Anaerobic Digestion: Factors Affecting Anaerobic Digestion Process

Lohani Sunil P., Havukainen Jouni

Anaerobic Digestion: Factors affecting AD Process

Sunil P Lohani *[1], Jouni Havukainen [2]

[1]School of Engineering, Kathmandu University, P.O. BOX 6250, Nepal

[2]Sustainability Science, Lappeenranta University of Technology, P.O. Box 20, FI-53851, Finland

Anaerobic digestion (AD) is a biological decomposition process that occurs in the absence of oxygen. The decomposition of organic matter is a multi-step process of series and parallel reactions that occurs in four stages namely hydrolysis, acidogenesis, acetogenesis and methanogene. Most of the control in anaerobic digestion is undertaken directly by the micro-organisms themselves, however, the operational conditions such as temperature, pH, essential trace nutrients and toxicants can play a major role in modifying reaction rates of individual sub-processes. The energy performance of the anaerobic digestion is depending mainly on the biogas production technology (wet or dry technology, mesophilic or thermophilic), raw materials and geographic location (ambient temperature). Since the feedstocks coming to anaerobic digestion have usually lower heating value as received and the usual energy efficiency calculation used for incineration plant is not useful. Most commonly used method is the input-output method and the estimation is dependent upon the chosen system boundary.

Keywords: Anaerobic Digestion, operational conditions, reaction rate, energy performance, system boundary

Corresponding Author: Sunil Prasad Lohani, Email: splohani@ku.edu.np

1. Introduction

Anaerobic digestion (AD) is a biological process that occurs in the absence of oxygen when organic materials are available. The process is accomplished with a consortium of microorganisms such as fermentative bacteria, hydrogen-producing acetogenic bacteria, hydrogen-consuming acetogenic bacteria, carbon dioxide-reducing methanogens, and aceticlastic methanogens (Appels et al., 2008). AD process makes use of these anaerobes to breakdown organic substances to biogas mainly composed of methane (CH_4) and carbon dioxide (CO_2). The amount of excess sludge production is very small (Mittal, 2011).

Biogas from organic waste usually contains 60-70% methane, 30 to 40% carbon dioxide and <1% nitrogen (Jonsson et al., 2003) in an ideal condition whereas some amount of hydrogen sulphide and ammonia is also produced otherwise (Jensen et al., 2000).

2. AD of organic material into methane

The decomposition of organic matter is a multi-step process of series and parallel reactions. This successive degradation process occurs in four stages, namely i) hydrolysis, ii) acidogenesis, iii) acetogenesis and iv) methanogenesis as shown in Figure 1. A brief discussion of each stage is presented below.
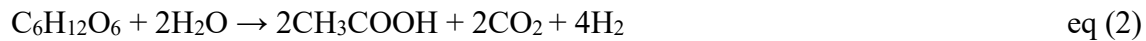
2.1 Hydrolysis

Hydrolysis of the complex organic matter is an important step of the anaerobic biodegradation process. During hydrolysis, the first stage of anaerobic digestion, bacteria transform the insoluble complex organic substrate (carbohydrates, proteins, lipids etc) into soluble monomers and polymers. This process is catalyzed by enzymes like cellulase, protease and lipase excreted by the microorganisms responsible for fermentation for the conversion of proteins to amino acids; lipids to long chain fatty acids (LCFA), polysaccharides, to simple sugars (Parawira, 2012; Ostrem, 2004). This group of microorganisms is considered to be composed of a large group of facultative bacteria that can thrive with or without oxygen (Botheju et al., 2010; Schluter et al., 2008). Hydrolysis is the rate-limiting process for the overall digestion of substrates with a high suspended solids (SS)/chemical oxygen demand (COD) ratio. It is usually not due to a lack of enzyme activity but to the availability of free accessible surface area of the particles and the overall structure of the solid substrate (Zeeman & Sanders, 2001; Van Lier et al., 2008). Moreover, at low temperature hydrolysis may limit the overall process (Lew et al., 2011) and thereby determining the required reactor design. The products of hydrolysis are the substrates for acidogenic bacteria. The equation 1 shows an example of hydrolysis reaction where organic waste is broken down into a simple sugar, in this case, glucose (Ostrem et al., 2004).

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2 \hspace{3cm} \text{eq (1)}$$
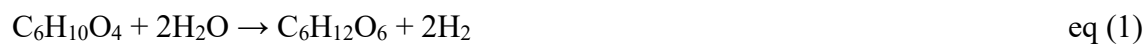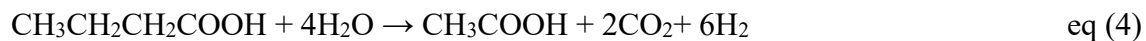
2.2 Acidogenesis

In the second stage, the hydrolysis products (amino acids, LCFA and simple sugars) which are relatively soluble compounds converted into variety of small organic compounds mainly volatile fatty acids (VFAs) that is acetate (CH_3COOH) and organic acids such as propionate (CH_3CH_2COOH), butyrate ($CH_3CH_2CH_2COOH$), valeric ($CH_3CH_2CH_2CH_2COOH$), formic (HCOOH), lactic ($C_3H_6O_3$) as well as H_2, CO_2 and ammonia (Zeeman et al., 1996; Ostrem, 2004; WtERT, 2014). This process is performed by a large group of hydrolytic and non-hydrolytic microorganisms and the types of end products depend on the conditions in the reactor medium. If H_2 is effectively removed by H_2 scavenging organisms such as methanogens, acetate will be the main end product. However, if methanogenesis is retarded and H_2 accumulates, more reduced products such as propionate and butyrate are likely to appear. Therefore, effluents of overloaded or perturbed anaerobic reactors often contain these more reduced intermediate products and become acidic (Van Lier et al., 2008.). From these products, the hydrogen, carbon dioxide and acetic acid will skip the third stage, acetogenesis, and be utilized directly by the methanogenic bacteria in the final stage as shown in Figure 1. Equations 2 and 3 represent typical acidogenic reactions where glucose is converted into acetic acid and propionate, respectively, (Ostrem, 2004; Bilitewski et al., 1997).

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \qquad \text{eq (2)}$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \qquad \text{eq (3)}$$

2.3 Acetogenesis

In the third stage, the short chain fatty acids (SCFA), other than acetate that are produced in the acidogenesis steps are further converted to acetic acid, carbon dioxide and hydrogen by the acetogenic bacteria as shown in Figure 1. There are two types of acetogenic bacteria namely hydrogen producing acetogens and homoacetogens (Parawira, 2012; Cavinato, 2011). Equation 4 and 5 shows the production of acetic acid from butyrate and propionate and by utilizing hydrogen producing bacteria (Ostrem et al, 2004).

$$CH_3CH_2CH_2COOH + 4H_2O \rightarrow CH_3COOH + 2CO_2 + 6H_2 \qquad \text{eq (4)}$$

$$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + CO_2 + 3H_2 \qquad \text{eq (5)}$$

$$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O \qquad \text{eq (6)}$$

Homoacetogenesis is the generation of acetic acid from dissolved H_2 and CO_2 by homoacetogens as shown in Equation 6.
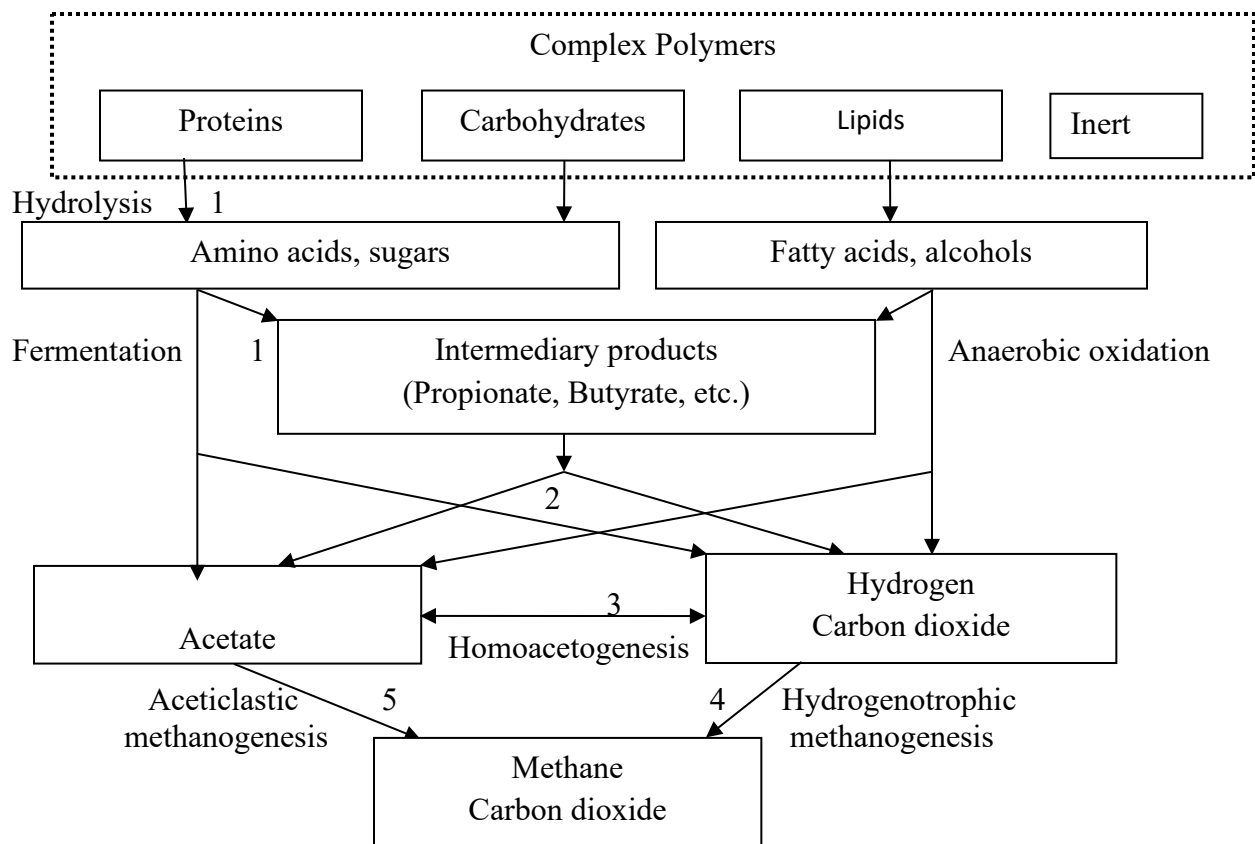
Figure 1: Reaction of the anaerobic digestion of polymeric materials (Numbers indicate the bacterial groups involved): 1. Hydrolytic and fermentative bacteria, 2. Acetogenic bacteria, 3. Homo-acetogenic bacteria, 4. Hydrogenotrophic methanogens, 5. Aceticlastic methanogens (Adapted from Gujer and Zehnder, 1983).

2.4 Methanogenesis

The final stage of overall anaerobic conversion is called methanogenesis in which stage the degradable organic material is finally converted to a gaseous form that automatically leaves the reactor system. Acetoclastic and hydrogenotrophic methanogens are responsible for this conversion (Parawira, 2012; Cavinato 2011). Acetoclastic metanogenesis is the final stage of anaerobic digestion in which acetic acid is converted into CH_4 and CO_2 by a group of Archaea known as acetoclastic methanogens. This is responsible for the production of about two third of methane as shown in Equation 7 (Cavinato, 2011; Ostrem et al., 2004).

$$CH_3COOH \rightarrow CH_4 + CO_2 \hspace{4cm} eq\ (7)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \hspace{4cm} eq\ (8)$$
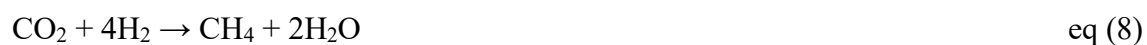
Hydrogenotrophic menthanogenesis is the production of CH_4 from dissolved H_2 and CO_2 by a group of slow-growing hydrogenotrophic methanogens. These methanogens produce the

remaining one third of methane by the reaction shown in Equation 8 (Cavinato, 2011; Ostrem et al., 2004). Methanogenic micro-organisms may compete with sulphate-reducing micro-organisms if sulphate is present at sufficiently high concentrations (Speece, 1996).

3. Factors affecting the rate of anaerobic digestion

Each of the four sub-processes has different rates depending on operating conditions and substrate concentration. The overall rate of stabilization therefore will be limited by the slowest or rate limiting step. The rate limiting step may change from one sub-process to another with time within a system dependent upon the substrate characteristics (Ma et al, 2013; McCarty and Mosey, 1991). In the case of high solid content an initial hydrolysis step to convert particulate matter into soluble substrate is required to obtain efficient AD. The hydrolysis step is appreciably affected by temperature and is usually the rate limiting step for low temperature conditions (Xia et al., 2016; Lew et al., 2011; Zeeman, 1991).

For predominantly dissolved organic waste, the rate limiting steps are the acetogenesis and the methanogenesis as these bacteria groups have the slowest growing rates (Xia et al., 2016; Gujer & Zehnder, 1983). Most of the control in anaerobic digestion is undertaken directly by the micro-organisms themselves. The environmental conditions such as temperature, pH, essential trace nutrients and toxicants can play a major role in modifying reaction rates of individual sub-processes (Xia et al., 2016; Mckeown et al., 2012; Cavinato, 2011). The IWA Task Group for Mathematical Modelling of Anaerobic Digestion Processes defined two categories of inhibition for microorganism: Biocidal and Biostatic inhibition. Biocidal inhibition describes the toxicity experienced by the microorganism due to normally irreversible conditions whereas in biostatic inhibition, the growth of the microbes cease during exposure to inhibitory conditions, but resume growth after re-establishment (Batstone et al., 2002b). Some of the inhibition factors are discussed below.

3.1 pH

Acetoclastic methanogenesis is particularly vulnerable to low pH conditions and quickly inhibited if the pH drops below 6.5 (Van Lier et al., 2008) which halts the removal of acids from the whole system. This happens when there is an increase in acid-producing rate (due to high organic loading rate) and decrease in acid removing rate (decrease in buffer) causing souring (Yuan & Zhu, 2016; Speece, 1996).

There are three principal bacteria types involved in biogas production; bacteria responsible for hydrolysis, fermentative bacteria, and methane-producing archaea. The fermentative bacteria can function in pH range from 8.5 down to pH 4 with their optimal pH range of 5.0 to 6.0 (Hwang et al., 2004), on the other hand, Methanogenic archaea can function in narrow pH interval from 5.5-8.5 with an optimal range of 6.5-8.0 (Boe, 2006). pH inhibition occurs as a result of disruption of homeostasis, and increase levels of non-dissociated VFA (Batstone et al., 2002b). The bicarbonate

produced by the methane-producing bacteria normally controls the pH reduction caused by acid-producing bacteria (Liu and Tay, 2004).

The greatest risk for digester failure is as a result of acid accumulation which would occur if the amount of volatile solids loaded into the digester from fresh waste increased sharply. The acidogenic bacteria would then flourish, producing high volumes of organic acids and further lowering the pH to below 5.0 which is lethal to methanogens. pH values above 8 is toxic to most anaerobic organisms which results in the inhibition of biological functions. High pH could be due to prolific methanogenesis resulting in a higher concentration of ammonia, impeding acidogenesis (Lusk, 1999). This can now be opposed by adding a greater amount of fresh feedstock (Ostrem, 2004).

Systems with low potential for generating alkalinity through metabolism may necessarily add alkalinity in the form of lime (CaO), carbonate, hydroxide or bicarbonate for buffering digestion (Speece, 1996).

3.2 Temperature

Anaerobic process can occur in a wide range of temperature that is psychrophilic (<20 $^{\circ}$C), mesophilic (25-40°C) and thermophilic (45-60°C) (Khalid et al., 2011; Mathew et al., 2014). Temperature has direct effect on physical-chemical properties of all components in the digester and also affects thermodynamic and kinetic of the biological processes. There are several advantages with increasing temperatures (Abdelgadir et al., 2014; Van Lier, 1996) for instance; increase solubility of organic compounds which makes them more accessible to the microorganisms, increase chemical and biological reaction rates that accelerate the conversion process so that the reactor can be smaller and can run with shorter HRT. It improves several physical-chemical properties such as improve diffusivity of soluble substrate, increase liquid-to-gas transfer rate due to lower gas solubility, improve liquid-solid biomass separation and increase death rate of pathogenic bacteria especially under thermophilic condition, which decreases retention time required for pathogen reduction (Bendixen, 1994; Smith et al., 2005). However, high temperature can have negative effects as well. Increasing temperature increases the fraction of free-ammonia (NH_3) which is inhibitory to microorganisms. In addition, increasing temperature increases VFA undissociated fraction, especially at low pH (4-5) (Van Lier, 1996). This makes the thermophilic process more sensitive to inhibition. The stability of the mesophilic process makes it more popular in current AD facilities, but achieved at longer retention times (Ostrem, 2004).

3.3 Organic Loading Rate (OLR)

The degree of starvation of microorganisms in biological systems is dependent on the OLR. At a high OLR, a fast microbial growth (but intoxication may occur with high quantities of organic matter) takes place whereas at a low OLR microorganism starvation takes place. However, if the applied OLR is too high, microorganism could not use up all produced organic acids and cause acidic state of the digester (Liu and Tay, 2004). OLR mainly determined based on feeding materials and reactor temperature.

3.4 Solid Retention Time (SRT)

SRT is a key parameter that affects biochemical properties of organic materials. The SRT plays an important role in anaerobic digestion especially for methanogens at low operational temperatures (Halalsheh et al., 2005). The SRT should be long enough to provide sufficient methanogenic activity. Methanogenesis starts at SRT between 5 and 15 days at 25 °C and between 30 and 50 days at 15°C (Halalsheh et al, 2005), however, it again depends on characteristics of feeding materials.
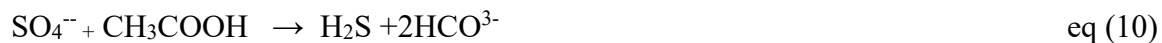
3.5 Nutrients

The nutrient requirements of anaerobic digestion are relatively small since nutrient requirement are essentially linked to the growth and anaerobic processes are characterized by low growth yields (Speece, 1996). However, it is essential to have sufficient nutrients to make sure the efficient anaerobic process.

3.6 Sulphate Reduction

The effect of sulphate reduction on anaerobic systems is complicated by the fact that the reduced product sulphide has an inhibitory effect on almost all the microbial groups (Batstone et al., 2002b). The methanogenic microorganism competing with sulphate-reducing microorganism for the common intermediate acetic acid, due to the presence of sufficiently high concentrations of sulphur (Speece, 1996).

However, reduction of sulphate leads to an increase of pH and the buffer capacity and leaves the system with H_2S gas as shown in Equation 9 and 10, respectively (Arceivala, 2007).

$$SO_4^{--} + 4\,H_2 \quad \rightarrow \quad H_2S + 2H_2O + 2OH^- \hspace{4cm} eq\ (9)$$

$$SO_4^{--} + CH_3COOH \quad \rightarrow \quad H_2S + 2HCO^{3-} \hspace{4cm} eq\ (10)$$

3.7 Denitrification

Denitrifying microorganisms have a higher cell growth yield per unit substrate consumed than methanogenic microorganism and compete for the same carbon source and electron source (e.g. acetate or H_2). Thus in anaerobic digestion, the presence of nitrate has significant impact in the form of microbial competition which leads to inhibition of CH_4 production. The reaction (Eq 11) shows the overall reduction of nitrate by acetic acid to produce N_2 (Batstone et al., 2002b; Foxon, 2006).

$$5CH_3COOH + 8NO_3^- + 8\,H_2 \rightarrow 4\,N_2 + 10\,CO_2 + 19\,H_2O \hspace{3cm} eq\ (11)$$

3.8 Ammonia

Nitrogen in the form of NH4-N is required by bacteria for their cell mass synthesis. The major nitrogen compound is obtained from nitrogenous materials available in organic matter usually proteins and urea. Ammonia is produced during hydrolysis of proteins and urea. Urea is readily

hydrolysed to ammonia and carbon dioxide by the enzyme urease present in organic matter (Arcievala et al., 2007). Urea is decomposed by bacteria via the following enzymatic catalyzed reaction as shown in Equation 12 (Fidaleo and Laveccio, 2003).

$$CO\ (NH_2)_2 + 2H_2O \rightarrow\quad 2\ NH_4^+ + CO_3^{2-} \qquad\qquad\qquad eq\ (12)$$

Also, hydrolytic bacteria further hydrolyze amino acids to form ammonia, H2, CO2 and VFAs (Tchobanoglous et al., 1993). The release of ammonia through the decomposition of urea, hydrolysis of amino acids are the primary parameter causes a rise in the bicarbonate-ammonia buffer (alkalinity) and controlling the pH and the process stability of the digester (Shanmugam and Horan, 2008). Consequently, a dramatic pH fall below 6 as a critical value hardly occurs (Wendland, 2008). Even if the formation of VFA (HAc- Acetic acid) decreases the buffer capacity but the formation of NH4+ increases the bicarbonate concentrations and the process stabilities.

Ammonia inhibits predominantly the methanogenesis (Wendland, 2008). Acetate utilizing methanogenic bacteria were found to be more sensitive to ammonia than hydrogen consuming ones (Fotidis et. al., 2013). Two different mechanisms were attributed to ammonia inhibition, firstly methanogens are directly inhibited by free ammonia and secondly in the bacterial cell wall free ammonia is rapidly converted to ammonium ion as shown in the Equation 13 (Kadam and Boone, 1996).

$$NH_3 + H_2O \rightarrow\quad NH_4^+ + H_2O \qquad\qquad\qquad eq\ (13)$$

4. Energy performance of AD

4.1 Methods used

The energy performance of the anaerobic digestion is depending mainly on the biogas production technology (wet or dry technology, mesophilic or thermophilic) and geographic location (ambient temperature). The feedstock of course have also an effect because the biogas yield is varying. In addition when utilizing cultivated feedstock the processes of obtaining the feedstock can consume significant amount of energy. Especially when utilizing wet digestion technology the main part of the parasitic energy demand is the heat required for heating the feedstock to the desired temperature. (Havukainen et al., 2014).

The energy performance of AD is difficult to calculate similarly to incineration since the lower heating value as received (LHV$_{as}$) can be even negative especially with feedstock coming for wet digestion. This means that the energy efficiency defined as produced energy (electricity and/or heat) divided by the fuel energy of the incoming waste would be negative. Therefore other methods have needed to be developed to ascertain the energy performance of AD. Table 1 describes some

methods which have been used in obtaining information about the different methods which have been used for energy performance calculation. These studies on energy performance include waste as well as energy crops as a feedstocks and have used varying system boundaries. Energy performance has been calculated as energy output divided by energy input (Prade et al., 2012; Tanaka, 2008) as well as energy input divided by energy output (Pöschl et al., 2010). However it seems that the output-input is most commonly used method among these studies.

Table 1: Methods for calculating energy balance of anaerobic digestion (modified from Havukainen et al., 2014)

Method	Inputs and outputs included	Result	Reference
Input/output 1	Input: Primary energy for obtaining raw material, transport, operation of biogas plant. Output: Biogas energy content.	20–40%	(Berglund and Börjesson, 2006)
Input/output 2	Input: Crop cultivation, collection, transport, biogas plant operation, digestate processing. Output: Energy produced from biogas.	10.5–64%	(Pöschl et al., 2010)
Input/output 3	Input: Production of inputs, cultivation, digestion, biogas processing and transport fuel delivery. Output: Biomethane energy.	22–37%	(Tuomisto and Helenius, 2008)
Output/input 1	Output: Methane. Input: Energy for cultivation, transport, fertilizer and pesticides.	7–25	(Gerin et al., 2008)
Output/input 2	Output: Heat, power and biomethane. Input: Crop production, transport, biogas production and upgrading.	3.5–8.2	(Seppälä et al., 2008)
Output/input 3	Output: Heat, power and biomethane. Input: Crop production and digestion, biogas and digestate use (direct and indirect energy).	1.8–3.3	(Salter and Banks, 2009)
Output/input 4	Output: Heat, power and biomethane. Input: Crop production and processing, reactor.	4.04–6.5	(Salter et al., 2005)
Output/input 5	Output: Electricity and heat. Input: Cultivation, harvesting, digestion, digestate.	5.5–6.8	(Navickas et al., 2012)
Biomethane yield (BMY)	BMY_1 = (methane potential of input biomass − methane potential of the digestate) / methane potential of the input biomass BMY_2 = effective specific methane produced / biomethane potential of input	BMY_1 and BMY_2 84–93%	(Schievano et al., 2011)
Energy efficiency	Mechanical energy of the tractor / (biogas energy + energy produced outside system e.g. electricity, diesel)	5.8–13%	(Lacour et al., 2012)
Relative biogas yield	Measured biogas yield / theoretical biogas yield	90–161%	(Djatkov et al., 2012)

Total annual efficiency	(produced electricity + used heat) / biogas energy	30.5–73%	(Laaber et al., 2007)
Electricity use	Parasitic electricity use / produced electricity	30.4%	(Banks et al., 2011)

Energy output divided by energy input has been used for example by (Berglund and Börjesson, 2006) and (Pöschl et al., 2010). (Berglund and Börjesson, 2006) studied the energy performance of wet anaerobic digestion operating at mesophilic temperature of energy crops, harvest residues, manure, industrial organic waste and municipal organic waste. The input/output range was calculated by using the primary energy used for the unit processes as input and biogas energy content as output. The input/output ratios ranged from 20-50% being lowest for grease trap sludge and highest for ley crops. The differences were mainly due to varying properties of raw materials, system design and allocation method. The heat and electricity consumption of biogas production was responsible of approximately 40-80% of the net energy consumption. Similarly (Pöschl et al., 2010) used primary energy to calculate primary energy input output (PEIO) ratio wet digestion at mesophilic digestion in two stage digester. The feedstocks include agricultural waste, energy crops, municipal solid waste and food industry residues. PEIO was 11-64% for single feedstock digestion and 34-55% for co-digestion.

(Salter and Banks, 2009) used output/input ratios for estimating energy performance of anaerobic digestion of energy crops (maize, fodder beet, lupin and perennial ryegrass) and found that ratio was 1.8-3.3 for energy crops being lowest for lupin and highest for maize. (Navickas et al., 2012) us also studied energy crops (fresh grass, hay and reed canary grass) and output ratio was highest for hay (6.8) and lowest for fresh grass (5.5).

4.2 System boundary

The comparison of energy balance values in Table 1 is difficult since the system boundaries around the anaerobic digestion systems are varying a lot. The system boundary can stop to the produced biogas (Berglund and Börjesson, 2006) or it can also include the energy produced from biogas (Salter et al., 2005). There are also significant differences in which energy consumptions are included. Gerin et al. (2008) excluded electricity and heat consumption of anaerobic digestion when studying energy crop biogas system, even though according to   Berglund and Börjesson (2006) anaerobic digestion is most energy consuming process also in energy crop biogas system. In most cases the indirect energy consumption in construction is excluded. However at least Salter and Banks (2009) included also the indirect energy use of construction and maintenance of digester and auxiliary equipment.

Comparing energy balances of different anaerobic digestion systems would require that some general system boundaries could be set. The energy performance of anaerobic digestion would

be better estimated with utilizing few different system boundaries. Figure 2 presents four system boundaries which can be used in calculating the different energy performance values which can be used in following the energy performance of given anaerobic digestion system and to compare to other systems.
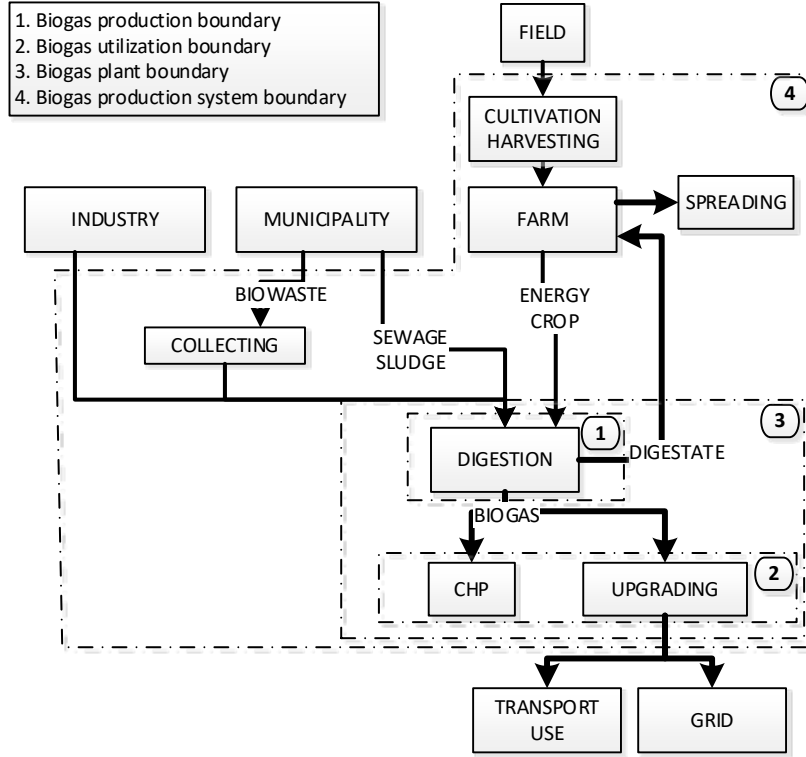

Figure 2: Different system boundaries for estimating energy performance of anaerobic digestion system (modified from Havukainen et al., 2014)

4.3 Output/input ratio calculation

The energy performance calculation can be done on biogas production alone, utilization of produced biogas from anaerobic digestion, for the anaerobic digestion plant or for the anaerobic digestion system. Energy performance of biogas production can be calculated by Equation 14 (Havukainen et al., 2014) utilizing the system boundary 1 in Figure 2

$$R_{pr2} = \frac{E_{bg}}{E_{el,par}+E_{h,par}} \qquad \text{(eq 14)}$$

where E_{bg} is the energy content of the produced biogas (MWh), $E_{el,par}$ is the parasitic electricity used for biogas production (MWh), and $E_{h,par}$ is the parasitic heat needed in biogas production processes (MWh). The energy performance of biogas utilization can be calculated by Equation 15 (Havukainen et al., 2014) utilizing system boundary 2 in Figure 2).

$$R_{ut} = \frac{E_{el,prod}+E_{h,prod}+E_{bm}-E_{el,par,CHP}-E_{el,par,up}-E_{h,par,up}}{E_{bg}} \qquad \text{(eq 15)}$$

where $E_{el,prod}$ is the produced electricity (MWh), $E_{h,prod}$ is the produced heat (MWh), E_{bm} is the energy content of produced biomethane (MWh), $E_{el,par,CHP}$ is the parasitic electricity need of the (CHP) equipment (MWh), $E_{el,par,up}$ is the parasitic electricity need of the upgrading process (MWh) and $E_{h,par,up}$ is the parasitic heat need of the upgrading process (MWh).

The Equation 16 (Havukainen et al., 2014) can be used for calculating energy performance for the anaerobic digestion plant (R_{pl}). System boundary 3 in Figure 2.

$$R_{pl} = \frac{E_{h,s}+E_{bm}+E_{el,s}}{E_{el,par,pl}+E_f+E_{h,par,pl}} \tag{eq 15}$$

where E_f is the energy content of other fuels used in the production of energy in the biogas plant, $E_{h,s}$ is the heat energy supplied to processes outside the biogas plant boundary, $E_{el,s}$ is the electricity supplied to the grid, $E_{el,par,pl}$ is the electricity need from the electricity grid and $E_{h,par,pl}$ is the heat need from outside the biogas plant.

The energy performance for the whole anaerobic digestion system (R_{sy}) can be calculated with Equation 16 (Havukainen et al., 2014).

$$R_{sy} = \frac{E_{h,s}+E_{bm}+E_{el,s}}{E_{t,d}+E_{t,fs}+E_{ch}+E_c+E_{sd}+E_{el,o}+E_f+E_{h,o}} \tag{eq 16}$$

where the fuel need is $E_{t,d}$ for transporting the digestate (MWh), E_{sd} for spreading the digestate (MWh), $E_{t,fs}$ for transporting the feedstock (MWh), E_c for the collection of biowaste (MWh) and E_{ch} for the cultivation and harvesting of the energy crop (MWh).

References

Banks, C., Chesshire, M., Heaven, S. & Arnold, R., 2011. Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance. 102, pp.612-20.

Berglund, M. & Börjesson, P., 2006. Assessment of energy performance in the life-cycle of biogas production. Biomass and Bioenergy, 30, pp.254-66.

Djatkov, D. et al., 2012. New method for assessing the performance of agricultural biogas plants. Renewable Energy, 40, pp.104-12.

Gerin, P.A., Vliegen, F. & Jossart, J.-M., 2008. Energy and CO2 balance of maize and grass as energy crops for anaerobic digestion. Bioresource Technology, 99, pp.2620-27.

Havukainen, J., Uusitalo, V., Niskanen, A., Kapustina, V., Horttanainen, M., 2014. Evaluation of methods for estimating energy performance of biogas production. Renew. Energy 66. doi:10.1016/j.renene.2013.12.011

Khalid, A. et al., 2011. The anaerobic digestion of solid organic waste. Waste Management, 31, pp.1737-44.

Laaber, M., Madlener, R., Kirchmayr, R. & Braun, R., 2007. Aufbau eines Bewertungssystems für Biogasanlagen - "Gütesiegel Biogas".

Lacour, S. et al., 2012. Energy and environmental balance of biogas for dual-fuel mobile applications. Renewable and Sustainable Energy Reviews, 16, pp.1745-53.

Navickas, K. et al., 2012. Influence of different biomass treatment technologies on efficiency of biogas production., 2012. 11th International Scientific Conference Engineering for Rural Development 24.-25.05.2012 Jelgava, Latvia.

Prade, T., Scensson, S.-E. & Mattsson, J.E., 2012. Energy balances for biogas and solid biofuel production from industrial hemp. Biomass and Bioenergy, 40, pp.36-52.

Salter, A. & Banks, C.J., 2009. Establishing an energy balance for crop-based digestion. Water Science & Technology, 59, pp.1053-60.

Salter, A. et al., 2005. Establishing an energy balance for crop-based digestion energy., 2005. 14th European Biomass Conference and Exhibition: Biomass for Energy, Industry and Climate Protection , Paris, France , 17 - 21 Oct 2005.

Schievano, A., D'Imporzano, G., Orzi, V. & Adani, F., 2011. On-field study of anaerobic digestion full-scale plants (Part II): New approaches On-field study of anaerobic digestion full-scale plants (Part II): New approaches. Bioresource Technology, 102, pp.8814-19.

Seppälä, M. et al., 2008. Biogas from energy crops—optimal pre-treatments and storage, co-digestion and energy balance in boreal conditions. Water Science & Technology , 58, pp.1857-63.

Tanaka, K., 2008. Assessment of energy efficiency performance measures in industry and their application for policy. Energy Policy, 36, pp.2887-902.

Tuomisto, H.L. & Helenius, J., 2008. Comparison of energy and greenhouse gas balances of biogas with other transport biofuel options based on domestic agricultural biomass in Finland. Agricultural and Food Science, 17, pp.240-51.