TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

SAMU VESA

MUNICIPAL WASTEWATER AND SLUDGE, ENERGY RECOVERY POSSIBILITIES

Bachelor’s thesis

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ABSTRACT

Tampere University of Technology
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In this thesis, a literature overview was made concerning the recent trends in the energy recovery possibilities of the wastewater and sludge treatment field. Several techniques were found to have potential for energy recovery. These techniques include anaerobic digestion, anaerobic-membrane treatment, incineration and co-incineration of sludge, gasification and pyrolysis, microbial fuel cells and heat pump systems.

The anaerobic digestion process is already widely applied and mature method for biogas production in the wastewater treatment. Nonetheless, the efficiency of the process can be improved via membrane-filtration in the bioreactor or with gasification or pyrolysis. Heat pump systems also provide big potential for energy recovery. Incineration and co-incineration were found to be feasible for large-scale plants if anaerobic treatment is not possible. Microbial fuel cells do not seem feasible in the near future, even though the laboratory scale studies have shown a high amount of potential.

Combinations of the different techniques are possible and seem to improve the total efficiency of the treatment process. It seems that the best energy recovery and wastewater treatment results could be achieved via combination of anaerobic membrane bioreactor, pyrolysis and a heat pump system. This combination was noticed to have annual energy recovery potential of as high as 0,7 MWh per capita.

TIIVISTELMÄ

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Tässä työssä tehtiin kirjallisuusselvitys koskien energian talteenottoa jäteveden ja lietteen käsittelyssä. Tässä työssä keskityttiin alan tämän hetken suuntauksiin ja tulevaisuuden näkymiin. Muutamien eri tekniikoiden havaittiin omaavan potentiaalia energian talteenottoon: nämä tekniikat ovat mädätys, anaerobi-kalvo –käsittely, poltto- ja yhteispoltto, kaasutus ja pyrolyysi, mikrobipolttokennot sekä lämpöpumput.

Mädätysprosessi on vakiintunut ja laajalti käytössä oleva keino biokaasun tuottamiseksi jätevettä käsiteltäessä. Siitä huolimatta prosessin tehokkuutta voidaan lisätä yhdistämällä perinteiseen prosessiin kalvosuodatus, kaasutus tai pyrolyysi. Lämpöpumpuilla voidaan ottaa lämpöä talteen tehokkaasti. Poltto- ja yhteispoltto on käyttökelpoista suurissa laitoksissa, joissa anaerobikäsittely ei ole mahdollista. Mikrobipolttokennot eivät vaikuta käyttökelpoisilta lähitulevaisuudessa, vaikka laboratoriotutkimusten mukaan mikrobipolttokennoissa on paljon potentiaalia.

Eri tekniikoiden yhdistelmät ovat mahdollisia ja näyttävät lisäävän käsittelyprosessin kokonaistehokkuutta. Työn perusteella parhaat energian talteenotto- ja käsittelytulokset saadaan yhdistämällä anaerobi-kalvo -käsittelyyn, pyrolyysi ja lämpöpumppujärjestelmä. Tämän yhdistelmän huomattiin tuottavan 0,7MWh:a energiaa asukasta kohden.

FOREWORD

I thank Maarit Särkilahti for the interesting thesis subject and good counseling during the process of getting this thesis done.

Tampere, 17.11.2014

Samu Vesa

CONTENTS

ABBREVIATIONS

AD	Anaerobic digestion
AnMBR	Anaerobic membrane bioreactor
BOD$_x$	Biochemical oxygen demand
COD$_x$	Chemical oxygen demand
CHP	Combined heat and power
COP	Coefficient of performance, electrical efficiency of a heat pump
HHV	Higher heating value
LHV	Lower heating value
TS	Total solids
WWTP	Wastewater treatment plant

1 INTRODUCTION

Reduction of the greenhouse gases has been one of the main goals in the global politics in recent years. The European Union is putting a lot of pressure on increasing the clean energy production and reducing the emissions in the member states. The decisions taken are reducing greenhouse gas emissions by 20%, increasing the share of renewable energy to 20% of total consumption, and at the same time increasing energy efficiency by 20% by 2020 (National Energy and Climate Strategy. 2013). That forces the member nations to seek new methods for achieving the goals mentioned above.

Utilizing wastewater and sewage sludge as a renewable resource in energy and heat recovery is getting increasing interest as a method for boosting the energy efficiency and lowering the greenhouse gas emissions to the atmosphere. There are several energy and heat recovery techniques in the field of wastewater and sludge treatment. These techniques include anaerobic digestion, incineration and co-incineration of sludge, gasification, pyrolysis, microbial fuel cells, utilization of heat pumps, and different kind of combinations of the techniques mentioned (Tyagi & Lo 2013). The methods above can be utilized for direct recovery of heat and generation of electricity or they can be used to produce biogas and biofuels for combustion or transportation fuels (Tchobanoglous et al. 2014; Tyagi & Lo 2013).

2 RECOVERABLE ENERGY RESOURCES IN WASTEWATER TREATMENT

There are three different types of energy stored in wastewater, which are chemical energy, thermal energy and hydraulic energy. Chemical energy is the energy that can be released by chemical reactions from the compounds such as organic molecules. Thermal energy is the heat contained in wastewater. Hydraulic energy is the sum of potential energy (caused by height difference), kinetic energy (caused by velocity of the flow) and energy depending on the pressure head (Tchobanoglous et al. 2014).

2.1 Wastewater and sludge characteristics

To reuse the wastewater and the sludge produced by wastewater treatment plant as effectively as possible, it is necessary to know the characteristics of the matter that will be processed. The composition of wastewater and sludge vary depending on the origin, the amount of aging and the process that has been used for the treatment (Tchobanoglous et al. 2014). Typical compositions of wastewater and untreated sludge are presented in Tables 2.1 and 2.2, respectively.

The strength of municipal wastewater tends to vary depending on the usage of water per capita. In the parch areas, where usage of water is more limited, wastewater influent is usually stronger compared to the areas with more fresh water sources and more water consumption per capita (Pescod 1992). In Viikinmäki WWTP in Helsinki, Finland, the wastewater influent is close to medium strength (BOD_7 237,8 mg/l; nitrogen 46,3 mg/l and phosphorus 6,3 mg/l) with water consumption of 285 l/ca·d (HSY 2011). On the other hand wastewater influent is very strong in Amman, Jordan (BOD_5 770 mg/l; nitrogen 150 mg/l and phosphorus 25 mg/l) with water consumption of 90 l/ca·d (Al-Salem 1987 according to Pescod 1992). The examples above were chosen to give a picture of how climate and water usage affect the wastewater strength. Jordan, as a parch country, and with limited fresh water sources, located in the Middle East, has a lot stronger wastewater influent than Finland, where there are a plenty of lakes and other fresh water sources and the water consumption is a lot higher.

Important factors of the sludge processing are the nutrient content which impacts the disposition options; the pH, alkalinity and organic acid content affect the anaerobic digestion process and have to be controlled carefully; the content of heavy metals, hydrocarbons and especially the thermal content of the sludge have an impact on the efficiency of thermal oxidation processes, such as incineration, gasification and pyrolysis (Tchobanoglous et al. 2014).

Table 2.1 *Typical composition of strong, medium and weak wastewater influent (Pescod 1992)*

Concentrations in mg/L	**Wastewater type**		
Item	**Strong**	**Medium**	**Weak**
Total solids	1200	700	350
Dissolved solids	850	500	250
Suspended solids	350	200	100
Grease and fats	150	100	50
Nitrogen (as N,)	85	40	20
Phosphorus (as P)	20	10	6
Chloride	100	50	30
Alkalinity (as $CaCO_3$)	200	100	50
BOD_5	300	200	100

Table 2.2 *Typical chemical composition of untreated primary and activated sludge (Tchobanoglous et al. 2014)*

	Primary sludge		**Activated sludge**	
Item	**Range**	**Typical**	**Range**	**Typical**
Total dry solids (TS), %	1 - 6	3	0,4 - 1,2	0,8
Volatile solids (% of TS)	60 - 85	75	60 - 85	70
Grease and fats (% of TS)	5 - 8	6	5 - 12	8
Protein (% of TS)	20 - 30	25	32 - 41	36
Nitrogen (N, % of TS)	1,5 - 4	2,5	2,4 - 5	3,8
Phosphorus (P_2O_5, % of TS)	0,8 - 2,8	1,6	2,8 - 11	5,5
Potash (K_2O, % of TS)	0 - 1	0,4	0,5 - 0,7	0,6
Cellulose (% of TS)	8 - 15	10	-	-
Iron (not as sulfide)	2 - 4	2,5	-	-
Silica ($SiO2$, of TS)	15 - 20	-	-	-
pH	5 - 8	6	6,5 - 8	7,1
Alkalinity (mg/l as $CaCO_3$)	500 - 1500	600	580 - 1100	790
Organic acids (mg/l as acetate)	200 - 2000	500	1100 - 1700	1350
Energy content, kJ/kg TS	23 000 - 29 000	25 000	19 000 - 23 000	20 000

2.2 Chemical energy resources

To recover and utilize the chemical energy of wastewater, the chemical compounds in wastewater that contain chemical energy have to be transformed into fuel (Tchobanoglous et al. 2014). The fuel produced is then used to generate heat and/or electricity. Most common practice for fuel recovery in wastewater treatment plants is biogas production from the sludge by anaerobic digestion process (Tyagi & Lo 2013). The biogas is then burned in combustion chamber to produce heat. Biofuels can also be produced via gasification and pyrolysis processes, or the dried sludge and the biosolids can be incinerated.

Higher heating value (HHV), which does not take the heat loss of water evaporation into account, of the organic constituents in wastewater can be estimated using Du-Long formula developed by Channiwala 1992 according to Tchobanoglous et al. 2014

$$HHV\ (MJ/kg) = 34{,}91\,C + 117\,H - 10{,}34\,O - 1{,}51\,N + 10{,}05\,S + 2{,}11\,A \qquad (2.1)$$

where C, H, O, N, S and A are the mass fractions of carbon, hydrogen, oxygen, nitrogen, sulfur and ash respectively. Lower heating value (LHV) takes the water evaporation into consideration, and is typically about 10 percent smaller than HHV. (Tchobanoglous et al. 2014).

The fuel types produced from wastewater can be divided in three categories, which are gaseous fuels, solid fuels and liquid fuels (Tchobanoglous et al. 2014). The gaseous fuels include biogas from anaerobic digestion process and syngas produced by gasification of the sludge. Sludge and biosolids are referred as solid fuels. These include primary and secondary sludge and stabilized biosolids. Producing liquid fuels and oils from solid contents of the wastewater is technologically possible but still uncommon (Tchobanoglous et al. 2014).

2.3 Thermal energy resources

The thermal energy in wastewater is in the form of heat. Change in thermal energy is expressed as:

$$Q = \dot{m}c\Delta T \qquad (2.2)$$

where Q = change in heat content, kJ/h
$\dot{m}$ = mass flowrate of water, kg/h
c = specific heat of a substance, kJ/kg°C
ΔT = temperature change, °C.

Thermal energy recovery comprises heat transferring from a heat source to a heat demand. Heat can be recovered from water (e. g. wastewater effluent) or heated air, such as exhaust gases from fuel combustion. Recovery of heat can be done using combined heat and power (CHP) system or utilizing heat pumps. Typical efficiency of combustion system without CHP is in range of 25 and 50 percent. System efficiency with CHP is typically in range of 70 to 85 percent (Tchobanoglous et al. 2014).

Heat recovery systems exchange thermal energy from one medium to another, and transfer the recovered energy to use. Usage of thermal energy in wastewater treatment plants includes space heating, heating of anaerobic digester, drying of sludge and biosolids, and electric generation (Tchobanoglous et al. 2014). Excess heat can be used to provide heat for district heating system.

2.4 Hydraulic energy resources

Hydraulic energy in wastewater fluid is in three forms (Tchobanoglous et al. 2014). These forms are elevation head ($\rho g z$), which is the relative position of the influent to effluent. Most conventional use of elevation head is to minimize the excess head at the end of the treatment process (Tchobanoglous et al. 2014). The second form of hydraulic energy is pressure head (p), which is the pressure difference in pressurized processes such as reverse osmosis. The third form is velocity head which is associated with the kinetic energy of the fluid expressed as ($\rho v^2/2$). Equation 2.3 can be used to determine the total head transferred to or received from the fluid

$$\pm H_t = (p_2 - p_1) + (\rho v_2^2/2 - \rho v_1^2/2) + (\rho g z_2 - \rho g z_1) + losses \qquad (2.3)$$

where H_t = total hydraulic head transferred into or received from fluid, kN/m^2
p = pressure, kN/m^2
ρ = density of water, kg/m^3
v = velocity of the flow, m/s
g = acceleration due to gravity, 9,81 m/s^2
z = height above an assumed surface, m
losses are caused by head transforming to non-recoverable sources such as noise or heat

Conversion of hydraulic energy to electrical power when flowrate of the fluid is known can be calculated using Equation 2.4

$$P = Q_v H_t \eta_t \qquad (2.4)$$

where P = electrical power obtained, W
Q_V = flowrate of the fluid, m^3/s
η_t = total efficiency of mechanical devices and electrical conversion devices (e.g., pumps, turbines etc.) as a dimensionless fraction

The most common applications for the hydraulic energy recovery are recovery of hydraulic potential from wastewater flow using hydraulic turbines or recovery of residual head in high-pressure processes such as reverted osmosis (Tchobanoglous et al. 2014).

3 ENERGY AND RESOURCE RECOVERY

There are several different techniques for energy and resource recovery in the field of wastewater and sludge treatment. Anaerobic digestion for biogas recovery is the most widely practiced method (Tyagi & Lo 2013). Incineration and co-incineration of the sludge have also been used to produce heat and electricity. Gasification and pyrolysis can be used to produce gaseous and liquid fuels (Rulkens 2008). With microbial fuel cells (MFCs) it is possible to generate electricity in the wastewater treatment plant (Rabaey & Verstraete 2005). Heat pumps can be utilized to recover heat from wastewater (Gu et al. 2011).

3.1 Anaerobic digestion for biogas recovery

Anaerobic digestion (AD) of sewage sludge is widely used technique in wastewater treatment plants. AD process transforms organic solids of the sludge to biogas, which is mainly a mixture of methane and CO_2 containing a bit of other gases like NH_3 and H_2S. Typical properties of the biogas produced are 55 to 70 percent methane concentration, 30 to 40 percent of CO_2 concentration, and the energy content is typically between 22 and 24 MJ/m^3 (Tchobanoglous et al. 2014). AD is utilized to remove biodegradable organic loads, odors and pathogens from the sludge, but it does not remove heavy metals and some of the other hazardous contents (Cao & Pawłowski 2012). It is necessary to utilize treatment methods with the AD that tackle the substances that AD is not able to remove.

The AD process contains four main steps which are hydrolysis, acidogenesis (which is also known as fermentation), acetogenesis and methanogenesis (Rulkens 2008). In hydrolysis organic solids such as polysaccharides, proteins and lipids are hydrolyzed and form monosaccharides, amino acids and long chain fatty acids. Acidogenesis (fermentation) step forms volatile fatty acids, CO_2, hydrogen and acetate acids. In acetogenesis step, intermediate products of acidogenesis are converted to acetate, hydrogen and CO_2. The final step of the process is methanogenesis that transforms acetic acids and hydrogen to CH_4 that can be recovered. The theoretical biogas production is

$$C_vH_wO_xN_yS_z + \left(v - \frac{w}{4} - \frac{x}{2} + \frac{3y}{4} + \frac{z}{2}\right)H_2O \rightarrow$$
$$\left(\frac{v}{2} + \frac{w}{8} - \frac{x}{4} - \frac{3y}{8} - \frac{z}{4}\right)CH_4 + \left(\frac{v}{2} - \frac{w}{8} + \frac{x}{4} + \frac{3y}{8} + \frac{z}{4}\right)CO_2 + yNH_3 + zH_2S \qquad (3.2)$$

The yield of methane depends highly on the pH of the digester because it affects the amount of CO_2 released to the gas phase (Tchobanoglous et al. 2014). To improve the quality of the biogas it has to be pretreated before combustion. Typical biogas treatment system for digester gas is shown in Fig. 3.1.

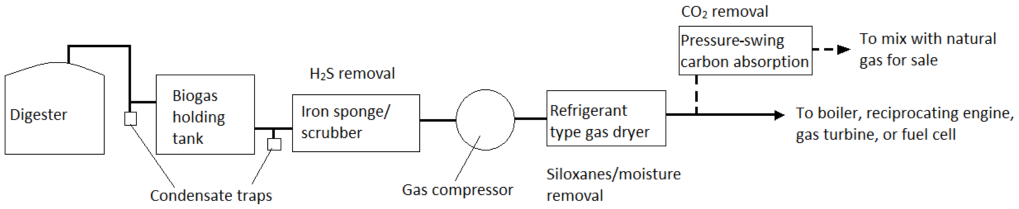

Figure 3.1 ***Typical digester gas pretreatment process (Tchobanoglous et al. 2014)***

The methane recovered can be used in the wastewater treatment plant to produce process heat and electricity to lower the energy input requirements of the plant, or it can be sold to the heat and/or electricity market. If the biogas is not utilized on-site, it can be used in biogas combustion plant to generate electricity or it can be refined into transportation fuel.

The annual reports of the WWTPs in the fifteen biggest Finnish towns were inspected and seven of them were found to utilize anaerobic digestion in their wastewater treatment processes. These WWTPs are located in Helsinki, Tampere, Jyväskylä, Lahti and Joensuu. In the WWTPs of Helsinki, the wastewater of Espoo and Vantaa are also treated.

In Suomenoja WWTP in Helsinki the biomethane produced is refined into transportation fuel for public buses. The produced biomethane lowers the emissions of the local public transportation by 4700 tons in CO_2 and 20 tons in NO_x (HSY 2011). In the Kariniemi and Ali-Juhakkala WWTPs in Lahti the biogas is combusted on-site to produce district heating and process heat (Lahti Aqua Oy 2013). The energy production per capita is the highest of the reports inspected (0,13MWh/ca). The other WWTPs, Viikinmäki in Helsinki, Nenäinniemi in Jyväskylä, Viinikanlahti and Rahola in Tampere, and Kuhansalo in Joensuu, utilize CHP in their treatment processes. The energy productions per capita for the WWTPs utilizing CHP are in range of 0,031 and 0,057 MWH/ca (HSY 2011; JS-puhdistamo OY 2014; Tampereen Vesi 2013; Joensuun Vesi 2013).

If the energy content of the biomethane produced is assumed to be 23 MJ/m^3, the suggestive efficiencies for the systems, where the biogas productions are reported, can be calculated. These are 31,5%, 69,9% and 95,7% for Viikinmäki, Kuhasalo and Kariniemi & Ali-Juhakkala, respectively. Even though the efficiencies are rough estimates, they give a good impression how important the system efficiency is, as the energy productions per capita for the Viikinmäki, Kuhasalo and Kariniemi & Ali-Juhakkala are 0,031; 0,053 and 0,13 MWh/ca, respectively.

The annual biogas and energy productions, utilization methods of the biogas, and the self-sufficiency levels of all the WWTPs mentioned above, are presented in Table 3.1.

Table 3.1 ***WWTPs in 15 biggest Finnish towns utilizing anaerobic digestion in their wastewater treatment process***

		Annual production			Self-sufficiency	
WWTP	Biogas utilization	Biogas	Electricity	Heat	Electricity	Heat
Viikinmäki, Helsinki	CHP	12,3 · 10^6 m^3 15,4 m^3/ca	24774 MWh total 0,031 MWh/ca		61 %	100 %
Suomenoja, Helsinki	transportation fuel	3,5 · 10^6 m^3 12,5 m^3/ca				
Nenäinniemi, Jyväskylä	CHP	not reported	2737 MWh 0,057MWh/ca	5875 MWh	48 %	100 %
Viinikanlahti, Tampere	CHP	not reported	3786 MWh 0,051 MWh/ca	3620 MWh	40 %	63 %
Rahola, Tampere	CHP	not reported	1222MWH 0,051 MWh/ca	2500 MWh	40 %	100 %
Kariniemi & Ali-Juhakkala, Lahti	Process heat, district heating	2,72 · 10^6 m^3 22,0 m^3/ca	0,13 MWh/ca	16625 MWh		100 %
Kuhasalo, Joensuu	CHP	730 000 m^3 12,0 m^3/ca	660 MWh 0,053 MWh/ca	2600 MWh		

One way for indirect biogas production in the wastewater treatment processes is transportation of the sludge to a waste treatment plant where the biogas is then produced. This method can be used if the on-site recovery of the biogas is not possible and a nearby waste treatment plant has already invested in biogas recovery system.

3.2 Anaerobic-membrane treatment

Anaerobic treatment utilizing anaerobic membrane bioreactor (AnMBR) is a promising technology for municipal wastewater treatment. The AnMBR is a hybrid process, combining anaerobic digestion with membrane separation. It could be able to overcome some of the draw-backs of the conventional anaerobic digestion, due to excellent water-sludge separation, which is achieved via micro- or ultrafiltration membrane (Wei et al. 2014).

In the laboratory scale studies COD removal rates of as high as >98% have been achieved. The biogas produced has been richer with methane (over 85 % of methane) than standard AD biogas. (Kim et al. 2011; Wei et al. 2014)

Wei et al. suggest that it could be possible for a WWTP to become a net energy producer via utilization of AnMBR with a heat pump system and/or with forward osmosis. Their example of a system including AnMBR, a heat pump, and forward osmosis is presented in Fig 3.2.

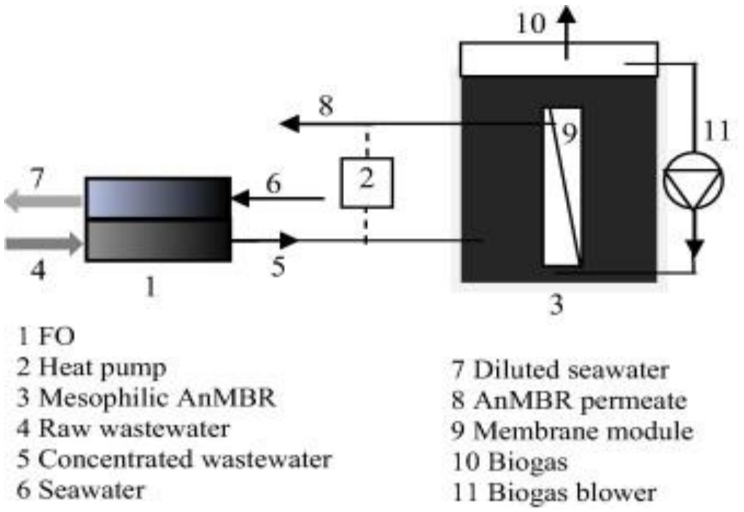

Figure 3.2 *An example of a process including AnMBR, a heat pump, and forward osmosis (Wei et al. 2014)*

3.3 Gasification and pyrolysis

Gasification takes place in high temperatures, approximately 600 – 1000 °C with limited air. The process has been in practice from the 19th century and is a well-known process for converting organic materials to a gaseous fuel called syngas. Syngas is a mixture of gases and its main constituents are CO, H_2, CO_2 and CH_4. It has typical energy content varying between 4,5 and 5,5 MJ/m^3 in the wastewater applications. That is approximately 25 percent of the heating value of the biogas produced by AD. Like the biogas produced by AD, syngas needs pretreatment before combustion. A typical pretreatment process for syngas from gasification is expressed in Fig. 3.3.

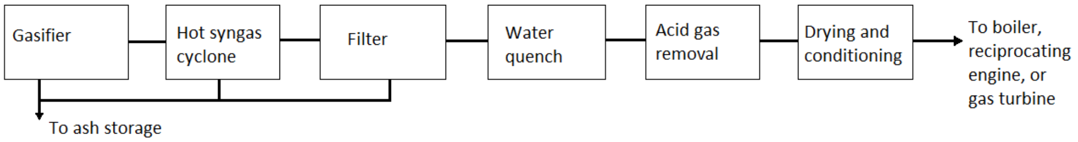

Figure 3.3 *Typical gasifier gas pretreatment process (Tchobanoglous et al. 2014)*

The development of gasification for sludge processing is in early stages but the overall interest to apply this technology to sludge processing is increasing. (Tchobanoglous et al. 2014)

In a demonstration plant in Bellingen, syngas with the LHV of 3,2 MJ/m^3 was produced, and in a pilot-scale plant of Mannheim, the syngas produced has the LHV of 4,7 MJ/m^3 (Judex et al. 2012). The energy recovery potential could be improved by combining the gasification process with AD (Lacroix et al. 2014). Lacroix et al. where able to extract 90% of the total energy content of the sludge with their AD-gasification treatment process. Furthermore excess energy in the process was evaluated to be 11,5 GJ/ton on dried sludge.

Pyrolysis is also an established technology in the chemical industry to produce charcoal, activated carbon and methanol. The process takes place in high temperatures, approximately 200 – 600 °C with no supplied oxygen. Similar to the gasification, pyrolysis also produces combustible gas with somewhat low energy content, but it can also be used to produce char and oil. Pyrolysis has not yet been practiced widely in wastewater applications. (Tchobanoglous et al. 2014)

Even though the pyrolysis process is not practiced in full scale, it contains a lot of potential. Cao & Pawłowski (2012) expect that the pyrolysis will be viable for full-scale operation in the near future. Pyrolysis can produce liquid fuels with very high heating value, up to 37 MJ/kg (Kim & Parker 2008). Pyrolysis treatment can be used on raw sludge or on anaerobically digested sludge. Better treatment results and a higher total efficiency is achieved when the pyrolysis is combined with AD (Cao & Pawłowski 2012).

3.4 Incineration and co-incineration of sludge

Incineration refers to total conversion of organic solids to oxidized end products, mainly carbon dioxide, water and ash. This ash can be reused to produce building materials or has to be disposed of (Tyagi & Lo 2013). In co-incineration process the sludge is combusted in coal-fired plant or with organic waste. Chemical process for complete combustion to determine the oxygen requirements is

$$C_aO_bH_cN_d + (a + 0{,}25c - 0{,}5b)O_2 \rightarrow aCO_2 + 0{,}5cH_2O + 0{,}5dN_2 \qquad (3.2)$$

The typical heating values of primary and activated sludge can be found in Table 2.1. Treatment of sludge by aerobic or anaerobic processes lowers these values thus incineration fits best for the untreated sludge (Tchobanoglous et al. 2014).

Pretreatment for incineration of biosolids or sludge typically includes thickening, dewatering and drying of the sludge. Standard process for combusting sludge or biosolids is presented in Fig. 3.4.

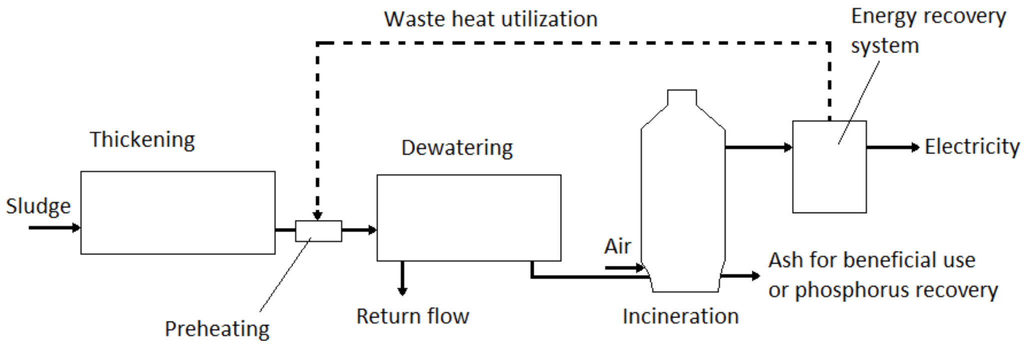

Figure 3.4 ***Typical process for energy recovery by combustion of solid fuels (Tchobanoglous et al. 2014)***

Incineration is most commonly practiced in medium to large sized plants that have limited disposal or reuse options (Tchobanoglous et al. 2014). It is well-known process for the energy recovery, but high capital and operating costs make it less attractive.

3.5 Electricity generation by microbial fuel cells

Microbial fuel cells (MFCs) provide a way to generate electricity directly on-site while treating wastewater. MFCs convert energy in a substrate to electricity. This is achieved when natural electron acceptor (e.g. oxygen, nitrate) of bacteria is switched to insoluble acceptor (MFC anode). The electrons then flow from the anode, through resistor, to the receiving end, the cathode, where the electron acceptor is reduced. MFC produces electrical current and carbon dioxide. MFC process is expressed in Fig. 3.5. (Rabaey & Verstraete 2005)

The MFC technology offers advantages to current technologies of converting organic matter to energy. MFCs have high conversion efficiency due to the direct conversion of substrate energy to electricity. MFCs operate on significantly lower temperatures than all current bioenergy processes. Additionally, no gas treatment is required as the only off-gas is carbon dioxide, which does not include any useful energy content. (Rabaey & Verstraete 2005)

Laboratory scale studies support the idea of MFCs being feasible in the aeration tanks of a WWTP. However, the first long-term study of MFCs installed into actual aeration tanks in real WWTP performed by Zhang et al. (2013) did not support the laboratory studies. Zhang et al. learned that the COD reduction rates were not improved compared to standard activated sludge process. Additionally, the energy balance was negative in two of the three MFCs and +/- 0 in the third one. They expect that it is possible to overcome most of the problems that occurred in their study, but some of the issues, such as cathode biofouling will oppose great challenges. (Zhang et al. 2013)

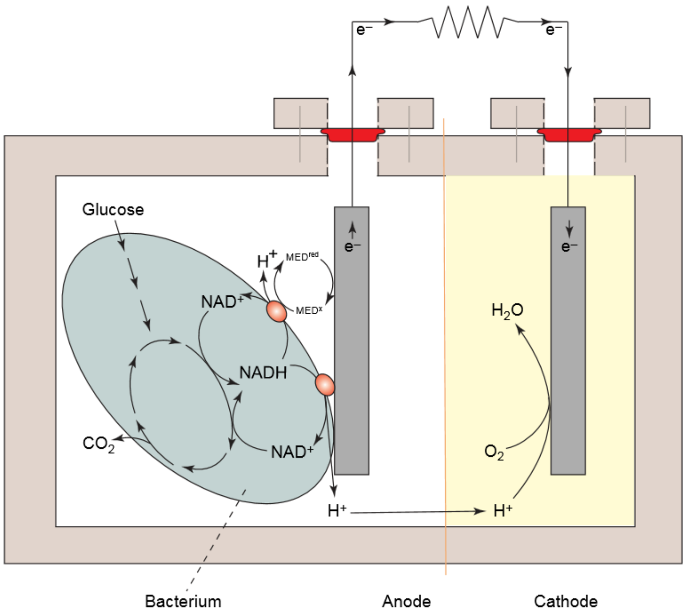

Figure 3.5 ***Typical anode-cathode reactions of a bacteria-run MFC (Rabaey & Verstraete 2005)***

3.6 Heat recovery with heat pumps

A heat pump is a device that uses a refrigerant to transfer heat from a heat source to another medium. The heat source is often at a lower temperature than the medium receiving the heat. A simple schematic of a heat pump is shown in Fig. 3.6. In a heat pump the low temperature-low pressure refrigerant is vaporized using a heat source. The vaporized refrigerant is then compressed to a high pressure-high temperature vapor using a compressor which requires energy. Then the vapor goes through a heat exchanger where the refrigerant is condensed to a liquid, and transfers the latent heat of vaporization to the space requiring the heating. The refrigerant then goes to an expansion valve where the temperature and pressure of the refrigerant are lowered. After the expansion valve the low pressure-low temperature refrigerant goes back to the first step to be vaporized. (Tchobanoglous et al. 2014)

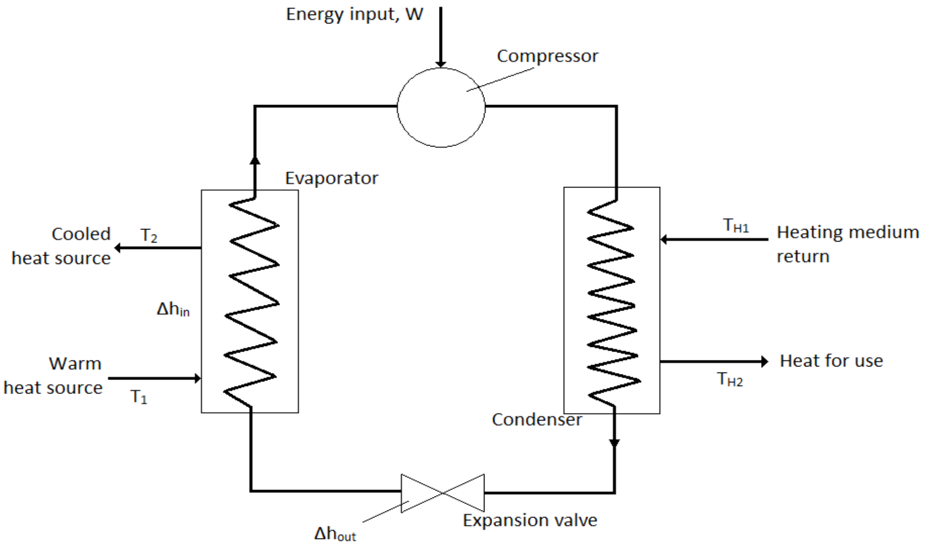

Figure 3.6 ***Simple schematic of a heat pump (Tchobanoglous et al. 2014)***

When wastewater is used as a heat source it is recommended to use an intermediate medium (e.g. propylene glycol) to avoid fouling and corrosion of the heat exchanger of the heat pump (Tchobanoglous et al. 2014). In the intermediate step the heat from wastewater is transferred to the intermediate medium and then the intermediate medium is used as a heat source for the heat pump.

The principles of a heat pump for heating can also be utilized opposite direction for cooling of a medium.

One of the major characteristics of a heat pump is coefficient of performance (COP) which is an expression for heat pump performance (Tchobanoglous et al. 2014).

$$COP = h_h/h_w \tag{3.3}$$

where, COP = coefficient of performance, unitless
h_h = heat output from heat pump, Joule
h_w = energy input to the heat pump, Joule

Turku Energy reports the COP of 5 for the heat pump system in the Kakola WWTP. The Kakola WWTP uses a combined heating and cooling system to improve the efficiency. Energy input is 6,5 MW, heat output is 19,5 MW and cooling output is 13,0 MW. The system covers 8% (150 GWh; 0,5 MWh/ca·a) of the district heating and 90% of the district cooling in the city of Turku (Turku Energy 2009). In Vaasa, the Pått WWTP uses heat pumps to recover the waste heat. The heat recovery system lowers the heat input of the WWTP by 62% (3,5 GWh, ~0,05 MWh/ca·a) (Vaasan Vesi 2013).

4 DISCUSSION

A lot of contribution has been aimed into the study of the energy recovery possibilities in the field of wastewater treatment in recent years. In this literature review several WWTPs in Finland were found to use AD in their treatment processes with very varying results. Most of the WWTPs (3 out of 4) using AD with CHP technology were noticed to be fully self-sufficient in the process heat and 40 to 61 % self-sufficient in electricity. The biggest one of those four WWTPs, the Viikinmäki WWTP, had the smallest energy production per capita (0,031 MWH/ca·a) while achieving the strongest self-sufficiency level (61% in electricity and 100% in heat). The Himmerfjärdsverket plant in Sweden, The Strass plant in Austria and the Grevesmühlen plant in Germany have achieved full self-sufficiency utilizing AD with CHP (Wiser et al. 2012). Laboratory scale studies show that effectiveness of AD in both, treatment and energy recovery, could be improved by hybrid process combining AD with membrane separation (Kim et al. 2011; Wei et al. 2014).

Two of the bigger WWTPs in Finland were noticed to utilize heat pump to recover the heat from the wastewater effluent. These two had a really big variation in their per capita productions, 0,5 MWh/ca·a and 0,05 MWH/ca·a, for Kakola WWTP and Pått WWTP, respectively. The Pått WWTP is located more north than Kakola WWTP, thus having colder environment, leading to colder wastewater effluent, but that alone does not explain the huge energy production difference.

Gasification and pyrolysis seem to have a lot of potential but are still in early stages of implementation to the field of wastewater treatment. Energy recovery potential of the gasification and the pyrolysis has been improved when combined with AD treatment (Lacroix et al. 2014; Cao & Pawłowski 2012).

Incineration and co-incineration of sludge can be utilized but are very costly and are not feasible for smaller scale plants. For the bigger plants it should still be more efficient to utilize anaerobic treatment instead of incineration.

MFCs have been shining in the laboratory scale studies and have achieved good results, but have not been able to generate positive energy balance in a full-scale study (Zhang et al. 2013). It does seem that MFCs won’t be feasible for full-scale treatment in the near future.

Combination of AD-membrane treatment with heat pumps could lead to energy production of as high as 0,7 MWh/ca·a in the Finnish conditions, as the AD-membrane treatment should not affect negatively to the conditions of the heat pump operation.

5 CONCLUSIONS

There is a lot of energy recovery techniques that show big potential. AD with CHP has already achieved very good results and improvement possibilities for that treatment type should be studied. Anaerobic-membrane treatment seems to be a very feasible improvement for the AD process because of the improved COD removal and production of methane-richer biogas.

The pyrolysis and gasification processes should be studied more as they provide a big potential. Lack of the pilot-scale studies do make it hard to judge them, though.

Incineration of sludge cannot match the benefits of anaerobic-membrane treatment, but is still feasible if other energy recovery possibilities are not applicable for some reason. MFCs do not seem to become feasible in the near future, but should still be studied as the laboratory scale studies have shown some potential.

At this point it seems that the biggest potential in the energy recovery in the field of the wastewater treatment is in the hybrid processes, and the different kind of combinations of the known treatment techniques. Anaerobic-membrane treatment with pyrolysis and a heat pump process should be able to make a WWTP a net energy producer.

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HSY, Environmental Services of Helsinki Region.

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