED)

The 'Cumulative Energy Demand' (CED) is an LCIA method and as such a potential part of an LCA. The CED reflects how much energy is 'withdrawn from nature' in order to provide a certain product or process. For example, the CED to provide 1 kWh electricity from coal reflects the energy content of the extracted coal, but also the energy for resources needed to burn the coal and transport the resulting heat or electricity. Background and methodology to determine the CED are described in detail in (Hischier and Weidema 2009) and (Verein deutscher Ingenieure (VDI) 2012).

All resources needed to produce microalgae biofuels, such as electricity, fertilisers or materials have a CED. The CED in this study is calculated with the software umberto (NXT LCA 7.1) and the method as documented in Hischier and Weidema (2009). This method accounts fossil resources with their higher heating value (HHV) and renewable resources with 1 MJ-equivalent (MJeq) per MJ produced electricity, following the approach of (Frischknecht *et al.* 1998). The Verein Deutscher Ingenieure (VDI) suggests using the lower heating value (LHV) to calculate the CED, though states that it is "more appropriate" using the HHV value regarding the CED as an indicator for resource efficiency (2012).

2.1.3 Net Energy Ratio (NER)

The net energy ratio (NER) relates the energy demand (without solar energy) for all processes needed to produce microalgae biofuels to the energy stored in the fuel (1), (Figure 2.2). This definition is in accordance with the one given in Slade *et al.* (2011b). In some studies, the NER is defined as the inverse of this value.

This definition of the NER reflects the LCA approach where all flows are related to the major output or functional unit (FU). Other definitions of energy ratios include for example the 'Energy Return on Investment' (EROI) as the "energy returned to society" divided by the "energy required to get that energy" (Hall *et al.* 2009). This is the inverse of the NER as defined in this study. Also used are 'energy yield', 'net energy yield', 'energy yield ratio' and others (Richards and Watt 2007, Gürzenich *et al.* 1999).

Since the CED is calculated with the HHV of resources (see 2.1.2), the NER is also calculated with the HHV of the produced algae biofuel. This is also suggested by Klöpffer and Grahl (2009). The energy demand for an LCI flow must be adapted to the considered time period. For example, to assess biofuel production during one year, the energy demand for a material that lasts 20 years must be divided by 20.

$$NER = \frac{\sum(CED_n \cdot x_n) - \sum(CED_{n,cred} \cdot x_{n,cred})}{HHV_{fuel} \cdot X_{fuel}} \quad (1)$$

NER	Net energy ratio [-]
n	Energetic relevant LCI flows
CED_n	Cumulative Energy Demand of an LCI flow [MJeq unit^{-1}] ($CED_{n,cred}$ Cumulative Energy Demand of credit)
x_n	LCI flow (required amount of resources within the considered time period) [unit] ($x_{n,cred}$ credited amount)
HHV_{fuel}	Higher heating value of the produced biofuel [MJ m^{-3}]
X_{fuel}	Produced biofuel (within the considered time period) [m^3]

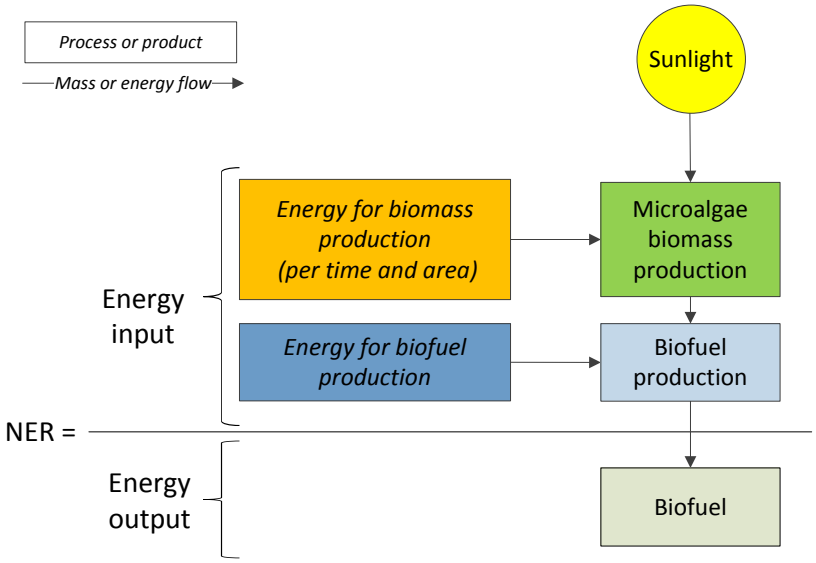


Figure 2.2: Simplified flow chart of processes to calculate the NER of microalgae biofuel production

2.2 Literature on microalgae biofuels: LCAs and reviews

This section introduces previous LCA meta-studies, LCA single studies and reviews about microalgae biofuels production, highlighting the research gaps.

2.2.1 Meta-studies and comparative LCAs

The largest and most comprehensive meta-analysis of LCAs was done within the large European project AquaFUELS ('Algae towards biofuels', see also Annex, Table A.5). LCA experts, supported by a team of microalgae experts, reviewed and evaluated seven LCAs (Table 2.1) regarding net energy ratio, cost and environmental performance of microalgae biofuels (five other studies about algae sustainability aspects were considered as well). Objective was to find strengths and weaknesses of the existing literature and provide a report that summarises what policy makers need to know about algae LCA.

The authors concluded in their final presentation, that "Micro- and Macro algae can produce a fascinating range of products – but biofuels are best viewed as a co-product." and further that "The viability of micro-algae for biofuels requires a leap of faith and imagination." (Slade *et al.* 2011a).

Specifically, the authors criticised the following aspects of LCA studies:

- System boundaries are sometimes incomplete. After equalising system boundaries, the authors found that "the net energy ratio for biomass production is unattractive, or at best, marginal".
- The energy demand assumed for cultivation and harvesting varied largely; key factors are: "the productivity of the algae, its calorific value and oil content".

- Data sources and assumptions are sometimes intransparent or open to interpretation.

Especially the last two points emphasise the need to consider dependencies of the most important parameters yield and cultivation energy.

Table 2.1: LCA studies reviewed within the European AquaFUELS project (Slade et al. 2011b).

Study	Title
Kadam 2002	*Environmental implications of power generation via coal-microalgae co-firing*
Lardon *et al.* 2009	*Life-Cycle Assessment of Biodiesel Production from Microalgae*
Clarens *et al.* 2010	*Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks*
Jorquera *et al.* 2010	*Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors*
Sander & Murthy 2010	*Life cycle analysis of algae biodiesel*
Stephenson *et al.* 2010	*Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors*
Campbell *et al.* 2010	*Life cycle assessment of biodiesel production from microalgae in ponds*

Regarding smaller comparative studies, Khoo *et al.* (2011) compared their results to 4 of the 7 previous named LCAs (Lardon *et al.* 2009, Clarens *et al.* 2010, Jorquera *et al.* 2010 and Stephenson *et al.* 2010). Analogue to the large meta-study, they found that LCA results depend largely on the system boundaries and that studies are difficult to compare because of different functional units, cultivation systems and technologies to produce biofuels. They further emphasised that biodiesel production from microalgae requires much energy.

Collet *et al.* (2013) reviewed fifteen LCA on microalgae biofuel production. Their aim was to identify options and variations between LCAs and derive guidelines to facilitate the comparison between studies. Regarding the energy balance, the found that the results varied largely depending whether or how the cumulative energy demand was included in the analysis.

Sills *et al.* (2012) followed another approach: They conducted their LCA by varying a large number of parameters within a range of literature values (using Monte Carlo Simulation with uniform, triangular, or lognormal distribution functions and most likely, minimum and maximum values). This represents the approach of including uncertainty in an LCA study (Heijungs and Huijbregts 2004) and resulted in a large range of partially contradicting results. The authors compared their results of the 'Energy Return On

Investment' (the inverse of the NER) to results of previous studies and concluded that no result is incorrect but "each represents a specific case". One of the main limitations according to the authors is, that they did not consider whether or how important process parameters are correlated.

2.2.2 Single LCA studies

Table 2.2 gives an overview over previous LCA studies, including information about the investigated cultivation system, final product and calculated impact category. Important comments and findings regarding energy demand, biomass yield, and future developments are summarised.

The conclusions and observations of the respective studies emphasise the need to investigate in more detail the dependency between cultivation energy and biomass productivities and their potential development:

- Results are often highly sensitive to parameters that affect productivities and/or cultivation energy, such as in (Stephenson *et al.* 2010, Weinberg *et al.* 2012, Zamolla *et al.* 2011).
- Many studies emphasise that their assumptions reflect or require technology improvement (Brentner *et al.* 2010, Sander and Murthy 2010, Hulatt and Thomas 2011, Shirvani *et al.* 2011, Woertz *et al.* 2014).
- Often, the improvement includes higher productivities and/or reduced cultivation energy (Campbell *et al.* 2011, Zamolla *et al.* 2011, Sevigné-Itoiz *et al.* 2012, Jonker and Faaij 2013, Chowdhurry *et al.* 2012, Vasudevan *et al.* 2012, Dassey *et al.* 2014).
- Although it is known that cultivation energy and biomass yields are related, those parameters were modelled independently of each other. Apart from Sevigné-Itoiz *et al.* (2012), who analysed the data obtained from a small pilot PBR, all studies obtained cultivation energy and biomass yields from different sources.

Apart from the research focus, two other observations can be made:

Most LCAs were conducted about microalgae cultivation in ponds. Reasons are that (a) ponds have been used to cultivate microalgae since a long time and (b) it is supposed that cultivation energy for ponds is lower than for photobioreactors.

By far the most investigated fuel is biodiesel. However, most studies find that biomass drying and lipid extraction takes very much energy (Lardon *et al.* 2009, Sander and Murthy 2010, Khoo *et al.* 2011, Dassey *et al.* 2014). As a consequence, some studies focussed on alternative ways to produce biodiesel e.g. (Sawayama 1999, Frank *et al.* 2011, Vasudevan *et al.* 2012) or even avoided this step in the LCA altogether (Jorquera *et al.* 2010, Tredici *et al.* 2015).

Table 2.2: Overview over previous LCA studies about microalgae biofuels production

Study	Cultivation system	Final product(s)	Impact	Comments and findings regarding energy demand, biomass yield, and future developments
Batan *et al.* (2010)	Flat plate, aerated (under-water)	Biodiesel	Energy, GHG	"Technology and biofuels system level improvements which are currently under investigation by a variety of researchers will improve the environmental performance and scalability of the microalgae-to-biofuels process"
Brentner *et al.* (2011)	Flat plate PBR, pond, tubular, annular	Biodiesel, biomethane	Energy (CED)	Best case: flat plate PBR The study emphasises the importance of technologic innovation in algae processing.
Campbell (2011)	Pond	Biodiesel	GHG, costs	"… it is likely that new systems and processes will be introduced that could dramatically reduce the economic and energy costs of harvesting and processing the algae"
Chowdhurry *et al.* (2012)	Pond	Biodiesel, biomethane	GHG, water, (energy)	"The water demand of algal biodiesel production, although high, can be lowered through improvement in biomass and lipid productivity."
Clarens *et al.* (2011)	Pond	Biomass	GHG, water use, land use, eutrophic-cation, energy	Compares microalgae production to switchgrass, canola and corn.

Collet *et al.* (2011)	Ponds	Biomethane	GHG, many other	"…impacts generated by the production of methane from microalgae are strongly correlated with the electric consumption. Progresses can be achieved by decreasing the mixing costs…"
Dassey *et al.* (2014)	Pond	Biodiesel	Energy	"While … slight improvements [in productivity and lipid content] could potentially make algal biofuels a reality for the best-case scenario, the current technology is less likely to produce a positive energy balance with biofuels as a singular energy provider"
Frank *et al.* (2011)	Pond	Biodiesel	GHG	Focus: hydrothermal liquefaction and lipid extraction pathways
Hulatt and Thomas (2011)	Horizontal tubular PBR	Biomass	Energy	"When comparing the solar energy conversion efficiency to the energy investment for culture circulation, significant improvements in reactor energy input must be made to make the system viable."
Jonker & Faaij (2013)	Pond, horizontal tubular PBR	Bioenergy	Energy, costs	"The implementation of different improvement options [e.g. increase of annual productivity] could reduce the indirect energy consumption ratio by fifty percent for both raceway ponds and horizontal tubular systems in the optimistic scenario."

Jorquera *et al.* (2010)	Pond, tubular PBR, aerated flat plate PBR	Biomass	Energy	The study did not consider the energy for harvesting and oil extraction "which could significantly add to the energy consumption parameter."
Kadam (2001)	Pond	Electricity (algae co-firing in an electrical power plant)	Energy, GHG, acidification, eutrophication, depletion of natural resources	n.a.
Khoo *et al.* (2011)	Pond (& unspecified aerated PBR for inoculation)	Biodiesel	Energy, GHG	Bottlenecks are lipid extraction and biodiesel production.
Lardon *et al.* (2009)	Pond	Biodiesel	GHG, many other	Main impact has the heat for biomass drying.
Murphy and Allen (2011)	Ponds	Biodiesel	Energy	Results indicate that "…energy required for water management alone is approximately seven times greater than energy output in the form of biodiesel and more than double that contained within the entire algal biomass"
Razon and Tan (2011)	Pond & aerated flat plate PBR for inoculation	Biodiesel, biomethane	Energy	Large energy deficits were observed even with highly optimistic assumptions.
Sander & Murthy (2010)	Pond	Biodiesel	Energy, GHG	Main impact has the natural gas drying of algal cake. There is a "need for new technologies to make algae biofuels a sustainable, commercial reality".
Sawayama *et al.* (1999)	Pond	Oil	Energy, GHG	Focus: thermochemical liquefaction

Sevigné-Itoiz *et al.* (2012)	Bubble columns	Biomass	Energy (CED), many others	Efforts should be made to decrease energy consumption. Highest energy consumption have the mechanical requirements of pumps and need for air injection.
Shirvani *et al.* (2011)	Pond	Biodiesel	Energy, GHG	"The production of advanced biofuels from algae-sourced biomass is heavily dependent on direct and indirect energy inputs, and is currently not environmentally feasible."
Sills *et al.* (2012)	Combination of aerated tubular PBRs and ponds	Biodiesel, biomethane	Energy	see 2.2.1
Stephenson *et al.* (2010)	Pond, tubular airlift PBR	Biodiesel	Energy, GHG	Results are most sensitive to oil yield, circulation velocity and CO_2 concentration in flue gas. The "… environmental performance of biodiesel produced from the algae harvested from raceways [ponds] would be highly sensitive to the power required to compress the flue gas"
Tredici *et al.* (2015)	Flat plate PBR	Biomass	Energy	"The NER of a process can be improved by increasing the energy output and/or decreasing the energy inputs."

Vasudevan *et al.* (2012)	Pond	Biodiesel	Energy, GHG, freshwater consumption	"Highest assumed oil productivity lies within range expected to be practical in the future and is contingent on optimization of cultivation and siting; chosen to be representative of a stretch R&D target."
Weinberg *et al.* (2012)	Pond, Flat plate PBR	Biodiesel, bioethanol, biomethane	GHG	Results are highly sensitive to assumptions about aeration rate and pressure loss which influence the energy demand for cultivation.
Woertz *et al.* (2014)	Pond	Biodiesel	GHG	The study "provides a guide to the research and development objectives that must be achieved to meet both economic and environmental goals for microalgae biodiesel production".
Zamolla *et al.* (2011)	Pond	Biomethane	Energy, costs	High biomass productivities "… will be crucial to exploit the potential of microalgae biomass for production of commodity kWh-energy."

The analysis of LCA studies shows that technology improvement is needed to attain a NER<1 for microalgae biofuels production. An inevitable question is thus: how far can the technology be developed?

2.2.3 Reviews showing challenges of technology improvement

Four recent reviews on microalgae biofuels production (Table 2.3) show the challenges of future development and emphasise the need to thoroughly understand the processes of microalgae growth and cultivation in order to analyse their potential improvement.

Borowitzka (2013) summarises the previous failed attempts to produce microalgae biofuels energetically (and economically) efficiently. Tredici (2010) emphasises the challenge of attaining high photosynthetic efficiencies especially outdoors. Walker (2010)

underlines the high energy and resource demand to cultivate microalgae. A detailed analysis of algae metabolism and improvement options is given in Williams and Laurens (2010). Further studies about specific aspects of microalgae biofuels production are cited within the following chapters.

Table 2.3: Title and short description of other reviews about microalgae biofuels production

Study	Title and short description
Borowitzka (2013)	*Energy from Microalgae: A Short History* The paper describes previous approaches and challenges to use microalgae energetically, from the 1940s to 2013.
Tredici (2010)	*Photobiology of microalgae mass cultures: understanding the tools for the next green revolution* The focus lies on processes of photosynthesis and potential biomass yields and challenges of outdoor cultivation.
Walker (2010).	*Biofuels – for better or worse?* This critical review "seeks to illustrate the misinformation on which some of the advocacy of biofuels has been based", its focus lays on sustainability aspects, such as high energy and resource demand.
Williams and Laurens (2010)	*Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics* The extensive review (37 pages + Appendices) gives background information about a number of metabolic processes and improvement options. The main results focus on economics.

3 Background to model microalgae growth, cultivation and biofuel production

This chapter gives the scientific background information which is necessary for understanding and thus modelling microalgae growth, cultivation and biofuels production.

Section 3.1 explains microalgae growth and its limitations, the implications of photosynthetic efficiency and the interaction of environmental conditions with microalgae growth. Section 3.2 introduces purpose and characteristics of photobioreactors, equations to calculate operation energy and further requirements to cultivate microalgae on large scale. Section 3.3 describes how biofuels can be made from microalgae, focussing on biomethane as biofuel with a low energy demand for production.

3.1 Microalgae growth

Microalgae are very small organisms (in size of a few micrometres) doing photosynthesis; they use solar energy to grow. Apart from this common feature, they are surprisingly distinct: Most belong to eukaryotes (like plants) but some are bacteria (e.g. cyanobacteria). They have manifold colours (blue, green, red, yellow) and forms and can live in all kinds of environments (Madigan *et al*. 2006). Algae can build their biomass from CO_2 as inorganic carbon source (*autotrophic* growth), organic substances (*heterotrophic*) or both (*mixotrophic*). This study investigates *autotrophic* algae growth which requires a CO_2 source.

Microalgae cultivated for energetic use have in common that they live in the water, do photosynthesis and grow by cell division. This section explains the basic principles and requirements of those mechanisms.

3.1.1 Basic mechanisms

Like any living organism, microalgae need (metabolic) energy to grow, move etc. In the following, the processes of photosynthesis and microalgae growth are explained.

Photosynthesis

In photosynthesis, light sensitive pigments in microalgae, the *chlorophylls*, (part of the photosystem) absorb light energy (photons). With this energy, the molecular bonds of water (H-O-H) are split. With the evolving protons (H^+) and electrons (e^-) the cell builds two important functional molecules: adenosine triphosphate (ATP), the 'fuel' of molecular reactions, and the so called *reduction equivalents* (e.g. NADPH/H+) which are needed to reduce other molecules (e.g. CO_2). The remaining O molecules form molecular oxygen (O_2). Since photons are needed for these processes, they are called *light reactions*.

The cell uses the ATP and reduction equivalents (in the following called *'metabolic energy'*) from the light reactions to reduce (or 'fix') CO_2 and assemble it to small sugar molecules in the so called *Calvin Cycle* (Madigan *et al.* 2006). Those processes do not require light and thus are called *light-independent* or *dark reactions*.

The dark reactions required to fix carbon and form biomass are orders of magnitude more slowly than the light reactions and thus limit microalgae growth (Goldman 1979, Kamen 1963).

Figure 3.1 shows the principle of photon use and electron flow in photosynthesis and the simplified light and dark reactions.

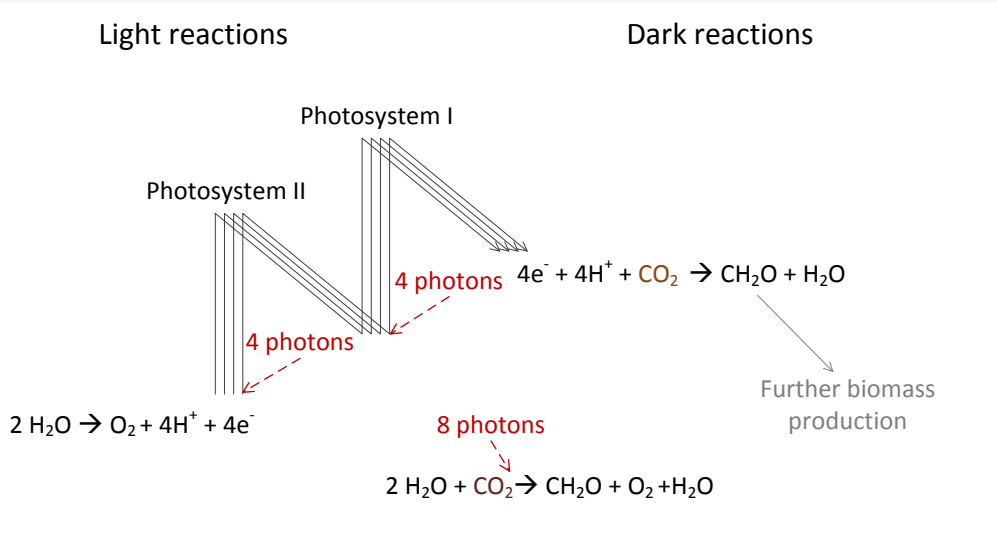


Figure 3.1: Scheme of photosynthesis (adapted from Walker 1992)

After photosynthesis: more dark reactions

With the initial small carbohydrates from photosynthesis, microalgae build larger carbohydrates, lipids and proteins. To build these molecules, microalgae require also nitrogen (N), phosphorous (P), oxygen (O), sulphur (S) and small amounts of *trace elements,* (e.g. iron, copper). The cell must take up all substances (in addition to CO_2) from the culture medium. This requires reduction equivalents.

With those 'building blocks' microalgae construct complex macromolecules (DNA, enzymes) and from those again new cell structures like membranes or other cell compounds (Figure 3.2). Before a cell can replicate, it must coordinate about 2000 biochemical reactions (Madigan *et al.* 2006). The scheme of biomass production is schematically shown in Figure 3.2.

When a cell has enough biomass to build another cell, it divides into two ('cell division') and the process starts again in each cell. All processes for biomass production are in the following summarised with the term 'growth'.

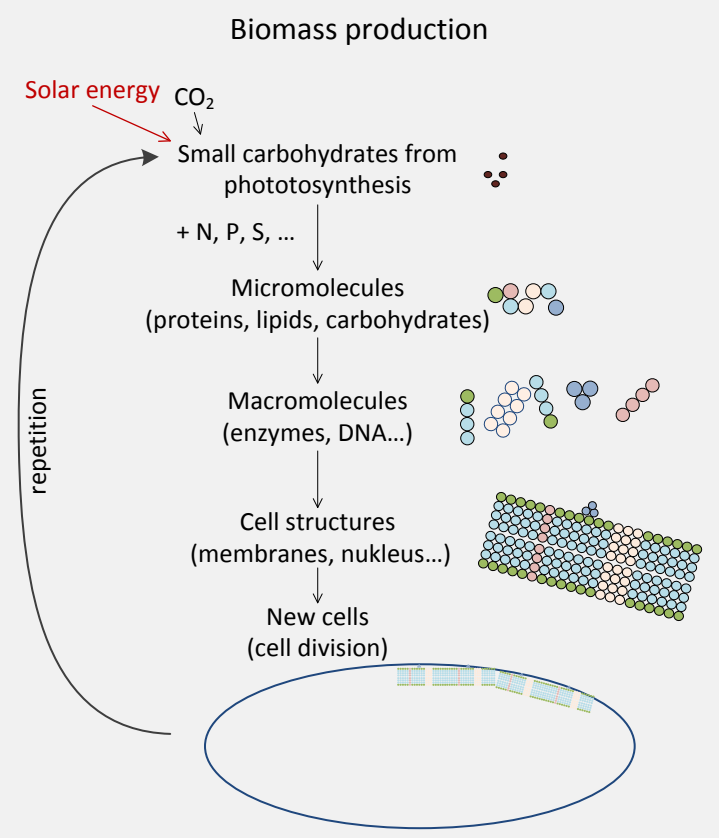


Figure 3.2: Scheme of biomass production in microalgae

How to measure microalgae growth

It is important to note that parallel to growth, algae always reconvert biomass into ATP and reduction equivalents to maintain their basic metabolic functions. This reverse process of photosynthesis is called *respiration*. All methods to measure microalgae growth thus determine the net growth (the result of the growth processes minus the respiration processes).

Microalgae growth can be measured by the increase in O_2 concentration or decrease in CO_2 concentration per time (see box photosynthesis). More usual though is it to determine the amount of cells suspended in a certain culture volume: the cell or biomass concentration (or density). It can be determined by:

- counting the cell number, e.g. in [No ml^{-1}],
- measuring the culture's light absorption with a spectrometer (optical density, OD [-])
- harvesting the cells (e.g. with a centrifuge), drying and weighing the cells (dry weight, DW, e.g. in [g L^{-1}]).

Usually, several spectroscopic measurements are related to a dry weight (calibration) and then the OD is measured further on. From these measurements, the growth rate (μ) can be determined. It describes the change of *logarithmic* biomass concentration per time related to the mass d(ln*c*)/dt (adapted from Nič *et al.* 2009).

Growth rate (μ) and concentration (c)

$$\mu = \frac{\ln\left(\frac{c_1}{c_0}\right)}{t_1 - t_0} \tag{2}$$

Solved for c_1:

$$c_1 = c_0 \, e^{\mu\,(t_1 - t_o)} \tag{3}$$

c_0 Biomass concentration at t_0 [kg m^{-3}] or [g L^{-1}]
c_1 Biomass concentration at t_1 [kg m^{-3}] or [g L^{-1}]
t_0, t_1 Time of measurement, e.g. [h]
μ Growth rate, e.g. [h^{-1}]

Special cases:

Biomass doubles ($c_1 = 2\ c_0$): $\mu = \ln(2)/t_d$,
with $t_d = t_1 - t_0$'doubling time'
Biomass remains constant ($c_1 = c_0$): $\mu = 0$
Biomass is lost ($c_1 < c_0$): $\mu < 0$

The growth rate has several characteristics. First and most important, it has an upper limit: The maximum growth rate (μ_{max}) depends on the maximum rate of dark reactions. Generally, small microalgae grow faster than large because they have a larger surface per cell volume. This accelerates mass transfer rates necessary for fast dark reactions (Madigan *et al.* 2006). The maximum growth rate is thus strain-specific.

Furthermore, high growth rates are only possible at optimal environmental conditions. Since microalgae inhibit each other, the growth rate usually sinks with increasing cell concentration (Tredici 2010).

Finally, it should be noted that the growth rate is in logarithmic scale: when the biomass concentration remains constant it is zero. It can be negative when biomass is lost (e.g. when no light is available and the respiration rate is high).

3.1.2 Photosynthetic efficiency (PE) and yield calculation

The 'potential' biomass yield from microalgae is usually not calculated from laboratory measurements or growth rates but 'top down' with the sunlight and the so called 'photosynthetic efficiency' (PE) (or also called 'photoconversion efficiency').

Definition and significance of PE

The photosynthetic efficiency is a percent value which describes the share of photonic energy per area and time which algae can convert into biomass energy. This definition is equivalent to that given in Franz *et al.* (2012):

$$PE = \frac{biomass\ energy\ /(area \cdot time)}{photon\ energy\ /(area \cdot time)} \tag{4}$$

The biomass energy per area and time results from the produced biomass per area and time (the so-called 'areal productivity') and the energy content of the biomass:

$$PE = \frac{\frac{biomass}{area \cdot time} \cdot\ biomass\ energy\ content}{\frac{photon\ energy}{area \cdot time}} \tag{5}$$

Vice versa, the PE together with the solar energy and the biomass energy content defines the areal productivity:

$$\frac{biomass}{area \cdot time} = \frac{PE \cdot \frac{photon\ energy}{area \cdot time}}{biomass\ energy\ content} \tag{6}$$

Therefore, the PE is a crucial parameter to determine the productivity based on the solar irradiation.

In the following, limitations and characteristics of the PE are explained. To do this, some definitions about light energy are given.

Light energy and photosynthesis

Light can be described as photons with a specific energy content, measured in micro-mol (µmol) or, synonymic, micro-Einstein (µE). The light hitting a square meter per second is called *photon flux density* (PFD), in (µmol m^{-2} s^{-1}].

The energy content of one mol photons depends on the wavelength and can be calculated as:

$$E_{phot} = \frac{hc}{\lambda} \cdot N_A \quad (7)$$

where:
- E_{phot} Energy content per mol photons [kJ mol^{-1}]
- h Planck's constant: $6.626 \cdot 10^{-34}$ Js
- c Speed of light: $2.998 \cdot 10^{8}$ m s^{-1}
- λ Wavelength [nm]
- N_A Avogadro constant: $6.022 \cdot 10^{23}$ mol^{-1}

Light with a wavelength of 550 nm contains for example 217 kJ mol^{-1}. Light that can be used for photosynthesis, the so called *photosynthetically active radiation* (PAR) has wavelengths of 400-700 nm and makes up about 45% of the solar irradiation depending on climate, latitude and weather (Jacovides *et al.* 2004). Solar light intensity measured in W m^{-2} can thus be converted into PFD and vice versa:

$$PFD = \frac{I_0}{E_{phot}} \cdot 0.45 \quad (8)$$

- PFD Photon flux density [µmol m^{-2} s^{-1}]
- I_0 Light intensity [W m^{-2}]
- E_{phot} Energy content per mol photons [kJ mol^{-1}]

For example, solar irradiation peaks in southern Europe of 1000 W m^{-2} correspond to a PFD of about 2074 µmol m^{-2} s^{-1} (PAR, 550 nm).

The maximum PE?

The theoretical maximum PE is calculated based on the processes in photosynthesis. The first approach is based on the theory that 8 photons are needed to fix one molecule of CO_2 (see box photosynthesis). Assuming that:

- CO_2 is stored in glucose ($C_6H_{12}O_6$) and $1/6^{th}$ glucose molecule contains 475 kJ mol^{-1}
- Chlorophylls need 8 photons with an energy content of 217 kJ mol^{-1} and absorb about 70% of the photonic energy (Madigan *et al.* 2006), and
- 45% of the total sunlight (PAR, see above) can be used for photosynthesis

the PE to transform solar energy into carbohydrates is $8.6\% = \left(\frac{475}{(8 \cdot 217)} \cdot 0.45 \cdot 0.7\right)$ (see also Tredici 2010). (Note that the PE can also relate to PAR and then is about twice as high; this study reports PEs relating to the global irradiation.) The theoretical maximum PE depends on assumptions about the number of required photons, their energy content, reflection losses etc. For example, Bolton and Hall (1991) also predict a maximum PE of 8-9%.

However, this calculation includes only the production of glucose and no further biomass production. As explained in section 3.1.1, microalgae require metabolic energy and thus more than 8 photons for further dark reactions, e.g. to take up nutrients and biosynthesise macromolecules (Wilhelm and Jakob 2011, Williams *et al.* 2008). Thus, the PE can never be as high when the whole growth process is considered (Walker 2009) – even under optimal growth conditions and neglecting biomass losses due to respiration.

The **maximum PE for biomass production** has been discussed controversially: Zhu *et al.* (2008) say 6% is the upper limit for biomass production. Tredici (Tredici 2010) estimates a PE of 5%, but stressed that it must be reduced significantly if algae produced other than carbohydrates. Walker (2009) suggests a maximum PE of about 4.5% considering all enzymatic reactions involved.

The power of the dark side – how dark reactions limit the PE

Microalgae growth velocity is not light-limited. In contrary: the metabolic dark reactions (in which solar energy is turned into biomass) need only few photons at a time to work fast (see 3.1.1). The maximum amount of photons algae need to grow is called *photosaturating* light intensity and is mostly around 80-100 µmol m^{-2} s^{-1} (Tredici 2010, Burlew 1953). Therefore, microalgae use low light intensities most efficiently (the PE is highest at *photosaturation*). More light at a time is not only 'lost' for photosynthesis – it can even inhibit or damage algae.

Thus, to use all sunlight efficiently (for example 2000 µmol m^{-2} s^{-1} which can occur on a summer day at noon), many algae must 'share' many photons. Since many algae inhibit each other, it becomes more difficult to ensure that each microalgae cell uses all photons efficiently.

Calculating the PE from other parameters – trade-offs and implications

The PE of a culture cannot be measured directly but must be calculated from other parameters (see also (5)).

$$PE = \frac{prod_{area} \cdot energy_{DW}}{I_0} \quad (9)$$

$prod_{area}$	Areal productivity during a certain time period, e.g. in [g m^{-2} h^{-1}], [g m^{-2} d^{-1}], [t ha^{-1} y^{-1}]
$energy_{DW}$	Energy content of the biomass, e.g. in [MJ kg^{-1}]
I_0	Light intensity during the same time period as the productivity is measured e.g. in [W m^{-2}] or [kWh m^{-2} d^{-1}]

The light intensity (I_0) can be measured with a photometer or received from databases for solar irradiation.

The energy content of the dry biomass ($energy_{DW}$) depends on the type of cultivated algae and its share of carbohydrates, lipids and proteins in the cell which again depends on the way the algae are cultivated. It can be determined by analytical methods (see 3.1.1) but is often estimated based on previous measurements or empirical values. It can range from about 16 MJ kg^{-1} (Sukarni *et al.* 2014) to about 27 MJ kg^{-1} in cells that stored lipids (Morweiser *et al.* 2010). Due to the metabolic limit of PE, either productivities or biomass energy content can be high, but not both (c.f. equation (9)) (Waltz 2009). Usually, the PE is even lower for cells that accumulate lipids since the higher energy content does not compensate lower productivities (Dillschneider *et al.* 2013).

The 'areal productivity' ($prod_{area}$) results from the 'volumetric productivity' multiplied with the culture volume per ground area (10). The latter depends on the design of the photobioreactor and is thus a technical parameter. (Note that some studies use the term areal productivity for the productivity per photobioreactor surface which can lead to confusion. In this thesis, the areal productivity is always related to the ground area.)

$$prod_{area} = prod_{vol} \cdot \frac{V_c}{a} \quad (10)$$

$prod_{area}$	Areal productivity, e.g. in [g m^{-2} h^{-1}]
$prod_{vol}$	Volumetric productivity, e.g. in [g L^{-1} h^{-1}]
V_c/a	Culture volume per area, e.g. [m^3 m^{-2}]

The 'volumetric productivity' ($prod_{vol}$) again describes the biomass yield per time and culture volume. It results from growth rate (μ) and biomass concentration (c) during a certain time (see 3.1.1). However, since μ and c depend on each other and keep changing, μ·c is either a snap-shot or an average value (11) (μ·c remains constant only in 'continuous cultivation', see 3.2.3).

$$prod_{vol} = \overline{\mu c} \tag{11}$$

$\overline{\mu c}$ Product of growth rate and cell concentration (average)

This method to calculate the PE from laboratory measurements is also defined in (Hu and Richmond 1996). With the above definitions, the PE can be expressed as ((10)and (11) in (9)):

$$PE = \frac{\overline{\mu c} \cdot \frac{V_c}{a} \cdot energy_{DW}}{I_0} \tag{12}$$

In summary, the PE has the following characteristics:

- The PE is related to the growth rate and thus depends in the same way on environmental conditions (e.g. temperature, mass transfer rates) as the growth rate.
- High PEs are not equivalent to high areal productivities. On the contrary: the PE is usually high at low light intensities – then productivities are low.
- The PE can relate to different time scales.

By rearranging equation (9), areal productivities can be calculated vice versa from the PE, light intensity and energy content of the biomass:

$$prod_{area} = \frac{PE \cdot I_0}{energy_{DW}} \tag{13}$$

To calculate the areal productivity, it is crucial to consider that the PE is linked to the conditions under which it is attained. For example, calculating the 'potential' maximum productivity from a maximum PE and the yearly irradiation (such as in Stephens *et al.* 2010) implies that optimal growth conditions are provided during the whole year.

3.1.3 Good and bad growth conditions

Microalgae need specific optimal conditions to grow fast – and thus attain high PE (turn photons efficiently into biomass). This section introduces the requirements for good growth conditions and the mechanisms responsible for growth inhibition and low PE.

Good growth conditions – and how they are usually provided

a) Enough light: mixing

Most algae need only around 80-100 µmol m^{-2} s^{-1} (*photosaturating* light intensity) to fuel their dark reactions (Tredici 2010, Burlew 1953). Outdoors, the light intensity is mostly much higher. Thus, light does not limit microalgae growth – unless algae shade each other. In their natural environments algae usually do not accumulate above a few mg L^{-1} and do

not shade each other significantly. Shading is indeed a problem in algae mass cultivation which aims for concentrations above several g L^{-1}. Tredici (2010) showed that a culture of 4 g L^{-1} absorbs almost all light within 6 mm. Therefore, cultures are mixed to bring each cell to the illuminated surface regularly.

It has been proposed that algae can 'harvest' very high light intensities in a short time and use them efficiently in complete darkness ('flashing light effect'). This must happen in well-defined periods of milliseconds; wrong cycle lengths have an adverse effect (Lehr 2012, Burlew 1953).

b) Concentrated CO_2: gassing

Algae can grow using CO_2 from the air (0.4 vol%) – but not fast. To make algae grow fast, concentrated CO_2 must be supplied to the culture. CO_2 supply is often coupled with O_2 removal since the O_2 produced in the light reaction inhibits photosynthesis. Gasses can be exchanged in various ways: within the PBR or using external devices; for an overview see (Carvalho *et al.* 2006). In aerated PBRs, the culture is sparged with CO_2 (pure or mixed with air). Aeration can also be used to mix the culture since the rising gas bubbles move the culture medium.

c) High mass transfer rates: mixing

Algae must be able to take up nutrients and CO_2 fast. Mixing distributes substances in the culture and removes boundary layers around the cells and thus enhances mass transfer rates (Hu and Richmond 1996, Grobbelaar 1994). Turbulence can be provoked by aeration (see above) or by pumping the culture medium through the reactor.

d) Optimal enzymatic reactions: temperature, pH and salt concentration

The numerous enzymes catalysing the dark reactions function well only within a very narrow range of temperature, pH and salt concentration (Figure 3.3), the respective optimal conditions depend on the algae strain. Thus, in order to attain high PE, the culture medium must provide optimal conditions at any time.

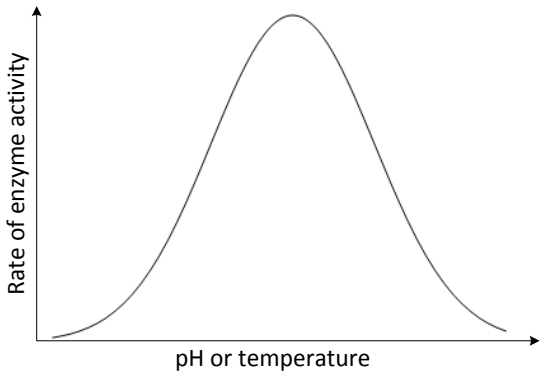


Figure 3.3: How enzyme activity depends on pH or temperature (qualitatively)

Bad growth conditions

When growth conditions are not optimal, algae grow more slowly or not at all, they can even loose biomass or die. In any case, the PE sinks. Adverse conditions and the underlying mechanisms are explained as follows:

e) Not enough light: photolimitation and respiration

Without enough light (*photolimitation*) algae grow slowly or even loose biomass when the respiration rate is higher than the growth rate. The faster algae grow, the more they respirate. Therefore, much biomass is lost when the light intensity suddenly sinks; photosynthesis stops but respiration rates remain high (Wilhelm and Jakob 2011, Kok 1953). Abrupt changes in light intensity should thus be avoided. This is a problem when algae shade each other at high biomass concentration.

f) Too much light or changing light intensities: photoprotection and photoadaption

When algae are exposed to high light intensities (above *photosaturation*, see above) for a longer time, they must protect their light-sensitive chlorophylls and other organs: algae reduce their chlorophyll content, build protective pigments and dissipate photonic energy as heat (Wilhelm and Selmar 2011, Perry *et al.* 1981). These processes take time (up to several hours) and metabolic energy.

Once adapted, algae can use also high light intensities efficiently (Tamiya *et al.* 1953, p. 209, Fig.3) although they still dissipate some photonic energy as heat. When the light intensity sinks again, the cell must reverse the adaptation processes: they remove protective pigments and build more chlorophyll again. High light adapted algae cannot use low light efficiently and vice versa (Tredici 2010). Irradiation outdoors can vary between complete darkness to over 2000 µmol m^{-2} s^{-1} within a few hours (see also Annex, Table A.1). Thus efficient light use is challenging outdoors.

Algae die when exposed to very high light intensities for a longer time (so-called *photoinhibition*). For example, the green algae *Chlamydomonas reinhardtii* is photoinhibited above 1600 µmol m^{-2} s^{-1} (Franz *et al.* 2012).

g) Too much oxygen: photorespiration

Algae produce oxygen during photosynthesis (see box photosynthesis). When many algae grow fast they build much oxygen. Oxygen can bind to – and thus inhibit – one of the major enzymes needed to fix CO_2 (Ribulose-1,5-bisphosphate carboxylase/oxygenase, 'RuBisCo'). The cells must actively detach the O_2 from RuBisCo (Sousa *et al.* 2012, Tredici 2010). This also costs the cell metabolic energy and the PE sinks. Oxygen builds also radicals which damage the cell. For example, an inhibiting oxygen concentration (120-200% of the oxygen concentration of ambient air) can occur already after 1 min in a tube without gas exchange (Posten 2009).

h) No nutrients: storage processes

Without N and P, algae cannot build functional molecules, such as proteins (see 3.1.1) and thus cannot grow (Waltz 2009, Wykoff *et al.* 1998). They have to store carbohydrates in form of starch or lipids in their cell body. When nutrients are available again, algae can

reconvert carbohydrates to functional molecules. These processes require additional metabolic energy which consequently cannot be used for growing; the PE sinks (Wilhelm and Jakob 2012).

Microalgae intended to make biodiesel should contain many storage lipids and thus are on purpose cultivated without N or P.

i) Wrong temperature: growth inhibition or death

The temperature limits the rate of enzymatic reactions. Since those are already growth limiting, the wrong temperature limits algae growth and photon use even more than the suboptimal light intensities (Tamiya *et al.* 1953).

Generally, heat is much more harmful to algae than cold: While low temperatures slow down metabolic reactions, heat disintegrates functional molecules (e.g. enzymes) and algae die. For example, most algae die within less than an 30 minutes when exposed to 50°C (Agrawal and Singh 2000). Temperature management is thus crucial to cultivate microalgae.

j) Contamination and mutual inhibition

Apart from physical and chemical circumstances, other micro- or macro-organisms inhibit and damage algae. For example, most water organisms feed on algae; fungi and viruses damage algae, and bacteria compete with algae for nutrients or light. Thus it must be avoided that other organisms contaminate the culture. Contamination can be avoided by using closed photobioreactors (PBRs) or by cultivating specific algae strains at extreme pH. Some algae attach to the reactor walls and build biofilms so that cleaning is necessary (Hulatt and Thomas 2011).

In addition to that, microalgae inhibit each other in every of the above mentioned aspects: they shade each other, compete for CO_2 and nutrients and excrete O_2 and other growth inhibiting substances (Harris 1970).

Figure 3.4 summarises how the energy output in form of biomass qualitatively depends on the growth conditions – and thus the energy demand for cultivation. Note that high mass transfer rates are a precondition for almost all requirements to ensure fast growth.

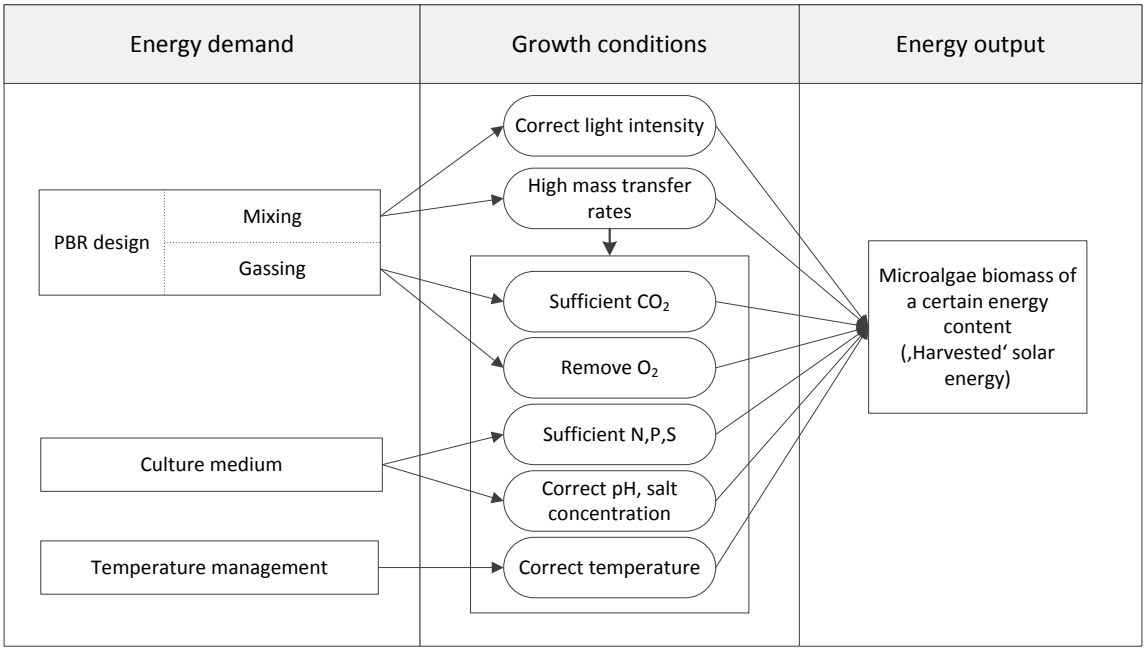


Figure 3.4: Qualitative dependencies between energy demand, growth conditions and biomass output

Important information summarised from section 3.1

- Microalgae biomass production is limited in two ways:
  - → Metabolic dark reactions are slow and limit microalgae growth rates.
  - → Light (photon energy) limits the 'potential' biomass yield.
- A single algae cell can only use a limited amount of light at a time.
- Many microalgae inhibit each other.
- The PE is related to the growth rate and thus depends, like the growth rate, on environmental conditions.

3.2 Photobioreactors and microalgae mass cultivation

Photobioreactors (PBRs) are technical systems containing the microalgae, water and nutrients. Different devices supply concentrated CO_2, remove O_2, and mix the culture. The purpose of PBRs is to provide good growth conditions as described in 3.1.2 and thus achieve high PE and high areal biomass productivities (Figure 3.5). In the following, options of PBR design and operation are introduced and discussed.

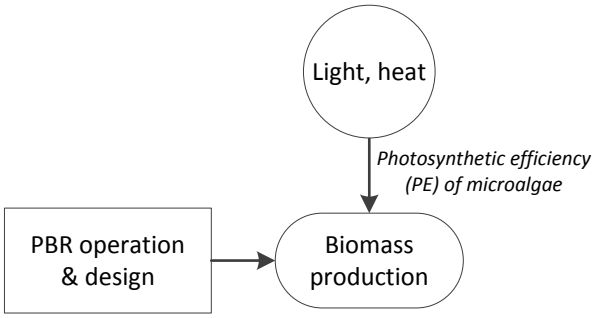


Figure 3.5: Interaction of PBR operation and design, PE and biomass production

3.2.1 Photobioreactor design

Photobioreactors can be shaped in any form, e.g. like tubes, columns, flat panels, bags (floating, hanging) etc. (see for example Pruvost 2011, Tredici 2003, Pulz 2001). To provide algae with sunlight, PBRs have either transparent or no (upper) walls.

Most studies distinguish between so called 'open (raceway) ponds' and other photobioreactors. Open ponds resemble stirred lakes where the culture is in contact with open air; they can be dug into the ground. PBRs are closed containments of glass or plastic and are suspended from frames or aligned on the ground. Advantages and disadvantages of different systems are compared in (Ugwu *et al.* 2008, Tredici 2003, Tredici and Materassi 1992).

Characteristic parameters

Any cultivation system can be described with a set of parameters, including:

- h Height [m]
- w Width [m] (also called 'light path')
- d Diameter [m] (used in tubular PBRs)
- l Length [m]

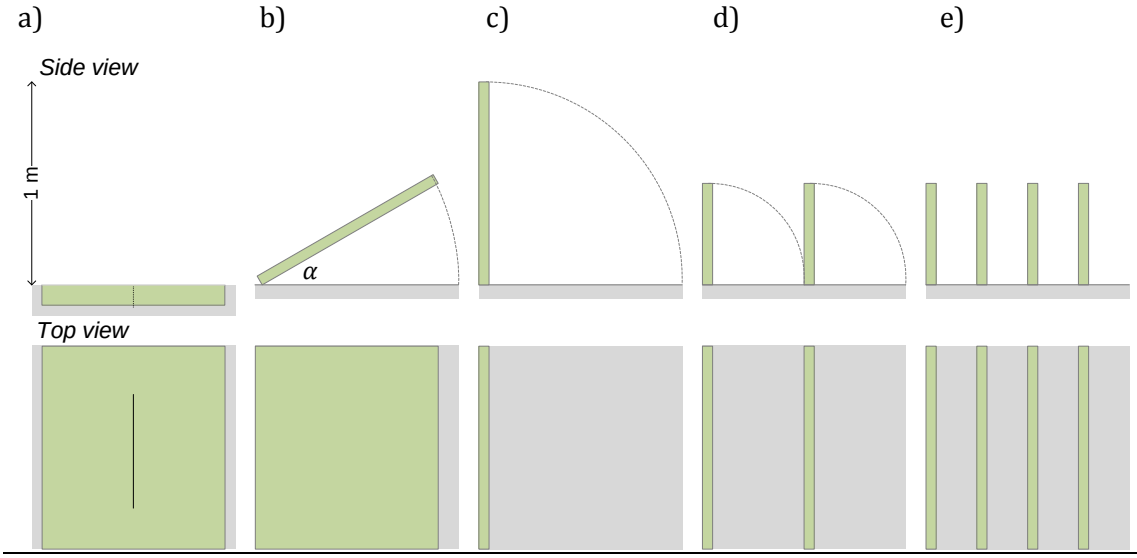
Those and the PBR design determine other characteristic parameters and quotients, like the culture volume V_c and the culture volume per area V_c/a.

- V_c Culture volume [L] or [m^3]
- a Land area occupied by the system [m^2]

The culture volume per area is a key parameter to calculate volume-related data from area-related data and vice versa. A low culture volume per area reduces the energy

demand per area (Morweiser *et al.* 2010). However, the lower the culture volume per area is, the higher must be the cell concentration to harvest all photons (see equation (12)) and the higher is the risk of overheating and oxygen accumulation. These factors have led to the breakdown of many outdoor microalgae plants (Tredici 2003, Janssen *et al.* 2003). Therefore the culture volume per area has a lower limit; PBRs outdoors usually contain 50 to 200 L m^{-2} (0.05 – 0.20 m^3 m^{-2}) (Tredici 2003); Morweiser *et al.* (2010) report best values of about 0.040 m^3 m^{-2}.

Figure 3.6 displays different rectangular cultivation systems and their characteristics. The volume per area depends on the design of the single cultivation system and on the distance of units to each other. For example in open ponds, the volume per area is about equivalent to the pond depth. In flat plate PBRs, it is equivalent to the reactor width (or 'light path') if the height equals the distance; placing vertical PBRs closer together increases the volume per area (see Figure 3.6, d) compared to e)).



Characteristics	**a)**	**b)**	**c)**	**d)**	**e)**
Open or closed	open	closed	closed	closed	closed
Width *w* [m] (or 'light path')	0.10	0.05	0.05	0.05	0.05
Volume per area V_c/a [m^3 m^{-2}]	0.10	0.05	0.05	0.05	0.10
Height *h* [m]	0.10	sin α	1.00	0.50	0.50
Captures all photons/ ground area	yes (w/o margin)	yes (w/o margin)	no	no	no

Figure 3.6: Different microalgae cultivation systems (side and top view) and their characteristics

Capturing the sunlight – orientation, temperature and light management

PBRs should capture most of the sunlight without overheating. Outdoors, the sun shines on PBRs at various angles and intensities during the day – from the side or from above (see Figure 3.6). To avoid overheating, temperature and light intensity can be controlled actively or passively.

Active temperature control – such as spray cooling or heat exchange – needs water, energy, and material depending on the type and operation mode (e.g. flow rates) (see for example Meyer and Weiss 2014).

Passive temperature control (e.g. shading with dark sheets, immersion in water, vertical position) simply avoids high light intensities – but thus also 'loses' the solar energy accordingly. Torzillo *et al.* (1986) for example reported that shading of tubular PBR with dark-coloured plastic sheets caused "a strong reduction in the amount of solar radiation received by the culture and consequently in the yield of biomass."

Vertical PBRs for example do not capture high solar irradiation at noon (Tredici and Materassi 1992) and shade each other, especially when the sun rises and sets. The exact amount of harvested photons depends on many parameters, such as the PBR geometry, material, orientation, and distance of units, on the location (latitude and season), and on the biomass concentration and light intensity at each cultivation time (Slegers *et al.* 2011). A positive effect of vertical PBRs is that algae can use the diffuse and low light more efficiently than direct light (see 3.1.2). However, Hu *et al.* (1996) showed that at otherwise identical cultivation conditions, a 30° inclined PBR attained higher productivities than a 60° and 90°(vertical) PBR for outdoor cultivation (June and July in Israel) – higher PE could not compensate for the lost solar energy (Figure 3.7). For aerated photobioreactors, a minimum inclination is needed to ensure that the gas bubbles rise.

In general, appropriate heat and light management depends on the region or location where algae are cultivated; for example it is less challenging to avoid overheating in Norway than in Spain.

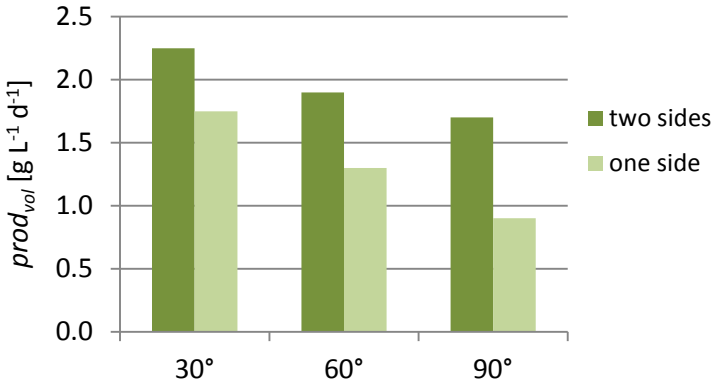


Figure 3.7: Volumetric productivity of a PBR positioned at different angles, illuminated from one or two sides (based on data of Hu *et al.* 1996)

Material

Photobioreactors are exposed to sunlight and different weather the whole year round. Thus their material must be extremely durable and stable. Some systems are thus protected, for example they are covered by a greenhouse or immersed in water (Posten 2009).

Above that, PBR material should be transparent, non-toxic, cheap, and easy to process (Tredici 2003). Polycarbonate (PC), polyethylene (PE), polyvinylchloride (PVC), polyethylene terephthalate (PET) and glass are suggested as reactor materials (Burgess and Fernández-Velasco 2007). Most PBRs are built of glass or thin plastic foils. After use, material could be combusted or recycled to recover energy.

Material demand for PBRs depends on the PBR form and the thickness and density of the used material. For example, for a rectangular PBR, it can be calculated as:

$$x_{mat} = (h \cdot l + w \cdot l + w \cdot h) \cdot 2 \cdot \rho_m \cdot th \quad (14)$$

x_{mat} Material demand [kg]
ρ_m Density of the material [kg m^{-3}]
th Thickness of the walls [m]

To calculate material demand for more complex designs, more parameters are required.

3.2.2 Calculating the operation energy

This section introduces and shortly discusses the most important parameters and equations needed to calculate the operation energy with a focus on aeration. Aeration can be used to provide CO_2, remove O_2 (exchange gasses) and to mix the culture at the same time. For different methods of gas exchange in microalgae cultures see Carvalho *et al.* (2006). Options to reduce operation energy which are directly visible from the equations are also shortly discussed.

Aeration rate (*vvm*)

The aeration rate is the delivered gas **v**olume per time ($\dot{V}_g$) and per culture **v**olume V_c (15); it is often indicated per **m**inute (***vvm***). The term *vvm* is commonly used for microalgae cultivation, and is mainly used in this study.

$$\frac{\dot{V}_g}{V_c} = \frac{v_g \cdot A_g}{V_c} \quad (15)$$

$\frac{\dot{V}_g}{V_c}$ Aeration rate (e.g. [m$^3_{gas}$ m^{-3} s^{-1}], mostly in vvm [m$^3_{gas}$ m^{-3} min^{-1}])
V_c Culture volume [m^3]
v_g (hypothetical or superficial) gas velocity [m s^{-1}] or [m min^{-1}]
A_g Flow cross-section gas [m^2]

The mixing effect (turbulence) of the aeration rate depends on the PBR design: the lower the flow cross-section is (A_g), the higher is the (superficial) flow velocity (v_g) and the better is the mixing. The flow cross section depends on the flow direction and is in rectangular systems usually (width · length), in tubular systems it is the diameter.

Aeration power

Aeration power results from delivery volume, pressure drop and pump efficiency (Hirschberg 1999) (16).

$$P = \dot{V}_g \cdot \Delta p \cdot \frac{1}{\eta} \tag{16}$$

P Power [W]
$\dot{V}_g$ Delivered gas volume [m^3 s^{-1}]
Δp Pressure drop [N m^{-2}]
η Pump efficiency [%]

The volumetric aeration power (P_{vol} in W m^{-3}) can be calculated by using the aeration rate instead of the delivery volume (see above). The areal aeration power (P_{area} in W m^{-2}) can then be calculated from the volumetric aeration power multiplied with the culture volume per area V_c/a [m^3 m^{-2}] (17). To reduce operation power, it is useful to cultivate algae in a small culture volume per area (see 3.2.1).

$$P_{area} = \frac{\dot{V}_g}{V_c} \cdot \Delta p \cdot \frac{1}{\eta} \cdot \frac{V_c}{a} \tag{17}$$

Aeration power can also be calculated from isothermal gas compression (Roels and Heijnen 1980) (18):

$$P = \ln\left(\frac{p_a + \Delta p_g}{p_a}\right) \cdot \dot{n}_g \cdot \mathrm{R} \cdot T \cdot \frac{1}{\eta} \tag{18}$$

p_a Ambient pressure (usually 1013 N m^{-2})
Δp_g Gas pressure
T Temperature [K]
R Ideal gas constant 8.314 J mol^{-1} K^{-1}
$\dot{n}_g$ Mol flux gas [mol s^{-1}] (results from the delivery volume and the ideal gas law)

Equation (16) is an approximation to calculate the aeration power. However, below 100 mbar gas pressure, aeration power calculated with (16) or (18) differs only by 5%.

Pressure drop aeration

For aeration, pressure is needed to pump the gas against the water head, but also through feed pipes and membranes, and to remove the off-gas (19).

$$\Delta p_g = \Delta p_h + \Delta p_{other} \quad (19)$$

Δp_g Gas pressure
Δp_h Water head
Δp_{other} Other pressure drop (e.g. for feed pipes, membranes, filters and off-gas removal)

The water head depends directly on the water column and thus on the reactor height:

$$\Delta p_h = \rho g \Delta h \quad (20)$$

Δh Height of the water column [m]
ρ Density of the medium [kg m^{-3}]
g Gravitational constant: 9.81 m s^{-2}

Consequently, to save aeration power, PBRs should have a low height to reduce the water head (c.f. Figure 3.6). This only applicable though, when the pressure drop for other devices is low (Ripplinger 2008).

Power and pressure drop liquid pumping

Pumps circulate the culture through PBRs to mix it (if not done by aeration) and transport it to a harvesting device. Power for liquid pumping can be calculated analogue to aeration power with (16). However, pressure drop becomes more important: The faster the culture flows and the thinner the PBR is, the better is the mixing (high turbulence) but the higher are also friction losses and thus energy demand (22), (23). Friction losses must be calculated iteratively and are usually measured (for details see Hirschberg 1999).

To merely transport the culture, no turbulence is necessary, plug-flow behaviour is sufficient. In that case, the water head usually determines the total pressure drop for pumping (21).

$$\Delta p_l = \Delta p_h + \Delta p_v + \Delta p_f \quad (21)$$

With:

$$\Delta p_v = \frac{\rho \, v_l^2}{2} \quad (22)$$

$$\Delta p_f = \frac{\zeta \rho v_l^2}{2} \cdot \frac{l}{D_h} \quad (23)$$

Δp_l Pressure drop for liquid pumping
Δp_f Friction loss
Δp_v Velocity head
ρ Density of the medium [kg m^{-3}]
l/D_h Length/hydraulic diameter [-]
ζ Friction factor [-](details, see Hirschberg 1999)

Yearly energy demand, operation time

The yearly energy demand depends on the operation time which again depends on climate data. Usually, the culture is mixed at full rate when the sun shines and at lower rates during the night (Tredici *et al.* 2015). The operation energy per cultivation day thus results as:

$$E_{op,area,d} = P_{area} \cdot \left(h_{prod,d} + r_{op}\left(24 - h_{prod,d}\right)\right) \quad (24)$$

$E_{op.area,d}$ Operation energy per cultivation day (24 h), e.g. in [kWh m^{-2} d^{-1}]
P_{area} Operation power per area [W m^{-2}]
$h_{prod,d}$ Productive hours per day [h d^{-1}]
r_{op} Operation rate night-time [%]

The yearly energy demand depends on the cultivation days per year:

$$E_{op,area,y} = E_{op,area,d} \cdot d_y \quad (25)$$

$E_{op,area,y}$ Operation energy per year, e.g. in [kWh m^{-2} y^{-1}]
d_y Cultivation days per year [d y^{-1}]

3.2.3 Further requirements for microalgae mass cultivation

Microalgae cultivation requires, apart from the cultivation system, carbon dioxide, water and nutrients. Furthermore, the microalgae biomass must be harvested. Requirements and conditions for these processes are shortly introduced.

CO_2 supply

Algae need concentrated CO_2 to grow fast (see 3.1.2). In the laboratory, CO_2 is supplied with gas bottles. For outdoor cultivation, CO_2 can be received for example from factories and must be transported to the plant, e.g. via pipelines. Transporting CO_2 over long distances takes much energy (Jonker and Faaij 2013, Kadam 2002) and thus a nearby CO_2

source is favourable. These places are very limited though. The distance to the next CO_2 source considerably limits the potential of microalgae cultivation (Skarka 2015).

The less efficient algae take up CO_2, the more must be transported to the culture. Doucha *et al.* (2005) for example measured 50% CO_2 uptake in an open thin layer PBR. CO_2 uptake is better in closed PBRs. Rate and amount of CO_2 absorption depends on the type of gassing, but also on the CO_2 concentration in the gas and the quality of mixing and mass transfer (Carvalho and Malcata 2001).

Nutrients and water

Apart from a carbon source, algae need nutrients such as nitrogen and phosphorous and further micronutrients (see 3.1.1). In the laboratory, the culture medium is sterilised and the nutrient mixture is optimised for each algae strain (Hu *et al.* 1996). This is not applicable for mass cultivation. For large scale microalgae cultivation, it is suggested to add fertiliser, such as used to cultivate crops, to the culture. The culture medium must contain more nutrients than algae consist of to ensure that algae can take them up.

To save fertiliser, some studies suggest cultivating algae in wastewater (Mu *et al.* 2014). Wastewater use is not assessed in this study for the following reasons: Wastewater has changing pH and salt concentrations, is often turbid and contains other microorganisms or growth inhibiting substances. Potential lower yields and/or pre-treatment of wastewater thus can offset fertiliser savings (Razon and Tan 2011). Besides, wastewater is usually available in urban areas where cheap and unused land is scarce (Fortier and Sturm 2012, Lundquist *et al.* 2010).

To use natural water sources and avoid transportation, the cultivation plant must be located near the coast or the shore of a lake respectively. Alternatively, groundwater could be used which must be pumped up.

Harvesting

Microalgae are extremely small. Consequently, much energy is required to separate them from the water. Usually, the culture is pumped to a harvesting device which separates the cells from the water with filters or shear forces (e.g. centrifuge). For a review of several harvesting options see Rawat *et al.* (2013).

To pre-concentrate cultures, they can be pumped into a pond and left there for a few hours or days so that algae settle on the ground. The residual water is removed. Chemicals (so called flocculants, e.g. salts of multivalent cations) can be added to the culture so that microalgae agglomerate and sink faster (Bilanovic *et al.* 1988). Flocculants can however inhibit other chemical processes needed to obtain a biofuel.

The biomass must be harvested in certain intervals, e.g. after a defined time period or when the culture reaches a certain concentration. Three different operation/harvesting modes can be distinguished:

- In so called 'batches', the whole biomass in a PBR is harvested. Fresh cells, e.g. from another PBR are used to inoculate a new culture medium.

- In 'semi-batch' or 'semi-continuous' cultivation only a part of the biomass is harvested. The remaining culture is filled up with fresh medium. Outdoor cultures are usually operated that way. The share of biomass which is needed to inoculate the next culture (and thus cannot be harvested) depends on the operation mode, cell concentration and growth rate.
- In 'continuous cultivation', newly grown biomass is being constantly harvested and fresh medium is constantly added at the same rate. (The dilution rate* must be equal to the growth rate). By this means the biomass concentration [g L^{-1}] is held constant. Continuous cultivation is the 'high art' of cultivating microorganisms and usually only possible in the laboratory under highly controlled conditions.
  *The dilution rate is reciprocal to the average time a particle (e.g. a single algae cell) or volume element of the culture stays in a bioreactor (hydraulic retention time, HRT) (Nič *et al.* 2009).

The harvesting method also determines biomass losses at night due to respiration: When most of the biomass is harvested, the starting concentration is low the next day. This results in low productivities, even at maximum growth rates (see definition of growth rate 3.1.1). On the other hand, high biomass concentrations overnight result in high respiration losses. Thus, a balance must be found between harvesting and respiration losses.

Harvesting energy is, like operation energy, usually related to a volume (e.g. kWh m^{-3}). For batch or semi-batch cultivation, the yearly harvesting energy depends on the culture volume and how often it is exchanged:

$$E_{harv,y} = E_{harv,vol} \cdot V_{c,y} \tag{26}$$

$E_{harv,vol}$ Harvesting energy per culture volume, e.g. in [kWh m^{-3}]
$V_{c,y}$ Culture volume per year [m^3 y^{-1}]

The latter depends on the cultivation time per year and the batch length:

$$V_{c,y} = V_c \cdot \frac{d_y}{d_{ex}} \tag{27}$$

d_{ex} Batch length, days between culture exchange

Energy for culture transport (filling and emptying the PBRs) is analogue:

$$E_{tr,y} = E_{tr,vol} \cdot V_{c,y} \cdot 2 \tag{28}$$

$E_{tr,vol}$ Pump energy per culture volume, e.g. in [kWh m^{-3}]

Important information summarised from section 3.2

- Good growth conditions depend on PBR operation and design.
- The aeration rate determines the quality of gas exchange and mixing and is directly proportional to the operation energy.

3.3 Microalgae biofuels production

This section shortly introduces how different biofuels can be made from microalgae biomass with a focus on biomethane as a benchmark for the net energy ratio.

3.3.1 Different fuels

Microalgae contain proteins, carbohydrates and lipids in different shares depending on the microalgae strain and the way it is cultivated. Thus, algae biomass can be turned into a variety of fuels, such as (bio-) ethanol, diesel or hydrogen or methane.

The most investigated fuel is biodiesel. To produce it, algae are cultivated without nutrients so that they store lipids (see 3.1.2). These lipids are extracted from the (dried) biomass, saturated and purified. Each process step can be done in different ways and thus almost an unlimited number of biofuels and process combinations can be examined. For an overview of some, see for example (Aitken and Antizar-Ladislao 2012, Khoo *et al.* 2011, Sander and Murthy 2010, Williams and Laurens 2010, Sialve *et al.* 2009).

To produce biohydrogen, specific algae and cultivation conditions are required: The green algae *Chlamydomonas reinhardtii* can digest its own biomass into hydrogen under anaerobic conditions and without sulphur (Hallenbeck and Benemann 2002).

Biomethane production is energetically 'cheap'

The focus of this study is set on biomethane production from the algae biomass because it requires the least efforts both during biomass production and downstream processing:

- For biomethane production, algae do not need to store lipids or produce other special substances; they only need to grow fast. This results in higher growth rates (Rodolfi *et al.* 2009) and photosynthetic efficiencies (Wilhelm and Jakob 2012).
- The wet biomass can directly be put into the biogas plant. It is not necessary to previously dry it or to extract substances – those processes costs very much energy. Sills *et al.* (2012) showed that drying as well as wet lipid extraction consumed more energy than is stored in the fuel (1.8 and 1.6 MJ MJ^{-1} respectively) (see also Woertz *et al.* 2014, Lardon *et al.* 2009, Sander and Murthy 2010, Khoo *et al.* 2011, Dassey *et al.* 2014).

Thus, biomethane production from microalgae biomass is investigated in this study. Already in 1959, Golueke and Oswald proposed the fermentation of microalgae biomass to produce methane (Borowitzka 2013).

Note that microalgae biofuels production is not economically feasible yet, either (Woertz *et al.* 2014). Thus, economically, it would make more sense to produce non-energetic high value products (HVP, for example vitamins, antioxidants, colorants etc.) with microalgae, as already done today.

Biofuels as a by-product? Methodological considerations

It has repeatedly been suggested to produce high value products (HVP) and biofuels from the same biomass. A 'coupled' production is not assessed in this dissertation for several reasons (see also 1.3).

First of all, very few microalgae products generate residues and thus the potential of biofuels as a by-product is marginal. Moreover methodological issues must be considered about how to calculate environmental burdens of a system with several outputs (Klöpffer and Grahl 2009). There are mainly two options:

a) Bioenergy and HVP are considered to be equivalent products.
   This can be dealt with so called 'allocation' and 'substitution' methods.

   - *Allocation* (energetic): The cumulative energy demand (CED) of the whole production chain is distributed between the products according to their energy content. Since HVP do not contain much energy, this accounts the major part of the energy demand to the biofuel. (Other allocation criteria are mass or prices, however it is compulsory to use 'energetic allocation' for assessing energy products (European Parliament and European Council 2009)).
   - *Substitution*: If the HVP from microalgae substitutes another substance, the biofuel can receive a credit for the 'avoided' energy to produce the respective other substance. This can lead to a wide range of credits depending on the substitute. ISO norms on LCA recommend the application of different substitution and allocation methods to assess how the results depend on the method.

   However, 'equivalent' production is rather hypothetical: the HVP is usually the main product of microalgae cultivation since it can be sold for higher prices.

b) Bioenergy is considered to be made from the 'waste' or residuals of HVP

   Wastes are defined to have zero life cycle emissions. The fact that waste can be used energetically should not lead to producing more waste. This is paradox is also a problem for other fuels from waste.

For the above named reasons, the NER is calculated for microalgae biomethane as the main and only product.

3.3.2 Biomethane production

To produce biomethane, biomass (the substrate) is mixed with anaerobic bacteria and heated for a certain time until the bacteria degraded most parts via hydrolysis and acidogenesis of the biomass into methane (CH_4), carbon dioxide (CO_2) and few other gasses (Deublein and Steinhauser 2011). The methane is then separated from other gasses and purified.

The type of substrate determines whether the fermentation processes is dry or wet, what temperature is needed, and whether it is operated (semi-)continuously or in batches (see also 3.2.2). Microalgae biomass can be fermented wet; for this, the ferment should contain 2-10% dry weigth (DW). Wet fermentation usually is done in batches of 15 to 32 days (Deublein and Steinhauser 2011).

The fermenting bacteria need about 1 nitrogen (N) molecule per 20-30 carbon (C) molecules (C/N-ratio of 20-30). More nitrogen reacts with hydrogen to ammonia which inhibits methane production. With less nitrogen, the digesting bacteria cannot form proteins (analogue to microalgae growth c.f. 3.1.2). Since most microalgae have a lower C/N-ratio than required, they should be co-digested, e.g. with maize (Sialve *et al.* 2009).

The biomethane yield per kg volatile substance (VS, the digestible part of microalgae) depends on the type of microalgae and the operation mode (Mussgnug *et al.* 2010). Experiments showed biomethane yields between 0.18 and 0.39 Nm^3 (normal cubic metre) per kg substrate for different microalgae species (Mussgnug *et al.* 2010); with lower values when biomass is dried previously. For further details about biomethane production, see (Meyer 2012, Deublein and Steinhauser 2011).

Important information summarised from section 3.3

- Microalgae can be turned into a variety of fuels. The type of biofuel depends on the algae strain, the growth conditions and type of downstream processing.
- The most energy efficient fuel is biomethane since it does not require lipid accumulation and needs least downstream energy.

4 Core model: relation between energy demand and biomass output

In chapter 3, the qualitative relations between energy demand and biomass productivity and the main limitations are described. In this chapter, a model is derived which allows to calculate the areal biomass productivity depending on the aeration rate.

A correlation between important parameters to model operation energy and productivity is derived from experimental data gathered in the laboratory (section 4.1) to ensure that all cultivation conditions are controlled and certain effects on algae growth are singled out. The correlation is validated with further experimental data and the effect of the PBR design is determined (section 4.2). Furthermore, correction factors are derived to apply the correlation to outdoor conditions (section 4.3). Finally, the resulting equation ('core model') is presented in the last section (4.4), together with assumptions regarding technology improvement.

The analyses are focussed on aerated flat plate photobioreactors for mainly two reasons: First, aerated flat plate PBRs are supposed to be better scalable and more energy efficient than other PBRs (Morweiser *et al.* 2010, Lehr and Posten 2009, Tredici and Materassi 1992). Therefore, many experiments have been done on this reactor type. Another important reason is that hardly any systematically measured correlations between energy demand, productivity and light intensity are available (Öschger and Posten 2012). Some studies report dependencies but only as relative values (e.g. Quinn *et al.* 2012). The most systematic and comprehensive data are available for aerated photobioreactors – predominantly in different studies of Hu *et al.* (Hu and Richmond 1996, Hu *et al.* 1996, Hu *et al.* 1998). Therefore, this analysis is based mainly on these studies.

4.1 Determining a correlation between aeration rate, PE and light intensity

The analyses and calculations are based on data provided in the study of Hu and Richmond (1996): Cyanobacteria (*Spirulina platensis*) were cultivated in a 2.6 cm flat plate PBR at different aeration rates (0.6, 2.1 and 4.2 *vvm*) and light intensities (500, 900 and 1800 µmol m^{-2} s^{-1} photon flux density, PFD). Volumetric productivities were measured during 48 hours (no dark period) for each combination of aeration rate and light intensity.

Table 4.1 shows the *maximum* productivities measured for each combination of aeration rate and light intensity versus the corresponding biomass concentration. Those are analysed further to determine dependencies between parameters.

Table 4.1: Maximum volumetric productivities and corresponding biomass concentration for different aeration rates and light intensities as measured in Hu and Richmond (1996)

Aeration rate (vvm) [$m^3\ m^{-3}\ min^{-1}$]	**0.6**		**2.1**		**4.2**	
	$prod_{vol}$	c	$prod_{vol}$	c	$prod_{vol}$	c
PFD	[$mg\ L^{-1}\ h^{-1}$]	[$g\ L^{-1}$]	[$mg\ L^{-1}\ h^{-1}$]	[$g\ L^{-1}$]	[$mg\ L^{-1}\ h^{-1}$]	[$g\ L^{-1}$]
500 µmol $m^{-2}\ s^{-1}$	0.07	2.4	0.10	5.0	0.11	5.0
900 µmol $m^{-2}\ s^{-1}$	0.12	4.0	0.16	8.0	0.20	10.0
1800 µmol $m^{-2}\ s^{-1}$	0.20	7.0	0.30	9.0	0.40	15.0

For all further calculations, it is important to note that all tested aeration rates provided enough CO_2 for fast growth and removed oxygen sufficiently: the conditions for gas exchange were not growth limiting. Furthermore, all other growth conditions, such as temperature, pH, and nutrients were kept constant and optimal for the algae and did not limit microalgae growth (Hu and Richmond 1996). As a consequence, the dependencies between aeration rate, light intensity and microalgae growth were exclusively based on the mechanisms of mass transfer and light management (see Figure 3.4).

4.1.1 Data analysis and interpretation

To investigate the dependencies between parameters, the PE is calculated from the respective maximum volumetric productivities with (29) (equals (8) and (11) in (12)):

$$PE = \frac{prod_{vol} \cdot \frac{V_c}{a} \cdot energy_{DW}}{PFD \cdot E_{phot}} \cdot 0.45 \qquad (29)$$

The photon energy content (E_{phot}) is 217 kJ mol^{-1} as reported by Hu and Richmond (1996). Biomass energy content ($energy_{DW}$) to calculate the PE is estimated with 20 MJ kg^{-1} (Franz *et al.* 2012). The culture volume per area (V_c/a) is, according to the authors, 0.024 $m^3\ m^{-2}$ without headspace. (A 2.6 cm wide PBR illuminated horizontally from one side corresponds to 0.026 $m^3\ m^{-3}$ (see Figure 3.6)).

Figure 4.1 (A) shows the PE over the aeration rate at different light intensities. Figure 4.1 (B) shows the PE over the light intensity for the same data.

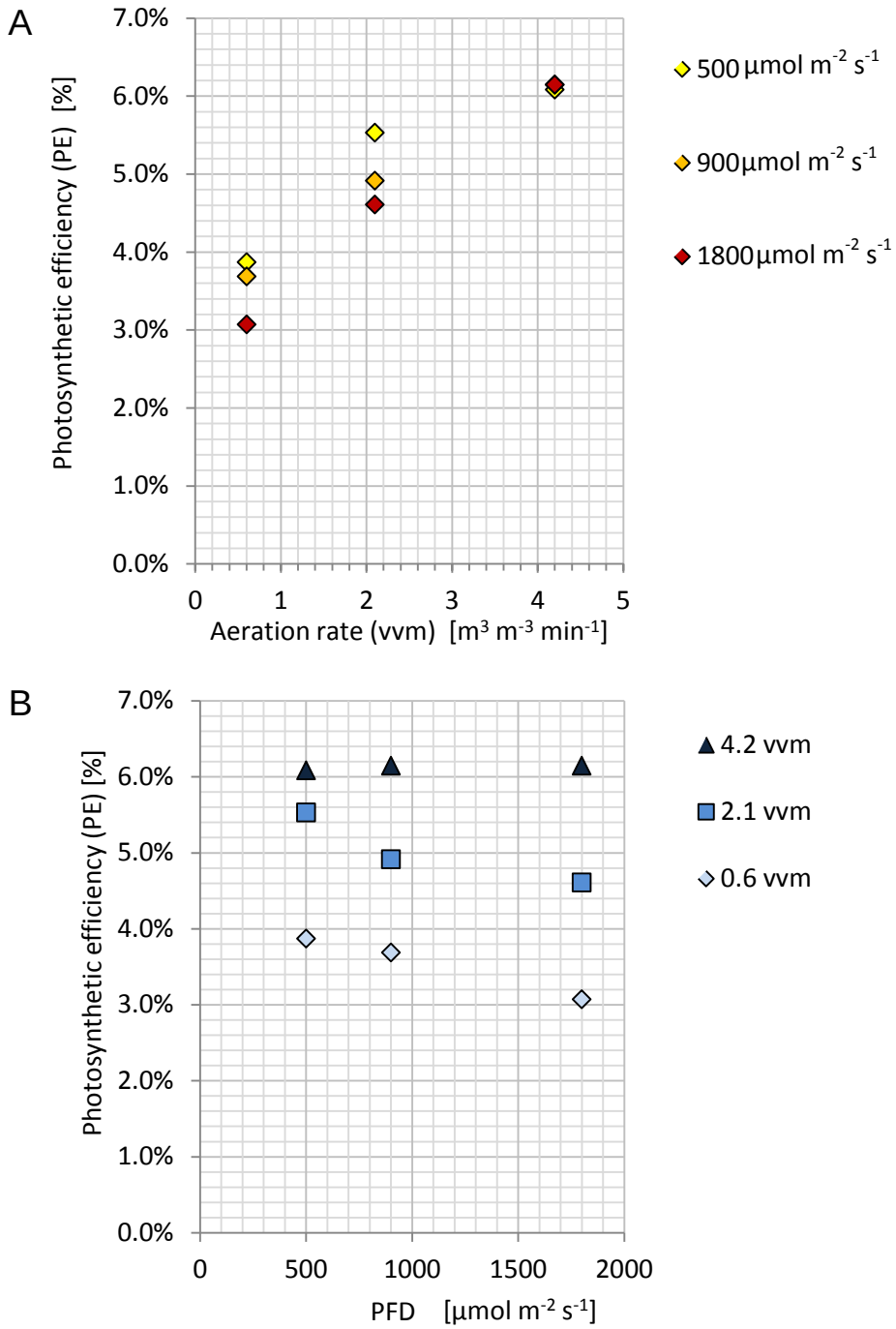


Figure 4.1: Dependencies between PE, aeration rate and light intensity: (A) PE over aeration rate, (B) PE over light intensity, based on data of Hu and Richmond (1996)

Figure 4.1 (A) clearly shows that the PE depends on the aeration rate. More interestingly, the correlation is non-linear: while the PE doubles in the best case (from 3% to 6% at 1800 µmol m^{-2} s^{-1}) the aeration rate increases sevenfold (from 0.6 to 4.2 *vvm*). Much more energy is needed to attain high PE (and thus a high biomass energy output) than low. Furthermore, it can be seen that at low aeration rates, the PE depends additionally on the light intensity (Figure 4.1 B).

These data confirm the theoretical background explained in chapter 3: High PE at high light intensities requires a high biomass concentration (see Table 4.1 and equation (12)). Since algae shade and inhibit each other, it becomes more difficult to attain high PE. Consequently, higher aeration rates (and thus more energy) are required to ensure that the individual cell:

- maintains high mass transfer rates needed for fast dark reactions and
- receives enough light but not too much (avoid photolimitation and photoinhibition).

Whether one or the other effect is responsible for the positive effect of mixing has been discussed controversially: Posten (2009) emphasises that high mass transfer rates are at least equally important as good light management. This can be seen also from Figure 3.4. Grobbelaar (1994) finds that a combination of light-dark cycles and mass transfer rates explain the positive effect of mixing; while Ugwu (2008) suggest that it is mainly the high mass transfer rates.

With the assumed energy content of 20 MJ kg_{DW}^{-1}, the maximum PE is around 6% (Figure 4.1 A and B). The authors' suggestion of *Spirulina* biomass energy content of 22.4 MJ kg_{DW}^{-1} resulted in even higher PE of around 7% (c.f. equation (12)). Nevertheless, a PE of 6% is the upper limit expected for biomass production (see 3.1.2). The PE could have come close to the theoretical maximum because (a) cyanobacteria are small and fast-growing (Madigan *et al*. 2006) and (b) had optimal growth conditions (temperature, nutrients, constant light intensities, see Figure 3.4). Therefore, the energy content of 20 MJ kg_{DW}^{-1} is used further on.

4.1.2 Areal energy balance and 'core energy ratio'

To further analyse the data of Hu and Richmond (1996), the areal operation energy is compared to the areal biomass energy output (areal energy balance). The quotient of these values is defined in this study as 'core energy ratio' (CER) (30). This presentation has two advantages:

First, it is easier to compare different studies based on these values. Data about operation energy and productivities are generally better available than PE or aeration rates. Second, the quotient already gives a first indication of the NER since it includes the parameters which mainly determine the NER. The NER is always higher than the CER since it includes further upstream and downstream energy demand. Areal energy balance and CER can also be calculated for other time units.

$$CER = \frac{E_{op,area,d}}{E_{biom,area,d}} \tag{30}$$

$E_{op,area,d}$ Operation energy input per area and day [Wh m^{-2} d^{-1}]

$E_{biom,area,d}$ Biomass energy output per area and day [Wh m^{-2} d^{-1}]

The areal biomass energy output is identical to the denominator in the PE (see equation (9)). It can thus be calculated from the areal biomass productivity and the biomass energy content (31):

$$E_{biom,area,d} = prod_{area,d} \cdot energy_{DW} \quad (31)$$

The areal operation energy (defined in 3.2.2, equation (24)) is directly proportional to the operation power and thus to the aeration rate (*vvm* or $\dot{V}/V_c$). It depends additionally on the pressure drop, pump efficiency, volume per area, operation hours and night-time operation (see (17)). The areal energy balance for a cultivation day for data of Hu and Richmond (1996) is calculated with the following assumptions:

- Regarding the operation energy: Pressure drop (Δp) is 100 mbar including pressure for water head, feed pipes, filters or membranes and off-gas removal, independent of the aeration rate. Pump efficiency (η) is 85%. The culture is operated during 12 hours per day ($h_{prod,d}$ = 12) and not during the night (r_{op}=0).
- Regarding areal productivity: The daily productivity results from the maximum hourly productivity multiplied with 12.

Figure 4.2 shows the areal energy balance of data from Hu and Richmond (1996). It is clearly visible that low aeration rates are more energy-efficient than high; the CER is lower. This is true for any light intensity.

The tested 1800 µmol m^{-2} s^{-1} PAR (870 W m^{-2} global irradiation) represent the light intensity on a summer day at noon. The yearly average daylight intensity in Karlsruhe, for example is around 320 W m^{-2} (660 µmol m^{-2} s^{-1} PAR) (see also Annex, Figure A.2).

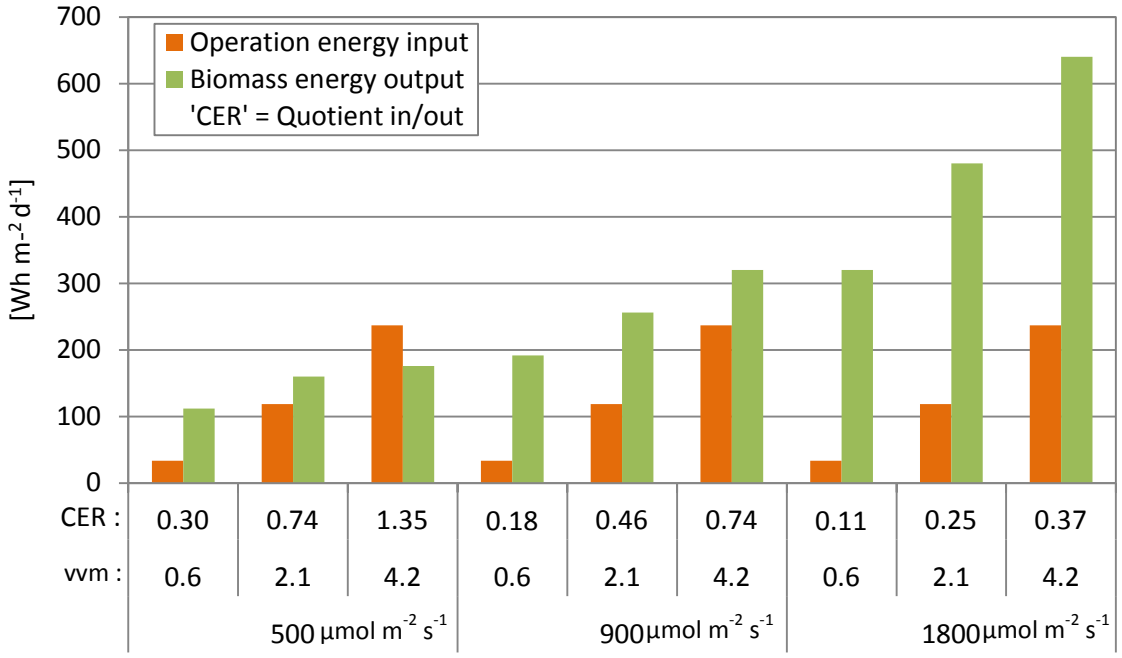


Figure 4.2: 'Areal energy balance' and 'core energy ratio' (CER [-]) at different aeration rates (vvm [m³ m⁻³ min⁻¹]) and light intensities based on data of Hu and Richmond (1996)

4.1.3 Deriving the function

The above analyses show that microalgae cultivation becomes more energy-efficient at lower aeration rates (Figure 4.2). To calculate the PE also at other aeration rates, a correlation between *vvm* and PE is determined. To do this, the quotient of *vvm*/PE is built and plotted over the vvm (Figure 4.3); it decreases linearly with the aeration rate.

The regression analysis shows the best data correlation (R^2=1) at the lowest light intensity (500 µmol m^{-2} s^{-1}). At higher light intensities, the metabolic processes of photoadaption photoprotection and photolimitation (see 3.1.3, e) and f)) could probably not be avoided and affected the PE to a greater extent.

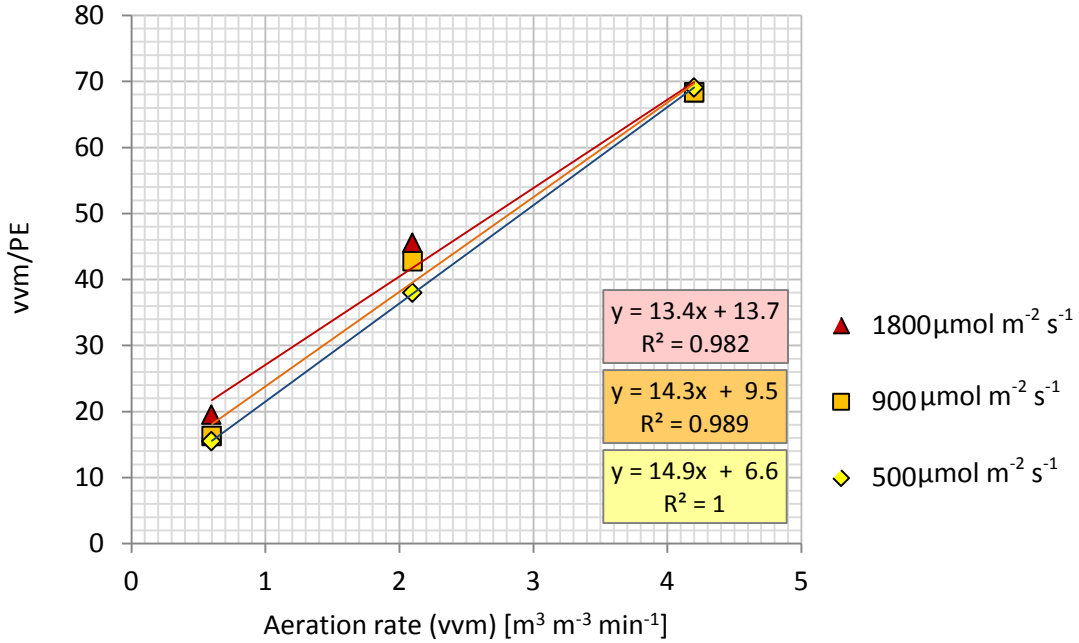


Figure 4.3: Quotient of aeration rate and PE over the aeration rate; based on data of Hu and Richmond (1996)

The correlation can be described with:

$$\frac{vvm}{PE} = b_1(I_0)\, vvm + b_2(I_0) \tag{32}$$

or, solved for the PE:

$$PE(vvm, I_0) = \left(b_1(I_0) + \frac{b_2(I_0)}{vvm}\right)^{-1} \tag{33}$$

With the *PE(vvm, I_0)*, it is possible to calculate areal biomass productivities depending on the aeration rate and light intensity ((33)in (13)):

$$prod_{areal}\,(vvm, I_0) = \frac{\left(b_1(I_0) + \frac{b_2(I_0)}{vvm}\right)^{-1} \cdot I_0}{energy_{DW}} \quad (34)$$

Values for b_1 and b_2 at different light intensities (Table 4.2) can be determined from the data of Hu and Richmond (1996). To determine these values, the biomass energy content and the share of photosynthetically active radiation (PAR) on the global irradiation do not play a role as long as the same data are used to calculate the *PE(vvm)* from productivities and vice versa.

Table 4.2: Parameters to calculate the *PE(vvm)* for different light intensities, based on data of (Hu and Richmond 1996)

Light intensity	$b_1(I_0)$	$b_2(I_0)$
500 µmol m^{-2} s^{-1}	14.9	6.6
900 µmol m^{-2} s^{-1}	14.3	9.5
1800 µmol m^{-2} s^{-1}	13.4	13.7

The resulting curves (Figure 4.4) of the PE over the aeration rate reflect mechanisms of microalgae growth: Without aeration, algae do not grow. The curve increases steeply in the beginning and then levels off showing that it becomes increasingly difficult to harvest all photons efficiently. Since it is easier to harvest all photons at low light intensities, the highest PE at a certain aeration rate can be attained at low light intensities (500 µmol m^{-2} s^{-1}, blue curve) (see also Figure 4.1 B). At high light intensities, the curves result in slightly higher PE at low aeration rates and at slightly lower PE than measured. At low light intensities, they exactly reproduce the measured data.

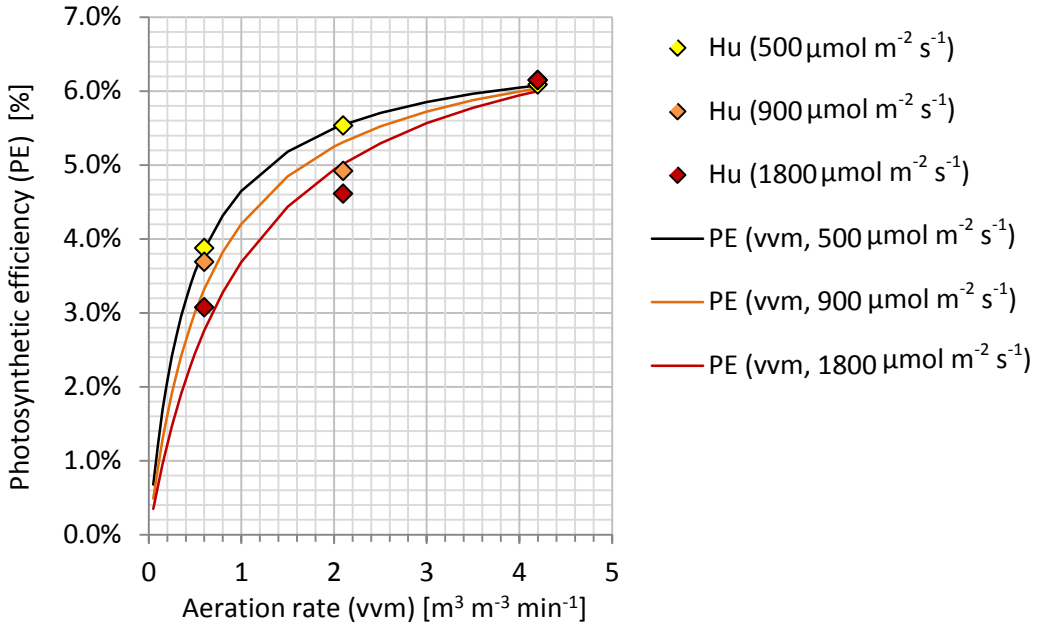


Figure 4.4: *PE(vvm)* at different light intensities (based on data of Hu and Richmond 1996) and thereof derived correlation

4.2 Validation and effect of improved PBR design

The data analysed in the previous section and the derived correlation are compared to and validated with other measurements as far as possible. It is also examined how PBR design could affect the correlation between aeration rate and PE.

4.2.1 Effect of photobioreactor width

Hu *et al.* (1998) investigated the effect of the PBR width (or 'light path') on the productivity. The authors illuminated vertical flat plate PBRs of different widths constantly from one side (at 900 µmol m^{-2} s^{-1}) and measured productivities of *Spirulina* aerated at 2.5 +/- 0.4 *vvm* (at 35°C).

Figure 4.5 shows the PE as calculated with (12) from the respective productivities, plotted over the reactor width (yellow squares, units on left y-axis) and the corresponding biomass concentration (green circles, units on right y-axis). The data of (Hu and Richmond 1996) measured at 2.1 vvm and 900 µmol m^{-2} s^{-1} (blue symbols) are inserted for comparison.

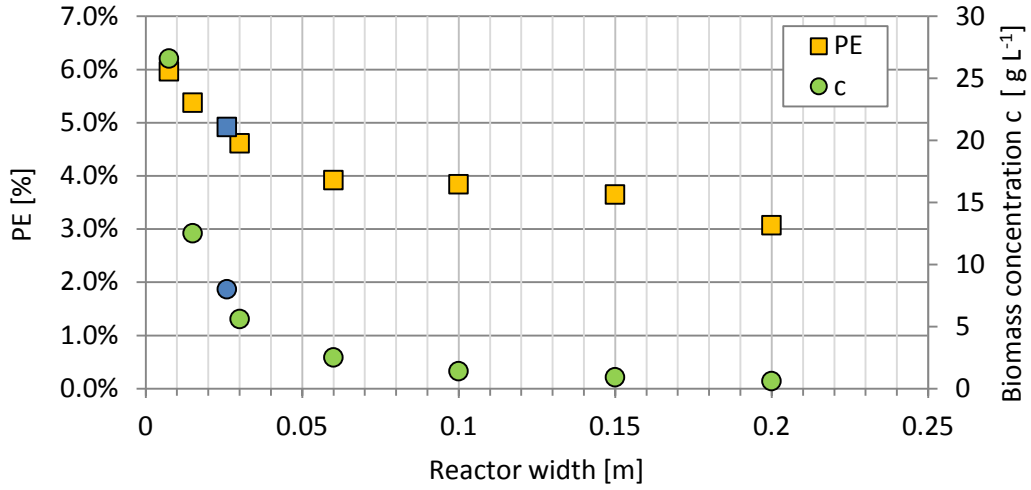


Figure 4.5: PE and respective biomass concentration depending on the reactor width at 2.5 (+/- 0.4) *vvm*, based on data of Hu *et al.* (1998); blue data: at 2.1 *vvm*, based on Hu and Richmond (1996) (both measurements with *Spirulina platensis* at 900 µmol m^{-2} s^{-1} and 35°C)

The data of Hu and Richmond (1996) correlate well with other measurements of Hu *et al.* (1998). The effect of reactor width on the PE was not investigated at lower aeration rates.

It can be seen that in thin PBRs, the same aeration rates results in a higher PE than in thick. Better light management and mass transfer are achieved due to the following effects:

- The flow cross-section is smaller and thus turbulence at constant aeration rate is higher (c.f. equation (15)).
- A single cell reaches the illuminated surface more often.

Consequently, photobioreactors should be thin to improve the relation between vvm and PE. However, Figure 4.5 also shows that very thin PBRs require extremely high biomass

concentration (above 10 g L^{-1}). This increases the risk of overheating and oxygen accumulation – conditions which strongly limit the PE outdoors (see also 3.2.1 and 3.1.3).

4.2.2 Effect of structured photobioreactors

A suggestion to save operation energy is inserting 'structures' into a PBR (Posten 2009, Janssen *et al.* 2003). Instead of using electricity to bring algae to the illuminated surface in regular intervals, the structures should 'distribute' or 'dilute' the light in the culture. By this means, algae should use high light intensities as efficiently as low.

This concept was tested by Jacobi *et al.* (2012): The PE was calculated for the cultivation of green algae *Chlamydomonas reinhardtii* in a 2.0 cm wide 'empty' PBR (total volume 280 ml) and again in the same reactor filled with 'light dilution structures'. Light intensity was 500 µmol m^{-2} s^{-1}. Aeration rates were 0.18 *vvm* in the empty PBR (50 ml min^{-1} in 280 ml) and 0.36 *vvm* in the structured PBR (50 ml min^{-1} in 140 ml), since the structures took 50% of the volume.

Figure 4.6 shows the PE over the aeration rate for the data of Jacobi *et al.* (2012) in the empty and structured reactor, compared to the PE calculated in this study from data of Hu and Richmond (1996) at 500 µmol m^{-2} s^{-1}, and the correlation derived from the latter.

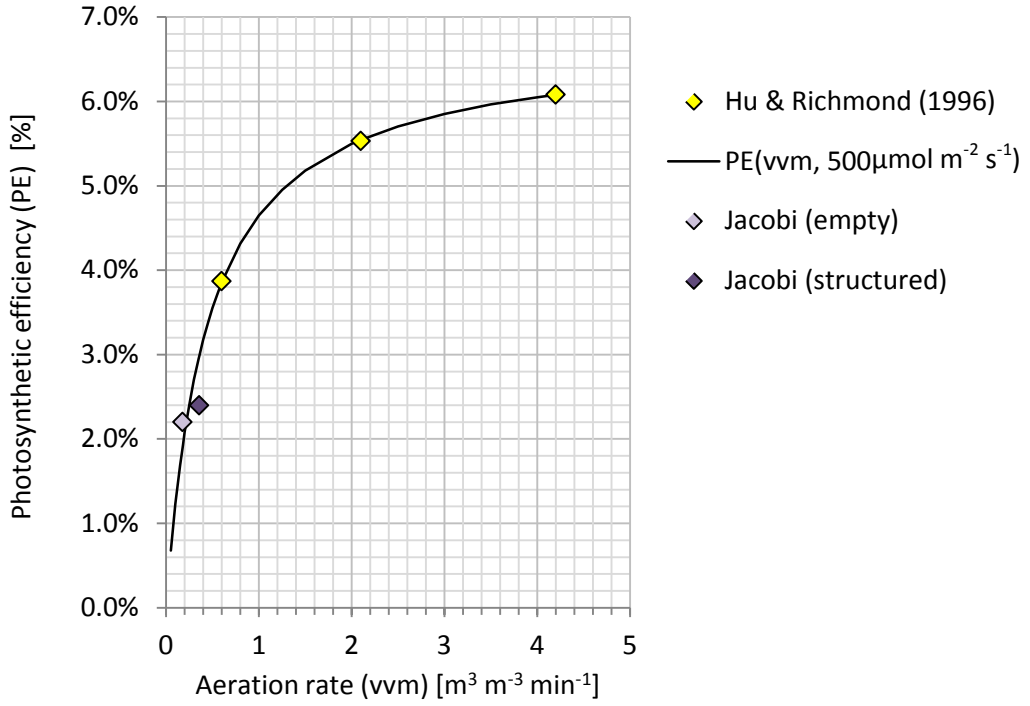


Figure 4.6: PE over vvm, comparison of data from structured PBRs (Jacobi *et al.* 2012) to data of Hu and Richmond (1996) (both measurements at 500 µmol m^{-2} s^{-1})

Remarkably, the PE attained in the empty reactor (2.2%) correlated very well with the PE derived from the correlation (1.9%). The slightly higher value could be explained by the fact that the PBR of Jacobi is 0.6 cm thinner (see 4.2.1). The PE in the structured PBR (2.5%) at 0.36 vvm was even lower than the *PE(vvm)* calculated with the correlation

(3.0%). One reason for this could be that the structures inhibited aeration induced mass transfer. Another reason could be the different growth behaviour of the green algae *Chlamydomonas* compared to the cyanobacteria *Spirulina*.

The authors expected higher PE at high light intensities due to the structures, this was not tested though. However, a high PE at high light intensities requires also higher biomass concentration (see equation (12) and 4.2.1). Biomass concentration was below 1 g L^{-1} in this experiment.

In summary, the correlation between *vvm* and PE is derived from data of a thin (2.6 cm wide) PBR and thus is optimistic. Data measured in other experiments confirm the correlation.

4.3 Effects of outdoor mass cultivation

The correlation derived in section 4.1.3 is based on laboratory measurements. Outdoors, temperature and light intensity keep changing; biomass is lost due to night-time respiration, harvesting, or even fouling or predators (see 3.1.3). To consider the respective aspects, correction factors are determined to apply the correlation to outdoor mass cultivation. The correction factors can be multiplied with the PE, the solar irradiation or the areal productivity since all parameters result from each other (see equation (13)).

4.3.1 Temperature correction

The interaction of temperature and microalgae growth (see 3.1.3 i) can be considered in three ways:

a) The temperature of the culture is not regulated; suboptimal temperatures decrease algae growth and thus the PE (Franz *et al*. 2012).
b) The culture temperature is controlled passively (e.g. by shading) and consequently a share of the solar energy is lost (see 3.2.1).
c) The culture temperature is actively regulated (e.g. by heat exchange or spray cooling) which requires energy.

Modelling the energy demand for temperature regulation (approach c) is beyond the scope of this work. For the other approaches, temperature correction factors are derived:

To model approach a), the temperature correction factor changes hourly according to the difference between the actual temperature and the optimal growth temperature of the strain. The respective correction factor is derived from a distribution function, as described in Franz *et al*. (2012). Irradiation and temperature at each cultivation hour are derived from climate data. Those are obtained exemplarily for a location in southern Germany (Karlsruhe) and southern Europe (Madrid) for the year 2012 (Huld 2013, Huld *et al.* 2012, example shown in Annex, Table A.1).

To model approach b), a constant correction factor is determined, representing photon losses due to passive temperature control.

a) Time dependent correction factor

The correction factor for temperature changes according to the respective hourly temperature (35). It is modelled with a Gaussian and additionally with a triangular distribution function, described in Table 4.3. Table 4.4 shows the parameters for the distribution functions as derived from literature. It is assumed that the culture temperature T_c is on average 5°C higher than the ambient temperature due to heat input of solar irradiation.

$$PE(vvm,T) = PE(vvm) \cdot f(T) \tag{35}$$

PE(vvm,T) *PE(vvm)* depending on the temperature

Table 4.3: Functions to determine temperature correction factors for triangular and Gaussian distribution

Condition	Triangular	Gauss
for $T_c \leq T_{min}$ *or* $T_c \geq T_{max}$	$f(T) = 0$	$f(T) = 0$
for $T_{min} \leq T_c \leq T_{max}$		$f(T) = e^{-\left[\frac{(T_c - T_{opt})}{s}\right]^2}$
for $T_{min} \leq T_c \leq T_{opt}$	$f(T) = \frac{T_c - T_{min}}{T_{opt} - T_{min}}$	
for $T_{opt} \leq T_c \leq T_{max}$	$f(T) = \frac{T_{max} - T_c}{T_{max} - T_{opt}}$	

With:

- $f(T)$ Temperature correction factor
- T_c Temperature of the culture medium with $T_c = T_{amb} + 5$°C and T_{amb}= Ambient temperature at each cultivation hour
- T_{opt} Optimal growth temperature (for Triangular +/- 2°C)
- T_{min} Minimum temperature to allow algae growth
- T_{max} Maximum temperature to allow algae growth
- s Variable to determine the curve's amplitude (for Gauss only)

Table 4.4: Parameters to calculate temperature correction factors

Parameters	Value	Source
T_{min}	10°C	(Günther *et al.* 2012)
T_{opt}	35°C	(Hu and Richmond 1996)
T_{max}	45°C	(Tredici and Materassi 1992)
s	13	(Franz *et al.* 2012)

Figure 4.7 shows the correction factors resulting from the assumed data with the different distribution functions. For example, at 20°C, the correction factor calculated with the triangular distribution function is 0.4 so that a PE of 5% at 35°C sinks to 2% at 20°C.

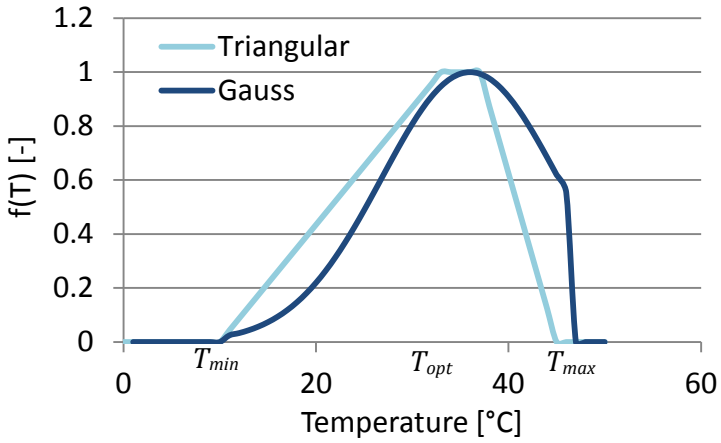


Figure 4.7: Distribution functions for PE temperature correction

b) Constant correction factor (passive temperature control)

Few quantitative data are available to determine a correction factor for passive light and temperature management (see also section 3.2.1). Photons losses of 40-60% were measured due to vertical position of PBRs (Tredici *et al.* 2015, Hu *et al.* 1996). The exact amount of 'lost' photons is difficult to estimate since it depends on a variety of factors, such as the design of the PBRs, but also on weather conditions. For example, on windy days, the water surface of a cooling water basin (e.g. as shown in Batan, *et al.* 2010) is agitated and reflects more light.

Based on these data, it is optimistically estimated that 10% of photons at a location with moderate light intensity (Karlsruhe) and 15% at a location with high light intensity (Madrid) are lost due to passive temperature control.

$$PE(vvm)_T = PE(vvm) \cdot (1 - c_T) \tag{36}$$

$PE(vvm)_T$ $PE(vvm)$ corrected for photon losses

Table 4.5: Correction factors for passive temperature control

Location	Symbol	Value	Literature data
Karlsruhe	$c_{T,\,KA}$	0.10	0.40-0.60
Madrid	$c_{T,\,MA}$	0.15	(Hu *et al.* 1996, Tredici *et al.* 2015)

Pre-analysis and choice of temperature modelling

Figure 4.8 shows the yearly areal productivities calculated for an initial PE of 3.5% without temperature correction (dark green bars) and modelled with the respective approaches. Without temperature control (approach a), the areal productivity is only 35-60% of the productivity at optimal growth temperature. The assumption of passive

temperature control results in the highest productivities and consequently is used for the core model.

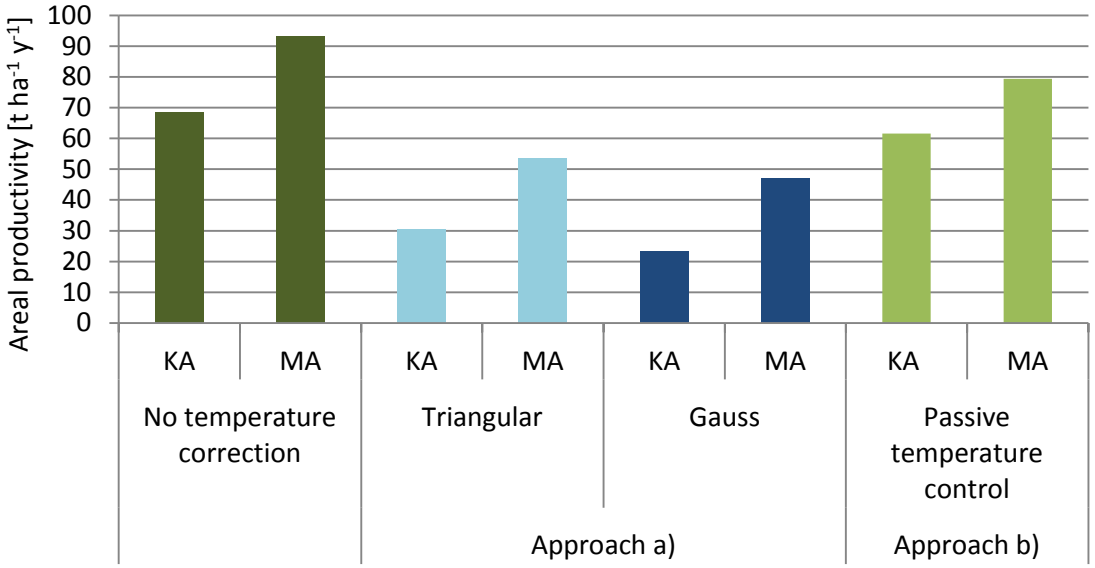


Figure 4.8: Calculation of yearly areal productivities with different types of temperature modelling (initial PE of 3.5%, cultivation period: March-October)

4.3.2 Correction factors for other conditions

Further correction factors for outdoor mass cultivation are based on literature and own estimations.

Correction factors for respiration and inoculation

Two important conditions cannot be avoided outdoors compared to laboratory conditions. These are biomass losses due to the fact that algae respirate at night (see 3.1.1) and that a share of the biomass is needed to inoculate the next culture (see 3.2.3).

As described in section 3.2.3, respiration, biomass concentration and harvesting modes are inherently linked. Modelling this in detail goes beyond the scope of this work. The correction factor to inoculate the next culture is optimistically estimated to be 5%. A correction factor of 5% for respiration (see 3.1.2) is derived based on Torzillo (1991): in *Spirulina* cultures in summer under optimal conditions, 4-6% of the dry weight reached at the end of the daylight period was lost during the night. This value is very low compared to respiration rates of up to 35% of daylight productivity (Geider and Osborne 1989, Torzillo 1991).

Aspects for which improvement is expected

Light intensity outdoors keeps changing (see for example Annex, Table A.1) and can also change quickly (e.g. when clouds are passing by the sun). This usually lowers the PE since algae adapt to different light intensities (see 3.1.2 f). In this study, it is assumed that changing light intensities do not affect the PE. Furthermore, it is assumed that, due to

improved algae strains, microalgae can use high light intensities as efficiently as low. This is goal of current research (Tredici 2010, Williams and Laurens 2011).

Biomass loss due to contamination or maintenance time for cleaning during the cultivation period (see 3.1.2 j) is not considered. Table 4.6 summarises the differences between laboratory and outdoors conditions and assumed consequences for the model.

Table 4.6: Laboratory versus outdoor conditions and assumed consequences for the core model

Conditions	Laboratory	Outdoors	Assumed consequences
Temperature	Constant	Changing according to latitude and climate, with season, weather and time of the day	Correction factor c_T= 0.10 or 0.15
Light intensity	Constant		No effect on *PE(vvm);* *PE(vvm,* 500 µmol m^{-2} s^{-1}) for all light intensities
Light angle	Constant		No effect on *PE(vvm)*
Respiration losses	Limited at optimal conditions	Night-time respiration	Correction factor c_{resp}= 0.05
Biomass for inoculation	Negligible at small scale	Required	Correction factor c_{inoc}= 0.05
Culture medium (nutrients, pH…)	Special medium, controlled	Limited preparation & control	No effect on *PE(vvm)*
Cleanliness, competing organisms	Sterilised devices & supplies	Sterilisation n.a., manual cleaning	No biomass loss due to fouling or contamination

4.3.3 Data comparison – laboratory and outdoor experiments

Data from outdoor experiments are analysed and compared to the correlation derived from the data of laboratory experiments.

Generally, few studies on outdoor experiments documented productivities as well as operation energy. Data of three studies of aerated flat plate PBRs (Quinn *et al.* 2012, Rodolfi *et al.* 2009, and Hu *et al.* 1996) are analysed. Note that only Quinn *et al.* (2012) reported data for the whole year, other studies were performed during a shorter time-period. The temperature in all outdoor pilot plants was regulated, either with water sprinklers (Rodolfi *et al.* 2009), heat exchangers (Hu *et al.* 1996) or with a temperature regulated water basin (Quinn *et al.* 2012).

First, the PE of outdoor experiments is calculated (as explained in 4.1.1) from the data reported in the respective studies (Table 4.7) and estimated climate data. The PE is plotted over the aeration rate (Figure 4.9). Error bars represent the PE at 100 µmol m^{-2} s^{-1} higher or lower light intensity. The results are compared to the correlation derived at 500 µmol m^{-2} s^{-1} and the corrected values (without temperature correction 'w/o temp',

and corrected for Karlsruhe (KA) or Madrid (MA)). It can be observed that the PE at a certain aeration rate is always lower outdoors than calculated based on the correlation. This shows that correction factors for outdoor cultivation are chosen rather optimistically and already reflect technology development.

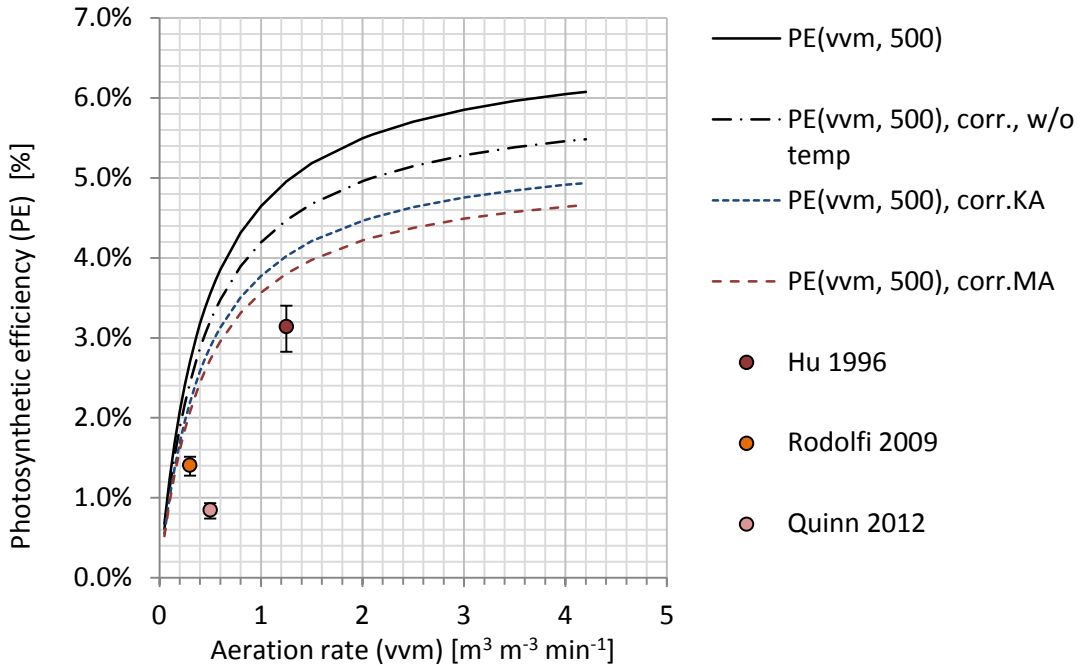


Figure 4.9: PE over aeration rate for derived correlation and outdoor experiments.

Furthermore, the areal energy balance and 'core energy ratio' (see 4.1.2) is calculated for the outdoor experiments. Figure 4.10 shows that the average biomass energy output sinks the longer the algae are cultivated. This emphasises that productivities attained in the summer or during a short time cannot be extrapolated to the whole year.

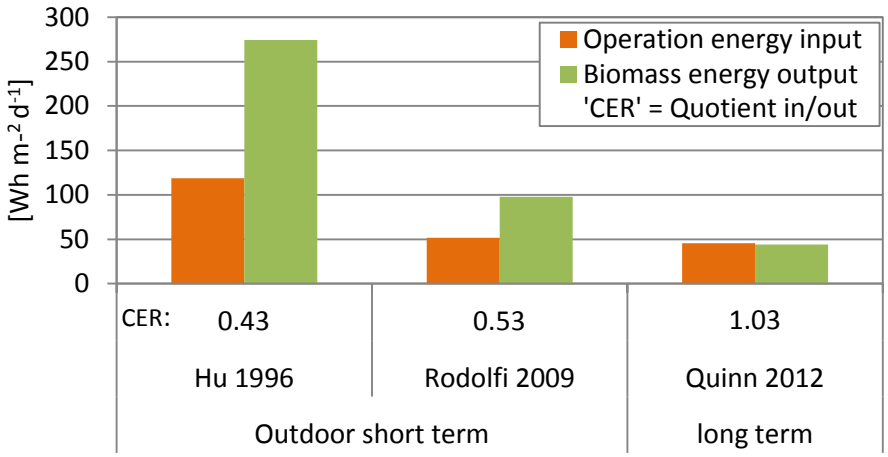


Figure 4.10: Areal energy balance for outdoor pilot plants, short term and long term measurements

Table 4.7: Data of outdoor pilot plant studies

Study	Hu *et al.* (1996)	Rodolfi *et al.* (2009)	Quinn *et al.* (2012)
Strain	*Spirulina*	*Nannochloropsis*	*Nannochloropsis*
Location	Israel	Italy	Colorado
Cultivation time	Sept. 1994	Summer 2006	Yearly average
PFD [µmol m^{-2} s^{-1}] (+/-100)	1100[a]	1200[a]	900[a]
T [°C]	≤35	≤30	19-26
vvm [m^3 m^{-3} min^{-1}]	1.25	0.3	0.4
V_c/a [m^3 m^{-2}]	0.024	0.045	0.050
$prod_{vol,d}$ [g L^{-1} d^{-1}]	1.5	0.36	0.16
$prod_{area,d}$ [g m^{-2} d^{-1}]	36	16.2	8
Δp_h [mbar]	35[b]	100[b]	28[b]
Δp_{other} [mbar]	50[c]	50[c]	50[c]
PE [%]	3.2	1.4	0.8
Areal operation energy [Wh m^{-2} d^{-1}]	60	52	46
Areal energy output[d] [Wh m^{-2} d^{-1}]	200	98	44

a) Estimated average, based on climate data (SoDa)
b) Calculated from the respective reactor height with (20)
c) not available (n.a.), estimation
d) Calculated with (31) and $energy_{DW}$ = 20 MJ kg^{-1}

4.4 Summary: calculation of areal biomass productivity based on aeration rate

As a result of the previous analyses, the areal biomass productivity can be calculated with equation (37). This results from the *PE(vvm, I_0)* as determined in 4.1 ((33) in (13)), the correction factors for outdoor cultivation from section 4.3.1 and the irradiation during the considered time period. Furthermore, the following assumptions are made:

- Improved cultivation systems or algae strains allow that algae use high light intensities as efficiently as low. Thus, the *PE(vvm)* is calculated for the parameters determined at low light (500 µmol m^{-2} s^{-1}) at any light intensity.
- Neither changing light angles nor changing light intensities lower the *PE(vvm)*.
- The culture medium provides adequate pH, salt concentration and nutrients at all times and thus does not influence the *PE(vvm)*.
- The culture does not break down and thus no biomass is lost due to overheating, oxygen accumulation contamination or fouling.

$$prod_{area,y} = \frac{\left(b_1 + \frac{b_2}{vvm}\right)^{-1} \cdot I_0}{energy_{DW}} \cdot (1 - c_T) \cdot \left(1 - c_{resp}\right) \cdot (1 - c_{inoc}) \quad (37)$$

Table 4.8: Parameters to calculate the areal productivity based on the aeration rate

Parameters	Symbol	Unit	Value	Source
Parameters to calculate *PE(vvm)*	b_1	-	14.9	4.1.3
	b_2		6.6	
Biomass energy content	$energy_{DW}$	MJ kg^{-1}	20	4.1.1
Correction factor for passive	$c_{T,KA}$	-	0.10	4.3.1
temperature control	$c_{T,MA}$		0.15	
Correction factor for respiration	c_{resp}	-	0.05	4.3.1
Correction factor for inoculation	c_{inoc}	-	0.05	4.3.1
Irradiation	I_0	kWh m^{-2} y^{-1}	based on (Huld 2013)	

5 Net energy ratio (NER) model

In this chapter, all further data and equations needed to model the net energy ratio (NER) of microalgae biomethane production are defined.

Section 5.1 gives an overview over the general model approach. In section 5.2, a generic PBR is defined based on the previous analyses. In section 5.2 further upstream and downstream resources are defined. Finally, section 5.4 introduces the scenarios and parameters that are changed to model their influence on the result.

5.1 Overview model and approach

The NER includes the energy demand of all processes required to produce biomethane, related to the biomethane energy content (Figure 5.1). The modelled processes include microalgae biomass production in generic flat plate photobioreactors (PBRs) during one year on one hectare (ha) land and conversion of the biomass into biomethane.

Specific and unique feature of this model is that the areal biomass productivity is calculated depending on the aeration rate. The correlation is determined in chapter 4 ('Core model').

The NER model combines the previous findings as follows:

- The areal biomass productivity is calculated with the *PE(vvm)* at low light intensity, the correction factors for outdoor cultivation and climate data (see 4.4).
- The areal operation energy is calculated based on the aeration rate (*vvm*) and further parameters of a generic photobioreactor which are derived based on the previous analyses.
- The energy demand for further upstream and downstream processes is calculated based on parameters derived from literature.

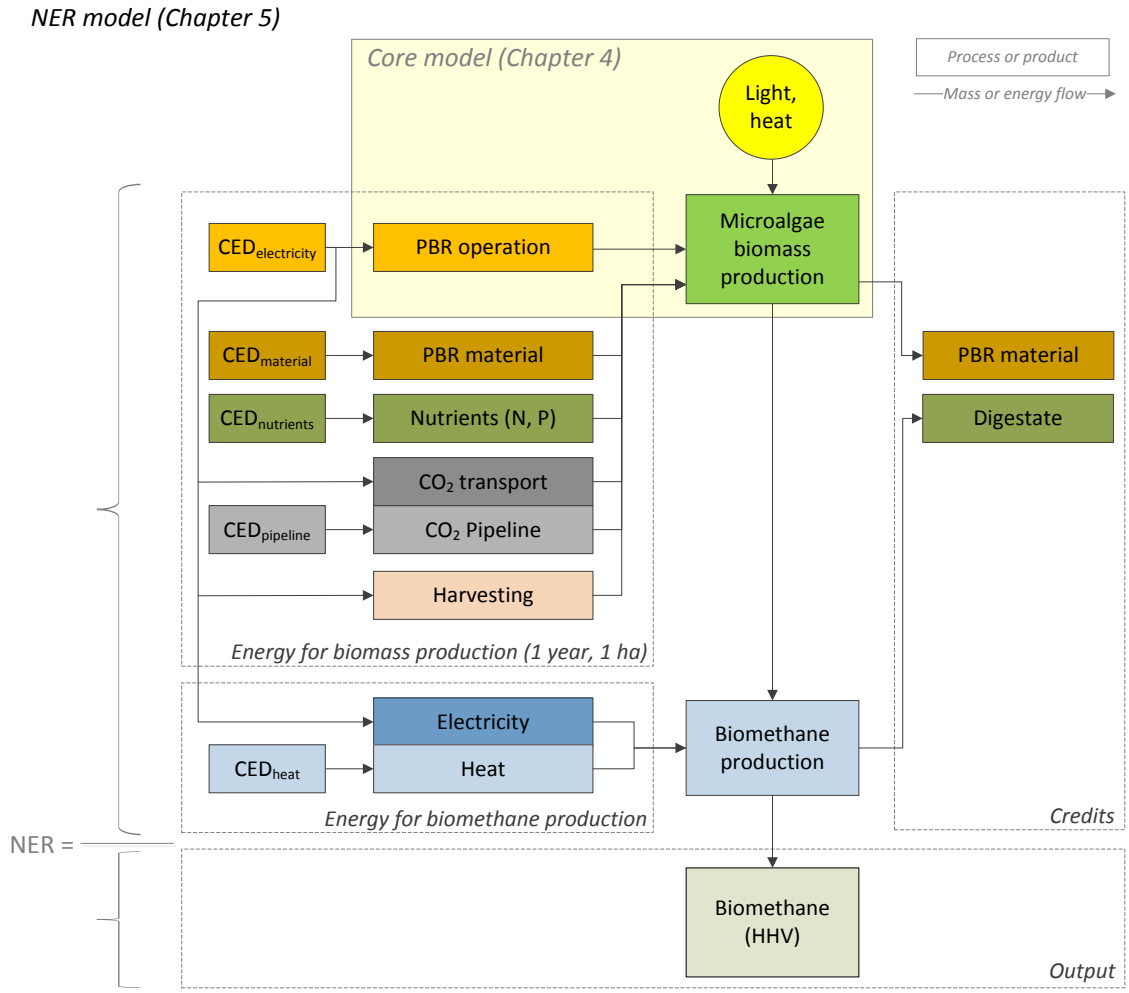


Figure 5.1: Flow chart of all processes modelled to calculate the NER, inclusion of core model

With the NER model, the following aspects are investigated:

- Initially, the NER of microalgae biofuels production is calculated for microalgae cultivation at the lowest aeration rate (*vvm*) tested in the laboratory and the corresponding areal productivity with climate data of Karlsruhe (base case).
- The effects of important parameters such as pressure drop, upstream energy demand, and infrastructure on the NER are investigated.
- As the focus of this study, the effect of changing aeration rates and thus changing productivities on the NER is analysed.
- The effect of parameters on the NER is again analysed at changing aeration rates.
- Additionally, the effects of different location and cultivation period which determine characteristic climate data (light intensity, temperature and sunlight hours) are investigated.
- Based on the results of the previous analyses, a best case is defined. The resulting NER is compared to that of previous studies, regarding system boundaries and assumptions about operation energy and biomass yield.

5.2 Definition of a generic photobioreactor (PBR)

This section defines a generic aerated flat plate PBR as a base to calculate operation energy and material demand (see section 3.2). The PBR (Figure 5.2) has the following characteristics:

- The culture volume per area is 0.040 $m^3\ m^{-2}$ (400 $m^3\ ha^{-1}$) which is necessary to avoid overheating and oxygen accumulation outdoors (Morweiser *et al.* 2010).
- The flat plate PBR is 30° inclined to harvest most of the photons (see 3.2.1) (Hu *et al.* 1996) and for a low water head (equation (20)).
- The PBR is aerated via a perforated tube at the bottom, analogue to (Hu and Richmond 1996).
- Since the reactor is 4 cm wide, the correlation between *vvm* and PE determined in a 2.6 cm wide PBR is thus optimistic (c.f. Figure 4.5).
- To cultivate algae on 1 ha, several PBRs are connected and separated every 2 meters by a vertical wall to enhance the stability.

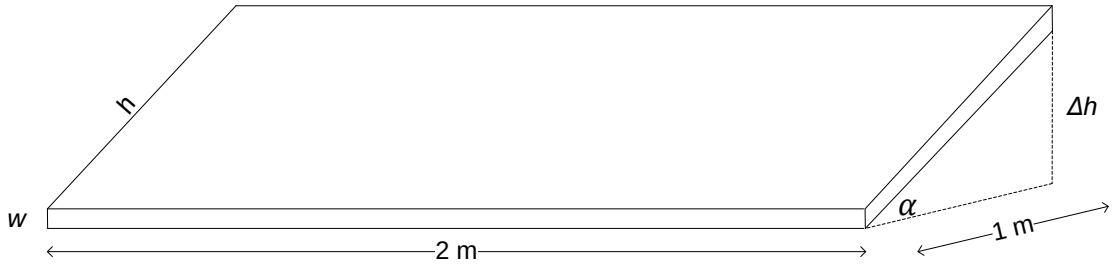


Figure 5.2: Scheme of generic flat plate PBR

Table 5.1: Photobioreactor design parameters

Parameters	Symbol	Unit	Values	Source or literature values
Volume per land area	V_c/a	$m^3\ m^{-2}$	0.040	0.040-0.200 (Tredici 2003)
Width	w	m	0.04	
Operation angle	α		30°	(Hu *et al.* 1996)
Length	l	m	2	(1m m^{-2})
Height water column	Δh	m	0.6	=tan α
Height of one plate	h	m	1.15	=1/cos α

5.2.1 PBR operation energy

Operation energy for PBRs is calculated with equation (38). This results from the equations introduced in 3.2.2 ((15)–(20), (24), (25)).

Parameters to calculate the yearly areal operation energy are summarised in Table 5.2; they result from the PBR design (Table 5.1), climate data (Huld 2013) and further assumptions. For example, it is optimistically assumed that a pressure drop of 100 mbar (Δp_{other} = 100 mbar) includes friction losses in PBR and feed pipes as well as pressure for membranes and off-gas removal. This value is extremely low compared to literature values of up to 1.5 bar (Table 5.3).

$$E_{op,area,y} = \frac{\dot{V}}{V_c} \cdot (\Delta p_h + \Delta p_{other}) \cdot \frac{1}{\eta} \cdot \frac{V_c}{a} \cdot \left(h_{prod,d} + r_{op} \cdot \left(24 - h_{prod,d}\right)\right) \cdot d_y \qquad (38)$$

Table 5.2: Parameters to calculate operation energy

Parameters	Symbol	Unit	Values	Source or literature values
Aeration rate	*vvm* ($\dot{V}/V_c$)	$m^3\ m^{-3}$ min^{-1}		Main variable
Water head	Δp_h	mbar	60	$=\rho g\, \Delta h$, see Table 5.1
Pressure drop, other	Δp_{other}	mbar	100	600-1500 (see Table 5.3)
Pump efficiency	η	-	0.85	EU goal (European Commission 2009)
Night-time operation rate	$r_{op,KA}$	-	0.10	assumption for Karlsruhe, 0.4 (Tredici 2015)
Cultivation days per year	d_y	d	245	March-October
Average operation hours per day (KA, Mar-Oct)	$h_{prod,d}$	h	12.3	Calculated based on (Huld 2013)

Table 5.3: Pressure drop – sources and literature values

Source of pressure drop	Symbol	Typical values	Source
Velocity head and friction loss (PBR and feed pipes)	Δp_v, Δp_f	n.a. (depends on v^2, l/D_h, ζ, turbulence)	(Hirschberg 1999), see equations (22), (23)
Membrane, filters	Δp_{other}	150-400 mbar	(Ripplinger 2008)
Off-gas	Δp_{other}	100 mbar	(Ripplinger 2008)
Total	Δp_{total}	600 – 1500 mbar	(Weinberg *et al.* 2012, Posten 2009)

5.2.2 Energy for PBR material

The PBR material demand is calculated with (39), the design parameters in Table 5.1, and the parameters summarised in Table 5.4, based on the following assumptions.

- Outer walls of 1mm polyethylene terephthalate (PET) are sufficient to build stable reactors of low height.
- Energy for constructing the PBRs and for other materials such as pipes, fittings, frames, membranes etc. are negligible.
- No other material is required to protect the PBR (e.g. a greenhouse).
- After use, material is combusted in an incineration plant to recover energy. This reduces the energy demand for materials according to (40).

The areal material demand can be calculated as:

$$x_{mat,area} = \left(2(h \cdot l + w \cdot l) + \frac{1}{2}(w \cdot h)\right) \cdot \rho \cdot th_{mat}\ (1 + exc_{mat}) \tag{39}$$

The energy demand for the material results from this:

$$E_{mat,area,y} = \frac{(CED_{mat} - cred_{mat}) \cdot x_{mat,area}}{lt_{mat}} \tag{40}$$

Table 5.4: Parameters to calculate the energy demand for reactor material

Parameters	Symbol	Unit	Value	Published values of existing PBR or source
Thickness	th_{PET}	m	0.001	0.002 – 0.01 (Tredici 2003, Cheng-Wu *et al.* 2001)
CED_{PET} (granulate)	CED_{PET}	MJeq kg^{-1}	80	ecoinvent v3.01*
Density	ρ_{PET}	kg dm^{-3}	1.27	
Lifetime	lt_{PET}	years	10	1 year (Wijffels and Barbosa 2010)
Combustion credit	$cred_{PET}$	MJ kg^{-1}	20	based on (Kalweit *et al.* 2012), HHV_{PET} - 20% loss
Excess material for production	exc_{mat}	-	0.10	n.a., estimation

*see also Annex Table A.3

5.3 Calculation of other energy demand

This section defines the energy demand for upstream and downstream resources. The energy demand for each resource results from the required amount (x_n), multiplied with the respective cumulative energy demand (CED_n) and credits where appropriate (see 2.1.2).

The nutrient and CO_2 demand is calculated directly proportional to the produced biomass, so is the energy to ferment the biomass. Electricity for harvesting is related to the culture volume (see 3.2.2). Infrastructure includes, apart from the PBR, only pipelines to supply CO_2.

5.3.1 Upstream: supply of resources

CO_2 and nutrients

The resources to supply CO_2 are calculated with (41) and (42), assuming that:

- Microalgae require 1.8 kg CO_2 per kg dry weight (Kliphuis *et al.* 2010) and take up 90% of the supplied CO_2.
- An industrial power plant provides CO_2; no energy is accounted for CO_2 separation.
- CO_2 is compressed to 22 bar for a low pressure transport over 15 km in pipelines (Skarka 2015).

$$x_{CO2,area,y} = prod_{area,y} \cdot \frac{s_{CO2}}{abs} \cdot E_{tr,CO2} \tag{41}$$

$$x_{pipeline,y} = \frac{length_{pip}}{lt_{pip}} \tag{42}$$

The nutrient demand is calculated with (43) under the assumptions that:

- Microalgae biomass consists of 6.6% and 1.3% (w/w) nitrogen and (N) phosphorous (P) respectively (Grobbelaar 2003). The culture medium contains 20% excess nutrients (Richmond and Cheng-Wu 2001) to ensure that microalgae can take them up sufficiently.
- 80% of N and 99% of P in the digested biomass could be used again as fertiliser (Rösch *et al.* 2012) and are credited as such. Excess nutrients are not taken up and thus not credited.

$$x_{(N,P),area,y} = prod_{area,y} \cdot s_{N,P}\left(exc_{N,P} - cred_{N,P}\right) \tag{43}$$

Furthermore, the following simplifications are made:

- Energy demand to supply other (micro-) nutrients is negligible.

- Energy to dispose the culture medium after harvesting is negligible.
- No chemicals or energy is required to clean the PBRs.
- The cultivation plant is located near a water source. No energy is required to pump water over long distances (seaside) or from the ground (groundwater).
- Energy demand to provide further infrastructure, e.g. for harvesting devices is negligible (Tredici *et al.* 2015)

Table 5.5 summarises all parameters to calculate the energy demand for supplies.

Table 5.5: Parameters to calculate energy demand for biomass supplies

Parameters	Symbol	Unit	Value	Source, comment
$CED_{pipeline}$	CED_{pip}	MJeq km^{-1}	$1.1 \cdot 10^6$	ecoinvent v3.01*
Pipeline length	$lenght_{pip}$	km	15	(Skarka 2015)
Lifetime pipelines	lt_{pip}	y	50	optimistic assumption, based on ecoinvent v3.01 (40y)
CO_2 demand	s_{CO2}	kg kg_{DW}^{-1}	1.8	(Kliphuis *et al.* 2010)
CO_2 absorption in the culture	*abs*	-	0.90	
Energy for CO_2 separation		MJ kg_{CO2}^{-1}	0	(Althaus *et al.* 2007), if CO_2 is otherwise emitted
Energy for CO_2 transport	$E_{tr,CO2}$	MJ kg_{CO2}^{-1}	0.256	(Skarka 2015)
Nitrogen (N) demand	s_N	kg_N kg_{DW}^{-1}	0.066	(Grobbelaar 2003)
Phosphorous (P) demand	s_P	kg_P kg_{DW}^{-1}	0.013	(Grobbelaar 2003)
Factor nutrient excess	$exc_{N,P}$	-	1.2	(Richmond and Cheng-Wu 2001)
CED_N (nitrogen as N)	CED_N	MJeq kg_N^{-1}	28.6	ecoinvent v3.01*
CED_P (phosphorous as P)	CED_P	MJeq kg_P^{-1}	8.1	ecoinvent v3.01* ($18.5 \cdot 0.436$ mol P/mol P_2O_5)
Credit N (in digestate)	$cred_N$	-	0.80	(Rösch *et al.* 2012)
Credit P (in digestate)	$cred_P$	-	0.99	(Rösch *et al.* 2012)

*see also Annex Table A.3

Cumulative energy demand (CED) electricity and background other CED

Electricity is supplied with an efficiency of 40%, based on (Umweltbundesamt 2014) including losses for transformation and transport. This is equivalent to 2.5 kWh kWh^{-1} (1/0.4) or a CED of 9 MJeq kWh^{-1}. The CED for other resources is reported in the respective tables. It is calculated based on the latest ecoinvent database (v.3.01), using the software umberto (NXT LCA 7.1) and the method of Hischier and Weidema (2009) (see also 2.1.2). The CED results exclusively from fossil and nuclear resources (see also Annex, Table A.3).

5.3.2 Downstream: harvesting and biomethane production

The energy for harvesting and culture transport is related to the culture volume. The energy for fermentation and biogas upgrading is proportional to the amount of produced biomethane (and thus also to the microalgae biomass).

Harvesting & culture transport

The energy demand for harvesting and culture transport is calculated with equations (26)-(28) and the following data and simplifications:

- Microalgae are harvested with a separator with 1.5 kW power demand and a capacity of 1.2 m^3 h^{-1}, resulting in a volumetric harvesting energy of 1.25 kWh m^{-3}. Posten *et al*. (2012) expect this energy demand for harvesting representing technical progress.
- The whole culture medium is exchanged every 10 days (d_{ex} = 10) and the pump for culture exchange requires 0.13 kWh m^{-3} (Norsker *et al.* 2011). The batch length does not influence the biomass productivity.
- No additional pump energy, devices, space or chemicals are required to pre-concentrate the biomass (e.g. by settling the algae in ponds).

Biomethane production

Energy for biomass fermentation is calculated with the data summarised in Table 5.6 and the following simplifications:

- Harvesting concentrates the biomass up to a total solids (TS) content of 2-10% required for wet fermentation.
- The biogas is upgraded to methane and fed into the natural gas network. The energy to operate the biogas plant is thus supplied externally (Jungbluth *et al.* 2007). (Different scenarios of internal and external biogas energy use are analysed in Weinberg *et al.* (2012)).
- The biogas plant has a long lifetime and is only partially used for algae biomass. Thus, the CED to construct the biogas plant is negligible compared to the operation energy.
- The methane yield is directly proportional to the microalgal biomass (44).

$$X_{meth,area,y} = prod_{area,y} \cdot m_{meth} \quad (44)$$

Table 5.6: Parameters to calculate the energy demand for biogas production and biomethane output

Parameter	Symbol	Unit	Value	Source, specification
Methane yield	m_{meth}	$Nm^3\ kg^{-1}_{DW}$	0.36	(Mussgnug *et al.* 2010)
Methane HHV	HHV_{meth}	$MJ\ Nm^{-3}$	38.3	(0°C, 1013 mbar)
Electricity for biogas production	E_{biog}	$kWh\ Nm^{-3}$	0.38	adapted from (Jungbluth *et al.* 2007)
Heat for biogas production	E_{heat}	$MJ\ Nm^{-3}$	6.09	adapted from (Jungbluth *et al.* 2007)
Electricity for biogas upgrading to biomethane	E_{upgr}	$kWh\ Nm^{-3}$	0.5	adapted from (Jungbluth *et al.* 2007)
CED_{heat} (natural gas)	CED_{heat}	$MJeq\ MJ^{-1}$	1.18	ecoinvent v3.01*

*see also Annex, Table A.3

5.4 Scenarios and parameter analysis

It is analysed how different parameters or sets of parameters (scenarios) affect the NER. No equations are changed; the only exception is the analysis of structured PBRs described in 5.4.3.

All parameters are initially analysed with climate data of Karlsruhe between March and October 2012 (Table 5.7). Karlsruhe is chosen since it has a moderate light intensity and temperature avoiding the risk of overheating and photoinhibition (see also Annex, Figure A.3, Figure A.4). The cultivation during the warmer season of the year represents a common practice; Tredici *et al.* (2015) for example report 240 cultivation days in Italy.

5.4.1 Definition of base case

As a starting point for the analyses, a base case is defined. This represents the lowest aeration rate tested in the laboratory and the corresponding PE corrected for outdoor conditions in Karlsruhe (Table 5.7). The climate data determine the cultivation days per year and the productive sunlight hours per day which are needed to calculate the operation energy (see 3.2.2, (24)(25)).

Table 5.7: Base case – important parameters

Input parameters	Symbol	Unit	Value
Aeration rate	*vvm*	$m^3\ m^{-3}\ min^{-1}$	0.60
Corresponding *PE(vvm)* (corrected)	*PE(vvm)*	%	3.1
Climate data (Karlsruhe, Mar-Oct 2012)			
Global irradiation	I_0	$kWh\ m^{-2}\ y^{-1}$	1098
Cultivation days per year	d_y	d	245
Productive hours per day	h_d	h	12.3

5.4.2 Parameter analysis

The effect of important parameters on the NER is analysed; first for the base case and then again for changing aeration rates. Parameters are varied as follows:

Cumulative energy demand scenarios

The CED is varied in two ways: First, the CED of all processes apart from heat is reduced equally by 30% ('CED 0.7'), implying strong technology improvement. This is equivalent to a conversion efficiency of primary energy into electricity of 57% instead of 40%. Second, it is assumed that electricity could be supplied from renewable resources with 80% efficiency ('CED renewable'). Fertilisers and plastics are produced from fossil and nuclear resources (Patyk and Reinhardt 1997) and thus it is assumed that the CED of other supplies sinks by 10%.

Producing biofuels with renewable electricity is rather a kind of energy transformation which is not focus of this study (see 'Objectives and scope'). Therefore, results of the case 'CED renewable' are discussed but not included in the best case. Table 5.8 summarises data of the respective CED scenarios.

Table 5.8: Cumulative energy demand scenarios

		CED [MJeq unit^{-1}]		
Flow	**Unit**	**'Reference'**	**'CED 0.7'**	**'CED renewable'**
$CED_{electricity}$	kWh	9.0	6.3	4.5
(% supply efficiency)		(40%)	(57%)	(80%)
CED_{heat}	MJ	1.18	1.18	1.18
CED_N	kg	28.6	19.9	25.6
CED_P	kg	18.5	12.9	16.6
$CED_{pipeline}$	km	$1.1 \cdot 10^6$	$8.0 \cdot 10^5$	$1.0 \cdot 10^6$
$CED_{material}$ (PETG)	kg	80.0	56.0	72.0

Pressure drop '50 mbar'

Pressure drop is, like the aeration rate, directly proportional to the power demand. The original assumption of 100 mbar for feed pipes, membranes, filters and off-gas removal is already very optimistic (see Table 5.3). For the parameter analysis, it is nevertheless assumed that other pressure drop (Δp_{other}) could be reduced by 50% to 50 instead of 100 mbar. The value is inserted in equation (38) to calculate the operation energy. To reduce pressure drop, filters and membranes could be removed. However, this brings along a higher risk for contamination. It is assumed that this has no effect on the biomass yield.

No pipeline

To investigate the effect of the pipeline on the NER, it is assumed that CO_2 could be supplied within existing pipelines. This is done for example to cultivate vegetables (OCAP 2012). This measure however drastically limits possible cultivation sites to places where unused pipelines exist.

Material

The lifetime of the PBR material is doubled to 20 instead of 10 years to test its effect on the NER.

5.4.3 Changing aeration rate

Main focus of this study is the effect of correlated parameters on the NER. To test this, aeration rates are varied between 0.05 and 1 *vvm* and the corresponding *PE(vvm)* is calculated based on the correlation at 500 µmol m^{-2} s^{-1} (Figure 5.3). As usual, the operation energy results from the *vvm* and the areal productivity is calculated based on the *PE(vvm)*, correction factors and climate data.

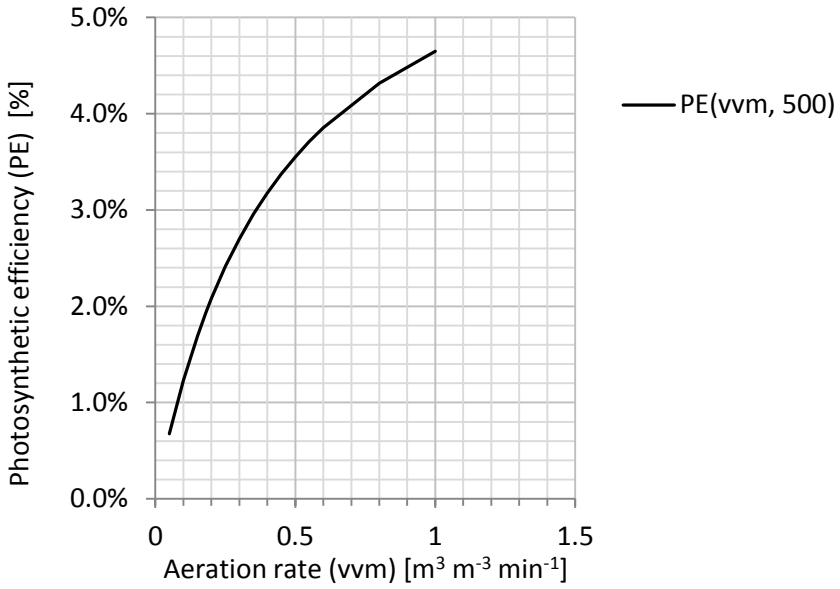


Figure 5.3: *PE(vvm)* as determined for aeration rates below 1 vvm at 500 µmol m^{-2} s^{-1} (detail of Figure 4.4)

For the parameter analysis at changing aeration rates, the effect of different CED scenarios on the NER is shown. Further parameter variation at changing aeration rates are analysed based on the scenario 'CED 0.7'.

Example of structured PBRs

Exemplarily, the suggestion to use structured PBRs is analysed, based on data of (Jacobi *et al.* 2012). For that case, it is assumed that:

- The PE is 2.2% at an aeration rate of 0.18 vvm ('empty PBR'); this is slightly higher than the *PE(vvm)* of 1.9% (see 4.2.2).
- In a corresponding 'structured PBR' the PE rises to 2.6%.
- The structures take 30% of the volume, resulting in a 30% reduced culture volume per area (V_c/a) of 0.028 m^3 m^{-2}. The aeration rate increases accordingly by 30% to 0.26 vvm. The areal energy demand thus remains constant (see (17)).

5.4.4 Location and cultivation period

Location and cultivation period are varied. Those determine light intensity, temperature and sunlight hours per day.

First, the effect of cultivating algae at a different location is determined. The areal biomass productivity at a certain aeration rate is calculated with climate data of Madrid (MA) instead of Karlsruhe (KA). To account for higher temperature and light intensity in Madrid (see also Annex, Figure A.2), a higher temperature correction factor and night-time operation rate is assumed (Table 5.9). The cultivation period remains constant (March-October, blue row in Table 5.10).

Second, it is analysed how the cultivation period affects the NER. For this, the cultivation period is reduced step-wise by two months, beginning with a year-round cultivation (see Table 5.10). Results are shown for both locations at a constant aeration rate. Exemplarily, it is shown for Karlsruhe how cultivation period and aeration rate interact.

Table 5.9: Temperature correction factors and night-time operation rate for Karlsruhe and Madrid

Parameter	Karlsruhe (KA)	Madrid (MA)	Literature data
c_T	0.10	0.15	0.40-0.60 (Hu *et al.* 1996)
r	0.10	0.20	0.42 Italy (Tredici *et al.* 2015)

Table 5.10: Location and cultivation period – input parameters, based on (Huld 2013)

Cultivation period (2012)	d_y	Average irradiation hours per day h_d		Solar irradiation [kWh m^{-2} y^{-1}]		Average light intensity (day) [W m^{-2}]	
		KA	MA	KA	MA	KA	MA
January-December	366*	10.4	10.7	1220	1790	320	460
February-November	304*	11.4	11.4	1180	1660	340	480
March-October	245	12.3	12.1	1100	1500	360	510
April-September	183	12.8	12.3	920	1230	390	550
May-August	123	13.3	12.5	680	920	420	600
June-July	61	13.8	12.7	340	480	400	630

*2012 is a leap year

6 Results and discussion

The NER of biomethane production from microalgae cultivated in generic aerated photobioreactors is calculated based on the correlation between aeration rate and PE determined in chapter 4 and further data and equations summarised in chapter 5. In this chapter, important results are shown and discussed.

Section 6.1 shows the NER of the base case. The influence of the different parameters on the base case is examined in section 6.2. In sections 6.3 and 6.4 as the central points of this investigation, it is demonstrated how the NER changes with the aeration rate – and how consequently parameter variations affect the NER at changing aeration rates. In section 6.5, the effects of a different location and different cultivation periods on the NER are shown – also in combination with changing aeration rate. In section 6.6, the main findings are summarised and a best case scenario is defined. This best case is in section 6.7 compared to the best cases of previous studies concerning (i) system boundaries and (ii) assumptions about key parameters. The potential technology improvement is also discussed. Finally, limitations of this approach and suggestions for further work are presented in section 6.8.

6.1 Base case

The base case represents the NER of biomethane production from microalgae cultivated in Karlsruhe during March-October in a photobioreactor aerated at 0.6 vvm. Table 6.1 summarises characteristic operation and productivity parameters of the base case.

Table 6.1: Operation and productivity parameters (base case)

Characteristic parameters	Symbol	Unit	Value
Operation power, volumetric	P_{vol}	W m^{-3}	188
Operation power, areal	P_{area}	W m^{-2}	7.5
Operation energy, areal (24h)	$E_{op,area,d}$	kWh m^{-2} d^{-1}	0.10
Yearly biomass yield	$Y_{ha,y}$	t ha^{-1} y^{-1}	62
Average areal productivity (per day)	$prod_{area,d}$	g m^{-2} d^{-1}	25
Average volumetric productivity (per day)	$prod_{vol,d}$	g L^{-1} d^{-1}	0.63

In total, all considered processes and substances require about 4 times more energy than the biomethane contains; the NER is 4.0 (Figure 6.1).

Operation energy dominates the total energy demand or input with around 65%. Additional 25% of the total energy demand is required for biomass production and harvesting; only about 10% are required to convert biomass into methane. Apart from operation energy, pipeline and material demand have a large share on the energy input. Nutrients hardly contribute to the high NER since it is assumed that the major part of nutrients remains in the digestate and could be recycled as fertiliser (Table 6.2).

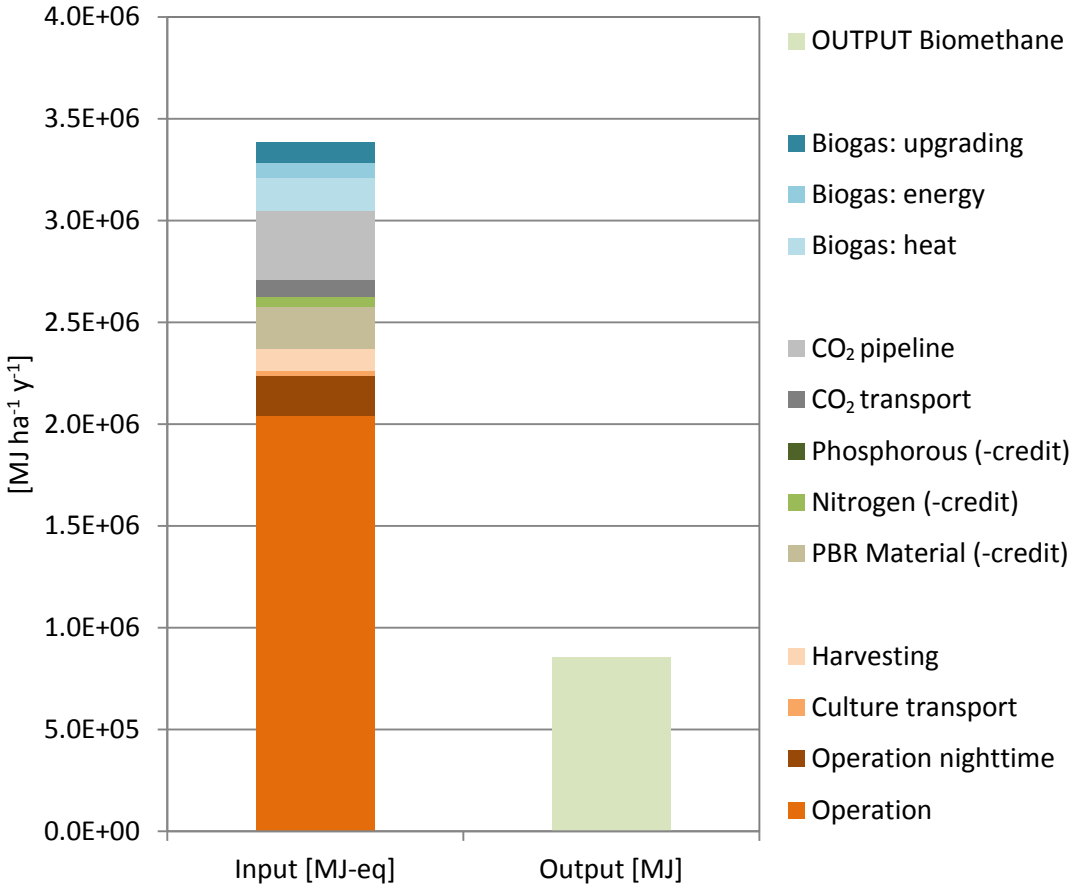


Figure 6.1: Energy input (cumulative energy demand) and output (HHV biomethane) per hectare and year (base case)

Table 6.2: Resource demand per hectare and year, resulting energy demand and NER (base case)

	Value	Unit $ha^{-1}\ y^{-1}$	Input [GJeq]	Credits [GJeq]	Output [GJeq]	MJeq MJ^{-1} methane
Operation	227	MWh	2042			2.39
Operation nighttime	22	MWh	194			0.23
Culture transport	2.6	MWh	23			0.03
Harvesting	12.5	MWh	113			0.13
PBR Material	3.4	t	270	67		0.24
Nitrogen	4.9	t	139	92		0.05
Phosphorous	1.0	t	8	7		0.00
CO_2 transport	8.8	MWh	79			0.09
CO_2 pipeline	0.3	km	341			0.40
Biogas: heat	136	GJ	161			0.19
Biogas: energy	8.4	MWh	76			0.09
Biogas: upgrading	11.1	MWh	100			0.12
OUTPUT Biomethane					856	
Totals			3546	166		4.0

The biomass yield of 62 tons per ha and year is within the range of 60–70 t ha^{-1} y^{-1} expected to be "realistic" for PBRs (Chiaramonti *et al.* 2013). The operation power of less than 200 W m^{-3} is a goal of current PBR development (Posten 2009).

Regarding the areal energy balance, the areal operation energy (227+22 MWh ha^{-1} y^{-1}, see Table 6.2) is still lower than the energy contained in the biomass, but already higher than the biomethane energy produced from that (Figure 6.2). Reasons are additional night-time operation and respiration losses but also that only a share of the biomass energy content can be turned into biomethane energy.

The biomethane yield together with its heating value results in 14 MJ_{HHV} kg^{-1}_{DW} (0.36 Nm^3 kg^{-1}_{DW} · 38.3 MJ Nm^{-3}, see Table 5.6). Compared to 20 MJ_{HHV} kg^{-1}_{DW} in the biomass (see Table 4.8), this corresponds to an 'energy yield' of 70%. This assumption is higher than for example that of Weinberg *et al.* (2012) who calculate with a biomethane yield of 11 MJ_{HHV} kg^{-1}_{DW} (10.4 MJ_{LHV} kg^{-1}_{DW}).

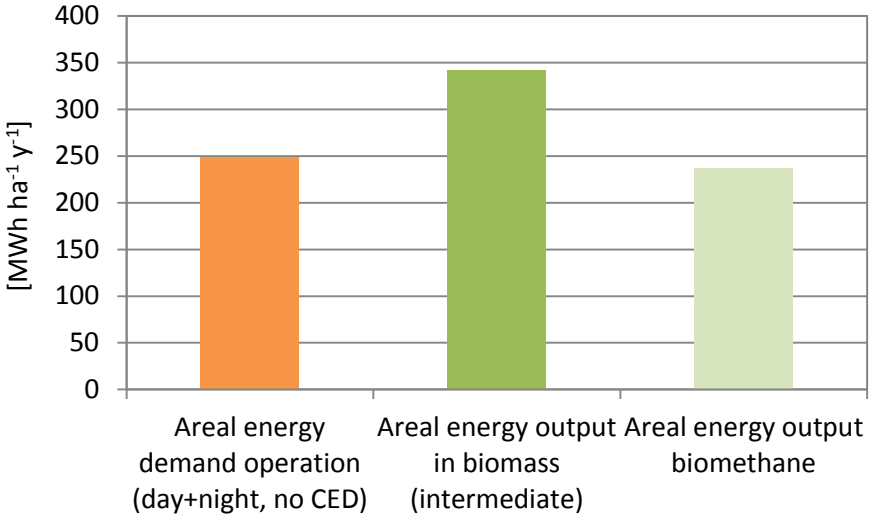


Figure 6.2: Areal operation energy, energy content in biomass (intermediate) and biomethane energy (base case)

6.2 Base case – parameter analysis

The impact of parameter changes on the base case is analysed.

6.2.1 Cumulative energy demand

The CED is linearly related to all input flows. Therefore, assumptions about the CED strongly influence the NER. Nevertheless, all CED scenarios result in a NER > 1. The CED for operation exceeds 1 but also without any operation energy, between 1.1-1.6 MJeq per MJ biomethane are needed for other supplies and processes (Table 6.3).

Note that the scenario 'CED 0.7' equally reduces all energy demand while the scenario 'CED renewable' reduces mainly energy demand for electricity and thus also changes the proportion of operation energy to other energy demand (Figure 6.3).

Assuming the use of renewable electricity ('CED renewable') has the biggest impact on the NER. Whether it is appropriate to use renewable electricity to produce a renewable energy carrier is rather a political decision.

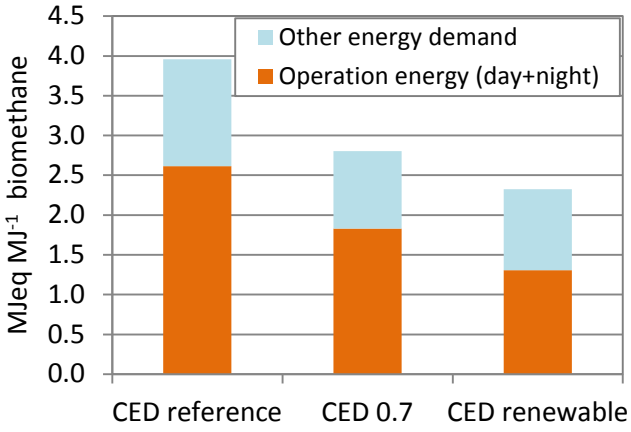


Figure 6.3: NER for different CED scenarios (applied to base case)

Table 6.3: MJeq per MJ biomethane of each process for different CED scenarios (applied to base case)

	MJeq MJ^{-1} biomethane		
Process	**'CED reference'**	**'CED 0.7'**	**'CED renewable'**
Operation	2.39	1.67	1.19
Operation nighttime	0.23	0.16	0.11
Culture transport	0.03	0.02	0.01
Harvesting	0.13	0.09	0.07
Material (-credit)	0.24	0.17	0.20
Nitrogen (-credit)	0.05	0.04	0.05
Phosphorous (-credit)	0.00	0.00	0.00
CO_2 transport	0.09	0.06	0.05
CO_2 pipeline	0.40	0.28	0.36
Biogas: heat	0.19	0.19	0.17
Biogas: energy	0.09	0.06	0.04
Biogas: upgrading	0.12	0.08	0.06
Total (NER)	4.0	2.8	2.3

6.2.2 Other parameters

Generally, parameters and boundary conditions are chosen quite optimistically to reflect expected or potential improvements. Parameters which dominate the energy demand are discussed in greater detail.

Operation energy dominates the energy demand and depends linearly on the pressure drop (equation (16)). Thus, reducing **other pressure** (Δp_{other}) to 50 instead of 100 mbar decreases the NER significantly to 3.2.

Pipelines have a large share on the total energy demand. This is despite a relatively short assumed distance of the CO_2 source to the cultivation plant of 15 km. If CO_2 could be supplied within existing pipelines as done for example to cultivate vegetables (OCAP 2012), the NER would sink to 3.6. This would however extremely limit potential cultivation sites. Still, energy is needed to compress CO_2 for transport. Especially in modern power plants, gasses leave the chimney with low heat and pressure which is not sufficient for transport over long distances. It should be noted that CO_2 transport even within the microalgae plant becomes more relevant at large plant sizes. For example, to take up the emissions of the Karlsruhe coal power plant, algae need to be cultivated on over 200 km^2.

Material energy has the second largest share on the energy demand for supplies. This is despite the assumptions that PBR walls of 1 mm PET last 10 years and part of embodied energy could be recovered by combustion. Reason is the high CED of plastic (PET) of 80 MJeq kg^{-1}. Glass is also a common used material for PBRs and has a lower CED (33 MJeq kg^{-1}). However, glass walls must be thicker than 1 mm which compensates savings (for example Cheng-Wu *et al.* (2001) reported 10 mm for a 1.10 m high PBR). A lifetime of 20 instead of 10 years decreases the NER only slightly to 3.9 instead of 4.0 since the credit for material combustion also sinks.

Impact of parameters on the NER at different CED scenarios

Parameters have a different effect on the NER depending on the CED scenario. For example, the assumption of renewable energy ('CED renewable') changes the proportion of operation energy to other energy (see Figure 6.3). Thus, the assumption of Δp_{other} = 50 mbar decreases the NER of the 'CED reference' and 'CED 0.7' equally by 20% but the NER in the 'CED renewable' only by 17% (Figure 6.4).

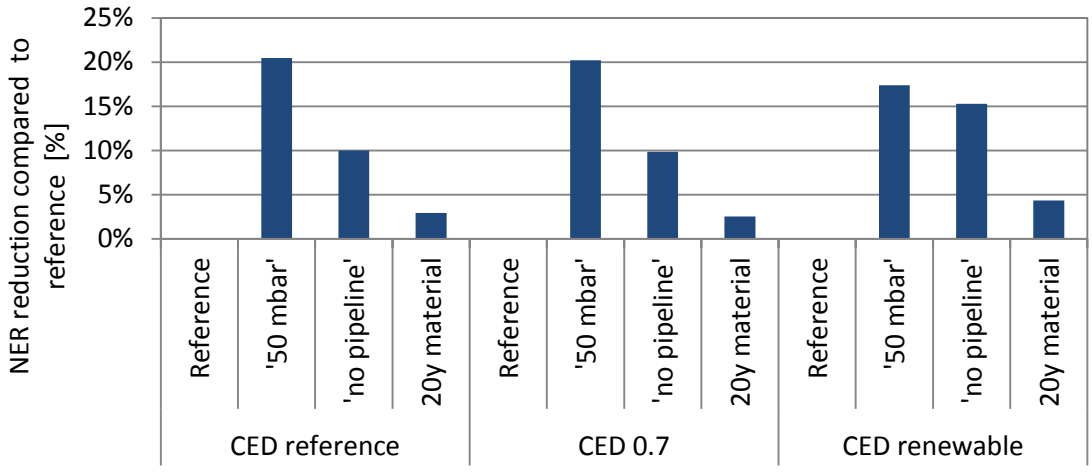


Figure 6.4: Interaction of other parameters with different CED scenarios

6.3 Changing aeration rate

As discussed in section 4, the PE and thus the productivity sinks with the aeration rate – however, also the ratio between energy demand and productivity ('core energy ratio') sinks so that microalgae cultivation becomes more energy-efficient. Therefore it could be expected that the NER sinks with the aeration rate.

The NER at changing aeration rates (between 0.05 and 1 vvm) is modelled based on the correlation between *vvm* and PE at 500 µmol m^{-2} s^{-1} as determined in the core model (chapter 4). Results are discussed exemplarily based on calculations with climate data of southern Germany (Karlsruhe) from March – October 2012 at the scenario 'CED 0.7'.

6.3.1 Results and analysis of contributions

With decreasing aeration rate (from right to left), the NER initially decreases as expected. However, from a certain point on, it increases again steeply (Figure 6.5).

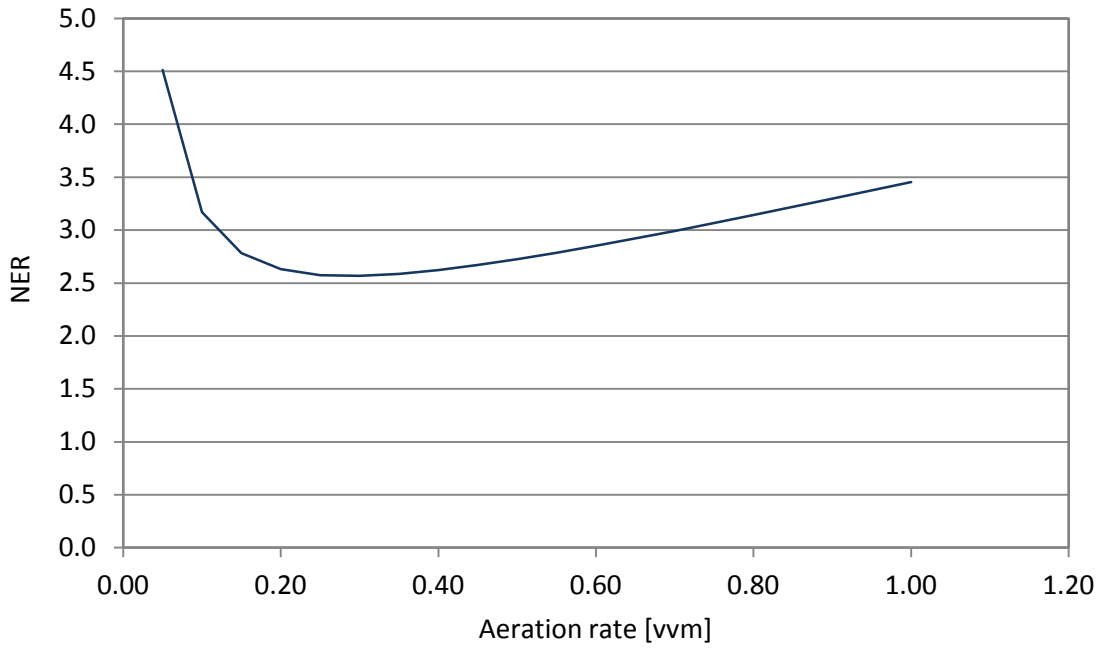


Figure 6.5: NER depending on the aeration rate (base case + 'CED 0.7')

To better analyse this result, the energy demand is clustered in three groups (Table 6.4).

Table 6.4: Clustering of NER contributions for the analysis

Cluster	Contains
Operation energy	Day- and night-time operation energy
Facilities and culture transport	Energy for PBR material, pipeline, harvesting and culture transport.
Biomass related	Energy directly proportional to the biomass: nutrients, CO_2 supply and biomethane production

Figure 6.6 shows the respective shares of each category on the NER. With sinking aeration rates, algae cultivation becomes more energy-efficient (orange circles). Less operation energy per PE (see also Figure 4.3) is equivalent to less energy per biomass yield and thus per MJ biomethane.

The share of biomass related energy demand (green dashes) on the total biomethane output remains constant: the less biomass is produced, the less up and downstream resources are also required.

However, PBR facilities are needed whether algae grow or not. Hence, their share on the energy input increases (brown diamonds). The PE and thus the biomethane output keeps declining with the aeration rate (see also Figure 4.4). Consequently, from a certain point on, the permanent energy demand dominates the NER so that the NER increases even more strongly than it sank before. This results in an optimum NER value which cannot be overcome.

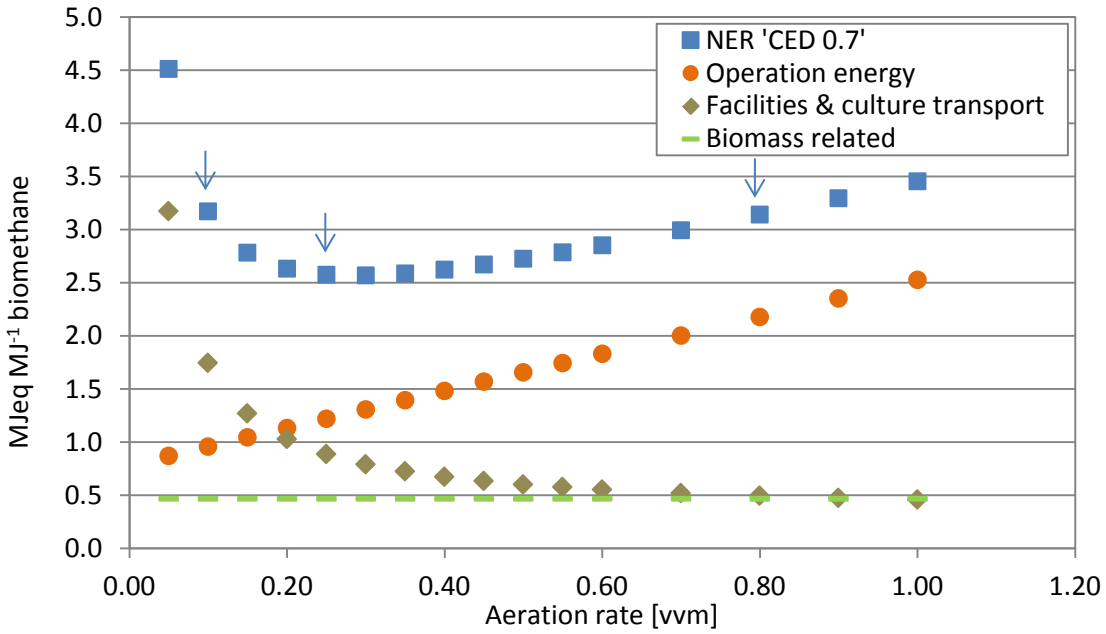


Figure 6.6: NER depending on the aeration rate, detailed analysis of contributions (base case + 'CED 0.7)

6.3.2 Equal NER with different contributions

Although NERs are similar at 0.1 and 0.8 vvm (left and right arrows, Figure 6.6), they result from different contributions (Figure 6.7). Cultivation at low aeration rates is more energy-efficient while high rates results in higher biomass yields. The energy inputs and outputs of the lowest NER are shown for comparison (middle arrow, Figure 6.6). If microalgae are cultivated for other purposes than biofuels, it might be more important to attain high yields (Table 6.5) than to produce them energy-efficiently.

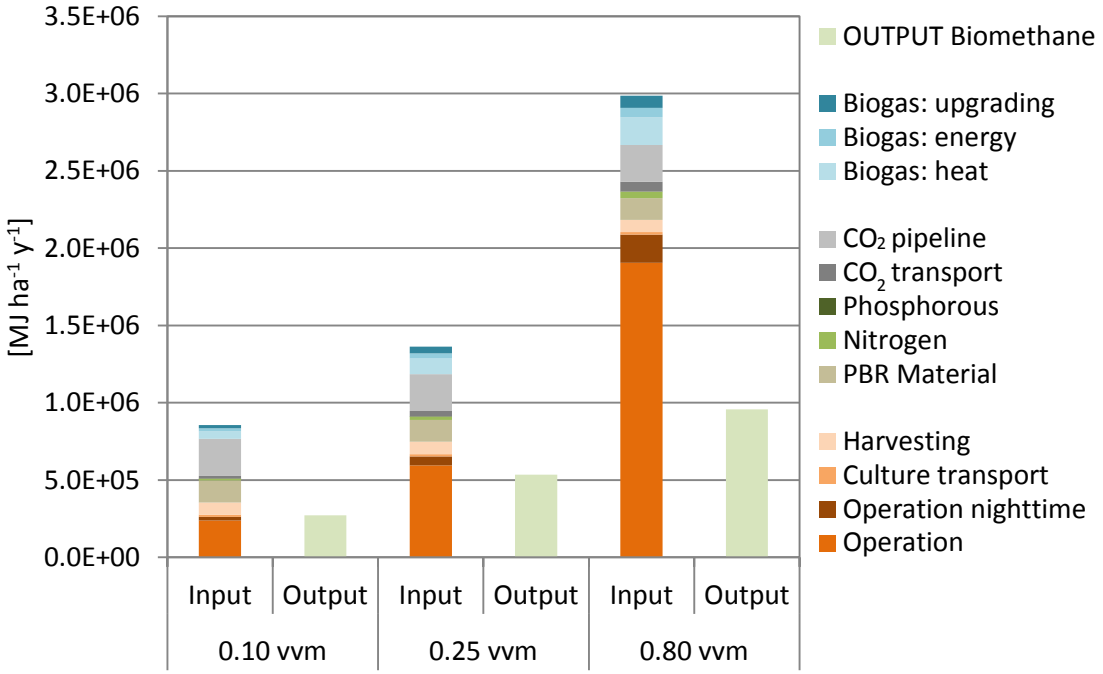


Figure 6.7: Energy input and output at different aeration rates as indicated in Figure 6.6

Table 6.5: Operation and productivity parameters at different aeration rates as indicated in Figure 6.6

Parameter	Symbol	Unit	0.10 vvm	0.25 vvm	0.80 vvm
Operation power, volumetric	P_{vol}	W m^{-3}	31	78	251
Operation power, areal	P_{area}	W m^{-2}	1.25	3.1	10
Operation energy, areal (24h)	$E_{op,area,d}$	kWh m^{-2} d^{-1}	0.017	0.042	0.135
Yearly biomass yield	$Y_{ha,y}$	t ha^{-1} y^{-1}	20	39	69
Areal productivity	$prod_{area,d}$	g m^{-2} d^{-1}	8	16	28
Volumetric productivity	$prod_{vol,d}$	g L^{-1} d^{-1}	0.20	0.39	0.7

6.4 Changing aeration rate – parameter analysis

With the aeration rate changes not only the NER and its contributions (c.f. 6.2.2) but also the effect of scenarios and parameters on the NER. These effects are shown in the following.

6.4.1 'CED renewable'

The use of renewable electricity 'CED renewable' adds less energy to each kWh of operation. This difference becomes more visible at high aeration rates (Figure 6.8, open versus closed circles). Vice versa, the less operation energy is needed, the less important becomes also the energy demand to supply it. Therefore, the two NERs converge with decreasing aeration rate (Figure 6.8, open versus closed squares). At low CED, a wider range of aeration rates enables a low NER (open squares).

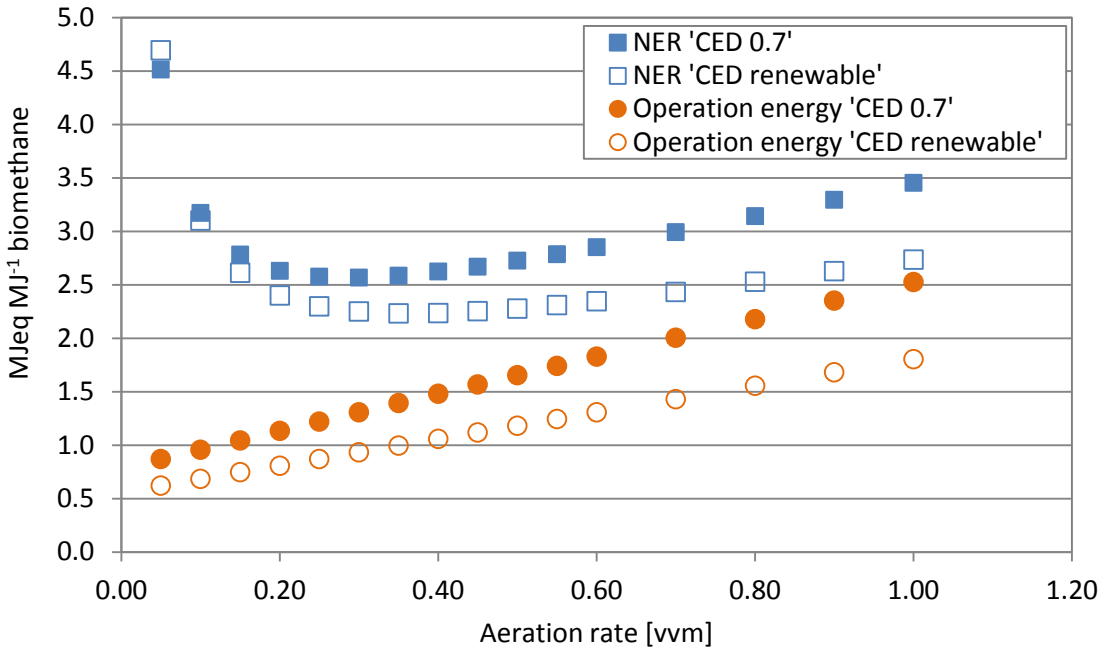


Figure 6.8: NER depending on the aeration rate, influence of CED scenarios

6.4.2 Other pressure drop '50 mbar'

Assuming lower pressure drop (Δp_{other} = 50 mbar) strongly reduces the operation energy demand. Thus, it has almost the same effect on the NER as assuming renewable electricity use ('CED renewable'). Together with the scenario 'CED 0.7', low pressure drop results in a NER of around 2.

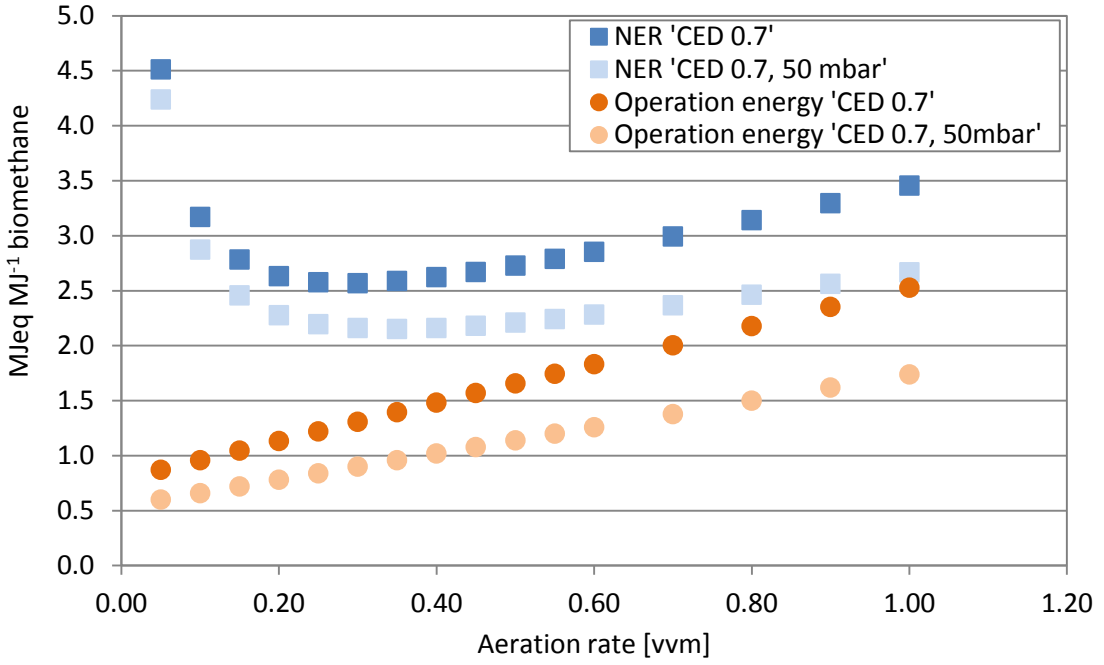


Figure 6.9: NER depending on the aeration rate, influence of reduced pressure drop

6.4.3 No pipeline

In contrary to the above investigated parameters, pipelines are part of the infrastructure. Consequently, with decreasing aeration rate the impact of the pipeline on the NER gets stronger and the NERs diverge (Figure 6.10, grey versus blue squares).

With low energy demand for facilities, a good balance between energy input and output becomes more important again: the NER is better at lower aeration rates. However, it must be considered that extremely low rates might not remove oxygen sufficiently (see Figure 3.4) so that the culture could break down.

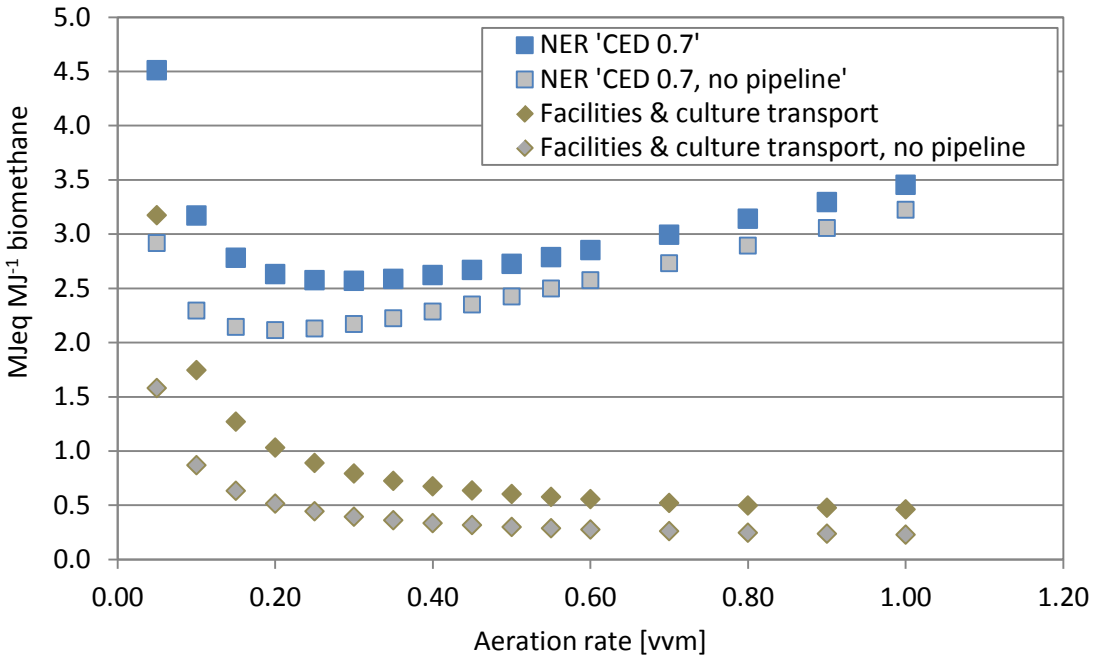


Figure 6.10: NER depending on the aeration rate, influence of pipeline

6.4.4 Structured PBRs

According to the suggestions for PBR development, it is assumed that a structured PBR could attain higher PE at equal areal energy demand. The NER is calculated based on the scenario 'CED 0.7' and '50 mbar'.

The NER of the 'structured' PBR is higher than the 'empty' PBR (2.8 instead of 2.0, Figure 6.11): The high material demand for the structures overcompensate the higher energy output due to higher PE. No such concept has been tested yet in an outdoor pilot plant (at least no data are published). This calculation should thus mainly emphasise the need to include also the material in the NER calculation, especially for PBRs which aim at light dilution or distribution with high inner or outer surfaces.

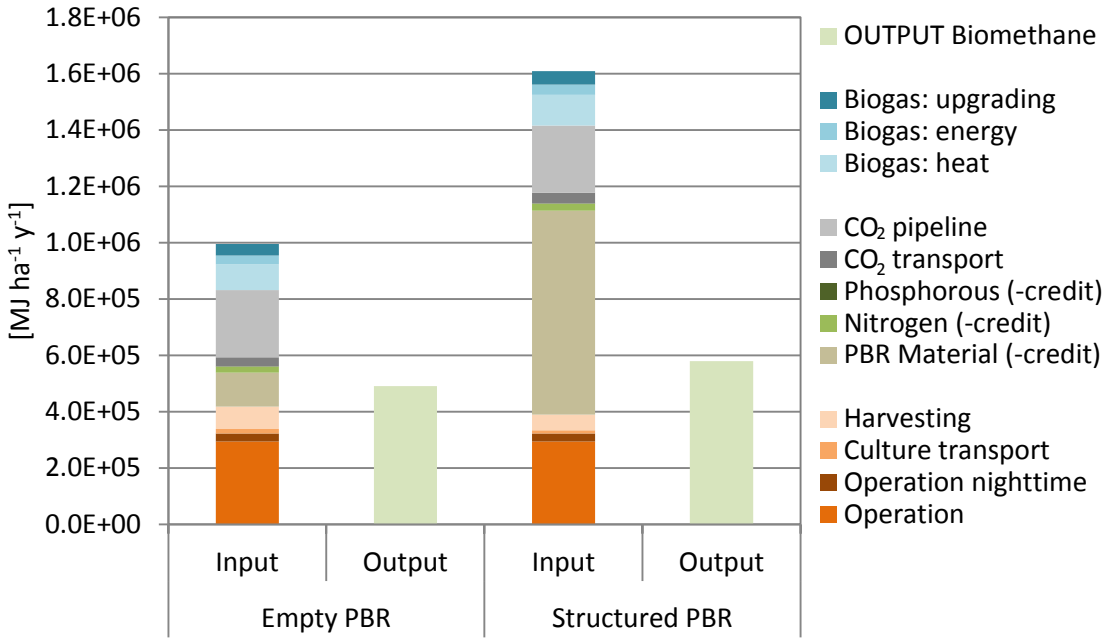


Figure 6.11: Energy input and output of an 'empty' compared to a 'structured' PBR (Karlsruhe, Mar-Oct, 'CED 0.7', '50 mbar')

6.5 Location and cultivation period

Location and cultivation period determine temperature, solar irradiation and the time period during which it is supplied. The temperature correction factor and night-time operation rate are adapted to reflect the higher temperatures and irradiation in Madrid compared to Karlsruhe. The NER is calculated with irradiation data of Karlsruhe or Madrid at different cultivation periods based on the scenario 'CED 0.7' and '50 mbar'.

6.5.1 Location

The NER is lower for climate data of Madrid than of Karlsruhe. Higher yields because of more solar energy compensate assumed higher photon losses and higher night-time operation energy. The difference between the locations does not depend considerably on the aeration rate (Figure 6.12).

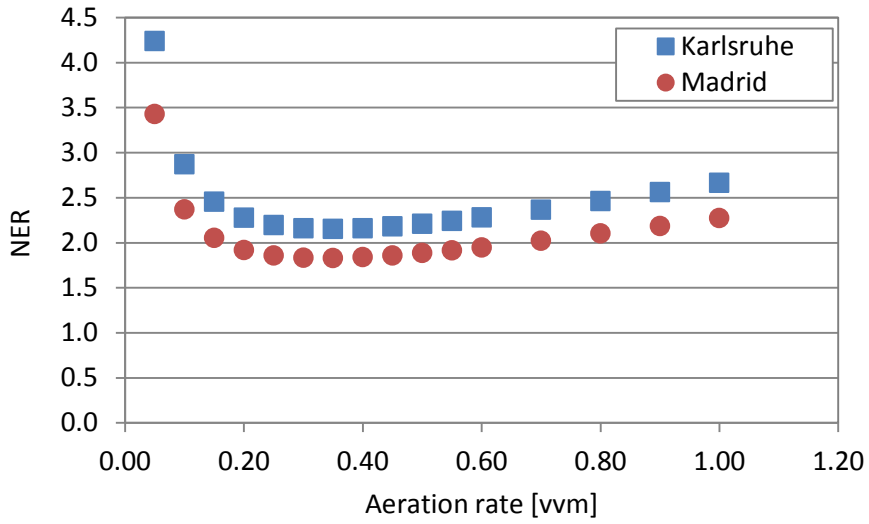


Figure 6.12: NER depending on the aeration rate – comparison Karlsruhe and Madrid (Mar-Oct, 'CED 0.7', '50 mbar')

This result is based on the estimated photon loss for passive temperature control. If cultivation in Madrid required more sunlight protection – more photons would be lost and the yield would sink – the NERs would converge. Furthermore, the assumption that the PE does not depend on the light intensity is more advantageous for climate data of Madrid than of Karlsruhe. In Madrid (in 2012), the light intensity was above 500 µmol m^{-2} s^{-1} in over 75% of sunlight hours (60% of time Karlsruhe) (c.f. Annex, Figure A.3). Moreover, photoinhibition and overheating – and thus culture breakdown due to high light intensities is more likely in Madrid where the light intensity is more often above 1800 µmol m^{-2} s^{-1} (c.f. Annex, Figure A.4).

In general, countries with more sunlight have potential higher biomass yields (see 3.1.2). At the same time, greater efforts are required to provide optimal growth temperature and light intensity. To compare different locations, it would be necessary to consider these trade-offs in greater detail.

Notably, the NER changes not as much as the areal productivity. For example, at 0.6 vvm the areal productivity and thus the biomethane output increases by almost a third (Figure 6.13). Yet, the NER sinks only from 2.2 to 1.9 since a higher biomass output requires also more energy for upstream and downstream processes.

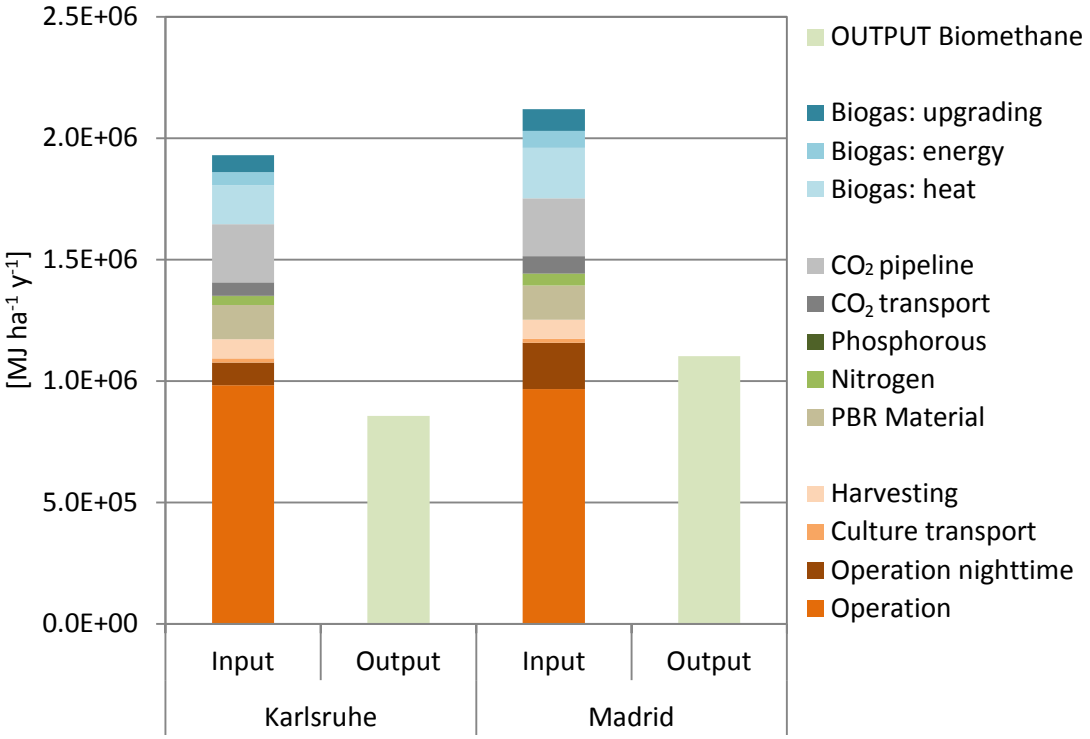


Figure 6.13: Energy inputs and outputs for cultivation in Karlsruhe and Madrid at 0.6 vvm (Mar-Oct, 'CED 0.7', '50 mbar')

6.5.2 Cultivation period

Shortening the cultivation time (beginning from a year-round cultivation) has a similar effect on the NER as decreasing the aeration rate: The NER initially sinks and then increases again more steeply (Figure 6.14). The effect is similar in Madrid (Figure 6.15). The reason is in that case however not the ratio of vvm to PE (see 6.3) which remains constant, but the light intensity: with less sunlight, the same PE results in lower yields (c.f. equation (13)). Winter days do not provide much sunlight, but the PBR must be operated nevertheless; thus cultivating microalgae during the whole year is less energy-efficient than cultivating them in months with high solar irradiation (see also Annex, Figure A.2). However, analogue to a very low aeration rate, a very short cultivation time results in too few biomass so that the share of infrastructure on the NER increases and the NER rises again.

Table 6.6 shows for example, that for a cultivation period between May and August, more biomass is produced per day (19 versus 12 g m^{-2} d^{-1}) but less during the whole year (24 versus 43 t ha^{-1} y^{-1}).

Preconditions for this effect are that (a) the PE does not depend on the light intensity and (b) that the culture does not break down due to overheating (see also discussion of the previous section).

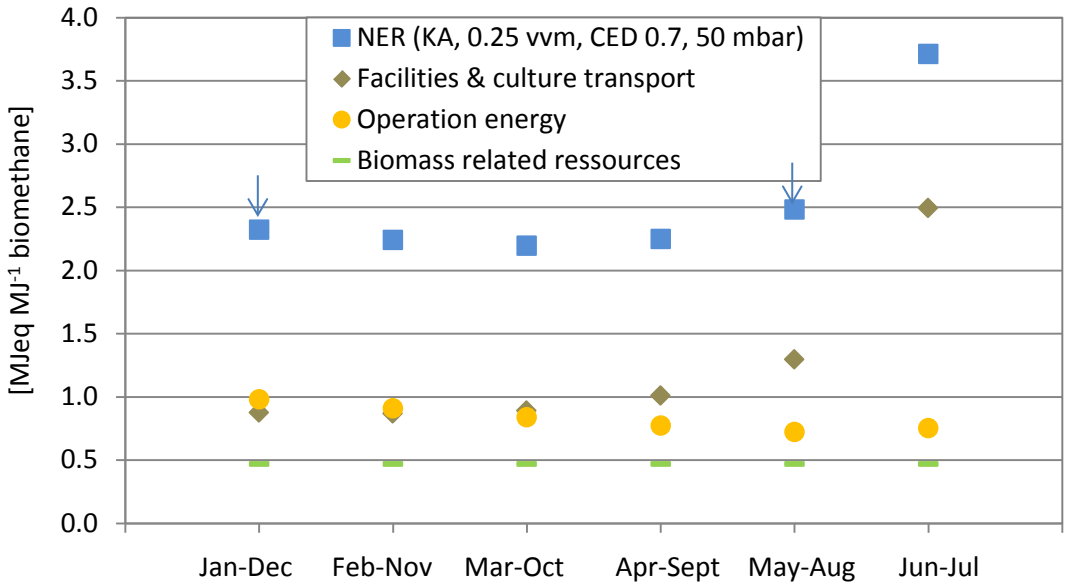


Figure 6.14: NER depending on the cultivation period (Karlsruhe, 0.25 vvm 'CED 0.7, 50 mbar')

Table 6.6: Operation and productivity parameters at different cultivation times as indicated in Figure 6.14

Parameter	Symbol	Unit	Jan-Dec	May-Aug
Operation power, volumetric	P_{vol}	W m^{-3}	54	54
Operation power, areal	P_{area}	W m^{-2}	2.2	2.2
Operation energy, areal (24h)	$E_{op,area,d}$	kWh m^{-2} d^{-1}	0.025	0.031
Yearly biomass yield	$Y_{ha,y}$	t ha^{-1} y^{-1}	43	24
Areal productivity	$prod_{area,d}$	g m^{-2} d^{-1}	12	19
Volumetric productivity	$prod_{vol,d}$	g L^{-1} d^{-1}	0.3	0.5

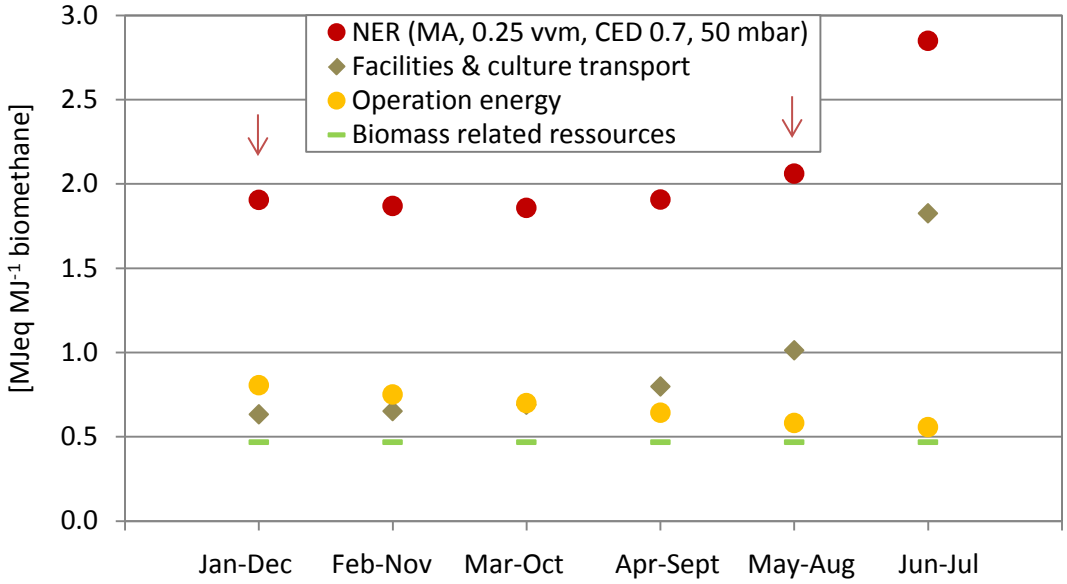


Figure 6.15: NER depending on the cultivation period (Madrid, 0.25 vvm 'CED 0.7, 50 mbar')

Table 6.7: Operation and productivity parameters at different cultivation times as indicated in Figure 6.15

Parameter	Symbol	Unit	Jan-Dec	May-Aug
Operation power, volumetric	P_{vol}	W m^{-3}	54	54
Operation power, areal	P_{area}	W m^{-2}	2.2	2.2
Operation energy, areal (24h)	$E_{op,area,d}$	kWh m^{-2} d^{-1}	0.029	0.032
Yearly biomass yield	$Y_{ha,y}$	t ha^{-1} y^{-1}	60	31
Areal productivity	$prod_{area,d}$	g m^{-2} d^{-1}	16	25
Volumetric productivity	$prod_{vol,d}$	g L^{-1} d^{-1}	0.41	0.62

Interaction of cultivation period an aeration rate

The optimal cultivation period for a low NER depends also on the aeration rate (Figure 6.14): At very high rates (dark blue squares), microalgae cultivation is only energy-efficient in months that provide much solar energy in a short time. At very low rates (light blue squares), it is better to cultivate microalgae during the whole year. At a good balance between aeration rate and biomass yield (middle blue squares), the cultivation period has a relatively low effect on the NER.

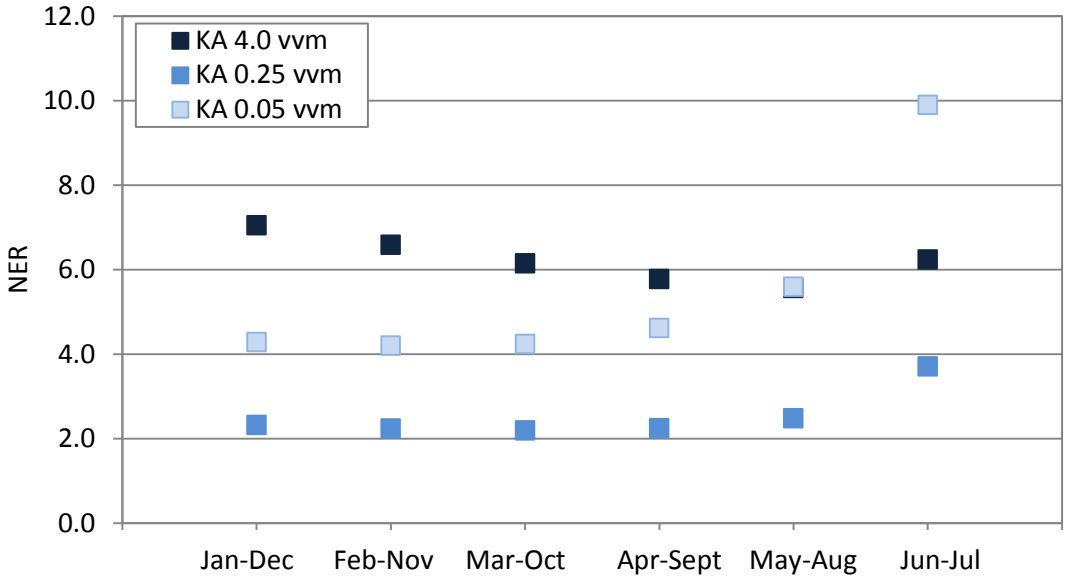


Figure 6.16: NER at different cultivation periods and aeration rates (Karlsruhe, 'CED 0.7, 50 mbar')

6.6 Summary of findings and definition of best case

Due to the correlated parameters, the lowest NER is attained at low aeration rates which are more energy-efficient. Nevertheless, because of the energy demand for infrastructure and the resources needed to produce and process the biomass, the lowest NER remains around two.

The impact of different parameters on the NER depends highly on the aeration rate. For example, while a reduced pressure drop changes the NER by around 20% at 1 vvm, it has a very low effect on the NER at 0.05 vvm (see 6.4.2). Generally, parameters related to the operation energy have a larger effect on the NER at high aeration rates because the share of operation energy on the total energy demand is large. Parameters related to infrastructure and supplies have a larger effect on the NER at low aeration rates. The parameters also interact with each other. For example, the optimal cultivation period depends on the aeration rate (see 6.5.2).

For the examined system, the lowest NER could be attained at an aeration rate of 0.25 *vvm*. Interestingly, 0.2 *vvm* or higher is also a standard value to operate PBRs (Öschger and Posten 2012). Thus, the model seems to reflect a good balance between operation energy demand and biomass yield. With the further assumptions about the flat plate PBR, this results in an operation power of 54 W m^{-3} or 2.2 W m^{-2}. These data are close to the goals defined by Posten (2009) who stated that "the use of auxiliary energy for mixing and gas transfer … should ideally not exceed 2 W m^{-2} which corresponds to approximately 50 W m^{-3}". Based on the correlation between aeration rate and PE and with climate data of Madrid (March – October) this results in a biomass productivity of 50 t ha^{-1} y^{-1}.

With these data, a NER of 1.8 (Figure 6.17) results with improved upstream resources ('CED 0.7') and cultivation technology ('50 mbar'). The use of renewable electricity ('CED renewable') with a supply efficiency of 80% would reduce the NER to 1.7. As this assumption is regarded inappropriate for the purpose of this study, the NER of 1.8 as 'best case' is further analysed. The resource and energy demand for each process is summarised in Table 6.8.

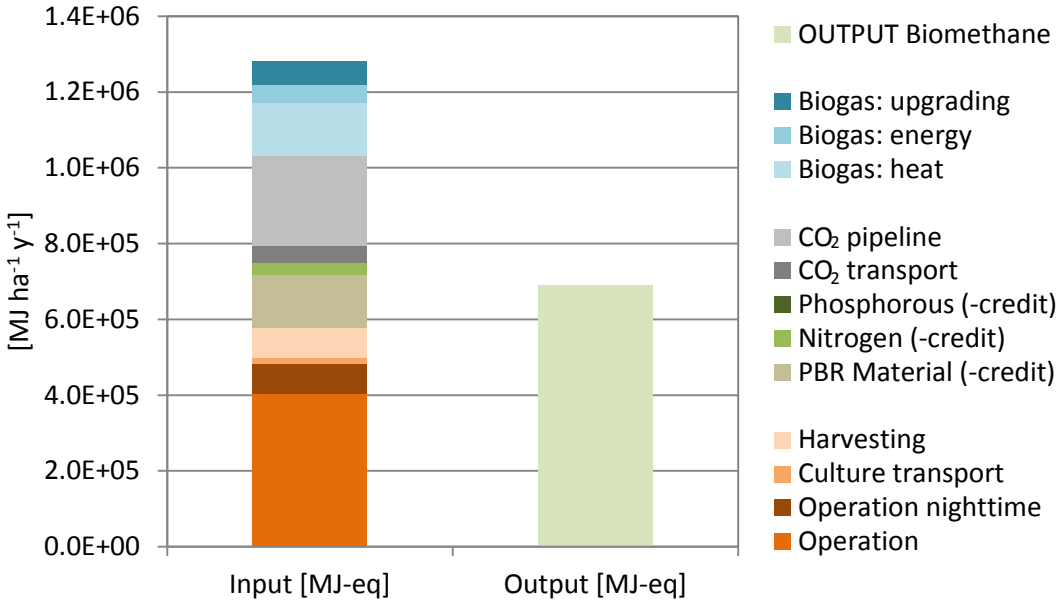


Figure 6.17: Energy input and output best case (Madrid, Mar-Oct, 0.25 vvm, CED 0.7, 50 mbar)

Table 6.8: Resource demand per hectare and year, resulting energy input and NER (best case)

	Value	Unit ha^{-1} y^{-1}	Input [GJeq]	Credits [GJeq]	Output [GJeq]	MJeq MJ^{-1} methane
Operation	64	MWh	403			0.58
Operation nighttime	13	MWh	79			0.11
Culture transport	2.6	MWh	16			0.02
Harvesting	12.5	MWh	79			0.11
PBR Material	3.4	t	189	67		0.18
Nitrogen	3.9	t	78	52		0.04
Phosphorous	0.8	t	4	4		0.00
CO_2 transport	7.1	MWh	44			0.06
CO_2 pipeline	0.3	km	239			0.35
Biogas: heat	109.6	GJ	130			0.19
Biogas: energy	6.8	MWh	43			0.06
Biogas: upgrading	9.0	MWh	57			0.08
OUTPUT Biomethane					689	
Totals			1361	123		1.8

6.7 Comparison with previous LCA studies

Previous LCAs are compared to this study in order to analyse how different NER results can be explained. Especially, the reasons for a NER <1 are analysed. The respective best cases are examined regarding (a) system boundaries and (b) assumptions about operation energy and biomass output.

Initially, the system boundaries of this study are adapted to the system boundaries of other studies and the resulting NERs are compared. If necessary, the NER as defined in section 2.1.3 is calculated from the original data.

The assumptions about operation energy and biomass output are investigated as follows: For all cultivation systems, the areal operation energy and the areal biomass energy output ('areal energy balance', as defined in 4.1.2) are calculated from the available data. For LCAs of aerated flat plate PBRs, additionally the PE is plotted over the aeration rate and results are compared to each other and to measured laboratory and outdoor data.

Focus of this comparison are studies which investigated aerated flat plate PBRs (Jorquera *et al.* 2010, Batan *et al.* 2010, Brentner *et al.* 2011, Tredici *et al.* 2015); three recent studies about other cultivation systems are also exemplarily analysed and shortly discussed (Sills *et al.* 2012, Jonker and Faaij 2013, Razon and Tan 2011). To facilitate reading, the first authors are named in the following.

6.7.1 System boundaries – all cultivation systems

Table 6.9 shows the system boundaries of each LCA and the resulting NER. All LCAs had different system boundaries. For example energy demand to provide CO_2 is included only in the LCAs of Jonker and Brentner though without the energy demand for pipelines. Nevertheless, also studies with similar system boundaries resulted in different NERs (e.g. Jorquera compared to Tredici).

The NER of this studies' best case (1.8) is higher than that of almost all other LCAs. Only exception is the best case of Razon. Reason for this could be the more energy intensive processes for biodiesel production. However, different system boundaries explain the differences only partially: With adapted system boundaries, the NER of this study is mostly closer to that of other studies (Figure 6.18), but not identical. Other assumptions are responsible for the remaining differences, as shown in the next chapters.

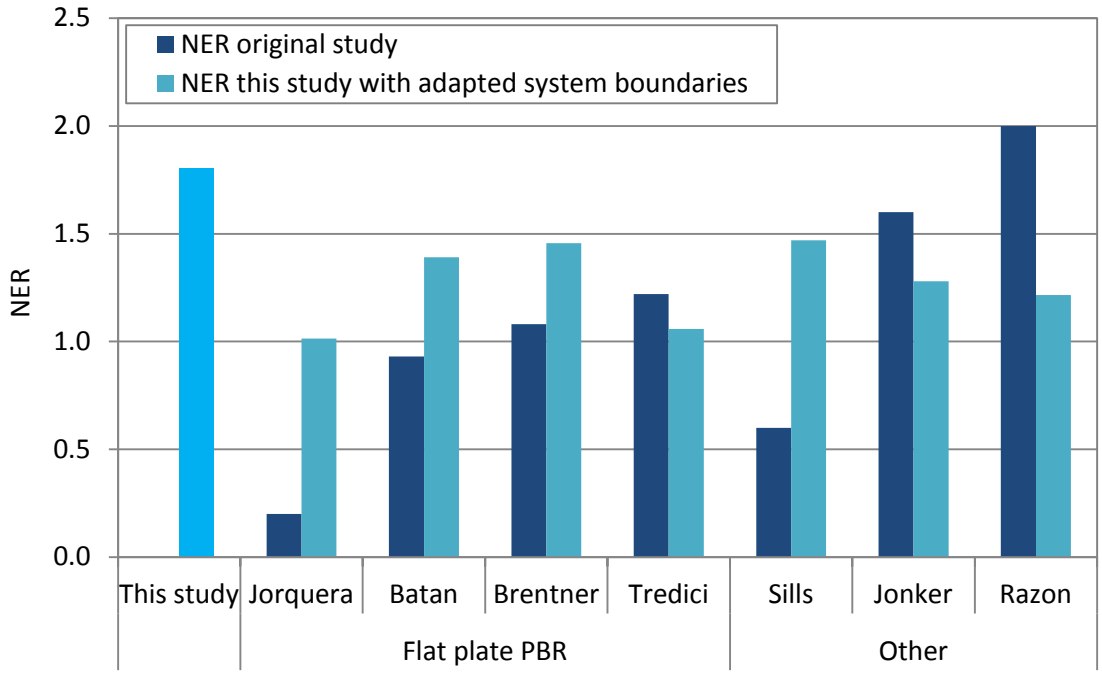


Figure 6.18: Comparison of NER of other studies to this study with the respective adapted system boundaries

Table 6.9: Comparison with previous studies – system boundaries

	This study	Jorquera *et al.* (2010)	Batan *et al.* (2010)	Brentner *et al.* (2011)	Tredici *et al.* (2015)	Sills *et al.* (2012)	Jonker and Faaij (2013)	Razon and Tan (2011)
Type of PBR	Flat plate, aerated	Flat plate, aerated	Flat plate, aerated (underwater)	Flat plate, aerated	Flat plate, aerated	Tubular, aerated & pond	Tubular, horizontal	Flat plate, aerated & pond
Type of fuel	Biomethane	Biomass	Biodiesel	Biodiesel & biomethane	Biomass	Biodiesel & biomethane	Bioenergy	Biodiesel & biomethane
Operation energy	yes	yes	yes	yes	yes	yes	yes	yes
Electricity supply	yes	yes	yes	yes	yes	yes	yes	yes
(type,efficiency)	(57%)	(hydropower, n.a.)	(US electricity mix, n.a.)	(n.a.)	(modern plant, 58%),	(n.a.)	(40.5%)	(natural gas fired CHP, 32%)
Reactor material (PBR)	yes	yes	yes	yes	yes	yes	no	no
(type, lifetime, thickness)	(PET 10y, 1 mm)	(LDPE 10y, 0.3 mm)	(PE 5y, 0.12 mm)	(LDPE 50y)	(LDPE, 1 y, 0.3 mm)	(LDPE 5y)		
Nutrients	yes	no	yes	yes	yes	yes	yes	yes
CO_2 supply (MJ kg^{-1} CO_2)	yes (0.26 MJ kg^{-1})	no	no	yes	no	no	yes (4 MJ kg^{-1})	no
Downstream	yes	no	yes	yes	no	yes	yes	yes
Credits	yes	no	yes	yes	no	yes	yes	yes
(type)	(nutrients, material)		(fish feed, glycerine)	(nutrients)		(nutrients)	(nutrients, glycerine)	(nutrients, glycerine, water)
NER	**1.8**	**0.2**	**0.9**	**1.1**	**1.2**	**0.6**	**1.6**	**2.0**

Table 6.10: Comparison with previous studies – important assumptions concerning operation energy and biomass yield

		This study	Jorquera	Batan	Brentner	Tredici	Sills	Jonker	Razon
Type of cultivation		Flat plate	Flat plate	Flat plate	Flat plate	Flat plate	Tubular PBR & pond	Tubular PBR	Flat plate PBR & pond
Culture volume/area	[$m^3\ m^{-2}$]	0.040	0.100	0.050	0.023[a]	0.032	0.143[b] PBR	n.a.	n.a.(0.12 pond)
Reactor width	[m]	0.04	0.07[c]	n.a.	0.07[c]	0.045	0.40 PBR	0.05	n.a. (0.12 pond)
Reactor height	[m]	0.6	1.5[c]	n.a.	1.5[c]	0.7	0.40 PBR	0.05	5.5
Other pressure drop	[mbar]	50	0[c]	n.a.	0[c]	~50	n.a.	n.a.	n.a.
Pump efficiency	[-]	0.85	1[c]	n.a.	1[c]	0.60	0.60 (pond)	n.a.	0.17
Operation power, volumetric	[$W\ m^{-3}$]	54 (11 night)	53 (Sierra *et al.* 2008)	8	53 (Sierra *et al.* 2008)	73 (31 night)	2.79[b] PBR	n.a.	50-70 (PBR)
Operation power, areal	[$W\ m^{-2}$]	2.2 (0.4 night)	5.3	0.4	1.2	2.3 (1.0 night)	0.4 PBR	2.4[d]	n.a.
Operation hours/day	[$h\ d^{-1}$]	12	10	24	10	10	20	n.a. (24)	n.a.
Aeration rate and/or flow velocity		0.25 vvm	0.23vvm[c]	n.a.	0.23vvm[c]	0.22 vvm	0.01 *vvm*[b] and 0.30 m s^{-1}(PBR)	n.a.	0.25 m s^{-1} (pond)
Areal productivity	[$g\ m^{-2}\ d^{-1}$]	20	27	25*	68	20	42	25*	16
Biomass energy content	[$MJ\ kg^{-1}$]	20	31.55	n.a.(20)	n.a.(20)	22.2	n.a.(20)	26.2	n.a.(20)
Cultivation days/year	[$d\ y^{-1}$]	245	365	365	n.a. (300)	330	360	300	360
Light intensity (+/-100)	[$kWh\ m^{-2}\ y^{-1}$]	1500	1790	1790	1660	1740	1790	1660	1790
Yearly areal yield	[$t\ ha^{-1}\ y^{-1}$]	50	98.6	91	204*	66	151*	76	58
Operation energy input	[$Wh\ m^{-2}\ d^{-1}$]	31	53	10	12	37	2.8(PBR+pond)[b]	58[d]	
Biomass energy output	[$Wh\ m^{-2}\ d^{-1}$]	113	237	139	378	123	233	182	89

a Calculated from original data: 0.26 m^3 on 11.3 m^2

b Calculated from original data: PBR: 2.79 kWh d^{-1}, 50 m^3, 350 m^2 (860 of 1210 ha); 20 $ft^3\ min^{-1}$, pond: 31.8 kWh d^{-1}, 11500 m^2 , 1500 m^3 (131 of 1210 ha)

c Calculated from original data of Sierra *et al.* (2008)

d Calculated from original data: 626 GJ $ha^{-1}\ y^{-1}$, 300 d_y, assumed operation hours: 24 h d^{-1}

* Calculated from: $prod_{area,d} \cdot d_y = Y_{ha,y}$

n.a. not available, in brackets: assumed value for calculation

6.7.2 Assumptions about operation energy and biomass production

The available data of each study about operation energy and biomass production are analysed in detail.

Areal energy balance – all cultivation systems

Figure 6.19 shows for all cultivation system the operation energy input (orange bars) and the biomass energy output (green bars) ('areal energy balance', see 4.1.2). These data are calculated based on the information in the respective studies summarised in Table 6.10. The quotient of these data is shown below the bars as the core energy ratio (CER).

Compared to this study, all other LCAs either expect a higher biomass energy output, a lower operation energy, or even both (Batan, Brentner and Sills). The only exception is Razon who expects a lower biomass energy output (areal operation energy is not directly available for this study). The assumptions of Tredici are closest to the ones in this study and thus the CER is also similar.

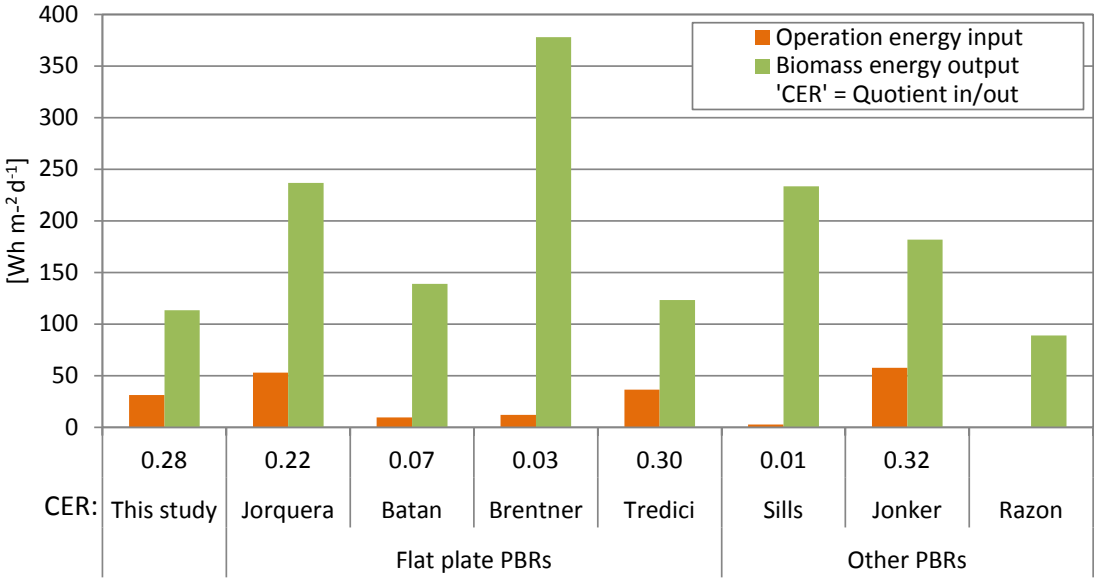


Figure 6.19: Comparison of 'areal energy balance' (operation energy input and biomass energy output) of all LCA studies

A more detailed analysis of the operation energy in the respective LCAs shows that the operation energy demand is in some cases incomplete. For example, the volumetric operation power cited by Jorquera and Brentner (53 W m^{-3} according to Sierra *et al.* (2008)) does not include the pump efficiency and additional pressure drop (see Table 6.10). The energy demand for the tubular PBR in Sills as well as for the flat plate PBR in Batan represents only the energy to transport the culture to a gas-exchange station (0.4 W m^{-2} calculated according to Weissman *et al.* 1988) – but not the energy for the actual gas exchange.

Aeration rate and PE – flat plate PBRs

To further compare the assumptions taken in LCAs of flat plate PBRs, the PE is calculated for each LCA study and plotted over the aeration rate. The PE is calculated with (9) from the yearly areal yield, the biomass energy content, and the light intensity during the respective cultivation period (see Table 6.10). The latter is estimated based on climate data of Madrid (+/- 100 kWh m^{-2} y^{-1}), (see also Table 5.10).

The aeration rate in aerated flat plate PBRs is only directly available in the LCA of Tredici. For the studies of Jorquera and Brentner, it is obtained by analysing the study of Sierra *et al.* (2008) which was cited in both LCAs for the volumetric energy demand. For the study of Batan, no aeration rate can be determined. The cited very low energy demand (0.4 W m^{-2}) does not apply to aeration but to transporting the culture to a gas exchange station (Weissman *et al.* 1988).

Figure 6.20 shows the PE over the aeration rate for the LCA studies (blue dashes), this LCA (blue triangle) and the PE calculated from data measured in the laboratory (diamonds) and outdoors (circles). (Error bars represent the PE of previous LCA studies at 100 kWh m^{-2} y^{-1} higher or lower solar irradiation.)

Notably, all previous LCA studies assume aeration rates around 0.2 vvm. However, the corresponding PEs (blue dashes) are not only higher than the PE calculated in this study for 0.25 vvm (blue triangle) – all values are even higher than the PE at the same aeration rate achieved in the laboratory under highly controlled growth conditions, at constantly low light intensities (yellow diamonds) and during a short time. The PE resulting from the assumptions of Brentner is higher than the theoretical maximum of 6% according to Zhu *et al.* (2008) (see also chapter 3.1.2).

All currently measured outdoor data are lower than the PE calculated in this thesis (as discussed in 4.3.3). Notably, also the PE of Tredici's base case (Tredici *et al.* 2015) which is partially based on measured outdoor data (15 g m^{-2} d^{-1} during 240 days, 36 t ha^{-1} y^{-1}) is with 1.5% lower than the PE calculated in this study at similar aeration rate. This demonstrates that the correlation derived in the core model already reflects technology improvement.

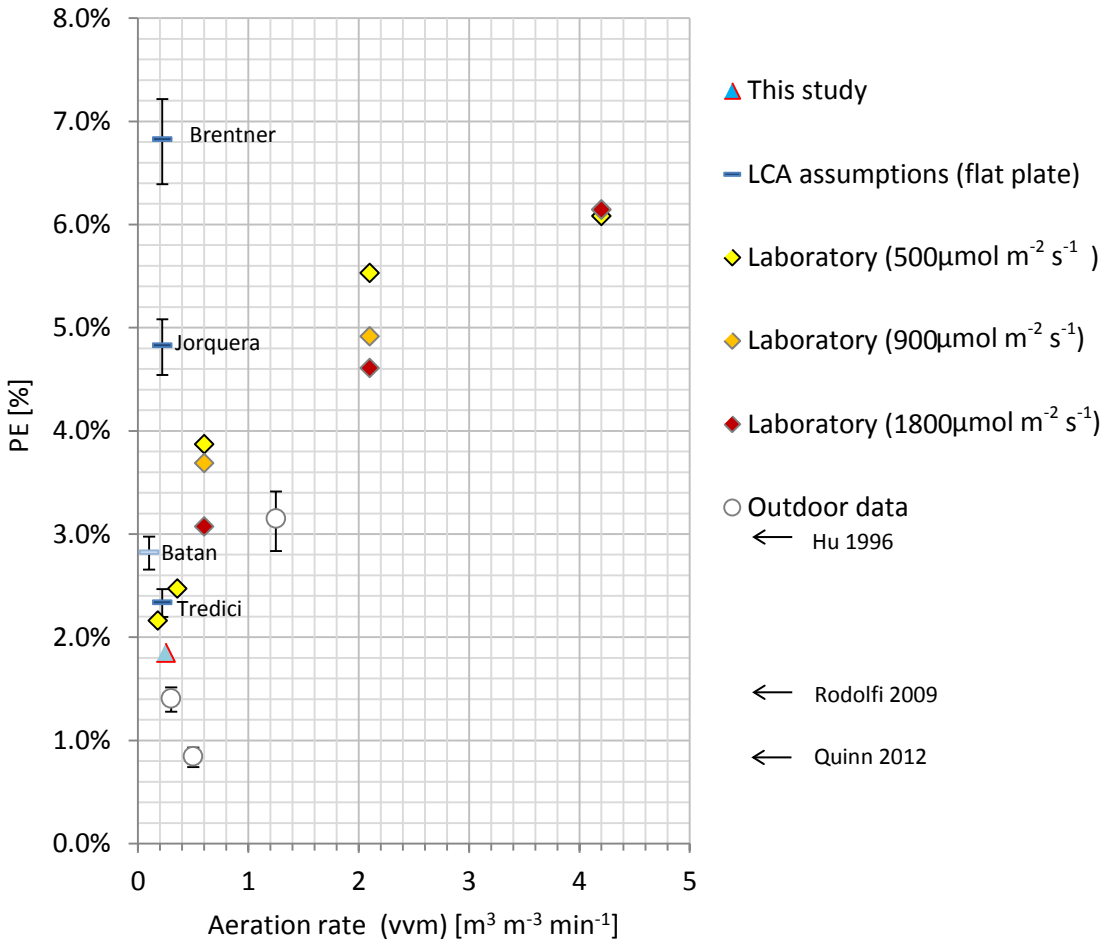


Figure 6.20: PE over vvm for aerated flat plate PBRs, comparison of LCA assumptions with laboratory and outdoor data

6.7.3 Potential improvements due to genetically modified algae?

As many other studies assumed a better relation between aeration rate and PE, the question is whether or how this can be achieved. The correlation between aeration rate and PE is due to mass transfer rates and light management (see 4.1.1). Could genetically modified algae (GMA) decrease the energy demand for high mass transfer rates and good light management?

Genetically modified algae cannot save the energy for mixing: all algae need high mass transfer rates for fast growth. Neither is it possible to accelerate the growth-limiting dark reactions of algae: they involve too many enzymes and metabolic processes (see 3.1.1). Even if it was possible to accelerate carbon fixation, one of the following enzymes in the complex cascade of dark reactions would still limit microalgae growth (Williams and Laurens 2010).

Due to the above described limitations, most of the research focusses on improved light management. In this thesis, it is assumed that algae can use high light intensities as efficiently as low (see 4.4) to calculate the PE depending on the aeration rate.

One suggestion to genetically engineer algae for better light use is for example to 'lock' microalgae in the state where they are adapted to high light (see also 3.1.3 f). In theory, "if the chlorophyll content is reduced, a greater number of photons are delivered to the deeper parts of the culture" (Williams and Laurens 2011). This could save mixing energy for light management – however, high mass transfer rates and gas exchange must be maintained. Algae that cannot adapt to changing light intensities any more can also be a disadvantage for outdoor cultures (Tredici 2010, Williams and Laurens 2010). Furthermore, energy is needed "to control light conditions in bioreactors" (Mussgnug *et al.* 2007). This might offset savings due to higher PE.

Cultivating GMA brings along disadvantages. For example, the genetically modified green algae *Chlamydomonas reinhardtii* (Stm6) grows only half as fast as the wild type (wt13) (1.2 d^{-1} (Franz *et al.* 2012) versus 2.5 d^{-1} (Jacobi *et al.* 2012)). This might also affect the PE. Apart from that, GMA tend to re-mutate and are poorly competitive with other species (Williams and Laurens 2011). It is thus questionable whether GMA can solve the problems of energy-efficient microalgae mass cultivation.

6.7.4 Potential improvements due to other cultivation systems?

Of the other recent studies which are exemplarily analysed in this thesis, only Sills *et al.* (2012) resulted in a NER below one in their best case. The authors themselves mentioned the limitation that they did not correlate important process parameters. In the following, it is shortly discussed to what extent other cultivation systems could improve the relation between energy demand and biomass energy output.

Tubular photobioreactors

Tubular PBRs need turbulent flow conditions to provide high mass transfer rates and to "avoid that the cells stagnate in the dark interior of a tube" (Acién *et al.* 2013). Turbulent flow conditions come along with high friction losses and thus a high energy demand (c.f. equation (22)), especially in long PBRs required on large scale. Furthermore in tubes, oxygen accumulates quickly and carbon is often limited so that many gas exchange station are required (Acién *et al.* 2013, Tredici 2003). Hulatt and Thomas (2011) experimented on a tubular reactor and found that it "consumed 15 times more energy in circulating the culture than it produced as biomass" (CER of 15). It has thus been proposed that microalgae cultivation in tubular PBRs requires more energy than in flat plate PBRs (Lehr and Posten 2009, Tredici and Materassi 1992, Hulatt and Thomas 2011).

Open ponds

In open ponds less energy is needed to cultivate algae but yields are also lower (Öschger and Posten 2012). According to calculations of Murphy and Allen (2011) energy for water management alone is with current technologies "approximately seven times greater than energy output in the form of biodiesel (this corresponds to an NER > 7) and more than double that contained within the entire algal biomass" (CER > 2).

Also in open ponds the energy demand is coupled with the quality of mixing and thus the productivity: turbulence (mixing) is provoked mainly on the bends and bends are also responsible for the head losses (Chiaramonti *et al.* 2013). Furthermore, productivities attained in small or short ponds (with many bends) cannot be extrapolated to large systems. Therefore, the main point of this dissertation also applies to microalgae cultivation in ponds. As Chiaramonti *et al.* (2013) emphasised, "… the energy demand alone cannot be considered as a sufficient parameter for the comparison of different cultivation systems, as the geometry, the materials, the water head of the channel and the velocity of the water significantly influence the performances and productivity."

6.7.5 Summary of comparison

Almost all NER results of previous LCA studies below or around one are due to the fact that energy demand and productivities are modelled (or cited) independently of each other. The independent and sometimes incomplete assumptions about cultivation energy and biomass productivity result in a low core energy ratio (CER, see also Figure 6.19) and/or a high PE (Table 6.11). Especially a combination of these data is unlikely. Other reasons for a NER < 1 are incomplete system boundaries.

Table 6.11: Summary of comparison of different LCA studies: NER, system boundaries, CER, and PE

		Flat plate PBRs				Other		
	This study	**Jorquera**	**Batan**	**Brentner**	**Tredici**	**Sills**	**Jonker**	**Razon**
NER	**1.8**	**0.2**	**0.9**	**1.1**	**1.2**	**0.6**	**1.6**	**2.0**
System boundaries		<<	<	=	<<	<	<	<
CER	0.3	0.2	0.07	0.03	0.3	0.01	0.3	n.a.
PE	1.8%	4.8%	2.8%	6.8%	2.3%	4.7%	3.3%	1.8%

=	equal to this study
<	lower than in this study (PE: higher than in this study)
<<	much lower than in this study (PE: much higher than in this study)
	combination of low CER and high PE

6.8 Limitations and suggestions for further work

Due to the limited availability of data and the scope and setup of this study, some questions remain open.

6.8.1 Limitations

The correlation between aeration rate and PE is derived from a limited number of data points. Especially at low aeration rates few data are available. This part of the curve is

however the more interesting since microalgae cultivation becomes more energy-efficient. The question is to what extent. It is for example likely that the culture completely breaks down below a certain aeration rate due to oxygen accumulation or other inhibitory effects, especially outdoors. The curve would then start later and increase more steeply in the beginning. Therefore, further measurements are required to evaluate the energy-efficiency of microalgae cultivation especially at low aeration rates and for outdoor cultivation. The determined correlation matches very well with the available data though.

Apart from the PBR design, the cultivated algae strain could influence the PE at a certain aeration rate. It might be possible that other microorganisms attain higher PE at the same aeration rate. This must be experimentally tested. The sensitivity of different algae strains to shear stress (Gudin and Chaumont 1991), oxygen, pH etc. can influence the correlation. Analyses of Hu *et al.* (1996) however showed that *Spirulina* attained higher volumetric productivities at the same experimental conditions compared to the cyanobacteria *Anabaena siamensis* and the eukaryotic *Monodus subterraneus* (2.25 , 1.9 and 1.7 g L^{-1} d^{-1} respectively). It can thus be expected that the correlation between *vvm* and PE determined from the small and fast growing *Spirulina* cultures is optimistic.

The correction factors for temperature control, night-time respiration and inoculation are constant. This does for example not reflect that the respiration rate depends on the culture temperature as well as on the previous growth rate (Wilhelm and Jakob 2011). The assumed data represent minimum expected values.

As a consequence of the missing data, uncertainties remain especially regarding the PE at low aeration rates and for outdoor cultivation. However, these do not challenge the general non-linear dependency between aeration rate and PE.

In the NER model several simplifications are made:

Energy demand for infrastructure and supply of resources is not completely considered. For example, the provision of water for cultivation might add to the energy demand, especially, when the water has to be transported over longer distances (Slade *et al.* 2011a). Similarly, the energy demand to provide CO_2 depends on the cultivation site (Skarka 2015).

In the fermentation process, analogue to the microalgae cultivation process, the energetic output depends on the energy input and other conditions. For example, a longer retention time in the digester increases the methane yield per kg biomass but also the heat and electricity demand to produce it (Mairet *et al.* 2011). Similarly, a pre-treatment of the algae cells can increase the biomethane output but consumes energy (Mussgnug *et al.* 2010). Furthermore, the biomethane yield depends on the microalgae strain and the composition of the biomass (Sialve *et al.* 2009). As the focus of this study lies on the microalgae cultivation process, these trade-offs are not modelled.

The simplifications in the NER model might rather lead to an underestimation of the energy demand for large-scale microalgae cultivation and thus of the NER.

6.8.2 Transferability of method

The correlation resulting from the experimental data of Hu and Richmond (1996) applies to microalgae cultivation (strictly speaking to cultivation of cyanobacteria *Spirulina*) in aerated photobioreactors only. However, the correlation is based on mechanisms which apply to all PBRs and algae (as explained in chapter 3). Therefore, also the general insight that it costs more energy to harvest all sunlight efficiently than only a share of it, can be transferred to other systems.

With the method developed in this thesis, the relation between operation energy and PE can be quantified also for other systems. To do this, a systematic experimental setup is required which singles out certain effects on the PE. All relevant biological and technical data to calculate the energy demand and the PE must be measured and documented. These include not only the volumetric productivity, but also the energy content of microalgae, the culture volume per area, the pressure drop etc. Moreover, the energy demand for each device that provides good growth conditions must be considered. Once this is ensured, the subsequent approach can be followed:

- The PE can be calculated from the measured data with (12) or (29) and plotted (for different light intensities) over the energy demand or a characteristic parameter which describes it. A curve can be fitted to the data (see 4.1).
- The correlation between energy demand and PE can be compared to and validated with further published data if available. The effect of modifications in the reactor design can be tested (see 4.2).
- Correction factors for outdoor cultivation can be derived according to 4.3. Ideally, the cultivation system is tested outdoors and for long-term conditions.

The NER can then be calculated based on the derived correlation between energy demand and PE. The NER must include all energetically relevant processes, e.g. for the reactor material since this can contribute largely to the energy demand (especially if materials are used to distribute light, see also 6.4.4). In case no detailed data are available, the 'areal energy balance' and 'core energy ratio' as defined in section 4.1.2 can be calculated from measured data as a first approximation of the NER.

By analysing the relation between input and output parameters (rather than focussing on one of these two aspects) further suggestions to improve reactor design or microalgae can be investigated. For example, Morweiser *et al.* (2010) suggest uncoupling mixing from gas supply via gassing by membranes in an ultra-thin and low PBR. This saves energy for the formation of gas bubbles but requires additional energy for mixing to ensure high mass transfer rates; more material per area is also required. It can also be evaluated, whether the excretion of small carbohydrates by algae as investigated by Günther *et al.* (2012) improves the relation between energy demand and biomass output. This approach avoids a large part of the growth-limiting dark reactions and could also save harvesting energy since the same cells could be used for a longer time period. However, high mass transfer rates to ensure carbon fixation are still required.

7 Conclusions and outlook

7.1 Conclusions

In this dissertation, the net energy ratio (NER) of microalgae biofuels production is calculated for the first time by reflecting the correlation between operation energy and biomass productivity. While dependencies between these parameters and the underlying mechanisms have long been known, their consequences have never been considered to calculate the NER for microalgae biofuels production.

The approach developed in this thesis consequently helps to obtain a deeper understanding of the trade-offs in microalgae cultivation and enables to predict more reliable NERs of microalgae biofuels production.

As microalgae cultivation method, aerated flat plate photobioreactors are analysed since these systems have been proposed for outdoor cultivation and are target of current research. Therefore, also most comprehensive data are available for these systems. As biofuel, biomethane production was exemplarily investigated since it requires low production energy.

The 'core model' for calculating the biomass productivity based on the operation energy and the light intensity is developed as follows: published data of laboratory experiments are analysed which show the dependencies between aeration rate, light intensity and photosynthetic efficiency (PE). A curve is fitted to the data and validated based on further experimental data. Correction factors are derived to reflect environmental conditions outdoors. To consider potential developments, it is assumed that algae use high light intensities as efficiently as low.

The net energy ratio (NER) of microalgae biomethane production results from the data of the core model and further definitions derived from literature, for example regarding improved reactor design and energy for further upstream and downstream processes.

In the following, important findings are summarised and the research questions are answered.

This study shows that **operation energy and biomass productivity** – the crucial parameters to determine the NER – are not only linked, but **related non-linearly**. When the produced biomass increases, the energy to produce it increases disproportionately. This is due to the fundamental limitations of microalgae growth: The metabolic dark reactions in microalgae are slow and thus each cell can only use a limited amount of sunlight at a time. Thus, to harvest all available sunlight, many algae must 'share' the light. Since many algae inhibit each other, it becomes increasingly difficult to provide optimal growth conditions for each cell. This effect can be observed at any light intensity.

As a consequence of the non-linear relation between operation energy and productivity, the **NER has an optimum**; it cannot fall below a certain value: Without operation energy,

no biomass is produced but energy is already required for infrastructure. With increasing aeration rate, more biomass is produced – though less energy-efficiently. Therefore, the NER optimum tends not to be at the highest biomass productivity but rather **at low productivities**. The lowest possible NER depends on many other parameters, such as the energy for infrastructure, the efficiency of energy supply, but also on climate conditions. These parameters interact with each other.

From the non-linear relation between operation energy and bioenergy output results also, that **the effect of parameters on the NER depends on the aeration rate**: improvements related to the energy for infrastructure have a larger effect on the NER at low aeration rates whereas improvements related to the operation energy (e.g. reduced pressure drop) have a larger effect on the NER at high aeration rates. The optimal NER depends also on the interaction of climate conditions and aeration rate. For example, at high aeration rates, the NER is lowest when algae are cultivated only during a short time during the year.

Regarding the NER for biomethane production in aerated flat plate PBRs, this dissertation shows that the optimal **NER remained above 1** in all cases – although expected technology improvement is considered. An optimal NER of around 1.8 is calculated at an aeration rate of 0.2 vvm, the corresponding operation power is 54 W m^{-3} or 2.2 W m^{-2} and the corresponding biomass productivity is 50 t ha^{-1} y^{-1}.

Assumptions and results of **seven other LCA studies** are analysed thoroughly. The analyses show that previous LCAs resulted in a NER below or close to one mainly when the biomass productivity was modelled or cited independently of the operation energy. Other reasons of a NER <1 are incomplete system boundaries.

Although this dissertation focusses on cultivation of microalgae in aerated flat plate photobioreactors, the **correlation between operation energy and productivity** is based on **mechanisms** which **apply to all cultivation systems and algae**. As a consequence, it is not possible to considerably increase the productivity and decrease the energy demand at the same time. This insight essentially affects the potential development of microalgae biofuel production. Above that, the findings of this study enable to cultivate microalgae more energy-efficiently which is a benefit for any application of microalgae biomass.

7.2 Outlook

This study investigated the NER specifically for biomethane production from microalgae cultivated in generic aerated flat plate PBRs with the discussed limitations. It can be extended in several aspects. Especially to compare different locations, it would be worthwhile analysing trade-offs between biomass productivities and the energy and resource demand for light and temperature management in greater detail. To do this, the energy demand for cooling or heating can be modelled based on climate data and different reactor configurations. Furthermore, the energy demand to supply important resources like water and nutrients can be modelled in detail based on the distance of the required resources to potential cultivation sites.

Results of this study imply that future research should focus on achieving a good balance between operation energy and biomass productivity output rather than achieving the maximum possible biomass productivity (or even improving it). The best possible NER for other cultivation systems can be determined by applying the method developed in this study.

Relevant data to further determine correlations between energy demand and biomass energy output could be gathered in the current large EU-funded microalgae biofuels projects (see Annex, Table A.5).

Finally, the systematic approach developed in this thesis to correlate important model parameters based on their underlying scientific mechanisms can also be used to evaluate the potential development of other technologies.

"[T]he best material model for a cat is another, or preferably the same cat."

(Rosenblueth and Wiener 1945)

Annex

A.1 Irradiation and temperature data

This section documents the background climate data of Karlsruhe and Madrid of the year 2012 as provided by (Huld 2013) in greater detail. Table A.1 gives an example of irradiation data (hourly resolution) and temperature data (3-hourly resolution). Figure A.1 shows average sunlight hours per day for each month. Figure A.2 displays the average irradiation per month in W m^{-2}. Figure A.3 and Figure A.4 illustrate the percentage of sunlight hours above 500 µmol m^{-2} s^{-1} and 1800 µmol m^{-2} s^{-1} in each cultivation month for Karlsruhe and Madrid respectively.

Table A.1: Example of irradiation and temperature data for Karlsruhe and Madrid (01.03.2012)

01.03.2012	I_0 [W m^{-2}]		T [°C]	
Hour	Karlsruhe	Madrid	Karlsruhe	Madrid
00:45	0	0	6.62	9.17
01:45	0	0	5.72	6.13
02:45	0	0	5.72	6.13
03:45	0	0	5.72	6.13
04:45	0	0	4.61	5.14
05:45	0	0	4.61	5.14
06:45	65	2	4.61	5.14
07:45	206	159	3.44	3.53
08:45	341	346	3.44	3.53
09:45	447	511	3.44	3.53
10:45	507	633	5.76	8.89
11:45	518	698	5.76	8.89
12:45	478	700	5.76	8.89
13:45	390	639	10.96	14.61
14:45	266	521	10.96	14.61
15:45	124	358	10.96	14.61
16:45	5	171	12.9	16.01
17:45	0	7	12.9	16.01
18:45	0	0	12.9	16.01
19:45	0	0	9.17	12.34
20:45	0	0	9.17	12.34
21:45	0	0	9.17	12.34
22:45	0	0	6.83	9.00
23:45	0	0	6.83	9.00

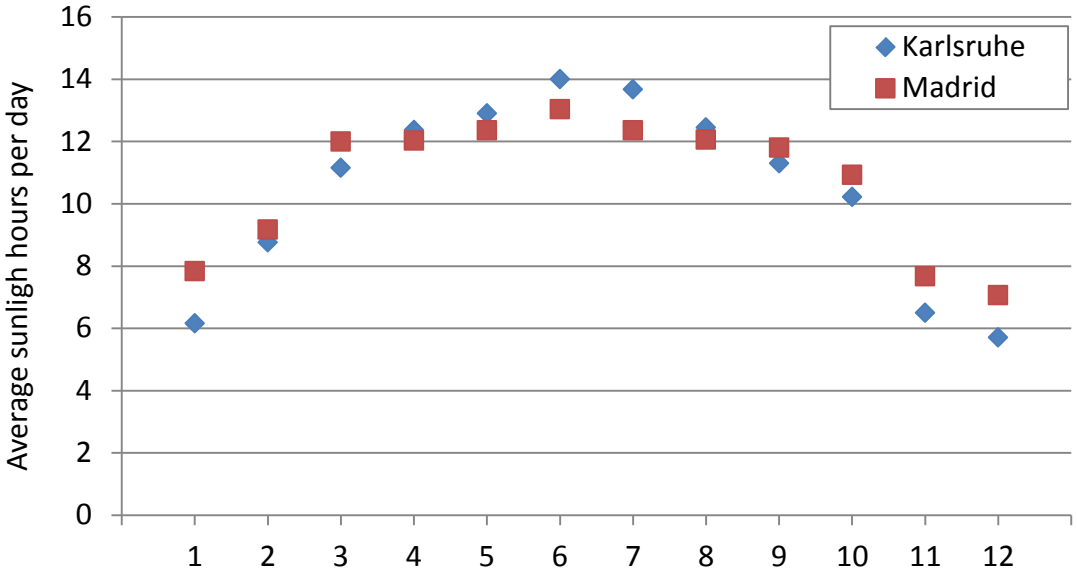


Figure A.1: Average sunlight hours per day (monthly) for Karlsruhe and Madrid 2012

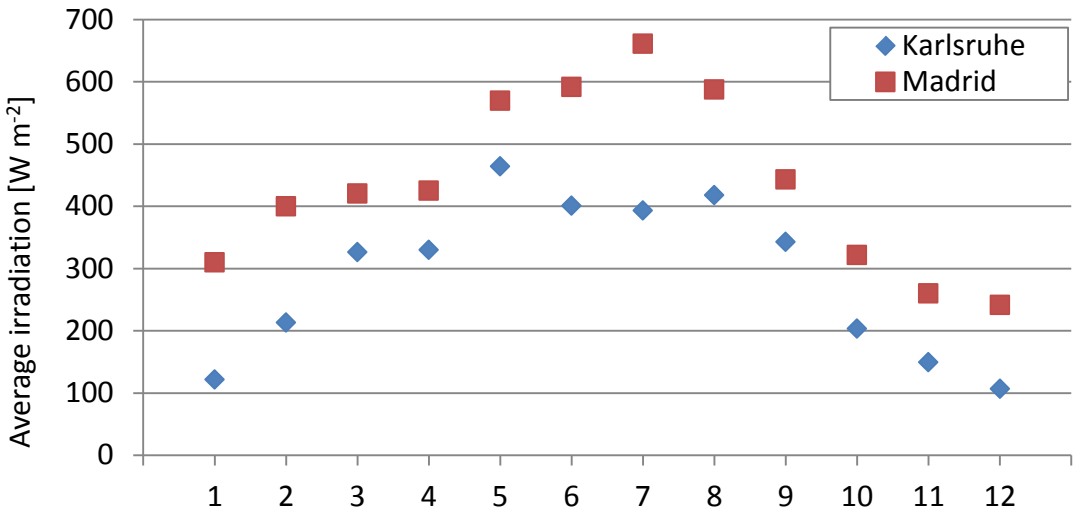


Figure A.2: Average irradiation per month (daylight hours only) for Karlsruhe and Madrid 2012

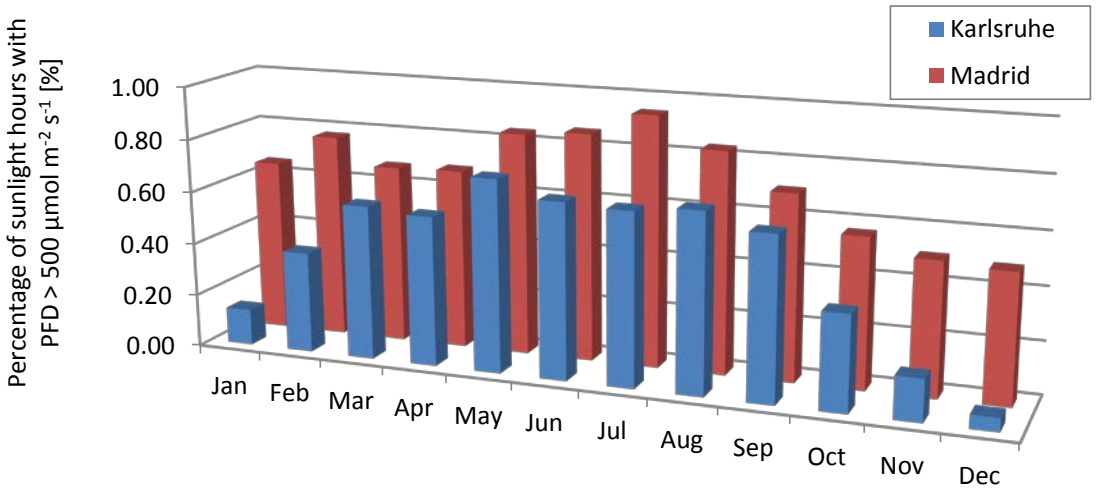


Figure A.3: Solar irradiation hours above 500 µmol m^{-2} s^{-1} (240 W m^{-2}) per month [%] for Karlsruhe and Madrid 2012

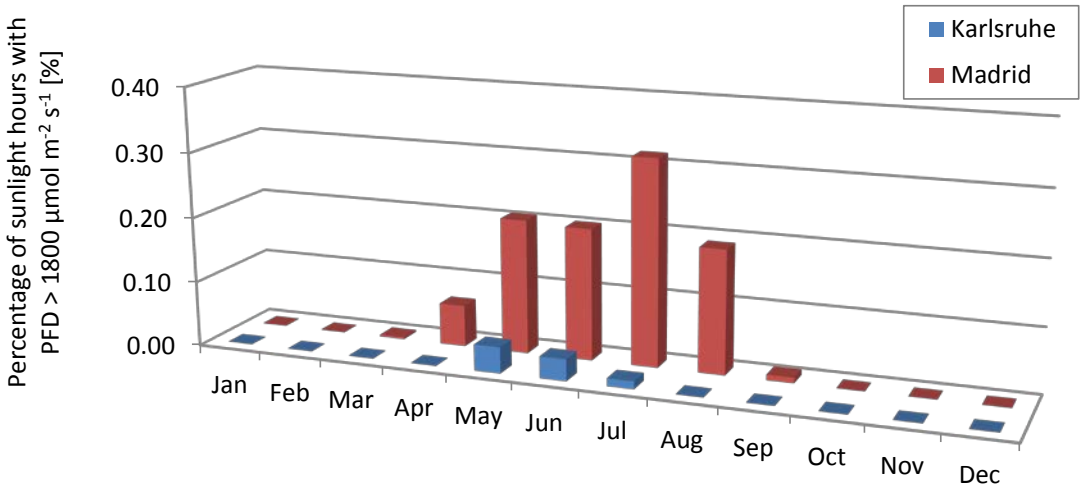


Figure A.4: Solar irradiation hours above 1800 µmol m^{-2} s^{-1} (870 W m^{-2}) per month [%] for Karlsruhe and Madrid 2012

A.2 Ecoinvent data

The following tables show the processes of the ecoinvent database (v3.01) used to calculate the CED (Table A.2) and the results of the CED calculation in umberto (NXT LCA 7.1) (Table A.3). Table A.4 shows the CED of selected potential reactor materials.

Table A.2: Ecoinvent processes (full name) used to model the CED

Flow	Name (ecoinvent database v3.01)	Unit
Heat	Heat production, natural gas, at boiler condensing modulating >100kW [Europe without Switzerland]	MJ
Nitrogen	Ammonium sulfate production [RER]	kg
Phosphorous	Ammonium nitrate phosphate production [RER]	kg
Pipeline	Pipeline construction, natural gas, high pressure distribution network [Europe without Switzerland]	km
PETG	Polyethylene terephthalate production, granulate, bottle grade [RER]	kg

Table A.3: CED of energetic relevant flows

	Heat	Nitrogen (as N)	Phosphorous (as P_2O_5)	Pipeline	PETG
Resource	**MJ**	**kg**	**kg**	**km**	**kg**
Coal, brown, in ground	0.01	0.52	0.74	$1.2 \cdot 10^4$	1.1
Coal, hard, unspecified, in ground	0.02	5.69	2.45	$2.7 \cdot 10^5$	9.3
Gas, mine, off-gas, process, coal mining	0.00	0.12	0.05	$5.3 \cdot 10^3$	0.17
Gas, natural, in ground	0.96	16.30	6.58	$3.1 \cdot 10^5$	29.15
Oil, crude, in ground	0.17	4.21	6.44	$4.7 \cdot 10^5$	35.3
Peat, in ground	0.00	0.01	0.01	$2.0 \cdot 10^2$	0.02
Uranium, in ground	0.02	1.62	2.18	$5.5 \cdot 10^4$	4.9
Total CED $unit^{-1}$	1.18	28.5	18.5	$1.14 \cdot 10^6$	80.0

Table A.4: CED of different photobioreactor materials

Material	CED [MJeq kg^{-1}]
Glass tube production, borosilicate	33
Polycarbonate production	117
Polyethylene terephthalate, granulate, bottle grade	80
Polyethylene production, low density, granulate	78

A.3 Algae projects

Table A.5 provides links of current and previous microalgae biofuels projects.

Table A.5: Links and further information of current and previous large algae biofuels projects

Current large algae biofuels projects (EU-funded)	**Links, comments, literature**
All-gas	www.all-gas.eu
Biofat	www.biofatproject.eu
InteSusAl	www.intesusal-algae.eu
EnAlgae	www.enalgae.eu; (Rösch *et al.* 2014)
Previous large algae biofuels projects	
Aquafuels project (EU)	www.aquafuels.eu Final report: n.a.; LCA results: (Slade *et al.* 2011b),
Aquatic species programme (US)	Link n.a.; Final report: National Renewable Energy Laboratory (NREL) (1998)

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Microalgae could be used as a feedstock for ‘third generation’ biofuels since their cultivation does not require arable land. However, a crucial problem is that, currently, much more energy is needed to produce the microalgae biomass and convert it into fuels than the biofuel finally contains. Can technological and biological developments overcome this hurdle?
This dissertation approaches this question by investigating a correlation not yet considered in the calculation of the energy balance: the dependency of the biomass yield on the cultivation energy.

Annika Weiss

ENERGY BALANCE OF MICROALGAE BIOFUELS