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Citation for the original published paper (version of record):

Nordlander, E., Olsson, J., Thorin, E., Yan, J. (2017)
Simulation of energy balance and carbon dioxide emission for microalgae introduction in wastewater treatment plants.
*Algal Research*, 24(part A): 251-260

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:
http://urn.kb.se/resolve?urn=urn:nbn:se:mdh:diva-36513
Simulation of energy balance and carbon dioxide emission for microalgae introduction in wastewater treatment plants

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Abstract

A case study is described in which the activated sludge process is replaced with a microalgae-activated sludge process. The effects on the heat and electricity consumption and carbon dioxide emissions were evaluated in a system model, based on mass and energy balances of biological treatment and sludge handling process steps. Data for use in the model was gathered from three wastewater treatment plants in Sweden. The evaluation showed that the introduction of microalgae could reduce electricity and heat consumption as well as CO\textsubscript{2} emissions but would require large land areas. The study concludes that a 12-fold increase in the basin surface area would result in reductions of 26-35% in electricity consumption, 7-32% in heat consumption and 22-54% in carbon dioxide emissions. This process may be suitable for wastewater treatment plants in Nordic countries, where there is a higher organic load in summer than at other times of the year. During the summer period (May to August) electricity consumption was reduced by 50-68%, heat consumption was reduced by 13-63% and carbon dioxide emissions were reduced by 43-103%.

Keywords:
Microalgae; Microalgae-activated sludge process; municipal wastewater; net energy usage; carbon dioxide; Model

1 Introduction

The potential to develop municipal wastewater treatment methods with a resource recovery process through the capture and provision of net energy processes has been discussed in previous studies [1-3]. Concerning energy recovery from wastewater, Garrido et al. [4] concluded that, from a theoretical point of view, there is enough organic matter in the wastewater for the process to be energy self-sufficient. The energy use is dependent on the treatment method applied as well as the size of the plant and operation. Reported average values for the energy used by municipal wastewater treatment plants in different countries of the world vary between 0.30-0.78 kWh m\(^{-3}\) [4-6].

Most biological treatment in municipal wastewater treatment plants is based on the activated sludge process, in which air is introduced into the water by blowers to create aerobic conditions for bacteria. The aeration consumes large amounts of electricity. Panepinto et al. [7] presented a study of the energy efficiency of wastewater treatment plants in Italy. Their evaluation shows that 50 % of the electricity consumption of the plant is used for the blowers. The oxygen produced by introducing microalgae into the biological process can reduce the aeration cost [8].

The cultivation of microalgae can also be used to reduce nutrients in the main wastewater stream [9] or as a treatment for nutrient-rich side streams such as reject water from sludge dewatering [10]. Algal-bacterial symbiosis systems have
shown promising results with respect to nutrient removal [11,12]. The study presented in [12] found that the algal-bacterial system had a higher nutrient removal rate than the reference activated sludge system, especially at low aeration rates. At higher aeration rates the two systems showed smaller differences due to oxygen inhibiting the microalgae growth.

The microalgae can be cultivated in open raceway ponds or closed photobioreactors that can be constructed in several different ways [13,14]. The first system is simple, with low capital costs, but limited possibilities for controlling growth conditions, while the second system provides better control options but higher capital costs [15]. The cultivated microalgae are harvested from the wastewater treatment step and can then be co-digested with primary sludge from the treatment process. A drawback of a microalgae wastewater treatment system is the large land area requirements, especially by raceway ponds [8]. Most microalgae systems rely on the sun as a light source, but artificial light could also be used as an alternative [16,17]. Artificial light has the advantage that it can be tailored to the specific system, reducing the risk for photoinhibition, but it will introduce an electrical cost for the lighting.

The potential for net energy production with inclusion of microalgae was discussed by [18], based on the potential for biomass production per nutrient uptake and biomass biogas potential; however, no overall process energy balance was presented. Sturm and Lamer [19] studied the energy balance of systems with the cultivation of microalgae in open ponds for nutrient removal of effluent water from a wastewater treatment plant followed by biodiesel production from the
algae and showed positive energy balances. However, the algal cultivation was not fully integrated into the wastewater treatment process, and the whole process was not included in their study.

In this paper, we develop a treatment plant model and use it to simulate the influence on the energy balance and carbon dioxide emissions of wastewater treatment as a result of introducing microalgae treatment steps. We study the impact of the illuminated surface. Three different cases based on real plant data from three wastewater treatment plants in Sweden have been investigated with the aim of capturing variations due to normal differences in conditions for standard process solutions.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{surf,reactor}}$</td>
<td>area of the reactor surface [m$^2$]</td>
</tr>
<tr>
<td>$\text{BOD}_{\text{red}}$</td>
<td>amount of BOD to be reduced in the biological treatment [kg]</td>
</tr>
<tr>
<td>$\text{BOD}_{\text{in}}$</td>
<td>amount of BOD entering the biological treatment [mg L$^{-1}$]</td>
</tr>
<tr>
<td>$\text{BOD}_{\text{out}}$</td>
<td>amount of BOD leaving the biological treatment [mg L$^{-1}$]</td>
</tr>
<tr>
<td>$\text{BP}_{\text{PS}}$</td>
<td>biogas potential of the primary sludge [m$^3$kg$^{-1}$ VS]</td>
</tr>
<tr>
<td>$\text{BP}_{\text{WAS}}$</td>
<td>biogas potential of the biosludge/waste activated sludge [m$^3$kg$^{-1}$ VS]</td>
</tr>
<tr>
<td>$C_{\text{BOD,CODb}}$</td>
<td>factor for converting BOD to CODb [kg CODb kg$^{-1}$BOD]</td>
</tr>
<tr>
<td>$C_{\text{H}_2\text{O}}$</td>
<td>heat capacity of water [kJ kg$^{-1}$K$^{-1}$]</td>
</tr>
</tbody>
</table>
COD_{b,red} amount of biological COD to be removed in the biological treatment [kg CODb]
COD_{need,Ph} COD need of the phosphorous reducing bacteria biomass [gCOD g\(^{-1}\)P removed]
COD_{red,Ph} COD reduced by the phosphorous reducing bacteria biomass [kg COD]
\( f_{\text{CO}_2,\text{abs,per,ma}} \) CO\(_2\) absorption by microalgae [g CO\(_2\) g\(^{-1}\) microalgae]
\( f_{\text{CO}_2,\text{abs,per,nit}} \) CO\(_2\) absorption by nitrification [g CO\(_2\) g\(^{-1}\)NH\(_4\)-N]
\( f_{\text{CO}_2,\text{em,COD}} \) CO\(_2\) emission: COD/P-reducing biomass [g CO\(_2\) g\(^{-1}\) COD]
\( f_{\text{bfac}} \) surface reflection factor [-]
bacteria biomass produced [kg VS]
microalgae biomass produced [kg VS]
emission of carbon dioxide in the base case plant [kg CO\(_2\)]
emission of carbon dioxide in the plant containing microalgae [kg CO\(_2\)]
molar mass of oxygen [g mol\(^{-1}\)]
amount of ammonium nitrogen to be reduced [kg]
amount of ammonium nitrogen entering the biological treatment [mg L\(^{-1}\)]
NH4-N_{out} amount of ammonium nitrogen leaving the biological treatment [mg L\(^{-1}\)]

N_{red, algae} amount of nitrogen reduced by the microalgae [kg NH\(_4\)-N]

N_{uptake, algae} amount of nitrogen that the microalgae can uptake/reduce per unit of microalgae [g NH\(_4\)-N g\(^{-1}\) VS]

N_{uptake, CODred, bacteria} amount of nitrogen that the COD reducing bacteria can reduce per unit of nitrogen [gN g\(^{-1}\) VS]

N_{uptake, heterobiomass} the amount of nitrogen take up by the COD reducing bacteria [kg N]

O\(_2\),avg, algae Average oxygen provided by the microalgae [kg O\(_2\)]

O\(_2\),need, nitrification oxygen consumed by nitrification biomass [g O\(_2\) g\(^{-1}\)NH\(_4\)-N removed]

O\(_2\),need, Pbiomass oxygen needed by the phosphorous reducing bacteria [g O\(_2\) g\(^{-1}\) COD\(_b\) removed]

O\(_2\),use, CODbiomass oxygen used by the COD reducing biomass [kg O\(_2\)]

O\(_2\),use, nitrification oxygen used by the nitrification bacteria [kg O\(_2\)]

O\(_2\),use, nitrification, bc oxygen used by the nitrification bacteria in the base case (without the microalgae) [kg O\(_2\)]

O\(_2\),use, Pbiomass the oxygen used by the phosphorous reducing bacteria [kg O\(_2\)]
<table>
<thead>
<tr>
<th>Index</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>131</td>
<td>$O_{2,\text{need,remaining}}$</td>
<td>remaining oxygen needed for the biological treatment [kg $O_2$]</td>
</tr>
<tr>
<td>132</td>
<td>$O_2$</td>
<td></td>
</tr>
<tr>
<td>133</td>
<td>$O_{2,\text{use,total}}$</td>
<td>total oxygen used/needed in the process [kg $O_2$]</td>
</tr>
<tr>
<td>134</td>
<td>$O_{2,\text{use,total,bc}}$</td>
<td>total oxygen used/needed in the process for the base case (without algae) [kg $O_2$]</td>
</tr>
<tr>
<td>136</td>
<td>$\text{PPD}_{\text{sun}}$</td>
<td>photosynthetic photon density [mol photons m$^{-2}$]</td>
</tr>
<tr>
<td>137</td>
<td>$P_{\text{aeration,bc}}$</td>
<td>power used for aeration in the base case [MWh]</td>
</tr>
<tr>
<td>138</td>
<td>$P_{\text{content,biogas}}$</td>
<td>energy content of the biogas [kWh m$^{-3}$]</td>
</tr>
<tr>
<td>139</td>
<td>$P_{\text{in}}$</td>
<td>amount of phosphorous entering the biological treatment [mg L$^{-1}$]</td>
</tr>
<tr>
<td>141</td>
<td>$P_{\text{aeration,new}}$</td>
<td>power used for the aeration when microalgae are utilised [MWh]</td>
</tr>
<tr>
<td>143</td>
<td>$P_{\text{biogas,bc}}$</td>
<td>amount of biogas in the base case in terms of power [MWh]</td>
</tr>
<tr>
<td>145</td>
<td>$P_{\text{digester,extra}}$</td>
<td>additional electricity required for the digestion due to the increased amount of sludge [MWh]</td>
</tr>
<tr>
<td>147</td>
<td>$P_{\text{digester,per,m3}}$</td>
<td>electricity consumption: anaerobic digestion treatment [kWh m$^{-3}$ sludge]</td>
</tr>
<tr>
<td>149</td>
<td>$P_{\text{extra,biogas}}$</td>
<td>additional biogas in terms of power [MWh]</td>
</tr>
<tr>
<td>150</td>
<td>$P_{\text{net,use,bc}}$</td>
<td>net use of power in the base case [MWh]</td>
</tr>
</tbody>
</table>
net use of power in the microalgae case [MWh]

all electrical consumption at the power plant that is not for aeration [MWh]

amount of phosphorous leaving the biological treatment [mg L\(^{-1}\)]

amount of phosphorous that the microalgae can uptake/reduce per unit of microalgae [gP g\(^{-1}\)VS]

amount of phosphorous to be reduced in the biological treatment [kg]

amount of phosphorous reduced by the microalgae [kg P]

increase in power used for the secondary treatment [MWh]

electricity consumption: secondary treatment excluding aeration [kWh m\(^{-3}\) sludge]

electricity consumption: sludge handling [kWh m\(^{-3}\) sludge]

additional electricity required for sludge handling due to increased amount of sludge [MWh]

heat use in the base case [MWh]

additional heat supplied to the digester due to increased amount of sludge [MWh]
\( Q_{\text{net,use,bc}} \) net use of heat in the base case [MWh]

\( Q_{\text{net,use,new}} \) net use of heat in the microalgae case [MWh]

\( q_{\text{month}} \) wastewater flow into the biological treatment in a particular month [m³]

\( \text{SRT} \) sludge retention time [d]

\( \text{SumVS}_{\text{PS}} \) sum of the primary sludge VS for the whole year [kg VS]

\( \text{SumVS}_{\text{WAS}} \) sum of the waste activated sludge VS for the whole year [kg VS]

\( T_{\text{ambient}} \) ambient temperature, assumed to be 285.15 K [K]

\( T_{\text{digester}} \) digester temperature [K]

\( V_{\text{biogas,bc}} \) base case biogas production for the whole year [m³]

\( V_{\text{extrabiogas}} \) amount of additional biogas due to extra sludge [m³]

\( V_{\text{increased,sludge}} \) additional sludge due to the microalgae in the system [m³]

\( V_{\text{sludge,bc}} \) amount of sludge produced from the biological treatment in the base case [m³]

\( V_{\text{reactor}} \) volume of the biological treatment basin [m³]

\( X_{\text{algae/O2}} \) microalgae biomass produced per unit of oxygen [g microalgae biomass g⁻¹O₂]

\( Y_{\text{biogas,PS}} \) yield factor for the primary sludge part of all biogas [-]
Y<sub>obs</sub> yield [kg VS sludge kg<sup>−1</sup>BOD]

γ<sub>need, O<sub>2</sub></sub> minimal quanta required to liberate oxygen for sunlight [photons O<sub>2</sub>−1]

γ<sub>sun</sub> number of photons provided by the sun [mol photons]

η<sub>electrical</sub> conversion efficiency: biogas to electricity [-]

η<sub>thermal</sub> conversion efficiency: biogas to heat [-]

ρ<sub>bacteria</sub> concentration of bacteria biomass [kg TS m<sup>−3</sup>]

ρ<sub>algae</sub> concentration of microalgae biomass [kg TS m<sup>−3</sup>]

ρ<sub>bac+alg</sub> concentration of total biomass [kg TS m<sup>−3</sup>]

φ<sub>vs, per, ts, bac</sub> fraction of volatile solids per total solids for the bacteria biomass [-]

φ<sub>vs, per, ts, ma</sub> fraction of volatile solids per total solids for the microalgae [-]

2 Method

The impact on the energy balance and CO<sub>2</sub> emissions caused by inclusion of a microalgae-based treatment step, i.e. a microalgae-activated sludge photobioreactor (MAASPR), was simulated for three existing Swedish wastewater treatment plants (WWTPs) using real plant data as input. The MAASPR investigated in this study is an open basin that uses natural sunlight for the microalgae photosynthesis and has sludge recirculation, see Figure 1. An
alternative for the MAASPBR would be to use artificial light to supply some of the light. This latter option was not evaluated as part of the calculation but its feasibility is expanded on in the subsequent discussion.

A model for the MAASPBR treatment plant was developed based on mass and energy balances of the biological treatment and sludge handling process steps.

**Figure 1 Basic concept of the MAASPBR**

The MAASPBR was designed to reduce the same amount of biological oxygen demand (BOD), biodegradable chemical oxygen demand (COD₆), phosphorus (P) and ammonium nitrogen (NH₄⁺-N) as the ASP (activated sludge process) currently in use. The changes in energy and heat consumption and the carbon dioxide emissions resulting from the inclusion of microalgae were calculated based on the “surface factor”, which is the ratio of the evaluated surface area to the original basin surface area.

2.1 **The existing wastewater treatment plants**

Three municipal wastewater treatment plants in the cities Västerås, Uppsala and Eskilstuna in the Mälardalen region in Sweden were studied (for specific plant data, see Table 1 and Table 2). These plants use processes that can be considered
to represent standard municipal wastewater treatment in Sweden. By including three different real cases in the energy balance evaluation, the results can reflect variations due to normal differences in conditions for standard process solutions.

The wastewater treatment plant in Västerås receives wastewater from the city of Västerås as well as from the surrounding area [20]. In 2014, 130 333 people were connected to the plant as well as a number of industries (8000 people equivalents (PE) yr⁻¹) [20]. This wastewater treatment plant has two treatment steps: primary treatment and secondary treatment. The primary treatment consists of the addition of iron sulphate, screens, a sand grit and pre-sedimentation. The secondary treatment consists of pre-denitrification and an activated sludge process followed by a biological sedimentation step. The sludge produced at the WWTP is stabilized with anaerobic digestion. The WWTP also receives sludge from nearby small WWTPs. The biogas is sent by pipeline to an upgrading facility to be upgraded to vehicle fuel.

Table 1 Data for the three WWTPs in 2014 [20-22]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Västerås</th>
<th>Uppsala C-block</th>
<th>Eskilstuna</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total connected people equivalents (1 PE = 70 g BOD₇ d⁻¹)</td>
<td>101800</td>
<td>148700³)</td>
<td>82107</td>
<td>PE yr⁻¹</td>
</tr>
<tr>
<td>Industrial waste</td>
<td>8000</td>
<td>25000¹)</td>
<td>4310</td>
<td>PE yr⁻¹</td>
</tr>
<tr>
<td>Total received wastewater</td>
<td>17438648</td>
<td>9434204</td>
<td>16788291</td>
<td>m³ yr⁻¹</td>
</tr>
<tr>
<td>Average incoming COD</td>
<td>3.5</td>
<td>500</td>
<td>166</td>
<td>mg L⁻¹</td>
</tr>
<tr>
<td>Average incoming Ptot</td>
<td>36</td>
<td>6.2</td>
<td>3.9</td>
<td>mg L⁻¹</td>
</tr>
<tr>
<td>Average incoming Ntot</td>
<td>36</td>
<td>54</td>
<td>26.4</td>
<td>mg L⁻¹</td>
</tr>
<tr>
<td>Average outgoing COD</td>
<td>27</td>
<td>&lt;31</td>
<td>37</td>
<td>mg L⁻¹</td>
</tr>
<tr>
<td>Average outgoing Ptot</td>
<td>0.14</td>
<td>0.085</td>
<td>0.1</td>
<td>mg L⁻¹</td>
</tr>
</tbody>
</table>
The wastewater treatment plant in Uppsala is the largest of the three. In 2014, 168,900 people were connected to the plant as well as a number of industries (25,000 PE yr\(^{-1}\)) [21]. The Uppsala WWTP, as described in [21], has three treatment steps: primary, secondary and tertiary treatment. The primary treatment consists of screens, a sand trap, flocculation and pre-sedimentation. The secondary treatment consists of an activated sludge process with nitrogen removal and secondary settling. The primary and secondary treatments are divided into three blocks, block A, B and C. Block C is the newest and handles 52% (in 2014) of the incoming wastewater. Most (83% in 2014) of the reject water from the dewatering of the sludge is handled by block C. The sludge produced at the WWTP is stabilized with anaerobic digestion. The WWTP also receives sludge from nearby small WWTPs. The tertiary treatment consists of flocculation and lamella clarification. Part of the biogas is used in a gas engine and gas boilers to produce heat and electricity for the

<table>
<thead>
<tr>
<th>Average outgoing N\text{tot}</th>
<th>11</th>
<th>11</th>
<th>11</th>
<th>mg L(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat consumption (district heating)</td>
<td>4020</td>
<td>1352(^5)</td>
<td>1916</td>
<td>MWh yr(^{-1})</td>
</tr>
<tr>
<td>Heat consumption (other)</td>
<td>0</td>
<td>1248(^5)</td>
<td>1808.6</td>
<td>MWh yr(^{-1})</td>
</tr>
<tr>
<td>Electricity consumption of air blowers(^6)</td>
<td>1486</td>
<td>1508(^5)</td>
<td>1328</td>
<td>MWh yr(^{-1})</td>
</tr>
<tr>
<td>Other electricity consumption</td>
<td>4019</td>
<td>2236(^5)</td>
<td>4888</td>
<td>MWh yr(^{-1})</td>
</tr>
<tr>
<td>Gas production</td>
<td>1810997</td>
<td>1015924(^3)</td>
<td>1784904(^3)</td>
<td>Nm(^3) yr(^{-1})</td>
</tr>
<tr>
<td>Energy content gas</td>
<td>6.2</td>
<td>6.2(^4)</td>
<td>6.2</td>
<td>kWh Nm(^{-3})</td>
</tr>
<tr>
<td>Amount of sludge treated by AD(^6)</td>
<td>123000</td>
<td>64258(^5)</td>
<td>90327</td>
<td>m(^3) yr(^{-1})</td>
</tr>
<tr>
<td>Total heat and electricity consumption</td>
<td>9525</td>
<td>6344(^5)</td>
<td>9941</td>
<td>MWh yr(^{-1})</td>
</tr>
<tr>
<td>Temperature AD</td>
<td>36</td>
<td>37.5</td>
<td>37</td>
<td>°C</td>
</tr>
</tbody>
</table>

\(^{1}\) = For the whole plant, not just the C-block. \(^{2}\) = Not measured. \(^{3}\) = At the Eskilstuna WWTP, food waste is also hygienised and used for biogas production, but the heat and biogas produced from the food waste is not easily distinguishable from those produced from the other substrates. \(^{4}\) Assumed to be the same as at the Västerås and Eskilstuna WWTPs. \(^{5}\) = Assumes that the C-block used 52% of all heat and electricity consumption and produced 52% of all sludge and biogas. \(^{6}\) Source: personal communication with plant operators. Exact figures for sludge amounts for 2014 were not available for Västerås and Uppsala WWTPs; estimates by plant operators using data from 2015 were used.
WWTP. The rest of the biogas is upgraded for use as a vehicle fuel. In this study, only the C-block part of the Uppsala WWTP is considered.

The municipal wastewater plant in Eskilstuna, described in [22], receives wastewater from Eskilstuna as well as from smaller settlements around Eskilstuna. In 2014, 89 093 people were connected to the wastewater network as well as a number of industries (4310 PE yr\(^{-1}\)). The treatment consists of primary, secondary and tertiary treatment. The primary treatment consists of the addition of iron sulphate, screens, pre-aeration, pre-sedimentation and a sand trap. The secondary treatment consists of tanks with aerated zones followed by unaerated zones and sedimentation. The tertiary treatment consists of a constructed wetland.

The sludge at the plant is stabilized with anaerobic digestion where it is co-digested with food waste.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Västerås</th>
<th>Uppsala C-block</th>
<th>Eskilstuna</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average incoming BOD(_T)</td>
<td>113</td>
<td>96</td>
<td>58.24</td>
<td>mg L(^{-1})</td>
</tr>
<tr>
<td>Average incoming P(_{tot})</td>
<td>2.9</td>
<td>2.1</td>
<td>1.70</td>
<td>mg L(^{-1})</td>
</tr>
<tr>
<td>Average incoming NH(_4^+)N</td>
<td>25</td>
<td>35.6(^1)</td>
<td>17.58</td>
<td>mg L(^{-1})</td>
</tr>
<tr>
<td>Average outgoing BOD(_T)</td>
<td>3.6</td>
<td>3.8</td>
<td>17.34</td>
<td>mg L(^{-1})</td>
</tr>
<tr>
<td>Average outgoing P(_{tot})</td>
<td>0.14</td>
<td>0.32</td>
<td>1.28</td>
<td>mg L(^{-1})</td>
</tr>
<tr>
<td>Average outgoing NH(_4^+)N</td>
<td>1.7</td>
<td>1.86</td>
<td>2.35</td>
<td>mg L(^{-1})</td>
</tr>
<tr>
<td>Size of active sludge basin</td>
<td>12690</td>
<td>13200</td>
<td>8800</td>
<td>m(^3)</td>
</tr>
<tr>
<td>Surface of active sludge basin</td>
<td>2820</td>
<td>2730</td>
<td>2436</td>
<td>m(^2)</td>
</tr>
</tbody>
</table>

\(^1\) = Calculated value (because it is not measured), assuming that 60% of all incoming N-\(tot\) (apart from reject water) is NH\(_4^+\)N (mean of Västerås WWTP’s 63% and Elskilstuna’s 57%). It is also assumed that all N-\(tot\) from the reject water is NH\(_4^+\)N (according to [28], almost all N-\(tot\) in the reject water is NH\(_4^+\)N).

2.2 The MAASPBR treatment plant model
The MAASPBR was investigated as an alternative to the “traditional” waste-activated sludge (WAS) process. The concept of algae-bacteria symbiosis systems has been described in previous studies [12,23]. Such systems are based on the inclusion of microalgae in the process, thereby reducing or eliminating the need for aeration. The microalgae produce the oxygen needed by the bacterial biomass as well as contributing to the reduction of nutrients from the incoming wastewater.

This study considered the introduction of the MAASPBR into existing wastewater treatment plants. It was assumed that the hydraulic retention time would be the same as in the current plants, leading to the same volumes in the biological treatment basins. No real PBR was involved in this study instead calculations of the microalgae and their properties were based on previous studies. Figure 2 presents an overview of the MAASPBR treatment plant model, and the following sections
explain the calculation steps in more detail. The parameters used are presented in Table 3 and the equations are shown in Table 4.

### Table 3 Parameters used in the calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface reflection factor ( f_{\text{reflec}} )</td>
<td>0.8</td>
<td>-</td>
<td>[24]</td>
</tr>
<tr>
<td>Minimal quanta required to liberate ( O_2 ) for sunlight ( (Y_{\text{need,O2}}) )</td>
<td>20</td>
<td>photons ( O_2 )⁻¹</td>
<td>[25]</td>
</tr>
<tr>
<td>( O_2 ) consumption: COD-reducing biomass ( (O_{2,\text{use,CODbiomass}}) )</td>
<td>0.51</td>
<td>g ( O_2 ) g⁻¹ COD₆ removed</td>
<td>[3]</td>
</tr>
<tr>
<td>( O_2 ) consumption: P-reducing biomass ( (O_{2,\text{use,Pbiomass}}) )</td>
<td>0.49</td>
<td>g ( O_2 ) g⁻¹ COD₅ removed</td>
<td>[3]</td>
</tr>
<tr>
<td>( O_2 ) consumption: nitrification biomass ( (O_{2,\text{use,nitrification}}) )</td>
<td>0.25</td>
<td>g ( O_2 ) g⁻¹ NH₄⁺-N removed</td>
<td>[3]</td>
</tr>
<tr>
<td>( CO_2 ) absorption by microalgae ( (f_{\text{CO2,abs,per,ma}}) )</td>
<td>2.0</td>
<td>g ( CO_2 ) g⁻¹ microalgae</td>
<td>Eq.2</td>
</tr>
<tr>
<td>NH₄⁺ reduced by microalgae ( (N_{\text{red,algae}}) )</td>
<td>0.08</td>
<td>g ( NH_4^+ ) N g⁻¹ microalgae</td>
<td>Eq.2</td>
</tr>
<tr>
<td>P reduced by microalgae ( (P_{\text{red,algae}}) )</td>
<td>0.043</td>
<td>g ( P ) g⁻¹ microalgae</td>
<td>Eq.2</td>
</tr>
<tr>
<td>( CO_2 ) absorption by nitrification ( (f_{\text{CO2,abs,per,ni}}) )</td>
<td>0.25</td>
<td>g ( CO_2 ) g⁻¹ NH₄⁺-N</td>
<td>[3]</td>
</tr>
<tr>
<td>N uptake by COD-reducing biomass ( (N_{\text{uptakeheterobiomass}}) )</td>
<td>0.12</td>
<td>g ( N ) g⁻¹ bacteria</td>
<td>[26]</td>
</tr>
<tr>
<td>COD uptake by P-reducing biomass ( (COD_{\text{red,Pbiomass}}) )</td>
<td>9.06¹)</td>
<td>g ( COD ) g⁻¹ P removed</td>
<td>[3]</td>
</tr>
<tr>
<td>( CO_2 ) emission: COD/P reducing biomass ( (f_{\text{CO2,em,COD}}) )</td>
<td>0.7</td>
<td>g ( CO_2 ) g⁻¹ COD</td>
<td>[3]</td>
</tr>
<tr>
<td>Conversion efficiency: biogas to electricity ( (\eta_{\text{electrical}}) )</td>
<td>40</td>
<td>%</td>
<td>Estimate, see 2.2.7</td>
</tr>
<tr>
<td>Conversion efficiency: biogas to heat ( (\eta_{\text{thermal}}) )</td>
<td>46</td>
<td>%</td>
<td>Estimate, see 2.2.7</td>
</tr>
<tr>
<td>Oxygen yield per microalgae ( (Y_{\text{need,O2}}) )</td>
<td>1.5</td>
<td>g ( O_2 ) g⁻¹ microalgae</td>
<td>[8]</td>
</tr>
<tr>
<td>Electricity consumption: secondary treatment excluding aeration ( (P_{\text{secondary,per,m3}}) )</td>
<td>0.008</td>
<td>kWh m⁻³ sludge</td>
<td>Uppsala WWTP</td>
</tr>
<tr>
<td>Electricity consumption: sludge handling ( (P_{\text{sludge,handl,per,m3}}) )</td>
<td>10.7</td>
<td>kWh m⁻³ sludge</td>
<td>Uppsala WWTP</td>
</tr>
<tr>
<td>Electricity consumption: anaerobic digestion ( (P_{\text{digester,per,m3}}) )</td>
<td>1.9</td>
<td>kWh m⁻³ sludge</td>
<td>Uppsala WWTP</td>
</tr>
</tbody>
</table>

¹) Assuming that all P is \( PO_4^{3-} \)-P
Table 4 Equations used in calculations

<table>
<thead>
<tr>
<th>Description</th>
<th>No</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reducution of nutrients</td>
<td>1</td>
<td>(\text{NH}<em>4^+ - \text{N}</em>{\text{red}} = (\text{NH}<em>4^+ - \text{N}</em>{\text{in}} - \text{NH}<em>4^+ - \text{N}</em>{\text{out}}) \times \frac{q_{\text{months}}}{1000})</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(\text{BOD}<em>{\text{red}} = (\text{BOD}</em>{\text{in}} - \text{BOD}<em>{\text{out}}) \times \frac{q</em>{\text{months}}}{1000})</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>(\text{COD}<em>{\text{red}} = \text{COD}</em>{\text{in}} \times \frac{\text{BOD}<em>{\text{red}}}{\text{BOD}</em>{\text{in}}})</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>(\text{Pred} = (\text{P}<em>{\text{in}} - \text{P}</em>{\text{out}}) \times \frac{q_{\text{months}}}{1000})</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>(\text{F}<em>{\text{red},\text{algae}} = \text{m}</em>{\text{algae,vs}} \times \text{F}_{\text{uptake,algae}})</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>(\text{N}<em>{\text{red,algae}} = \text{m}</em>{\text{algae,vs}} \times \text{N}_{\text{uptake,algae}})</td>
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<tr>
<td></td>
<td>7</td>
<td>(\text{COD}<em>{\text{red,biomass}} = \left(\text{Pred} - \text{Pred}</em>{\text{algae}}\right) \times \text{COD}_{\text{need}})</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>(\text{m}<em>{\text{bacteria,vs}} = \text{BOD}</em>{\text{red}} \times \text{Y}_{\text{obs}} [27])</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>(\text{CO}_2 + 0.70 \text{H}_2\text{O} + 0.12 \text{NH}_4^+ + 0.01 \text{H}_2\text{PO}_4^- \rightarrow \text{CH}_3\text{COO}^- \cdot \text{H}_2\text{O} + 0.36 \text{N}<em>2 + 0.12 \text{P}</em>{\text{0.01}} [25]) + (+ 1.18 \text{O}_2 + 0.11 \text{H}_2\text{O})</td>
</tr>
<tr>
<td>Microalgae biomass production</td>
<td>12</td>
<td>(\gamma_{\text{sun}} = \text{F}<em>{\text{reflec}} \times \text{PPD}</em>{\text{sun}} \times \text{A}_{\text{sur reactor}})</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>(\text{O}<em>{2,\text{avg,algae}} = \frac{\text{M}</em>{\text{O}<em>2} \times \gamma</em>{\text{sun}}}{\gamma_{\text{need}} \times 0.2})</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>(\text{m}<em>{\text{algae,vs}} = \frac{\text{X}</em>{\text{algae}}}{0.2} \times \text{O}_{2,\text{avg,algae}})</td>
</tr>
<tr>
<td>Biogas potential of bio sludge</td>
<td>15</td>
<td>(\text{BP}<em>{\text{WAS}} = \left(\text{V}</em>{\text{biogas,lac}} / \text{Y}<em>{\text{biogas,PS}} \times \text{Sum}</em>{\text{VS}} \times \text{Sum}_{\text{VWS}}\right))</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>(\text{BP}<em>{\text{PS}} = \left(\text{Y}</em>{\text{biogas,PS}} \times \text{BP}_{\text{WAS}}\right))</td>
</tr>
<tr>
<td>Oxygen needed by bacteria</td>
<td>17</td>
<td>(\text{O}<em>{2,\text{use,nitrification}} = \left(\text{NH}<em>4^+ - \text{N}</em>{\text{red}} - \text{N}</em>{\text{red,algae}} - \text{N}<em>{\text{uptake,algae}}\right) \times \text{O}</em>{2,\text{need,nitrification}})</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>(\text{O}<em>{2,\text{use,nitrification,lc}} = \left(\text{NH}<em>4^+ - \text{N}</em>{\text{red}} - \text{N}</em>{\text{uptake,algae}}\right) \times \text{O}_{2,\text{red,nitrification}})</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>(\text{O}<em>{2,\text{use,CODbiomass}} = \left(\text{COD}</em>{\text{red}} - \text{COD}<em>{\text{red,biomass}}\right) \times \text{O}</em>{2,\text{need,CODbiomass}})</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>(\text{O}<em>{2,\text{use,biomass}} = \text{O}</em>{2,\text{need,biomass}} \times \text{COD}_{\text{red,biomass}})</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>(\text{O}<em>{2,\text{use,total,lc}} = \text{O}</em>{2,\text{use,nitrification,lc}} + \text{O}<em>{2,\text{use,CODbiomass}} + \text{O}</em>{2,\text{use,biomass}})</td>
</tr>
<tr>
<td>Energy demand of sludge handling</td>
<td>23</td>
<td>(\text{V}<em>{\text{increased,sludge,digester}} = \frac{\text{m}</em>{\text{algae,vs}}}{1000})</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>(\text{P}<em>{\text{secondary,incr,algae}} = \text{P}</em>{\text{secondary,per,m}3} \times \text{V}_{\text{increased,sludge}})</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>(\text{P}<em>{\text{sludge,incr}} = \frac{\text{P}</em>{\text{sludge,handl,per,m}3} \times \text{V}_{\text{increased,sludge}}}{1000})</td>
</tr>
<tr>
<td>Digester heating and electricity consumption</td>
<td>26</td>
<td>(\text{Q}<em>{\text{digester,extra}} = \left(\text{V}</em>{\text{increased,sludge}} \times 1000\right) \times \text{C}_{\text{H}<em>2\text{O}} \times \text{T}</em>{\text{digestion,ambient}} / (3600 \times 1000))</td>
</tr>
<tr>
<td>Biogas production</td>
<td>27</td>
<td>(\text{V}<em>{\text{extra,biogas}} = \text{BP}</em>{\text{WAS}} \times \text{m}_{\text{algae,vs}})</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>(\text{P}<em>{\text{extra,biogas}} = \left(\text{V}</em>{\text{extra,biogas}} \times \text{P}_{\text{content,biogas}}\right) / 1000)</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>(\text{P}<em>{\text{biogas,lc}} = \left(\text{V}</em>{\text{biogas,lc}} \times \text{P}_{\text{content,biogas}}\right) / 1000)</td>
</tr>
<tr>
<td>Energy for aeration</td>
<td>31</td>
<td>(\text{O}<em>{2,\text{need,remaining}} = \left(\text{O}</em>{2,\text{use,total}} - \text{O}_{2,\text{avg,algae}}\right))</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>(\text{P}<em>{\text{aeration,net}} = \left(\text{O}</em>{2,\text{need,remaining}} / \text{O}<em>{2,\text{use,remaining}}\right) \times \text{P}</em>{\text{aeration,lc}})</td>
</tr>
<tr>
<td>Energy balance</td>
<td>33</td>
<td>(\text{Q}<em>{\text{net,case,net}} = \left(\text{Q}</em>{\text{digester,extra}} + \text{Q}<em>{\text{cond,lc}}\right) - \left(\text{P}</em>{\text{extra,biogas}} + \text{P}<em>{\text{bio,imp}}\right) \times \text{P}</em>{\text{thermal}})</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>(\text{Q}<em>{\text{net,case,biogas}} = \text{Q}</em>{\text{cond,lc}} \times \text{P}<em>{\text{bio,imp}} \times \text{P}</em>{\text{thermal}})</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>(\text{P}<em>{\text{net,case,new}} = \left(\text{P}</em>{\text{other}} + \text{P}<em>{\text{aeration,net}}\right) \times \text{P}</em>{\text{digester,extra}} - \left(\text{P}<em>{\text{extra,biogas}} + \text{P}</em>{\text{bio,imp}}\right) \times \text{P}_{\text{electrical}})</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>(\text{P}<em>{\text{net,case,bc}} = \text{P}</em>{\text{other}} + \text{P}<em>{\text{aeration,bc}} \times \text{P}</em>{\text{bio,imp}} \times \text{P}_{\text{electrical}})</td>
</tr>
<tr>
<td>CO₂ absorption and emission</td>
<td>37</td>
<td>(\text{m}<em>{\text{CO}<em>2,\text{emission,mas}} = \text{COD}</em>{\text{red}} \times \text{f}</em>{\text{CO}<em>2,\text{em}} \times \text{COD} + \left(\text{f}</em>{\text{CO}<em>2,\text{abs,per,mas}} \times \text{m}</em>{\text{algae,vs}}\right) + \left(\text{NH}<em>4^+ - \text{N}</em>{\text{red,algae}} - \text{N}<em>{\text{uptake,algae}}\right) \times \text{f}</em>{\text{CO}_2,\text{abs,per,nn}})</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>(\text{m}<em>{\text{CO}<em>2,\text{emission,bc}} = \text{COD}</em>{\text{red}} \times \text{f}</em>{\text{CO}<em>2,\text{em}} \times \text{COD} + \left(\text{NH}<em>4^+ - \text{N}</em>{\text{red,algae}} - \text{N}</em>{\text{uptake,algae}}\right) \times \text{f}_{\text{CO}_2,\text{abs,per,nn}})</td>
</tr>
<tr>
<td>Biomass concentration</td>
<td>39</td>
<td>(\text{m}<em>{\text{algae}} = \text{SRT} \times \text{m}</em>{\text{bacteria,vs}} / 365 \times \text{V}<em>{\text{reactor}} / \text{P}</em>{\text{aer,per,mas}})</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>(\text{m}<em>{\text{algae}} = \text{SRT} \times \text{m}</em>{\text{algae,vs}} / 365 \times \text{V}<em>{\text{reactor}} / \text{P}</em>{\text{aer,per,mas}})</td>
</tr>
</tbody>
</table>
2.2.1 Calculations of available sunlight and microalgal biomass (Eq. 12-14)

The algal biomass produced each month was calculated from the amount of sunlight on the basin surface, the amount of photons needed for oxygen liberation and the microalgal biomass productivity per oxygen liberated. The available sunlight for Eskilstuna, Västerås and Uppsala was retrieved for each month of 2014 from the STRÅNG database [28]. It was assumed that 20% of the light was lost by reflection at the surface (as suggested in [24]). It was also assumed that 20 mol of photons were needed to release one mol of O₂, as suggested by Boelee et al. [25]. The minimum amount of photons needed for the release of O₂ is reported in [26] as 10 photons per O₂ molecule. However, photons are also needed for maintenance of the microalgal cells.

Using data found in the literature, a value for a real application was also estimated for comparison. Hu et al. [29] reported that for two pilot raceway ponds (1000 m²) in Roswell, USA, the maximum productivity was 50 g m⁻² d⁻¹, and the average productivity was 10 g m⁻² d⁻¹. There are a number of different factors that can limit productivity. For these calculations, it was assumed that the amount of photons needed for oxygen liberation was the limiting factor when productivity was the highest, and that it was achieved during the part of the year when the solar irradiation was the highest (May). An estimate of the amount of photons needed was calculated using the average solar irradiance data for Roswell in May (7.06 kWh m⁻² day⁻¹ [30]), the method to convert kWh m⁻² day⁻¹ to mol photons m⁻² suggested in Boelee et al. [25] and the oxygen production per microalgal biomass.
given by Eq.13. The photon requirement is 18/22 mol of photons per mol of O₂ for the highest productivity (20% surface reflection /no surface reflection). These values match the 20 mol of photons per mol of O₂ used in this study. However, the presence of photoinhibition and self-shading of the biomass are factors that could increase the photon requirement. The reactor in this study is situated at a northern latitude where solar irradiance low in comparison to the tropics, thus photoinhibition is not considered. Self-shading is accounted for by calculation of the biomass concentrations and comparison with the normal values for photobioreactors. Previous studies [25,26] have not taken self-shading into account.

Using the minimum quanta needed, the O₂ produced by the microalgae was calculated. In addition to the aeration calculations, the produced O₂ was also used to calculate the microalgal biomass produced using the amount of oxygen produced per amount of microalgal biomass (presented in Table 3).

2.2.2 Nutrient reduction and oxygen requirement (Eq 1-11, 17-22, 31)

The same amount of biological oxygen demand (BOD), biodegradable chemical oxygen demand (CODₘ), phosphorus (P) and ammonium nitrogen (NH₄⁺-N) are to be reduced in the MAASPBR as in the ASP (activated sludge process) currently in use. It was assumed that only bacteria would reduce COD and BOD as microalgae would use carbon dioxide as a carbon source as described in Eq.11 (Table 4). The incoming and outgoing values for each nutrient were used to calculate how much each nutrient was reduced in the process; see Table 2 for values.
The stoichiometric formula given in [25] for the growth of the microalgae was used, see Eq. 11 (Table 4). According to the stoichiometric formula, the microalgae use carbon dioxide as the carbon source and light as the energy source. It was assumed that the microalgae reduce NH$_4^+$-N and P but do not COD$_b$. The NH$_4^+$-N and P not reduced by the microalgae are reduced by the bacterial biomass in the same way as in the normal activated sludge process. The amounts of NH$_4^+$-N and P reduction per mass of microalgae were calculated from Eq. 11 (Table 4) using the molar mass for microalgae given in Table 3 [26]. The actual amounts of N and P reduced by microalgae depend on the conditions and species of microalgae.

Experimental studies reported in the literature [31, 32] show N removal rates of 0.05-0.16 g N/g microalgae and N content of 1% to 14% of dry mass, and P removal rates of 0.013-0.028 g P/g microalgae and P content of 0.05% to 3.3% (removal rates calculated from microalgae production rates and removal rates presented in [31]). The amount of oxygen needed by the bacteria to reduce COD$_b$, P and NH$_4^+$-N (eq 17-22, Table 4) was calculated using the values presented in Table 3. Bacteria need COD$_b$ to reduce P. The amount of O$_2$ produced by the microalgae was subtracted from the O$_2$ required by the bacterial biomass to calculate the additional O$_2$ required. This O$_2$ requirement was compared to the O$_2$ requirement of the base case. It was assumed that the aeration could be reduced linearly with the reduction in O$_2$ requirement.

2.2.3 Conversion of BOD$_7$ to COD$_b$ (Eq.3)

For the oxygen calculations required for the bacterial biomass and CO$_2$ absorption and emission, COD$_b$ and the parameters in Table 3 are needed. However, COD$_b$ is
not measured at the WWTPs in this study, although total COD is measured in incoming water and wastewater, and biochemical oxygen demand (BOD) is measured in streams within the plant as well as in outgoing and incoming water. According to Metcalf and Eddy [27], COD is approximately 1.6 BOD. At the WWTPs, the BOD is measured as BOD, and BOD is approximately 1.17 BOD [33]. The conversion used in this study was COD = (1.6/1.17) BOD.

### 2.2.4 Calculation of CO₂ absorption and emission (Eq 37-38)
Carbon dioxide is reduced by the microalgae and also to some extent by the nitrifying bacteria. The CO₂ is emitted by COD-reducing and P-reducing bacteria as they absorb the COD. The absorption and emission of the microalgal and bacterial biomass were calculated using the parameters presented in Table 3. The CO₂ absorption by microalgae calculated using Eq 11 (Table 4) was supported by the experimental study by Kim et al. [31] where the CO₂ fixation rate for Scenedesmus sp. was 1.5 - 1.9 g CO₂/g microalgae depending on light wavelength.

### 2.2.5 Sludge separation and handling (23-25)
Chemical coagulation/flocculation combined with sedimentation is currently used at the WWTPs for the separation of the sludge. It is a cheap and simple method [34]. It was assumed that it would still be used if microalgae were introduced. Mennaa et al. [35] found that for seven microalgal species tested, this method resulted in a biomass recovery efficiency of over 90%, showing that it is also effective for microalgae.

The equation for sludge production based on observed yield, presented in [27], was used to calculate the sludge production (Eq. 10, Table 4). Because the
observed yield was calculated based on the base case data of the plants, and BOD is only reduced by bacteria, sludge resulting from the bacterial biomass is assumed to be the same in the microalgae case. The sludge contribution from the microalgae is equal to the amount of produced microalgal biomass (in kg VS).

It was assumed that the energy use for thickening, pumping, flocculation and dewatering of the sludge would increase linearly with an increase in the amount of sludge. The energy usage for the different steps has been well documented at the Uppsala WWTP but not at the other two plants. Using the data from the Uppsala WWTP, the energy usage per m³ of sludge was calculated and used to calculate the additional electricity required for handling the increased sludge volumes (values used are presented in Table 3).

2.2.6 Biogas potential of microalgal sludge (Eq 15-16)

In order to avoid overestimating biogas production, it was assumed that the microalgae would not affect the amount of biogas produced per unit of sludge from the secondary treatment, because the possible synergetic effects shown in some studies [36,37] are yet not fully understood or quantified. However, the microalgae could lead to a higher total amount of sludge. The additional biogas due to increased sludge production was taken into account. Primary sludge (PS) usually has higher biomethane potential than secondary sludge. Using the result presented by Ara et al. [38], the PS yielded approximately 50% more biogas than WAS on a VS basis (so that biogas yield PS = 1.50* Biogas yield WAS). This relationship was used to estimate the contribution of the WAS sludge in the WWTPs at present (knowing the amount of biogas produced and the incoming amount of primary sludge and
WAS sludge). The biogas potential of the WAS sludge was then used to calculate
the biogas production of the additional MAASPBR sludge produced.

2.2.7 Heat requirements of digestion, and conversion of biogas to heat and
electricity (Eq. 26-30)

The energy used for the anaerobic digestion was assumed to be dependent on the
amount of incoming sludge. The additional heating demand for the sludge was
calculated using the heat capacity of water and the temperature difference from 12°C to the temperature of the digestion chamber (temperatures presented in Table
1). The additional heat requirement for keeping the extra sludge warm during the
retention time was neglected.

The majority of the biogas in the three WWTPs is upgraded to vehicle fuel.

However, to facilitate a comparison between energy balances, it was assumed that
the biogas was converted to heat and electricity. The conversion factors used were
as follows: 40% of the energy in the biogas would be converted into electricity and
46% into heat. The conversion factors were set based on the efficiencies for
existing gas engines, found to be 37.0-42.8% electrical efficiency and 84.2-87.6%
for total efficiency [39-41].

2.2.8 Adaptation used for the Eskilstuna WWTP

At the Eskilstuna WWTP, the sludge is co-digested with the organic fraction of
municipal solid waste, grease and ice-cream from a nearby factory. The total
biogas contribution from these substrates was estimated using the biogas potential
values from Carlsson & Uldal [42] (food waste 600 m³ CH₄/ton VS; ice-cream was
estimated as grease trap sludge with a potential of 682 m³ CH₄/ton VS and VS of
The methane content was assumed to be 60%. The biogas from the extra substrates was subtracted when calculating the biogas potential of the sludges and added when calculating heat and electricity production.

3 Results and discussion

If the same current basins are used for the MAASPBR, the decrease in power and heat consumption is quite small (<10%), see Figure 3. The microalgae are dependent on light for growth, and the existing basins have quite a small surface area compared to the total volume. As the surface area is expanded, an increasing amount of heat and electricity can be saved. The potential decrease in heat and electricity consumption almost doubled in the summer months compared to the whole year.

Figure 3 Change in net energy usage for the three WWTPs compared to the base case, dependent on the surface area for both the whole year and for the summer months
The basin surface areas and volumes are not the same at the three plants, see Table 2. They are similar, but at 12 times the current surface area, the surface-to-volume ratio becomes quite different, see Table 5. At the largest surface area, the basins become shallow, see Table 5. However, HRAPs are usually shallow, and the typical depth is 0.3 m [8]. The Uppsala C-block has the highest percentage change in heat consumption because it also has the lowest heat consumption. In the calculations, it was assumed that the C-block that treats 52% of the incoming wastewater at the Uppsala WWTP also uses 52% of the heat used. However, this results in the Uppsala C-block having significantly lower heat consumption than the other two plants.

<table>
<thead>
<tr>
<th>Table 5 Surface areas of the biological treatment at the plants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit</strong></td>
</tr>
<tr>
<td>Surface area base case</td>
</tr>
<tr>
<td>Surface-to-volume ratio base case</td>
</tr>
<tr>
<td>12* base case surface area</td>
</tr>
<tr>
<td>Maximum surface-to-volume ratio</td>
</tr>
<tr>
<td>Smallest depth</td>
</tr>
<tr>
<td>Current area of whole plant</td>
</tr>
</tbody>
</table>

¹) Area includes wetlands. Area excluding wetlands = 70 000 m² ²) whole Uppsala plant.

Because the microalgae consume CO₂, they will reduce the net CO₂ emissions from the biological treatment compared to the current emissions. The reduction in CO₂ emissions were calculated for the WWTPs using the same surface factors as for the calculations of net energy use. The nitrifying bacteria absorb some CO₂, and with less ammonium nitrogen available for the nitrifying bacteria (due to the microalgae), they also absorb less CO₂. Despite this, the net emission of CO₂ is decreased because the microalgae absorb a large amount of CO₂. The larger the...
The greater the surface area, the more microalgae and the greater the reduction in net CO₂ emission, see Figure 4.

Figure 4 Change in CO₂ emissions from the biological treatment compared to the base case for the three WWTPs, dependent on selected surface area for the whole year and for the summer months.

For a comparison of the actual amounts of CO₂, the CO₂ emission values are presented in Table 6 for the base case and for the microalgae case with the largest surface area studied. The actual surface areas are presented in Table 5. The CO₂ emissions are positive for all months of the year for all plants except for one or two months for Eskilstuna (for surface factor > 9) and Uppsala (for surface factor > 10). As long as the CO₂ emission is positive, no additional CO₂ needs to be added to the process; it will instead be provided by the bacterial biomass. When the CO₂ emissions are negative, additional CO₂ is needed, and one alternative is to use CO₂ produced by the anaerobic digestion.
Table 6 CO₂ emission for the WWTPs for the base case and for the largest surface area

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Eskilstuna</th>
<th>Uppsala C-block</th>
<th>Västerås</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated CO₂ emission base case,</td>
<td>tonnes CO₂</td>
<td>636</td>
<td>795</td>
<td>1794</td>
</tr>
<tr>
<td>whole year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculated CO₂ emission base case,</td>
<td>tonnes CO₂</td>
<td>214</td>
<td>268</td>
<td>605</td>
</tr>
<tr>
<td>May to August</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculated CO₂ emission, 12*surface</td>
<td>tonnes CO₂</td>
<td>295</td>
<td>417</td>
<td>1396</td>
</tr>
<tr>
<td>area, whole year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculated CO₂ emission, 12*surface</td>
<td>tonnes CO₂</td>
<td>-7</td>
<td>23</td>
<td>347</td>
</tr>
<tr>
<td>area, May to August</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As discussed in previous studies [8,25], the land requirements are significant. The largest surface factor corresponds to a significant increase in land use and may not be a viable option for all plants (Table 5). The largest surface area tested here is almost the same size as the Västerås and Uppsala WWTPs. The Eskilstuna WWTP uses a much larger land area because of the wetlands. The low intensity Nordic winter light conditions mean that a large land area is needed to ensure that sufficient photons are incident on the surface (as observed by comparing the results for summer and annual conditions in Figure 3 and Figure 4). Of the plants studied, the Eskilstuna plant is the most viable at present due to the issue of land use, even if it would not achieve the largest reductions in energy use and CO₂ emissions. In these scenarios, aeration is still present even though microalgae reduce the aeration need. However, as the area of the basin increases, aeration might become more difficult, or at least another aeration strategy might be needed. Another option could be to increase the amount of photons reaching the reactor without increasing land use. This could be achieved by using stacked tubular photobioreactors or by internally lighting the volume by artificial lighting (so that
the “illuminated surface area” is increased). Both tubular photobioreactors [8] and artificial light [26] can carry a high cost. The aeration efficiency for mechanical and air-blowing aeration is in the range of 1.5 to 5.9 kg O₂/kWh [43]. The photosynthetic photon flux (PPF) efficacy of commercial horticultural LEDs ranges from 2.00 μmol/J to 3.05 μmol/J, depending mainly on wavelength [44,45]. Using a photon requirement per mol oxygen of 2.7 μmol/J yields an aeration efficiency of approximately 0.016 kg O₂/kWh (or 0.032 kg O₂/kWh if the minimum photon requirement of 10 photons per O₂ is used). Either way, this efficiency is much lower than the mechanical aeration efficiency. Unless artificial lighting can offer other benefits or its efficiency can be greatly improved, it is not very promising from an energy perspective. The electricity cost of artificial lighting would also exceed the electricity cost of the corresponding aeration. Another alternative is concentrating and introducing natural light into the reactor through other means, such as optical cables [46] and Plexiglas rods [16]. During the winter, the light intensity is generally low, and even concentrating the light and introducing it into the reactor might not yield a much higher number of photons. However, it is possible that internal lighting will be better at spreading the light to the microalgae and reducing the amount of photons needed per mol of oxygen.

The WWTPs in Sweden that could be well suited for MAASPBR are those that have more people connected during summer. An example is the WWTP in Visby on the island of Gotland. During the summer, the connected PE is doubled, calculated from daily PE values from the plant [47]. Another example is the Omholmens WWTP, where the number of connected people is quadrupled in summer [48]. If sufficient land area is available, the MAASPBR could be used in summer to greatly
reduce energy use and carbon dioxide emissions. Boelee et al. [25] envisioned such a seasonal microalgae treatment system for a WWTP in the Netherlands. The challenge then becomes the maintenance of the microalgal population in winter and how rapidly and efficiently a new culture can be started each spring. For the calculations concerning the summer period, it was assumed that the annual heat and electricity consumption would be evenly spread out over the year. In reality, it is likely that the heat and electricity consumption would be lower during summer. Consequently, the MAASPBR will account for a larger share of the heat and electricity consumption in summer than these calculations show. However, it is also possible that some of the people connected to the WWTPs will go on vacation in summer, reducing the amount of incoming nutrients, leading to lower biomass and biogas production.

Mutual shading can limit biomass growth [49,50], and the higher the biomass concentration, the more likely this will occur. In this study, it was assumed that there would be sufficient stirring to avoid mutual shading. However, at very high biomass concentrations, it will not be possible to stir the material or to have basins shallow enough to avoid self-shading. Vandamme et al. [49] stated that the biomass concentration is often low in photobioreactors, approximately 5 g/l. In this study, the total biomass concentration was approximately 4.8-5.8 g L⁻¹ (estimated using an SRT of 12 days, microalgae VS of 62% TS [36] and current basin volumes).

3.1 Sensitivity analysis
A sensitivity analysis was conducted to test the robustness of the solution. All the microalgae related parameters in Table 3 were tested (CO₂ absorption by microalgae, NH₄ reduced by microalgae, P reduced by microalgae, minimal quanta required to liberate O₂ for sunlight), as well as the observed yield for bacterial biomass (Y_{obs}). Each parameter was individually changed to +/- 50% of its original value and the effects on calculated CO₂ emission, heat and electricity consumption and biomass concentration for each WWTP were examined. A surface factor of 12 was chosen for the sensitivity analysis since the impact of the parameter on the result would be expected to increase with increasing surface factor. The result of the calculation was insensitive to changes in the ability of the microalgae to remove P and N. The observed yield of the bacteria, Y_{obs}, had a large impact on the biomass concentration and a smaller impact on the other results (<10% for a 50% change of Y_{obs}). The bacteria make up the majority of the biomass and it is therefore not surprising changing Y_{obs} had an almost 1:1 effect on the biomass concentration. The CO₂ absorption ability had a large impact on the CO₂ emissions from the plant but not on the other results. This also depended on the operating conditions, as shown in [31] where emissions varied from 1.5 to 1.9 gCO₂ g⁻¹ microalgae depending on the light wavelength.

The oxygen yield per microalgae and minimal quanta needed to liberate O₂ are the two parameters that have the largest impact on the calculations. The quanta needed to liberate O₂ can be especially difficult to determine since this quantity is affected by the operating conditions. If the biomass concentration in the reactor becomes too high and/or the stirring is not sufficient the quanta needed will increase since the microalgae will encounter less sunlight as a result. If the quanta
need is too high, the microalgae population will be so small that it will have no impact on the system. However, it should be noted that according to the calculations the biomass concentration in the basins is on the same order as those usually found in photobioreactors [49]. Further details and figures for the sensitivity analysis are presented in the supplementary information.

4 Conclusion

The microalgae-activated sludge process (MAASP) has the potential to decrease electricity and heat consumption as well as carbon dioxide emissions. However, to achieve a large reduction, the land requirements are significant, especially when using microalgae year around. The largest reduction in energy use achieved was 35% (whole year) and 68% (summer period). For carbon dioxide emissions, it was 54% (whole year) and 103% (summer period). The MAASP can therefore be suitable for a seasonal system where a WWTP that has a higher incoming load in summer can benefit (for example, a WWTP at a tourist location).

5 Acknowledgements

This work was supported by the Knowledge Foundation (KKS) and the co-production partners within the framework Future Energy ABB and the VEMM group (Vafab, Eskilstuna Energi och Miljö and Mälarenergi). The STRÅNG data used here were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) and were produced with support from the Swedish Radiation Protection Authority and the Swedish Environmental Agency. The solar irradiance data for Roswell, USA, were obtained from the NASA Langley Research Center.
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