universität wien

DIPLOMARBEIT

Titel der Diplomarbeit

„Physics of the urban production of algae in photo-bio reactors for the utilization in vertical farms “

Verfasser

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angestrebter akademischer Grad

Magister (Mag.)

Wien, 2012

Studienkennzahl lt. Studienblatt:	A 411
Studienrichtung lt. Studienblatt:	Physik
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Acknowledgments

TECHNISCHE UNIVERSITÄT WIEN

VIENNA UNIVERSITY OF TECHNOLOGY

universität wien

Energy Economics Group

DIPLOMA THESIS

Titel

„Physics of the urban production of algae in photo-bio reactors for the utilization in vertical farms “

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Thank you for „writing“ this thesis with me!

Thank you Lukas Kranzl for your positiv input.
Special thanks to Prof. Haas and Prof. Rumpf for making this cooperation possible.
Thank you Sonnleitner Andrea and Dina Bacovsky from Bioenergy2020 for an entire library of literature!
Thanks also to Vincent Garcia for the LaTeX template.

Abstract

§ 0.1 English

Todays agricultural food production highly depends on the availability of non-renewable resources like crude oil, natural gas and phosphor rocks. Tomorrow's food security can only be ensured by reducing this dependency. *There are open questions concerning the methods that can be used for the production of renewable sources in order to achieve this goal. Is it technically and economically feasible, for instance, to produce micro-algal fertilizer in photo-bio reactors to recycle N and P from waste water streams? Is this furthermore possible by avoiding the combustion of non-renewable energies to become energy self-sufficient?*

Relevant examples from literature will be used to investigate the micro-algal potential to extract nutrients from urban waste water streams for the re-injection into the food chain of the population. The production of algae and heat will be described in a bio-physical way to calculate the mass- and energy flux in photo-bio reactors, attached to walls of buildings in Vienna. It will be suggested to decompose the generated bio material through anaerobic digestion to increase the N- and P share on one hand and to produce methane as an energy carrier on the other hand. The calculation model will be used to estimate the costs of producing a micro-algal fertilizer in Vienna. Furthermore a possible utilization of the generated fertilizer in vertical farms will be discussed.

About $271t$ micro algae per year could be produced on a $100m * 100m$ wall in Vienna. The combustion of the produced biogas could meet the entire heat-

and electrical-energy demand of the production process. By demonstrating the technical feasibility of every single part of the energy self-sufficient production chain, the technical feasibility of the whole concept is ensured. The costs of this product, however, would be nine times higher than the costs of commercial fertilizer. The bio-refinery in question still has a great potential when it comes to saving a high amount of non-renewable resources, thus making it an attractive alternative to the exclusive use of biomaterial as an energy carrier. This can be further shown by comparing the sunlight irradiation on a photo-bio reactor with the calorific value of the produced micro algae: This calculation yields an energy conversion efficiency of about 4% which could be surpassed by the electricity production of every available photovoltaic system.

§ 0.2 Deutsch

Die heutige Lebensmittelindustrie verlangt nach einer großen Menge nicht erneuerbarer Ressourcen wie Rohöl, Erdgas und Phosphatgestein. Um die Ernährungssicherheit der kommenden Generationen zu garantieren ist es notwendig diese Abhängigkeiten zu minimieren. *Dabei stellen sich die Fragen, welche Technologien zur Gewinnung von erneuerbaren Energieträgern dafür genutzt werden könnten. Ist es zum Beispiel großtechnisch und ökonomisch möglich Algendünger in Photobioreaktoren zu produzieren und so N und P aus dem Abwasser zu recyceln? Ist es des Weiteren möglich diesen Prozess energieautark zu gestalten um so die Verwendung von nicht erneuerbaren Energieträgern zu vermeiden?*

Anhand von Beispielen aus der Literatur untersucht diese Arbeit das Potential von Mikroalgen, städtischem Abwasser Nährstoffe zu entziehen um diese wieder in den urbanen Lebensmittelkreislauf zurück zu führen. Eine biophysikalische Beschreibung der Algen- und Hitzeproduktion in Photobioreaktoren an Wiener Hausfassaden dient zur Berechnung des Masse- und Energieflusses. Die Verfaulung der produzierten Biomasse wird vorgeschlagen um deren Düngereffizienz zu steigern und um gleichzeitig CH_4 als Energieträger zu gewinnen. Die Ergebnisse des Rechenmodells werden zur Abschätzung der Kosten für eine Algendüngemittelproduktion in Wien verwendet. Der mögliche Einsatz des Biodüngers in vertikalen Farmen wird

diskutiert.

In Wien könnten an einer $100m*100m$ Hausfassade jedes Jahr $271t$ Mikroalgen wachsen. Die Verbrennung des produzierten Biogases könnte dabei den Heiz- und Strombedarf decken. Da die einzelnen Glieder dieser energieautarken Prozesskette bereits existieren, ist diese Art der Biodüngerproduktion mit Hilfe von $PBRs$ technisch realisierbar. Das Produkt wäre jedoch selbst nach optimistischer Abschätzung neun mal so teuer wie kommerzieller Dünger. Dieses Konzept einer Bioraffinerie birgt jedoch ein enormes Einsparungspotenzial für Rohöl, Erdgas und Phosphorgestein und ist damit der alleinigen Nutzung von Biomasse als Energieträger einen Schritt voraus. Bestätigt wird das durch die Berechnung des Wirkungsgrades für die Umwandlung von Sonneneinstrahlung zu Algenbiomasse für eine direkte Verbrennung: Mit knapp 4% liegt dieser weit unter dem moderner Photovoltaikanlagen für die Stromproduktion.

- Chapter 1 -

Introduction

§ 1.1 Brief history of fertilizer utilization

About 12,000 years ago, in the *neolithic revolution* the way of human living changed more and more from a hunting- and gathering- into an agriculture- and settlement-kind of lifestyle [Flannery, 1973, p.276]. By observing acreage and crop yield, different cultivation methods for edible plants have been developed and optimized over time. Even though food security could largely increase for a larger number of consumers because of technical and organizational progress, most questions about the biological processes that are important for plant growth and thus for agriculture stayed unanswered for a long time. One of these questions gives an ancient controversy about the source of nutrients which are used by plants for the accumulation of mass: Is it the dead organic material that is rotted to humus that provides the necessary matter for plant growth or is it possible, that minerals unrelated to any living thing are in charge of this business?

This dispute was mainly settled in the 19*th* century by three German scientists: *Albrecht Thaer* (1752-1828), a former medic, developed the humus theory and can be seen as the founder of *phytotrophology* - the science of plant nutrition. His own student *Carl Sprengel* (1787-1859) disproved this theory around 1826 by showing that the fertilizing effect of humus relies in its embodied mineral nutrient content. *Justus von Liebig* (1803-1873) finally gave the mineral theory its scientific acceptance. He composed several fertil-

izers by using the knowledge of his own scientific field: Chemistry. With his profound systematical investigations *Liebig* stands for the beginning of *agricultural chemistry*. He still had to fight a long time against the supporters of humus theory who thought that only organic materials can assist plant growth. This fight reenforced his ambitions to bring his theses to perfection. While he initially talked about the need of an artificial addition of phosphorus (P) and potassium (K) to the farmland, he had to admit at a later date that also nitrogen-scarcity (N) can be the reason for a poor harvest.

The need for N was proven through the greater success of *Guano* than *Liebig's* patented fertilizers. *Guano* is a natural resource containing an average amount of 15% N, 9% equivalent phosphoric acid and 3% potassium. It can be found in dry climates and consists of bird and bat feces. Even though ancient cultures in South America, especially in Peru, knew about its fertilizing value earlier, *Guano* first became important for Europe in the middle of the $19th$ century. Its import displaced several professional guilds and industries that where in charge of collecting and **recycling** resources for the fertilizer production and also the production of explosives.

The robber economy of the Europeans led to a climax denoted as "*peak-Guano*" in the early $20th$ century. Two important developments drew off attention from this resource before its supplies could have been exhausted totally: The production of industrial *superphosphate fertilizer* out of phosphor rocks (PR) mined in Maraca plus the invention by *Fritz Haber* and *Carl Bosch* to synthesize ammonia out of air. Although both processes asked for a high amount of electrical and thermal energy they appeared to give inexhaustible sources for the production of N- and P-fertilizer. This made it possible that world population could grow to over seven billion people living on Earth today.

§ 1.2 Resources used in today's agriculture

It is a sad fact that nearly one eighth of the world population do not have enough to eat [FAO, 2010, p.4]. It is important to note this. Although this topic will not be further discussed in this work, it should always be kept in mind. The food security of the industrialized countries highly de-

pends on three non-renewable resources: Crude oil, methane (CH_4) and *PRs*. With about $95\frac{EJ}{year}$ the food sector accounts for around 30% of the world's total energy consumption [FAO, 2011a, p.11]. More than one per cent is used solely for the production and distribution of N-,P- and K-fertilizers [Dawson and Hilton, 2011, p.17]. The burning of worldwide reserves of crude oil and natural gas provides most of this energy. A simple shift to renewable energy sources is necessary but would not entirely free food production from the dependence on fossil fuels.

The *Haber-Bosch process* for example was developed at the beginning of the $20th$ century and was improved over years reaching a today's energy consumption close to the theoretical minimum [Appl, 1997, p.25]. The formation of ammonia (NH_3) requires hydrogen (H_2). H_2*-stripping* out of CH_4 is the best available technology, making this resource highly important for fertilizer industries. [Dawson and Hilton, 2011, p.21] estimate that if all reserves of natural gas would only be used for ammonia production, the demand could be satisfied for thousands of years.

Furthermore oil refinery is the basis of many different economic sections. Amongst others it is the main producer of sulphur. Sulphur is further burned to get sulphur dioxide. Sulphur dioxide is water-soluble and produces sulphuric acid, which is "...the 'acid of choice' for the dissolution of *PR*..." [Dawson and Hilton, 2011, p.19]. Thus it becomes evident, that there is a double dependence on crude oil: It is needed for the extraction of sulphur as well as for the burning of the latter. [FAO, 2008, p.35] gives a forecast for phosphate fertilizer supply for 2011/2012 of about $45 * 10^6$ tonnes P_2O_5. The origin of this phosphate is mainly *PR*, thus making world reserves of this mineral highly interesting. About 42% of these reserves are assumed to lie under Moroccan territory [Cohen, 2007]. Related to the upcoming oil peak a so-called *peak phosphorus* is expected in the next decades [White and Cordell, 2009]. Better technologies to dissolve P_2O_5 out of the residues saved from todays *PR*-mining could prolong the reserves' lifespan but would not change the fact that this resource is finite. According to [Cohen, 2007] and [Dawson and Hilton, 2011, p.18] a consumption rate related to today's lifestyle could only be ensured for the next 100-400 years.

Another large part of the mentioned 30% of the world's total energy consumption is used for the transportation, processing, retailing and production of food [FAO, 2011a, S.49]. Energy is mainly provided by fossil fuels. Combined with CH_4 released into the atmosphere from livestock farming, food production contributes a large share in global green house gas (GHG)-emissions. Growing consumption increases the amount of emissions as well as the land and water used for food production. In 2008 about 11% of the world's ground surface was used for crop production and 70% of all water withdrawn from aquifers, streams and lakes were used for irrigation. [FAO, 2011c, p.13]. Several concepts to work against these trends have been developed. [FAO, 2011a] predicts that a change to diets including "...the use of more fresh and local foods..." is indispensable. This would also reduce food losses and the demand for energy, water and land. In fact one third of the food is lost during production, processing and distribution today [FAO, 2011b, p.4]. This does not take into account that only a small share of used fertilizer can be found in food meant for the consumer. N and P are also lost at the prae-harvesting stage through erosion into lakes and rivers and finally into the ocean thus causing *eutrophication* changing ecological systems.

Alternative methods for the production of high quantities of food are quite common in less developed countries and strictly forbidden in Europe because of their destructive impacts on nature and consumers. One is known as the technique of *slash and burn*: Large parts of forests are slashed every year around the world before the dry seasons. In times with less rainfall the wood can dry and is burned afterwards to release its nutrients into the subjacent soil. This gives a short-term boost of soil fertility which is exhausted after a few crops because of high erosions. When harvest turns out badly the farmer moves to another part of the forest to repeat the procedure, leaving behind land which cannot be reafforested easily. The negative impact on ecosystems and the often-occurring non reversibility of the soil condition is well known and is still caused by between three and seven per cent of the world population who use this technique [Cornell, 2011], most often because of the lack of other possibilities.

Another common method is the direct use of human feces from waste wa-

ter streams. According to the World Health Organization (*WHO*, cited by [Eichenseher, 2010]) nearly $700 * 10^6$ people are reliant on a food supply, produced using *human fecal fertilizers*, triggering diarrhoea related diseases such as cholera killing $2.2*10^6$ every year. Although this is yet another proof of bad conditions in these countries, *recycling* of nutrients from sewage could be an option for the rest of the world as well. The International Water Management Institute (*IWMI*) argue that "...the social and economic benefits of using untreated human waste to grow food outweigh the health risks." The "...dangers can be addressed with farmer and consumer education..." (*IWMI*, cited in [Eichenseher, 2010]). The author of this thesis suggests that an advanced technology for the recycling of essential elements could reduce the first world's dependence on the fertilizer industry and in that context on fossil fuels and *PRs*.

§ 1.3 Concept for the urban food supply chain of tomorrow

The world population prospect of the UN's department of economic and social affairs (*ESA*) released different growth forecasts for the upcoming decades. Their overall conclusion is that the number of people living on this planet will increase until 2050 to a value between 8 and 12 billion [ESA, 2010]. About 9 billion people would need a 70%-increase in food supply compared to the 2005-07 period [FAO, 2009, p.2]. Looking at the previous paragraphs shows that a concept developed to meet this food demand has to consider also how to save water, land and non-renewable resources at once:

[Despommier, 2010] discusses the idea of a fully controlled agriculture. In so-called **vertical farms**, food could be produced minimizing cultivated area and shifting production into town at the same time. Many models have been developed in regards to the architecture and function of such farms. All of them are following the same guidelines: Multi-storeyed buildings hosting different cultivation methods should produce the nutrient demand of the citizens living within a short radius around the location of production. Different well-known techniques could ensure a year-round harvest

in perfectly controlled environments. [Despommier, 2010, p.162ff] predicts that *pythotrophology* is advanced enough to create healthy food in an artificial environment. Some of the numerous advantages are listed below (after [Despommier, 2010, p.145ff]):

- Year-round crop production
- No weather-related crop failures
- Use of 70-95% less water
- Greatly reduced food miles
- More control over food safety and security

If demand is covered by this kind of "indoor" agriculture, conventional farming could be abandoned, thus allowing the ecosystems to recover. After shrubs and bushes have regained territory, growing trees would bind atmosphere's carbon dioxide (CO_2) building a serious opponent against *GHG*-emissions. Another advantage would consist in the low consumption of N- and P-fertilizers because of the erosion prevention. How to provide vertical farms with the still needed amount of N and P without the use of non-renewable resources will be further discussed:

As mentioned in the last paragraph, recycling of essential elements (in this work focusing on N and P) out of urban wastewater will be necessary in the future. **Algae** have been the object of research for the purpose of recycling since the middle of the previous century [Golueke and Oswald, 1963]. Because some algal strains also generate a high amount of lipids, the production of algae showed promises for the competition against petroleum industries. Looking at the undesired effects of eutrophication in water bodies contaminated by sewage, the need for a controlled combination of wastewater treatment and algal production leaps to the eye. This thesis wants to give a thought-provoking impulse how to utilize the product of this artificial eutrophication process. About 60 years after *M.K. Hubbert* defined the meaningful expression of peak oil [Hubbert, 1956], many scientists make an effort for two different achievements: One group tries to substitute fossil fuels and the other optimizes processes to minimize energy demand. Using algae as fertilizer which contain N and P from urban wastewater could help

to save that one percent of world's energy demand consumed by the fertilizer industry today (paragraph 1.2). The prior condition for a process concerning this efficiency enhancement would be a minimum use of non-renewable resources, as well as a minimum use of land and water.

Different methods for the cultivation of algae have been developed in the last decades. Most of them rely rather on the production of micro algae than macro algae such as seaweed. Depending on the strain, micro-algal growth can be accomplished by *photoautotrophic*, *heterotrophic* or *mixotrophic* cultivation. While in *heterotrophic* cultivation, algae are fed a carbon source, such as sugar, and grow without light, *photoautotrophic* cultivation strategies use large surfaces to capture photons for photosynthetic plant metabolism [Rittmann and McCarty, 2001, p.29]. As the name says *mixotrophic* cultivation uses both, *photoautotrophic* and *heterotrophic* techniques. For large scale applications only solar radiation (compared to artificial lighting) is considered feasible as a photon source for *photoautotrophic cultivation*. Literature gives plenty of data about this method of algal production in several systems including *photobioreactors*(*PBR's*), *open pond-* and *race way-*systems. In contrast to *immobilized cultures*, where algae grow on a thin film [Zhang et al., 2008] these systems contain high amounts of water in which micro algae can move and are mobile. Medium with sufficient sunlight for *photoautotrophic* algal growth is called photoactive volume (PAV). Therefore PAV directly stands for the system's sunlight utilization efficiency. Because of their architecture highest $PAVs$ mixed with the smallest ground surface area possible can be found in modern $PBRs$:

A young Austrian company called *Ecoduna* predicts that their specially designed vertical flat plate *photobioreactors* can offer 100% of PAV
[Mohr and Emminger, 2012]. In their system micro algae sediment down a long thin transparent pipe to reach the entrance on the bottom of the next pipe where CO_2 and air is pumped in. The rising gas carries along the organic particles to the top where they can access the next neighboring sedimentation tube. Many of these pipes together form a flat transparent plate hence it is called a flat plate PBR. Because algae need carbon dioxide for their metabolism this method kills two birds with one stone: To avoid that micro algae bind together, which would negatively affect PAV and

functionality of the reactor, algae have to stay mobile while accumulating CO_2. Twelve flat plates are fixed together and their surface normal is always adjusted with 90° to the incident sunlight. This ensures an uniformly distributed photon flux inside the *PAV*, avoiding too high sunlight intensities which could harm micro-algal growth. Harvesting and production should be carried out in the same velocity. With this continuos cultivation method, micro-algal concentration can be held constant in the reactor ensuring the highest production rate possible.

Next to sunlight and CO_2 micro algae need N, P and other trace elements to grow. In the rest of this work these essential elements will be called nutrients. As mentioned above and acknowledged by [Hingsamer et al., 2011], these nutrients should be delivered from wastewater streams not only for ecological but also for economical reasons. The produced biomass can further be converted to fertilizer [Collet et al., 2011, p.210]. If urban sewage is used for this process and the product is fed into *vertical farms*, a closed city-internal nutrient cycle could be achieved. Figure 1.1 shows the suggested system and its boundary.

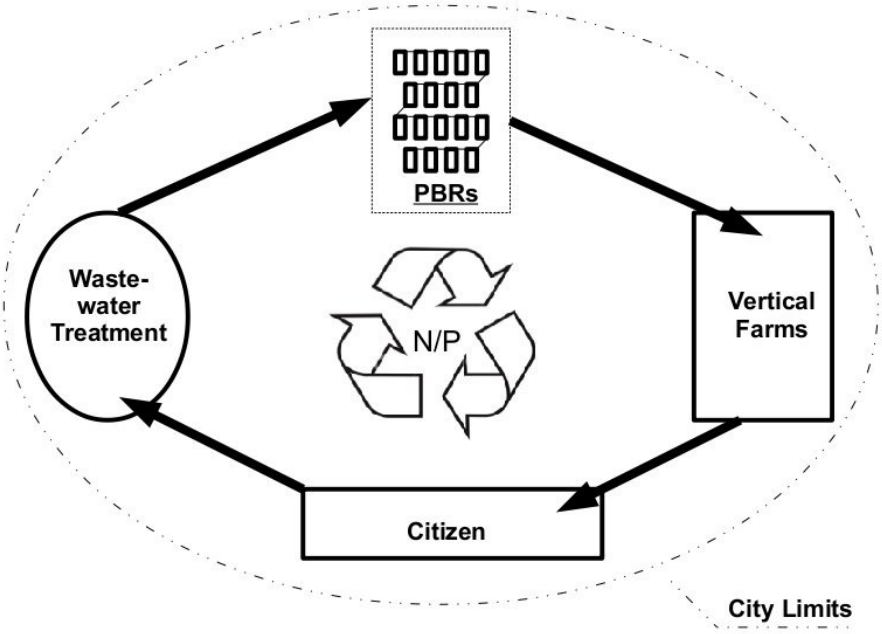

Figure 1.1: *The urban nutrient cycle*

- Chapter 2 -

Ecological Stoichiometry

To calculate the productivity of *PBRs* it is necessary to illuminate the process of algal growth. Therefore several principles have to be investigated. Many of them are obvious and well known, yet it is the formulation of them that make these laws into powerful tools:

Plants, animals and humans mostly are built up of carbon (C), oxygen (O) and H. The composition differs from species to species and so does the amount of trace elements. If the elemental compositions of different individuals of one species are compared, a common proportion can be found. Since life obeys this law of constant compositions it is useful to look at micro algae expressed by a fixed stoichiometry. [Park et al., 2011, p.39] mentioned a typical relation between the main elements of micro-algal biomass as follows:

$$C_{106}H_{181}O_{45}N_{16}P_1 \tag{2.1}$$

The relation of N to P is $16:1$ on an atomic scale. This proportion has a greater meaning than one would primarily expect. *Alfred C. Redfield* (1890-1983), an oceanographer from Harvard found the same relation empirically by analyzing dissolved P-and N- contents in ocean water, sampled from different regions of this planet [Redfield, 1958]. His theory called the pythoplankton into account for this relation. Pythoplankton like micro algae form the bottom of the oceanic food chain. Their elemental composition determines an entire mass flow of the largest habitat based on a globally constant proportion that did not change much over time.

This so-called *Redfield-ratio* ($N : P = 16 : 1$) is a molar relation. To use this relation for any kind of mass flow calculation modification is necessary. Through multiplication with the atomic masses of the compounds a mass ratio of $N : P = 7 : 1$ is achieved. The same modification is furthermore applied on the H-, O- and C- content given by formula 2.1. This produces an average mass distribution for micro algae that will be used in the following chapters. Table 2.1 lists the molar relation, the atomic masses of the compounds and the resulting mass relation.

Following the law of conservation of matter this mass has to be accumulated from the environment - either algae are grown in the sea or cultured in *PBRs*. Because micro algae "are what they eat", their reproduction is determined by the following principle: *Liebig's law of the minimum* defines the scarcest nutrient as the limiting one, not allowing biomass to grow further and neither change the ratio. Energy for the metabolism is provided through photosynthesis. This is shown in formula 2.2 by the last part where Planck's constant (h in [J*s]) is multiplied by the frequency of the light (ν in $[\frac{1}{s}]$). This leads to an energy content through *Einstein's equation*. The variable x gives the number of photons that are used for the photosynthetic process. As it will be discussed later on, not every frequency found in sunlight is suited to play a role in micro-algal reproduction.

Table 2.1: *Mass distribution*

element	C	H	O	N	P	total
atomic mass $[\frac{g}{mol}]$	12	1	16	14	31	
mols in algae	106	181	45	16	1	349
% of mass	52.4	7.5	29.6	9.2	1.3	100

[Narasimhan, 2010] gives a stoichiometric overview of the production and destruction of a certain micro-algal species. The calculation was modified to fit to the stoichiometric formula 2.1. The discussed principle of mass conservation can be easily identified. Energy delivered by photons is written in parentheses in this formula and has only the symbolic meaning described above. Because the overview consists of stoichiometric formulas, the inaccuracy of the energy utilization can be ignored but should at least be

indicated.

$$81H_2O + 106CO_2 + HPO_4^{2-} + 16NO_3^- + 18H^+ + (xh\nu) \tag{2.2}$$

$$\begin{gathered}\text{photosynthesis}\\ \leftrightarrow\\ \text{dark respiration}\end{gathered}$$

$$C_{106}H_{181}O_{45}N_{16}P_1 + 150O_2 \tag{2.3}$$

Algae and dioxide are formed out of water, CO_2, and minerals through the utilization of light via photosynthesis. In the absence of photons, algae can use chemically stored energy to survive. This process is called *dark respiration* because CO_2 is produced. This "energy-sapping" leads to a loss of micro-algal mass.

Furthermore algae can contain trace elements like S, K, Fe, Ca, Mg, Mn, Mo, Cu, Zn or V. Even if these elements mostly play a micro nutrient role some algal species can use them as macro nutrients. Special *Chlorella*-forms require sulfur for cell division or P-deficient *Scenedesmus*-algae cells can accumulate sulfur as a substitute for P as described by [O'Kelley, 1968, p.89]. This topic should be considered when focusing on certain algae strains in nutrient-limited environments.

Well-studied strains of unicellular micro algae for example are *Chlamydomonas reinhardtii*, *Chlorella* or *Dunaliella salina*
[Rittmann and McCarty, 2001, p.21]. Literature searches produced an unconfirmed picture, that for example the genus *Chlorella vulgaris* is a desired object of investigation. Wastewater experiments also use a species called *Scenedesmus obliquus* or *Scenedesmus rubescens*. This thesis will provide no further specialization in a certain algal strain.

- Chapter 3 -

About the Utilization of Light

This chapter investigates the utilization of sunlight as a limiting factor for micro-algal growth. Therefore it is necessary to illustrate the quite complex process of photosynthesis. The profundity of this process makes it hard to trim the explanation to just a few pages. It is also noteworthy that the author of this thesis is no biologist. The content is pictured and understood only to such a depth as needed for the following estimation of biomass production which is the true focus of this chapter.

§ 3.1 Photosynthesis by algae

An international team, including Austrian scientists, recently found evidence for the origin of today's plants to be an *endosymbiotic process* more than one billion years ago: An *eukaryote*, a simple organism with at least one cell enclosed by a membrane, united with a certain bacterium. This combination had the great advantage to permit photosynthesis and use its products for the rest of the cell. Finding an ancient link to this special bacterium in the genomes of different plants today makes a single event responsible for the whole evolution of the *eukaryote supergroup Plantae* including every single plant we know today. [Price et al., 2012]

The knowledge of the principles of this effective process of "light-harvesting" is indispensable for a solid estimation of micro-algal biomass production. Even if micro algae do not belong to the *Plantae*-group, their photosyn-

thetic process is similar as found in simple *C-3 plants*:

The handicap of *C-3 plants* compared to *C-4 plants* like maize and sugarcane is *dark respiration.* As explained in chapter 2, *dark respiration* has the negative effect of the depletion of the plant's own biomass. It takes place when the plant has to struggle with too high temperatures and/ or too low light irradiance. On the other hand *C-3 plants* do have a simpler structure thus making the light-harvesting process easier to understand.

Algae contain chloroplasts with membranes, the *thylacoid membranes* surrounding the *thylacoid lumen* isolating it from the *thylacoid stromen.* These membranes are filled with pigments, *chlorophyll* or *carotenoids*, with specific light absorption rates. In case of absorbing a photon ($h\nu$) an electron (e^-) gets transited to a higher state. The e^- now has two possibilities: Either it relaxes back to its ground state by emitting a photon or its energy gets transferred to another adjacent and similar molecule by excitation of an e^- of the *neighboring chlorophyll.* This excitation/energy-transfer takes place as long as the *neighboring chlorophyll* has the same or lower energetic requirements for the excitation as the first one. This so called *antenna center* transports the energy to the *reaction center* which consists simply of a *chlorophyll molecule* with the lowest energy level for the excited state. Due to this difference the e^- of the last *antenna center chlorophyll* now has the possibility to relax back not to his own ground state but to get conducted to the excited state of the *reaction center.* This last step, a quasi radiation-less e^--transfer, produces an *anion* and leaves a *cation*, a *photooxidized chlorophyll*, behind. For further steps two different photosystems must now be distinguished:

The *antenna chlorophyll* pigments of *Photosystem II (PSII)* absorb light with a wavelength of $680nm$ hence they are called *P680.* The created *cation chlorophyll* ($P680^+$) attracts an e^- from the so called *water oxidizing complex.* To oxidize two molecules H_2O, it is necessary to extract four e^- and four protons. The oxidization forms one molecule O_2 and four $H^+ ions$ which are released to the *thylakoid lumen.*

The extra e^- from the *anion chlorophyll* of *PSII* gets (indirectly) further

transported to a *cation chlorophyll* of *Photosystem I (PSI)*. There it can substitute an e^- that was excited by light with the wavelength of $700nm$ and transferred to the reaction center of *PSI*. This reaction center is happy to give its extra e^- to a *nicotinamide adenine dinucleotide phosphate* ($NADP^+$). This $NADP^+$ will be reduced to a $NADPH_2$ by four e^-. $NADP^+$ as well as *adenosine diphosphate* ADP are dropped by the *carbon reactions pathway*. They are used as "energy carriers". Mainly because of the *water oxidizing complex* a H^+ excess emerges in the *lumen*. The so generated *PH-gradient* between *lumen* and *stromen* is furthermore the driving force to reduce ADP to ATP thus "refilling" this "energy carrier" for the reuse in the *carbon reactions pathway*.

In the *carbon reactions pathway*, also called the *Calvin Cycle*, CO_2 diffuses into the *stromen* to be metabolized in different steps by *Ribulose-1.5-biphosphate* ($RuBP$) to *Glycerinaldehyd-3-Phopshate* ($G3P$), the pre-stage of sugar. Five $G3P$ are reused for the *Calvin Cycle* while one is the plant's profit that leaves the *carbon reactions pathway*.

To process one molecule of CO_2 in the *Calvin Cylce* two $NADPH_2$ and three $ATPs$ are necessary [Zhu et al., 2008, p.154]. To provide two $NADPH_2$ eight electrons are used thus eight photons are consumed. Six molecules of CO_2 can be converted to one molecule of *glucose* ($C_6H_{12}O_6$). Therefore a minimum of 48 photons are processed to provide the energy for this mass accumulation. This calculation will be a part of the estimation of the biomass production in paragraph 3.7.

§ 3.2 Total sunlight irradiance

The sunlight irradiance depends on several well understood factors:
The zenith angle (ξ) of the shafts of direct sunlight depends on time and location on the earth's surface as well as the day of the year. This angle can be further used to calculate the optical path length ($m(\xi)$) between the top of the atmosphere (TOA) and the earth's surface. Therefore the altitude of TOA and the elevation of the location give the optical path length for the sun at zenith (m_o).

$$m(\xi) = \frac{m_o}{\cos \xi} \tag{3.1}$$

These factors should be enough to estimate which part of the solar irradiance available at TOA can really reach the location of the *PBR*. This assumption proves to be quite useful on a day with clear sky and without air pollution. Yet on most days the result is highly influenced by weather conditions. This makes it impossible to compute the solar irradiation for any chosen period and place on earth's surface.

Measured data from meteorological stations can put things right:

Primarily to provide a tool for the estimation of photovoltaic (PV) energy generation in European countries [Suri et al., 2007] collected the data of solar irradiance at a $1km * 1km$ resolution in 30 European Union and candidate countries. The combination of this data with a geographical information system (GIS) can be found as an interactive map on the website of the photovoltaic geographical information system [PVGIS, 2010].

For the estimation of incident solar irradiance on *PBRs* the values of *PVGIS* for twelve days, each representing an average day of every month in a year, are further used for this work. The irradiance in $[\frac{W}{m^2}]$ is given by the *global irradiance* (G) as well as the *diffuse irradiance* (G_d), because particles in the atmosphere scatter sunlight and bring solar irradiance into corners where no direct light can get. *PVGIS* provides these values for horizontal surfaces averaged on a fifteen minutes basis under a real sky.

The next step investigates which part of this incident light can reach the surface of the *PBRs*:

Paragraph 3.6 will highlight the reason why it is beneficial to avoid direct sunlight irradiance on the reactor's surface. To achieve this avoidance the surface of the reactor plates can be turned with the changing azimuth. This method can constantly **avoid** direct sunlight on the main surface of the

reactor plates. G_d reaches the reactor walls from every direction because it is diffuse. As it is given in watt per horizontal square meter it is assumed that 50% of this part of the solar irradiance is lost through the conversion to vertical square meter [Slegers et al., 2011, p.3349]. *Direct irradiance* and G_d add up to G. *Direct irradiance* can be reflected by objects located near the *PBRs*. If the utilization of urban area should be optimized, such a reflecting object could be the cladding of a skyscraper on which the reactors are mounted. Change of the light intensity through reflection can be manipulated by using the optimal painting for the wall. It is assumed, that a rough white wall acts like a *Lambertian reflector* when irradiated. Incident light is scattered in every direction from -90° to $+90^o$ around the surface normal weighted by the factor $\cos(\alpha)$. α is the observation angle; i.e. the angle between the area vector and the "observer". The *direct irradiance* that is scattered by such a type of wall also becomes diffuse. Its light intensity can be averaged over the full range of scattering angles ($-90^o < \alpha < +90^o$) if the entire irradiance can further reach the reactor's surface. This calculation gives an intensity reduction of around 36% for the sunlight that shines at the wall.

$$\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{\cos\alpha}{\pi} d\alpha \approx 0.63662 \tag{3.2}$$

For the irradiance on the surface of a flat-panel *PBR* mounted on a white wall it is assumed, that 50% of G_d, 64% of $(G - G_d)$ and another wall-reflected share of G_d $(0.5 * 64\% * G_d)$ play a role. Thus a surface irradiance (I_{PBR}) on the *PBRs* is calculated as given by the following formula:

$$I_{PBR} \approx (0.5 + 0.32)G_d + 0.64(G - G_d) \tag{3.3}$$

This formula could further be improved by including the transformation of *direct irradiance* measured horizontally to a *direct irradiance* on a vertical surface.

§ 3.3 Reflections on the reactor surface

Photons reaching the reactor's surface are confronted with different *refractive indices*. Due to that change, a part of the irradiance is reflected and another part transmitted. The irradiance values resulting from this reflexion and transmission are given by the *Fresnel equations*. They depend on the *refractive indices* (η) of the different media, the incident angles (θ) and the *polarization* (two possibilities:*s- or p-polarization*) of the light rays [Slegers et al., 2011, p.3351].

$$R_s = \left[\frac{\eta_i \cos\theta - \eta_t \sqrt{1 - (\frac{\eta_i}{\eta_t} \sin\theta)^2}}{\eta_i \cos\theta + \eta_t \sqrt{1 - (\frac{\eta_i}{\eta_t} \sin\theta)^2}} \right]^2 \tag{3.4}$$

resp.

$$R_p = \left[\frac{\eta_i \sqrt{1 - (\frac{\eta_i}{\eta_t} \sin\theta)^2} - \eta_t \cos\theta}{\eta_i \sqrt{1 - (\frac{\eta_i}{\eta_t} \sin\theta)^2} + \eta_t \cos\theta} \right]^2 \tag{3.5}$$

The *refractive indices* of the considered media are given by η_i, for the medium of the incident light, and η_t, for the medium of the transmitted light.

Assuming that glass is quite too heavy for the construction of *PBRs*, reflections were computed with the *refractive indices* of *Polymethyl methacrylate* (*PMMA, Acrylic glass*) with a value of $\eta = 1.49$. After the transmission into the transparent wall a second change of medium -from *PMMA* to water- leads to further *Fresnel reflections* of the transmitted light. The following table 3.1 shows the *refractive indices* for the two media that light has to pass to reach the inside of the *PBRs*: All values are obtained from [Ciddor, 1996]. Furthermore the angle of transmission θ_t is given by the incident angle θ_i:

Table 3.1: *Refractive indices*

	$AIR - PMMA$	$PMMA - H_2O$
η_i	1	1.49
η_t	1.49	1.33

$$\sin\theta_t = \sin\theta_i * \frac{\eta_t}{\eta_i} \tag{3.6}$$

This calculation only plays a role for the light transmitted into the *PMMA*. Therefore formula 3.6 gives a new angle for the second change of media where the photons are finally transmitted to the water.

Sunlight is generally *unpolarized*. This means that if *S- and P-polarization* were measured a 50%-share of each part would be found. This makes it possible to continue with the average of the *Fresnel equations*. The irradiance on the reactor wall I_{PBR} furthermore consists only of diffuse light as described in detail in paragraph 3.2. Computing the *Fresnel equations* for each angle between 0° and 90° in 1°-steps equals in 90 different reflections of *unpolarized* light. This estimation is performed for both surfaces including the change of the incidence angle. Aim is to estimate the intensity reduction of the sunbeams when traveling through the walls of the *PBRs*. Averaging over the sum of angles results in a total transmitted irradiance (I_t):

$$\frac{I_t}{I_{PBR}} = 1 - \overline{\overline{air - PMM} + (1 - \overline{air - PMM}) * \overline{PMM - H2O}} \approx 0.844 \tag{3.7}$$

$\overline{air - PMM}$ for example stands for the average reflection of *S- and P-polarized* light at a surface between air and *PMMA*.

In total an average of about 84% of I_{PBR} is transmitted into the water filled center of the photo-bio reactor. The rest is reflected. Further reflections at the surface between *PMMA* and air, as well as between *PMMA* and water could lead to an addition of another but very small percentage of transmitted irradiance. This inaccuracy was neglected in the calculation.

§ 3.4 Absorption in algal culture

The water-filled center of the *PBRs* contains micro-algal cultures hence it is called the *cultural volume*. The proportion between dry mass of the micro-algal biomass and the surrounding water is given by the concentration (C_x) in $[\frac{kg}{m^3}]$. C_x can be held constant in the reactor artificially by adjusting the harvesting velocity (chapter 6) to the production velocity. Furthermore the entire culture is always in motion, not only because of the heat motion of every particle but also because of the directed mass flow through the *PBR* that is given by the architecture, gravitation and aeration. Due to this fact

it is assumed that a dependence of C_x on time and location in the *cultural volume* can be excluded.

Light travels through the *cultural volume* after transmission through the reactor walls where it can be absorbed by the micro algae. The potential for the absorption of light is given by the *specific absorption coefficient* (β), a material specific value in units of $[\frac{m^2}{kg}]$. β varies between different micro-algal strains. The *Beer-Lambert-Bouguer law* (formula 3.8) gives the relation between the light intensities before (I_o) and after (I_1) light passes a liquid or gas that contains absorbing material The length of the light path through the medium is denoted by d.

$$I_1 = I_o * e^{-C_x \beta d} \tag{3.8}$$

Light intensity before the absorption is the same intensity that is already transmitted through the reactor walls into the *cultural volume*. Therefore I_o equals I_t from paragraph 3.3. The calculation is simplified by the assumptions, that there are no other particles in the water than micro algae and β of pure water equals zero. The energy rate transferred to the micro-algal system (P), can be calculated through the following formula:

$$P = I_t - I_t * e^{-C_x \beta d} \tag{3.9}$$

It is of note to which depth of the *cultural volume* there are enough photons to be absorbed by micro algae. This part forms the *PAV* (*photo active volume*). The design of the *PBRs* used in this work gives a very small light path in the *cultural volume* compared to other methods of algal cultivation (like open ponds). To assure a 100% *PAV*, a smaller d allows a higher C_x when the value of β does not change. This is the main advantage of the flat-plate *PBRs* architecture that is described in chapter 1.3 compared to other cultivation methods. Table 3.2 gives an overview for the values and their references used for the estimation of micro-algal biomass production.

Table 3.2: *Microalgal culture values*

	Units	Value	Comment	Reference
C_x	$\frac{kg}{m^3}$	1	dry mass/volume	[Slegers et al., 2011]
β	$\frac{m^2}{kg}$	75	for *P. tricornutum*	[Slegers et al., 2011]
d	m	0.03	-	-

§ 3.5 Photosynthetically active radiation

An object that solely emits photons because of its internal energy (a *black body*) radiates at all wavelengths. Every single wavelength is connected to a certain photon energy. *Planck's law* gives a distribution of these energies. If applied to the Sun's surface temperature of $5800K$, a maximum of the radiation intensities at approximately $500nm$ can be found. Earth's atmosphere absorbs most of the high energy radiation that corresponds to wavelengths below $400nm$ because of ozone and oxygen. Other gas molecules produce absorption bands above a $900nm$ edge leaving the visible light largely untouched. It is within this region where all kind of plants absorb photons for photosynthesis. The light accounting to this *photosynthetically active band* (400-700nm for C_3*-plants*) [Cuaresma et al., 2009, p.353] amounts to approximately $\eta_{par} \approx 43\%$ of the incident solar energy on the Earth's surface for the considered algae species. This value varies depending on $m(\xi)$, the suspended matter and the cloud cover of the atmosphere. The above mentioned value of $\eta_{par} \approx 43\%$ is calculated using average energy densities measured on different places of the North American continent. This distribution of radiation intensity can be obtained from the homepage of the American Society for Testing and Materials [ASTM, 2004] and is plotted in figure 3.1

The part of the irradiance that is calculated to be absorbed by the micro algae consists of the entire *spectrum*, of all wavelengths, of the available sunlight in the *PBR*. As previously mentioned approximately 43% of this energy can be utilized for photosynthesis hence this part is called *PAR*. This assumption neglects the reflections:

Most algae are green like other plants. That is because of the relatively

weak absorbance of chlorophyll in the green band. This part forms about 10% of PAR and reduces the rate of energy transformed by photosynthesis P_{PS} [Zhu et al., 2008, p.154].

In summary approximately 38% of the absorbed light intensity can further be used by the photon capturing mechanism of the plants:

$$P_{PS} \approx 0.43 * P - 0.1 * 0.43 * P = 0.382 * P \tag{3.10}$$

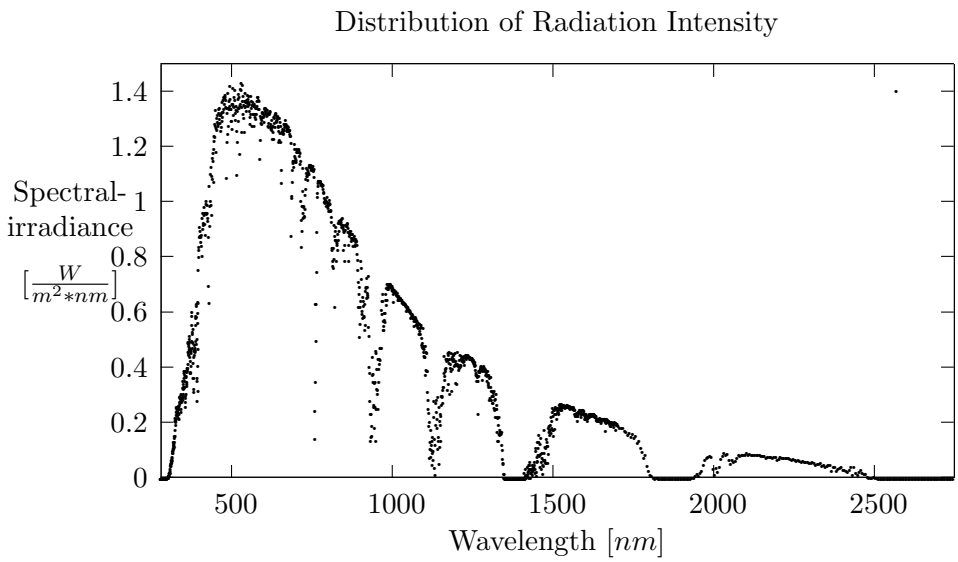

Figure 3.1: *Solar irradiance on Earth's surface [ASTM, 2004]*

§ 3.6 Solar conversion efficiency

As mentioned in paragraph 3.5 different wavelengths of the sunlight correspond to different energies. Photons between $420nm$-$480nm$ for example contain more energy than ones between $630nm$-$800nm$. Looking at figure 3.1 and considering this fact illuminates the true meaning of the graph. It shows how many photons can be found according to their wavelengths.

The wavelength (λ) can be written as $\lambda = \frac{c}{\nu}$ with the speed of light ($c \approx$

$300,000\frac{km}{s}$). The energy content of one specific photon is given by *Einstein's equation*:

$$E(\lambda) = h\nu = \frac{hc}{\lambda} \tag{3.11}$$

Through the multiplication with *Avogadro's constant* (N_A), the energy content of one mol of photons with a specific wavelength can be calculated:

$$E_\lambda = \frac{N_A hc}{\lambda} \qquad [\frac{J}{mol}] \tag{3.12}$$

Assuming that the wavelengths of the light used for photosynthesis ($400nm$-$700nm$) can be fitted by a Gaussian curve allows us to compute the energy of a mol of photosynthetically active photons. However the wavelengths of the algal *photosystems* are more specific. *PSI* uses photons at $700nm$ and *PSII* needs photons at $680nm$. Therefore a micro alga needs light with a lower energy content than the plant on average absorbs. This matches the explanation in paragraph 3.1. Pigments in the *antenna center* capture photons and the excited e^- transport the energy to the *reaction center* with the lowest energy level for an excited state. This energy transport gives a total deviation between the energy of the incident photon and the electron used in the end for photosynthesis. In this way the wavelengths are adjusted to the *photo systems* and the difference of the energies is emitted as heat radiation. This difference accounts for approximately 20% of the energy absorbed by the pigments allowing approximately 80% of P_{PS} to be converted into chemical energy [Zhu et al., 2008, p.154]:

$$\eta_{CH} \approx \frac{E_{690}}{E_{550}} \approx \frac{173.5\frac{kJ}{mol}}{218\frac{kJ}{mol}} \approx 0.80 \tag{3.13}$$

E_{690} gives the average energy per mol of photons best suited for *PSI* and *PSII*. E_{550} is the average energy per mol of *PAR*.

The conversion between irradiance to chemical energy therefore is expressed in a linear dependence. In fact this is an estimation that proves to be sufficient in a certain range, yet for this thesis a closer look is necessary:

Micro algae can protect themselves against a too high accumulation rate

of chemical energy. Before the whole light harvesting apparatus can get disrupted because of too high light intensities, algae decompose their pigments in a renewable process. This mechanism is called the *light saturation process.*

For the gathering of information about this *light saturation process* of micro algae from literature it is necessary to understand the concept of *photon flux density* (*PFD*) which has to be explained before continuing with the main topic:

While P_{PS} equals an energy conversion rate depending on photons with an average wavelength of $550nm$, the energy content of one mol of photons with $550nm$ is given by E_{550}. The *PFD* that is available for the *antenna centers* (ϕ) can now be computed by a simple division of the captured sunlight irradiance through E_{550}. Comparing the units of this calculation results in $[\frac{mol\ of\ photons}{m^2 s}]$. An older notation which does not solely consist of *SI-units* but is quite popular in the scientific community substitutes $[mol\ of\ photons]$ with *Einstein* $[E]$. In the end of this chapter the average energy content of photons suited for *PSI* and *PSII* (E_{690}) will be used to calculate an algal yield out of the consumed *PFDs.*

$$\phi \approx \frac{P_{PS}}{E_{550}} \qquad [\frac{E}{m^2 s}] \tag{3.14}$$

[Ho et al., 2011] and [Melis, 2009] for example observe a *light saturation constant* of about $400\frac{\mu E}{m^2 s}$. A higher *PFD* leads to no further increase in production of chemical energy.

In fact there is even a limit for *light saturation.* When light intensity becomes too high the productivity starts to decreases. This *light inhibition process* might be the case at *PFDs* over $1300\frac{\mu E}{m^2 s}$ [Xue et al., 2011]. To avoid this region, the PBRs considered in this thesis are always directed away from direct sunlight. Therefore a saturation curve would be sufficient for the presented estimation to relate ϕ with the production rate of chemical energy. In the absence of light algae can use the chemical energy stored in their cells. For this metabolism the plants use O_2 and emit CO_2 hence the process is called *dark respiration.* This process is symbolized in the stoichiometric formula of

chapter 2 through the "up-arrow". The consequence is a loss of the micro-algal biomass. The *dark respiration constant* is therefore the needed *photon flux density* to compensate the mass loss with mass production through photosynthesis. Because no explicit value for this compensation point could be found in literature the *dark respiration* was neglected. This leads to a small over estimation of the micro-algal production.

To sum up, a conversion from ϕ, the *PFD* useable for *antenna centers*, to Φ, the *PFD* that is suited for the *reaction center* and is further used to produce chemical energy has to consider the following factors:

- Until light saturation occurs the dependence should be quasi linear following η_{CH} from equation 3.13.
- The curve gets saturated at $400\frac{\mu E}{m^2 s}$. 80% of this *PFD* can be converted to chemical energy.
- After a *light saturation* region follows *light inhibition* and therefore the decrease of photosynthesis and productivity.

A curve following these instructions was created by using the *manipulate environment* of *Mathematica* The equation for this conversion curve follows. The values of the fitting parameters are given in table 3.3 and have the dimension [1]. They have no further individual meaning:

$$\Phi = f * \frac{\phi^a}{b(\phi)} \quad with \quad b(\phi) = i + \frac{u}{\phi^s} \tag{3.15}$$

Table 3.3: *Fitting parameters to describe light saturation/inhibition*

	a	f	i	s	u
Values	-1.064	57.2	0.0001	2.25	176

§ 3.7 Biomass yield

PSI and *PSII* of the micro algae convert photon energy into chemical energy by reducing $NADP^+$ to $NADPH_2$ and ADP to ATP. An average reaction

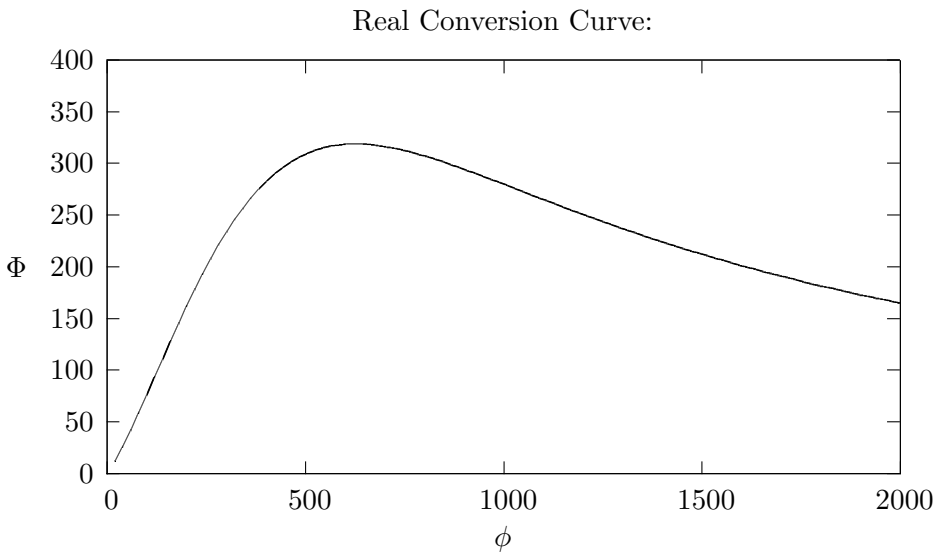

Figure 3.2: *Light saturation and inhibition, a conversion curve*

could look like the following:

$$8h\nu + 2NADP^+ + 3ADP + 3P + H^+ \rightarrow O_2 + 2NADH_2 + 3ATP + H_2O \quad (3.16)$$

The production of $2NADPH_2$ and $3ATPs$ as mentioned in paragraph 3.1 is therefore shown. This is exactly the chemical energy that is needed to process one molecule of CO_2 to one sixth of sugar (CH_2O). Assuming that Φ can entirely be converted into sugar, one eighth of its value can be found as the energy conversion rate to algal internal energy.

$$P_{algae} \approx \frac{\Phi}{8} \quad (3.17)$$

Because of the molar mass of one sixth of sugar ($\frac{30g}{mol}$) and the energy content of the chemically stored photons (E_{690}) the yield rate can be given in $[\frac{g}{m^2 s}]$:

$$Yield_{CH_2O} = \frac{P_{algae}}{30 * E_{690}} \quad (3.18)$$

Burning one mole $C_6H_{12}O_6$ in a calorimeter produces $2808kJ$ of heat [Walker, 2009, p.509]. Therefore a *photosynthetic solar conversion efficiency* of approximately 34% was used above. This is a direct conclusion of the *Law of Lavoisier and Laplace* which predicts that *"the quantity of heat required to decompose a compound into its elements is always equal and opposite to the heat evolved when that compound is formed from its elements"*.

$$\eta_{pho} \approx \frac{2808}{6 * 8 * E_{690}} \approx 33.7\% \tag{3.19}$$

Looking up *photosynthetic solar conversion efficiency* in literature points out different values. That is because of the lack of definition for this term. The *Food and Agriculture Organization* for example calculates with ten or more photons needed to produce one CH_2O. Furthermore the resulting value is multiplied with the percentage belonging to the PAR to get a maximum efficiency of solar energy conversion of approximately 11% [FAO, 1997].

Other papers also take into account the whole process including an average value for *photo inhibition* or the final production of biomass out of the primary photosynthetic product, glucose. In this thesis *photosynthetic solar conversion efficiency* is specified to the simple conversion of already captured and assimilated photon energy to sugar. If this value is also multiplied by the percentage of PAR and the loss because of reflection in the green band and the loss occurring in the transport chain of the *antenna centers* is taken into account, a value of 10% for the conversion of incident light to sugar can be calculated. This value can lead to misunderstandings if compared to other values in literature because of the lack of an uniform definition. Its only reason of mentioning is to give the reader a feeling why it is important to look at every "single step" in the production chain of photosynthesis if a solid estimation of its yield is needed.

While the product that leaves the *Calvin Cycle* is sugar, micro algae mainly consist of *lipids*, *proteins*, *carbohyrates* and *nucleic acids*. The distribution of these bio-products varies strongly between different algal strains. In contrast to the generation of biofuel, where a high *lipid*-content is important,

the production of algal fertilizer requires a high N- and P-fraction. While the majority of N can be found in *proteins*, P is predominantly accumulated either in *nucleic acids* or in special *lipids*, so called *phospholipids*. Next to that information [Williams and Laurens, 2010] provide an estimation of mass loss for the conversion of $C_6H_{12}O_6$ to algal biomass with different contents of *lipids*, *proteins* and *nucleic acids*. To avoid the required specialization and investigation into the considered algal strains, a quite radical assumption is made:

Conversion of CH_2O to algal biomass provides an upgrade in the *calorific value* of the biomass. This difference equals the mass loss that occurs within this process. For an algal strain with a calorific value of $21\frac{kJ}{g}$ (for *S. platensis* after Watanabe and Saiki, 1996 cited by [Xue et al., 2011]) the difference to the calorific value of one sixth of sugar ($15.6\frac{kJ}{g}$) equals an energy upgrade of $5.4\frac{kJ}{g}$. According to the assumption the mass lost, when $Yield_{CH_2O}$ is converted to the total biomass yield ($Yield_{Algae}$) can be calculated by multiplication with the energy ratios:

$$Yield_{Algae} \approx Yield_{CH_2O} * \frac{15.6}{21} \approx Yield_{CH_2O} * 0.74 \tag{3.20}$$

As mentioned above [Williams and Laurens, 2010, p.565] give an equation to estimate this mass loss. Some calculations have been made with low *lipid*-micro algae which lead to similar percentages.

The entire chapter gives an estimation of the production of micro algal biomass.To complete this chapter a short review of the used parameters should bring clarity:

$Yield_{Algae}$ was calculated out of G and G_d. $Yield_{Algae}$ is given in $[\frac{g}{m^2 s}]$ because G and G_d are delivered in $[\frac{W}{m^2}]$. $[W]$ is a derived unit of power and gives the energy per second $[\frac{J}{s}]$. Therefore the *irradiation time* is necessary to calculate the irradiation for one square meter *PBR*. In paragraph 3.2 the origin of the values of G and G_d is stated to be the *PVGIS*. These values are based on 15 *minutes*-averages.

For this work a spreadsheet was fed with these values according to the

measurements (obtained from [Suri et al., 2007]) in Vienna. The so generated data consists of twelve single days which represent the average days of each month. With a measured total *irradiation time* of 143.75 *hours* an amount of biomass of $191\frac{g}{m^2}$ is estimated. Multiplication with 30 *days* for every month gives a calculated value of approximately $5.7\frac{kg}{m^2}$ a year. To compare these values with results found in literature, they are converted into a production with the unit $[\frac{g}{L}]$. This can be achieved by picturing *PAV* behind the wall of one square meter of the *PBR*. With $d = 3cm$ the calculation gives $1 * 1 * 0.03m^3$, thus resulting in $30L$ of *PAV* behind one m^2 of *PBR*-wall. Applied to the production per m^2 gives a value for comparison of $193\frac{g}{L}$ of algal dry mass in one year. Looking at the artificially constant C_x in the *PAV* ($C_x = 1\frac{kg}{m^3} = 1\frac{g}{L}$) shows a daily growth rate of approximately 0.53 which is quite plausible. Results and comparisons with other works are listed in table 3.4.

Even if $[\frac{kg}{L}]$ seems to be the best comparable unit for the production of

Table 3.4: *Theoretical PBR-yields and comparison*

	Yield	Sunhours	Source
$year_{tot}$	$193\frac{g}{L}$	$5212.5h$	-
day_{avg}	$529\frac{mg}{L}$	$12.0h$	-
day_{max}	$862\frac{mg}{L}$	$15.5h$	-
day_{avg}	$0.53\frac{1}{day}$	$12.0h$	-
day_{avg}	400-900$\frac{mg}{L}$	–	Richmond,A. (1990) cited in [Di Termini et al., 2011]

micro-algal dry mass in a cultural volume it turns out to be unusual in literature. [Slegers et al., 2011] for example give the production rate for their *PBR*-panels in three different regions in $[\frac{kg}{panel}]$ while measurements for open ponds as well as for *PBRs* can often be found in $[\frac{kg}{m^2}]$. The lack of knowledge of the *cultural volume*-size makes it hard to give a fair comparison. It is also noteworthy that no data on large scale experiments with flat plate *PBRs* could be found in scientific journals. The given values from [Di Termini et al., 2011] describe outdoor ponds (400-700$\frac{mg}{L}$) and an outdoor tubular coiled bioreactor ($900\frac{mg}{L}$). Better comparable experimental results are expected in the near future.

§ 3.8 Calculations-Summary

In this paragraph the calculation of the micro-algal production in a *PBR* in Vienna will be summarized:

Global irradiance (G) and diffuse irradiance (G_d) in $[\frac{W}{m^2}]$ were downloaded from the photovoltaic geographical information system [PVGIS, 2010]. This homepage provides an interactive tool to look up measured sunlight irradiance at any location in Europe. The position $48.208N$ and $16.374E$ was selected which corresponds to the city center of Vienna. The radiation database used here is named "Classic PVGIS". Daily average irradiance for a fixed plane with 0° inclination and orientation plus daytime temperatures (T_{air}) were downloaded as a text file. 12 text files containing the irradiance averaged on a $15min$-basis represented 12 average days, one for every month in a year. In total 695 sets of data containing G as well as G_d and T_{air} were then transferred into spreadsheet 1. Every following calculation listed in this paragraph was performed for every data set individually:

First the irradiance on the *PBR* surface was calculated. [Slegers et al., 2011] assume that 50% of the irradiance on a 0° inclined plane can be calculated for a 90° inclined plane. A raw white wall next to the *PBR* would act like a *Lambertian reflector* when irradiated and could reflect 64% of the direct light ($G - G_d$):

$$I_{PBR} \approx (0.5 + \frac{0.64}{2})G_d + 0.64(G - G_d) \tag{3.21}$$

- Averaged reflection
  Spreadsheet 2 was equipped with 45 data points. From 0 to 90 every even natural number was used to estimate the transmitting performance of the PMMA-walls of *PBRs*. cos and sin were calculated for each data point and used to compute the reflection of s-polarized and p-polarized light. Refractive indices were $\eta_i = 1$ (for air) and $\eta_t = 1.49$

(for PMMA):

$$R_s = \left[\frac{\eta_i \cos\theta - \eta_t \sqrt{1 - (\frac{\eta_i}{\eta_t} \sin\theta)^2}}{\eta_i \cos\theta + \eta_t \sqrt{1 - (\frac{\eta_i}{\eta_t} \sin\theta)^2}} \right]^2 \tag{3.22}$$

resp.

$$R_p = \left[\frac{\eta_i \sqrt{1 - (\frac{\eta_i}{\eta_t} \sin\theta)^2} - \eta_t \cos\theta}{\eta_i \sqrt{1 - (\frac{\eta_i}{\eta_t} \sin\theta)^2} + \eta_t \cos\theta} \right]^2 \tag{3.23}$$

Because sunlight is unpolarized, these values could be averaged which is denoted as $\overline{air - PMM}$. New values for cos and sin were calculated using the transmission refractive index for PMMA:

$$\sin\theta_t = \sin\theta_i * \frac{\eta_t}{\eta_i} \tag{3.24}$$

3.22 and 3.23 were performed a second time with the new angles and the incident refractive index for PMMA $\eta_i = 1.49$ and the transmission refractive index for water $\eta_t = 1.33$. The two polarizations were averaged and denoted as $\overline{PMM - H2O}$. Because the transmission (T) is $T = 1 - R$, the average transmission of the diffuse irradiance through the reactor walls can be calculated as follows:

$$\frac{I_t}{I_{PBR}} = 1 - \overline{\overline{air - PMM} + (1 - \overline{air - PMM}) * \overline{PMM - H2O}} \tag{3.25}$$

The spreadsheet gives a value of 0.844 which means that about 84% of I_{PBR} is transmitted into the water filled center of the *PBRs*.

After calculating the transmission

$$I_t \approx I_{PBR} * 0.844 \tag{3.26}$$

the absorption rate by the algal culture was computed:

The *Beer-Lambert-Bouguer law* was applied using the density of the culture ($C_x = 1\frac{kg}{m^3}$), the specific absorption coefficient for the micro algae ($\beta = 75\frac{m^2}{kg}$) and the light path through the photo active volume ($d = 0.03m$).

$$P = I_t - I_t * e^{-C_x \beta d} \tag{3.27}$$

- photo active radiation
  The spectral irradiance was obtained from the American Society of Testing and Materials [ASTM, 2004]. Spreadsheet 3 was downloaded with the measured spectral irradiance between $280nm$ and $4000nm$. The sum of the "Global tilt $[\frac{W}{m^2nm}]$" for the spectrum between $400nm$ and $700nm$ was divided by the sum of the entire column. After this calculation about 43% of P lies in the range between $400nm$ and $700nm$ thus can be photo active.

Another 10% of this photo active irradiance is further lost because of the relatively weak absorbance of plants in the green band [Zhu et al., 2008, p.154]. Therefore about 38% of the incident light can be further used for photosynthesis.

$$P_{PS} \approx 0.43 * P - 0.1 * 0.43 * P = 0.382 * P \tag{3.28}$$

The photosynthetic active radiation has a mean wavelength of $550nm$. Therefore the energy of one mol of photons can be calculated using Avogadro's constant ($N_A \approx 6.02 * 10^{23} \frac{1}{mol}$), Planck's constant ($h \approx 6.63 * 10^{-34} Js$) and the speed of light (c):

$$E_{550} = \frac{N_A hc}{550} \qquad [\frac{J}{mol}] \tag{3.29}$$

The photosynthetic energy transformation rate P_{PS} was converted into a photon flux density ϕ with the units $[\frac{mol\ of\ photons}{m^2 s}]$=$[\frac{E}{m^2 s}]$:

$$\phi \approx \frac{P_{PS}}{E_{550}} \tag{3.30}$$

To calculate the conversion of photons into chemical energy a conversion curve was modeled. Due to the difference of the average wavelength of photons available for photosynthesis ($\lambda_{PAR} = 550m$) and the wavelength used to activate the e^- of the photo systems ($\lambda_{\overline{PSI-PSII}} = 690nm$) about 80% of the energy is lost for $PFDs$ under $400\frac{E}{m^2 s}$. For $PFDs$ higher than $400\frac{E}{m^2 s}$ the photo systems get saturated before photo inhibition occurs:

$$\Phi = f * \frac{\phi^a}{b(\phi)} \quad with \quad b(\phi) = i + \frac{u}{\phi^s} \tag{3.31}$$

The fitting parameters for this conversion curve are given in the table below. They have the dimension [1] and have no further individual meaning: This

Table 3.5: *Fitting parameters to describe light saturation/inhibition*

	a	f	i	s	u
Values	-1.064	57.2	0.0001	2.25	176

$PDFs$ (Φ) effecting the photo systems provides the energy to produce sugar through photosynthesis. Eight mol photons provide the energy for one mol of one sixth of sugar (CH_2O). Using the energy content of one mol photons with $\lambda_{\overline{PSI-PSII}}$ (E_{690}) and the molar mass of one sixth of sugar ($\frac{30g}{mol}$), the sugar yield rate was calculated:

$$Yield_{CH_2O} = \frac{P_{algae}}{30 * E_{690}} \tag{3.32}$$

The difference between the calorific value of one sixth of sugar ($15.6\frac{kJ}{g}$) and the calorific value of the micro algae ($21\frac{kJ}{g}$) gives the energy upgrade performed by the algal growth metabolism. The energy difference equals the mass loss. Therefore the micro-algal yield rate can be computed:

$$Yield_{Algae} \approx Yield_{CH_2O} * \frac{15.6}{21} \approx Yield_{CH_2O} * 0.74 \tag{3.33}$$

Each row of spreadsheet 1 was multiplied by the period of $15min = 900s$ to estimate the biomass accumulation averaged on a $15min$ basis for 12 days of example under real sky conditions in Vienna. This micro-algal yield in $[\frac{g}{m^2}]$ was further converted into $[\frac{g}{L}]$. Behind $1m^2$ of PBR-surface $30L$ photo active volume was assumed. These theoretical PBR-yields are listed in the following table:

The global sunlight irradiation in Vienna for one year accounts for about $4,044\frac{MJ}{m^2}$. Approximately $2,957\frac{MJ}{m^2}$ are calculated for the PBR surface and around $120\frac{MJ}{m^2}$ can be found in the produced micro algae. Therefore a solar irradiation conversion of 4% can be found.

Table 3.6: *Theoretical PBR-yields*

	Yield	Sun hours
January	$178\frac{mg}{L}$	$8.5h$
February	$313\frac{mg}{L}$	$10.0h$
March	$511\frac{mg}{L}$	$11.5h$
April	$702\frac{mg}{L}$	$13.5h$
May	$820\frac{mg}{L}$	$15.0h$
June	$860\frac{mg}{L}$	$15.8h$
July	$862\frac{mg}{L}$	$15.5h$
August	$765\frac{mg}{L}$	$14.0h$
September	$602\frac{mg}{L}$	$12.5h$
October	$403\frac{mg}{L}$	$10.5h$
November	$203\frac{mg}{L}$	$9.0h$
December	$130\frac{mg}{L}$	$8.0h$
$Year_{tot}$	$193\frac{g}{L}$	$5212.5h$

Table 3.6: According to the estimation in this thesis, the amount of produced micro algae in PBRs in Vienna vary between $178mg$ in January and $862mg$ in July per liter photosynthetically active volume.

- Chapter 4 -

Nutrients

The stoichiometric formula in chapter 2 gives the five most limiting elements that micro algae depend on for their growth metabolism. If there is sufficient light algae convert CO_2 and water into $C_6H_{12}O_6$. Thus CO_2 and water can be addressed as the most important resources for micro-algal growth. This importance can be shown by comparing the molar share of C, H and O to other elements enclosed in the algal biomass. The generated sugar is further processed together with different molecules, mainly containing N and P, to *lipids*, *proteins*, and *nucleic acids*. How this elemental demand can be met will be investigated in the following paragraphs:

§ 4.1 Carbon dioxide

Earth system research laboratory [ESRL, 2012] gives a concentration of CO_2 in the global atmosphere of about $390ppm$ as a mean value for the year of 2011. CO_2 bound over millions of years is now being released through burning fossil fuels, thus increasing the concentration constantly. Then and now algae bind CO_2 through the carbon cycle. [Bilanovic et al., 2009, p.263] list a series of experiments about CO_2-binding potentials of different micro-algal strains, concluding that especially marine *chlorella* strains could be grown under any condition in the range of 0.038-70$\frac{\%vol}{vol}$. [Moller and Clayton, 2007, p.41] give an optimal range of algal growth between 30-70$\frac{\%vol}{vol}$ and also mention the possibility for algal growth at 100$\frac{\%vol}{vol}$ when the change of pH is controlled. To guarantee a good and economical micro-algal production in

PBRs it is necessary to link the production site to any kind of CO_2-producer. Such a producer could be for example a combined heat and power (*CHP*)-plant that burns gas from *anaerobic digesters* (*A.D.*).

According to the *stoichiometric formula* of chapter 2, one ton of micro-algal biomass contains about $524kg$ carbon. If this content should be delivered in a gaseous form, around $1.9t$ CO_2 are necessary. This shows the high potential of CO_2 capturing that lies in micro-algal production. With a theoretically daily algal yield of $529\frac{mg}{L}$ about $1015\frac{mg}{L}CO_2$ could be bound in the *PBRs* discussed in this work. Because only the N and P content are interesting for the production of algal fertilizer, it is of special interest to restore the C content for further micro-algal production. Such an artificial C-cycle could provide energy through CH_4. This method will be explained in chapter 6.

§ 4.2 Recycling nutrients from waste water treatment plants

The task of the concept presented in this thesis is to outline the chance to reuse essential nutrients from urban waste water streams. By re-injecting these nutrients into the origin of the food supply chain a N- and P-cycle could be closed. Before Europe started to import resources for the production of fertilizer such urban nutrient-cylces where quite common [Cordell et al., 2009]. Several techniques were invented in the last century to revitalize this task. Many of them derive from a relative modern trend to clean the effluent from the sewer system before it is released into further water bodies. The technique presented in this work also goes along with common wastewater treatment facilities (*WWT-plants*) which are meanwhile necessary and obligatory for big communities and cities. Real values from the main *WWT-plant* in Vienna (*EBS-Wien*) will be applied in this thesis. Due to the planned upgrade of this facility in 2015-2020 with an $A.D$-unit it is of special interest to investigate this new treatment path.

To draw the right picture of the meaning of several technical terms a short introduction in waste water treatment is necessary:

The sewage system of Vienna is directed to the topographically lowest point in the city. The *EBS-Wien* had to deal with around $197,558,000m^3$ effluents for the whole year of 2011 [MA53, 2012]. According to the biological share of this amount a *population equivalent* (PE) of 3.25 Mio can be calculated [EBS, 2012]. The PE is calculated by dividing the mass flux of the waste water treatment plant in 24 hours by the average production of feces by a person in 24 hours. Until 2020 *EBS-Wien* has to work with three main processes, one mechanical and two biological treatment-stages: About 30% of the waste can be removed by skimming off and through sedimentation. This pre-treatment stage is driven mechanically. The next two stages remove the organic components through *activated sludge*. Air and *biological flocs* (bacteria and *protozoans*) work together to oxidize carbonaceous matter. Oxidizing nitrogenous matter is accomplished through *nitrification* and *denitrification*. Temperature and aeration has to be adjusted to the waste water conditions for this process. Furthermore P is eliminated with the help of *ferrous sulfate* in *EBS-Wien*. Most of the *activated sludge* that is removed in the *final clarifier* is brought to a *sludge concentrator* while a small fraction is used again for the maintenance of the system. The water leaving the *final clarifier* is released into the *Donaukanal*.

As mentioned above in 2015 an $A.D.$-unit will be constructed for *EBS-Wien*. Six digestion tanks will give enough space for further processing of the produced *activated sludge*. Through the exclusion of air and with the right temperature micro organism can break down biodegradable materials in different processes. First *polymers* such as *carbohydrates* are hydrolyzed. Through the splitting of their water molecules this material now becomes suitable for *acidogenic bacteria*. They can convert sugars and amino acids into CO_2, hydrogen, NH_3 and organic acids. After *acetogenesis*, the last step the *methanogenesis* produces CH_4 and further CO_2. This mixture of gas can be cleaned to enrich the CH_4-content and burned to produce heat and electrical energy. This energy is further used for drying the decomposed *digestate*.

Through the explained upgrade *EBS-Wien* should become energy self sufficient by 2020. To get an idea of the whole process and especially of its dimensions it is necessary to look at already existing $A.D.$-units at other

WWT-plants. A facility that works under similar conditions should be considered as a good comparison. Such a facility can be found in Hamburg. Table 4.1 gives the values of treated waste water for 2011 [Harald Hanssen, personal communication]. To show the similarity these values are compared with values given by *EBS-Wien*. The last three rows in the table give the content of the residual liquid after the drying process process of the decomposed *digestate*. This liquor will further be denoted as "centrate". In Hamburg the "centrate" is led back to the biological treatment-stages and only the dewatered *digestate* leaves the *WWT-plant*. The author of this work suggests that this liquor should be considered as a nutrient source for the production of **algal fertilizer**.

N_{out} and P_{out} for *EBS-Wien* had to be calculated through the N-reduction

Table 4.1: *Anaerobic digestion at WWT-plant*

$01.01 - 31.12.2011$	Hamburg	Vienna
PE	$2.9 * 10^6$	$3.25 * 10^6 L$
Input	$159 * 10^6 m^3$	$198 * 10^6 m^3$
N-reduction	81%	83.5%
P-output	$0.7 \frac{mg}{L}$	$0.84 \frac{mg}{L}$
N_{in}	$11600t$	$10625t$
P_{in}	$1490t$	$1348t$
N_{out}	$2200t$	$1753t$
P_{out}	$108t$	$153t$
$tKN_{centrate}$	$1760t$	–
$P_{centrate}$	$58t$	–
Centrate	$1.1 * 10^6 m^3$	–

and the P-output respectively. Their meaning lies in the nutrient loading that was emitted into the *Donaukanal* or in case of Hamburg into the *Elbe* in 2011. In the same year $1.1 * 10^6 m^3$ "centrate" was produced from dewatering the *digestate* from the German *A.D.*-unit. $tKN_{centrate}$ gives the *total Kjeldahl Nitrogen*. That is the sum of organic N, NH_3 and ammonium (NH_4^+) [Minnesota Pollution Control Agency, 2012] found in the "centrate". $P_{centrate}$ gives its share of contained P.

Values from Hamburg and *EBS-Wien* differ very little. Even if Hamburg is a smaller city than Vienna the *PE* is comparable. This is because the Ger-

man *WWT-plant* receives its material not only from the city but also from the urban hinterland. Even if *PE* is still smaller for Hamburg, the amounts of N_{in} and P_{in} exceed the ones from Vienna. To find a reason to explain this fact and to calculate the effect on the theoretical "centrate"-output for *EBS-Wien* in 2020 a profound investigation of the environments would be necessary, which is, however, beyond the scope of this work. For the following concept the data from Hamburg is used to describe the "centrate"-output that can theoretically be found in Vienna in 2020.

The largest part of $tKN_{centrate}$ consists of NH_4^+ because of *acidogenesis* in the *A.D.* process. This accounts for 81.25% of the effluent from Hamburg. Though plants mostly prefer nitrate NO_3^-, many micro-algal strains can satisfy their N demand with NH_4^+. The most important strains for this task are different *Chlorella* and *Scenedesmus* forms [Pittman et al., 2011], [Li et al., 2011] and [Bhatnagar et al., 2009]. Ammonia loadings of $1300\frac{mg}{L}$ as found in the Hamburg-"centrate" are toxic even for these strains and need to be diluted. If mixed with tap water the $N : P$-ratio stays nearly the same. To provide good conditions for algal growth in *PBRs* a $N : P$-ratio of $7,1 : 1$ would be necessary according to chapter 2. That the ratio of the "centrate" differs strongly $(25 : 1)$ is because most P stays in the dry residue of the dewatering process for the *digestate*.

Bacteria and protozoen have to be reduced to avoid a negative impact on micro-algal growth. In some experiments this is achievied by *autoclaving* where the "centrate" is heated under high pressure [Ruiz et al., 2011, p.886]. *Autoclaving* requires a large amount of energy, thus making it less economic. [Cho et al., 2011] compared three different ways of bacteria and protozoa reduction. Next to *autoclaving* irradiation with *UV-C* light has the same effect for micro-algal growth. Interestingly it is the use of $2 * 10^{-7}m$-pore size filters that leads to an algal production increase. The decrease of suspended solids positively affects photosynthetic efficiency, but also a productive relationship between micro algae and bacteria cannot be ruled out [De-Bashan and Bashan, 2004, p.4226].

Another interesting fact can be found when looking at the input $N : P$-ratios from the urban waste waters given in table 4.1. They give a ratio of

$7,8 : 1$ and $7,9 : 1$ respectively. It is fascinating that these relations are quite similar to the relation *Redfield* [Redfield, 1958] found in ocean water from different regions of this planet. But also the clean water released into the *Donaukanal* has a $N : P$-ratio closer to the *Redfield-ratio* than the "centrate" $(12 : 1)$. Utilization of this water for the production of algal fertilizer should also be considered, when looking for a closed urban nutrient cycle.

P-uptake in general needs more time than the uptake of nitrogen from NH_4^+ ([Aslan and Kapdan, 2006, p.69] for *Chlorella Vulgaris*). Because microalgal production in flat plate *PBRs* as investigated within this work is a continuous process, the uptake velocity could be handled by controlling the parameters and the addition of "centrate" and extra P. For getting an idea of the amount needed, the theoretical daily micro-algal yield of chapter 3.7 of $529\frac{mg}{L}$ is investigated. This yield would accord to an average daily N- and P-uptake of $49\frac{mg}{L}$ and $7\frac{mg}{L}$ respectively.

- Chapter 5 -

Temperature

Most plants do have a specific range of temperatures which seems to provide the perfect condition for growing and reproduction. While some higher lifeforms have the possibility to control their temperatures through warm blood, the temperature of plants and also of algae mostly depends on the irradiance and the ambient conditions. Both mentioned factors vary with time in natural conditions. To ensure a constant micro-algal culture temperature for a maximum yield it is of special interest to study the thermodynamics of photosynthesis. Therefore the estimation of the production of micro algae in *PBRs*, that is mainly formed by the investigation of the utilization of sunlight (see chapter 3), is enhanced by an estimation of the production of heat. Main interest is to find out how much energy has to be delivered externally to artificially provide an optimum temperature for constant growth. Therefore the first law of thermodynamics is used. Looking at the internal energy of the micro-algal system (ΔU) and comparing it to the light that had to be absorbed to produce its sugar (ΔW_{abs}), a loss converted to heat (ΔQ) should be found:

$$\Delta U = \Delta W_{abs} - \Delta Q \tag{5.1}$$

This assumption asks for confirmation. The next paragraphs will lead the reader once more through the process of *light harvesting* of micro algae to highlight the spots where the plants convert sunlight to heat. The whole

chapter will then be concluded with an estimation of the heating and cooling demand of *PBRs* mounted on the wall of a multi-storeyed building.

§ 5.1 Photosynthetically non active radiation and inhibition

Comparing the sum of *global irradiance* in Vienna in one year and the theoretical production calculated by using the estimation in chapter 3 gives an average utilization of the sunlight through the described flat plate *PBRs* of about 4%. That is even though an average percentage of 64% of total sunlight can be absorbed by the algae. The biggest losses occur because only nearly about half of this light (see paragraph 3.5) is in the right range of wavelengths for *PSI* and *PSII* and because micro algae get inhibited when irradiated with too high amounts of light (see paragraph 3.6). It can be assumed, that these losses are converted into heat energy.

The first part will be denoted as *photosynthetically non active radiation* (*PnAR*). It is simply the absorbed irradiance that does not lie in the range of 400-700nm. This part of the absorbed sunlight is converted to heat energy by the algae and is denoted as P_{Q1}.

$$P_{Q1} = 0.57 * P \tag{5.2}$$

This equation follows the calculation mentioned in paragraph 3.5. The unit for P_{Q1} is $[\frac{W}{m^2}]$. Therefore it is the energy conversion rate which gives the produced heat by the micro algae which currently can be found behind one square meter of the reactor wall every second. Paragraph 5.3 will give a calculation to convert the resulting heat energy into a difference of temperature of the algal system and discuss the question how this heat affects the environment.

The second part belongs to the rest of absorbed sunlight with the right wavelength that cannot be utilized because of *photo inhibition*. It is computed by subtracting the *PFD* that is actually used for photosynthesis (Φ)

and the *PFD* consisting of photons suited for *PSI* and *PSII* (ϕ).

$$P_{Q2} = \Phi - \phi \ [\frac{microE}{m^2 s}] \tag{5.3}$$

The reader recognizes that the units for P_{Q2} and P_{Q1} differ from each other. The reason lies in the transformation of an energy flux to a photon flux consisting of photons with the same wavelength. This transformation is described in paragraph 3.6. It is necessary to transform P_{Q2} to P^*_{Q2} in $[\frac{W}{m^2}]$. For this transformation the mean wavelength of *PAR* ($550nm$) was used.

§ 5.2 Photosynthetic inefficiency

The next paragraph will lead to further parts in the *light harvesting process* where heat is produced. The difference to the former paragraph is only the order of the resulting values. They will generally be smaller, which should not be a surprise as approximately half of the absorbed light is converted to heat in the course of not being photosynthetically active.

In the production chain, starting with eight photons at the *reaction center*, ending with one sixth of sugar (CH_2O), further energy is converted to heat. As mentioned in paragraph 3.7 sugar has a *calorific value* of $2808\frac{kJ}{mol}$. This value is also known as the *enthalpy of combustion* of sugar ($\Delta\ H_{CH_2O}$). Because $\Delta\ H_{CH_2O}$ accounts for just one third of the energy of eight photon mols of the right wavelength, two thirds of this energy are converted to heat as energy has to be conserved. This energy transformation rate will be denoted as P_{Q3}. Even if the production chain contains several, in some parts very complex steps, P_{Q3} can be calculated in the proposed generalized way, according to *Hess's Law* [Meschede, 2006, p.258].

$$P_{Q3} = 0.663\Phi \tag{5.4}$$

It is necessary to transform P_{Q3} to P^*_{Q3} in $[\frac{W}{m^2}]$. For this the mean wavelength used for the photo systems ($690nm$) was used.

In further metabolism steps that are described in paragraph 3.7, $C_6H_{12}O_6$ is converted into micro-algal biomass. This process is accompanied with an

upgrade of the *calorific value*. In this work it is assumed that this difference (ΔH_{meta}) is provided by the *enthalpy of combustion* of some amount of sugar mass that is burned for these metabolism steps. Picturing the energy contents over time of this *endothermic reaction* leaves the following question behind: What happens with the rest of energy needed to push the *calorific value* (see figure 5.1)? This rest is called *energy of activation* (ΔA) and

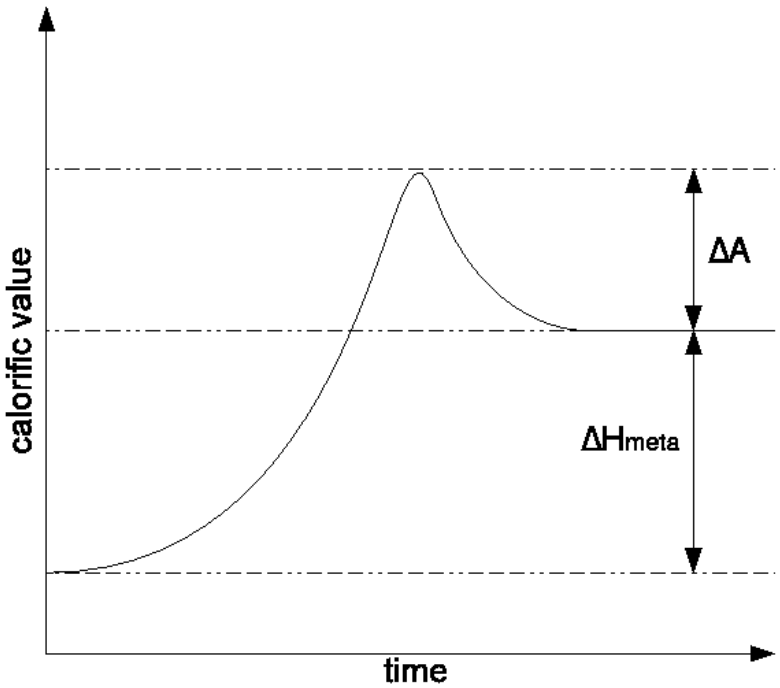

Figure 5.1: *Energy of activation*

has most likely also to be added to the micro-algal heat production. While P_{heat}, the sum of the energy transformation rates that is produced through *PnAR*, *photo inhibition* and the *photosynthetic inefficiency* add up to an average value of 95% (!) of the totally absorbed irradiance, the *energy of activation* must be the integral of a small percentage of the 5% of the irradiance that is used to produce $C_6H_{12}O_6$ that is converted to algal biomass. This comparison underlines the negligibility of the *energy of activation* for this calculation.

§ 5.3 Total heat produced

As mentioned above the total energy transformation rate (P_{heat}) that forms the produced heat is the sum of the different parts that account for it.

$$P_{heat} = P_{Q1} + P^*_{Q2} + P^*_{Q3} \quad [\frac{W}{m^2}] \tag{5.5}$$

This heat production rate gives the heat produced every second from the large part of sunlight that is absorbed by the micro algae in the *PAV* behind one square meter of *PBR wall*. The assumption that this heat can be calculated using the first law of thermodynamics seems to be inexact because still a small part of the absorbed sunlight, the green light, is not absorbed. To derive a heat energy for further calculations, P_{heat} has to be multiplied by the proper time of irradiation to derive Q_{algal} with the unit $[\frac{J}{m^2}]$.

[Klippel and Müller, 1997] give a rigorous thermodynamic analysis of what further happens with the micro-algal heat energy. Their conclusions are, that the laws of thermodynamics only can be obeyed if this heat is not only radiated, but also lost through a mass flux through the plants. Through evaporation of water in the emitted air a large change of *entropy* can be assured, thus cooling the plant.

If algae are cultured in *PBRs* with a low C_x, the produced heat affects primarily the surrounding water. The specific heat of water (footnote 2) gives the change of temperature in $[K]$ if an amount of heat is added.

$$\Delta T = \frac{Q}{c_P m} \tag{5.6}$$

While Q_{algal} is given per square meter of *PBR*-wall, the mass (m) of the surrounding water of this area has to be used. With d of *PAV* of $3cm$, one square meter accounts to $30L$. With the density of water of approximately $1000\frac{kg}{m^3}$ one square meter reactor wall contains $30kg$ of water. Working with the C_x of table 3.2, the amount of micro algae can be neglected for the former calculation.

[2] $c_P(H_2O) = 4183\frac{J}{kgK}$ *at* 20^oC *and* $1bar$ [Wikibooks, 2012]

In case of a perfectly isolating reactor wall, temperature within the *PBR* would rise rapidly after receiving the first sunlight. Because this is not the case the transport of energy through water and *PMMA* has to be investigated:

The *thermal conductivity* (k) gives the material's ability to conduct heat. Values of interest for this work are listed in the following table 5.1: These

Table 5.1: *Thermal conductivities*

	H_2O	$PMMA$	Air
$k[\frac{W}{mK}]$	0.5984	0.19	0.0262
$T[C^o]$	20	23	27
cite	[Wikibooks, 2012]	[GoodFellow, 2012]	[Haynes, 2011]

are the values for a pressure of $0.1MPa$ and the temperature T. For further calculations these values will be held constant because of practical reasons. Because the *PBR* is symmetric and has two walls of *PMMA* on each side of the $30mm$ *PAV*, heat has to travel an average of $\frac{30mm}{4} = 7.5mm$ through the water to reach the wall. The coefficient of heat conductivity G_{th} of one square meter is given by the distance for the transfer (x) and k. G_{th} is an expression that is calculated for this thesis following *Fourier's law* (after [Grote and Feldhusen, 2011, p.28]).

$$G_{th} = \frac{k}{x} \quad [\frac{W}{m^2K}] \tag{5.7}$$

The value for the average path in the water for the heat exchange is approximately $G_{th}(H_2O) \approx 80.0\frac{W}{m^2K}$. *PMMA*-wall strength is assumed to be $3.5cm$. Its *coefficient of heat conductivity* is about $G_{th}(PMMA) \approx 5.4\frac{W}{m^2K}$. Summing up the reciprocal values leads to a total average *coefficient of heat conductivity* for one square meter of $G_{th} \approx 5.1\frac{W}{m^2K}$. This means that a temperature gradient of $1K$ between the surrounding air and the culture volume leads to an energy flux of around $5\frac{J}{s}$ from hot to cold for each square meter of *PBR*-wall.

It is important to mention that these values depend on temperature and on pressure. The exact calculation of the production of heat in a *PBR* is beyond the scope of this thesis. The impreciseness of the current estimation

is justified by a commonly used concept in the field of *process engineering*. This field gives *coefficients of heat conductivity* for different building elements used in the construction industry. These values are usually also held constant and can be found as *overall heat transfer coefficients*. They are used e.g. to estimate the isolation of a building. [Earle, 1983]

§ 5.4 Ensuring culture temperature for maximum yield

A good temperature for the cultivation of micro algae lies between 25^oC and 30^oC [Martinez et al., 1999, p.238]. To achieve this *optimum temperature* (T_{opt}) (footnote 3) in *PBRs* different strategies have to be found for different reactor locations. In general the *PAV* has to be cooled or heated depending on the amount of sunlight absorbed by the micro algae and on the temperature of the surrounding air (T_{air}). This information can be extracted as an average value over 15 *min* from *PVGIS* that is mentioned in paragraph 3.2. For Vienna an averaged value over every single sunlight hour in one year of about 12^oC is determined. For this T_{air} the difference to T_{opt} gives $\Delta T_{opt} = 16K$. By multiplication with G_{th}, the average loss of energy for this reactor architecture can be computed:

$$G^*_{th} = 5.1\frac{W}{m^2K} * 16K = 81.6\frac{J}{m^2s} \tag{5.8}$$

This value can now be compared with P_{heat}. The average amount of transferred energy that can be found as heat accounts coincidentally also to $81.6\frac{W}{m^2}$ with the difference that this value has to be halved. Because the *PBR* has two parallel walls of *PMMA*, one half of this heat is transported to the surrounding air respectively. Because this produces a value smaller than G^*_{th} means that in average the *PBR* loses more energy than micro algae convert to heat from sunlight when the reactor temperature is held constant at 28° and is located in Vienna. The conclusion is, that the reactor has to be heated rather than cooled.

For the estimation of the energy demand for the heating of the *PBRs*, ΔT_{opt}

[3] the rounded mean value of 28^oC is further been used

was averaged over 15 min. Furthermore it was expected that the heat produced by the algae in the water of the PAV is transported to the outer face of the reactor wall. There it could be saved and used to decrease ΔT_{opt}. Out of this the energy demand (F_E^{demand}) for the heating of the micro-algal culture was computed (after [Klippel and Müller, 1997, p.129]):

$$F_E^{demand} = \sigma(T_{opt} - T_{air} - \Delta T)^4 \quad [\frac{W}{m^2}] \tag{5.9}$$

Necessary for this calculation is *Stefan-Boltzmann's constant* ($\sigma \approx 5.67 * 10^{-8} \frac{J}{sm^2K^4}$).

ΔT could be saved by upgrading the parallel plates of the PBR with extra $PMMA$ walls enclosing one whole reactor module that consists of twelve plates. This $8 * 3 * 3m^3$ $PMMA$-housing could than be flushed with any medium with a convenient heat capacity. By this method every single square meter of the PBR has to be provided with around $6.6MJ$ in one year. Dividing by the productivity of one square meter yields the energy demand for the production of one kg micro-algal biomass. Taking into account the values from the estimation in chapter 3, this energy demand is around $1.2MJ$ for every kg dry mass of produced micro-algal biomass. This value will be further used to find the *net energy* for the entire micro-algal cultivation process.

§ 5.5 Calculations-Summary

In this paragraph the calculation of the micro-algal heat production in a PBR in Vienna will be summarized:

To estimate which part of the algal internal energy is transferred as heat into the surrounding water, spreadsheet 1 was extended. The irradiance energy transformation rate to heat was denoted as P_{heat}:

$$P_{heat} = P_{Q1} + P_{Q2}^* + P_{Q3}^* \quad [\frac{W}{m^2}] \tag{5.10}$$

P_{Q1} accounts for the energy transformation rate because of photosynthetic not active irradiance, P_{Q2} for the energy transformation rate because of

saturation and inhibition of the photo systems and P_{Q3} for energy transformation rate because of the energetic difference between eight photons and one sixth of sugar:

$$P_{Q1} = 0.57 * P \tag{5.11}$$

resp.

$$P_{Q2} = \Phi - \phi \tag{5.12}$$

resp.

$$P_{Q3} = 0.663\Phi \tag{5.13}$$

These values were calculated for every single row of spreadsheet 1. P_{Q2} and P_{Q3} in $[\frac{microE}{m^2 s}]$ were transformed into P^*_{Q2} and P^*_{Q3} in $[\frac{W}{m^2}]$ by using λ_{PAR} and $\lambda_{\overline{PSI-PSII}}$ respectively.

Because P_{heat} represented the change of algal heat energy every second for a $15min$ average, each row was multiplied by $900s$ to obtain the produced heat (Q_{algal}). To calculate the transferred heat to the surrounding water a constant value for the specific heat of water was used ($c_p(H_2O) = 4183\frac{J}{kgK}$) and multiplied with $30L \approx 30kg$ for the water content behind one m^2 PBR-wall:

$$\Delta T = \frac{Q_{algal}}{30c_P} \tag{5.14}$$

As mentioned in the chapter on algae production, every row of spreadsheet 1 contained the ambient temperature on an $15min$ average (T_{air}). The optimal temperature for algal growth (T_{opt}) was stated to lie at 28°. Using these values and *Stefan-Boltzmann's constant* ($\sigma \approx 5.67 * 10^{-8}\frac{J}{sm^2K^4}$) the daily energy demand (F_E^{demand}) for heating the micro algae was computed:

$$F_E^{demand} = \sigma(T_{opt} - T_{air} - \Delta T)^4 \quad [\frac{W}{m^2}] \tag{5.15}$$

These 12 values were divided by the daily production of algal biomass to get a specific heat demand in $[\frac{MJ}{kg}]$:

Table 5.2: *Theoretical specific heating demand*

	Heating demand	average ambient temperature
January	$7.5\frac{MJ}{kg}$	-1.5^oC
February	$5.4\frac{MJ}{kg}$	2.6^oC
March	$3.0\frac{MJ}{kg}$	6.3^oC
April	$0.9\frac{MJ}{kg}$	12.4^oC
May	$0.1\frac{MJ}{kg}$	18.0^oC
June	$25\frac{kJ}{kg}$	20.9^oC
July	$7\frac{kJ}{kg}$	22.5^oC
August	$8\frac{kJ}{kg}$	22.3^oC
September	$0.2\frac{MJ}{kg}$	16.9^oC
October	$0.7\frac{MJ}{kg}$	11.9^oC
November	$3.3\frac{MJ}{kg}$	5.6^oC
December	$7.8\frac{MJ}{kg}$	0.5^oC
$Year_{tot}$	$1.2\frac{MJ}{kg}$	11.6^oC

Table 5.2: Ambient temperatures in Vienna were summed up with the heat produced by micro algae and compared with the optimal temperature for algal growth. This specific heating demand varies strongly depending on sunlight irradiance and ambient temperature. In the summer months hardly no external energy is necessary while in December and January the heating demand contributes to more than one third of the calorific value of the produced micro algae ($21\frac{MJ}{kg}$).

- Chapter 6 -

Getting Energy Self-sufficient, A Harvesting Method

The primary target of this chapter is to investigate the possibility to harvest algal biomass that is produced in *PBRs* in a way, that generates an output usable as **algal fertilizer**. Therefore it is important that no bound N and P is lost and that the share of these nutrients in the cultural volume is increased. The C-content should be used to produce CH_4, thus improving the net energy balance. How such a smart harvesting method could look like will be shown in the following paragraphs. This concept will further be adapted for the example of micro algal production in the *PBRs* calculated for Vienna to yield practical values for the production of micro-algal fertilizer.

§ 6.1 Raising algal density

During the production in PBRs the density of algae should be held constant. This guarantees the access to sunlight for micro algae at any location in *PAV* (see paragraph 3.4). In literature several ways to raise the biomass density in the effluent can be found. For the *biofuel industries* with the main interest to extract algal oil, the process of increasing density or simply the process of drying seems to be the tricky part. Different harvesting methods are used: The effluents from *PBRs* are treated with centrifuges and filters in sedimentation tanks, with the help of *chemical flocculants*, *vaporization or flotation techniques* [Shelef and Sukenik, 1984]. Frequently the combination of two or three of these harvesting methods produces dry algal biomass, or

at least one that is dry enough for further processing [Chen et al., 2011].

For the first density increase of micro algae in PAV a sedimentation or a settling reactor can be used. Such a sedimentation reactor could simply consist of a reservoir with input and output at the top separated far enough from each other. Micro algae passing through this tank are affected by sedimentation. [Collet et al., 2011, p.209] gives a sedimentation velocity of $3.575\frac{m}{d}$ which allows to raise the concentration to about $10\frac{g}{L}$ through adjusting the medium circulation velocity. Further packing could now be achieved by centrifugation. An algal dry mass density of $50\frac{g}{L}$ should be achieved for a possible following biogas production process.

§ 6.2 Biogas as a joint product

Because only N and P are interesting for the production of algal fertilizer a method to raise the share of these elements in the biomass is investigated. This could happen by consuming the C-, H- and O- content through $A.D.$ (see paragraph 4.1). Looking at the theoretical approach of methane release shows an overall stoichiometric formula for this process [Sialve et al., 2009, p.410]:

$$C_aH_bO_cN_d + (\frac{4a-b-2c+3d}{4})H_2O \tag{6.1}$$

$$\rightarrow$$

$$(\frac{4a+b-2c-3d}{8})CH_4 + (\frac{4a-b+2c+3d}{8})CO_2 + dNH_3 \tag{6.2}$$

This equation, where the relation between a,b,c and d stands for the atomic ratio of the elements, also considers the N-content of the micro algae because of the accumulation of ammonia in the fermentation tanks. To obtain the methanization yield (B_{CH_4}) in L for every gram of micro algae, the CH_4-share from formula 6.2 has to be divided by the molar mass of an "algal-molecule" and by the density of methane ($\rho_{CH_4} \approx 0.72\frac{kg}{m^3}$ at 0° and $1013.25hPa$ [Wikibooks, 2012]):

$$B_{CH_4} \approx \frac{4a + b - 2c - 3d}{12a + b + 16c + 14d} * \frac{1}{0.72} \tag{6.3}$$

Furthermore the relation between B_{CH_4} and the produced CO_2 (B_{CO_2}) can be derived:

$$\frac{B_{CH_4}}{B_{CO_2}} = \frac{4a + b - 2c - 3d}{4a - b + 2c + 3d} \tag{6.4}$$

Performing these calculations with the stoichiometric composition given in chapter 2 gives a composition of the theoretically produced biogas of $272\frac{mL}{g}$ CH_4 and $222\frac{mL}{g}$ CO_2 respectively. After [Sialve et al., 2009] the calculated value lies at the lower end of most *A.Ds* working with a high *hydraulic retention time* (*HRT*). This factor gives the time that biomass needs to undergo the different steps of the process. Comparing with lower *HRTs* shows that the *carbon conversion efficiency* increases with retention time.

The further estimation is calculated after [Collet et al., 2011] who give the mass flow and energy consumption for digesting algal biomass: Within that work a *HRT* longer than 40 days is stated as necessary to obtain a methanization yield superior to 75%. Furthermore it is suggested that a part of the biogas should be directly burned in a boiler to produce the heat that is necessary to keep the *A.D*-unit at an optimal temperature. The residual flue gas can be led to a *purification plant* to get rid of the CO_2. Because of the high solubility of CO_2 it can be washed out by bubbling through high pressurized water. This could produce a gas rich at 96% CH_4 [Collet et al., 2011, p.209] and a calorific value of $37.0\frac{MJ}{m^3} * 0.96 \approx 35.5\frac{MJ}{m^3}$ [Elert, 2002].

[Collet et al., 2011] give a necessary specific heat to operate the *A.D.* of about $2.5\frac{MJ}{kg}$. This heat should be delivered by a *C.H.P*-unit through burning the produced flue gas. Following the production rate calculated above, a theoretical output of CH_4 with a value of $9.6\frac{MJ}{kg}$ can therefore

be converted either to electricity or heat. Experiments with the microalgal strain *Chlorella vulgaris* give an average methanization yield of $375\frac{mL}{g}$ [Collet et al., 2011]. This would correspond to an energetic CH_4-value of about $13.3\frac{MJ}{kg}$. The mean value of the calculated and the measured results will be further used ($11.5\frac{MJ}{kg}$).

Next to the necessary heating, a mass flux in the $A.D.$ has to be maintained. This would be accomplished by mixing with a stirrer and would consume another $0.4\frac{MJ}{kg}$. Pumping from the settling tanks, centrifugation before digestion and the purification of the gas account for another $0.6\frac{MJ}{kg}$, $0.2\frac{MJ}{kg}$ and $0.3\frac{MJ}{kg}$ respectively. [Collet et al., 2011] The net energy and mass flow of the entire harvesting step will be shown in paragraph 6.4.

§ 6.3 Final treatment

Effluent from the $A.D.$-unit can be centrifuged once more to reach a concentration of 30% of dry matter. The product is a solid algal fertilizer ready to be checked for the utilization as soil conditioner or post treatment. The liquid part is considered by [Collet et al., 2011, p.210] as fertilizer for the algal production process itself. It should also be investigated to be used as common fertilizer for agriculture if produced in a non-N/P-limited way. The second centrifugation step would consume another $0.1\frac{MJ}{kg}$ [Collet et al., 2011].

§ 6.4 Net energy of the harvesting process

As mentioned in the beginning of this chapter the main target is to increase the share of P and N in the final product. Therefore an extraction out of the surrounding water and an elimination of C, O and H is helpful. This paragraph gives the net energy of the chosen harvesting method in table 6.1 and shows a figure for a better understanding of the process:

Table 6.1: *Net energy of the harvesting process*

	C_x	Energy Demand $[\frac{MJ}{kg}]$	CH_4
input	$1\frac{g}{L}$		
sedimentation	$10\frac{g}{L}$	0.55	
centrifugation 1	$50\frac{g}{L}$	0.15	
fermentation		0.39	55%
heating		2.45	
purification		0.58	96%
centrifugation 2	$\approx 300\frac{g}{L}$	0.09	
overall		3.65	

Table 6.1: The energy demand for the different harvesting steps were calculated and summed up to obtain an overall demand for the entire harvesting process in $[\frac{MJ}{kg}]$. Heating of the A.D. unit contributes the biggest part for this calculation in form of thermal energy. The result will be further used to compute the net energy of micro-algal production.

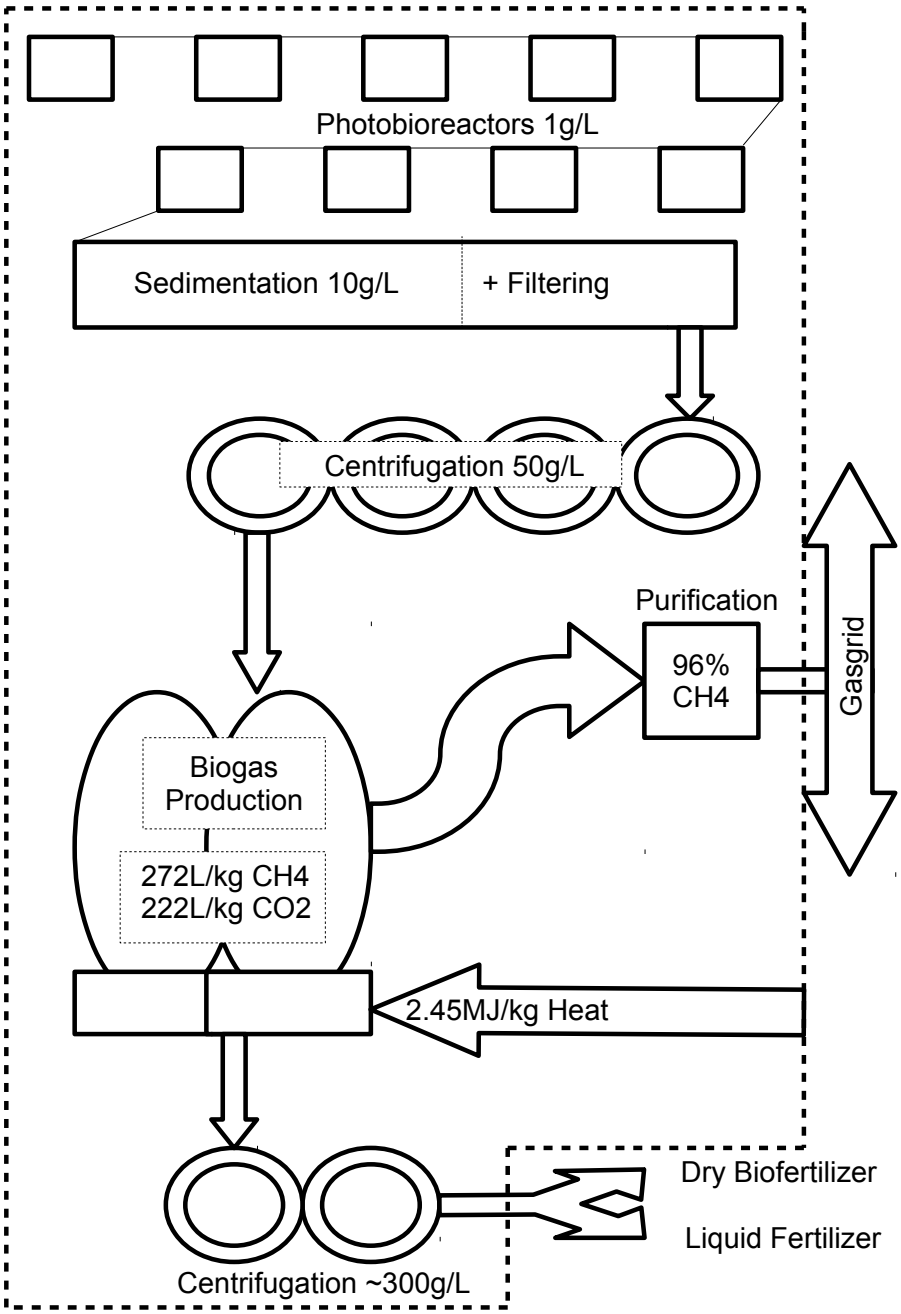

Figure 6.1: *Energy-self-sufficient harvesting of algal biomass, the harvest of bio-fertilizer with bio-gas as joint-product*

- Chapter 7 -

Estimating Algal Fertilizer Production in Vienna

To produce micro-algal biomass in *PBRs* an energy input is necessary. While the majority of this energy is delivered by sunlight (see paragraph 3.2) the rest has to be provided either by heat (see paragraph 5.4) or in form of for example electricity for the aeration. In the course of this work the theoretical efficiency of the production in Vienna is estimated. The following paragraph compares the overall energy consumption and production to show whether the whole process is energy self-sufficient or not. Furthermore a cost-benefit calculation gives an insight into the economics of this concept.

§ 7.1 Total net energy

Whereas the need for heat and electricity for the harvesting process is listed in chapter 6 the values for the production step have to be looked up in literature. For the calculated method of flat plate *PBRs* the energy demand in $[MJ]$ per $[kg]$ dry mass algal biomass are given for the following parameters:

- Aeration:
  While micro algae consume CO_2 in the photosynthetic metabolism, a continuous flow through *PAV* has also to be ensured. The investigated system can deliver both at once by pumping CO_2 from the bottom at every second section in a flat plate. Thus an upwards flow is provided for the micro algae which consume CO_2 and emit O_2 at the same time. At the top of the reactor O_2 is extracted and controlled while the plants can sink down the next section because of the lack of CO_2

bubbles. This combination of circulation and nutrient supply is one of the main advantages of the chosen *PBR* technology.

- Turning the modules:
  For a beneficial light distribution and to avoid direct sunlight as well as shading, the single plates are held in motion directing the edge always towards the sun. Because of sunlight's parallelism this can be accomplished by turning the whole module. Thus twelve flat plates attached together in one module are moved at once by a simple electric motor.

- Infrastructure:
  A continuous production of algae needs continuous pumping between the modules, feeding with nutrients and control of the environment. These factors are summarized in the parameter called infrastructure.

- Heating:
  Originally the flat plate *PBRs* were designed to be located inside a big glass house. This should facilitate the task to provide the culture with T_{opt}. For the author's outdoor concept, the single modules are theoretically mounted to the wall of a high building. The difference between T_{opt} and the ambient temperature plus the heat produced through absorption of photons by algae was calculated in paragraph 5.4. How this heat is supplied remains an unsettled question. It should be mentioned that this problem could be solved by enclosing every module with *PMMA*. Without any estimation or reference it is supposed that a second glass wall for the whole building would be more complicated to calculate and control.

A list of these values is shown in table 7.1 and added up with the energy consumption of the harvesting process according to chapter 6. While the heating value would vary strongly with the reactor location, the harvesting values primarily depend on the used algal strain.

The joint product of this harvesting process is CH_4 with a quality of 96%. This is slightly below the quality of natural gas in the European grid [Wikipedia, 2012]. As mentioned in the chapter on harvesting, this gas should be added to the *biogas* produced and burned on the *WWT-facility*.

For the combustion of *biogas* normally a *CHP*-unit is chosen [Franz, 2012]. Therefore the part of the energy of the output gas that cannot be converted into electrical energy is not lost but saved in heat.

It is also possible to inject the produced biogas into commercial gas grids. The next paragraph will give economic estimations for this possibility.

Table 7.1: *Total net energy*

	Consumption $[\frac{MJ}{kg}]$	Production $[\frac{MJ}{kg}]$	Reference
aeration	3.2		[Mohr, 2011]
infrastructure	1.9		[Mohr, 2011]
turning modules	0.6		[Mohr, 2011]
heating	1.2		paragraph 5.4
harvesting	3.7	11.5	paragraph 6.2
overall	10.4	11.5	

Table 7.1: Specific thermal and electrical energy demand are summed up to be compared with the calorific value of biogas produced out of 1kg micro algae. The calculation gives an energy self-sufficient algal fertilizer production. The difference between energy consumption and production lies at $1.1\frac{MJ}{kg}$. Aeration of PBRs and the harvesting process have the highest potential to improve the total net energy of the presented concept.

§ 7.2 Costs, fertilizer value and other benefits

The cost-benefit calculation is kept quite simple to give a manageable overview of the parameters:

- *photobioreactors:*
  The costs of $1.4 * 10^6 L$ *PAV* of the considered flat plate *PBRs* used for this estimation are given by their inventor [Mohr, 2011]. It is assumed that this volume is the maximum that a $100m * 100m$ façade could tolerate if only the needed space is taken into account. Because such a wall has to carry an extra weight of more than $1,400t$, this asks for special static solutions for the building. Such thoughts are not included in the cost-benefit calculation, only the *PBRs* for a horizontal hectare (ha_{hor}) are considered and would cost 2,240,000-2,800,000 €.

- fermentation tanks:
  The method for the production of biogas out of algae is the same as production of *flue gas* in *A.D.*. Financing such an *A.D.*-unit in Michigan, USA is described by [Greer, 2007]. A *mixing tank* of a diameter of about $20m$ and a loading rate of $2,082m^3$ costs 367,000 €. These costs include the main digestion tank, a liquid storage tank, the separation equipment and the construction costs.

  Calculating with a *hydraulic retention time* (HRT) of 30 *days* one hectare of flat-plate *PBR* produces $32t$ algal dry mass in June according to the authors' estimation. In the *A.D.*-units the concentration of micro algae lies around $\frac{50g}{L}$ thus giving a volume of $724\frac{m^3}{ha}$ for the most productive month. Using about 91% of the volume, a $800m^3$ fermentation tank is necessary. Down scaling the above mentioned costs for such a system would amount to about 144,477 € for one *ha* and a *HRT* of 30 *days*. Because this estimation neglects that downscaling factors normally are not equal to one, another reference is investigated:

  [Timmerer and Lettner, 2005, p.103] give costs depending on the size of different *A.D.*-units found in literature. Comparing the highest hourly flow rate obtained from one hectare of *PBRs* shows, that the proportion of the necessary digestion tanks belong to the lower end of this regression curve. With $1,006\frac{L}{h}$ (with $720\frac{h}{month}$) a visual inspection of the regression curve will yield costs between 171,000-213,000 €. For estimating the costs these values where averaged for an upper cost of 192,000 € for the digestion of the product from one hectare *PBR*.

- centrifuges:
  Costs of a centrifuge with a loading rate of $2.99\frac{m^3}{h}$ can be found. According to [Molina Grima et al., 2003, p.505] such a device plus the corresponding pumps would cost about 94,000 €. Two different centrifuges are necessary for the harvesting method mentioned in chapter 6. Once more the maximum loading rate can be found by calculations using the most productive day of the year. In centrifuge one the daily product of $1,207\frac{kg}{ha*day}$ is concentrated to $\frac{10g}{L}$ thus giving a loading rate of $5.0\frac{m^3}{h}$. Upscaling the value given above results in costs for this centrifuge of about 158,145 € including the pumps.

For the centrifuge after the $A.D.$ with $50\frac{g}{L}$, the loading rate decreases to $0.6\frac{m^3}{h}$. Downscaling gives a cost for this second device of about 18,977 € including the pumps.

- gas washing:
  An optimal overview of costs generated from washing the biogas to increase the CH_4-content can be found in [Timmerer and Lettner, 2005, p.190]. On an average day in June the estimation in this thesis yields a micro-algal production of about $50kg$ an hour. The $A.D.$-unit produces $324\frac{L}{kg}$ biogas thus giving a value of $16,261\frac{LCH_4}{h}$. The mentioned reference gives a regression function for further calculation. Using the above mentioned value and the overall production of the yearly estimation produces costs of about 19,592 € for washing the gas (see footnote 4).

- connection fee:
  [Timmerer and Lettner, 2005, p.241] show average costs for the connection between a biogas producer and the gas distribution system. Gas fed into a communal grid has to meet several claims. A connection accomplished with a pipeline length of $250m$ would generate costs between 21,746-43,486 €. A mean value of 32,616 € is used further.

- operation and maintenance:
  For the maintenance yearly costs of 4% of the above mentioned installation fees can be assumed [Molina Grima et al., 2003]. Labor and taxes are not included. The power supply is also ignored, with the argument, that through the CH_4 production the whole process becomes energy self-sufficient.

- CH_4 excess:
  Every kg of produced micro algae generates an excess of methane with a heating value of $1.0MJ$. [Timmerer and Lettner, 2005, p.297] estimates a price for the year 2004 of $1.63\frac{cent}{kWh}$ for CH_4 out of the grid. On the other hand, refunds are granted for the injection of produced biogas into the grid. Depending on the amount of biogas, these refunds amount to 13-18.5$\frac{cent}{kWh}$ in the year 2012 in Austria (Wirtschaftsministerium cited by [APA, 2012]).

[4] This value is calculated by using a depreciation of 15years

- CO_2 certificates:
  Profits for binding CO_2 can be calculated according to the changing certificate price listed on [BlueNext, 2012]. Even if a crisis impacts this market drastically the theoretical profit should be considered. $519tCO_2$ could be accumulated from one hectare *PBRs* in one year. For the years 2011-2012 the price fluctuation was analyzed. The maximum was found for March $5th$ in 2011 with $16.93\frac{Euro}{tCO_2}$ and the minimum on April $4th$ 2012 with $6.04\frac{Euro}{tCO_2}$. Calculating with the CO_2-binding potential of the micro algae, between 3,136-8,791 € could be sold.

- waste water bonus:
  Disposing of $1m^3$ waste water in Vienna in 2012 costs $1.89\frac{Euro}{m^3}$ [MA31, 2012]. The effluent from the *anaerobic digestion* on the *WWT*-plant adds to that sort of water. According to [Harald Hanssen, personal communication], $1.1 * 10^6 m^3$ of this liquid rich in nutrients contains about $1,430t$ ammonium. One *ha PBR* would need about $32t$ ammonium a year to convert the containing $25t$ N into algal biomass which corresponds to about $15,286m^3$ "centrate". If the used water can be released directly into water bodies 46,704 € for waste water disposal can be recovered.

- fertilizer value:
  The sum of the product's P- and N-content is calculated through the stoichiometric formula given in chapter 2. Even if these contents are separated in a liquid and a dry part the overall value of the fertilizer can be consulted to calculate the economics of the process. [Matzenberger, 2009, p.54] gives the cost of a ton N and P of 800 € and 1,000 € respectively. On one hectare about $219t$ algal dry mass could be produced. This would contain $25t$ N-active substance and $4t$ phosphorus. Even if these amounts are placed in two different products, a liquid and a dry one, the sum would accord to 19,955 € and 3,448 € respectively.

In table 7.3 the yearly costs can be compared with the yearly benefits:

Table 7.2: *Estimated and rounded values for the installation costs*

	Costs in €	Dimensioning	after Reference
PBR	2.24-2.8 $* 10^6$	$1.4 * 10^6 L\ PAV$	[Mohr, 2011]
heat/power unit	0	–	–
centrifuge C1	$158,000$	$4.5 \frac{m^3}{h}$	[Molina Grima et al., 2003]
centrifuge C2	$19,000$	$0.9 \frac{m^3}{h}$	[Molina Grima et al., 2003]
gas wash	$20,000$	$29,499 \frac{L}{h}$	[Timmerer and Lettner, 2005]
connection	$22,000$-$44,000$	$250m$	[Timmerer and Lettner, 2005]
fermenters	$145,000$-$192,000$	$800m^3$	[Timmerer and Lettner, 2005],[Greer, 2007]
$\Sigma_{Installation}$	2.6-3.2 $* 10^6$	–	

Table 7.2: Costs for the production of micro-algal fertilizer in PBRs are summed up with the costs of the production and distribution of the joint product, biogas. Prices for the installation of PBRs outweigh the costs of the harvesting process. This thesis investigates the production of micro algae in special PBRs. Thus prices for other PBRs cannot be used for this estimation.

Table 7.3: *Estimated and rounded values for yearly benefits and costs*

	Costs in €	Dimensioning	after Reference
depreciation	174,000-216,000	15 years	[Timmerer and Lettner, 2005]
maintenance	104,000-129,000	4% a year	[Molina Grima et al., 2003]
Σ_{Costs}	278,000-345,000	a year	
fertilizer value P	$-4,000$	$4t$	[Matzenberger, 2009]
fertilizer value N	$-20,000$	$25t$	[Matzenberger, 2009]
centrate bonus	$-47,000$	$25,000m^3$	[MA31, 2012]
CO_2 certificates	$-3,000$-$-9,000$	$519t$	[BlueNext, 2012]
CH_4 excess	$-10,000$-$-14,000$	$78,000kWh$	[Timmerer and Lettner, 2005]
$\Sigma_{Benefits}$	$-83,000$-$-93,000$	a year	

Table 7.3: Depreciation, calculated for 15 years and maintenance (4%) sum up to the Σ_{Costs}. The fertilizer value of the P- and N content of the produced biomass contributes only a small part of the benefits $\Sigma_{Benefits}$. The biggest part of the income is generated by using the effluent from *EBS-Wien*. CO_2 certificates could be sold as well as biogas. Refunds for the biogas are granted by ÖMAG [APA, 2012] and are many times higher than the natural gas price. Refunds for the connection to the gas grid as well as for biogas production in general could be found for Germany (GasNZV) [Albrecht, 2012, p.25], but could not be confirmed for Austria. Even though the cost-benefit estimation in this chapter underestimates the possible income of the considered bio-refinery, it gives a clear message if Σ_{Costs} and $\Sigma_{Benefits}$ are compared: The concept is not economically feasible. Refunds could help out, but the best way would be to develop cheaper PBR-technologies.

- Chapter 8 -

Conclusions

§ 8.1 Sensitivity analysis

The technical feasibility of an urban N- and P-cycle is shown. It cannot be ignored, however that the costs for the installation and the maintenance would outweigh the benefits of such a process. Dividing the yearly investments with the possible income that is generated by selling the products, a ratio between 3.1 and 4.1 can be calculated. That means, that the price for biogas, N- and P-fertilizer, WW-bonus and CO_2-certificates have to rise three- to four-fold to make this recycling concept economically feasible.

Calculating with the lowest costs and highest benefits shows a N- and P-fertilizer value of 7200 € and 9000 € per ton respectively. This is the nine fold of the actual market prices.

Figure 8.1 shows the parameters that were investigated in this work. They are furthermore listed in table 8.1 and the spreadsheet used for the calculation can be found by following the link given by [Schipfer, 2012].

It is noteworthy, that the entire calculation is based on the sunlight irradiance and temperatures measured in Vienna for one year. The micro algal yield is computed following theories about the photosynthetic mechanism. The energy necessary to heat the $PBRs$ is calculated based on the fact, that the optimal temperature for micro-algal production is $T_{opt} = 28C^o$. Reduc-

ing this temperature to $25C^o$ would change the cost-benefit ratio to $2.9-3.9$. This example for improvement asks for experimental confirmation as well as many other values that where achieved by computation within this work:

The most sensitive parameter is given by the production of biogas through digesting the micro algae. The calculation is performed with a mean value of the theoretical and an experimental value for the CH_4-production. Using only the theoretical value described in chapter 6 yields the need to buy natural gas to meet the demand of electric- and heat energy for the given process. This demand of $0.8\frac{MJ}{kg}$ would lead to extra costs of 98,000 € which are higher than the possible benefits.

Every used parameter asks for deeper investigations to ensure the energy self-sufficiency of the developed concept and thus to improve its economics. Another opportunity lies in the investigation of the potential of micro algae to generate products like sugars, lipids, dyes or antioxidants which do have a higher specific market value than the mentioned N- and P- fertilizer values. A method for such a production chain is shown by [Kölling et al., 2010]. Therefore it is necessary to put a bio-refinery step for the extraction of these products before the *A.D.*-units. The potential of such a *biophotonic combined energy system* (*BCES*) should be investigated in detail.

§ 8.2 Food for thought

Today the scientific community, especially researchers in the biomass sector face one basic question: To which extent should land be used for food- and to which extent for energy(crops)? The author of this work had the great honor to follow some of the most interesting debates on this topic at the 20th European Biomass Conference and Exhibition in Milan. There Stefan Bringezu from the *United Nations Environment Program/International resource panel* argued that the main trend today shows an expansion of cropland just to feed the world population of tomorrow. The only way to meet the upcoming food demand is to reduce waste, change to better diets and to improve the efficiency of food- and energy-supply. That confirms also the author's proposition that energy consumption should rather be reduced than its source substituted.

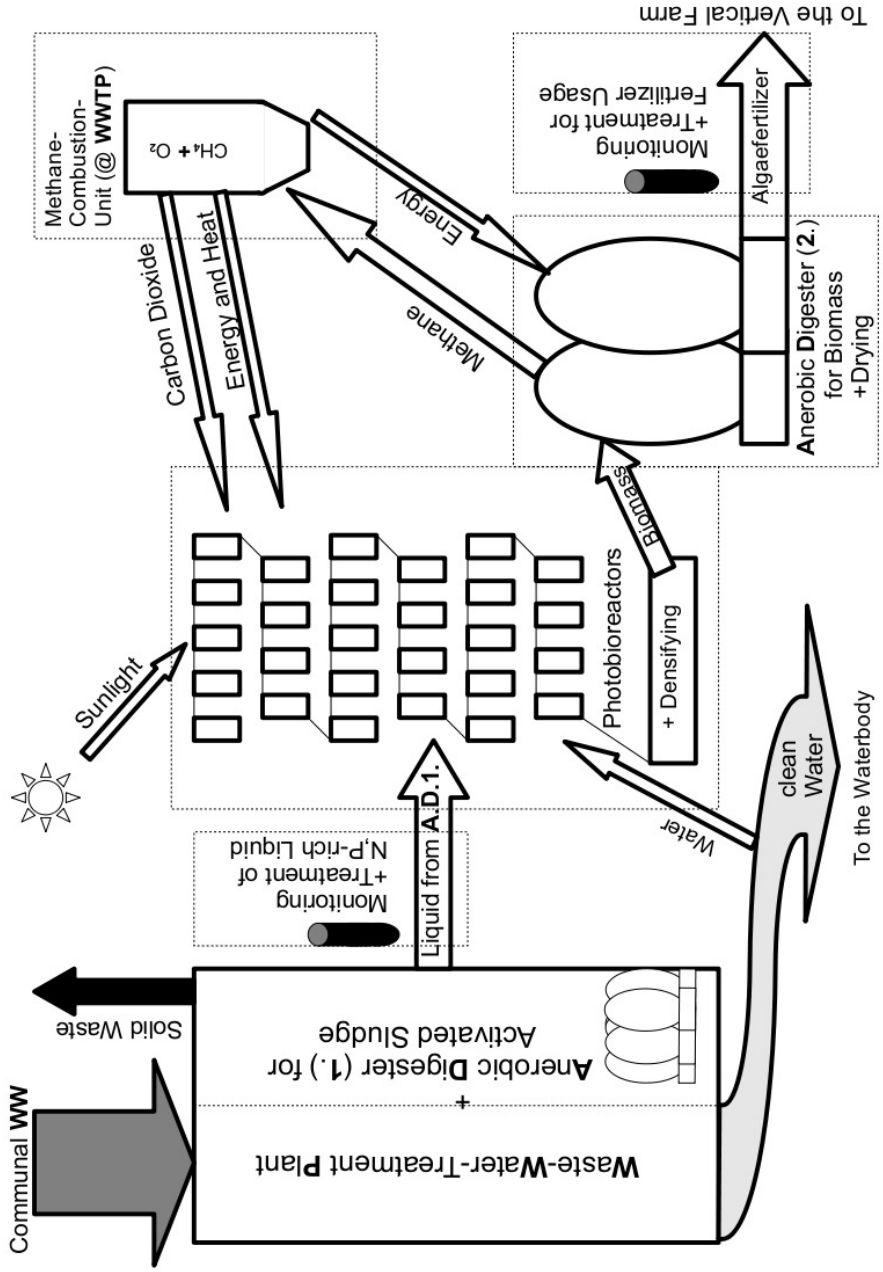

Figure 8.1: *Investigated parameters and their area of influence*

This work is based on the opinion that food production has to be the first priority but next to that it could be supported through the "biomass-to-energy" sector which could help to improve the efficiency of food production. A possibility for such a cooperation is shown. The investigated parameters and their area of influence are summarized in the former paragraph. The net energy has been calculated and the costs have been compared with the profits. Even if energy prices need to undergo a multiple price increase to make the concept of this work economically feasible the ecological advantages of the presented idea compared to today's food production chains could conduce to its success. This thesis demonstrates a promising approach for an energy self-sufficient N- and P- recycling method that can be applied on any vertical surface. It provides a smart city concept to tackle GHG-emissions and fossil fuel consumption without taking up valuable urban area. A city's waste water stream with a *population equivalent* of $2.9 * 10^6$ would provide enough nutrients through the liquid effluent of the *anaerobic digestion* of the *activated sludge* to grow micro algae in 45 vertical hectares. This would recycle 15% and 4% of the consumed nitrogen and phosphorus respectively. Combined with the concept of vertical farming, life cycle assessments of the food consumed by tomorrow's citizens could do without a single transport mile, thus freeing the population from a great part of the current traffic at the same time. Through this more efficient way of using earth's surface, food security for a much larger world population could be ensured and atmospheric CO_2 concentration could be reduced through reforestation. The waste of food, fertilizer and water could be reduced considerably. Avoiding nutrient run off would also contribute to the countless ecological benefits, which have to be further investigated.

The presented concept uses different, not (yet) entirely computable processes to create a theoretical bio-refinery. Therefore the feasibility of a large scale application cannot be predicted. For example algal cultivation in PBRs nowadays only exists in pilot plants. Interviews on the 20th biomass conference reflect the common opinion that there is not enough experimental data to forecast a commercial production of algae in PBRs in almost the same manner as the potential of artificial eutrophication in general cannot be addressed. The advantage that gives a possible feasibility of the pre-

sented concept should rely on the fact, that every single featured process does already exist at least at a small scale and studies for their linkages can be found.

Further research for the entire concept will be needed. The calculation should be performed for other cities as well as for other harvesting techniques. The waste water industry has developed many different concepts for reusing essential elements like N and P, which should also be investigated and considered. Another important future project regarding the presented idea would be to spot the algal strain best suited for this task. Furthermore a biological and medical point of view would be interesting and is necessary for the development of a closed urban nutrient cycle. To complete this work it should be mentioned a last time, that this is just one concept that tries to cover a large number of topics concerning the sustainability of the world's food supply. The more people are aware at least about the problems concerning its complexity, the more ideas to fight them can be expected. We should not hesitate to look for evidence of their feasibility in every single detail without losing sight of what should be our main target- ensuring food, energy and resource security, because these sectors are closely linked and cannot be treated independently of each other.

Table 8.1: *Investigated Parameters:*

	Parameter	Subparameter
Production	Light	Sunlight irradiance in Vienna
		PBR-surrounding
		PBR-architecture
		Reflectance of the material
		Absorption in algal culture
		Photosynthetically active radiation
		Photoinhibition
		Conversion from chemical energy to sugar
		Conversion from sugar to microalgal biomass
	Nutrients	CO_2
		Centrate from WWT-plant N-share
		Centrate from WWT-plant P-share
	Heat	Temperatures in Vienna
		Photosynthetically non active radiation
		Photoinhibition
		Photosynthetically inefficency
		Heating of the surrounding water
		Thermal conductivity
		Optimal temperature for algal production
Harvesting	Densification	Sedimentation
		Centrifugation 1
		Centrifugation 2
	Biogas	Production
		Upgrade
Economics	Costs	*PBRs*
		Centrifuge 1
		Centrifuge 2
		Biogas upgrading
		Gas-grid connection
		A.D
		Maintenance
	Benefits	N-fertilizer value
		P-fertilizer value
		WW-boni
		CO_2-certificates
		CH_4-excess

- Appendix A -

Spreadsheets

Table A.1: *Spreadsheet 1*

Column	Name	Equation	Reference
B	time	-	-
C	global irradiance	-	-
D	diffuse irradiance	-	-
E	ambient temperature	-	-
G	irradiance on PBR	$0.63662 * C + 0.1816 * D$	3.2
H	reflections	$0.844 * G$	3.3
I	transmissions	$H - H * exp^{-1*75*0.03}$	3.4
J	green band	$I * 0.9$	-
K	photo active radiation	$J * 0.43$	-
L	photon flux density	$(K * 0.55)/0.1198$	3.13
M	conversion	$\frac{57.2*(L*(-1.064))}{0.0001+176/(L^2.25)}$	3.3
N	metabolism	$M * 0.337$	3.7
O	sugar-algae	$N * 0.742857$	3.7
P	yield($\frac{g}{m^2}$)	$(O * 900)/120952$	-
Q	yield($\frac{g}{L}$)	$P/30$	-
S	produced heat	$(M - N) * 0.1198/0.69+$ $+(L - M) * 0.1198/0.55 + J * 0.57$	5.5
T	heating demand	$28 - E$	-
U	water temperature	$(S * 900)/125490$	5.5
V	necessary heat	$5.67 * 10^{-8} * (T - U)^4$	5.5

Table A.2: *Spreadsheet 3*

Column	Name	Equation	Reference
B	angle	-	-
C	cos	$cos(B) * \pi/180$	-
D	sin	$sin(B) * \pi/180$	-
E	s-polarized	$\frac{(C - 1.49 * \sqrt{1 - ((1/1.49) * D^2)})^2}{(C + 1.49 * \sqrt{1 - ((1/1.49) * D^2)})^2}$	3.3
F	p-polarized	$\frac{(\sqrt{1 - ((1/1.49) * D^2)} - 1.49 * C)^2}{(\sqrt{1 - ((1/1.49) * D^2)} + 1.49 * C)^2}$	3.3
G	average	$(E + F)/2$	-
H	cos(neu)	$\cos \arcsin I$	-
I	sin(neu)	$D/1.49$	-
J	s-polarized	$\frac{(1.49 * H - 1.33 * \sqrt{1 - ((1.49/1.33) * I^2)})^2}{(1.49 * H + 1.33 * \sqrt{1 - ((1.49/1.33) * I^2)})^2}$	3.3
K	p-polarized	$\frac{(1.49 * \sqrt{1 - ((1.49/1.33) * I^2)} - 1.33 * H)^2}{(1.49\sqrt{1 - ((1.49/1.33) * I^2)} + 1.33 * H)^2}$	3.3
L	average	$(J + K)/2$	-
O	transmission	$1 - G - (1 - G) * L$	3.25

- Appendix B -

Glossary

abbreviation	explanation
A.D.	anaerobic digestion
ADP	adenosine diphosphate
ASTM	American Society for Testing and Materials
ATP	adenosine triphosphate
CHP	combined heat and power
EBS-Wien	main waste water treatment plant Vienna
ESA	economic and social affairs
ESRL	Earth system research laboratory
GHG	green house gas
GIS	geographical information system
G3P	glycerinaldehyd-tri-phopshate
HRT	hydraulic retention time
IWMI	International Water Management Institute
$NADP^+$	nicotinamide adenine dinucleotide phosphate
$NADPH_2$	methylenetetrahydrofolate reductase
PAR	photosynthetically active radiation
PAV	photosynthetically active volume
PBR	photo bio reactor
PE	population equivalent
PFD	photon flux density
PMMA	Acrylic glass
PR	phosphorus rock
PSI	photo system 1
PSII	photo system 2
PV	photovoltaic
PVGIS	photo voltaic geographical information system
RuBP	Ribulose-1.5-biphosphate
tKN	total Kjeldahl Nitrogen
TOA	top of atmosphere
UN	United Nations
UV-C	ultraviolet C
WHO	World Health Organization
WWT	waste water treatment

abbreviation	explanation
c_p	specific heat of water
C_x	micro-algal concentration
d	length of PAV
E_{550}	average energy per mole of PAR
E_{690}	average energy per mole of ($680nm$-$700nm$)
F_E^{demand}	Energy demand to heat algal culture
G	global irradiance
G_d	diffuse irradiance
G_{th}	heat conductivity
ΔH_{CH2O}	enthalpy of combustion of sugar
I_t	irradiance transmitted into PAV
I_{PBR}	irradiance on surface
k	thermal conductivity
$m(\xi)$	optical path length
P	energy absorption rate
P_{algae}	energy conversion rate into algal internal energy
P_{heat}	total heat production rate
P_{PS}	energy transformation rate through PS
P_{Q1}	heat production rate because of PnAR
P_{Q2}	heat production rate because of photo inhib.
P_{Q3}	heat production rate because of PS-inefficency
ΔQ	general loss converted into heat
Q_{algal}	heat produced by algae
R_s, R_p	coefficients of reflection
ΔT	algal induced temperature
T_{air}	ambient temperature
T_{opt}	optimum temperature for algal production
ΔU	internal energy of micro-algal system
ΔW_{abs}	general light absorbed to produce sugar
$Yield_{algae}$	algae production yield rate
$Yield_{CH2O}$	sugar yield rate

abbreviation	explanation
β	specific absorption coefficient
Θ	incident light angle
λ	wavelength
ξ	zenith angle
Φ	PFD suited for the reaction center
Φ	PFD available for the antenna center

Table B.1: *Used constants*

constant	explanation	value
c	speed of light	$299,792,358\frac{m}{s}$
h	Planck's constant	$6.626068 * 10^{-34}\frac{m^2kg}{s}$
N_A	Avogadro's number	$6.02214 * 10^{23}$
σ	Stefan-Boltzmann's constant	$5.67 * 10^{-8}\frac{J}{m^2sK^4}$

- Appendix C -

Paper and Poster presented on BC&E 2012

ASSESSMENT OF MICROALGAE PRODUCTION IN PHOTO-BIOREACTORS FOR VERTICAL FARMING IN URBAN AREAS

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ABSTRACT: In 2050 around nine billion people will live on this planet with the majority situated in mega-cities or urban areas. Securing food supply and at the same time considering the finiteness of resources, calls for smart concepts towards closed loop cycles in order to reduce transport loss and distance and the need for (fossil) nutrient supply. With about 95 EJ a year the food sector accounts for around 30% of the world's total energy consumption including the production and distribution of fertilizers. A key technology in this respect could be the artificial eutrophication process triggered by the effluent from urban wastewater treatment plants. The cultivation of microalgae in closed photo-bioreactors (PBRs) has attracted significant research efforts in the last decades. PBRs mounted on the claddings of multi-storeyed buildings could continually generate high amounts of biomass and might even qualify for carbon credits. In the proposed concept anaerobic fermentation tanks produce methane out of the algal carbon and hydrogen content to provide energy. The nitrogen and phosphorus content of this biomass is used as fertilizer in vertical farms, thus reducing food production chain to a minimal volumetric expansion of a few city blocks. In case of Vienna it is shown that an energy self-sufficient nutrient recycling method allowing a city intern food production to be independent from phosphor rocks and fossil fuels is possible.
Keywords: biofertilizer, biogas, centralized, microalgae, recycling

1 INTRODUCTION: TODAYS FOODPRODUCTION

It is a sad fact that nearly one eighth of the world population does not have enough to eat [1]. It is important to note this although this topic will not be further discussed in this paper, it should always be kept in mind. The food security of the industrialised countries highly depends on three non-renewable resources, fossil fuel, methane (CH_4) and phosphor rocks (PRs). With about 95 EJ a year the food sector accounts for around 30% of the world's total energy consumption [2]. More than one per cent is used solely for the production and distribution of *nitrogen, phosphorus- and potassium-fertilizers* [3]. The burning of worldwide reserves of crude oil and natural gas mostly provides this energy. A simple shift to renewable energies is necessary but would not entirely free food production from the dependence on fossil fuels.

The *Haber-Bosh process* for example was developed in the beginning of the 20th century and was improved over years reaching a today's energy consumption close to the theoretical minimum [4]. The formation of NH_3 requires hydrogen. H_2-stripping out of CH_4 is the best technology available, making this resource highly important for fertilizer industries. Dawson and Hilton [3] predict that if all reserves of natural gas would only be used for ammonia production, the demand could be satisfied for thousands of years.

Furthermore oil refinery is the mother of many different economic sections. Amongst others it is the main producer of sulphur. Sulphur is further burned to get sulphuric acid, which is "...the 'acid of choice' for the dissolution of PR..." [3]. Thus it becomes evident, that there is a double dependence on crude oil: It is needed for the extraction of sulphur as well as for the burning of the latter. FAO-2008 [5] gives a forecast for *phosphate fertilizer* supplies by 2011-2012 of about $45*10^6$ tonnes P_2O_5. The origin of this phosphate is mainly PR, thus making world reserves of this mineral highly interesting. About 42% of these reserves are assumed to lie under Moroccan territory [6]. Related to the upcoming *oil peak* a so-called *phosphor peak* is to be expected in the next decades [7]. Better technologies to dissolve P_2O_5 out of the residues saved from todays PR-mining could prolong the reserve's lifespan but would not change the fact that this resource is finite. According to Cohen, D. [6] and Dawson and Hilton [3] a consumption rate related to todays lifestyle could only be ensured for the next 100-400 years.

Another great part of the mentioned 30% of the world's total energy consumption is used for the transportation, processing, retailing and production of food excluding fertilizer industries [2]. Energy is mainly provided by fossil fuels. Combined with CH_4 released into the atmosphere from livestock farming, food production makes for a great share in global green house gas (GHG)-emissions. Growing consumption increases the amount of emissions as well as of the land and water used for food production. In 2008 about 11% of the world's ground surface was used for crop production while using 70% of all water withdrawn from aquifers, streams and lakes for irrigation. [8].

Several concepts to work against these trends have been developed. FAO-2011 [2] predicts that a change to diets including "...the use of more fresh and local foods..." is indispensable. This would also reduce food losses and the demand for energy, water and land. In fact 1/3 of the food is lost during production, processing and distribution today [9]. This does not take into account that only a small share of used fertilizer can be found in food meant for the consumer. Nitrogen (N) and phosphorus (P) are also lost during farming through erosion into lakes and rivers and finally into the ocean thus causing eutrophication changing ecological systems.

Alternative methods for the production of high quantities of food are quite common in lower developed countries and strictly forbidden in Europe because of their destructive impacts on nature and consumer. One is

known as the technique of slash and burn: High amounts of forests are slashed every year around the world before the dry seasons. In times with less rainfall the wood can dry and is burned afterwards to release its nutrients into the subjacent soil. This gives a short-term boost to the soil's "nutritiousness" being exhausted after a few crops because of high erosions. When harvest turns out badly the farmer moves to another part of the forest to repeat the procedure, leaving behind a field badly qualified for reforestation. The negative impact on ecosystems and the often-occurring non reversibility of the soil condition is well known but slash and burn is still used from between three and seven per cent of the world population [10] most times because of the lack of possibilities.

Another common method is the direct use of human faeces from wastewater streams. According to the WHO, as cited in [11] nearly 700 Million people are reliant on a food supply, the production of which involves the use of human faecal fertilizers, triggering diarrhoea related diseases such as cholera killing 2.2 Million of them every year. Although this is yet another proof of bad conditions in these countries, recycling of nutrients from sewerage could be an option for the rest of the world as well. The *International Water Management Institute* (IWMI) argue that "...the social and economic benefits of using untreated human waste to grow food outweigh the health risks." The "...dangers can be addressed with farmer and consumer education..." (IWMI, cited in [11]). We suggest that an advanced technology for the recycling of essential elements could reduce 1st worlds dependency on the fertilizer industry and in that context on fossil fuels and PRs.

2 ROOM FOR IMPROVEMENT

The world population prospects of the *UN's Department of Economic and Social Affairs* (ESA) gives different forecasts for this century. Their overall conclusion is that the amount of people living on this planet will increase until 2050 to a total number between eight and twelve billion [12]. About nine billion people would need a 70% increase of food production compared to 2005-2007 [13]. To meet this demand and to ensure food security for the next generations, new food production chains have to be developed. In order to achieve this several factors have to be improved:

2.1 Reducing food miles

From a today's point of view it seems quite impossible to reach the "20/20/20-targets" given by the European Commission [36] in the next eighteen years. The information that a 20% share of renewable resources in commercially used energy is hard to reach shows us, that the consumption should rather be avoided than its sources substituted. This could largely be achieved by reducing food transportation. Sensitisation of the consumer about the ecological costs of imported luxury goods could do one´s bit as well as logistic improvement or a decrease of the volumetric expansion of the delivery chain for essential nutrition. These changes would have another positive effect:

2.2 Avoiding food losses

Distribution plays a great role in wasting edible material. Its consequences differ from region to region according to the average temperature and the availability of cooling systems. Big regional differences can also be found in "kitchen-related" food wastes as well as in the generally high crop losses [9]. In order to avoid these wastages, including the one generated by post harvesting storage, new techniques and models for food production are required.

2.3 Managing Earths finite surface

The fact that we have to be on the lookout for other techniques and models becomes also obvious when considering the increasing need for land. Because of earths environmental limits this need has the potential to become a limiting factor for the growth of the world population and for food security.

2.4 Less irrigation

As the SOLAW-report [8] shows, in many parts of the world with a high physical water scarcity a large amount of water is used for irrigation. The knowledge about plant physiology helps to decrease watering of the fields by using low budget upgrading ideas and outlines the benefits of higher technologies used for example in green houses.

2.5 Freezing of mineral *N- and P-fertilizer*

Another benefit of more controlled environments like green houses is the lower nutrients run off. This does not only positively effect the surrounding water bodies but also the respective economy. Furthermore the "entanglement" of mineral *N-and P-fertilizer* production with non-renewable resources calls for a search for alternatives!

3 A CONCEPT TO ENSURE FOOD SECURITY…

3.1 Vertical farms

Despommier, D. [14] discusses the idea of a fully controlled agriculture. In so-called *vertical farms*, food could be produced minimizing cultivated area and shifting production into town at the same time. Many models have been developed in regards to what such farms could look like, all of them are following the same guidelines: Multi-storeyed buildings sheltering different cultivation methods should produce the nutrient demand of the citizens living within a small radius around the production place. Different well-known techniques could ensure a year-round harvest in perfectly controlled environments. Despommier, D. [14] predicts that *pythotrophologie* is advanced enough to create healthy food in an artificial environment. Some of the numerous advantages are listed below (after [14]):

- Year-round crop production
- No weather-related crop failures
- Use of 70-95% less water
- Greatly reduced food miles
- More control of food safety and security

If demand is covered by this kind of "indoor" agriculture, conventional farming could be abandoned, thus allowing the ecosystem to recover. After shrubs and bushes have regained territory, growing trees would bind atmosphere's carbon dioxide (CO_2) building a serious

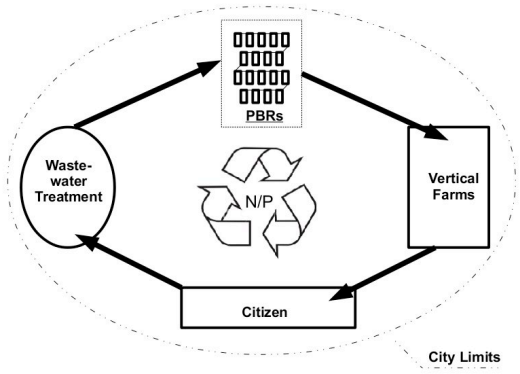
opponent against GHG-emissions. Another advantage would consist in the low consumption of *N-and P-fertilizers* because of the prevented erosion. How to provide vertical farms with the still necessary amount of N and P without the use of non-renewable resources will be further discussed:

3.2 Bio fertilizer production in photo-bioreactors

As mentioned in the introduction, recycling of essential elements (in this paper focusing on N and P) out of agricultural and urban wastewaters will be necessary in the future. Algae have been the object of research for the purpose of recycling since the mid of the previous century [15]. Looking at the undesired effects of *eutrophication* in water bodies contaminated with sewage, the need for controlled combination of wastewater treatment and algal production leaps to the eye. Modern wastewater treatment plants offer different linkages to a commercial production of algae. In general they generate effluents with nutrient loadings, too high to be released into water bodies. One example is the "centrate" generated when *activated sludge* is dewatered after undergoing an *anaerobic digestion process*. With around 1600mg/L *total Kjeldahl nitrogen* and 53mg/L phosphorus (see note 1) this liquor is rich in nutrients and would be well suited for artificial algal production in a thinned out form. Up to 15% and 4% N and P deposited into canalization could respectively be reused in this way. For this purpose the amount of bacteria and protozoa have to be reduced. This could be accomplished by means of several techniques. According to their research Cho et al. [16] suggest a $2*10^{-7}$m-pore size filter rather than *autoclaving* or a high radiation with *UV-C* light.

Different methods for the cultivation of algae have been developed in the last decades. Most of them rely rather on the production of microalgae than macroalgae - like seaweed. Depending on the strain, microalgal growth can be accomplished through *photoautotrophic*, *heterotrophic* or *mixotrophic cultivation*. While in *heterotrophic* cultivation, algae are fed a carbon source, such as sugar, and grow without light, *photoautotrophic cultivation* strategies use big surfaces to capture photons for photosynthetic plant metabolism' [17]. For large scale applications only solar radiation (compared to artificial lightning) is considered feasible as a photon source for *photoautotrophic cultivation*. Literature gives plenty of data about this method of algal production in several systems including *photo-bioreactors* (PBRs), *open pond-* and *race way-systems*. In contrast to *immobilized cultures*, where algae grow on a thin film [18] the previously named systems contain high amounts of water in which microalgae can move and are mobile. Because of their architecture, highest values for photoactive volume (PAV) mixed with the smallest surface area possible can be found in modern flat plate PBRs. This combination supports the highest production rate related to the volumetric expansion of the facility. To reduce needed ground area PBRs could be mounted vertically on the claddings of cities buildings. This would not only save land but would produce the biomass in the vicinity of its consumption place.

For the production of biofertilizer, only the N and P content of the algal biomass is of importance. This allows the application of a harvesting method completely different to the one normally used in the *biofuel sector* where a high lipid content of the algal product is the ultimate goal. After a simple settlement process *anaerobic fermenters* could extract carbon, hydrogen and oxygen content of the water-algae mixture. This content would form CH_4 and CO_2. The biogas could produce the necessary energy for further centrifugation of the *fermenter effluent* and for other parts of the production chain. After centrifugation the dry part could be used as soil conditioner as predicted in Collet et al. [19]. But the liquid part should also be investigated in view of its potential as common fertilizer for agriculture if produced in a non-N/P-limited way.



Picture 1: A carbon intelligent food production chain

The combination of vertical farming and the recycling of nutrients from wastewater streams through a *controlled eutrophication* in PBRs mounted on the claddings of the cities buildings, would result in a truly carbon intelligent food production chain (q.v. **Picture 1**). The impact on traffic, the stability of the world's non-renewable resource reserves and on the GHG-emissions could be highly positive.

4 … COMPUTED FOR VIENNA

As an example the concept of nutrient recycling in PBRs will closer be investigated with regards to the prevalent conditions in Vienna. The only location-specific parameters necessary for a profound estimation are the sunlight irradiance intensity, duration and the temperature of the surrounding air. This data is measured and recorded by meteorology stations. Primarily to provide a tool for the estimation of *photovoltaic* (PV) *energy* generation in European countries Suri et al. [20] collected the data of solar irradiation in a 1km-1km resolution for 30 European and candidate countries. The combination of this data with a *geographical information system* (GIS) can be found as an interactive map on the website of the *photovoltaic geographical information system* (PVGIS) [21]. The radiation power in [W/m^2] is given by the global irradiance (G) and the diffuse irradiance (G_d), hence particles in the atmosphere scatter sunlight and bring solar radiation into corners where no direct light can get. PVGIS provides these values for horizontal surfaces averaged on a fifteen minutes basis under a real sky.

When converted into a horizontal surface, 50% of these

irradiances are lost (after Slegers et al. 2011 [22]). Furthermore direct sunlight irradiance should be avoided because of its negative effect, the *photo-inhibition*. This can be achieved by always directing flat plate PBRs surfaces away from the sun. Only the façade-reflected light and the diffuse irradiation remain. It can be assumed, that a rough white façade acts similarly to a *Lambertian-scatterer* when radiated. Incident light is being scattered in every direction from -90° to +90° around the surface normal with an average intensity mitigation of 36%. For the average G- and G_d- values in Vienna a sunlight irradiance on the reactors surface of about $I_{PBR} \approx 158 W/m^2$ was calculated according to **formula (4.1).**

$$I_{PBR} \approx (0.5 + 0.32)G_d + 0.64(G - G_d) \qquad \textbf{(4.1)}$$

Due to the fact that I_{PBR} consists of *unpolarized* sunbeams with no excellent direction, the average intensity of the light reaching the photoactive volume can be estimated. With the *refractive indices* of *Plexiglass*, air and water this share (I_{trans}) accounts for approximately 84% of I_{PBR} [23].

Light after transmission through the reactor walls travels through cultural volume. This is where it can be absorbed by the algal culture. The potential for absorbing light is given by the *attenuation coefficient* (α). Slegen et al. [22] for example give an *attenuation coefficient* of $75m^2/kg$. Together with a small reactors' cross-section area of d=3cm and a cultural density of $C_x=1kg/m^3$ the absorbed sunlight (I_{abs}) may be calculated by the *Beer-Lambert-Bouguer law.*

The spectrum of more than the half of this absorbed radiation lies beyond the *photosynthetically active band.* Light with a wavelength between 400 and 700nm can be further used for algal photosynthesis hence it is called *photosynthetically active radiation* (PAR). This has to be corrected because of the relatively week absorbance of chlorophyll in the green band. This part forms about 10% of PAR and reduces the amount of energy used for photosynthesis E_{PS} [24]. In short approximately 39% of the absorbed light intensity can be further used by the photon capturing mechanism of the algae [23].

Assuming that the wavelengths of the light used for photosynthesis are distributed normally provides us with yet another noteworthy difference to the wavelengths suited for activating algal *reaction centers, which* lie at 680nm and 700nm respectively. Fitting PAR, which is accomplished by means of algal *antenna centers,* consumes another 20% [23]. Coming from an average incident irradiance a quite low value of around $I_{PS}=37W/m^2$ can now be converted into chemical energy. This kind of reactor avoids direct sunlight. Here *photo inhibition* does not occur and the entire energy flux can be used to compute further metabolism of the plant.

Like in the stoichiometric formula of the process a minimum of forty-eight moles of photons are necessary to synthesise one mole of sugar in the *Calvin cycle* [24]. The energy content of these photon moles can be computed by using *Einsteins' equation* and the average wavelength suited for the *reaction centres.* One mole of photons belonging to the 690nm spectrum transports an energy of about 174kJ. Compared to 2808kJ heat energy produced by burning one mole of sugar in a calorimeter [25] a maximum *sugar production efficiency* of 33.7% can be found.

The conversion of sugar to algal biomass provides an upgrade in the calorific value of the biomass. It is assumed that this difference equals the mass loss occurring within this process. For an algal strain with a *calorific value* of 21kJ/g the difference to the calorific value of on sixth of sugar (15.6kJ/g) equals an energy upgrade of 34%. An authentication of this assumption is given by mass loss calculations described by Williams and Laurens [26].

Be reminded that the data used for this estimation is obtained from average sunlight irradiances given in [W/m^2]. Energy converted to algal biomass per square meter can now be calculated by multiplying with the total duration of sunlight irradiance [21]. The division through the calorific value of the algae shows the specific yield related to the surface. For Vienna a total irradiation durability of 5212.5 hours a year is used. This value leads to an average yearly production of approximately $7.4kg/m^2$. The small cross-section area used for the flat plate PBRs in this estimation gives a yearly *algal dry weight* yield of around 245g for one litre PAV.

If the calculation is conducted with exact values, the energy losses that belong to algal heat production can be summed up and compared to the temperatures of the Viennese air. By doing so the need for heating and cooling to obtain the optimal temperature for algal growth can be computed. According to Schipfer, F. [23] this leads to an energy demand of around 1.2MJ for every kg *algal dry weigh*t produced in the PBRs.

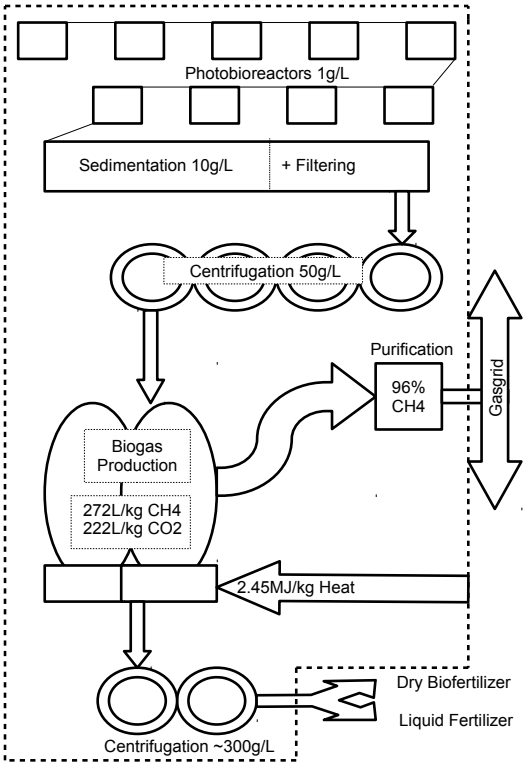
To generate this energy, biogas should be considered as a *joint product*. A theoretical conversion of the algal carbon content to CO_2 and CH_4 can be achieved through high *retention periods* in anaerobic fermentation tanks. According Sialve et al. [27] one half of this carbon (C) could form the CH_4 content in the produced biogas. If one gram algal dry weight contains about 520mgC [28] this amount would produce 272mL CH_4. After washing out the CO_2 content, the biogas could be burned to produce heat and electrical energy. After subtraction of the heat necessary for the *anaerobic fermentation process*, about 9.03MJ *calorific value* biogas would remain for the processing of a single kg *algal dry weight* [23]. **Picture 2** shows the mass flow of such a harvesting process according to Collet et al. [19].

Further physical and economic values for flat plate PBRs are gained from the Austrian company *Ecoduna* [30]. Their technology is distinguished for a quite small energy consumption for the biomass production process. The following **Table I** shows the *specific net energy* for this process, when the reactors are mounted on the claddings of a Viennese building and biogas is used as a joint-product in the harvesting process.

Table I: Specific net energy [MJ/kg]

	Consumption	Production	Reference
Aeration	3.16		[31]
Infrastructure	2.47		[31]
Heating	1.16		[23]
Harvesting	5.99	11.48	[23]
Overall	10.44	11.48	

The estimation promises an energy-self sufficient biomass production. With the nutrients gained from the cities wastewater treatment facility (EBS-Wien), which will be upgraded with *anaerobic digesters* and a flue gas combustion unit, algal fertilizer production could present an interesting alternative to today's mineral fertilizer industry.



Picture 2: Harvesting algal-fertilizer

The other side of the picture is marked by quite high installation and maintenance costs arising in the presented theoretical concept. According to Mohr, M. [30] $1.4*10^6$ L PAV in flat-plate PBRs could cost about 2.240.000€. It is assumed that this volume is the maximum that a 100m*100m façade could tolerate. The installation costs to ensure a mass flow on such a horizontal hectare can be found in **Table II**. References used for calculating these values through up- and downscaling are cited as "Following".

Table II: Estimated and rounded costs

	Costs in €	Dimensioning	Following
PBRs	2.240.000	$1,4*10^6$L	[30]
Centrifuge1	158.000	$5,0m^3/h$	[31]
Centrifuge2	19.000	$0,6m^3/h$	[31]
Gas Wash	20.000	$16,3m^3/h$	[32]
Connection	33.000	250m	[32]
Fermenters	168.000	$800m^3$	[32], [37]
$\Sigma_{Installation}$	2.638.000		

The purification of the biogas can be found as "Gas Wash". "Connection" stands for an access to the commercial gas grid with *coagulants*, *safety system* and *odour addition*.

After Molina Grima et al. [31], yearly maintenance costs of 4% of the above mentioned installation fees are calculated. With an energy self-sufficient biomass production in mind, no further charges for electricity have to be computed. Depreciation (set for 15 years) plus maintenance are the yearly costs that will later be compared with the benefits.

The main idea behind the concept is the production of biofertilizer. The theoretical products of this model are dry soil conditioner on the one hand and *liquid algal fertilizer* on the other. For the calculation of the benefits, these two products will not further be distinguished but will be treated as one. According to Park et al. [28] the N-and P-share of the produced biomass will be estimated and multiplied with the fertilizer values given by Matzenberger, J. [33].

Methane excess is fed to the gas grid and generates a yearly income depending on regional gas prizes. Timmerer and Lettner [32] estimate a value of 1.63cent/kWh for the year 2004. Furthermore profits for binding carbon dioxide can be calculated according to the certificate prize listed on *BlueNext* [34]. Even if a crisis hits this market the theoretical profit should be considered. To accumulate the C-content of 1kg algae around $1,9tCO_2$ can be bound [28]. The income of this sector is calculated with the averaged prize of $6,99€/tCO_2$ from April 2012 [34].

Another profit is generated through facilitating EBS-Wien from wastewater. Disposing $1m^3$ sewage in Vienna in 2012 costs 1,89€ as set by the respective Municipal Department [35]. Supposing that the same prize would be paid for absorbing $1m^3$ wastewater, this provides a good source of income.

For the profits the averaged algal dry weight production, calculated for this paper was used and multiplied with the theoretical PAV for one vertical hectare. Results are shown in **Table III**.

Table III: Estimated and rounded balance

	Costs in €	Dimensioning	Following
Depreciation	176.000	15 years	
Maintenance	106.000	4% a year	[32]
$\Sigma_{Expenses}$	281.000	a year	
N-fertilizer	20.000	25t	[33]
P-fertilizer	4.000	4t	[33]
WW-boni	47.000	$25.000m^3$	[35]
CO_2-Certif.	4.000	519t	[34]
CH_4-Excess	1.000	78.000kWh	[32]
Σ_{Income}	75.000	a year	

The estimation of the biomass production with exact values generates benefits 33% lower than given in **Table III** [23]. The reason for the overestimation in this paper mainly lies in ignoring *photo inhibition,* which would have to be considered in the summer months. This leads to an overall assumption, that the concept could only

become economically feasible if fossil fuels, fertilizer, wastewater boni and CO_2-certificates undergo a 4-fold price increase.

5 CONCLUSIONS AND OUTLOOK

Except for the CO_2-certificates no price increase can truly be expected in the near future. The only assumption for the economic part of this paper that can be made in good conscience is that the balance will turn positive at the latest with the expiration of natural gas, crude oil or PR-resources. This paper demonstrates a promising approach for an energy self-sufficient N- and P- recycling method that can be applied on any vertical surface. It provides a smart city concept to tackle GHG-emissions and fossil fuel consumption without exhausting valuable urban area. Combined with the concept of vertical farming, life cycle assessments of the food consumed by tomorrow's citizens could do without a single transport mile, thus freeing the population from a great part of the current traffic at the same time. Through this more efficient way of using earth's surface, food security for a much larger world population could be ensured and atmosphere's CO_2 could be mitigated through reforestation. The waste of food, fertilizer and water could be reduced considerably. Avoiding nutrient run off would also contribute to the countless ecological benefits, which have to be further investigated.

Further research will be needed. Different climates should be computed as well as other harvesting techniques. The wastewater industry has developed many different concepts for reusing essential elements like N and P, which should also be investigated and considered. Another important future project regarding the presented idea would be to spot the algal strain, best suited for this task. Furthermore a biological and medical point of view would be interesting and is necessary for the development of a closed urban nutrient cycle.

7 NOTES

(1) After an E-mail from Harald Hanssen, Hamburg Wasser, 19.03.2012.

Wastewater treatment in Hamburg provides comparable values for the wastewater treatment in Vienna according to their *population equivalents*.

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9 ACKNOWLEDGEMENTS

- Our special thanks to the Technical University of Vienna (TU Wien), especially to the Energy Economics Group, for making a Diploma Thesis about this topic possible and for the financial and personal support.
- Furthermore I would like to thank the University of Vienna, especially Regina Hitzenberger from the Faculty of Physics for important advices concerning the estimation of algal sunlight utilization, for a sympathetic ear and for the allowance to cooperate with the TU Wien.
- Best thanks to my friend Marianne Schlögl who took up the fight to save the readers from my “Austrian Englisch”.

ASSESSMENT OF MICROALGAE PRODUCTION IN PHOTO-BIOREACTORS FOR VERTICAL FARMING IN URBAN AREAS

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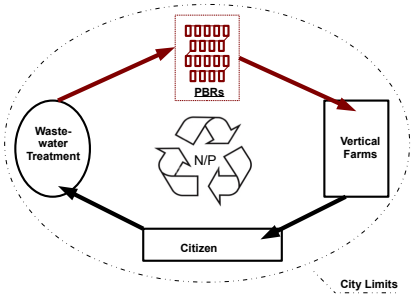
Keywords: biofertilizer, biogas, centralized, microalgae, recycling

„The great challenge the world now faces is to develop global food systems that emit fewer GHG emissions, enjoy a secure energy supply and can respond to fluctuating energy while at the same time support food security and sustainable development." [1]

In 2050 over 9 Billion people will live on this planet with about 70% situated in mega-cities or urban areas [2]. With about 95 EJ a year the food sector accounts for around 30% of the world's total energy consumption including the production and distribution of fertilizers. [1]

How can we ensure food security?

With an urban food production and the recycling of nitrogen and phosphorus out of agricultural and urban WW-streams:



PBRs mounted on the 100m*100m façade of a building in Vienna/ Austria could produce
≈271.000 kg algal dry weight/ year

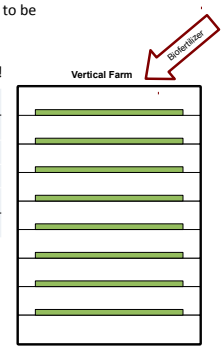
Algal N- and P-contents are of interest for further use as biofertilizer.
In the proposed concept C- and H-content are used to form CH_4 in anaerobic fermentation tanks as a joint-product.

Due to environmental conditions in Vienna, reactors have to be heated with about 1,16 MJ/kg algal dry weight.

CH_4 combustion makes this process **energy self-sufficient**!

	Consumption	Production	Ref.
Aeration	3,16 MJ/kg		[3]
Infrastructure	2,47 MJ/kg		[3]
Heating	1,16 MJ/kg		
Harvesting	5,99 MJ/kg	11,48 MJ/kg	
Overall	10,44 MJ/kg	11,48 MJ/kg	

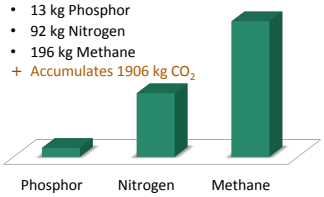
Energy self-sufficient algal fertilizer production!
CO_2 is pumped through the circulating photo active volume of turning flat plate PBRs (*Aeration/ Infrastructure*). Providing the right temperature leads to microalgae production. During the harvesting process, biogas is extracted and provides the needed energy.



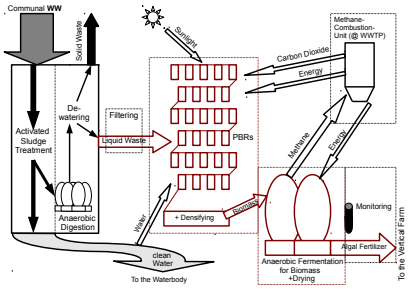
Cultivation of microalgae pruducing methane as a joint-product:

1 tonne algae can supply
- 13 kg Phosphor
- 92 kg Nitrogen
- 196 kg Methane

\+ Accumulates 1906 kg CO_2



The process –from communal waste-water to the vertical farm:



Products and reliefs of the nutrient recycling process:
- Dry algal fertilizer (Soil Conditioner)
- Liquid algal fertilizer
- CH_4-Excess
- CO_2-Certificates
- WW-centrate-boni

The priceless advantages:
- Independency on crude oil
- Positive energy balance - No use of natural gas
- An alternative to phosphor rocks
- Oxygen- instead of GHG-Emissions

Further use of biofertilizers in vertical farms [4]:
- Substantially reduce food miles
- Use of 70-95% less water
- More control of food safety and security
- Year-round crop production

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