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WASTE TO ENERGY- A REVIEW

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ABSTRACT

Waste materials can be used as a valuable resource for reuse, recycling or energy recovery. In this paper a review on using waste as energy resource, done in the REMOWE project, included in the EU funded Baltic Sea Region Programme, is presented. Five main conversion paths have been identified; combustion, pyrolysis, gasification, anaerobic digestion and fermentation. Combustion and anaerobic digestion are mature and well-proven technologies for waste treatment but improvements are needed to make the processes more efficient as energy conversion processes. For anaerobic digestion feedstock pre-treatment, avoidance of inhibition, mixing, residues utilization, and monitoring and control are identified development areas. A more recent trend is development of dry digestion technology for the treatment of municipal waste. The possible improvements of the combustion process using waste as fuel includes plant efficiency, improved emission control and ash handling. Pyrolysis and gasification have been used for waste treatment but the technologies are still in the development stage. Identified development areas are process operation conditions, gas and by-product quality, gas cleaning and plant efficiency.

Studies comparing waste to energy systems found do not give a clear picture of what waste to energy technology that is most favourable. The results of the comparisons are dependent on the conditions chosen for the study such as location, economic activities, population, and possible system combinations.

Keywords: waste, energy, REMOWE, review, conversion

NOMENCLATURE

Abbreviation

CHP combined heat and power
CSTR continuously stirred tank reactor
DME dimethyl ether
FT Fischer-Tropsch
LCA life cycle analysis
MSW municipal solid waste
OHW organic household waste
PDF packaging derived fuel
PPF paper and plastic fraction
PEF processed engineered fuel
RDF refuse derived fuel
REF recovered fuel
SLF shredder light fraction
SNG synthetic natural gas
SRF solid recovered fuel or specified recovered fuel
SSCF simultaneous saccharification and co-fermentation
SSF simultaneous saccharification and fermentation

1. INTRODUCTION

Waste management often has a focus on minimizing problems that left over materials can cause. However, waste materials can be used as a valuable resource for reuse, recycling or energy recovery. The use of waste for energy purposes is studied in the project REMOWE, a project included in the EU funded Baltic Sea Region Programme. The project addresses the problem concerning how to facilitate the implementation of sustainable systems for waste to energy. This paper presents the results of an investigation of the state of the art of waste to energy conversion processes done in the project. More information can be found on the project homepage [1].

Waste is a heterogeneous energy source and several conversion processes are possible. The main conversion paths have been identified to be two based on biological conversion processes; anaerobic digestion and fermentation and three based on thermal conversion processes; combustion, pyrolysis, and gasification.

2. BIOLOGICAL CONVERSION PROCESSES

The biological conversion processes uses microorganisms to convert the waste material into energy products such as biogas (anaerobic digestion technology) and ethanol (fermentation technology).

2.1 ANAEROBIC DIGESTION

The application of anaerobic technology has evolved with time. In Europe it started to be applied for the treatment of sewage sludge in the 1920's. Later, the technology was gradually adopted in the treatment of other organic waste: manures, organic industrial waste, co-fermentation of sewage sludge with municipal waste, digestion of biowaste and finally (since approximately 1995) the anaerobic digestion of residual municipal waste. It involves complex interactions between various microorganisms and consists of four phases: hydrolysis, acidogenic, acetogenic and methanogenic phases. [2, 3, 4, 5]

Depending on the waste composition and properties, different types of technology can be chosen [6]. It is common to classify biogas plants into batch and flow plants. Nowadays, almost all biogas plants are flow plants. Other parameters for biogas plants grouping are temperature and type of microorganisms (mesophilic or thermophilic) and technology (one, two or multi-stage). Another possibility to distinguish digesters is water content of the substrates inside the digesters; wet or dry digestion. Which operating system is chosen depends mostly on the used feedstock. If the feedstock is liquid, wet digestion is preferable. In case of stackable substrate or material with high content of disturbants as e.g. unsorted municipal waste contains, dry digestion could be more suitable. The methane producing bacteria acquire their nutrients out of the liquid phase, which means that the bacteria cannot work without water. Therefore also dry digesters require certain amounts of water [7], typically 65%-85%.

The dry digestion process is mainly based on a batch wise operation with a high dry matter content ranging from 20 to 50 %. About 60 % of the installed capacity in Europe in 2010 for digestion of municipal solid waste (MSW) used dry processes [8]. Compared to wet digestion, the demands on feedstock are extremely low. Any organic solid mass that can be tipped, such as biowaste, cuttings and manure with up to 60% of dry substance can be used. Another advantage is also higher loading rates for the reactor in a dry process and with that smaller reactor for the same amount of substrate compared to a wet process. However, a disadvantage is that the equipment for handling the dry material has to be more robust and with that usually more expensive. [8, 9]

The dry anaerobic digestion technology can be applied both for separately collected biowaste and for the residual waste as pre-treatment prior to landfilling. The major difference lies in the mechanical pre-treatment for waste which is more complex for residual waste [4]. The most recent trend in dry anaerobic digestion is to separate the fraction <60 mm from the residual waste. This fraction has proven to be the richest in biodegradable matter and still free from foils which disturb the process. The fraction over 60 mm may be used for RDF production and may require applying additional drying (e.g. biological drying to reduce its water content) [10, 11].

Most dry digesters operate as plug flow digesters, in which the digester contents are not completely mixed, but move as a plug through the reactor from the feed port to the exit. This prevents inoculation of the incoming waste. Therefore, most of the digester designs include an inoculation loop in which the incoming waste is mixed with some of the exiting digestate paste prior to loading. The most widely applied technologies for the dry digestion of solid waste is Kompogas, Dranco and Valorga. In total, 77 facilities used one of these process technologies by the year 2008 and 24 of these have been in operation for 10 years or longer. The biogas yield of the systems ranges from 0.2 to 0.5 m^3/kg organic matter. [12, 13]

The mineral non-biodegradable fraction (stones, gravel, glass, hard plastics) can be removed before entering the digester, while sand and plastic foils are usually not removed. Some plants were reported to have problems with sediments, e.g. in Hille (Dranco), Barcelona Ecoparque II (Valorga) and Rioja (Kompogas) in Spain. The capacity of the heavy fraction separators had to be refitted to achieve a higher separation rate. The Dranco-type dry digestion plant in Kaiserslautern is equipped with a pressure extrusion machine (VM-Press) for the pre-treatment of crushing glass and stones to avoid problems with sedimentation in the dry anaerobic digestion process [10].

Digesters with more than 85% water content are referred to as wet digesters. The wet digestion process is most commonly used in agricultural biogas plants and municipal wastewater treatment plants. Usually continuously stirred tank reactors (CSTR) are used [8, 14]. In the wet biogas production process the substrate needs to be mixed with water if the dry solids content is too high.

An area of importance for the wet process design and performance is the circulation of the material in the digester. The biogas production process inside the digester is dependent on proper and even mixing for distribution of microorganisms and nutrition, inoculation of fresh feed, homogenizing of the material and for the removal of end products of the metabolism [15].

The digestion process is also sensitive to inhibitors. Inhibitors can have a negative effect on microorganisms in small quantities and consequently the amount of gas produced. Oxygen and light could inhibit the activity of methane producing bacteria and the digester should work in an oxygen free environment without any light. Such disinfectants as herbicides, heavy metals, trace elements, detergents, oil products or antibiotics can also disturb the process essentially in a higher concentration. Hydrogen sulphide is a product of the digestion process, which can restrain the decomposition process as a cellular poison. With water, it can be converted to sulphuric acid. Hydrogen sulphide and sulphuric acid are highly corrosive and could damage the plant. At the same time sulphur is an essential trace element for bacteria growth. Another cellular toxin is ammonia. A high ammonia concentration can be caused by high nitrogen and ammonium concentrations under certain circumstances (e.g. temperature). Therefore, substrates with high nitrogen content are diluted or mixed with nitrogen-poor substrates. In this case, ammonia and ammonium must be analysed regularly. [16, 17]

Co-digestion of different substrates can be done to improve the biogas yields due to better balance of nutrients in the mixed substrate or to lower costs due to more efficient use of equipment. An investigation of 22 co-digestion studies shows a growth in biogas production of up to 60% due to increased organic loading rates. [18, 3]

For improving the biogas production capacity, the substrate can be pre-treated to make the material more available for the microorganisms. There are several possible pre-treatment methods such as mechanical pre-treatment, steam pre-treatment and electroporation.

Biogas residues can be used as a fertilizer on farmland supplying the soil with both nutrients and organic carbon [19]. Especially for sanitation purposes, the quality of compost, in terms of heavy metals and pathogens, has to be taken into consideration when speaking about utilization of the digestion residues from MSW, municipal wastewater treatment plants or animal faeces [20].

2.2 FERMENTATION

Wastes suitable for fermentation into ethanol include lignocellulosic materials in agricultural and forestry wastes, such as straws, wood chips and barks, and sawdust. In addition, a large quantity of wastewater generated in certain industrial plants like breweries, sugar mills, distilleries, food-processing industries, tanneries, and paper and pulp industries can be suitable for ethanol production. [21]. There are several technical options to design the bio-ethanol production process from lignocellulosic materials, but regardless of which is chosen, the following features should be considered carefully and comprehensively in comparison with the sugar- or starch-based bio-ethanol production:

- Efficient de-polymerization of cellulose and hemicellulose to soluble sugars.
- Efficient fermentation of a mixed-sugar hydrolysate containing six-carbon (hexoses) and five-carbon (pentoses) sugars as well as fermentation inhibitory compounds.
- Advanced process integration to minimize process energy demand.
- Lower lignin content of feedstock decreases the cost of bio-ethanol.

Usually, five steps are involved to design a complete production process including: pre-treatment, hydrolysis, fermentation, product recovery and effluent treatment through different technologies, see Fig. 1.[22]

The technology of production of bio-ethanol is developing considerably, but the underlying principles remain unchanged. In the beginning of the 21st century several non-technical limiting factors that influence the further development of the bio-ethanol industry were reported on. These limiting factors include feedstock prices,

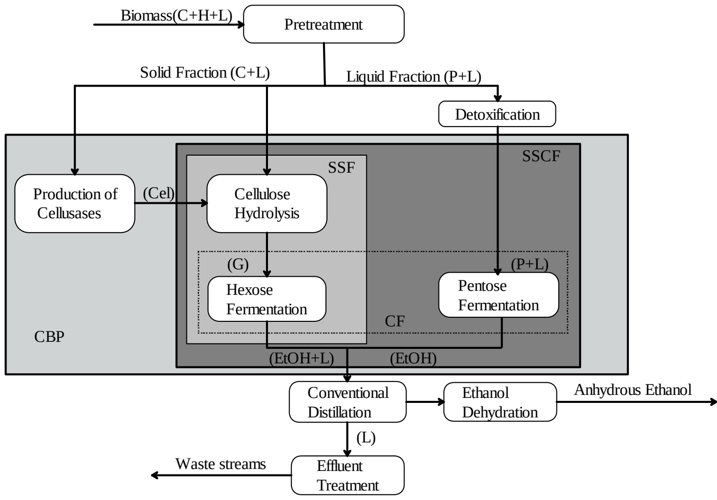

Figure 1 Generic block diagram of fuel ethanol production from lignocellulosic waste. Possibilities for reaction–reaction integration are shown inside the shaded boxes: CF, co-fermentation; SSF, simultaneous saccharification and fermentation; SSCF, simultaneous saccharification and co-fermentation; CBP, consolidated bioprocessing. Main stream components: C, cellulose; H, hemicellulose; L, lignin; Cel, cellulases; G, glucose; P, pentoses; I, inhibitors; EtOH, ethanol [22]

bio-ethanol production costs, cellulolytic enzymes prices, oil prices, taxation of energy products and stimulative policies from government, among which feedstock, bio-ethanol and cellulolytic enzymes production has been pointed out as most important [23]. Furthermore, a good strategy to improve the economics of bioethanol production is to integrate the production with biofuel-fired combined heat and power plants (CHP) to produce more bioenergy products [24, 25].

Waste can also be fermented into butanol. In recent years butanol has attained an interest as a potential stand-alone transportation fuel or blended with petrol or diesel. Butanol is produced in similar way as ethanol but with other microorganisms in the fermentation process. It can also be produced from similar feedstock as ethanol. Compared to other biofuels butanol has properties closer to petrol with for example higher energy density. [26]

Among studies on production of butanol from waste laboratory experiments on production of butanol from corn stover and switchgrass [27], from steam exploded corn stover [28], and from lactose-rich waste water in the form of cheese way [29] can be mentioned. Kumar and Gayen [30] presents a review on butanol production including yields for raw materials such as straw, corn stover and whey. The studies indicate that the process for producing butanol from waste is still immature and has not been demonstrated in scaled-up plants. Development is needed to increase the yield and production rate. For processes using lignocellulosic feedstock the problem of inhibition of the butanol producing microorganisms has to be overcome.

3. THERMAL CONVERSION PROCESSES

Many different wastes can be utilized for electricity, heat and gas production in combustion, pyrolysis and gasification processes. The lower heating value vary a lot depending on the type of waste and can for example be as low as 0.5 MJ/kg for sewage sludge but as high as 25 MJ/kg for refuse derived fuel (RFD)[31]. RFD is the coarse, high caloric fraction produced by pre-treatment of MSW. In the pre-treatment the high caloric fraction of waste is separated and metal, stone and glass are sorted out and removed. The waste is also dried, cut, shredded or milled and pressed to bales, briquettes or pellets. Biological drying, where the waste is dried by air while heat is provided by exothermic decomposition of the readily decomposable waste fraction, can be used. The term RDF can sometimes also be used for sorted residues from packaging wastes or processed industrial wastes. Other terms in use are Recovered Fuel (REF), Packaging Derived Fuel (PDF), Paper and Plastic Fraction (PPF), Processed Engineered Fuel and Solid Recovered Fuel or Specified Recovered Fuel (SRF). SRF, however, is produced according to the requirements of a quality label. Besides increasing the heating value the pre-treatment also gives a more homogenous and less contaminated fuel which open up the possibility to use the fuel in more energy conversion processes. [31, 32, 33, 34, 35, 36, 37, 38]]

3.1 COMBUSTION

Wastes that can be used in combustion processes includes MSW, RDF, bulky waste, product specific industrial waste, packaging waste, hazardous waste, sewage sludge, clinical waste, waste cooking oil, waste lubrication oil, straw, and combustible fraction from fragmentation of metal scrap (SLF, shredder light fraction) [31, 39, 40, 41].

The boiler and the flue gas cleaning system are important parts of the waste combustion plant. In the boiler the waste is combusted and heat recovered by boiling water. The steam can then be used for power production in a steam turbine or for heat production. Heat can also be recovered from the steam leaving the steam turbine.

Grate furnace, fluidised bed and rotary kiln are techniques for combustion of waste, where grate furnace seems to be the most commonly used technique at least for MSW [31, 42; 43; 44]. According to [31] 90% of the installations in Europe for combustion of MSW had grate furnaces in 2006 and according to [45] 70 % of the installations in Germany for MSW and RFD in 2010 used this technique. In fluidised beds the fuel particle size cannot be too large. For straw, grate furnaces are recommended since it has a low ash melting point and it can cause the bed particles in a fluidised bed to stick together. Development to optimise the conditions in fluidised beds to use this technique also for straw is going on [40, 46].

The flue gas from waste combustion can have high concentrations of corrosive substances, as for example chlorides, which influence the boiler design and steam data used, due to avoiding corrosion problems. Modest steam temperature and pressures around 40 bar and 400 °C are usually used with some higher temperatures, up to 540 °C, possibly for straw combustion. [31, 40, 42, 43, 44]

A solution to reduce corrosion problems for wastes with high content of metals and chlorine, as for example SLF, can be to co-combust the waste with other fuels [41].

Energy efficiency improvements of the waste combustion process can for example be done by flue gas condensation, extracting heat from flue gases from combustion of wastes with high water contents, or integrating the process with other energy conversion processes as for example a gas turbine in a hybrid dual-fuel cycle, where the steam produced in the boiler can be superheated with the flue gases from the gas turbine. [31, 47]

3.2 PYROLYSIS

Pyrolysis can be described as the direct thermal decomposition, or degassing, of an organic matrix in the absence of oxygen producing an array of solid, liquid and gas products. The process is a complex set of reactions involving the formation of radicals. Pyrolysis is used for commercial production of a wide range of fuels, solvents, chemicals and other products from biomass feedstock.

While the combustion process is exothermic, pyrolysis is an endothermic process. The composition, heating value and yield of the pyrolysis products are dependent on compositions of the feedstock, temperature, residence time and heating rate. For a high yield of gas products high temperature, low heating rate and long gas residence time should be applied. Slow pyrolysis has been used for the production of charcoal and short residence time pyrolysis of biomass has been used for production of high yield liquid products. [31, 48, 49; 50, 51, 52]

The temperature range for pyrolysis is from 250 °C to 800 °C depending on the feedstock used. The pyrolysis process can be combined with combustion of the produced gas and of the solid carbon rich fraction and oil. The advantages of this process compared to direct combustion are reduced flue-gas amounts and with that the requirements of flue-gas cleaning. The same techniques as used for combustion can also be used for pyrolysis. There are examples of pyrolysis plants using MSW as feedstock in Japan, Austria, Germany, Italy, Korea and Switzerland where the first plants were set in operation during the end of the 1980´s. Other types of wastes investigated for pyrolysis are RDF, synthetic waste, used tires, auto shredder residue, waste cooking oil, waste lubricating oil, plastic waste, sludge, rapeseed cake, crop residues, and forestry residues. The development activities include catalytic pyrolysis, process conditions (temperature, residence time and atmosphere) and product quality and use. The mentioned energy products of interest are vehicle fuel, heat and/or power (from pyrolysis oil or gas), and solid fuel (from char). Other possible products mentioned are soil amendment (providing carbon and nutrients), activated coal and adsorbent (from char). [31, 39, 48, 50, 53, 54, 55, 56, 57, 58, 59]

3.3 GASIFICATION

Gasification is thermo-chemical conversion of a solid material to a gas at oxygen- carbon ratios lower than 1. The main components of the gas are CO_2, CO, CH_4, H_2, H_2O and small amounts of C_2-hydrocarbons. [31, 60, 61]

The design of the gasifier can be divided into three main types: fixed bed, fluidised bed, and entrained suspension bed gasifiers (also called entrained flow gasifiers). The main advantage with fixed bed gasifiers is a simple design but the gas they produce is of low calorific value and the tar content is high. In the fluidised bed gasifier a uniform temperature distribution in the gasification zone is possible. A difficulty can be slagging of the bed material due to the ash content of the fuel. The entrained suspension bed gasifiers are operated at high temperatures and give a gas with low char and methane content but the feedstock needs to be finely divided. [31, 62; 63; 64]

All three techniques have been reported for different types of waste, for example gasification of MSW, RDF, industrial waste, salmon waste, hazelnut shells and wood waste in fixed bed gasifiers [65, 66, 67,:68], gasification of MSW, RDF, plastic waste, auto shredded residues, forest residues, sawdust, straw, and olive oil residues in fluidised bed gasifiers [62, 64, 65, 69, 70] and gasification of liquid, pasty or granulated rice husk, sawdust, and hazardous wastes in entrained suspension bed gasifiers [31, 71].

Gasification processes for the residue black liquor from pulp production has been studied both experimentally and theoretically since the 1990´s. An important part of this process, besides producing gas, is recovering of cooking chemicals for the pulp process. The processes can be divided into two groups, one that operates at low temperatures, 600–850 °C, below the melting point of the inorganic material in the waste, and one operating at high temperatures 900–1000 °C. In the first group fluidised bed based processes can be found and in the second processes based on entrained flow gasification. [72, 73]

Another technique for gasification of waste is using an electrically generated plasma arc torch, which gives fast reaction times and large throughputs due to high-energy density and temperatures, the possibility to treat solids, liquids and gases, and that no fuel is combusted. Thermal plasma gasification has for example been reported for hazardous wastes, waste from steelmaking, chlorine containing wastes, pelletized RDF from carpet and textile waste and MSW [74, 75, 76, 77].

Just as for pyrolysis of waste, gasification of waste can be combined with combustion of the produced gas for heat and/or power production, which for example is the case for the plant being built in Lahti, Finland where 250000 tons of waste from businesses and households will be used to generate 90 MW of heat and 50 MW of power per year. The gas can also be processed to vehicle fuels such as DME, SNG and Fischer-Tropsch (FT) fuel [31, 60, 61, 65, 78, 79]

Important development areas that has been reported for gasification of biomass, including also waste, are gas cleaning, tar reduction, process operation conditions and increasing system energy efficiency [65, 80, 81].

4. WASTE TO ENERGY SYSTEMS

To choose a suitable waste to energy system different possible conversion paths need to be evaluated. Several studies comparing alternative processes for waste to energy utilization exist and in Table 1 some of the studies are listed. The comparisons have been made based on different analysis methods, including life cycle analysis (LCA), calculation of CO_2 emissions, and calculation of energy efficiency and economic evaluations. Finnveden et al [82] and Pires et al [83] present reviews of different methods for assessment of waste management systems and system analysis techniques applied on systems for municipal solid waste handling, respectively. The studies presented in Table 1 also concerns different countries or regions. The study by Münster and Lund [91] shows that the alternative including biogas production is more favourable compared to the systems with combustion of waste. This is opposite to what Gómez et al [90] and Fruergaard and Astrup [87] found in their studies. However, Münster and Lund have done a more complex energy system analysis including different possible energy products and also CO_2 emission reduction. Gómez et al have studied a different part of Europe, Spain, where heat demand is of minor importance and therefore have not been included while Münster and Lund have studied Denmark where heat demand and CHP are important factors in the energy system. However, the studies by Münster and Lund, Fruergaard and Astrup and Kirkeby et al [86] all consider Denmark and still the results are very different.

Finnveden et al [84] point out the difficulty to compare combustion and anaerobic digestion of waste due to the fact they have different advantages and disadvantages and the environmental impact of digestion is dependent on many factors that vary with the studied situation. They conclude that anaerobic digestion is a good alternative for waste fractions such as manure, waste from food industry and some fractions of household waste.

5. RESULTS AND DISCUSSION

Table 2 summarises the characteristics of and products from the different waste to energy conversion processes.

The products from anaerobic digestion, fermentation, gasification and pyrolysis include fuels for use in transportation or for power and/or heat production by combustion in an oven, gas engine or gas turbine. Ethanol from fermentation is usually used as fuel in transportation and the gas from anaerobic digestion can, after upgrading, be used for this purpose. The gas from gasification can also

Table 1 Studies comparing waste to energy systems. The best alternative is marked in bold.

Systems compared	Country/ Region/ Area	Comparison method	Reference
MSW -landfill gas recovery -**sorting, up-graded biogas, electricity from combustion** -electricity from combustion	Italy Roma	LCA	[85]
MSW[1] -sorting, electricity and heat from biogas and combustion -**electricity and heat from combustion**	Denmark Aarhus	LCA	[86]
MSW-RDF -combustion without energy recovery -**electricity and heat from combustion** **-electricity and heat from co-combustion with coal** *MSW-organic* -combustion without energy recovery -**electricity and heat from combustion** -up-grade biogas -electricity and heat from biogas	Denmark	LCA	[87]
All collected waste Different numbers, locations and types of waste management plants. **Inclusion of combustion slightly better than gasification.**	England	LCA	[88]
Agriculture residues for self-sufficiency system -ethanol, electricity and heat from combustion using straw -**up-graded biogas, electricity and heat from biogas using ley**	Sweden	LCA	[89]
***MSW**, Sewage sludge or Manure* -**electricity from combustion** -electricity from landfill gas -electricity from biogas	Spain	Economic	[90]
MSW -electricity from combustion -**fuel gas, electricity and heat from gasification of MSW** *RDF* -electricity from combustion -electricity from co-combustion with coal *OHW and manure* -**electricity and heat from biogas** **-up-graded biogas (OHW+manure)** *Animal fat* -biodiesel *Straw, grass and paper waste* -ethanol, electricity and heat from biogas of fermentation residues	Denmark	Energy efficiency CO_2emissions Economic	[91]
All wastes **electricity** and fuel from biogas, **gasification**, pyrolysis, and different options for combustion	Netherland	Primary energy saving	[92],93]
MSW - electricity and heat from combustion - **electricity and heat from gasification** - **up-graded biogas** - electricity and heat from biogas	Ireland	Economic, market	[94]

[1]Small differences between the two cases

Table 2 Characteristics and products for different waste conversion processes [8, 19, 24, 25, 38, 40, 42, 43, 44, 50, 53, 55, 56, 57, 58, 59, 61, 69, 74, 95, 96, 97]

Conversion process	Conversion characteristics	Main products	By-products
Anaerobic digestion	35-55 °C (for hygienisation 70 °C), anaerobic, reactor size 10-10 000 m^3	Gas (main components CH_4 and CO_2)	Fertiliser
Fermentation	20 to >200 °C (dependent on process steps, configurations)	Ethanol (or butanol)	Solids of lignin (pellets, fuel) Stillage (biogas, animal feed)
Combustion	Steam data 40-110bar/400-540 °C, thermal capacity 5-120 MW (smallest only for heat production)	Heat, Electricity	Ash
Pyrolysis	250-800 °C, absence of oxygen	Char, Oil or Tar, Gas (CO, CH_4, hydro-carbons, H_2, CO_2 (dependent on feedstock +process conditions))	Char (soil amendment, activated coal, sorbent)
Gasification	350-1800 °C, air, oxygen, steam or near or supercritical water medium, 1-30 bar Thermal plasma up to 20 000 °C	Gas (CO, CH_4, H_2, CO_2, H_2O, N_2 (dependent on feedstock + process conditions))	Ash, Vitrified slag from thermal plasma gasification (roadbed and concrete aggregates)

be further reformed for production of other types of transportation fuels. It has been considered to be good to combine combustion and pyrolysis to be able to reach a more efficient emission control. However, during recent years an increased interest can be found for production of fuels and other products from pyrolysis of waste. For anaerobic digestion feedstock pre-treatment, avoidance of inhibition, mixing, residues utilization, and monitoring and control are identified development areas. Also the development of dry digestion technology for the treatment of municipal waste is a more recent trend of interest.

Fermentation for ethanol production is a mature and well-proven technology for sugary waste but the utilization of lignocellulosic waste in this process is still on the research stage. Here the development areas include increasing the yield, improving process design and energy efficiency, where a good example includes the possibilities for integration with other processes. In addition, another development area is the production of butanol from waste.

The possible improvements of the combustion process using waste as fuel includes plant efficiency, improved emission control and ash handling. Concerning pyrolysis and gasification these are conversion processes that have been used for waste treatment but the technology is still in the development stage. Identified development areas are process operation conditions, gas and by-product quality, gas cleaning and plant efficiency.

So far most interest has been for studies concerning the use of MSW, sludge from waste water treatment and agriculture waste as an energy source. In later years also more studies concerning industrial and commercial waste can be found. Examples of such studies are the once presented by Lee and Padney [98] and Lupa et al [99].

6. CONCLUSIONS

Combustion and anaerobic digestion are mature and well-proven technologies for waste treatment but improvements are needed to make the processes more efficient as energy conversion processes.

Pre-treatment of the waste is a development area of common interest for several conversion processes. For the thermal conversion processes also gas cleaning/emission control and ash handling/by-product quality and use are development areas of interest.

Several studies comparing different waste to energy systems can be found. However, no clear conclusions about what waste to energy technology that is most favourable can be drawn. This is due to that waste to energy systems are complex with many possible combinations and system boarders that are also dependent on local conditions.

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REFERENCE

[1] REMOWE project homepage, www.remowe.eu
[2] Park C, Lee C, Kim S, Chen Y, Chase HA. Upgrading of anaerobic digestion by incorporating two different hydrolysis processes. J. Biosci. Bioeng. 100, 2005;164–167
[3] Khalid A, Arshad M, Anjum M, Tariq M and Dawson L. The anaerobic digestion of solid organic waste, Waste Manage 2011;31:1737–1744
[4] Yebo L, Park SY, Zhu J. Solid-state anaerobic digestion for methane production from organic waste Renewable and Sust Energ Rev 2011;15: 821–826
[5] den Boer E, den Boer J, Szpadt R. Solid waste management, Łódź: PRINTPAP, 2011

[6] Karagiannidis A, Perkoulidis G. A multi-criteria ranking of different technologies for the anaerobic digestion for energy recovery of the organic fraction of municipal solid wastes, Bioresource Technol 2009; 100: 2355–2360
[7] Behrendt A, Vasilic D, Ahrens T. Strategies concerning digestion residues utilization, REMOWE ,Report no: O.3.2.3.2, 2011
[8] De Baere L, Mattheeuws B, Velghe F. State of the art of anaerobic digestion in Europe, 12th World Congress on Anaerobic Digestion, October 31 –November 4, 2010 Guadalajara, Mexico.
[9] Kayhanian M, Tchobanoglous G, Brown RC. Handbook of Energy Conservation and Renewable Energy, Taylor & Francis Group, 2007
[10] Greuel M. MBA ZAK Kaiserslautern – erste Betriebserfahrungen mit der mechanischen Vorbehandlung nach dem VM-Press-Verfahren Witzenhausen-Institut für Abfall, Umwelt und Energie GmbH Quelle: 19 Kasseler Abfallforum-2007 (April 2007)
[11] Velis CA, Longhurst PJ, Drew GH, Smith R, Pollard SJT. Biodrying for mechanical–biological treatment of wastes: A review, Bioresource Technol 2009;100:2747–2761
[12] Rapport J, Zhang R, Jenkins BM, Williams RB. Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste, California Integrated Waste Management Board, California Environmental Protection Agency, 2008
[13] Li Y, Park SY, Jiying Z. Solid-state anaerobic digestion for methane production from organic waste, Renew Sust Energ Rev 2011;15:821–826
[14] Weiland P. Biogas production: current state and perspectives, Appl Microbiol Biot 2010; 85: 849–860.
[15] Deublein D, Steinhauser A. Biogas from waste and renewable resources - an introduction, Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA, 2008
[16] Genutis A, Gulbinas A, Navickas K, Šateikis I Atsinaujinantys energijos šaltiniai/ Mokomoji knyga, Kaunas, Technologija, 2003
[17] Chen Y, Cheng JJ, Creamer KS. Inhibition of anaerobic digestion process: A review, Bioresource Technol 2008;99:4044-4064
[18] Alatriste-Mondragón F, Samar P, Cox HHJ, Ahring B, Iranpour R. Anaerobic codigestion of municipal, farm, and industrial organic wastes: A survey of recent literature, Water Environ Res 2006;78,6:607-636
[19] Odlare M, Arthurson V, Pell M, Svensson K, Nehrenheim E, Abubaker J. Land application of organic waste-Effects on the soil ecosystem, Appl Energ 2011;88,6:2210-2218
[20] Tambone F, Scaglia B, D’Imporzano G, Schievano A, Orzi V, Salati S, Adani F. Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost, Chemosphere 2010;81:577–58
[21] Prasad S, Singh A, Joshi HC, Ethanol as an alternative fuel from agricultural, industrial and urban residues. Resoure Conserv Recy 2007;50:1–39
[22] Cardona CA, Sanchez OJ. Fuel ethanol production: Process design trends and integration opportunities, Bioresource Technol 2007;98:2415-2457
[23] Marina Enguídanos M, Soria A, Kavalov B, Jensen P, Techno-economic analysis of Bio-alcohol production in the EU: a short summary for decision-makers. Report EUR 20280 EN, 2002
[24] Eriksson G, Kjellström B. Assessment of combined heat and power (CHP) integrated with wood-based ethanol production, Appl Energ 2010;87:3632-3641
[25] Song H, Dotzauer E, Thorin E, Yan J. Annual performance analysis and comparison of pellet production integrated with an existing combined heat and power plant. Bioresource Technol 2011;102:6317-6325
[26] Shapovalov OI, Ashkinazib LA. Biobutanol: Biofuel of Second Generation, Russ J Appl Chem 2008;81,12:2232–2236
[27] Quresh N, Saha BC, Hector RE, Dien B, Hughes S, Liu S, Iten L, Bowman MJ, Sarath G, Cotta MA. Production of butanol (a biofuel) from agricultural residues: Part II – Use of corn stover and switchgrass hydrolysates, Biomass Bioenerg, 2010;34:566-571
[28] Wang L, Chen H. Increased fermentability of enzymatically hydrolyzed steam-exploded corn stover for butanol production by removal of fermentation inhibitors, Process Biochem 2011;46,2:604-607
[29] Napoli F, Olivieri G, Russo ME, Marzocchella A, Salatino P. Butanol production by Clostridium acetobutylicum in a continuous packed bed reactor, J Ind Microbiol Biot 2010;37:603–608
[30] Kumar M, Gayen K. Developments in biobutanol production: New insights**,** Appl Energ 2011;88,6:1999-2012
[31] European Commission. Integrated Pollution Prevention and Control, Reference Document on Best Available Techniques for the Waste Incineration, BREF (08.2006), 2006
[32] Gendebien A, Leavens A, Blackmore K, Godley A, Lewin K, Whiting KJ, Davis R, Giegrich J, Fehrenbach H, Gromke U, del Bufalo N, Hogg D. Refuse derived fuel, current practice and perspectives, b4-3040/2000/306517/ mar/e3, Final Report, Commission of EC Directorate General Environment, Swindon, WRc, 2003
[33] Cherubini F, Bargigli S, Ulgiati S. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration, Energy 2009;34: 2116–2123.
[34] McDougall FR, White PR, Franke M, Hindle P. Integrated Solid Waste Management: a Life Cycle Inventory, John Wiley & Sons Ltd; 2008
[35] Rada EC, Ragazzi M, Panaitescu V. MSW bio-drying: an alternative way for energy recovery optimization and landfilling minimization, U.P.B. Science Bulletin, Series D 2009;71,4:113-120

[36] Nicosia S, Lanza PA, Spataro G, Casarin F. Drawing the materials balance for an MBT cycle form routine process measures in MBT plant located in Venice, International Symposium MBT, 22–24May, 2007, Hanover, Germany.
[37] Bartha BK. Entwicklung einer steuerungsstrategie für die biologische abfallbehandlung im dynamischen reaktor, (Development of a Control Strategy for the Treatment of Biological Waste in a Dynamic Reactor), PhD Thesis, Technische Universität Dresden, 2008
[38] Adani F, Baido D, Calcaterra E, Genevini, P. The influence of biomass temperature on biostabilization–biodrying of municipal solid waste, Bioresource Technol 2002;83:173–179
[39] Singhabhandhu A, Tezuka T. Prospective framework for collection and exploitation of waste cooking oil as feedstock for energy conversion, Energy 2010;35:1839–1847
[40] Hinge J. Elaboration of a Platform for Increasing Straw Combustion in Sweden, based on Danish Experiences, Värmeforsk project no. E06-641, 2009
[41] Gyllenhammar M, Victorén A, Niemi J, Johansson A. Energiåtervinning av brännbar fraktion från fragmentering av metallhaltigt avfall (Energy recovery of combustible fraction from fragmentation of metal scrap), Project No. WR-08, Waste Refinery, 2009 [in Swedish]
[42] Johansson A, Niklasson F, Johnsson A., Fredäng J, Wettergren H. Drift och underhåll av avfallsförbränningsanläggningar – en jämförelse av två tekniker och strategier, (Operation and maintenance of Waste Combustion plant – development of a method for economical comparison of different techniques and strategies), WR-09, Waste Refinery, 2009 [in Swedish]
[43] Buchhorn B. Optimisation And Extension Of The WTE Plant Dordrecht, Netherlands, ISWA World Congress, 15-18 –November, 2010, Hamburg, Germany
[44] Weiler C, Grotefeld V.. Licensation, Design and Erection of the RDF-CHP Plant in Bernburg and Enhancement of MWIP, ISWA World Congress, 15-18 November, 2010, Hamburg., Germany
[45] Fendel A, Firege H. Competition of Different Methods for Recovering Energy from Waste Leading to Overcapacities, ISWA World Congress, 15-18 November, 2010, Hamburg, Germany
[46] Chunjiang Y, Jianguang Q, Hu N, Mengxiang F, Zhongyang L. Experimental research on agglomeration in straw-fired fluidized beds, Appl Energy 2011;88 :4534–4543
[47] Udomsri, S. Combined electricity production and thermally driven cooling from municipal solid waste, Doctoral Thesis in Energy Technology, TRITA KRV Report 11/02, Royal Institute of Technology, Stockholm;2011
[48] Cheremisinoff NP, Rezaiyan J. Gasification Technologies - A Primer for Engineers and Scientists, CRC Press; 2005
[49] Yaman S. Pyrolysis of biomass to produce fuels and chemical feedstocks, Energ Convers Manage 2003;45:651–671.
[50] Karayildirim T, Yanik J, Yuksel M, Bockhorn H. Characterisation of products from pyrolysis of waste sludges, Fuel 2005;85:1498–1508.
[51] Bridgwater AV, Peacocke GVC. Fast pyrolysis processes for biomass, Renew Sust Energ Rev 2000; 4:1-73
[52] Di Blasi C. Modeling chemical and physical processes of wood and biomass pyrolysis Prog Energ Combust 2007;34:47–90
[53] Malkow T. Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal, Waste Manage 2004:24:53–79
[54]Panda AK, Singh RK, Mishra DK. Thermolysis of waste plastics to liquid fuel A suitable method for plastic waste management and manufacture of value added products—A world prospective, Renew Sust Energ Rev 2010;14:233–248
[55] Smets K, Adriaensens P, Reggers G, Schreurs S, Carleer R, Yperman J. Flash pyrolysis of rapeseed cake: Influence of temperature on the yield and the characteristics of the pyrolysis liquid, J Anal Appl Pyrol 2011;90: 118 – 125
[56] Puy N, Murillo R, Navarro MV, López JM, Rieradevall J, Fowler G, Aranguren I, García T, Bartrolí J, Mastral AM Valorisation of forestry waste by pyrolysis in an auger reactor, Waste Manage 2011;31,6:1339-1349
[57] Önal EP, Uzun BB, Pütün AE. Steam pyrolysis of an industrial waste for bio-oil production, Fuel Process Technol 2011;92: 879–885
[58] Brown TR, Wright MM, Brown RC. Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis, Biofpr 2011; 5:54–68
[59] Hossain MK, Strezov V, Chan KY, Ziolkowski A, Nelson, PF. Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar, J Environ Manage 2011;92:223-228
[60]Ptasinski KJ. Thermodynamic Efficiency of Biomass Gasification and Biofuels Conversion, Biofpr 2008;2:239-253
[61] Valleskog M, Marbe Å, Colmsjö L. System- och marknadsstudie för biometan (SNG) från biobränslen (System and market study for bio methane from bio fuels), Report SGC 185; 2008 [in Swedish]
[62] Li XT, Grace JR, Lim CJ, Watkinson AP, Chen HP, Kim JR. Biomass gasification in a circulating fluidized bed, Biomass Bioenerg 2004;26: 171 – 193
[63] McKendry P. Energy Production from Biomass (Part 3): Gasification Technologies, Bioresource Technol 2002;83:55-63.
[64] Alimuddin Z, Alauddin BZ, Lahijani P, Mohammadi M, Mohamed AR.Gasification of Lignocellulosic Biomass in Fluidized Beds for Renewable Energy Development: A Review, Renew Sust Energ Rev 2010;14:2852-2862.
[65] Arena U. Process and technological aspects of municipal solid waste gasification. A review. Waste Management 2011, doi:10.1016/j.wasman.2011.09.025
[66] Rowland S, Bower CK, Patil KN, Dewitt CAM. Updraft Gasification of Salmon Processing Waste, J Food Sci 2009;74:E426-E431

[67] Dogru M, Howarth CR, Aka G, Keskinler B, Malik AA. Gasification of Hazelnut Shells in a Downdraft Gasifier, Energy 2002;27**:** 415-427
[68] Sheth PN, Babu BV. Experimental Studies on Producer Gas Generation from Wood Waste in a Downdraft Biomass Gasifier, Bioresource Technol 2009;100**:** 3127-3133
[69] Palonen J, Anttikoski T, Eriksson T. The Foster Wheeler gasification technology for biofuels: refuse-derived fuel (RDF) power generation, Power-Gen Europe, 30 May-1 June,2006, Kölnmesse, Cologne, Germany
[70] Göteborg Energi, Gothenburg Biomass Gasification Project, GoBiGas, http://www.goteborgenergi.se, last visited 20120123
[71] Zhou J, Chen Q, Zhao H, Cao X, Mei Q, Luo Z, Cen K. Biomass–oxygen gasification in a high-temperature entrained-flow gasifier, Biotechnol Adv 2009;27:606–611
[72] Dahlquist E, Jones A. Presentation of a dry black liquor gasification process with direct caustization, Tappi J 2005;15,19:15-19
[73] Naqvi M, Yan J, Dahlquist E. Black liquor gasification integrated in pulp and paper mills: A critical review, Bioresource Technol 2010;101:8001–8015
[74] Gomez E, Amutha Rania D, Cheeseman CR, Deegan,D, Wise M, Boccaccini AR. Thermal plasma technology for the treatment of wastes: A critical review, J Hazard Mater 2009;161:614–626
[75] Lemmens B, Elslander H, Vanderreydt I, Peys K, Diels L. Assessment of plasma gasification of high caloric waste streams, Waste Manage 2007;27:1562–1569
[76] Willis KP, Osada S, Willerton KL. Plasma Gasification: Lessons Learned at Eco-Valley WTE Facility, Paper no. NAWTEC18-3515, 18th Annual North American Waste-to-Energy Conference, May 11–13, 2010, Orlando, Florida, USA
[77] Clark BJ, Rogoff MJ. Economic feasibility of a plasma arc gasification plant, City of Marion, Iowa, Paper no. NAWTEC18-3502, 18th Annual North American Waste-to-Energy Conference, May 11–13, 2010, Orlando, Florida, USA
[78] European Investment Bank. Energy-from-waste plant keeps Finnish city warm, http://www.eib.org, last visited 20110302
[79] Chemrec, www.chemrec.se, last visited 20120123
[80] Kirkels AF, Verbong, GPJ. Biomass gasification: Still promising? A 30-year global overview, Renew Sust Energ Rev 2011; 15: 471-481.
[81] Kumar A, Jones DD, Hanna MA. Thermochemical Biomass Gasification: A Review of the Current Status of the Technology, Energies 2009;2:556-581
[82] Finnveden G, Björklund A, Moberg Å, Ekvall T, Moberg Å. Environmental and economic assessment methods for waste management decision-support: possibilities and limitations, Waste Manage Res 2007;25:263–269
[83] Pires A, Martinho G, Chang NB. Solid waste management in European countries: A review of systems analysis techniques, J Environ Manage 2011;92:1033-1050
[84] Finnveden G, Björklund A, Carlsson Reich M. Flexible and robust strategies for waste management in Sweden, Waste Manage 2007;27:1-8
[85] Cherubini F, Bargigli S, Ulgiati S. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration, Energy 2009;34:2116–2123
[86] Kirkeby JT, Birgisdottir H., Lund Hansen T, Christensen TH, Singh Bhander G, Hauschild M. Evaluation of environmental impacts from municipal solid waste management in the municipality of Aarhus, Denmark (EASEWASTE), Waste Manage Res 2006;24:16–26
[87] Fruergaard T, Astrup T. Optimal utilization of waste-to-energy in an LCA perspective, Waste Manage 2011;31:572–582
[88] Tunesi S. LCA of local strategies for energy recovery from waste in England, applied to a large municipal flow, Waste Manage 2011;31:561–571
[89] Kimming M, Sundberg C, Nordberg Å, Baky A, Bernesson S, Norén O, Hansson PA. Life cycle assessment of energy self-sufficiency systems based on agricultural residues for organic arable farms, Bioresource Technol 2011; 102: 1425–1432
[90] Gómez A, Zubizarreta J, Rodrigues M, Dopazo C, Fueyo N. (2010). Potential and cost of electricity generation from human and animal waste in Spain, Renew Energ 2010;35: 498–505
[91] Münster M, Lund H. Comparing Waste-to-Energy technologies by applying energy system analysis, Waste Manage 2010;30:1251–1263
[92] Dornburg V, Faaij APC, Meuleman B. Optimising waste treatment systems Part A: Methodology and technological data for optimising energy production and economic performance, Resoure Conserv Recy 2006;49:68–88
[93] Dornburg V, Faaij APC. Optimising waste treatment systems Part B: Analyses and scenarios for The Netherlands, Resoure Conserv Recy 2006;48:227–248
[94] Murphy JD, McKeogh E. Technical, economic and environmental analysis of energy production from municipal solid waste, Renew Energ 2004;29:1043–1057
[95] SEKAB, www.sekab.com, last visited 20120203
[96] Börjesson P. Good or bad bioethanol from a greenhouse gas perspective – What determines this?, Appl Energ 2009;86:589-594
[97] Matsumura Y, Minowa T, Potic B, Kersten SRA., Prins W, Van Swaaij WPM., Van De Beld B, Elliott DC, Neuenschwander GG, Kruse A, Antal MJ. Biomass Gasification in near- and Super-Critical Water: Status and Prospects, Biomass Bioenerg 2005;29**:**269-292
[98] Lee J, Pandey BD. Bio-processing of solid wastes and secondary resources for metal extraction – A review, Waste Management 2012;32:3–18
[99] Lupa CJ, Lois J, Ricketts LJ, Sweetman A, Herbert BMJ. The use of commercial and industrial waste in energy recovery systems – A UK preliminary study, Waste Manage 2011;31:1759–176

