THEORETICAL STUDY TO IMPROVE THE ENERGY BALANCE IN WASTEWATER TREATMENT PLANT

Investigation of microalgae photobioreactor in biological treatment step and open algal pond in reject water treatment in Uppsala and Västerås

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ABSTRACT

The self-treatment system of nature cannot handle man-caused high rate water pollution on its own, therefore cleaning in wastewater treatment plant (WWTP) is necessary to avoid eutrophication – excessive enrichment of nature by nutrients. Current technologies applied in WWTPs are old, outdating and highly energy demanding, especially biological treatment step generally requires large amount of energy for aeration of water. The alternative to current system could be microalgae treatment step, which would use green algae to consume pollutants present in the waste water, namely nitrogen, phosphorus and heavy metals. Via photosynthesis it could produce oxygen required for biological oxidation of organic matter. Furthermore carbon source is necessary for microalgal growth, this can be added to the water as CO2 produced in other industries and so decrease global greenhouse gas footprint. Co-digestion of microalgae with undigested wastewater sludge under mesophilic conditions can give a synergic effect for biogas production, therefore harvested and co-digested microalgae could contribute to positive energy balance of WWTP.

Full-scale microalgae cultivation in WWTP can be achieved only when good grow is guaranteed. This is a result of many factors, particularly access to nutrients, light condition, water temperature, and pH. The goal of master’s thesis was to understand and evaluate main factors influencing algal growth using literature review, propose design of microalgae treatment step with artificial lights and evaluate energy balance, of wastewater treatment plants in Uppsala and Västerås with new design.

The work proposed two different designs of microalgae treatment steps, modelled in Excel and applied to current state of municipal WWTP in Västerås and Uppsala with belonging satellite plants.

The first design of microalgae activated photobioreactor (MAASPBR) aimed to replace current biological treatment step. This is possible in Västerås and Uppsala WWTPs if microalgae can consume 75% of total nitrogen (N_{tot}) and produce at least 13.5 and 2.4 tonne O_2/day in Västerås and Uppsala respectively. The sensitivity analysis showed that minimal volumetric algal yield of 0.15 kg/m^3,day and 0.25 kg/m^3,day is required for Västerås and Uppsala respectively, when oxygen production rate of 1.92 kg O_2/kg microalgae is assumed. Furthermore harvested and co-digested algae with sewage sludge contributes to significant increase of biogas production and negligible transportation energy increase.

The second design of open algal pond for reject water (OAPRW) aims to cultivate microalgae on reject water with high concentration of nutrients, generated in sludge centrifuge. The model assumed high algal growth due to excessive amount of nutrients and increased water temperature to 24°C. Results show a possible 23% and 20% electricity saving on blowers in the biological treatment in Västerås and Uppsala respectively.

Both models have positive impact on energy balance in all WWTPs, however MAASPBR has greater uncertainties, because this type of photobioreactor has not been tested unlike OAPRW which has been tested in pilot plant scale.
KEY WORDS

Energy balance, Wastewater treatment plant, Microalgae, Photobioreactor, Open algal pond

PREFACE

This research has been performed during the spring semester of 2015 in close collaboration with ACWA team in Mälardalen University and cooperation with Uppsala and Västerås WWTP in order to get master’s degree in School of Business, Society and Engineering at Mälardalen University. The work began with literature review to deeply understand processes in wastewater treatment, factors influencing microalgal growth and previous works in microalgae treatment. Input data were collected and used in models, which were built in Microsoft Excel. Equally divided workload resulted in deep discussion between the authors, the calculation part was more performed by Richard and report writing by Matej. This work could not be accomplished without strong help of several people to whom we would like to express our gratitude. First, we are thankful to Jesper Olsson and Eva Thorin for supervision and their expertise and thorough knowledge of the subject. We also want to give special thanks to Ernst-Olof Swedling from Kungsängen-Uppsala WWTP, and Peter Granath from Kungsängen-Västerås WWTP for their help with collecting necessary data.
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<tr>
<td>CH$_2$O</td>
<td>Organic compounds</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Carbon dioxide</td>
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<tr>
<td>CO$_3^-$</td>
<td>Carbonate</td>
</tr>
<tr>
<td>FeCl$_2$</td>
<td>Iron chloride</td>
</tr>
<tr>
<td>FeSO$_4$</td>
<td>Iron sulphate</td>
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<tr>
<td>HCO$_3^-$</td>
<td>Hydrogen carbonate</td>
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<tr>
<td>NH$_4^+$</td>
<td>Ammonium</td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>Nitrate</td>
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<td>NO$_2^-$</td>
<td>Nitrite</td>
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<tr>
<td>P$_{tot}$</td>
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<tr>
<td>PO$_4^{3-}$</td>
<td>Inorganic orthophosphate</td>
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<tr>
<td>PO$_4^{3-}$</td>
<td>Orthophosphate</td>
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<tr>
<td>BMP</td>
<td>Biochemical methane potential</td>
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<td>BOD</td>
<td>Biochemical oxygen demand</td>
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<td>BY</td>
<td>Biomass yield</td>
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<tr>
<td>Ca(OH)$_2$</td>
<td>Calcium hydroxide</td>
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<tr>
<td>DAF</td>
<td>Dissolved air flotation</td>
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<td>DO</td>
<td>Dissolved oxygen</td>
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<tr>
<td>HRT</td>
<td>Hydraulic retention time</td>
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<tr>
<td>MAAS</td>
<td>Microalgae activated sludge</td>
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<tr>
<td>MAASPBR</td>
<td>Microalgae activated sludge photobioreactor</td>
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<tr>
<td>PAR</td>
<td>Photosynthetically active radiation</td>
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<tr>
<td>RWP</td>
<td>Raceway pond</td>
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<td>RWP$s$</td>
<td>Raceway pound systems</td>
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<tr>
<td>TS</td>
<td>Total solids</td>
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<td>VS</td>
<td>Volatile solids</td>
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<td>WWTP</td>
<td>Wastewater treatment plant</td>
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1 INTRODUCTION

Sustainable development is necessary to satisfy demands of society in aspect such as food production, land, water and energy usage. These sources are however strictly limited because population growth and longer life expectancy, combined with higher standards result in a global increase of demand. Therefore it is necessary to focus on the development of renewable energy sources, produce energy with higher efficiencies and reduce greenhouse gas emissions.

Currently about 2.8 billion people are facing water scarcity and estimates by Rodriguez et al. (2013) show that almost half of the global population will be exposed to higher water shortages by 2030. This will drastically influence food and energy security.

The environment is dramatically influenced by humanity’s industrial production, agriculture as well as households. Pollutants are released to the water at high rates. Therefore, the self-treatment system of nature cannot handle it on its own and water needs to be cleaned by humans. This water is collected in wastewater treatment plants (WWTPs) where it is purified by various processes of physical, chemical or biological character. After treatment, water can be either discharged back to natural bodies or reused for specific purpose according to its quality (Hammer, 2001). In order to achieve a greater efficiency in the cleaning process and energy use, new technologies need to be developed and applied. As an example is ongoing research within the field of microalgae treatment in wastewater treatment plant, where microalgae helps to clean water from pollutants. The emphasis is laid on ability to produce dissolved oxygen which is necessary for reducing organic materials in water. It is expected that using the microalgae in WWTP will result in positive contribution to the overall energy balance.

1.1 Background

Conventional treatment of wastewater is done in 3 consequent steps: primary, secondary (biological) and optionally tertiary step (Malik, 2014). Typical municipal wastewater treatment systems consist of one big plant in a city, where sludge is digested under mesophilic or thermophilic condition, and satellite plants outside the city (Svensk Vatten AB, 2010).

A purpose of the primary step is to remove solid particles and decrease biochemical oxygen demand (BOD), which is the amount of oxygen required to be consumed by microorganisms for breaking down organic material present in wastewater. The mechanical processes, screening and raking, remove large solids and increase the amount of dissolved oxygen in the water, which is suitable for aquatic organisms. After sedimentation, approximately 60% of solid particles are removed and BOD is decreased by 20% – 30%. (Malik, 2014)

The secondary step is designed to significantly reduce organic particles that were not caught in first step, and is also responsible for nitrogen removal. For this purpose biological processes
are used where microorganisms are fed by the organic particles in the water. Secondary treatment requires a great amount of electricity, consumed by compressors, for increasing the amount of dissolved oxygen (DO) in water, which is consumed by microorganisms in order to reduce BOD up to 85% and total nitrogen (N$_{tot}$) up to 70%. (Malik, 2014; Binh, 2013)

The tertiary step uses advanced technologies to remove the remaining pollutants. Especially important is to remove phosphorus, which can cause eutrophication - excessive enrichment of natural bodies by nutrients. In this treatment step heavy metals are also removed. Among optional technologies for the third step belong filtration by sand or active carbon, sedimentation in wetlands and biological treatment by macrophytes (aquatic plants possible to see) and small invertebrates. In some treatment plants chlorine is added to disinfect before the water is returned to nature. This step makes WWTP very expensive, but in total 99% of impurities can be removed from wastewater. (Hammer, 2001; Malik, 2014)

The sludge produced from water treatment is commonly stabilized by anaerobic digestion resulting in nutrient rich fertilizer and combustible biogas with high methane content. Biogas production should be increased and optimized because its production has a positive impact on the overall energy balance of WWTP. It is also considered as a renewable energy source, which contributes to the conversion from fossil fuels. (Tchobanoglous & Burton, 2002)

It was shown by Oswald (1988), de la Noüe et al. (1992), Garcia et al. (2000) and Larsdotter (2006) that typical wastewater composition contains carbon sources, nitrogen (N), phosphorus (P) and other trace elements in advantageous ratios for microalgal growth. The elements N and P, which are considered as main pollutants in wastewater, can be treated by microalgae and considered as their food. Therefore the opportunity arises to replace the old biological treatment step with microalgal cultivation ponds.

Algal growth is sensitive to many different factors (see chapter 2.1), but it is mainly affected by light conditions. Algal growth can be performed under natural sunlight or artificial light. The example of naturally illuminated systems are open algal ponds, also called raceways. They offer relatively low cost solutions with low level of protection from non-desired species, big areal footprint and limited regulation of growth conditions, especially optimal light and temperature (Chestney, 2012). On the other hand, artificially illuminated closed photobioreactors can solve the problems of open pond systems, although the investment cost is significantly higher. Their design varies extensively from simple plastic bags up to sophisticated photobioreactors, which can monitor and regulate light intensity, flow of water and microalgae harvesting (Rittmann, 2008).

In order to cultivate microalgae for water treatment in a full-scale system it has to be harvested continuously. This causes obstacles on the way from laboratory experiments to full scale WWTP (Nyomi et al., 2010). The work of Granados et al. (2012) tested various methods for separation, and concluded that the most efficient procedure is to flocculate microalgae with cationic polymers followed by gravimetric sedimentation or flotation. The high concentrations obtained by the proposed method of separation allowed microalgae dewatering equipment to be smaller and therefore cheaper.
It was show by Brune et al. (2009), Khalid et al. (2011) and Mata-Alvarez et al. (2011) that increased C/N ratio of digestant has a positive impact on biogas yield. The co-digestion of microalgal biomass, collected from wastewater treatment, is rich in proteins and could increase nitrogen content and produce more biogas. In theory, it is expected that carbon and nutrient content available in microalgae could also contribute to greater biogas production. The recent study of Olsson et al. (2014) showed a possible synergetic solution for increased biogas production by co-digestion of microalgae and sewage sludge in specific ratios resulting in 23% increase of methane production, when microalgae represented 37% of digestant. Wang et al. (2013) also came to conclusion in favour of co-digestion when testing the sole digestion of Chlorella sp. and co-digestion with waste activated sludge, resulting in 73-79% bigger biogas yield when microalgae was co-digested comparing to sole digestion of microalgae.

Taking into account all previous studies and tests, wastewater treatment with microalgal nutrient removal, harvesting microalgal biomass and its co-digestion with sewage sludge could be a promising solution for increased efficiency of heat and electricity production in WWTP.

1.2 Purpose

The WWTPs in Uppsala and Västerås (detailed description in chapter 3.2) are using old technologies to treat sewage water, and probably are not operating with highest possible efficiencies. The goal of this study is to collect data of heat and electricity consumption/production and to perform an overall energy balance on the plants involved. In order to easily compare different plants all energies are related to the unit of treated water and energy balances of satellite plants are incorporated in an overall energy balance.

The work will propose two different designs for energy balance improvement, microalgal activated sludge photobioreactor (MAASPBR) and open algal pond for reject water (OAPRW). Both solutions should remove significant amounts of total nitrogen and continuously produce microalgal biomass, which can be co-digested with untreated sludge and result in greater biogas yield. Furthermore, microalgae produces oxygen as a side product of photosynthesis, thus it can dramatically reduce the operating cost of air blowers.

New algal systems have different consumptions of electricity and also treating efficiencies, therefore new energy balances are recalculated for both WWTPs with both designs. Since assumptions made in the work are strong, based on different works and experiences of experts, the sensitivity analysis reveals conditions which leads to an improvement in the energy balance. The main question is, if the proposed designs of microalgae treatment can have a positive or negative impact on the overall energy balance.
1.3 Scope and limitations

The energy balance will investigate overall heat and power consumption/production of the main municipal WWTPs in Kungsängen-Västerås and Kungsängen-Uppsala where the sludge is digested together with external sludge from 2 and 11 satellite plants respectively.

The total influent wastewater consist of water from households, industry and rainfall, also melted snow, which has influence on water temperature, furthermore on life of aquatic organisms and microalgae.

More in detail will be evaluated electricity consumption of the secondary treatment step with focus on blowers consumption and nutrient removal efficiency. Since the sludge from satellite plants has to be transported to digesters of main plants the delivery by trucks will be taken into the energy balance evaluation. The microalgae treatment step should be capable of nitrogen and phosphorus uptake to vague, therefore chemicals currently used for removal could be saved. The production and transport energy for chemicals will not be considered in the energy balance because they are delivered from other companies.

Evaluation of two different designs with microalgae treatment is applied to full-scale operation of WWTPs. Both designs use similar conditions for wastewater inputs: incoming wastewater flow, temperature and pollutants, also number of connected people and precipitation. More details about certain plants is stated in chapter 3.2

The research is strictly limited to evaluate energy perspectives, no further economic analysis is performed.

1.4 Research Questions

- Will the addition of microalgae treatment step have a positive or negative impact on the overall energy balance?
- What will be the impact of using microalgae in biological treatment step on nutrients removal efficiency?
- What is necessary oxygen evolution by microalgae in order to remove satisfying amount of BOD$_7$?
- What is the effect of co-digestion of microalgae with undigested sludge with respect to biogas production?
- How could a different microalgae treatment step designs effect overall energy balance?
- What will be the impact of increased biomass production on energy use for transport?
2 MICROALGAE

In the past microalgae has been grown on a small scale especially for application in food and feed in North America and Asia. Today, approximately 15 000 tonnes/year of dried microalgae are produced worldwide, which utilize different cultivation systems and have numerous usages e.g. food production, fertilizers, bioplastics, pharmaceuticals, dyes and food ingredients such as omega-3 fatty acids. (Benemann, 2013; Votano et al. 2004)

Microalgae has a potential to remove pollutants present in wastewater with high efficiency at a low energy demand. Optimal algal growth, influenced mainly by light intensity, temperature, pH and suitable ratio of carbon, nitrogen and phosphorus, is necessary to achieve required treatment levels (Grönlund, 2002; Larsdotter, 2006; Votano et al., 2004). Algal growth conditions, as well as application of microalgae in wastewater treatment, are reviewed in following chapter. Practical experiences with algal cultivation are also obtained from biofuel and food production, mainly in USA and China.

Algae and other green plants are basic forms of life called primary producers, since they utilize energy of sunlight to produce living tissues. They are photosynthetic microorganisms with a typical size of 1-50 micrometres in diameter (without roots and leaves). The aquatic animals are not able to manufacture their own food and therefore have to obtain their energy and nutrients by consuming either plants or smaller animals. Therefore, microalgae are placed on the first position in the aquatic food chain (Hammer, 2001). There exist many species living in both fresh and seawater with different properties but the most common are blue-green algae, which are also called cyanobacteria. Energy obtained from light is subsequently used for converting carbon dioxide (CO₂) into energy-rich organic compounds (CH₂O), which are used as building blocks for microalgal growth (equation 1). The oxygen is released and mainly dissolved in water as a side product of photosynthesis. (Janssen, 2002; Larsdotter, 2006)

\[
CO_2 + H_2O+'light energy' \rightarrow CH_2O + O_2
\] (1)

2.1 Algal growth

The main requirement for successful treatment of wastewater by using microalgae is their good growth. To achieve the optimal conditions for the growth of microalgae it is necessary to understand influencing factors. These factors are divided into several groups: chemical factors (nutrients, carbon dioxide, pH), biological factors (competition between species), physical factors (temperature, light) and operational factors, which encompasses mixing and dilution rate. These factors are clearly shown in the Error! Reference source not found. below. (Larsdotter, 2006)


| Table 1 Factors that influence algal growth in a high rate algal pond (Larsdotter, 2006) |
|---------------------------------|---------------------------------|
| Abiotic factors, physical and chemical | Light intensity |
| Environmental factors | Temperature |
| | Concentration of $N_{tot}$, $P_{tot}$, $CO_2$, Heavy metals, $O_2$, pH |
| Environmental factors | Salinity |
| Environmental factors | Toxic chemicals |
| Biotic factors | Pathogens (bacteria, fungi, viruses) |
| Biotic factors | Predation by zooplankton |
| Biotic factors | Competition between species |
| Operational factors | Mixing |
| Operational factors | Dilution rate |
| Operational factors | Depth |
| Operational factors | Harvesting frequency |

Microalgal growth rate is strictly dependent on factors mentioned above, as well as design of reactor. Growth rate of microalgae cultivated in open algal pond, measured in laboratory scale ranges from 0.05-0.20 kg dw/m³, day (Benemann, Jarvis, Milbrant, & Ringer, 2011). However the realistic picture gives experimental microalgae WWTP in Chiclana de la Frontera, operating pilot plant for 3 years in size of 192 m² and prototype plant operating for 6 months in size of 1 000 m². Highest measured growth rate was from 0.30-0.45 kg dw/m³, day. (Rogalla et al., 2015)

When the microalgae was cultivated on reject water (laboratory experiment) 6.2 kg dw/m³, day growth rate was achieved. (Rusten, Sahu, & Vik, 2009)

2.1.1 Light and temperature

Light

As mentioned above the microalgae are using an energy from light, however there exist some strains, which are able to grow in the dark using the organic compounds and carbon sources as energy. According to Oswald (1988) more than 90% of the total solar energy used by microalgae is converted to the heat and less than 10% into chemical energy. To avoid shadowing of algae in lower layers by algae in upper layers in ponds it is recommended to keep water depth between 15-30 cm. In order to avoid photoinhibition (lower photosynthetic effectivity caused by too long exposure of microalgae to sunlight) the accurate mixing is crucial. (Larsdotter 2006; Oswald 1988)

Temperature

It has been proved that temperature between 15-25°C is suitable for most algal species (Borowitzka, 1998). The temperature around 15°C can cause that microalgae easily get photoinhibited by high light intensities, which means it can cause operational constraints on outdoor WWTP in cold climates. On the other hand too high temperature (>35°C) also causes
declined growth of algae (Abu-Rezq et al., 1999), this overheating is a problem especially in humid climates. (Larsdotter, 2006)

2.1.2 pH

Different authors come to different conclusions with respect to the effect of pH on algal growth and species compositions. For example, according to Fontes et al. (1987) optimal pH for cyanobacterium is between 8.2 – 8.4. However, when the pH is around 9, the productivity of microalgae is decreasing significantly and even more in the range of pH 9.7 – 9.9 the cells are unable to thrive. On the other hand Anbalagan (2015) claimed the best conditions for microalgae productivity and nitrifying bacteria growth is the level of pH between 7 and 8, which could be controlled and kept in the required range by CO₂ injection.

2.1.3 Carbon and nutrients

The average algae cell has a typical composition of C₁₀₂H₁₈₁O₄₅N₁₆P. The optimal growth conditions are when a body of water contains these elements in similar mixture. Limiting ratios between nitrogen and phosphorus are 30:1 and 5:1 respectively, however these limits are overcome easily in wastewater treatment due to nutrient concentration often 3 times higher than natural concentration. Therefore light and carbon sources become more limiting growth factors. Nutrient uptake by algal cells depends on concentration difference of specific element in and out of the cell. Turbulent conditions increase diffusion rate and so mass transfer of nutrients is enhanced. (Larsdotter, 2006)

Carbon

Microalgae typically assimilates inorganic carbon in the form of CO₂ or HCO₃⁻ (hydrogen carbonate), which requires inhibition by carbonic anhydrase to be converted to CO₂. Some algal species have the ability to use organic carbon, sugars, organic acids, or glycerol (Oswald, 1988). Some species, Scenedesmus and Chlorella can switch from autotrophic to heterotrophic mode, which can be especially useful in wastewater treatment, where a shortage of dissolved CO₂ can occur. (Larsdotter, 2006)

The amount of dissolved CO₂ can be increased by aeration, but since the concentration of atmospheric CO₂ is 0.00039% it would be very inefficient and energy demanding to reach required concentration (Mauna Loa Observatory, 2015). The solubility of CO₂ radically depends on pH, if higher than 9, then most of inorganic carbon is in form of CO₃²⁻ (carbonate) which is not suitable for algae intake at all.

Nitrogen

Nitrogen exists in a variety of different forms, however the most commonly assimilated forms by microalgae are ammonium (NH₄⁺) and nitrate (NO₃⁻). The preferred compound is ammonium, but concentration is recommended to be no more than 20 mg NH₄⁺-N per litre since higher values become toxic. Another useful forms of nitrogen is urea and nitrite, however these might be toxic even in lower concentrations. (Larsdotter, 2006)
Phosphorus

Next essential element for algal growth is phosphorus, consumed as inorganic orthophosphate (PO$_4^{3-}$). The organic phosphorus can be transformed to PO$_4^{3-}$ at the surface of microalgae cells, especially when there is not enough inorganic phosphorus. In case there is an abundance of available PO$_4^{3-}$ it can be stored within the cells as granulate and used in time of its absence. This attribute makes algae less vulnerable to changes of external phosphorus conditions. (Yaakob et al., 2011)

2.2 Algal cultivation

2.2.1 Open ponds

The most common worldwide cultivation systems are raceway (open) pond, which are shallow, usually 15-30 cm deep and with an elliptical shape. Mixing is achieved by using a wheel, which maintains culture’s velocity between 15-30 cm/s. The substantial advantages of this system are relatively low capital and operating costs. According to International Energy Agency production of biomass in raceway pond systems (RWPs) fall in the range between 15-40 g/m$^2$day (Benemann et al., 2011). On the other hand, RWPs need a large extent of land and the other disadvantages are caused by difficulties in controlling culture contamination, water evaporation and the system is more susceptible to infections. RWPs are not the most effective cultivation system because only 10% of sunlight can be converted into chemical energy in biomass via photosynthesis, but in real conditions this value is much smaller. According to Votano et al. (2004) this value is only 1.5% in algal ponds, which is largely limited by penetration of sunlight into the turbid algal pond. (Chiaramonti et al., 2013; Votano et al., 2004)

2.2.2 Closed photobioreactors

Closed photobioreactors can be flat panel reactors or tubular photobioreactors, which are long transparent tubes with diameter in range 3-6 cm and with a length from 10-100 m. They can be constructed in several different ways: single layer of horizontal tubes (with a small or large number of U-bends); vertical, coiled as a cylinder or a cone; tubes are connected in three-dimensional space with many layers of tubes that are placed vertically on top of each other. In comparison with open ponds the closed photobioreactors have some advantages e.g. possibilities of temperature control, easy salinity control, lower use of water and much higher productivity (in a long term). On the other hand this system also has undesirable features as high capital and operating costs and higher O$_2$ concentration, which can achieve the critical level and will be toxic to microalgae. (Borowitzka, 2012; Janssen, 2002; Votano et al., 2004)

The flat panel reactors consist from series of parallel, transparent, rectangular boxes with a depth of 1-5 cm and with optional height and width, but in practise the maximum size is one meter for both dimensions. The suspension is mixed with air introduced via perforated tube at
the bottom of the reactor. The biggest disadvantage of this system is high energy consumption for mixing and keeping the algae in the suspension. (Janssen, 2002; Votano et al., 2004)

2.3 Harvesting

The major bottleneck for companies is separating algae from water, partly because of the small size of the algae cells (unicellular *eukaryotic* algae 3-30 μm and *cyanobacteria* with size between 0.2–2 μm) and in addition other cultures in range 200-600 mg/l are commonly dilute in the water and therefore large volume of the water treatment is required. The initial harvesting step in the process is not only costly but it also effects the later processes downstream, hence most wastewater treatment lagoons, especially in U.S., omit the harvesting of algae. There exist several removal methods suitable for WWTPs such as granular media filters, centrifugation, filtration and a very common approach is chemical coagulation followed by sedimentation or dissolved air flotation (DAF). (Christenson & Sims, 2011; Larsdotter, 2006)

2.3.1 Sedimentation and flotation

The most common method in full-scale facilities is sedimentation without addition of chemicals (Garcia et al., 2000). Many species of algae have natural tendency to float on the surface of water in order to catch as much light as possible and therefore sedimentation without treatment can be difficult. A more efficient and rapidly operating process than sedimentation is flotation, which achieves a higher solid fraction (up to 7%) in the concentrate (Larsdotter, 2006). The problem with flotation of unicellular algae is that they have a hydrophilic cell surface on which air bubbles will not attach, and therefore flocculation is required. The flocculation can be achieved by addition of flocculants such as alum, lime, cationic polyelectrolytes, FeCl₃, and Ca(OH)₂. After all, the flotation is more rapid than sedimentation but this process requires the specific algae and the addition of chemicals, which makes the entire process more expensive. (Christenson & Sims, 2011; Vandamme, 2014)

2.3.2 Filtration

The filtration of microalgae in WWTPs can be carried out by different methods and technologies where some of them are more established and more efficient than others. Very efficient ways of water filtration is diaphragm filter presses where up to 100% of algae can be harvested (Larsdotter, 2006). The primary screening methods in harvesting of microalgae are microstrainer and vibrating screen filters. Microstrainers are machines consisting of rotating filters with fine sieve with frequent backwash, which serve for harvesting algae. This method is characterized by low investment, easy operation, high filtration rate and simple function and construction. According to (Chen, Yeh, Aisyah, Lee, & Chang, 2011) the filters working with pressure or vacuum can recover large pieces of microalgae, although they are not suitable for dimensions of algae approaching bacterial size. A high rate method for harvesting microalgae, which recovers 70 - 89% freshwater algae, is called tangential flow filtration. (Chen et al., 2011)
2.4 Activated sludge process

The most important parameter for achieving optimal aeration tank volume, sludge production and the best performance of the process in biological treatment step is sludge retention time (SRT) or sludge age as it is also called. The wastewater comes in large quantities to the WWTP, therefore retention time of water (for whole cleaning process) is usually set for one day. Retention time of water in biological treatment step is just a few hours, which is not enough for activation of sludge, thus the recirculation of the sludge is applied. The total SRT is average time (in days) of the stay (recirculation) of sludge in the process before it is removed as excess sludge. The SRT in activated sludge process must be set up on optimal time which means long enough to provide nitrification and denitrification. (Kang et al., 2008; Wennerholm, 2014)
3 METHODS

The energy balances were calculated according to measured data of energy consumptions gathered during one year, which were obtained from Uppsala and Västerås WWTPs. An investigation of the main energy demanding equipment was carried out.

The following data was collected from two municipal WWTPs and their constituent satellite plants:

- Electricity consumption of every step of the process in every WWTP with focus on biological treatment (blowers).
- Heat consumption of whole plant.
- Volumes of produced and imported external sludge to the main plants.
- The distances for transportation of external sludge.
- Detailed description of mechanical treatment equipment.
- Poly-electrolyte consumption for thickening and other chemicals.
- Pollutant content of incoming water, especially $N_{tot}$, $P_{tot}$ and $BOD_7$.

All necessary theoretical data for design and calculation of photobioreactor were based on scientific reports, which aimed to evaluate the theoretical energy use of these types of reactors in practise. Other assumptions important for energy balance calculations are based on practical experiences of staff at WWTPs and recommendations of supervisors at Mälardalen University, Sweden.

The work results in comparison of current situation and proposed changes in the WWTPs. Microsoft Excel was used for designing 2 different models, calculation of energy balances, and performing sensitivity analysis. All calculations and equations are described in detail and uncertainties of the results are argued in the discussion chapter. The structure of municipal WWTPs with satellite plants, sludge flow chart and above mentioned data are presented in subchapter 3.2 Case studies.

3.1 Energy balance

The energy balance is simple methodology used to investigate the flow of energy, discovers the biggest consumers and opportunities to improve overall efficiency of certain plants. During the studied period used, delivered or stored energy of each equipment, within the boundaries of investigation, is measured. The study of Hopkowicz (2000) used an energy balance to investigate possibility of further use of produced biogas, in WWTP Nowy Sacz, as a fuel for co-generation unit or gas engine driven heat pump. The total consumed and produced energy for water treatment is related to the unit of treated water, which allows energy dependency comparison of different treatment plants. This principle was used in the investigation to see the energy dependency before and after applying models.

The current study uses an energy balance to discover if a biological treatment step can be replaced by MAASPBR, or if there are possible energy savings when the open algal pond is
applied to reject water, which occurs after digester. More in detail is evaluated current state of biological treatment, taking into account municipal WWTPs Västerås, Uppsala and also their satellite plants. The first step is to perform an overall energy balance of both municipal WWTPs described by equation 2.

\[ Q_{\text{water,in}} + Q_{\text{el, I}} + Q_{\text{el, II}} + Q_{\text{el, III}} + Q_{\text{heat}} = Q_{\text{water,out}} + Q_{\text{sludge}} + Q_{\text{DH}} + Q_{\text{biogas}} + Q_{\text{losses}} \]  

Where

- \( Q_{\text{water,in}} \) – energy of incoming wastewater to all WWTPs
- \( Q_{\text{el, I}} \) – electricity consumption in main plant
- \( Q_{\text{el, II}} \) – electricity consumption of heat pumps
- \( Q_{\text{el, III}} \) – electricity consumption in satellite WWTPs
- \( Q_{\text{heat}} \) – heat consumption of buildings and digester
- \( Q_{\text{water,out}} \) – energy of outgoing treated water from all WWTPs
- \( Q_{\text{sludge}} \) – energy of dewatered sludge
- \( Q_{\text{DH}} \) – energy transferred to district heating system
- \( Q_{\text{biogas}} \) – energy of produced biogas
- \( Q_{\text{losses}} \) – overall losses in WWTPs

The detailed balances are performed with annual values of consumption (heat, electricity and transport of sludge from satellites to main plants with digester) and production (energy of raw biogas). The data was collected from annual reports and plant’s employees, therefore measurement uncertainties were not taken into account. The unitary energy in kWh/m\(^3\) of treated water is calculated as a difference of annually demanded or utilized energy divided by volume of annually treated water.

The model of MAASPBR could be used in all plants including satellites, because it assumes replacement of biological treatment step, although OAPRW is designed for reject water treatment and therefore is applied only in Kungsängen-Västerås and Kungsängen-Uppsala.

### 3.2 Case studies

This subchapter will present the current state of WWTPs in Uppsala and Västerås including technology and processes that are used. The most recent overall data collected from 2014 is presented and the linkage between municipal WWTPs and their satellites is explained.

#### 3.2.1 Kungsängen – Uppsala WWTP

The wastewater treatment plant is located near the river Fyrisån in Uppsala, Sweden. The WWTP consists of mechanical, biological and chemical treatment. The purification process separates visible impurities, oxygen demanding substances, phosphorus and nitrogen. The parts of plant for mechanical and biological treatment are parallel blocks A, B and C, connected with lines (see Figure 2). In addition, there is also chemical treatment of wastewater, sludge
handling and purification of biogas. The present construction is dimensioned for 200 000 pe\(^1\) and the present load is 148 700 pe. Of the total flow to the plant, 7% is estimated to originate from industries, of which the main contributors come from medical companies and food industries (Vatten, 2013). The fundamental construction of the treatment plant is shown in Figure 1.

The wastewater is pumped to the treatment plant through seven main pumping stations and collected into two sub-streams. The wastewater from the eastern parts of Uppsala is always routed to block C. Other wastewater is treated either in block A, B or in C by transfer of wastewater from chemical treatment. WWTP is dimensioned to treat 4 800 m\(^3\)/h of wastewater, which is divided into 3 blocks, where both blocks A and B are dimensioned to clean 1 000 m\(^3\)/h and block C 2 800 m\(^3\)/h. Wastewater flows through screens and grit chambers, sedimentation tank, biological treatment and tertiary treatment step dimensioned to 15 000 m\(^3\)/h, 11 000 m\(^3\)/h, 7 800 m\(^3\)/h and 7 200 m\(^3\)/h respectively (Vatten, 2013). The summary of the most important overall data is shown in Table 2.

\[\text{Table 2 General information about Kungsängen-Uppsala, 2014}\]

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of connected people</td>
<td>168 900</td>
</tr>
<tr>
<td>Incoming wastewater</td>
<td>18 142 700  m(^3)/year</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>26 838 MWh/year</td>
</tr>
<tr>
<td>Heat consumption</td>
<td>5 000 MWh/year</td>
</tr>
<tr>
<td>Sludge</td>
<td>75 400 tonnes/year</td>
</tr>
<tr>
<td>Biogas production</td>
<td>1 953 700 Nm(^3)/year</td>
</tr>
<tr>
<td>Volume of reject water</td>
<td>350 m(^3)/day</td>
</tr>
<tr>
<td>Reject water temperature</td>
<td>33 °C</td>
</tr>
</tbody>
</table>

\(^1\) pe (person equivalent) - unit used in wastewater treatment; represents water pollution by industries during 24 hours, recalculated to pollution by one person which is 70 g BOD\(_7\)/person, day
Figure 1: Overview of Kungsängen-Uppsala WWTP
The first step consists of mechanical treatment which includes removal of gross contamination, paper and rags in screens. The heavier particles and sand with a diameter less than approximately 0.15 mm are separated in aerated sand trap and lighter particles are separated in sedimentation tank. The result of presedimentation is primary sludge, rich in fat content, with a high total solids (TS) content, which is directly send to the first digester. (Åmand, 2008; Vatten, 2013)

Biological treatment consist of an activated sludge process in an aeration tank followed by sedimentation tanks. The water enters the aeration tanks and is mixed with activated sludge (for growing microorganisms) and oxygenated by blowers, which account for the major part of annual electricity consumption, 40% in 2014. The nitrogen in wastewater occurs as ammonia and the rest is bound to organic material. The ammonium nitrate (NH₄NO₃) is first converted to nitrate (NO₃⁻) and then to nitrogen gas (N₂), which is released to the air. The purification processes are called nitrification and denitrification, respectively. Nitrifying bacteria, which require access to oxygen grow slowly and have a small contribution to the sludge forming. Denitrifying bacteria thrive in oxygen-free conditions. A good supply of organic matter increases the speed of denitrification. (Vatten, 2013)

According to Figure 2 the nitrogen removal achieved by ordinary predenitrification occurs in all three lines in block B and in the line 1-2 in block A. Feed predenitrification with three stages is implemented in lines 3-5 in block A and in block C. The influent wastewater is sequentially fed to the inlet predenitrification and to the three anoxic zones. Each block contains secondary clarification tank with area of 6 250 m². Treatment efficiency of $N_{tot}$ removal is 78%. (Åmand, 2008; Vatten, 2013)

![Figure 2 Schema of wastewater treatment in Kungsängen-Uppsala](image-url)
In block C there are several denitrification and nitrification zones in each line. The biological treatment process in this block are shown in Figure 3 where approximately one third of the incoming wastewater is fed to each stage. These stages are divided to separate zones which have mixing or aeration equipment, or both. The total area of two sedimentation tanks (in each process line) in the secondary sedimentation step is 3 600 m² and a depth of 5 m. (Åmand, 2008; Vatten, 2013)

![Figure 3: The process in block C. Several compartments in the activated sludge basin can be either aerobic or anoxic](image)

After the secondary treatment step the wastewater from all blocks is pumped to the tertiary treatment step, where 99% of phosphorus and residual bio solids are removed by addition of small amount of iron chloride. Subsequently the wastewater goes through lamella settler where the flocks are separated. The purified water is passed through a heat pump system to transfer heat from the water to district heating and then released with lower temperature into river Fyrisån. The heat produced by heat pumps in 2014 was 64 GWh while theirs electricity consumption accounted for 21.3 GWh. (Vatten, 2013)

**Handling sludge – biogas production**

Primary sludge, originating from the primary treatment of lines A and C, is pumped to the sludge thickener. The sludge from block B is pumped to the thickener directly or through the sedimentation tanks in A2. Chemical sludge from the final sedimentation is pumped into tanks in block B. Fat and floating sludge is separated in sedimentation tank in A2 and subsequently enters to the special sludge drain. The fat is removed with a sludge vacuum truck and delivered to the external sludge reception of block A and B. Floating sludge from the basins in block B is pumped to the inlet A and B. Floating sludge from block C is fed back to the inlet of the basin block.

The excess sludge from biological treatment can be handled differently, in order to support inoculation of nitrifying bacteria between all blocks when necessary. Thickened sludge is pumped to the anaerobic digester, where the sludge is digested 18 days at a temperature of 37.5°C. The digested sludge is led to a stirred storage tank and then pumped to the mechanical dewatering machine (centrifuge), where polyelectrolyte is added, which helps to separate sludge from the water. Reject water, rich in nutrient content, is sent back to aeration tanks in the biological treatment step. Dewatered sludge is stored in silos and then it is transported to deposit-Hovgården. In 2014 Kungsängen sludge production amounted 11 970 tonnes. Undigested sludge consist of sludge from main plant, 6 satellite plants and external sludge, in total amount of 113 333 tonnes. There are 4 others satellite plants which do not import sludge
to Kungsängen, therefore those are excluded from energy balance. Björklinge transports dewatered sludge without further processing directly to the deposit. Storvreta has its own digester where sludge from Vattholma and Skyttorp WWTPs is delivered. The sludge flow and general information regarding plants are shown in Figure 4 and Table 3.

The biogas produced in Kungsängen amounted to 1 953 700 Nm³ in 2014, out of which 66% were upgraded to vehicle fuel and 30% where burned in a boiler or combined heat and power unit. In order to avoid leaking of methane to the atmosphere the excess gas was burned.

**Table 3 General information about satellite plants, 2014**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Björklinge</td>
<td>391</td>
<td>111</td>
<td>360 780</td>
<td>0*</td>
<td>80</td>
</tr>
<tr>
<td>Gåvsta</td>
<td>201</td>
<td>96</td>
<td>73 220</td>
<td>24</td>
<td>800</td>
</tr>
<tr>
<td>Järlása</td>
<td>208</td>
<td>96</td>
<td>122 870</td>
<td>30</td>
<td>1030</td>
</tr>
<tr>
<td>Knutby</td>
<td>187</td>
<td>96</td>
<td>65 250</td>
<td>39.5</td>
<td>960</td>
</tr>
<tr>
<td>Länna</td>
<td>307</td>
<td>96</td>
<td>143 230</td>
<td>17</td>
<td>5660</td>
</tr>
<tr>
<td>Ramstalund</td>
<td>77</td>
<td>23</td>
<td>23 550</td>
<td>16.2</td>
<td>820</td>
</tr>
<tr>
<td>Skyttorp</td>
<td>134</td>
<td>39</td>
<td>106 250</td>
<td>14.7</td>
<td>90</td>
</tr>
<tr>
<td>Storvreta</td>
<td>375</td>
<td>90</td>
<td>657 080</td>
<td>0**</td>
<td>640</td>
</tr>
<tr>
<td>Vattholma</td>
<td>161</td>
<td>66</td>
<td>150 180</td>
<td>7.2</td>
<td>290</td>
</tr>
<tr>
<td>Vänge</td>
<td>236</td>
<td>96</td>
<td>149 080</td>
<td>15.5</td>
<td>2130</td>
</tr>
</tbody>
</table>

* The sludge is not digested, just dewatered and transported to deposit

** The sludge is digested directly in the plant without transport
3.2.2 Kungsängen – Västerås WWTP

The WWTP is situated in the southern part of the Västerås, next to the lake Mälaren, Sweden. The main purpose of the plant is to clean water from the central parts of town and surrounding areas. Total of 133 652 people were connected to WWTP in 2014, which represents 101 880 pe. A number of industries are connected to treatment plant as well, accounting for 8% of total water pollution. If water cannot be treated by the plant, than companies are obligated to have their own water treatment. (Mälarenergi, 2013; Mälarenergi, 2014)

The plant is dimensioned to process 125 000 pe, which is a bit smaller than in Uppsala. The cleaning process consists of chemical, mechanical and biological treatments, performed in one block with two steps, primary and secondary. The sludge is stabilised by anaerobic digestion, which results in biogas production and digested sludge. The thermal potential of water is used by heat pumps before water is discharged to the lake and the heat is distributed to the local district heating and cooling system. The heat transferred by heat pumps in 2014 was 17 GWh while their electricity consumption accounted for 8.4 GWh (Mälarenergi, 2015; Mälarenergi, 2014). The general information and fundamental construction about the plant are shown in Error! Reference source not found. and Figure 5.

Table 4 General information about Kungsängen-Västerås, 2014

<table>
<thead>
<tr>
<th>Description</th>
<th>Value(2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of connected people</td>
<td>130 333</td>
</tr>
<tr>
<td>Incoming wastewater</td>
<td>17 438 647 m³/year</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>13 973 MWh/year</td>
</tr>
<tr>
<td>Heat consumption</td>
<td>4 020 MWh/year</td>
</tr>
<tr>
<td>Sludge</td>
<td>28 839 tonnes/year</td>
</tr>
<tr>
<td>Biogas production</td>
<td>1 810 997 Nm³/year</td>
</tr>
<tr>
<td>Volume of reject water</td>
<td>300 m³/day</td>
</tr>
<tr>
<td>Reject water temperature</td>
<td>33 °C</td>
</tr>
</tbody>
</table>

The primary treatment step is designed similarly to one used in Uppsala. Iron sulphate in the amount of 3 010 tonnes is added to incoming stream in order to treat phosphorus. Incoming water is pumped up by screw pumps and passed through screens to remove large particles. A sand trap tank is used to remove grit particles, which are later cleaned and reused in industry. The first step ends with primary gravitation tank, generating two streams, primary treated water and primary sludge. (Mälarenergi, 2015)

The secondary treatment principles are exactly the same as in Uppsala, but the purification with N\text{tot} removal efficiency of 69% takes place only in one block. Water passes through six aerated tanks, where each has two basins with a combined capacity of 12 600 m³. The dissolved oxygen demand required for removal of nitrogen and BOD\text{7} is secured by 4 turbo compressors, which accounts for 27% of the annual electricity consumption. Water then passes through secondary settling tanks, where activated sludge is separated and either recycled back to aerated tanks or treated in sludge handling. Cleaned water is directly discharged to the lake since phosphorus is already precipitated up to 96% due to iron sulphate applied in the primary step. (Sudthanom, Faraz, & Zaidi, 2011)
Figure 5 Overview of Kungsängen-Västerås
Primary sludge is passed to sludge handling via gravimetric thickener and subsequently send to the first digester. The sludge from secondary settling tank goes through sludge presser, where polymers are added in order to increase TS content from 2% to approximately 4%, to the second digester. The sludge is digested in digesters, over a period of 20 days, under a constant temperature of 36°C. After digestion sludge is collected in the sludge storage chamber that serves as a buffer tank. To achieve an efficient sludge dewatering a polyelectrolyte is added. The slurry is then dewatered in two centrifuges. Reject water, rich in nutrient content, is sent back to WWTP influent and dewatered slurry is transported to deposit. (Mälarenergi, 2013)

The biogas produced in the digester is dried and compressed before it is sent through the pipes to the biogas upgrading plant, Växtkraft. Biogas is cleaned there along with gas from their production and used as vehicle fuel. (Mälarenergi, 2013)

External sludge produced in satellite WWTPs in Skultuna and Kvicksund is transported by vehicles to Kungsängen-Västerås. It is stored in special tanks, where it waits until it gets processed in thickener together with sludge from Kungsängen. Similar to Uppsala, there are also another external sludge sources, which amounted 64 194 tonnes (Mälarenergi, 2014). The Table 5 contains general info about satellite plants belonging to Kungsängen-Västerås.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kvicksund</td>
<td>67</td>
<td>33.5</td>
<td>53 462</td>
<td>30.2</td>
<td>996</td>
</tr>
<tr>
<td>Skultuna</td>
<td>221</td>
<td>110.5</td>
<td>341 469</td>
<td>17.3</td>
<td>3 971</td>
</tr>
</tbody>
</table>

3.3 Design of new technology

The first concept MAASPBR is designed to replace current biological treatment steps in all WWTPs including satellite plants. Due to the importance of sufficient light intensity for optimal growth of microalgae (Oswald, 1988) MAASPBR includes immersed artificial light. This kind of photobioreactor is not used in any full scale system and therefore the design data are based on literature review, lab experiments and pilot plants with similar design.

The second design is an open algal pond known from food and biofuel production, commonly used in countries with warm climate and high average annual light intensity. The open pond is placed as an additional treatment step for the rejected water which comes from sludge treatment with high levels of nutrients and high temperature.
3.3.1 Microalgae activated sludge photobioreactor MAASPBR

The MAASPBR is a design of a photobioreactor which uses activated sludge bacteria together with microalgae Scenedesmus and Chlorella vulgaris to treat wastewater. Naturally these green algae types occur in the nearby Lake Mälaren. The temperature of incoming wastewater is usually around 15°C, which according to literature is within the lower boundaries for microalgal growth (Oswald, 1988), and during the summer months achieve about 18°C. The temperature conditions in the lake during summer are similar to wastewater temperature, and therefore good microalgal growth is assumed in the photobioreactor. The assumptions of the microalgal growth are based on data from literature, experiments and pilot projects. The literature and results from different experiments provide diverse values therefore the sensitivity analysis was executed. (International Lake Environment Committee Foundation, 1999)

The length of MAASPBR is calculated from the volume of aeration tanks in biological treatment, divided by depth and width. In order to preserve the same area of current basins the depth of new photobioreactor is considered 5 m and width 10 m.

Sufficient light intensity is secured with artificial lights immersed in to the tanks, because the depth of tank is bigger than light can penetrate from surface. According to Yan et al. (2013) the optimal irradiance for algal growth is 2000 µmole/m² sec, which is equal to the maximal daylight intensity. The photobioreactor model assumed two types of LED lights, red and blue, in ratio 3:1. The electricity consumption per illuminated area is 5.37 W/m² and 14.27 W/m² for red and blue lights respectively. In order to avoid short circuit the LED lights are placed in transparent non-conductive tubes with diameter 0.05 m. The total electricity consumption of photobioreactor is directly related to number and diameter of light tubes. The total illuminated area is calculated according to equation 3.

\[ A = n\pi dh \]  \hspace{1cm} (3)

Where:
- \( A \) – total illuminated area [m²]
- \( n \) – number of light tubes [-]
- \( d \) – diameter of light tubes [m]
- \( h \) – height of light tubes [m]

The equation 4 describes electricity consumption of LED lights in ratio 3:1.

\[ Q_{LED} = \frac{3}{4} A Q_{red} + \frac{1}{4} A Q_{blue} \]  \hspace{1cm} (4)

Where
- \( Q_{LED} \) – total electricity consumption of LED lights [W]
- \( Q_{red} \) – electricity consumption of red LED lights [W/m²]
- \( Q_{blue} \) – electricity consumption of blue LED lights [W/m²]

Mixing is important for securing equal amount of nutrients and light for each microalgae cell and prevents sedimentation on the bottom. On the other hand, the high speed of paddles could
cause damage to the microalgae cells and increase the electricity consumption (Möller & Clayton, 2007). Slow stirring similar to mixing of tertiary treatment in Uppsala with 16 stirrers and consumption 250 W per each is assumed (Nehrenheim, 2015).

The waste water comes to the WWTPs in large volumes, therefore its retention time is set up for one day. The HRT of microalgae has to be big enough to consume pollutants as BOD$_7$, N$_{tot}$, P$_{tot}$ and heavy metals. In order to achieve satisfactory concentration of microalgae and secure a required removal efficiency of pollutants the microalgae activated sludge age can be increased by recirculating settled sludge from the end of aeration tank.

Currently, blowers produce required amount of DO for oxidizing N$_{tot}$ and BOD$_7$ with high energy consumption. If microalgae can consume significant amount of N$_{tot}$ and produce sufficient amount of oxygen via photosynthesis, then blowers can be turned off. In order to remove 1 kg of BOD$_7$ and 1 kg of N$_{tot}$ is required 2 and 4.6 kg of DO respectively (Svenskt Vatten, 2010). The model assumes nitrogen removal efficiency of 75% (Wang et al., 2010) and oxygen production rate 1.9 g DO/g algae (Sahu, 2014).

The microalgae WWTP project ALL-Gas, located in South of Spain, Chiclana de la Frontera is used as an example for MAASPBR, however their technology uses open algal pond. Due to differences of outdoor temperature, sunlight and technology the lower value of dry weight microalgae yield from the measured range 0.3-0.45 kg dw/m$^3$.day in ALL-Gas was used for developing the MAASPBR model. (Rogalla et al., 2015)

Harvesting method directly influences the ratio of obtained biomass yield. According to Rogalla et al., (2015) dissolved air flotation (DAF) equipment can separate microalgae, resulting with TS between 4 – 5% and consuming less than 0.04 kWh/m$^3$. This technology is applied in the model assuming the average separation efficiency is 4.5% TS.

The microalgae slurry amount added to digester originates from Kungsängen plus satellite WWTPs. Calculation of added amount is based on dry weight BY and TS content of microalgae in the slurry after DAF. The mass of water content in slurry is calculated according to equation 5. Mass of a microalgae activated sludge is sum of BY and m$_w$.

\[
m_w = BY \left(1 - \frac{TS}{100}\right) \text{[tonne]} \tag{5}\]

Where

\- m$_w$ – mass of water in the algae slurry after DAF [tonne]
\- BY – algal biomass yield [tonne]
\- TS – total solids [%]

From material balance perspective, forming of microalgae cells removes nutrients, which has negative impact on growth of nitrifying and denitrifying bacteria in biological sludge. The ratio of biological sludge to primary sludge is 40% to 60% and it is assumed that biological sludge is replaced by microalgae production. The new volume of incoming sludge to the digester consist of microalgae slurry, primary sludge produced both in main WWTP and satellite plants plus external sludge.
Theoretical additional biogas is calculated from the new incoming volume of sludge, assuming a volatile solids content (VS) of 3.66% (Olsson et al., 2014). Olsson et al. (2014) measured that the biochemical methane potential (BMP) of undigested sludge is 280 (Nm³ CH₄/tonne VS), and that co-digestion of microalgae with undigested sludge in certain ratios leads to increase of BMP. The highest increase by 23% was obtained with mixture containing 37% microalgae and 63% sludge (based on VS ratio). The new methane production ($V_{CH₄}$) was calculated according to equation 6, and subsequently it was recalculated to biogas, which in average contains 60% of methane and has an energy value of 6.2 kWh/Nm³.

$$V_{CH₄} = m_{mixture} \cdot VS \cdot BMP$$  (6)

Where

$V_{CH₄}$ – volume of produced methane [m³/year]  
$m_{mixture}$ – amount of sludge-algae mixture incoming to digester [tonne/year]  
VS – volatile solids content [%]  
BMP – biochemical methane potential [Nm³ CH₄/tonne VS]

The mixture of algae, primary sludge and external sludge has greater volume than previous sludge, therefore more heat will be consumed in the digester. Additional heat is calculated as the difference of heat required for microalgae slurry and biological sludge. The temperature has to be raised from 15 to 36.5°C and the heat capacity $c_p$ of sludge is 4.18 kJ/ kg.K equal to $c_p$ of water, since 96% of the sludge is water. The equation 7 shows additional heat requirement excluding losses in the digester.

$$Q_{additional} = c_p m (t_2 - t_1)$$  (7)

Where

$Q_{additional}$ – additional heat for microalgae slurry [MJ]  
$c_p$ – heat capacity of water [kJ/kg K]  
m – mass of microalgae slurry together with biological sludge [tonne]  
t₁,₂ – sludge temperature before and inside digester [°C]

### 3.3.2 Open algal pond for reject water OAPRW

The main aim of this concept is to use the open algal pond as an additional treatment step, which is treating reject water generated in sludge centrifuge. The open pond is using the same species of microalgae as the MAASPBPR, *Scenedesmus* and *Chlorella vulgaris*. The following table shows qualities of reject water in Uppsala and Västerås.

<table>
<thead>
<tr>
<th>Daily reject water [m³]</th>
<th>Temperature [°C]</th>
<th>$P_{tot}$ [mg/l]</th>
<th>$N_{tot}$ [mg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uppsala 350</td>
<td>33</td>
<td>10</td>
<td>1200</td>
</tr>
<tr>
<td>Västerås 300</td>
<td>33</td>
<td>8.7</td>
<td>1086</td>
</tr>
</tbody>
</table>
Operation of the OAPRW is assumed for 7 months, from April till October, because 82% of annual sunshine hours occurs in those months and from November till March is too cold for microalgae strains (Weather-averages, 2014). A horizontal irradiation, $Q_h$, of OAPRW is 775 kWh/m² obtained during 7 months (Solargis, 2014). The total energy of sunlight is calculated as multiplication of $Q_h$ by area of pond.

Conventional open algal ponds are using paddle wheel for mixing water. OAPRW is using a new technology for mixing, developed by FCC Aqualia, where one section of the tank is narrowed to the tube with axial stirrer (Rogalla et al., 2015). The new technology consumes 0.025 kWh/m³ of electricity compared to the paddle wheel with 0.4 kWh/m³ electricity use. Both designs are shown in Figure 6.

![Figure 6 Open algal pond with conventional design (above) and OAPRW with innovative stirring design](image)

The same harvesting technology, DAF, as in MAASPBR concept is proposed. Additional electrical consumption for pumping of diluted reject water is proportionally recalculated according to energy audit in Kungsängen-Uppsala.

The microalgae production rate of 6.2 kg/m³, day was assumed for OAPRW according to laboratory tests with reject water treated by microalgae, performed by Rusten et al. (2009).

Treated water enriched with DO is pumped back to WWTP influent. Consumed $N_{tot}$ and produced DO contributes to reduction of air produced by blowers, therefore some portion of electricity is saved. The assumed DO production rate is 1.9 g O₂/g algae, the same as measured in (Rogalla et al., 2015). Wang et al., (2010) tested algal growth in samples collected from different treatment steps of WWTP and measured $N_{tot}$ and $P_{tot}$ removal efficiencies of 82.8% and 85.6% respectively.
Since the reject water remains in OAPRW for 3 days, its temperature will decrease due to heat transfer to surrounding environment. Heat loss is calculated according to equation 8. The volume of OAPRW is 3 times daily reject water, diluted by treated water in order to reach limiting concentration of $N_{tot} \leq 600 \text{ mg/l}$ (Olsson, 2015). The depth of OAPRW is assumed to be 0.30 m, which implies its area.

$$Q_{loss} = c_p m (t_2 - t_1)$$ (8)

Where

- $Q_{loss}$ – heat loss [MJ]
- $c_p$ – heat capacity of reject water [kJ/kg K]
- $m$ – mass of reject water [tonne]
- $t_{1,2}$ – temperature of reject water at the beginning and end of OAPRW [°C]
4 RESULTS AND DISCUSSION

This chapter is summarising the results obtained from calculations of the two models, created in Excel, applied in the specific WWTPs studied. The first part gives an overview of proposed microalgae treatment step designs for understanding their application in current WWTPs. Uncertainties, assumptions and different forms of energies, changed due to the new technology which are presented and discussed in subchapter 4.2 WWTPs – Västerås and Uppsala.

The sensitivity analysis is conducted on specific growth rate, which influences biomass yield, volume of sludge, pumping, heating, dewatering and transport energy as well as oxygen production. Since different authors concluded different BMP of microalgae ranging from 100 to 380 Nm$^3$ CH$_4$/tonne VS, the sensitivity analysis for biogas production was also performed.

The overall energy balance has shown that the biological treatment accounts for 27% and 40% of the total electricity consumption in Västerås and Uppsala respectively.

4.1.1 MAASPBR

The design of MAASPBR treats wastewater from the primary treatment step and was applied for all municipal WWTPs including satellite plants. The electricity consumption of the proposed design is caused by stirring and LED lights. Stirring is assumed only in 2/3 of tanks volume, since last third is dedicated for sedimentation of microalgae activated sludge, which has to be recirculated to tanks influent in order to increase the sludge age. The Figure 7 shows general application of MAASPBR in current WWTP setup. The number of lights varies in different WWTPs because of different tank volumes. Specific information regarding proposal for different WWTPs is found in 7. The polyelectrolyte and small dosage of coagulant has to be added to air flotation tank in order to achieve 4.5% TS concentration after separation (Rogalla et al., 2015). Microalgal slurry is mixed with primary sludge and directly injected to the digester.

The growth rate of microalgae in basic scenario is assumed to 0.3 kg/m$^3$, day which was measured as lower value of growth rate in the ALL-GAS project (Rogalla et al., 2015). BMP of sludge-algal mixture is assumed to 350 Nm$^3$ CH$_4$/ tonne VS.

The $N_{tot}$ and $P_{tot}$ removal efficiency of 75% and 50% respectively are assumed, which resulted in part of electricity savings (see chapter 4.2.2 Electricity) and saving of chemicals used for phosphorus removal, which are iron chloride or iron sulphate, depending on WWTP. (Rogalla et al., 2015; Wang et al., 2010)

Since the microalgae can have an uptake of half of the incoming phosphorus the calculated savings are approximately 50% of currently used FeCl$_2$ or FeSO$_4$. 
Table 7 Specific information of MAASPBR in all WWTPs

<table>
<thead>
<tr>
<th>WWTP</th>
<th>Volume of tank [m³]</th>
<th>Number of light tubes [-]</th>
<th>Total el. Consumption [MWh/year]</th>
<th>P&lt;sub&gt;tot&lt;/sub&gt; removal [tonne/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kungsängen-Västerås</td>
<td>12 600</td>
<td>2 268</td>
<td>1 989</td>
<td>1 505</td>
</tr>
<tr>
<td>Skultuna</td>
<td>253</td>
<td>46</td>
<td>46</td>
<td>30.31</td>
</tr>
<tr>
<td>Kvicksund</td>
<td>40</td>
<td>7</td>
<td>15</td>
<td>4.75</td>
</tr>
<tr>
<td>Kungsängen-Uppsala</td>
<td>31 340</td>
<td>5 641</td>
<td>2 347</td>
<td>980</td>
</tr>
<tr>
<td>Gävsta</td>
<td>84</td>
<td>15</td>
<td>19</td>
<td>234</td>
</tr>
<tr>
<td>Järnlåsa</td>
<td>137</td>
<td>25</td>
<td>17</td>
<td>83</td>
</tr>
<tr>
<td>Knutby</td>
<td>57</td>
<td>10</td>
<td>15</td>
<td>123</td>
</tr>
<tr>
<td>Länna</td>
<td>157</td>
<td>28</td>
<td>20</td>
<td>257</td>
</tr>
<tr>
<td>Ramstalund</td>
<td>23</td>
<td>9</td>
<td>12</td>
<td>67</td>
</tr>
<tr>
<td>Vänge</td>
<td>156</td>
<td>28</td>
<td>25</td>
<td>486</td>
</tr>
</tbody>
</table>

The CO<sub>2</sub> should be added to control pH requirement, for good algal growth, in the range 7-8, however energy use for dissolving CO<sub>2</sub> to water and algal uptake was not evaluated in the model created in Excel.

Figure 7 Schema of MAASPBR

4.1.2 OAPRW

The design of the OAPRW treats the reject water generated in sludge centrifuge and is applied for Kungsängen-Västerås and Kungsängen-Uppsala only. The electricity consumption of OAPRW is caused by innovative design in tube axial stirrer, DAF and pumping of microalgae slurry to digester. The Figure 8 shows general application of OAPRW in current setup. Microalgal slurry harvested by DAF is mixed with current amount of sludge and directly injected to the digester.

Assumed N<sub>tot</sub> and P<sub>tot</sub> removal efficiencies according to Wang et al., (2010) resulted in negligible savings of chemicals. For P<sub>tot</sub> removal is saved only 0.8% and 0.6% of current chemicals usage in Västerås and Uppsala respectively. This is because concentration of P<sub>tot</sub> is
2-3 times higher in reject than in incoming wastewater, but the volume of reject water is 166 times smaller.

4.2 WWTPs – Västerås and Uppsala

4.2.1 Overall results

The data regarding current electricity, heat and transport energy use and biogas production are collected from 2014 for main WWTPs and their satellite plants, presented and compared with the new technologies in 8 and 9. The electricity is consumed in all plants, heat consumption occurs only in main plants and transport energy means energy of fuel consumed when sludge is transported from satellite plants to the main plants. The increased energy for transport of digested, dewatered sludge is not taken into account because of unknown distance from Kungsängen-Västerås to deposit. The electricity consumption and heat production in
heat pumps is not considered in detailed energy balance, since new technologies have no influence on it. All types of energies are evaluated more in detail in chapters 4.2.2 - 4.2.4.

The unitary energy in Västerås is 0.078 kWh/m³ and -0.072 kWh/m³ of treated water in Uppsala. A notable difference between companies is caused by the different designs applied in treatment process and quality of treated water, namely 3 blocks of biological step and additional tertiary step in Uppsala instead of one block in Västerås.

Overall energy balance is improved by applying both microalgal treatment steps. Västerås is in energy surplus 0.421 or 0.118 kWh/m³ with MAASPBR and OAPRW respectively. Uppsala is in surplus 0.514 kWh/m³ with MAASPBR, although with OAPRW only -0.027 kWh/m³ is needed. In case of MAASPBR the used amount of electric energy is slightly increased but the biogas energy is doubled, which makes great positive impact. On the other hand OAPRW predicts lower consumption of electricity, greater heat consumption and biogas production, compared to current state.

MAASPBR improves current situation dramatically, although in favour of OAPRW are facts that reject water has optimal temperature, abundance of nutrients and low energy dependency.

Table 8 Energy balance of Västerås with current, MAASPBR and OAPRW technology

<table>
<thead>
<tr>
<th>Energy</th>
<th>Current [MWh/year]</th>
<th>MAASPBR [MWh/year]</th>
<th>OAPRW [MWh/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity consumption</td>
<td>5 793</td>
<td>6 212</td>
<td>5 487</td>
</tr>
<tr>
<td>Heat consumption</td>
<td>4 020</td>
<td>6 187</td>
<td>4 415</td>
</tr>
<tr>
<td>Transport</td>
<td>23</td>
<td>37</td>
<td>23</td>
</tr>
<tr>
<td>Energy of biogas</td>
<td>11 228</td>
<td>19 931</td>
<td>12 014</td>
</tr>
<tr>
<td><strong>Unitary Energy, kWh/m³</strong></td>
<td><strong>0.078</strong></td>
<td><strong>0.421</strong></td>
<td><strong>0.118</strong></td>
</tr>
</tbody>
</table>

Table 9 Energy balance of Uppsala with current, MAASPBR and OAPRW technology

<table>
<thead>
<tr>
<th>Energy</th>
<th>Current [MWh/year]</th>
<th>MAASPBR [MWh/year]</th>
<th>OAPRW [MWh/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity consumption</td>
<td>8 416</td>
<td>7 424</td>
<td>7 880</td>
</tr>
<tr>
<td>Heat consumption</td>
<td>5 000</td>
<td>7 584</td>
<td>5 510</td>
</tr>
<tr>
<td>Transport</td>
<td>63</td>
<td>78</td>
<td>63</td>
</tr>
<tr>
<td>Energy of biogas</td>
<td>12 113</td>
<td>24 847</td>
<td>12 961</td>
</tr>
<tr>
<td><strong>Unitary Energy, kWh/m³</strong></td>
<td><strong>-0.072</strong></td>
<td><strong>0.514</strong></td>
<td><strong>-0.027</strong></td>
</tr>
</tbody>
</table>

4.2.2 Electricity

Since the historical data of electrical consumption of satellite plants are missing, the rendered graphs, Figure 9 and Figure 10 Error! Reference source not found., compare electricity consumption of current technology, MAASPBR and OAPRW just in Kungsängen-Västerås and Kungsängen-Uppsala.

The results show that production of O₂ is sufficient to turn off the blowers in MAASPBR, which leads to electricity savings equal to their consumption. On the other hand MAASPBR generate
more sludge, which requires additional electricity for pumping. In case of Västerås new overall electricity consumption is greater than current, unlike in Uppsala.

Bigger amount of sludge produces more energy in the form of biogas, which contributes to improve the overall energy balance. For the results of biogas production see subchapter 4.2.4 Biogas.

As is clear from Figure 9 and Error! Reference source not found. the electricity consumption of OAPRW is lower in both WWTPs, Kungsängen-Västerås and Kungsängen-Uppsala. This is due to the fact that open algal pond is less energy intensive, because it handles smaller volumes than MAASPBR. Additional electricity consumption occurs in stirrer, pump and machine for harvesting of microalgae.

Figure 9 Electricity consumption in Kungsängen-Västerås WWTP

Figure 10 Electricity consumption in Kungsängen-Uppsala WWTP
4.2.3 Sludge and transport

The exact energy requirements for sludge transport to the deposit in Västerås is not evaluated, since the distance is unknown due to the fact that external company takes responsibility of sludge disposal. The dewatered sludge amount will increase by 278%, but the transport energy is relatively low comparing to increased biogas energy production. In Uppsala the sludge amount increased by 269% which represents additional transport energy of 77 MWh when the distance to deposit is 19.2 km. The Figure 11 and Figure 12 show annual sludge production in Kungsängen-Västerås with MAASPBR, OAPRW and current technology with historical data from 2009.

![Figure 11 Sludge production in Västerås](image)

![Figure 12 Sludge production in Uppsala](image)
4.2.4 Biogas

The biogas production is strictly dependent on BMP of the substrate and microalgal yield. In Kungsängen-Västerås the microalgae slurry amounted 118 891 tonnes/year of wet slurry, when volumetric algal yield of 0.3 kg/m³ with 3.01% VS and 4.5% TS was assumed. Algal slurry is mixed with primary and external sludge of total amount 64 194 tonnes/year and assumed 2.7% VS and 3.5% TS. Co-digestion of microalgae in certain ratios of microalgae VS to sludge VS showed synergetic effect with highest biogas yield increase by 23% when ratio was 37/63 (Olsson, Chemistry, et al., 2014). The MAASPBR algal production gives ratio 65/35, which was not tested for synergetic effect, however the calculation was performed with maximal BMP 350 Nm³ CH₄/tonne, VS reached in ratio 37/63. The new biogas production is 3.2 mil. Nm³/year. Calculated Biogas yield of MAASPBR and OAPRW together with historical data is projected in Figure 13 for Västerås and Figure 14 for Uppsala.

In Kungsängen-Uppsala 123 476 tonnes/year of wet algal slurry is produced, which in turn gives 54/46 (VS/VS) ratio. The same assumptions of mixture composition and volumetric algal yield is used. The new biogas production is 4 mil. Nm³/year.

For OAPRW the ratio 13/87 and 14/86 (VS/VS) is reached in Västerås and Uppsala respectively, therefore both models assume biogas production increase by 7% as it was proved by Olsson et al. (2014) for mixture 13/88 (VS/VS). New calculated biogas production is 1.9 and 2 mil. Nm³/year in Västerås and Uppsala respectively.

![Figure 13 Biogas production in Västerås](image)
There is high uncertainty regarding volumetric algal growth in MAAPBR, since data used in models are taken from pilot plant in south Spain, therefore sensitivity analysis is performed on algal growth together with oxygen production rate in order to find out if microalgae is capable to produce sufficient amount of O$_2$ for BOD and leftover N$_{tot}$ removal. It is calculated that sufficient O$_2$ production is 13.5 tonne O$_2$/day in Västerås and 20.4 tonne O$_2$ in Uppsala, when 75% of N$_{tot}$ is consumed by microalgae. The analysis is performed with algal growth rate from 0.10 to 0.45 kg/m$^3$day which is equivalent to daily algal production of 4.78 to 21.2 tonne/day. The O$_2$ production rate was assumed to be in the range from 1.24 to 1.92 tonne O$_2$/tonne microalgae.

The Figure 15 and Figure 16 show in which combinations the sufficient DO production is reached. If combination of assumed growth rate and O$_2$ production is in green field the impact of new technology on energy balance is positive. The chance to achieve sufficient O$_2$ evolution is greater in Kungsängen-Västerås, because requirement is lower by 34%.

The assumptions are literature review based, although growth rate, recalculated for volumetric BY is from open pond situated in the south of Spain, which creates uncertainties, when applied in Sweden. More realistic values will be available in future from ongoing photobioreactor pilot experiment in Kungsängen-Västerås.
Figure 15 Biomass-oxygen production rate sensitivity analysis for MAASPBR, Kungsängen-Västerås

Figure 16 Biomass-oxygen production rate sensitivity analysis for MAASPBR, Kungsängen-Uppsala
5 CONCLUSION

The work investigated possible energy balance improvements by microalgae treatment step in specific WWTP in Västerås, Uppsala and their satellite plants. Two different designs were modelled in Excel, one with microalgae activated sludge photobioreactor (MAASPBR) and another with open algal pond for reject water treatment (OAPRW).

The MAASPBR can replace current biological treatment step in case if microalgae can consume 75% of total nitrogen (N\text{tot}) and produce at least 13.5 and 20.4 tonne O\textsubscript{2}/day, in Västerås and Uppsala respectively. The second design of OAPRW aims to cultivate microalgae on reject water with high concentration of nutrients, generated in sludge centrifuge. Result showed possible 23% and 20% electricity saving on blowers in biological treatment in Västerås and Uppsala respectively. Both models have positive impact on energy balance in all WWTPs, however MAASPBR has greater uncertainties, because this type of photobioreactor has not been tested unlike OAPRW which has been tested in pilot plant.

The proposed designs of microalgae treatment step show opportunity to reduce electricity consumption of blowers in the case of OAPRW or even turn them off in case off MAASPBR.

6 SUGGESTIONS FOR FURTHER WORK

The positive results argues for further research on utilization of microalgae not only in Västerås and Uppsala, but also many other WWTPs in Sweden that have similar type of structure and condition.

The assumed volumetric algal growth resulted in yields which was not tested for co-digestion. Suggestion is to test co-digestion of microalgal slurry with undigested primary sewage sludge, where microalgae slurry represents 54-65% (VS/VS based) of mixture.

The tubes with LED lamps in MAASPBR basins are likely areas where the biofilm can be formed, which will decrease photosynthetic active radiation dramatically, which implies low algal growth therefore also low treatment efficiency. The simple solution with mechanical cleaning should be developed or different materials for light tubes should be tested on biofilm affinity.

Optimization of process in WWTP with microalgae treatment step should be performed with focus on artificial lights in photobioreactor, it means that the intensity of the artificial lights will be regulated depending on the amount of solar flux, which rises and falls with seasons.

An investment analysis should be performed to discover total cost of new equipment, maintenance cost, payback period, internal rate of return.
LIST OF SOURCES


Grönlund, E. (2002). Microalgae at Wastewater Treatment in Cold Climate. Luleå University of Technology, 18.


