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Abstract:

Production of biogas from small farms in China is decreasing because of the decrease in farm animals at these farms. It is needed a replacement for the animal manure. The replacement looked into in this paper is an algae pond with wet organic solid waste (WOSW) in combination with an anaerobic digester (AD). The main focus of the algae type and the type of WOSW were Chlorella Vulgaris and wheat straw respectively.

It was developed a chemical oxygen demand (COD) balance in Microsoft Excel to investigate the theoretical production of biogas. The two cases that were tested were the case with algae pond and WOSW and a case with algae pond and silage. The pond was investigated for surface areas of 10, 20, 30, 40 and 50 m^2. It was shown that theoretically the increase of biogas is 0.1 m^3 CH_4 gas per day when you increase the pond size by 10 m^2. In the silage case it was investigated on how much mass that was needed to produce twice the volume of biogas from the AD. The same mass that was found in the silage case was then used in different ways to investigate the WOSW. In both cases the production of biogas will increase. How much the biogas will increase depends on the size of the farm and the space available to build the pond.

Connecting WOSW and algae pond to an AD looks like a promising way to increase the biogas production. It should be look into in more detail and with experiments.

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Preface

This thesis is submitted to the Faculty of Technology, Telemark University College (TUC), for the requirements for the Degree of Master of Science in Energy and Environmental Technology, under the subject code FMH606.

It is suggested some knowledge about anaerobic digestion.

Microsoft Excel was used to calculate the COD balances in the different cases.

I would like to thank my supervisors Rune Bakke and Wang Shuai for guiding me with the thesis and being a source of information.

Porsgrunn, 03.06.2014

Magnus Bjerkely

Nomenclature

AD - Anaerobic digestion

COD - Chemical Oxygen demand

WOSW - Wet Organic Solid Waste

TS - Total Solids

RS - Rice Straw

1 Introduction

In anaerobic digestion micro-organisms break down organic matter and generate biogas. The limiting factor for methane production is the availability for suitable waste. For small farms in China it has been a decrease in farm animals thus a decrease in manure available for biogas production. To keep the production going it is needed to find replacements for this manure. In this paper I have taken a closer look and investigate the possibility to add algae growth and wet organic solid waste into a typical single farm small scale anaerobic digester for manure. By adding WOSW and algae it is expected to increase the production of methane gas from the anaerobic digester. It was looked into two different alternatives to add the WOSW to the anaerobic digester, either in an open pond system or through a silage system.

In this thesis it was looked closer into wheat straw as WOSW. Asia contributes most to the production of wheat straw globally. The global production of wheat is 529 Tg per year and about 20 Tg per year of the wheat production is lost as waste (Kim and Dale 2004).

1.1 Problem description

This is a theoretical study with the purpose to investigate how to enhance biogas production by connecting a pond to the anaerobic digestion. The following has been the main focus of this thesis:

- Make conceptual models of pond-AD process schemes.
- Literature review of algae COD pond production potential.
- Literature review of waste (WOSW, e.g. straw) COD potential
- Develop a mass balance model.
- Simulate alternative schemes of waste combinations and pond size for a farm case.

2 COD balances

COD balances were developed for two main cases for how WOSW can be used to increase biogas production in farm scale manure based AD. These are presented here and compared later. Process details and assumptions are also given in this chapter.

2.1 WOSW silage

The anaerobic digestion case connected with a "silo" and a pond was investigated by developing a COD balance in Microsoft excel for a specific cases described here. In the calculations the "silo" and the algae pond were two separate parts (the model was developed with the "silo", WOSW pond and algae pond where it was possible to set the part you did not want to 0 so it would be excluded from the calculations). The pond size used in the calculations is reported to be the surface area of the water in the pond. To estimate the gas production from the anaerobic digester it was used a COD balance as described by Tchobanoglous, Burton et al. (2004). The size of the anaerobic digester was assumed to be 8 m^3. Figure 2-1 shows a simple schematic diagram used for the COD balance calculations.

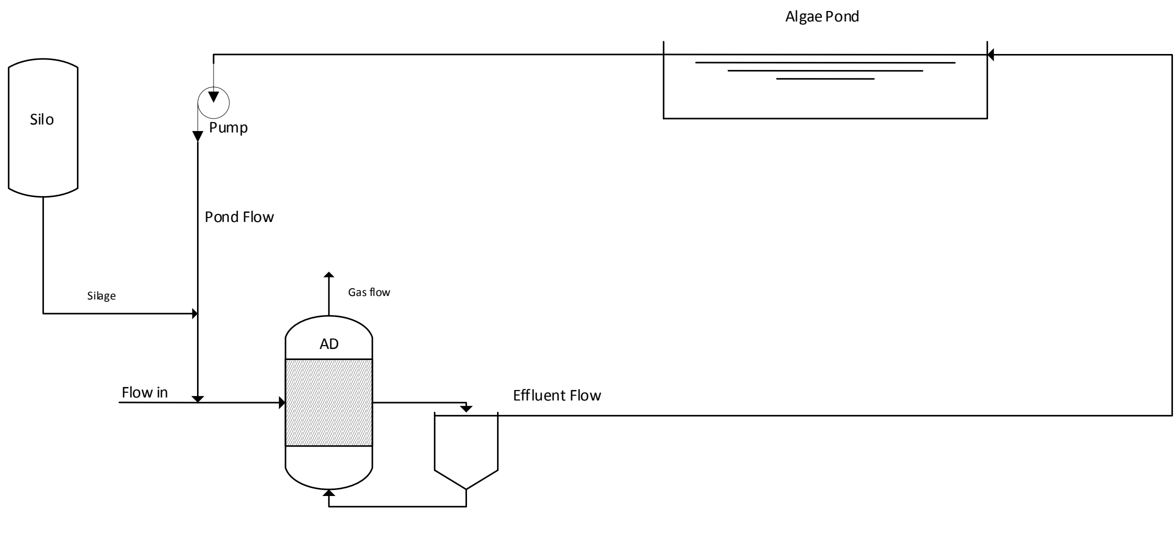

Figure 2-1 Schematic for the silage case

The flow in of waste was assumed to have a COD content of 6000 g/m^3 and a flow rate of 0.5 m^3/d. The flow rate cycled through the pond was assumed to be 1 m^3/d, which gave a hydraulic retention time of 5.3 days in the AD.

2.2 WOSW in pond

The anaerobic digestion case connected with the pond was investigated with the same COD balance in Microsoft excel as in chapter 2.1. To simplify the calculations the pond was divided into two parts, one for the algae and one for WOSW, in reality it could be one pond.

The size of the anaerobic digester was assumed to be 8 m^3. Figure 2-2 shows a simple schematic diagram used for the COD balance calculations.

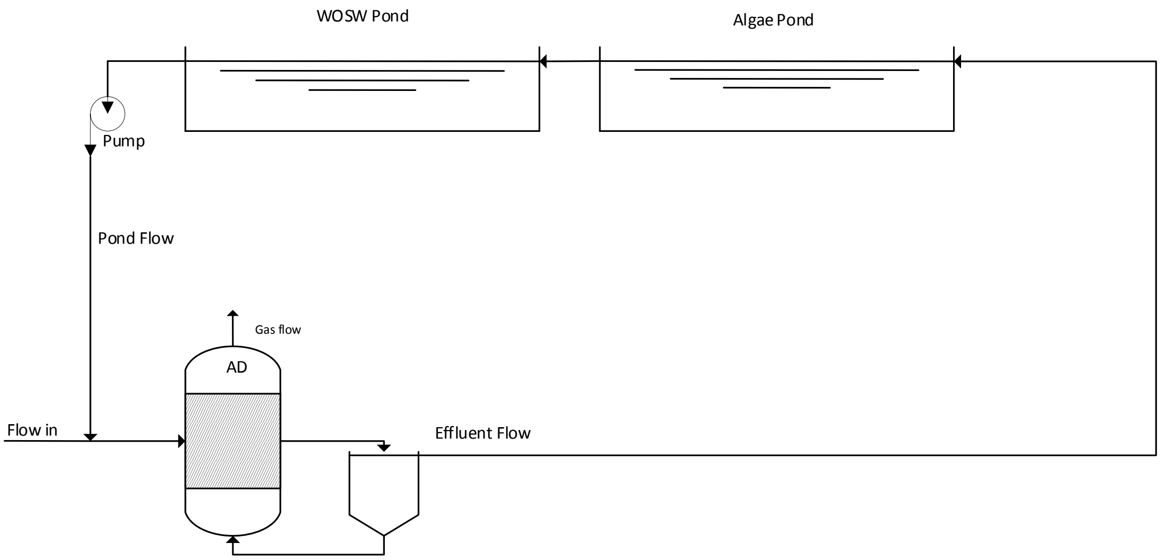

Figure 2-2 Schematic diagram used for the COD balance

The flow in of waste was assumed to have a COD content of 6000 g/m^3 and a flow rate of 0.5 m^3/d. The flow rate cycled through the pond was assumed to be 1 m^3/d, which gave a hydraulic retention time of 5.3 days in the AD.

2.3 Algal growth

The algal ponds are open so the culture will be mixed with a variety of algae, but for simplicity a monoculture is assumed. The algae investigated were *Chlorella Vulgaris* as this is a widely used alga in biogas production. For simplifications for the model the unit for algal growth rate is g m^{-2} d^{-1}. There exist different values for the growth rate depending on the experiment procedures and analytical calculations ranging from 17 g m^{-2} d^{-1} (Pruvost, Van Vooren et al. 2011) to 24.75 g m^{-2} d^{-1} (Mairet, Bernard et al. 2011).

It is also possible to get a rough estimate of the oxygen produced by *Chlorella Vulgaris* by using an oxygen production rate of 10 mmol/(L_{algae} h) (Lee and Palsson 1994) and eq. (2-1).

$$O_{2,Produced}\left[{}^{m}/_{t}\right] = O_{2,Production\,rate}\left[{}^{m}/_{V} \cdot {}_{t}\right] \cdot Algae\ in\ pond\ [V] \qquad (2\text{-}1)$$

2.3.1 Algae composition

Table 2-1 shows the elementary composition of the algae *Chlorella Vulgaris* as proposed by Lardon, Helias et al. 2009 (this is 55% of the algae, the rest is oxygen and hydrogen bound in the lipids, carbohydrates and protein of the algae). From this composition it is possible to calculate the amount of nutrients needed, assumed that the nutrients are used with 100% efficiency.

Table 2-1 Composition of Chlorella Vulgaris (Lardon, Helias et al. 2009)

Element	Gram per gram algae [g/g]
Carbon (C)	0.48
Nitrogen (N)	0.046
Phosphorous (P)	0.0099
Potassium (K)	0.0082
Magnesium (Mg)	0.0038
Sulfur (S)	0.0022

Eq. (2-2) is used to calculate the amount needed of the basic elements in the algae. By comparing the amount needed per day to the AD effluent flow it is possible to figure out if the algae are getting enough nutrients to grow properly.

$$Amount\ needed\ per\ day = \ Gram\ per\ gram\ algae\ \cdot gram\ alge\ per\ day \qquad (2\text{-}2)$$

2.4 Effluent

The effluent used in the calculations (Table 2-2) for this case is taken from an anaerobic digestion plant in Japan. The substrate used was pig manure and kitchen waste (Lei, Sugiura et al. 2007).

Table 2-2 Assumed effluent characteristics

Total Carbon	3046 g/m^3
Total Nitrogen	1770 g/m^3
Total Phosphorus	432 g/m^3

2.5 COD calculations

2.5.1 Algae

The COD of the algae was calculated with the help of the chemical formulas for protein, lipid and carbohydrate. Table 2-3 shows the different formulas as suggested by Geider and La Roche (2002).

Table 2-3 Chemical formula for protein, lipid and carbohydrate

	Chemical Formula	Molecular Weight [g/mole]	COD [g/g]
Protein	$C_{4.43}H_7O_{1.44}N_{1.16}$	99.44	1.47
Lipid	$C_{40}H_{74}O_5$	634	2.83
Carbohydrate	$C_6H_{12}O_6$	180	1.07
Oxygen	O_2	32	-
Chlorella Vulgaris	-	-	1.27-1.66

To find the COD it is important to balance the chemical equations as done in eq.(2-3), eq. (2-4) and eq. (2-5) for protein, lipid and carbohydrate respectively.

$$C_{4.43}H_7O_{1.44}N_{1.16} + 4.59\ O_2 \rightarrow 1.16\ NH_3 + 4.43\ CO_2 + 1.76\ H_2O \qquad (2\text{-}3)$$

$$\mathrm{C_{40}H_{74}O_5 + 56\ O_2 \rightarrow 40\ CO_2 + 37\ H_2O} \qquad (2\text{-}4)$$

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O \qquad (2\text{-}5)$$

Eq. (2-6) is used to calculate the COD for protein, lipid and carbohydrate as shown in Table 2-3. From this it is possible to find the COD of the microalgae by using the composition of protein, lipid and carbohydrate. The composition of the microalgae *Chlorella Vulgaris* is 51-58% dry matter, 14-22% dry matter and 12-17% dry matter, proteins, lipids and carbohydrates respectively according to (Becker 2007). The calculated COD of the microalgae *Chlorella Vulgaris* ranges from 1.27 to 1.66 g COD/g algae.

$$\mathrm{COD} = \frac{\text{Molecular weight of needed oxygen}}{\text{Molecular weight of the substance}} \qquad (2\text{-}6)$$

2.5.2 Rice straw

The COD of rice straw, which is a of possible waste from farms, was found by Mussoline, Esposito et al. (2012) to be 1002.2 g/(kg TS) and the total solids of rice straw where 92.9%. From the total mass of rice straw added per day the COD of the rise straw can be calculated by eq. (2-7)

$$COD_{RS} = COD\ per\ TS \cdot TS \cdot mass\ RS\ per\ day \qquad (2\text{-}7)$$

2.5.3 Wheat straw

Wheat straw is another likely source of waste from farms. Pohl, Heeg et al. (2013) found that the wheat straw used in their experiment had a COD of 1.19 g/g. Wheat straw was used as WOSW in the calculations.

2.5.4 Other WOSW

It is possible to use a wide range of waste as an organic source. Depending on the case and what type of waste that is easy accessible it is possible to modify the system with different wastes. Veeken and Hamelers (1999) list wholewheat bread (COD 1.39 g/g VS), leaves (COD 1.70 g/g VS), bark (COD 1.42 g/g VS) and orange peelings (COD 1.21 g/g VS) as some examples of possible usable waste.

2.6 Hydrolysis

"*Macromolecular complex organic matter such as carbohydrates, proteins and fatty acids (the three main categories commonly encounter in AD) must be broken down into smaller soluble molecules to be consumed by acidogenic organisms. This process is commonly known as hydrolysis and is carried out by acidogenic micro-organisms using their extra cellular enzymes. Hydrolysis can occur under both aerobic and anaerobic conditions*." (Botheju 2010).Botheju (2010) found that adding some oxygen in AD can enhance the hydrolysis.

It is assumed that the algae in the pond studied here will produce an excess of oxygen that will increase the hydrolysis rate. The mechanism for this can be that oxygen will increase the biomass of the acidogenes which will increase the excreted enzymes that are the main cause of hydrolysis (Botheju 2010).

2.6.1 Hydrolysis limitations

Lignocellulose is composed of cellulose, hemicellulose and lignin. The lignocellulose in straw makes it resistant to hydrolysis and only a small part will be converted to biogas in an anaerobic digester. Lignin need oxygen to be degraded and will therefore not be degraded with anaerobic digestion alone, it is important to pretreat lignocellulosic material (Zhong, Zhang et al. 2011). Some pretreatment methods are explained in chapter 3.2.

2.6.2 Hydrolysis numbers

The rate constant of hydrolysis is highly dependent on temperature, it is found to go from 0.024 d^{-1} for 20 °C (Veeken and Hamelers 1999) to 0.299 d^{-1} for 55 °C for straw in anaerobic digestion (Pohl, Heeg et al. 2013). Others factors that are mentioned in chapter 3.2.1 also affect the hydrolysis rate. Pohl, Heeg et al. (2013) found that the rate constant for unchopped wheat straw was 0.249 d^{-1} and for the chopped straw to be 0.299 d^{-1} both at a temperature of 55 °C. Depending on the material used, pretreatment and the temperature the hydrolysis rate may range from 0.024 d^{-1} to 0.47 d^{-1} (Veeken and Hamelers 1999).

The hydrolysis of wheat straw by white rot fungi which is under aerobic conditions was found to be 0.041-0.12 d^{-1} and 0.017-0.088 d^{-1} for reducing sugars and glucose respectively (Hatakka 1983). In this thesis it is assumed that the white rot fungi will be the main cause for the hydrolysis.

2.7 Calculating COD of WOSW from the hydrolysis

By assuming that all the lignocellulosic material is converted to reducing sugars by hydrolysis it is possible to calculate the amount of COD per day from the straw. The decrease in mass because of hydrolysis will also reduce the amount of COD produced per day. The COD of glucose ($C_6H_{12}O_6$) is calculated in chapter 2.5 (the COD of reducing sugars and glucose is assumed to be equal).

Table 2-4 Lignocellulosic composition of rice straw and wheat straw

	Cellulose [%]	Hemicellulose [%]	Lignin [%]	reference
Rice straw	32	28	20	(Shawky, Mahmoud et al. 2011)
Wheat straw	42	22	22	(Borrion, McManus et al. 2012)

Table 2-4 shows the assumed content of cellulose, hemicellulose and lignin in rice straw and wheat straw, the sum of these values is the fraction of lignocellulose in the straw. By using eq. (2-8) and eq. (2-9) it is possible to calculate the amount of COD per day from the straw.

$$\text{Glucose}\left[{}^{\text{mass}}/_{\text{time}}\right] = \text{mass of straw} \cdot \text{lingnocellulose fraction} \cdot \text{hydrolysis rate} \qquad (2\text{-}8)$$

$$\text{COD from straw}\left[{}^{\text{mass}}/_{\text{time}}\right] = \text{glucose} \cdot \text{COD}_{C_6H_{12}O_6} \qquad (2\text{-}9)$$

2.8 Silage

Instead of putting the straw directly in the pond it is possible to put it in a "silo" where it is made acidic to decompose. Such processes are used in agriculture to store and prepare grass as feed for animals. An acidic liquid called silage can be extracted from such silos. The silage is another possible way to obtain a higher gas production. Silage is also already well known in agriculture. For the silage calculations it is used grass because there is more available information on grass and it is assumed that it is comparable to wheat straw. According to Hansen, Solemdal et al. (2003) it is possible to get 0.2-0.3 m^3 silage from 1000 kg of grass which also matches the technical guidelines from the Norwegian department of agriculture (NLH 1993) shown in Table 2-5. Table 2-5 also shows the needed diameter of the silo with respect to tonne grass added per day. Abu-Dahrieh, Orozco et al. (2011) found the COD of grass silage to be 350 000 g/m^3.

To calculate the COD and flow of the silage to the system it was assumed a minimum, average and maximum case with values for 0.002 $m^3/(d \cdot kg)$, 0.0025 $m^3/(d \cdot kg)$ and 0.003 $m^3/(d \cdot kg)$ respectively.

Table 2-5 Design silage and diameter (NLH 1993)

Silo diameter [m]	Tonne grass per day	Design silage effluent [m^3/d]
3	10	2.5-3
4	12	3-3.5
5	20	5-6
6	30	8-9
7	40	10-12
8	50	13-15
-	75	19-22

The situation in Norway today is that the use of silo at farms is small, today they mainly use round bale in agriculture in Norway.

3 Literature studies

3.1 Increase COD of algae

There is a possibility to increase the COD of the algae by nitrogen starvation. This will increase the lipid content of the algae, decrease the nitrogen content and should improve the digestion of the algae. However the increase in the digester performance is small and it is a possibility to jeopardize the overall productivity by affecting the productivity of the algae (Mairet, Bernard et al. 2011). Also in this case it is assumed that this will complicate the process and increase the price too much to defend the increase.

The depth of the pond is a factor in increasing the algae productivity. Sutherland, Turnbull et al. (2014) tested with three different depths of 200 mm, 300 mm and 400 mm while every other factor were the same for the tests. With the depth of 400 mm they achieved the highest productivity. One of the reasons for this is the accumulation of carbon in the pond with 400 mm depth, this is carbon that may be wasted in the other depths and is not going to be used by the algae. Another important point is that under heavy rain more of the algae biomass will be washed away in the 200 mm one than in the 400 mm.

In this study they used paddle wheels and achieved turbulent mixing. This was easy to obtain because of the small size, in large scale it is harder to achieve turbulent flows and it is much more likely to become a laminar flow. This may actually have a positive effect because in the 400 mm depth the algae may remain longer in the water column thus avoid settling in the pond bottom. The higher proportion of non-algal organic matter may encourage lager flocks of algae. The 400 mm depth will also provide more carbon to the algae and at the same time reduce the oxygen concentration. High oxygen concentration may be inhibitory for the algal growth (Sutherland, Turnbull et al. 2014).

3.2 Hydrolysis Pretreatment

By pretreating it is possible to increase the hydrolysis rate. Chen, Zhang et al. (2014) discovered that the time needed for rice straw to produce 80% of the maximal methane production reduced to 32 days for extrusion pretreated rice straw from 67 days for untreated rice straw. For milling pretreated rice straw they found the 80% of maximal methane production was achieved after 50 days.

There are mainly four pretreatments methods that are used; physical, physico-chemical, chemical and biological. In the physical method the main goal is to reduce the cellulose crystallinity of the lignocellulosic material with milling, chipping and grinding. Usually it is possible to achieve a size of the material from 30 mm to 0.2 mm. One of the most common used pretreatment for lignocellulosic material is steam explosion, the biomass exposed to saturated steam in the temperature range 160-260 °C for a period of time before it goes back to atmospheric pressure. This causes an explosive decompression which degrades the hemicellulose and transforms the lignin which increasing the hydrolysis. Another pretreatment that is similar to steam explosion is ammonia fiber explosion only that the materials are exposed to high pressure and temperature ammonia. In acid and alkaline hydrolysis concentrated acids and bases are used to treat the materials. In the biological treatment microorganisms degrade the lignocellulosic materials by producing enzymes. This process requires low energy and is mild to the environment (Sun and Cheng 2002).

In this thesis the main focus and investigation regarding pretreatment will go towards cutting and biological pretreatment.

3.2.1 Affecting factors on enzymatic hydrolysis

There are many important factors that affect the enzymatic hydrolysis. Some of the most important factors are; substrates, cellulase activity, temperature and pH. Substrate concentration is an important factor to affect the rate of hydrolysis. The increase of substrate may give an increase in reaction rates of hydrolysis, this however is only when the substrate levels are low. In high substrate levels an increase in substrate concentration may cause inhibition. To achieve a higher yield and rate of the hydrolysis it is possible to increase the cellulase, but this will also make the cost of the process much higher (Sun and Cheng 2002).

4 Modeling conditions

In the calculations it was assumed that a household on a small farm in china produce a wastewater flow rate of 0.5 m^3/d with a COD content of 6000 g/m^3. This was used as a base for the methane production in the anaerobic digester. The production from the algae pond was investigated for 10, 20, 30, 40 and 50 m^2 pond area.

In The silage case it was investigated how much mass that needed to be added each day to produce two times more methane gas than in the base case with only algae pond and anaerobic digestion. In the silage case it was also assumed that the grass would be used as fodder etc.

The WOSW case was compared to the silage case by using the same mass as in the silage case. It was chosen three values to investigate the minimum, average and maximum needed mass added each day to produce enough silage to double the methane production. In Table 4-1 the initial mass in the WOSW pond is the same as the mass that needs to be added each day in the silage case. In the pond the mass needed to add each day is much smaller than in the silage to keep the production constant and at same levels.

Table 4-1 Needed mass of straw added per day. The hydrolysis rate assumed here is 0.12 d^{-1}

kg in 10 m^2 pond	kg added per day [kg/d]
32	3.8
38	4.6
47	5.6

kg in 20 m^2 pond	kg added per day [kg/d]
35	4.2
41	4.9
52	6.2

kg in 30 m^2 pond	kg added per day [kg/d]
37	4.4
45	5.4
56	6.7

kg in 40 m^2 pond	kg added per day [kg/d]
41	4.9
49	5.9
61	7.3

kg in 50 m^2 pond	kg added per day [kg/d]
43	5.1
52	6.2
65	7.8

In Table 4-2 and Table 4-3 the initial mass needed in the pond was calculated so that the mass needed to be added each day was the same as in the silage case. The hydrolysis rate in the calculations is 0.12 d^{-1} and 0.017 d^{-1} respectively ("best" and "worst" case).

Table 4-2 Needed mass of straw added per day. The hydrolysis rate assumed here is 0.12 d^{-1}

kg in 10 m pond	kg added per day [kg/d]
267	32
317	38
392	47

kg in 20 m pond	kg added per day [kg/d]
292	35
342	41
433	52

kg in 30 m pond	kg added per day [kg/d]
308	37
375	45
467	56

kg in 40 m pond	kg added per day [kg/d]
342	41
408	49
508	61

kg in 50 m pond	kg added per day [kg/d]
358	43
433	52
542	65

Table 4-3 Needed mass of straw added per day. The hydrolysis rate assumed here is 0.017 d^{-1}

kg in 10 m pond	kg added per day [kg/d]
1882	32
2235	38
2765	47

kg in 20 m pond	kg added per day [kg/d]
2059	35
2412	41
3059	52

kg in 30 m pond	kg added per day [kg/d]
2176	37
2647	45
3294	56

kg in 40 m pond	kg added per day [kg/d]
2412	41
2882	49
3588	61

kg in 50 m pond	kg added per day [kg/d]
2529	43
3059	52
3824	65

5 Results

With only the standard anaerobic digester application on this farm it produce 0.96 m^3 CH_4/d which gives an energy output of ~30 MJ/d (Figure 5-1). This yield depends on the amount and composition of the manure fed into the AD so it can increase or decrease. This level is assumed to be typical and used as the base case to evaluate the possibilities of increased production from algae and WOSW.

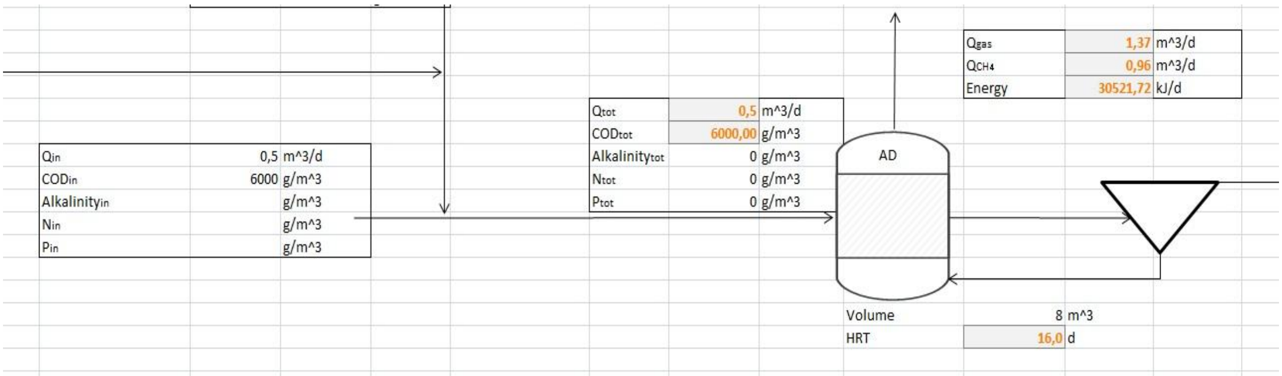

Figure 5-1 Picture of the massbalance over the anaerobic digester

5.1 Anaerobic digester + algae pond

If the pond with just algae growth is added to the anaerobic digester there will be a small increase of the produced methane gas. Table 5-1 shows that the increase will be 0.1 m^3 CH_4 gas per day when you increase the pond size by 10 m^2. This is based on the assumptions made in chapter 2 and represents about 10 % increase per 10 m2 pond.

Table 5-1 Produced gas/energy from algae growth depending on algae pond sizes

Pond size m^2	CH_4 gas m^3/d	Energy MJ /d
0	0.96	30.5
10	1.06	33.6
20	1.16	36.8
30	1.26	39.9
40	1.36	43.1
50	1.45	46.2

5.1.1 Discussion

The limiting nutrient for the algae growth is carbon with the assumptions given in chapter 2.4. The pond sizes here are small so it will be enough nutrients for the algae. The algae production will not increase anymore if the pond size is over ~450 m^2 because it will then be limited by nutrients and not by sun light.

Even if the gas increase from the algae is small the pond would still be useful to build. The pond may also function as storage for the effluent which many farms use as a fertilizer. With the storage you do not have to fertilize the crops every day, which actually is bad for the crops, but you can fertilize when it is needed. The pond may also help maintain production during times when there is low supply of wastewater.

5.2 Anaerobic digester + algae pond & Silage

The algae and WOSW pond were compared to a case where instead of the WOSW you add a silo and store the straw, grass etc. in (Figure 2-1). It was investigated how much mass you would need to double the production of methane from the anaerobic digester. Silage was chosen as an alternative because it is well known in agriculture. Figure 5-2 shows how much mass of grass is needed to produce the needed silage to get a doubling of the produced methane depending on the size of the algae pond. Here it is assumed that the grass stored will also be used for feeding etc.

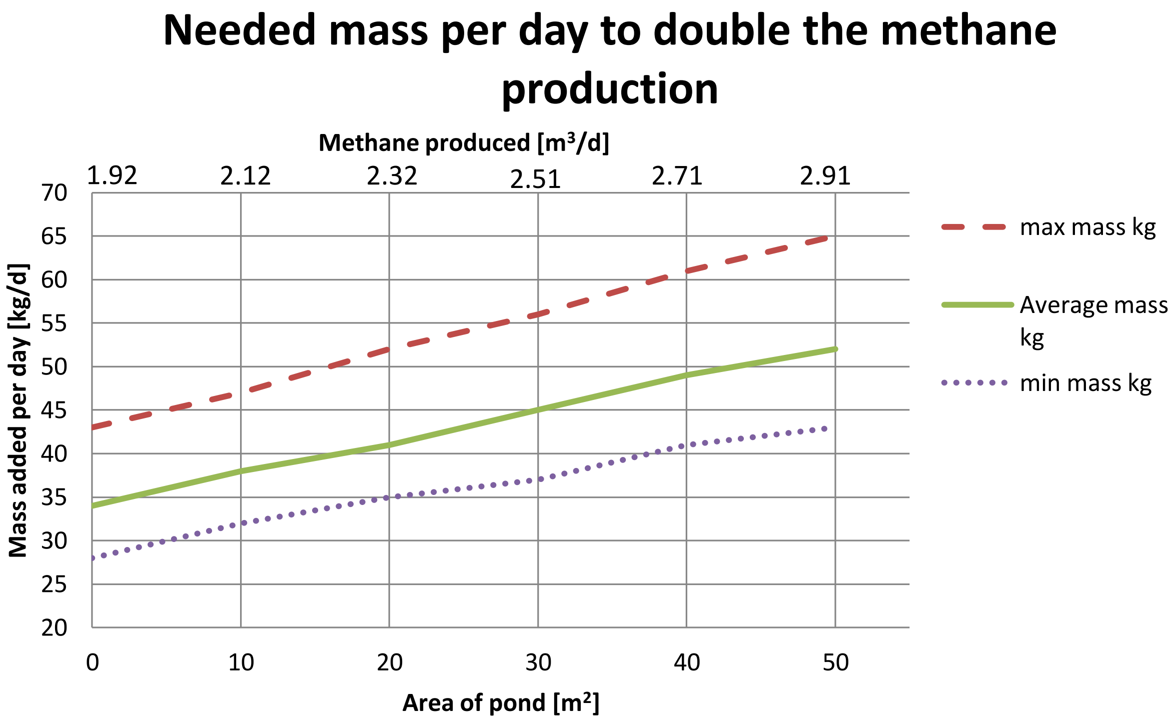

Figure 5-2 Graph of how much grass that needs to be added each day to double the methane production

5.2.1 Discussion

In the case of silage it may be dependant of the size of the farm and if they need or want a silo for storage. The silage helps with the production of methane and it will also help the farm with feed for livestock. The reason the average mass is not the exact average of the min and max values comes from the fact that the anaerobic digester in the calculations uses 80% of the COD to create gas.

5.3 Anaerobic digester + WOSW & algae pond

The case with WOSW and algae pond was tested against the case with silage (Figure 2-2). The mass value that was chosen comes from the mass needed to double the production of methane with silage (Figure 5-2). In

Figure 5-3 to Figure 5-7 the blue, red, green and black line represent the highest mass, average mass, minimum mass and methane production when only the AD and algae pond are connected respectively. The hydrolysis rates of minimum reducing sugars and maximum reducing sugars can be seen as a "worst" and "best" case respectively. It is likely that the actual hydrolysis rate would be somewhere between these two values.

Figure 5-3 show the case with the 10 m^2 pond, here the production goes from 1.5 to 3 m^3/d.
Figure 5-4 show the case with the 20 m^2 pond, here the production goes from 1.7 to 3.3 m^3/d.
Figure 5-5 show the case with the 30 m^2 pond, here the production goes from 1.8 to 3.6 m^3/d.
Figure 5-6 show the case with the 40 m^2 pond, here the production goes from 1.9 to 3.9 m^3/d.
Figure 5-7 show the case with the 50 m^2 pond, here the production goes from 2.1 to 4.1 m^3/d.

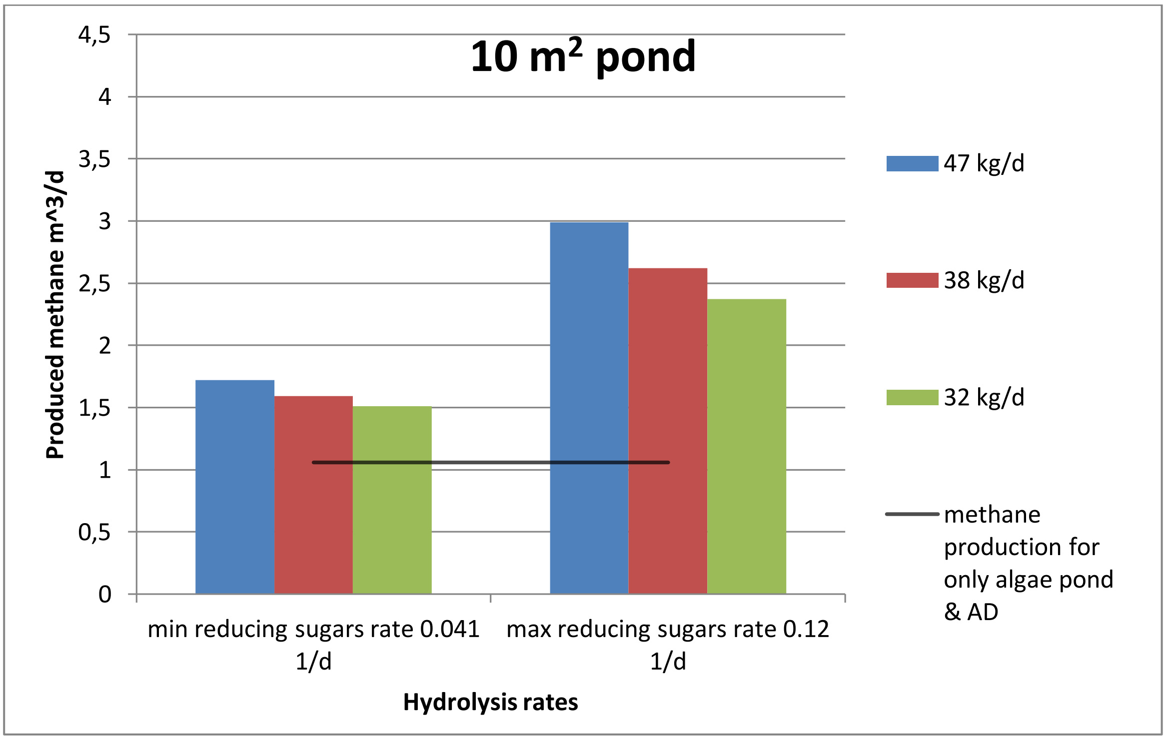

Figure 5-3 Methane production from a 10 m^2 pond

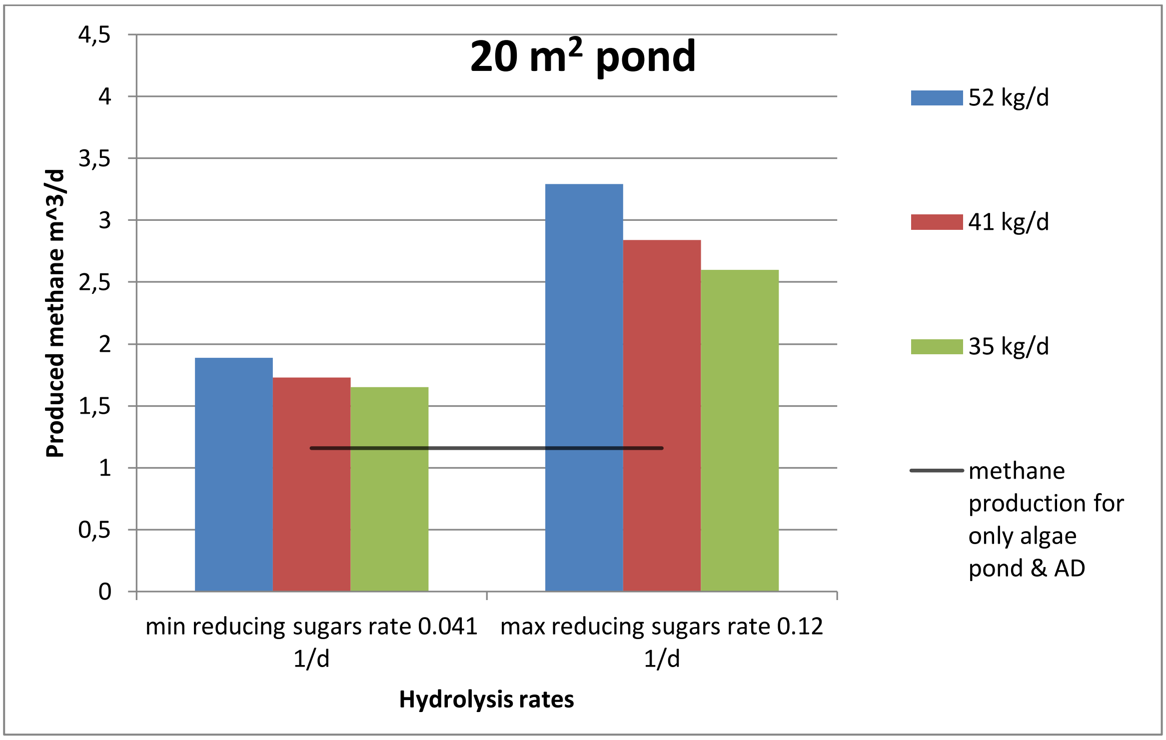

Figure 5-4 Methane production from a 20 m^2 pond

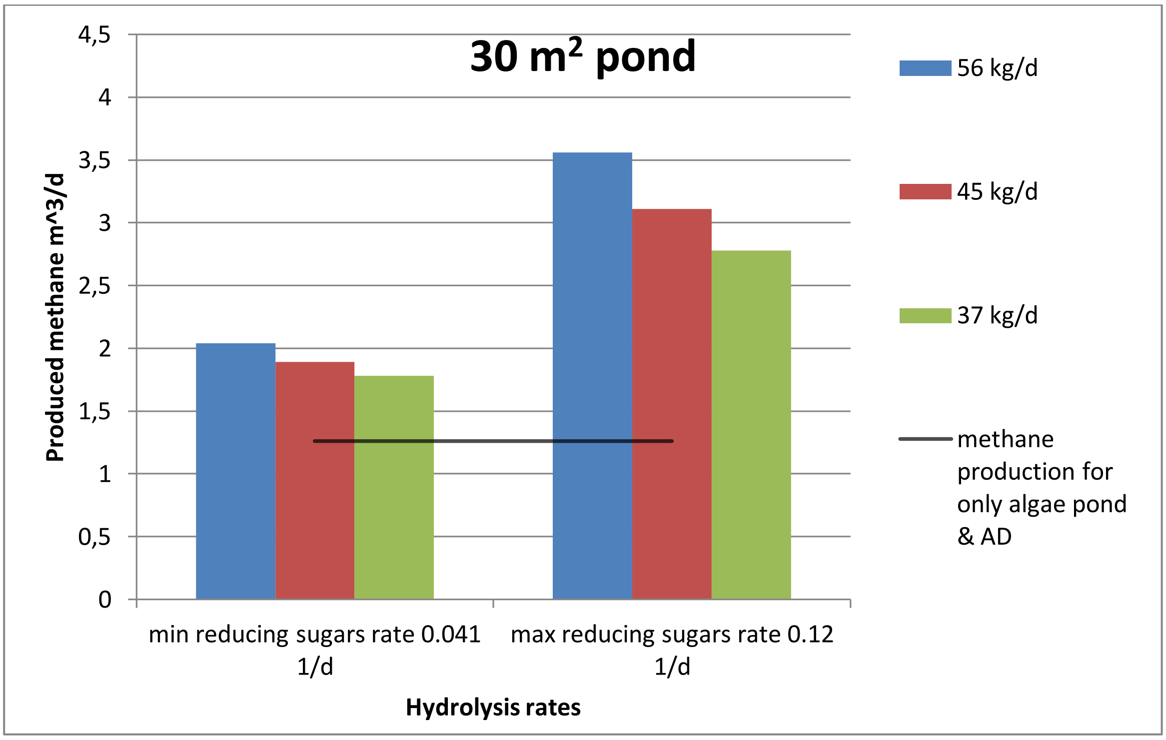

Figure 5-5 Methane production from a 30 m^2 pond

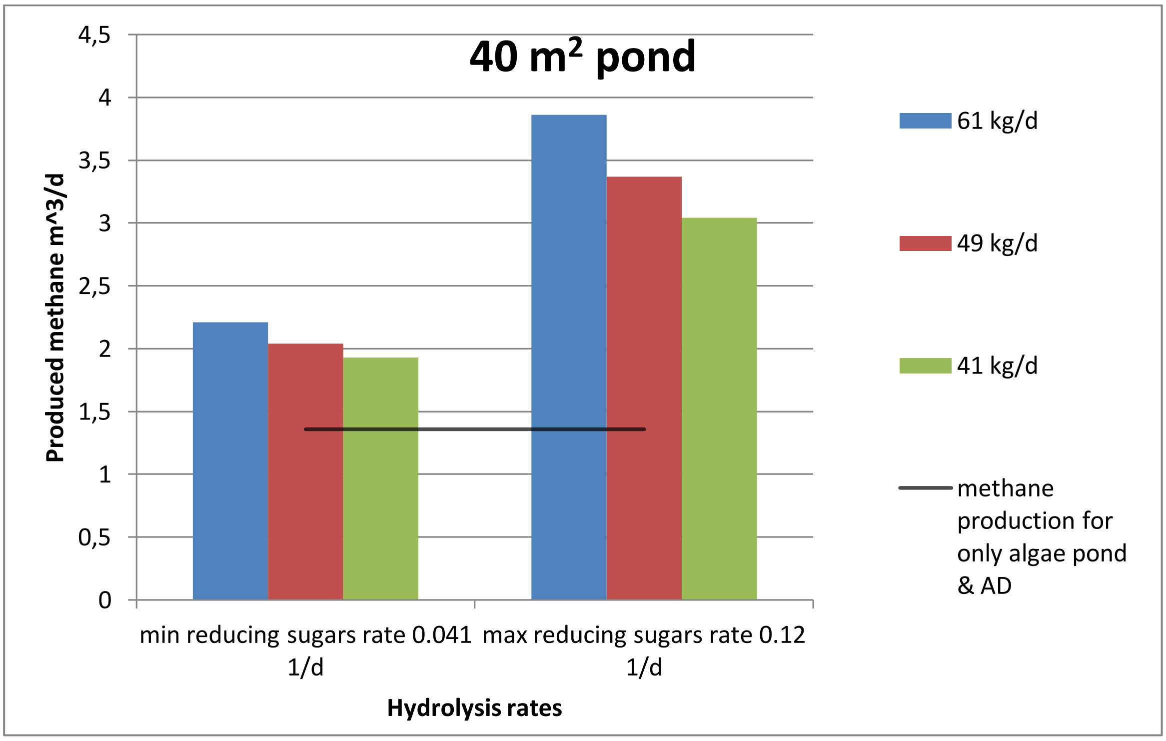

Figure 5-6 Methane production from a 40 m^2 pond

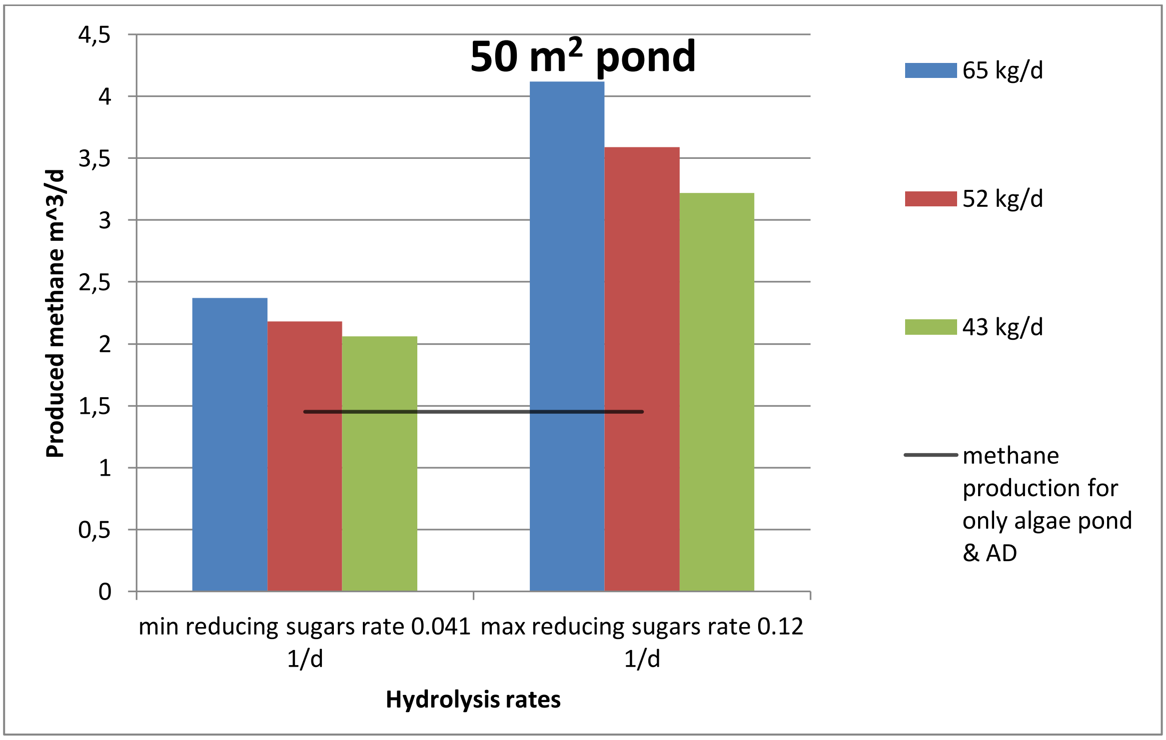

Figure 5-7 Methane production from a 50 m^2 pond

5.3.1 Same mass per day as in the silage case

Another interesting view would be how much initial mass is needed if we want to add the same mass per day as in the silage case (chapter 5.2). Table 4-2 show the initial mass in the pond and how much we need to add under the assumption that the added masse per day is the same as the silage case.

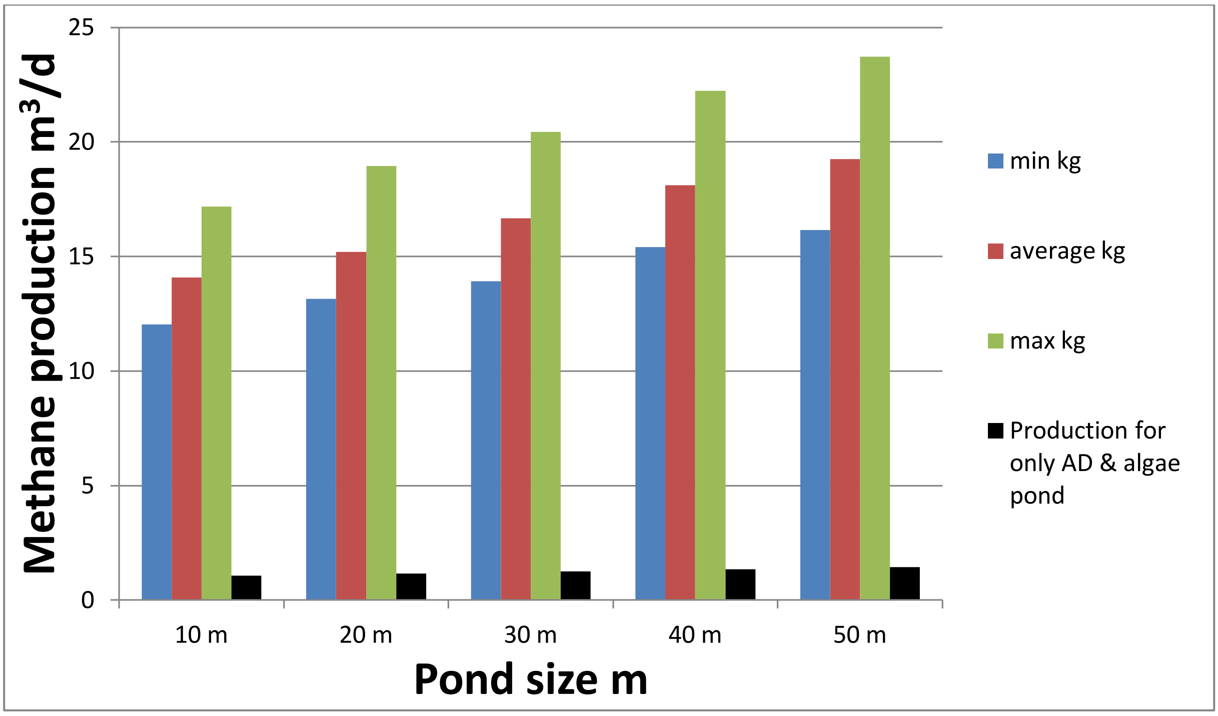

Figure 5-8 Methane production when the same mass as in the silage case is added each day

5.3.2 Discussion

The average value of the hydrolysis rate of reducing sugars is 0.0805 d^{-1}. The figures in chapter 5.3 show that it is possible to get an increase of the methane production. But it is also important to consider the actually mass needed to get these values. For the silage case the same mass need to be added every day, while for the WOSW case only about 12% of the mass needs to be added every day to keep the production constant. The value of 12% comes from when the hydrolysis rate is 0.12 d^{-1}, if the hydrolysis rate decreases the initial mass needed would also increase (Table 4-2 and Table 4-3).

When the same mass per day as in the silage case is added the methane production is 10 to 20 times higher than the production with algae pond and AD depending on the case and assumptions (Figure 5-8). The methane production would be the same for all values of the hydrolysis rate because the amount of released COD will be the same for all the rates, but the initial mass would change depending on the expected hydrolysis rate. The initial mass needed depending on the hydrolysis rate and pond size range from 267 kg to 3824 kg, it may not be suitable to put this mass range in the pond, it is not looked into if it would fit physically.

5.4 Methane production over time

It would be interesting to see how the production changes as the mass decreases because of hydrolysis. It was assumed a hydrolysis rate of 0.0805 which is the average of the minimum and the maximum value of the hydrolysis rate for reducing sugars. In Figure 5-9 the calculations were done for a 10 m^2 pond with an initial mass of 300 kg. In Figure 5-10 the pond size were kept at 10 m^2 but the initial mass was increase to 500 kg.

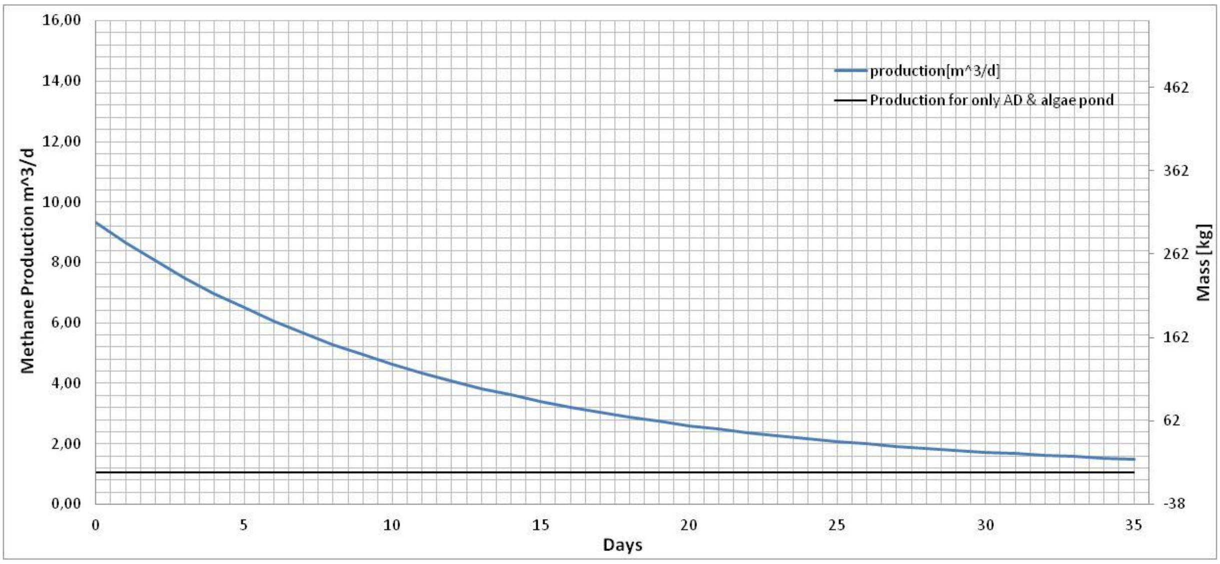

Figure 5-9 Methane production of a 10 m^2 pond when not replacing the mass lost from hydrolysis (initial mass 300 kg)

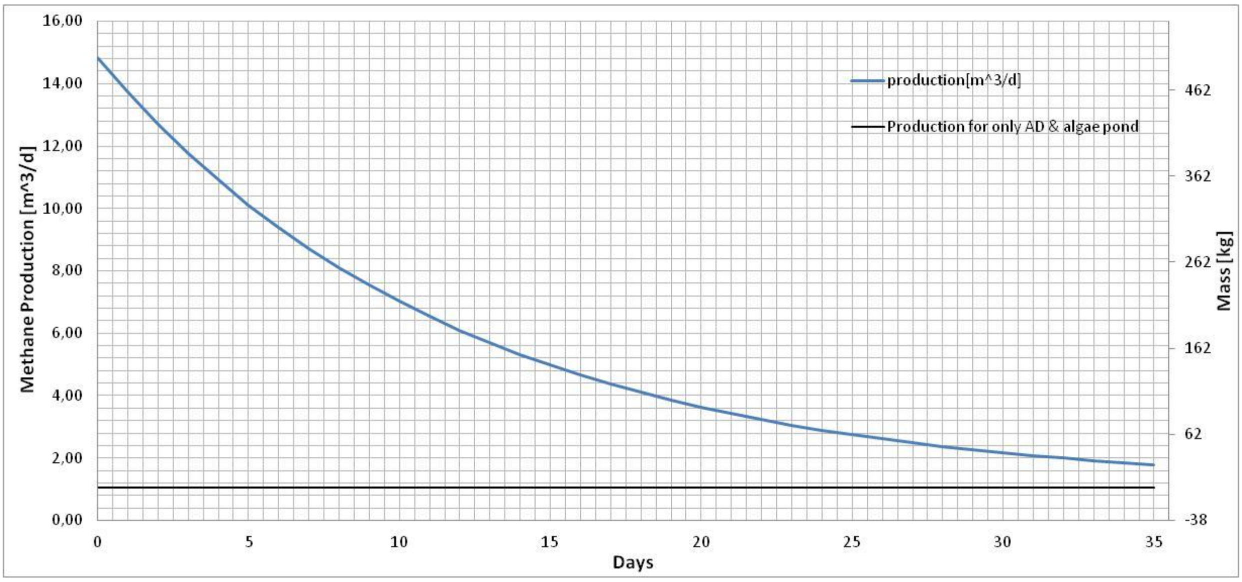

Figure 5-10 Methane production of a 10 m^2 pond when not replacing the mass lost from hydrolysis (initial mass 500 kg)

In Figure 5-11 the calculations were done for a 50 m^2 pond with an initial mass of 300 kg. In Figure 5-12 the pond size were kept at 50 m^2 but the initial mass was increase to 500 kg.

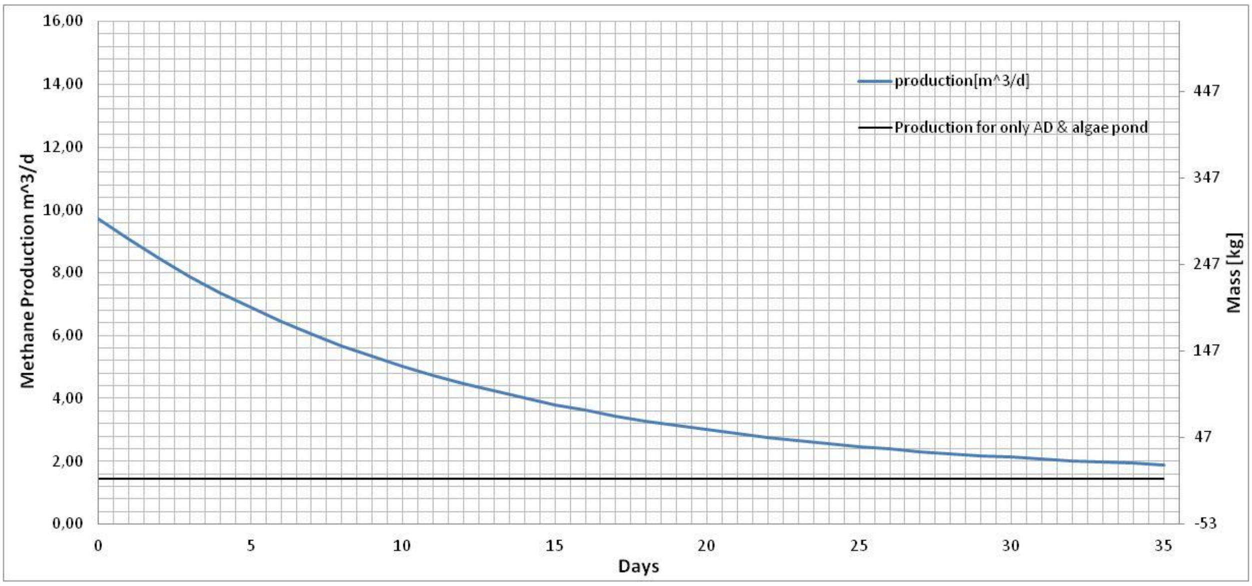

Figure 5-11 Methane production of a 50 m^2 pond when not replacing the mass lost from hydrolysis (initial mass 300 kg)

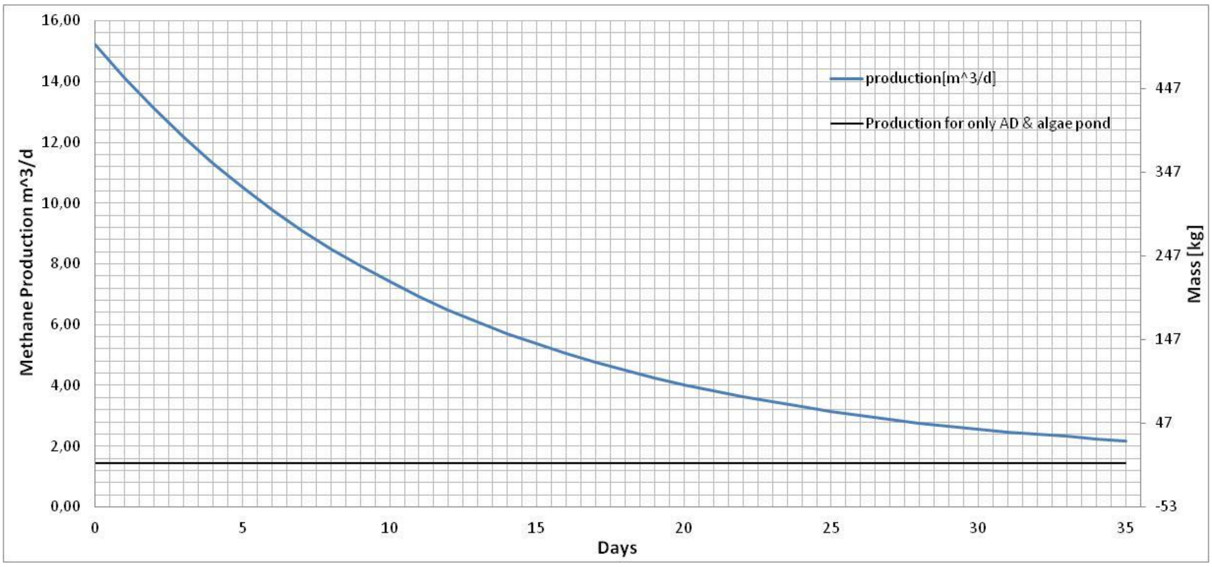

Figure 5-12 Methane production of a 50 m^2 pond when not replacing the mass lost from hydrolysis (initial mass 500 kg)

5.4.1 Discussion

For the 10 m^2 pond and the 50 m^2 pond with a mass of 300 kg it takes 27 and 23 days respectively to reach a methane production of 20% of the initial value (9.3 m^3 methane/day and 14.8 m^3 methane/day respectively). For the 10 m^2 pond and the 50 m^2 pond with a mass of 500 kg it takes 33 and 26 days respectively to reach a methane production of 20% of the initial value (9.7 m^3 methane/day and 15.2 m^3 methane/day respectively).

This show that maybe there is no need to refill the mass every day but rather wait some days depending on what is needed and the wanted production.

5.5 General discussion

Adding a pond with algae growth and WOSW will increase the production of methane from an anaerobic digester. Since different farms produce different types, different amount of crops and have different area available for an anaerobic digester with a pond and WOSW it should be investigated for each case to see what would suit that farm the best. If the plan is to sell the methane then it may happen that the silage case where you get grass for fodder may be the best option. This depends on the price for methane and the price for fodder, which was not looked into in this thesis.

It may also be possible that a good solution for bigger farms would be to have a system of silage, WOSW and algae pond. This is if the farm would also want fodder but only for self use and not to sell it. Then excess grass, wheat straw etc. that is not needed for fodder can be added to the pond to get an increase in the biogas production.

6 Further studies

The idea of WOSW in a pond needs to be studied further and preferably with experiments. The WOSW and algae pond could be investigated separately as a start to get a closer look at contribution for each of them. Later they could be brought together either in one tank of two tanks, one for algae and one for WOSW. It should be possible to investigate this with a simple setup with an aquarium or an open tank. It is important to add fungus, bacteria and/or enzymes in the aquarium/tank, depending on what you would want to investigate.

With a small scale lab setup similar to Figure 2-2 it should be possible to investigate and get a clearer view on the contribution from the bacteria and the fungi to the gas production.

Figure 6-1 shows a schematic for another case that could be tested. Here the effluent flow from the AD is pumped directly into a "silo" where grass is stored. Here the effluent will contribute to the degradation of the grass and hopefully increase the hydrolysis rate of the grass and produce more silage. It may be that the environment inside the "silo" has a lower oxygen concentration than the outside air. If this is the case it is expected that the lignin will use much more time to be degraded because the degradation of lignin is dependent on oxygen. But it may happen that the cellulose and hemicellulose will get an increased hydrolysis rate.

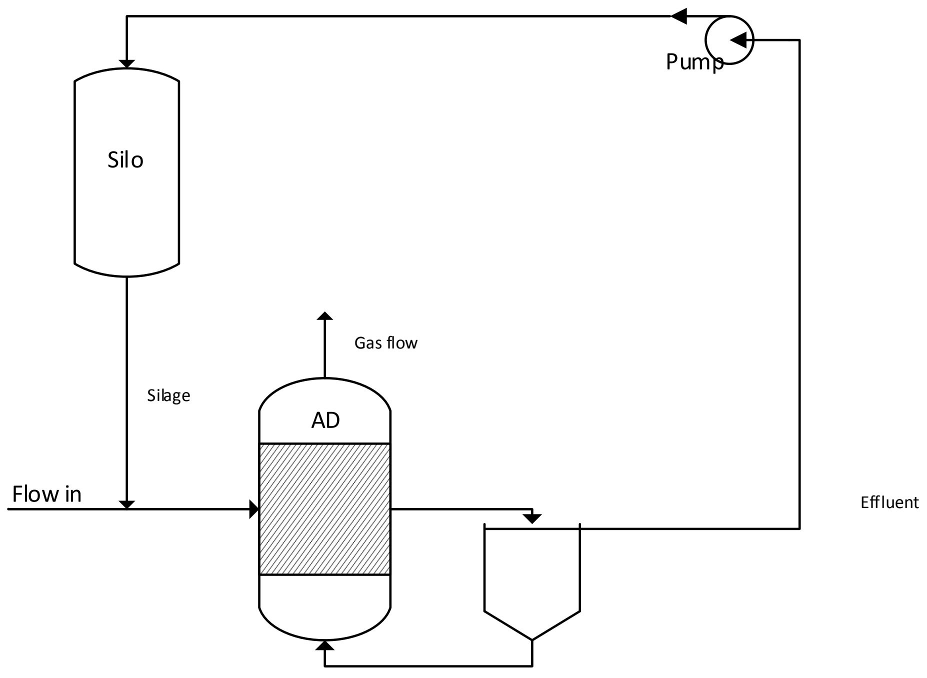

Figure 6-1 Schematics for single AD and silage

It is expected that the silage case would be much closer or equal to the WOSW and algae pond if all the grass were used for the silage.

Figure 6-2 shows how a case for a large farm that also could be more investigated. Here the thought is that the farm would want to produce some fodder for self use and then use excess raw materials to produce biogas. This would probably be best suited for large farms with high production of straw and with a lower number of animals.

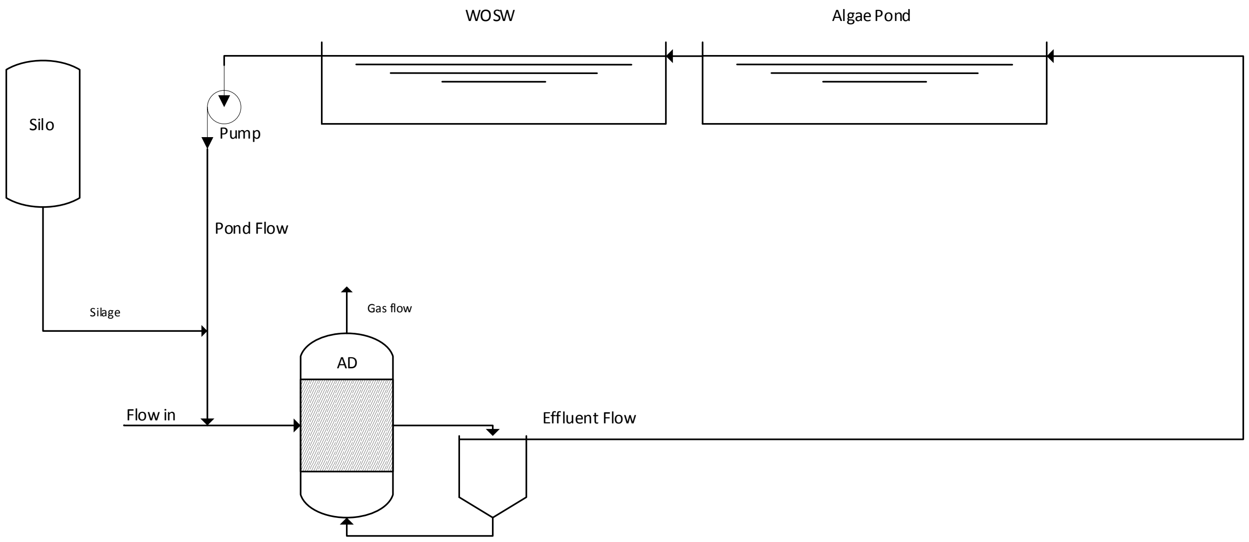

Figure 6-2 Combination of silage, WOSW and algae

7 Conclusion

The idea of connecting WOSW and algae pond to an AD looks promising but it should be investigated more. The WOSW and algae pond produces more biogas than the silage case where you also get fodder. It is also important to evaluate what would be the best case for the farm where it is going to be added depending on available waste, wanted production and the size of the farm.

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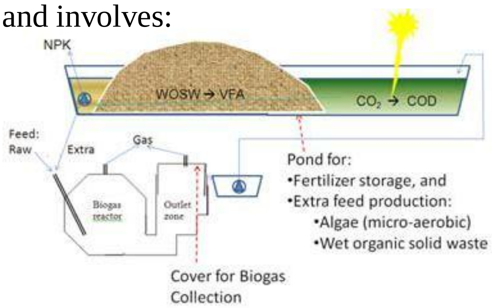
Appendices

Appendix A: Task definition

FMH606 Master's Thesis

Title: Ponds and anaerobic digestion (AD) combinations
TUC supervisors: Rune Bakke and Wang Shuai
External partner: -
Task description:

The aim is to investigate how and to what extent ponds can be connected to AD to enhance
biogas production. The study is theoretical and involves:



- Make conceptual models of such process schemes.
- Literature review of algae COD pond production potential.
- Literature review of waste (WOSW, e.g. straw) COD potential.
- Develop a mass balance model.
- Simulate alternative schemes of waste combinations and pond size for a farm case.

Task background:
Anaerobic digestion, AD, is a method where micro-organisms break down organic matter and generate biogas. Availability of suitable wastes for AD is becoming a limiting factor for the production of methane as the demand for such is increasing fast. The idea to be investigated is to add “primary production” (convert solar energy to biomass by photosynthesis, e.g. algea growth) and wet organic solid waste (WOSW) degradation in ponds to conventional AD to obtain much more methane from existing AD (example illustrated in Figure 1).

Student category:

EET student.

Practical arrangements:

The work will be carried out at TUC

Signatures:

Student (date and signature):

Supervisor (date and signature):

Appendix B: COD balance in Excel