STATE OF THE ART IN THE WASTE TO ENERGY AREA
Technology and Systems

Eva Thorin, Lilia Daianova, Johan Lindmark, Eva Nordlander, Han Song, Ari Jääskeläinen, Laura Malo, Emilia den Boer, Jan den Boer, Ryszard Szpadt, Olga Belous, Taivo Kaus, Maarja Käger
May 2011

Disclaimer
This publication has been produced with the assistance of the European Union (http://europa.eu). The content of this publication is the sole responsibility of authors and can in no way be taken to reflect the views of the European Union.
# Index

**SUMMARY** .................................................................................................................. 4  

**1. INTRODUCTION** ...................................................................................................... 6  
  1.1 The REMOWE project ............................................................................................... 6  
  1.2 Waste utilisation pathways ....................................................................................... 7  

**2. BIOLOGICAL PROCESSES** .................................................................................... 9  
  2.1 Biogas from waste .................................................................................................... 9  
    2.1.1 The biological process ....................................................................................... 10  
    2.1.2 Pre-treatment .................................................................................................... 11  
    2.1.3 Process design and operation ........................................................................... 11  
    2.1.4 Process modelling and control .......................................................................... 17  
    2.1.5 Gas upgrading ................................................................................................... 19  
    2.1.6 The use of residuals ........................................................................................... 19  
  2.2 Ethanol from waste .................................................................................................. 20  
    2.2.1 Waste feedstock for ethanol production ............................................................ 20  
    2.2.2 Pre-treatment .................................................................................................... 21  
    2.2.3 Process design and operation ........................................................................... 22  
    2.2.4 The use of residuals ........................................................................................... 24  
    2.2.5 Other aspects .................................................................................................... 27  
    2.2.6 Utilization of bio-ethanol ................................................................................... 27  
  2.3 Butanol from waste .................................................................................................. 28  

**3. THERMAL PROCESSES** ......................................................................................... 29  
  3.1 RDF - Refuse Derived Fuel ....................................................................................... 29  
    3.1.1 Preparation of RDF ........................................................................................... 30  
    3.1.2 Quality criteria for RDF ................................................................................... 32  
    3.1.3 RDF use ............................................................................................................ 33  
  3.2 Combustion ............................................................................................................. 34  
    3.2.1 Process design and operation ........................................................................... 34  
    3.2.2 Other aspects .................................................................................................... 39  
  3.3 Pyrolysis of waste .................................................................................................... 40  
    3.3.1 Process design and operation ........................................................................... 41  
  3.4 Gasification of waste ............................................................................................... 42  
    3.4.1 Process design and operation ........................................................................... 42  
    3.4.2 Process modelling ............................................................................................. 49  
    3.4.3 Gas cleaning ...................................................................................................... 51
3.4.1 Uses of the gas ........................................................................................................52
3.4.2 Other aspects ........................................................................................................53

4. BIOREFINERY AND INTEGRATED SYSTEMS .......................................................... 54

5. COMPARISONS OF DIFFERENT CONVERSION PROCESSES ............................... 56

6. CONCLUSIONS .......................................................................................................... 59

7. REFERENCES .............................................................................................................. 62
Summary

The aim of this report is to describe the state-of-the-art concerning systems and technologies for utilising waste for energy purposes. The work presented is part of the project REMOWE - Regional Mobilising of Sustainable Waste-to-Energy Production part-financed by the European Union (European Regional Development Fund) as one of the projects within the Baltic Sea Region Programme.

Waste is a heterogeneous energy source and different types of waste can be converted to different energy products in different conversion processes. The conversion processes can be divided into biological processes, that use microorganisms to convert a feedstock to energy rich products, and thermal processes where the feedstock is converted to heat, electricity and/or gas at high temperatures.

In anaerobic digestion biogas, mainly consisting of methane, is produced. A large variety of wastes are digested such as sludge from waste water treatment, grease trap sludge, manure, biowaste, municipal solid waste, food wastes, refuse derived fuel and industrial waste water. Important parameters in the design and operation are the temperature, the moisture content in the reactor, the number of steps and phases of the process, the mixing in the reactor, and the type and number of feedstock. Anaerobic digestion is today a well-proven technology for waste treatment but development is needed concerning feedstock pre-treatment, avoidance of inhibition, mixing, and monitoring and control.

Another biological conversion process that can use waste as feedstock is fermentation to ethanol or butanol. Wastes of interest for fermentation are industrial waste waters and lignocellulosic wastes such as straw and wood wastes. Fermentation of sugary wastes to ethanol is a mature and well-proven technology but fermentation of lignocellulosic waste and fermentation to butanol is still at the research stage. The development areas include increasing the yield, process design, and increasing the energy efficiency including process integration.

Combustion is a mature and well-proven technology that has been used for waste treatment of many types of wastes such as municipal solid waste, refuse derived fuels, agriculture wastes, wood wastes, packaging waste, industrial waste, hazardous waste, and sludge from waste water treatment. Still, there are needs for development making the process more efficient as an energy conversion process, including improved emission control, plant efficiency and ash handling.

Pyrolysis and gasification have been used for waste treatment but the technology is still in the development stage. For pyrolysis the influence of process parameters on the gas and by-product quality and plant efficiency are of interest for further development. While, for gasification gas cleaning, tar reduction, process operation conditions and increasing plant energy efficiency are development areas. Types of wastes that are used in both pyrolysis and gasification processes are municipal wastes, refuse derived fuels and sludge from waste water treatment. There are also examples of other more specific wastes such as synthetic waste and...
used tires that have been used for pyrolysis and packaging waste and hazardous wastes that have been used for gasification.

Anaerobic digestion, fermentation, gasification and pyrolysis give products that can be used as fuel in further energy conversion. Ethanol from fermentation is usually used as a fuel in transportation. The gas from anaerobic digestion can also, after upgrading, be used as fuel for transportation but it can also be used directly in an oven, gas engine or gas turbine for heat and power production. The gas from gasification and pyrolysis can be used in a similar way as the gas from digestion but it can also be further reformed for production of other types of transportation fuels.

Process modelling can be a usable tool for understanding complex energy conversion processes and for optimisation of operation conditions. Process modelling also offers the possibility to control the process and predict its outcome. For biogas production in anaerobic digestion and for thermal gasification there exist different modelling approaches.

Different waste to energy systems have been compared in literature. However, no clear conclusions about what waste to energy technology that is most favourable can be drawn from the studies found. The results of the comparisons are dependent on the conditions chosen for the study as for example where the system is located and what combinations that are included in the options compared.
1. Introduction

The aim of this report is to describe the state-of-the-art concerning systems and technologies for utilising waste for energy purposes. The authors of the report come from the following organisations:

Eva Thorin, Lilia Daianova, Johan Lindmark, Eva Nordlander, Han Song
Mälardalen University, School of Sustainable Development of Society and Technology, P.O. Box 883, SE-721 23 Västerås, Sweden

Ari Jääskeläinen
The Municipal Federation of Savonia University of Applied Sciences, P.O. Box 6, FI-70201, Kuopio, Finland

Laura Malo
Centre for Economic Development, Transport and the Environment for North Savo (CNS), North Savo Ympäristö ja luonnonvarat, PL 1049 Sepänkatu 2B, FI-70101 Kuopio, Finland

Emilia den Boer, Jan den Boer, Ryszard Szpadt
Wrocław University of Technology, Institute of Environment Protection, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

Olga Belous
Klaipeda University, H. Manto g. 84, LT-92294 Klaipeda, Lithuania

Taivo Kaus, Maarja Käger
Estonian Regional and Local Development Agency, Ahtri 8, EE-10151 Tallinn, Estonia

1.1 The REMOWE project

The work presented is a part of the project REMOWE - Regional Mobilising of Sustainable Waste-to-Energy Production part-financed by the European Union (European Regional Development Fund) as one of the projects within the Baltic Sea Region Programme.

The overall objective of the REMOWE project is, on regional levels, to contribute to a decreased negative effect on the environment by reduction of carbon dioxide emissions by creating a balance between energy consumption and sustainable use of renewable energy sources. Reduction of carbon dioxide emissions and use of renewable energy sources are broad areas and this project will focus on energy resources from waste and actions to facilitate implementation of energy efficient technology in the Baltic Sea region within the waste-to-energy area. The focus is to utilize waste from cities, farming and industry for energy purposes in an efficient way. The problem addressed by the project concerns how to facilitate the implementation of sustainable systems for waste-to-energy in the Baltic Sea region and specifically, as a first step, in the project partner regions.

The project partnership consists of Mälardalen University, with the School of Sustainable Development of Society and Technology coordinating the project, and The County
First, partner regions will do parallel investigations on the current status, the bottle-necks and the needs for development and innovation. Partnering regions will then jointly study possible future status and paths to get there, taking into consideration the basis of each region. Possibilities to build a regional model of the waste-to-energy utilization will be piloted in the project, with North Savo in Finland as the target region.

The project activities are divided into 5 work packages (WP). WP 1 concerns project management and WP 2 contains the project communication and information activities. In WP 3 the current status of the partner regions is explored, in WP 4 the possible future status is investigated and in WP 5 modelling of a sustainable regional waste-to-energy system will be studied.

The work presented in this report is part of the work in WP 4. The aim of this WP is to find and improve possibilities within the whole partnership for development in the waste-to-energy area. The starting point will be the current status in the partner regions, investigated in WP3. To be able to find possible future systems it is also important to include knowledge about the state of the art for waste- to-energy production systems and technology and to develop it further for the conditions in the partner regions. Another aim of this WP is to promote new and innovative solutions and strategies for development in the waste-to-energy area. For this it is important to include views and wishes from versatile players in the field, including both international experts in the area and regional stakeholders such as SME:s.

This state of the art report presents knowledge in the waste-to-energy area reported in international journal publications, EU-project reports, national reports and websites of companies and organisations. The focus is on areas of interest for the project partners and the further work in the project to find possible future systems and improvements within the waste-to-energy area.

1.2 Waste utilisation pathways

Waste is a heterogeneous energy source and different types of waste can be converted to different energy products in different conversion processes. Figure 1.1 shows an overview of possible pathways for waste to energy conversion.

In Chapter 2 and 3 of this report an overview of the conversion processes and problems and development discussed in literature today is given. In Chapter 4 and 5 some examples on integration of several systems and studies concerning comparison of different systems for waste-to-energy utilisation is presented. The report is finalised with some conclusions of the information found.
Figure 1.1 Waste to energy conversion pathways.
2. Biological processes

In biological processes microorganisms are used to convert a feedstock to energy rich products such as biogas and ethanol.

2.1 Biogas from waste

Biogas is produced using microorganisms that transform the raw material into methane and carbon dioxide in an anaerobic digestion process. Depending on the used material for digestion (e.g. waste) also H$_2$S and NH$_3$ in the range of ppm can occur as well as additionally trace gas compounds in ppb range (Ahrens, 2011).

Germany is the leading country for biogas production in Europe and in year 2000 there were 850 biogas plants in Germany, in 2006 the number was 3500 and there are plans to construct 43000 biogas plants until year 2020 (Deublein and Steinhauser, 2011). According to De Baere et al. (2010) the number of installed digesters for anaerobic digestion of municipal solid waste (MSW) and biowaste in Europe is about 200, with a total capacity of about 6 million tons per year. In Figure 2.1.1 the percentage of the biogas production in Europe for the European countries is presented.

Most research on anaerobic digestion for biogas production has concerned using sludge from municipal waste water treatment plants or manure as the substrate. However, interest in producing biogas from any kind of organic waste as well as from different crops and farm land residues has increased. For example in Germany, biogas production began with using manure as a substrate. After year 2000 pre-sorted organic wastes were started to be used and energy crops became a matter of interest after 2004. Today, the technology for biogas production is not optimized, and for biogas to be fully commercially competitive with other types of fuels, improvements have to be made. There are for example questions

![Figure 2.1.1 Percentage of total biogas production in Europe 2009 (in total 8.3 million tons of oil equivalent). (Euroobserver, 2010)](image-url)
concerning the influence of the microbiological community, inhibition of different substances, like ammonia, on the process and discussions about different pre-treatment methods (Nielsen and Angelidaki, 2008; Palatsi et al., 2009; Weiland, 2010). The influence of the substrate used on the gas is also a matter of interest.

2.1.1 The biological process

The biogas process can be divided into four steps: hydrolysis, acidogenic phase, acetogenic phase and methanogenic phase, see Figure 2.1.2.

The incoming substrate is built of carbohydrates, proteins and fats and these compounds are not water-soluble. These undissolved compounds are broken down into water-soluble fragments (monomers) by exoenzymes produced by bacteria. The bacteria can produce two kinds of enzymes, endoenzymes and exoenzymes. The difference is that endoenzymes break down substances within the bacteria cell while exoenzymes are released from the bacteria and brakes down substances outside the bacteria cell. Not all bacteria produce exoenzymes and typically one exoenzyme can only degrade one type of substrate so a large group of bacteria is needed for this process. The products of this stage are some simple sugars, fatty acids and amino acids. The monomers that were the products of the hydrolytic phase can now be taken up by the bacteria, even those that do not produce exoenzymes, and be further degraded into short-chain organic acids, alcohols, hydrogen and carbon dioxide.

Acetogenesis can either be seen as a separate step or as a part of the acetogenic phase. The product of the acetogenic phase is acetate. Acetate is important because it is the primary substrate used by methanogenic microorganisms. In the methanogenic phase the methanogenic microorganisms form methane using mostly acetate, carbon dioxide and hydrogen gas. Methane can also be formed from some other organic compounds but all compounds that are not degraded by the methanogenic bacteria will accumulate in the digester. (Gerardi, 2003; Deublein and Steinhauser, 2008)

Weiland (2010) mentions that the further development of the biogas production process includes better understanding of the influence of the structure of the community of microorganisms on the stability of the process and the biogas yield.
2.1.2 Pre-treatment

For improving the amount of biogas that can be produced from the substrate feed to the digester 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.

In the pre-treatment method called electroporation the substrate is exposed to electrical pulses with the aim to form pores in the cell membrane of the material. The method is on the research stage and has been studied for pre-treatment of sewage sludge (Choi et al., 2006), source-sorted municipal organic solid waste (Carlsson et al., 2008; Uldal et al., 2009) and ley crop silage (Lindmark et al. 2010). The studies have shown an increase of biogas production, compared to untreated material, of up to 14 % for municipal waste (Uldal et al., 2009), up to 100 % for ley crop silage (Lindmark et al. 2010) and up to 150 % for sewage sludge (Choi et al., 2006). Lindmark et al. also showed that the energy balance for the pre-treatment is positive and gives 2-5 times larger energy output in the form of methane compared to the electric energy input for the process. The method has to be further developed to be possible to use in full-scale. For example, the influence of the shape and size of the reaction container and of the electrodes on the performance of the treatment has to be studied as well as optimal field strength, frequency and the specific energy input per pulse (Lindmark et al., 2010; Lebovka, 2002; Bazhal et al., 2003; Ade-Omowaye et al., 2000).

2.1.3 Process design and operation

In a paper presented by Hilkiah Igoni et al. (2008) the key analyses involved in the design of anaerobic digesters for the production of biogas from municipal solid waste are reviewed. The authors draw the conclusion that not much can be found in literature about the design of processes using solid waste for biogas production. In a book by Deublein and Steinhauser (2011) the current knowledge about biogas production and plant design is summarized.

De Baere et al.(2010) defines three categories of digesters for anaerobic digestion of municipal waste and biowaste based on capacity, smaller plants (8000-15 000 tons/year) medium sized plants (30 000-50 000 tons/year) and large plants (100 000 to 200 000 tons/year) and conclude that new installations in Sweden, Norway, Austria and Switzerland are often smaller plants, while medium sized plants are more common in Germany, Belgium and Italy and large plants in UK and France. The type of plants that are used can be classified by several different design and operation parameters. The most important parameters are summarised in Table 2.1.1

In Table 2.1.2 data for some existing biogas plants are given. In Figure 2.1.3 examples of process layouts for biogas plants using waste as substrate are presented and Figure 2.1.4 shows a biogas plant in Kitee, Finland.
Table 2.1.1 Design and operation parameters used for classification of anaerobic digestion plant types. (De Baere et al., 2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Mesophilic (35°C to 40°C)</td>
</tr>
<tr>
<td></td>
<td>Thermophilic (50°C to 55°C)</td>
</tr>
<tr>
<td>Moisture content in reactor</td>
<td>Wet (&lt; 10 % dry solids)</td>
</tr>
<tr>
<td></td>
<td>Dry (&gt; 15 % dry solids)</td>
</tr>
<tr>
<td>Complexity</td>
<td>One step/phase</td>
</tr>
<tr>
<td></td>
<td>Two steps/phases</td>
</tr>
<tr>
<td>Number of feedstock</td>
<td>Single material</td>
</tr>
<tr>
<td></td>
<td>Co-digestion of several materials</td>
</tr>
<tr>
<td>Type of feedstock</td>
<td>Residual/mixed waste</td>
</tr>
<tr>
<td></td>
<td>Biowaste</td>
</tr>
</tbody>
</table>

**Temperature**

Mesophilic operation temperatures are more common than thermophilic for digestion of MSW and biowaste. About 70% of the installations done in Europe from 1991 are mesophilic even though thermophilic installations have increased after 2005 (De Baere et al., 2010). Also for agricultural biogas production mesophilic operation is most common (Weiland, 2010). Weiland also points out that with increased use of heat from combined heat and power (CHP) biogas plants or biogas production where the gas is not used for CHP but for example is upgraded and injected into the natural gas grid the mesophilic process could also be more energy efficient. Suryawanshi et al. (2010) summarise knowledge about thermophilic anaerobic digestion. They present data from 12 studies of thermophilic anaerobic digestion of waste of which 9 were lab-scale studies. Most studies concerned MSW or cow manure as substrate but there are also some studies on industrial wastes. Their conclusion is that thermophilic operating temperature is interesting since it gives faster reaction rates and higher gas production but also because of better possibilities for destruction of pathogens at high operating temperature. The drawbacks mentioned are high energy demands, long start-up time, higher sensitivity of the microorganisms for environmental changes and with that a more unstable process.

**Moisture content in the reactor**

The dry digestion process is an anaerobic digestion technology for solid, stackable biomass and organic waste, which cannot be pumped. It is mainly based on a batch wise operation with a high dry matter content ranging from 20 to 50% at mesophilic temperatures. According to De Baere et al. (2010) about 60% of the installed capacity in Europe in 2010 for digestion of MSW uses dry processes and the plug flow type reactor is the most commonly used technique in Europe. 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 of the dry material has to be more robust and with that usually more expensive. (De Baere et al., 2010; Kayhanian et al., 2007). The Dranco (Dry ANaerobic COMposting) process was developed in Belgium for high-solids anaerobic digestion of refuse derived fuel (RDF). The RDF is prepared by sorting incoming urban solid waste. The Dranco system is capable of removing most metals, glass, plastic, stone, recoverable paper, and other non-biodegradable items. The anaerobic treatment takes place in a vertical digester for a
Table 2.1.2 Biogas production techniques in some existing biogas plants using waste as feedstock. (Svensk Växtkraft, 2007; Malo and Turunen, 2010; Tianguan Group, 2011; Juvonen, 2010; Juvonen, 2011, Bioenergia, 2011)

<table>
<thead>
<tr>
<th>Plant (year started)</th>
<th>Temperature</th>
<th>Moisture content</th>
<th>Process design</th>
<th>Retention time [days]</th>
<th>Gas production [MNm$^3$/year]</th>
<th>Feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Växtkraft, Västerås, Sweden (2005)</td>
<td>Mesophilic 37-45°C (target 37 °C)</td>
<td>Wet (90-92%)</td>
<td>One step 4000 m$^3$ Gas mixing</td>
<td>20</td>
<td>2.7</td>
<td>Household biowaste 14 000 Restaurant organic waste 4000 Ley crop silage 5000</td>
</tr>
<tr>
<td>ZAK – Zweckverband, Germany (1992)</td>
<td>Thermophilic 55°C</td>
<td>Dry (70 %)</td>
<td>One step 1 300 m$^3$</td>
<td>20</td>
<td>2 (6100 Nm$^3$/day)</td>
<td>Biowaste 18 000</td>
</tr>
<tr>
<td>Benc Bioenergiezentrum, Germany (2000)</td>
<td>Mesophilic 35°C</td>
<td>?</td>
<td>Two lines one with hygienisation, one without Two steps – 600 m$^3$ and 1200 m$^3$</td>
<td>60 (with hygienisation) 30</td>
<td>?</td>
<td>12 000 Dairy waste (50%) Biowaste (20%) Horse manure (5%) Potato waste (5 %), Sugar beet, grain and other biomass (20%)</td>
</tr>
<tr>
<td>Tianguan Group, Nanyang, Henan province, China (2010)</td>
<td>Thermophilic 55°C and 37°C</td>
<td>Wet (96.5%)</td>
<td>Two steps (1st 55°C, 2nd 37°C) 20 x 10 000 m$^3$ natural circulation</td>
<td>12 (aim 4)</td>
<td>50 (aim 150)</td>
<td>Distillers waste from bioethanol production + waste water from corn processing plant 35 000 Nm$^3$/day</td>
</tr>
<tr>
<td>Biokymppi Oy’, Kitee, Finland (2010)</td>
<td>Mesophilic</td>
<td>Wet</td>
<td>Two lines, 1 000 m$^3$ 2 700 m$^3$ (One for manure and biowaste one for other materials)</td>
<td>48</td>
<td>1.5 (full load)</td>
<td>Up to 19.000 bio waste, packed bio waste, animal manure, water treatment sludge, food industry waste, grease trap sludge, green grass and coarse fish</td>
</tr>
</tbody>
</table>
Figure 2.1.3 Examples of two biogas plants using several waste streams (co-digestion) as substrate. In process (a) the substrates are organic MSW (1), sewage sludge (2) and fat removal sludge, distiller’s waste, remains from biooil production and confiscated liquor (3) and in process (b) the substrates are organic MSW and grease trap sludge (1) and ley crops silage (2). In both plants the raw biogas is upgraded to vehicle fuel.
period of 12–18 days, followed by a post-digester with a retention time of 2–3 days. The digester operates under mesophilic conditions. (Kayhanian et al., 2007)

Through the pre-treatment by mixing and storing the substrates first aerobic biological conversion is provoked in the material for dry digestion. The temperature increase in this aerobic phase is catalysing the start of the anaerobic mesophilic or thermophilic operation. The initial self-heating reduces the heat requirements during the process. The biomass is digested under airtight conditions after inoculation or flooding with digested substrate. The further inoculation with bacterial matter is taking place through recycling of a bacteria rich percolation liquid, which is sprayed over the biomass. When necessary the temperature of the process can be regulated through a built in floor heating system in the digester and an installed heat exchanger in the tank for the percolation liquid. (Köttner, 2002)

The wet digestion process is the most common used in agricultural biogas plants (Weiland, 2010) and usually continuously stirred tank reactors (CSTR) are used (De Baere et al., 2010; Weiland, 2010). In the wet biogas production process the substrate needs to be mixed with water if the dry solids content is too high. One area with improvement possibilities in the wet biogas production process is the handling of process water. To reduce the amount of fresh water needed, it can be of interest to recirculate water in the process. At Mälardalen University studies have been done to investigate the possibility to improve the performance of a biogas production plant by membrane filtration of the process water (Thorin et al., 2009, Lindmark et. al, 2010). Membrane filtration in connection with anaerobic digestion processes have been described in several studies, for example Pillay et al. (1994), Ince et al. (2001), Saddoud et al. (2007), Zhang et al. (2008), and Stamatelatou et al. (2009). The main focus in those studies was, however, to use the digestion process and membrane filtration for waste water treatment to reduce the COD (chemical oxygen demand) of a stream to be emitted.
Complexity

Another area of importance for the process design and performance is the circulation of the material in the digester. The biogas production process inside the digester is dependent on good 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 (Deublein and Steinhauser, 2011). Good mixing also gives a uniform temperature gradient in the reactor, destructs floating and sinking layers and prevents the substrate from leaving the digester prematurely because of short circuiting of the flow (Deublein and Steinhauser, 2008; Weiland, 2010). There is a lack of knowledge about how much mixing is needed to get a good gas production. A general recommendation from the United States Environmental Protection Agency (EPA) is a power input of 5 to 8 W/m$^3$ of digester volume (US EPA, 1979). Many researchers today argue the case that too much mixing could be bad for the process and that a reduction in mixing intensity leads to better process performance (Stroot, et al., 2001; Vavilin, et al., 2005). The microorganisms themselves are sensitive to too intense mixing and can be harmed because of it (Deublein and Steinhauser, 2008). Even though mixing is considered to be an important parameter for the biogas production few publications on work being done in this area can be found. Weiland (2010) points out the development of new mixing technologies as one area of importance for development of the biogas production process. The mixing inside the digester can be made in several ways. It can be made mechanically, hydraulically by using pumps and pneumatically by using the gas itself for mixing the liquid. Mechanical mixing with different types of agitators is the most common type of mixing being used in Europe today (Deublein and Steinhauser, 2008; Weiland, 2010). Pneumatically forced circulation stands for about 12% of the used mixing systems in Europe and can be used for wet processes. An advantage of the pneumatically forced circulation is that there are no moving parts in the digester (Weiland, 2010). However, studies have shown the risk for poorly mixed zones when using this technique (Karim et al., 2004; Karim et al., 2007; Lindmark et al., 2009). The hydraulically mixing with pumps is only used for some few specific types of reactors (Weiland, 2010).

Due to the possibility to optimize the conditions for the different steps in the anaerobic digestion process (see Chapter 2.1.1) a two phase process with two reactors in series can be used in the biogas production process. Concerning digestion of MSW De Baere et al. (2010) conclude that the share of two phase processes has declined during later years and only about 5% of the new installations during 2005 to 2010 was two phase systems. This is due to that the benefit of higher output is not considered to compensate for the higher complexity and higher costs for a two phase system. Weiland (2010) also point out the difficulty of controlling the process parameters for achieving the wanted conditions in the two different phases. For energy crop digestion processes it is an advantage to have a two-step process with two reactors but here both hydrolysis and methanation takes part in both reactors (Weiland, 2010). It is also possible to have two steps with different temperatures, a so called temperature-phased process, which has been shown to give higher methane production than a two phase process for some co-digestion cases (Schmit and Ellis, 2001).
Feedstock
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 (Alatriste-Mondragón et al., 2006). Alatriste-Mondragón et al summarised the results of 22 co-digestion studies. Organic MSW, MSW and cattle manure were the most common substrates studied and the most common co-digestates were agriculture material, industrial wastes and municipal food and vegetable wastes. The conclusion is that most studies show good results with an increase in biogas production of up to 60% mainly due to increased organic loading rates.

2.1.4 Process modelling and control
The microorganisms in the biogas production process are sensitive to changes in their environment and because of this, controlling and predicting the process is challenging. According to Weiland (2010) process monitoring and control are among the improvements needed for further development of the biogas production process. By process modelling the process can be studied in a cost and time efficient way to get a better understanding of the process and its optimal working conditions. Furthermore, a model also offers the possibility to control the process and predict its outcome. The development of mathematical models for describing anaerobic digestion has a long history. The first dynamic mathematical model was developed by Andrews in 1969 (Lübken et al., 2010). This model and many following models, were based on the concept of a rate-limiting step. The models assumed that the aceticlastic methanogenic process step was rate limiting and therefore the models only considers this step. However, later studies found that this is not always true. Instead the first step, hydrolysis, was more likely to be limiting (Tomei et al., 2009). Tomei et al. made a review on the modeling of anaerobic digestion of sludge and divided the models in three main groups, classified according to how advanced the characterization of the substrate is: simple substrate characterization models, intermediate substrate characterization models and advanced substrate characterization models. The simple substrate characterization models do not distinguish between different components of the substrate. These models are early models (1980s) and are also of rate-limiting step kind. The modern models are classified as advanced characterization models. Tomei et al. describes three such models: Angelidaki et al. model, Siegrist et al. model and Anaerobic Digestion Model No. 1. In Angelidaki et al's model (Angelidaki et al., 1999) the substrate is defined by its organic and inorganic composition. The organic components are carbohydrates, proteins, lipids and their degradation intermediates. The inorganic components included are: ammonia, phosphate, carbonate, hydrogen sulfide, anions and cations. There are six kinetic equations used in the model, one for each step. The steps are: (1) hydrolysis, (2) acidogenic glucose-degrading, (3) lypolytic, (4) LCFA-degrading acetogenic, (5) VFA- degrading acetogenic and (6) aceticlastic methanogenic steps.

The ADM1 model
In 1998 the International Water Association (IWA) formed a task group called the IWA Task Group for Mathematical Modelling of Anaerobic Digestion Processes to create a common platform for anaerobic process modeling and simulation. The model was first presented in 2001 and is called Anaerobic Digestion Model No. 1 (ADM1). The task group had several
members and it can be noted that both Angelidaki and Siegrist (mentioned above as researchers behind two of the more modern models) were members of it. The model considers both biochemical processes (involving living organisms) as well as physicochemical processes (not involving living organisms). The biochemical processes described are disintegration, hydrolysis, acidogenesis, acetogenesis and methanogenesis. Concerning the physicochemical processes, liquid-gas processes (liquid-gas transfer) and liquid-liquid processes (ion association/dissociation) are described but not solid-liquid processes due to difficulties in describing them. (Batstone et al., 2002). However, Kleerebezem and van Loosdrecht have pointed out some weaknesses in ADM1. Their three main points were that there are inaccuracies in the stoichiometry, some problems with the solid retention time and that there is a lack of restrictions for the thermodynamic boundaries. (Kleerebezem and van Loosdrecht, 2006).

The ADM1 has been used by several researchers. Blumensaat and Keller (2005) used it to model a two-step digester (a digester that has a thermophilic pre-treatment step and a mesophilic main treatment step) and needed to make several modifications in order to get the model to be in agreement with the data from their pilot-scale process. Derbal et al. (2009) used the ADM1 to model co-digestion of organic waste with activated sludge and found the model to show “acceptable simulating results, regarding the number of parameters involved and processes considered”. However, the authors mean that the model is limited in simulating complex processes. They admit that it may be due to that some of the input parameters were obtained from literature. Furthermore, Lübken et al. (2007) used ADM1 to model an anaerobic digester with cattle manure and energy crops feed stock. They also had some trouble in setting up the parameters for the model and also utilized literature values to some extent. This illustrates one of the greater difficulties with ADM1, that it requires a detailed characterization of the substrate (Daels et al., 2009, Kleerebezem and van Loosdrecht, 2006), requiring measurements that are not usually made when investigating a biogas plant or wastewater treatment plant and that might not be possible to do on a regular basis. There have been some attempts to circumvent this problem.

Kleerebezem and van Loosdrecht described one method for waste characterization that only needs measurements of Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), organic nitrogen (Norg) and alkalinity (Alk) that, according to the authors, are usually included in periodic measurements of anaerobic digesters. Zaher et al. (2009a) also created a procedure to characterize waste in order to generate input variables for ADM1. They based their procedure on methods previously created by others, among them Kleerebezem’s and van Loosdrecht’s method and later on generalized their procedure and implemented it as a general transformer model that can interface ADM1 to “any combination of co-digestion wastes” (Zaher et al., 2009b).

**Other modeling approaches**

However, ADM1 is not the only model used at present. An example of another model is a model developed by Abu Qdais et al. (2010) which models biogas production with the aim of optimizing the process, using an artificial neural network. The input for their model was temperature, total solids, total volatile solids and pH and the output is the percentage of
methane in the gas stream. Abu Qdais et al. tested their model with input data was gathered from a full-scale biogas plant and there was a good match between the model data and the actual data. There are a few other artificial neural network models in the field but none that has been directly aimed at modeling the amount of biogas produced. Nopharantana et al. (2003) created a model describing the operation of a sequential leach bed even though the focus was not on biogas production. Nopharantana et al. (2007) also created a model for anaerobic batch digestion of MSW. The model is described as a dynamic mass balance. The substrate is represented by two components, an insoluble part and a soluble part. The biodegradable proportions of these parts were determined by experiments. Four bacterial groups were identified and stoichiometry equations were set up for each group as well as rate expressions. The kinetic parameters were then either determined through experiments or from literature.

2.1.5 Gas upgrading
Upgrading the biogas includes removing carbon dioxide to increase the content of methane and to remove hydrogen sulphide and water which can cause damage in the gas utilization system (Weiland, 2010; Petersson and Wellinger, 2009). Other possible impurities are nitrogen, oxygen, ammonia, siloxanes, and particles (Petersson and Wellinger, 2009).

Desulphurisation can be done biologically, either in the reactor headspace or in filters outside the reactor, or it can be done by binding to ferrous compounds (Weiland, 2010). Carbon dioxide can be removed by scrubbing with water or organic solvents, pressure swing adsorption with activated carbon or molecular sieves, chemical washing with alkanol amines, using membrane technology or cryogenic separation where the two first techniques are the most common (Weiland, 2010) and cryogenic separation is a new technology under development (Petersson and Wellinger, 2009). Other methods to separate carbon dioxide studied on the research level are in situ methane enrichment, with desorption of carbon dioxide from digester sludge recirculated to the digester, and ecological lung using the enzyme carboanhydrase (Petersson and Wellinger, 2009). Adsorption with activated carbon and molecular sieve is also mentioned as possible processes to remove water (Petersson and Wellinger, 2009). Other alternatives for removing water are cooling, compression, adsorption on silica oxide or absorption in glycol solutions or hygroscopic salts (Petersson and Wellinger, 2009). According to Petersson and Wellinger (2009) the most used techniques for biogas up-grading are pressure swing adsorption, water scrubbing, organic physical scrubbing and chemical scrubbing.

The main driving forces for development of the gas-upgrading techniques are to lower the costs both for investment and operation and to decrease the methane emissions (Petersson and Wellinger, 2009).

2.1.6 The use of residuals
Biogas residues can be used as fertilizer on farmland supplying the soil with both nutrients and organic carbon. This is for example done with the residues from the Växtkraft biogas plant in Västerås, Sweden and from the Biokymppi Oy plant in Kitee, Finland, both presented in Table 2.1.2. Their fertilizers are also approved as organic fertilizers. To make this possible
the Biokymppi Oy plant has two process lines, one line is for raw materials which are accepted for organic fertilizers such as manure and separately collected biowaste and the other line is for municipal sewage treatment sludge and other materials which are not accepted for organic fertilizers. The Växtkraft biogas plant only use feedstocks accepted for organic fertilizers. The Biokymppi Oy plant can produce fertilizers for 1 000 - 1 500 hectares. (Svensk Växtkraft, 2007; Juvonen, 2010; Juvonen, 2011; Bioenergia, 2011). In a study by Odlare et al. (2010) it is shown that the biogas residue can provide the necessary plant nutrients and has the ability to produce nearly 88 % of the crop yield compared to mineral fertilizer.

The main product from a dry digestion process, apart from biogas, is compost. Especially for sanitation purposes the quality of the compost in terms of heavy metals and pathogens has to be taken into consideration (Köttner 2002). Rösch et al. investigated the use of hay together with corn silage as a substrate for a dry biogas process. As it was assumed that the grassland was not fertilised, the residues from the fermentation process could be used completely as fertilizer for the corn plants. (Rösch et al., 2009)

2.2 Ethanol from waste

Among the circumstances, pointing at that ethanol produced from agricultural waste can become a promising alternative from energy, cost and environmental perspectives are that agricultural crop residues, for example of cereal straw, usually have lower market prices than e.g. cereal grains and do not compete with food production, and the potential to minimize CO₂ emissions, as long-distance transport can be avoided (compared with e.g. imported biofuels). However, the introduction of local, lignocellulose based ethanol production is limited by some factors, such as the higher market price compared with ethanol derived from sugarcane and imported from Brazil. The current cost of ethanol production in Brazil is about 0.2 €/l, while ethanol derived from lignocellulosic feedstock in Europe costs about 0.4-0.5 €/l (SEKAB, 2010b).

Ethanol is considered as one of the important alternatives to fossil fuels. The whole world’s ethanol production is estimated to pass 91 Gl in 2012 (Market Research Analyst, 2008). In EU, the biofuels directive sets the target of 2 % substitution of conventional transport fuels by biofuels by December of 2005 and a further substitution of 5.75 % by December of 2010 (European Parliament and Council, 2003). The leading country for ethanol production, Brazil, provided almost one third of the global ethanol production, equal to 25 Gl, in 2009 (Renewable Fuels Association, 2011) and has become the only country, which can not only increase significantly the ethanol production to meet the expected domestic demand but also has the excess of capacity to provide ethanol to the world.

2.2.1 Waste feedstock for ethanol production

Ethanol can be produced from the raw materials, which contain sugars or can be converted into sugars. The raw materials can be grouped as directly fermentable sugary materials, starchy materials, lignocellulosic materials/wastes and urban/industrial wastes. For the
substrates that are not directly fermentable, substrate pre-treatment for conversion into sugar monomers are necessary.

Biofuels produced with conventional technology from easily convertible raw materials, such as direct fermentable sugary material, are often referred to as first generation biofuels, while biofuels produced in more advanced processes from lignocellulosic material are called second generation biofuels (UN-Energy, 2007). Examples of sugary waste materials that can be used for ethanol production are sugarcane molasses by-product of sugar industry, but also some wastes from food industry such as fruit juice industry.

Sources of lignocellulosic materials suitable for ethanol production are agricultural wastes, for example straws and wood wastes. On the basis of the technology available today, about 409 litres of ethanol can be produced from one ton of lignocellulose. Despite the strong interest also in other feedstock materials to produce ethanol, there are studies pointing out that the long-term sustainability of ethanol production will ultimately depend on the use of lignocellulosic wastes (Flavell, 2007; Farrell et al., 2006; Kszos et al., 2001; Kim and Dale, 2005a; Kim and Dale, 2005b; Adler et al., 2007). Considerable efforts have been made to develop new technical routes for ethanol fuel production from the lignocellulosic wastes. Given the arable lands constrains, there is a policy of diversifying the feedstock used to produce ethanol in China. Some pilot plants are established to use the acid and enzymatic hydrolysis of sawdust, rice straw and stalk of sugar sorghum for ethanol production (Zhenhong, 2006). Recently, some lignocelluloses-based plants started that operate on a commercial scale, though there exist some technical, economical and commercial barriers (Japan for Sustainability, 2007).

Part of the MSW could be used for ethanol production. Also wastewater generated in certain industrial plants like breweries, sugar mills, food-processing industries, tanneries, and paper and pulp industries could also be reused to produce ethanol (Prasad, 2007)

### 2.2.2 Pre-treatment

Pre-treatment is a very important step of the bioconversion process of cellulososes and hemicellulososes into ethanol. The primary goal of any pre-treatment is to alter or remove the structural and compositional impediments to hydrolysis so as to improve the rate of enzyme hydrolysis and increase the yield of fermentable sugars, mainly in the form of hexose and pentose as well as reduce the size of feedstock (Mosier et al., 2005). A successful pre-treatment should follow the rules: 1, improve and increase the ability of sugars formation; 2, decrease and avoid the degradation or loss of carbohydrate; 3, reduce the formation of by-products inhibitory to the sequent hydrolysis and fermentation process; 4, be cost-effective (Silverstein, 2004). Possible pre-treatment methods for ethanol production are:

- Steam explosion pre-treatment
- Ammonia fibre/freeze explosion
- Acid pre-treatment
- Alkaline pre-treatment
- Biological pre-treatment
Steam explosion is a process where high-temperature and high-pressure steam is used for segregating the individual fibres with minimal loss of materials (Mosier et al., 2005). There is evidence that steam explosion pre-treatment is a cost-effective pre-treatment method for hard wood, while it is less effective for soft wood (Silversterin, 2004).

In ammonia fibre/freeze explosion pre-treatment pre-wetted lignocelluloses are placed into a pressure vessel with a loading of NH₃ at 1-5kg/kg dry biomass. Pressure over 12 bar is needed for the process at ambient temperature (Silversterin, 2004). It is effective for the pre-treatment of corn stover, but less effective for those lignocellulosic wastes, which contain high content of lignin. The ammonia can be recovered by an evaporation operation (McMillan, 1997).

Many types of acids, such as sulfuric acid (McMillan, 1997), hydrochloric acid (Kurakake et al., 2005), peracetic acid (Teixeira et al., 1999), nitric acid (Brink, 1993) and phosphoric acid (Hussein et al., 2001), can be used for acid pre-treatment. In general, acid pre-treatment can utilize dilute or concentrated acids to improve the hydrolysis of lignocellulosic material. However, the former one is the most studied and used (Karimi et al., 2006; Dale and Moehlman, 2000; Tucker, 2003; Chung et al., 2005). There are mainly two types of dilute acids pre-treatment processes: one is a continuous-flow process with low solids loading (5-10 mass-%) and high temperature (higher than 160 °C); the other is a batch process with high solids loading (10-40 mass-%) and low temperature (lower than 160 °C) (Wyman, 1999). In recent years, treatment of lignocellulosic biomass with dilute sulfuric acid is adopted widely for hemicelluloses hydrolysis and pre-treatment before enzymatic hydrolysis of celluloses. Some improvements of the dilute acid method are presented by Knauf and Moniruzzaman (2004), which combines the high-temperature separation and washing treatment of pre-treated solids, preventing the re-precipitation of lignin and xylan. The re-precipitation of lignin will negatively influence the following enzymatic hydrolysis of pre-treated solids.

Alkaline pre-treatment can be operated at ambient temperature and lower pressure compared to other types of pre-treatment, whose reaction time is measured in terms of hours or days rather than minutes and seconds at ambient conditions. Contrary to the enzyme-catalyzed acid pre-treatment, some part of alkali is converted into irrecoverable salts or incorporated as salts into the biomass (Börjesson, 2006) but alkali pre-treatment can more easily remove the lignin content from the lignocelluloses with little effect on other components (McMillan, 1997). Dilute NaOH solution is mostly used, due to its lower price and less impact on the environment than concentrated solution.

Biological pre-treatment can simplify the pre-treatment process, but the reaction time is very long and little experience of this process exists. In addition, the special microorganisms needed are very expensive (Wyman, 1999).

2.2.3 Process design and operation
Currently, there is a large amount of studies regarding the utilization of lignocellulosic wastes/materials as a feedstock for ethanol production. There are several technical options to design the production process, but regardless of which is chosen, the following features...
should be considered carefully and comprehensively in comparison with the sugar- or starch-based production (Dong et al., 1997)

- 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 costs.

The ethanol production process from lignocellulosic wastes/materials will contain five steps: 1, feedstock pretreatment; 2, cellulose hydrolysis; 3, fermentation of hexoses; 4, separation and distillation; 5, effluent treatment, seen in Figure 2.2.1 (Carlos et al., 2007).

Hydrolysis and fermentation can be designed according to several approaches: separate hydrolysis and fermentation (SHF), with C5 and C6 fermented in different reactors; simultaneous saccharification and fermentation (SSF), with cellulose hydrolysis and C6 fermentation carried out in the same reactor (Öhgren et al., 2007) or simultaneous
saccharification and co-fermentation (SSCF), with cellulose hydrolysis and fermentation of C5 and C6 simultaneously carried out in one reactor (Hamelinck et al., 2005). However, SSF is shown to be superior to SHF when the whole slurry from the steam pre-treatment of softwood is used (Söderström et al., 2005). Consolidating the two process steps also results in a lower capital cost by eliminating a separate hydrolysis reactor. More importantly, this strategy avoids the problem of product inhibition associated with enzymes; the presence of glucose inhibits hydrolysis (Aly and Megeed, 2008). The fact that the ethanol concentration is higher during SSF than SHF reduces the risk of contamination (Wyman et al., 1992). A two-step acid hydrolysis technology is developed in a pilot plant by SEKAB, see Figure 2.2.2 a, (SEKAB, 2010a) and another similar in Oregon, USA (Aden, 2000), see Figure 2.2.3. In figure 2.2.2 b a SSF process integrated with a combined heat and power (CHP) plant, also used at SEKAB (SEKAB, 2010a) is shown.

In the hydrolysis step, cellulose and hemicellulose is converted to mainly glucose and xylose. High pressure steam is used to get high C6 sugar yields. The process can be catalysed by dilute acid, concentrated acid or enzymes (cellulase) (Wyman, 1999). The latter is preferred due to their mild reaction conditions with temperatures in the range of 45-50°C and pH at 4.8. The maintenance of equipments is also relatively cheap and easy compared to the former two, which have serious corrosion problems (Chandel et al., 2007). Hydrolysis with proceeding pre-treatment has a yield of more than 90 %, whereas yields are less than 20 % without pre-treatment (Zhang and Lynd, 2004). For a commercial-scale production, the enzymes are too expensive and instead sulphuric acid is widely utilized. A disadvantage of utilizing sulphuric acid in hydrolysis is that glucose readily degrades at high-temperature condition, which is usually needed for cellulose hydrolysis. It is more difficult to perform the hydrolysis of lignocellulosic biomass than of the pure celluloses because of the presence of non-glucan components like lignin and hemicelluloses (Zhang and Lynd, 2004). In the fermentation step C6 sugars are converted to ethanol. Glucose can be fermented with regular baker’s yeast whereas xylose requires specially selected or genetically modified microorganisms (Reith et al., 2001). The non-fermentable material, mainly lignin, is separated before or after fermentation depending on the configuration of the process. The feed to the fermentation step has to be cooled to 37 °C. The material from the fermentor is filtered, often in a membrane filtration unit, and the broth from filtration is distilled by super-heated steam and the ethanol product is obtained.

In Table 2.2.1 data for some exiting ethanol plants using waste as feedstock is presented.

### 2.2.4 The use of residuals

After membrane filtration of the effluent from the fermentation step, mainly solids of lignin can be collected. The moisture content (MC) of this material is 0.5 to 0.6 kg/kg. After drying,
Fig. 2.2.2 a) A two-step acid hydrolysis process developed in a pilot plant by SEKAB, b) A SSF based ethanol production process integrated with CHP plant (SEKAB, 2010a)

dis this material can be utilized as raw materials for pellets production or for combustion for heat and/or electricity production. The stillage can be used for biogas production by anaerobic digestion (Callander et al., 1986). According to Morgen and Henriksen (2006) the use of the stillage to produce animal feed might be more economically rewarding. Börjesson (2006; 2009) points out that it is vital that the by-products are utilized efficiently and that the energy required for drying the by-products for animal feed production is substantial. So instead, the possibility to produce biogas by anaerobic digestion is more energy-efficient.
Figure 2.2.3 Bio-ethanol production process in Oregon (Aden, 2000).

Table 2.2.1 Examples of some existing plants producing ethanol from waste feedstock. (Aden, 2002; SEKAB, 2010b; Shi and Chao, 2009), MC=Moisture content

<table>
<thead>
<tr>
<th>Plant (year started)</th>
<th>Process design</th>
<th>Ethanol yield</th>
<th>Ethanol production</th>
<th>Feedstock</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot plant National Renewable Energy Laboratory (NREL), USA (2010)</td>
<td>SSF, dilute acid pre-hydrolysis + enzymatic hydrolysis</td>
<td>449.5 l/ton oven dry feedstock</td>
<td>516.9 Ml/year</td>
<td>Corn stover 2000 ton/day (15 % MC)</td>
<td>Integration with CHP, 1.6 kWh electricity /l ethanol Ethanol selling price 0.166 €/l</td>
</tr>
<tr>
<td>SEKAB, Örnsköldsvik, Sweden</td>
<td>SSF</td>
<td>-</td>
<td>300-400 l/day</td>
<td>wood chips (sugarcane bagasse, wheat, corn stover, energy grass, recycled waste planned to be used)</td>
<td>Previously used two-step hydrolysis CHP, calculated total energy efficiency 80%</td>
</tr>
<tr>
<td>Tianguan group, China (2006)</td>
<td>SHF, Enzymatic hydrolysis</td>
<td>-</td>
<td>5000 ton/year (planned to increase to 10000 ton/year)</td>
<td>straw</td>
<td>CHP ethanol production cost 0.51-0.55 €/l CO₂ from fermentation used for PPC plastic production</td>
</tr>
</tbody>
</table>
2.2.5 Other aspects

The technology for production of bio-ethanol is developing. However, at present, several non-technical factors limit the further development of the bio-ethanol industry. These limiting factors include feedstock prices, bio-ethanol production costs, enzymes prices, oil prices, taxation of energy products and stimulative policies from government. (Enguídanos et al., 2002).

It is hard to estimate the production cost of ethanol from wastes because it is greatly dependent on the specific process designs chosen by the investors (Wyman, 1999). Furthermore, different studies often show different results, and poor economics are more often the consequence of poor process designs than a measure of the economic viability of the technology. Some process costs and by-product values are given in Table 2.2.3.

One important development area for ethanol production is integration to achieve the economic feasibility; another is how to cut down yeast costs to an acceptable level. Now, the Butalco Technology GmbH (Pressebox, 2010) has announced that genetically-optimized C-5 yeast can increase ethanol production by 30%, which really helps reduce the cellulose-based ethanol production cost to a competitive level, compared to traditional fossil fuel.

2.2.6 Utilization of bio-ethanol

Bio-ethanol is mixed with gasoline or diesel fuel in different proportions to produce fuel blends.

- Low bio-ethanol / fossil fuel blends: mixture of 5-22 % bio-ethanol with gasoline (E5-E22G) and up to 15 % bio-ethanol (with special additives) in diesel fuel (so called “Oxy-diesel”, e.g. E10D, E15D).
- High bio-ethanol / gasoline blends: e.g. 85 % bio-ethanol in gasoline (E85G), requiring engine modifications.
- Bio-ETBE is produced by combining bio-ethanol and isobutylene. Bio-ETBT may be used in blends of 10-15 % in unmodified engines.
- Utilized for production of hydrogen.

### Table 2.2.3: Production costs of ethanol (€/1000 l ethanol) (Sourie and Rozakis, 2001; Teagasc, 2010)

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Feedstock cost</th>
<th>Process cost</th>
<th>By-product</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>343 high 220 low</td>
<td>284</td>
<td>145</td>
<td>482 high 359 low</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>324 high 200 low</td>
<td>218</td>
<td>3</td>
<td>539 high 415 low</td>
</tr>
<tr>
<td>Straw</td>
<td>240</td>
<td>355</td>
<td>38</td>
<td>557</td>
</tr>
</tbody>
</table>
2.3 Butanol from waste

Butanol is a 4-carbon alcohol originally central to a number of industrial chemical processes. In recent years, butanol has gained attention within the scientific and environmental community as a potential alternative fuel with superior characteristics compared to ethanol and used as a stand-alone transportation fuel or blended with petrol or diesel. The production of biobutanol is similar to the process for producing ethanol, but using other microorganisms for the fermentation. Butanol can be produced from cereal crops, sugar cane and sugar beet, etc., but can also be produced from lignocellulosic materials and agriculture waste.

The properties of butanol share a closer similarity to gasoline than other biofuels. It has a higher energy density, lower evaporative emissions, is less corrosive and can be shipped through existing petroleum pipelines; and can with that be integrated directly into the existing petroleum infrastructure. (Shapovalov and Ashkinazi, 2008)

Some recent studies investigating the production of butanol from waste are laboratory experiments on production of butanol from agriculture waste in the form of corn stover and switchgrass (Qureshi et al., 2010) and in the form of steam exploded corn stover (Wang and Chen, 2011), experiments on butanol production in a continues packed bed from lactose-rich wastewaster in the form of cheese way (Napoli et al., 2010) and a review on butanol production including yields for raw materials such as straw, corn stover and whey (Kumar and Gayen, 2011).

There are still questions to be solved to reach high yields of butanol and high production rates. One problem is that some compounds that are formed during the degradation of lignocelluloses inhibit the butanol producing microorganisms. Also the above mentioned studies indicate that the production of butanol from waste has still not been demonstrated in scaled up plants and still do not show economic feasibility.
3. Thermal processes

The energy in the waste can be converted to heat, electricity and gas by thermal processes like combustion, pyrolysis and gasification. This chapter begins with a description of possible pre-treatment of waste for thermal processes after which the different thermal processes for waste to energy purposes are described.

3.1 RDF- Refuse Derived Fuel

Solid waste usually has a calorific value of one-quarter to one-half of that of coal and an ash content between 20-40% (McDougall et al., 2008). Municipal solid waste can be pre-treated prior to thermal treatment. The high caloric fraction produced in by pre-treatment is called Refuse Derived Fuel (RDF). RDF is produced from the fraction of the solid waste containing plastics, paper, wood, textiles and rubber. The term RDF is sometimes also used in a wider sense, e.g. also including sorting residues from packaging wastes or processed industrial wastes. Also other terms are in use, such as Recovered Fuel (REF), Packaging Derived Fuel (PDF), Paper and Plastic Fraction (PPF) and Processed Engineered Fuel (PEF) (Gendebien et al., 2003). RDF is similar to Solid Recovered Fuel or Specified Recovered Fuel (SRF). SRF however, is produced according to the requirements of a quality label. Other advantages of using RDF in thermal conversion processes for utilizing the energy in waste, compared to using unsorted waste, besides the higher heating value, are:

- RDF is more homogeneous and treatment technologies that have difficulties treating mixed waste directly (e.g. fluidised bed reactors) can be used
- RDF is less contaminated than mixed waste, thus its thermal treatment needs less complex flue gas cleaning technologies
- regular fuels can be directly substituted (Cherubini et al., 2009; McDougall et al., 2008; European Commission, 2006).

In Figure 3.1.1 a simplified overview is given of the effects of the production of RDF (e.g. in a mechanical-biological pre-treatment plant. In this exemplary schedule it can be observed, that by splitting the input waste flow a high caloric flow of RDF originates.

![Figure 3.1.1 Exemplary effects of RDF production (based on Fehrenbach et al., 2007)](image-url)
3.1.1 Preparation of RDF

In a report from the European Commission (2006) techniques for preparing solid fuels from waste are described. They define two types of fuels—shredded or fluff like material and densified fuels (pellets, cubes and briquettes) but also mention that it is also possible to just separate out the non-combustible fractions and by that double the lower heating value of the material. Further they report on a big variation in the data on lower heating value for the densified fuels recovered from waste ranging from 3 and up to 40 MJ/kg. The different steps of preparing solid waste to fuels are illustrated in Figure 3.1.2. Cranes and wheel loaders are usually used for feeding the process. For some co-combustion applications shredding the fuel product to fluff, crushing it or pulverizing it before use can be necessary. (European Commission, 2006)

Biological drying is a variation of aerobic decomposition, used to dry and partially stabilise residual municipal waste. Biological drying can produce a high quality RDF, high in biomass content. In the reactors waste is dried by air convection, while heat is provided by exothermic decomposition of the readily decomposable waste fraction. The main difference to biological stabilisation is that here the main goal is to dry and preserve most of the biomass content of the waste matrix, rather than fully stabilise it. Commercial process cycles are completed within 7–15 days, with mostly H₂O and organics losses of ca. 25–30 mass-%, leading to moisture contents of lower than 20 mass-%. The air leaving a drying box is normally close to 100% saturated with air (100% relative humidity). Typical water losses of 25% waste weight were reported by Rada et al. (2009), which constitute the sum of both water and organic matter loss. The ratio of weight losses between organic matter and condensed moisture is approximately 1:7 (Velis et al. 2009). The main goal of biological drying is to minimize the water content of the final product. On the other hand moisture is one of the main parameters of microbial activity. For the composting process water content of 20% was reported to prevent the microbial decomposition (Haug, 1993). In this case the temperature in the reactor will drop to the ambient temperature at which the efficiency of the drying process can be very low. High airflow rate and moisture removal in the re-circulated process air provide

<table>
<thead>
<tr>
<th>Separation</th>
<th>Size reduction</th>
<th>Size increasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>handpicking, drum sieve, air classifier, magnet, eddy current separator, dryer, screen, moving grate</td>
<td>mill (hammer, cascade) shredder (shear, single shaft) rotary cutter</td>
<td>press (flat bed, ring die) disc agglomerator</td>
</tr>
<tr>
<td>water, metal, stone, glass</td>
<td></td>
<td>bales briquettes pellets</td>
</tr>
</tbody>
</table>

Figure 3.1.2 Preparation steps for production of fuels from solid waste and techniques used for the different steps. (European Commission, 2006)
for effective drying. Thus, the main objectives considered for the technology design are:

- to achieve a good quality RDF, with
  - increased energy content through moisture reduction (from above 40% to less than 20%) and separation of non-combustible materials,
  - reduced contaminants content through mechanical sorting and removal of metals, fines, PVC etc
- to pre-treat waste at the lowest possible residence time (5-15 days, preferably less than 10 days)
- to use heat from the exothermic biological decomposition process to dry the waste, but at a minimum organic matter loss in order to preserve the caloric value,
- to deliver stable RDF, suitable for storage and transport

The biological drying reactors design includes a container coupled with an aeration system; containers can be either enclosed, or open tunnel-halls, or rotating drums.

Biological drying requires forced aeration in order to provide necessary air for the decomposition process, heat transfer involving removal of excessive heat and adjusting the matrix temperature, and to transport out the water vapour. The main process parameters are described below.

**Mechanical pre-processing**

Mechanical pre-treatment operations include shredding and/or mixing, affecting the physical properties of the matrix, such as the resistance to airflow. Properties such as moisture content, air-filled porosity, permeability, mechanical strength, and compaction of matrix, have the potential to affect the resistance to flow of air and, in turn, the level of airflow rate necessary for effective biological drying. Currently, the pre-processing strategy in most biological drying plants is limited to coarse shredding, e.g., at 300–150 mm maximum particle size (Velis et al., 2009).

**Aeration system type**

Air management in biological drying varies according to reactor design and process complexity. In enclosed reactors, the usual configuration is with overpressure, forcing air through the matrix flooring, and collecting off-gasses through openings located at the top. In static biodrying reactors problems with uneven air distribution occur, leading to uneven waste drying efficiency. To overcome this problem the bottom of a commercial biodrying reactor (Herhof Rottebox) is divided into 12 parts enabling airflow to vary in each segment, facilitating control of temperature and moisture in the whole reactor (Nicosia et al., 2007). Moreover, some problems may occur in the lower parts of the reactors due to the downwards leachate flow. Two solutions to mitigate this problem have been proposed: a) static reactors with alternating aeration systems: blowing and pulling air through the matrix: and b) rotating reactors, enabling constant mixing of waste, and even distribution of temperature and moisture (Bartha, 2008). These solutions have been tested in pilot applications and especially the latter one proved to improve the temperature distribution and homogeneity of dried waste (Velis et al., 2009). Air partial recirculation systems are often used in biological drying to reduce the volume of exhaust air requiring treatment. Additionally air recirculation
can be used to pre-heat the cold ambient air in-flow to the reactor in the winter season. This is done after vapor removal by cooling in a heat exchanger and cooling tower.

**Aeration rate and temperature**

Aeration rate is a crucial parameter for biological drying process control. Aeration rates in biological drying are much higher than in biological stabilization. Generally higher out-flow temperatures should improve the process performance, due to a higher water/air carrying capacity. On the other hand too high temperatures (of over 60°C) may become a limiting factor for microbial growth and thus slow down the decomposition rate and energy release. Results of experiments indicate more effective heat removal at higher aeration rates resulting in lower waste temperatures), with an optimal waste temperature of approximately 45 °C and corresponding airflow rates of approximately 0.023 m³/kg dry matter per hour. (Skourides et al., 2006; VanderGheynst et al., 1997). Contradicting results were reported in another trial where a temperature of 60°C, which was maintained at the airflow rate of 0.0143 m³/kg waste per hour (for 150 hours) yielded a 4% higher moisture reduction than the same experiment at 50°C with at specific airflow rate of 0.0164 m³/kg waste per hour. Most commercial biodrying processes operates in the temperature range of 40–70°C for the outlet air during the major part of the residence time (Velis et al. 2009). Herhof Rottebox applies a staged outlet air control, consisting of four phases over one week: (1) start up and biomass acclimatization: 40 °C; (2) degradation: 40–50 °C; (3) sanitation and drying: 50–60 °C; (4) cooling to room temperature (60 °C to ambient temperature) (Nicosia et al., 2007).

**Degree of organic matter decomposition**

During the decomposition of organic matter energy is released which is used for heating up the waste matrix and for transferring water from liquid state to water vapour. Thus the amount of heat needed can be estimated based on the quantity of water to be removed from the system. On the other hand the objective is to preserve the maximum amount of biomass in the RDF. This enhances the energy balance of the process and yields a fuel with higher biomass content, which is beneficial in a context of biomass recovery. A biological drying process completed in a short time (150 yours) at a high airflow rate was reported to yield product waste with a higher remaining energy content, than the product from longer lasting trials (Adani, 2002). Biological drying which took 250 hours to complete resulted in significantly higher biomass decomposition. Thus the general objective is to shorten the decomposition time in order to limit the overall decomposition, but at the same time obtain a sufficient drying effect.

**3.1.2 Quality criteria for RDF**

Currently, there are no EU-wide quality requirements for RDF. The reason for this is the fact that various installations using RDF as a fuel have different requirements. Receiving installations have to comply with the emission limits for co-incineration and based on the technology and regular fuel they use this may lead to different demands for contaminant level and heating value. As a result, individual installations do have requirements for their suppliers, but no EU-wide legal criteria were set. For SRF however, in some countries national quality criteria exist, e.g. in Finland, Germany and Italy (van Tubbergen et al. 2005).
The CEN/TC 343 Working Group 2 “Fuel Specifications and Classes” had planned to come up with EU quality criteria for SRF in 2010. So far, a proposal was made, which is based on three factors:

- economic aspect: Net Caloric Value (the higher, the more regular fuel can be substituted)
- technology aspect: Cl content (Chloride leads to corrosion in the installations)
- environmental aspect: Hg (+Cd) content

Based on these factors five different classes of SRF can be distinguished, which are shown in Table 3.1.1. This classification is based on the specific needs of cement kilns, power plants and RDF plants.

### 3.1.3 RDF use

RDF can be used as an additional fuel in industrial processes or be treated in dedicated RDF plants producing energy or syngas. Examples of installations using RDF as a main or additional energy input are cement kilns, lime shafts, power plants, coke ovens, brick furnaces, district heating plants and syngas production plants.

In plants using RDF as an additional fuel, a wide variety of technologies is in use. In dedicated RDF plants the material is mostly gasified. The thermal processes combustion, pyrolysis and gasification will be further presented in Chapter 3.2 to 3.4.

The production and use of RDF has been on the rise in the last decade. Reasons for this strong growth are the implementation of landfill bans for untreated municipal waste and the high costs of landfilling. The production of SRF amounted:

- 3 million tons in 2001
- 12 million tons in 2008 (of which 47% in Germany, followed by Sweden (8%), Italy (6%), Austria (5%) and the United Kingdom (4%).
- expected for 2015: 16.5 million tons

(Gascoyne, 2010)

**Table 3.1.1 Proposed quality criteria for five different classes of Solid Recovered Fuel (van Tubergen et al. 2005)**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Unit</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Calorific Value</td>
<td>MJ/kg ar*</td>
<td>≥25</td>
<td>≥20</td>
<td>≥15</td>
<td>≥10</td>
<td>≥3</td>
</tr>
<tr>
<td>Cl content</td>
<td>% d.m.**</td>
<td>≤0.2</td>
<td>≤0.6</td>
<td>≤1.0</td>
<td>≤1.5</td>
<td>≤3.0</td>
</tr>
<tr>
<td>Hg content</td>
<td>mg/MJ ar***</td>
<td>≤0.02</td>
<td>≤0.03</td>
<td>≤0.08</td>
<td>≤0.15</td>
<td>≤0.50</td>
</tr>
</tbody>
</table>

* ar = as received (related to wet material)
** d.m. = dry matter
*** mg/MJ : related to energy content, not to mass. For Hg is related to median values of at least 10 measurements, Cl and NCV are mean values. For Hg alternatively an 80 percentile value exists, which is 2 times higher as the portrayed median values.
3.2 Combustion

Burning of a fuel to obtain thermal energy is usually called combustion within the energy sector while the word incineration is often seen in connection with burning of waste. Since this report is focused on using waste as an energy source we have chosen to use the word combustion for the process including burning of waste. The energy content that can be converted to thermal energy is different for different types of waste fuels. In Table 3.2.1 heating values for some waste fuels from households and industry are given.

Singhabhandhu and Tezuka (2010) report on that in Japan waste cooking oil and waste lubricating oil is used in combustion. The waste cooking oil is collected and burned together with household wastes.

A waste from the agriculture sector of interest for combustion is straw which has a lower heating value of about 14 MJ/kg (EUBIA, 2011). In Denmark a lot of experience of using straw as fuel also in larger CHP plants can be found. The straw can be used in big bales, chafed or as straw pellets but the big bales are considered to be the most feasible way. Moisture contents of up to 20 % are usually acceptable. (Hinge, 2009)

With increasing requirements on recovery of material or energy from waste new types of wastes of interest for combustion appear. One example of that is the combustible fraction from fragmentation of metal scrap, called SLF (shredder light fraction). (Gyllenhammar et al., 2009).

3.2.1 Process design and operation

Two important parts of the waste combustion plant are the boiler and the flue gas cleaning system. 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. In Figure 3.2.1 a schematic of a waste combustion plant is shown.

In 2006 the European Commission presented the Best Available Technology for waste combustion (European Commission, 2006). They subdivide the sector in five areas based on the fuel used; mixed municipal waste, pre-treated waste, hazardous waste, sewage sludge and clinical waste. The techniques they mention for combustion is grate furnace, fluidised bed and rotary kiln. In Table 3.2.2 the most common techniques for the different wastes given in the report by the European Commission are summarised.

<table>
<thead>
<tr>
<th>Table 3.2.1 The table gives the range of lower heating values for some waste fuels. (European Commission, 2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household and commercial waste</td>
</tr>
<tr>
<td>Lower heating value [MJ/kg]</td>
</tr>
</tbody>
</table>
In 2006, 90% of the installations in Europe for combustion of mixed municipal waste used grates and specially reciprocating grates in many later installations (European Commission, 2006). According to Fendel and Friege (2010) still in 2010 grate furnaces is the most common technique used for municipal waste and RDF plants in Germany, where 70% of the about 100 existing plants use this technique. When the fuel has a heating value above about 10 MJ/kg the grate is usually water cooled and with the increasing heating value of the waste fuels used in Europe an increase in water cooled grate furnaces have been seen (European Commission, 2006). Grate furnaces are also recommended for straw combustion (Hinge, 2009).

Fluidised beds can be used for fuels with not too large particle sizes. Here the fuel is fed to a bed of inert material, for example sand, which is fluidised with air. The temperature in the space above the bed is usually about 850 to 950 °C. In a circulating fluidised bed the gas speed is high and part of the bed material is removed and then circulated back to the combustion chamber while in a stationary or bubbling bed the gas speed is lower and the bed material is not removed during the combustion process. (European Commission, 2006). Straw is not suitable for fluidised bed boilers since it has a low ash melting point and it can cause the bed particles to stick together (Hinge, 2009).

<table>
<thead>
<tr>
<th>Mixed municipal waste</th>
<th>Pre-treated waste</th>
<th>Hazardous waste</th>
<th>Sewage sludge</th>
<th>Clinical waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most commonly used</td>
<td>Reciprocating grate</td>
<td>Reciprocating grate</td>
<td>Rotary kiln</td>
<td>Rotary kiln</td>
</tr>
<tr>
<td>Also applied</td>
<td>Other types of grate furnaces</td>
<td>Other types of grate furnaces</td>
<td>Fluidised beds</td>
<td>Static hearth</td>
</tr>
<tr>
<td></td>
<td>Fluidised beds</td>
<td>Fluidised beds</td>
<td>Fluidised beds</td>
<td>Fluidised beds</td>
</tr>
</tbody>
</table>
In Table 3.2.3 some examples on existing waste combustion plants in Europe and their characteristics are given. In Table 3.2.3 an example of a CHP plant in Denmark using only straw as fuel is given. There is also several power plants in Denmark where straw is co-combusted with coal and/or wood chips (Hinge, 2009).

The design of the boiler in a waste combustion plant is dependent on the flue-gas characteristics which are dependent on the waste content. Especially, high concentrations of corrosive substances, as for example chlorides, makes it necessary to use modest steam pressures and the risk for corrosion problems also influences the physical design of the boiler. The most common steam data used for plants using waste as fuel and producing electricity are 400 °C and 40 bar and usually natural circulation steam boilers are used.

### Table 3.2.3 The combustion and flue gas cleaning techniques in some existing waste combustion plants.
(Johansson et al., 2009; Buchhorn, 2010; Weiler and Grotefeld, 2010; Hinge, 2009) BFB= Bubbling Fluidised Bed

<table>
<thead>
<tr>
<th>Plant (year built)</th>
<th>Combustor</th>
<th>Steam data [°C/bar]</th>
<th>Capacity thermal [MW]</th>
<th>Flue gas cleaning steps</th>
<th>Efficiency [%]</th>
<th>Capacity waste [ton/year]</th>
</tr>
</thead>
</table>
| Borås Energi och miljö, Sweden (2004) | 2 BFB-Boilers | 405/49               | 20                    | NOx – SNCR (NH₃) particles- textile filter  
HCl, SO₂, metals, dioxin- active carbon + lime in filter                                                                                      | 89             | 100 000 (20-30 % household waste, 70-80 % industrial waste) |
| Renova, Gothenburg, Sweden (1994 and 2001) | 4 grate furnaces flue gas recirculation | 400/40               | 45                    | NOx - SNCR (NH₃) particles-electrostatic precipitator  
HCl, HF, metals, dioxin, particles-wash and condensing reactor                                                                              | 89             | 500 000 (50/50 household and industrial waste) |
| Gevudo, Nordrecht, Netherlands (1972, 1997 and 2010) | 3 grate furnaces flue gas recirculation | 400/40               | 75                    | NOx- SCR** particles-electrostatic precipitator  
HCl, HF -quench  
SOₓ, HCl, HF. two-stage scrubber (caustic soda in step 2)  
particles-wet electrostatic filter                                                                                                      | ?              | 396 000 (municipal solid waste) |
| Bernburg, Germany (2009) | 3 furnaces | 410/42               | ?                     | NOx – SNCR** dioxin, Hg- activated carbon acid- sodium bicarbonate particles, heavy metals, loaded sodium-textile filter  
particles – textile filter  
HCl, SO₂- flue gas condensation                                                                                                           | ?              | 552 000 (RDF) |
| Vattenfall, Fynsverket, Denmark (2009) | Vibrating grate | 540/110              | (35 MWₑl 86MWheat (including 11 MW flue gas condensing) | particles – textile filter  
HCl, SO₂- flue gas condensation                                                                                                           | El. 33        | 150 000 (straw) |

*selective non-catalytic reduction, **selective catalytic reduction
Another important aspect in boiler design is the heat transfer surface cleaning since the flue gases from waste combustion usually have a high content of ash. (European Commission, 2006). One suggested solution to reduce the corrosion problems is to reduce the bed temperature in fluidised bed boilers and with that decrease the amount of alkali chlorides in the flue gas (Niklasson, 2009). Straw is a more homogenous fuel than waste but also for straw combustion the steam temperature has previously been kept below 500 °C due to corrosion problems but according to Hinge (2009) good experiences with using new materials has led to that it is no longer considered a problem to use steam temperatures up to 540 °C. SLF usually have a high content of metals and chlorine and metals like lead and zinc form chlorides which can give corrosion problems at lower temperatures than alkali metals (Gyllenhammar et al., 2009). Gyllenhammar et al. therefore recommend co-combustion of SLF with other wastes.

The thermal efficiency of a power and heat plant using a fuel with high moisture content can be increased with flue gas condensation, utilizing the latent heat of the water vapour in the flue gas. This has been applied at the Högdalen waste combustion plant in Stockholm, Sweden. However, the possibility to use low temperature heat is crucial and a return water temperature not higher than 50 °C is necessary, which can be the case for district heating water in the northern part of Europe. (European Commission, 2006). Another possibility to increase the efficiency is to integrate a gas turbine in a hybrid dual-fuel cycle. The steam produced in the boiler can then be superheated with the flue gases from the gas turbine. Several different integration possibilities has been studied by Udomsri (2011).

The flue gas cleaning system consists of different components with different possible designs and a lot of different combinations are possible. In the report by the European Commission (European Commission, 2006) an overview of possible flue gas cleaning systems for waste combustion plants shows over 400 possible combinations. Some examples of flue gas cleaning systems can be found in Table 3.2.3. The following list gives the content of the gas that should be removed and also the main techniques that can be used for cleaning (European Commission, 2006):

- particles (electrostatic precipitator, wet scrubbers, fabric filters, cyclones)
- acid gases, HCl, HF, SO₂ (dry sorption, washing (agents: lime, sodium bicarbonate, sodium hydroxid))
- NOₓ (furnace control, flue gas recirculation, SNCR (selective non-catalytic reduction), SCR (selective non-catalytic reduction) (agent ammonia or urea for SNCR and SCR))
- Hg and other heavy metals (scrubber, activated carbon)
- dioxin and other organic carbon compounds (activated carbon, quench, SCR, scrubber with carbon impregnated plastics)

In Table 3.2.4 the emission levels that can be achieved by applying the in the report by the European Commission (2006) identified best available techniques for combustion of waste are presented. Hinge (Hinge, 2009) report on emission values for combustion of crops and straw in Denmark. Examples are given for plants from 5 to 33 MW and the emission ranges are for particles from below 0.1 to 37 mg/Nm³, HCl below 1 mg/Nm³ (one value), SO₂ below 1 to 215 mg/Nm³, NO₂ from 220 to 912 mg/Nm³. Data is also given on dioxin emissions from
Table 3.2.4 Emission levels to air during operation of waste combustion plants using best available techniques
(European Commission, 2006)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Emission (24 hours average) [mg/Nm³]</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>1-5</td>
<td>Fabric filters</td>
</tr>
<tr>
<td>HCl</td>
<td>1-8</td>
<td>Wet based system</td>
</tr>
<tr>
<td>HF</td>
<td>&lt;1</td>
<td>Wet based system</td>
</tr>
<tr>
<td>SO₂</td>
<td>1-40</td>
<td>Wet based system</td>
</tr>
<tr>
<td>NOₓ (expressed as NO₂)</td>
<td>40-100</td>
<td>SCR</td>
</tr>
<tr>
<td>NOₓ (expressed as NO₂)</td>
<td>120-180</td>
<td>SNCR</td>
</tr>
<tr>
<td>Hg</td>
<td>0.001-0.02</td>
<td>Carbon based reagents</td>
</tr>
<tr>
<td>Dioxin and furans'</td>
<td>0.01-0.1</td>
<td>Combustion conditions + Carbon absorbent</td>
</tr>
<tr>
<td>CO</td>
<td>5-30</td>
<td>Combustion conditions</td>
</tr>
<tr>
<td>TOC</td>
<td>1-10</td>
<td>Combustion conditions</td>
</tr>
</tbody>
</table>

* not 24 hours average but from non-continues samples, unit ng-TEQ/Nm³ (TEQ= Toxic Equivalent)

Some other straw fired plants including both small- scale farm combustion and larger heating plants (up to 95 MW) ranging from 0.01 to about 2 ng-TEQ/Nm³ with high values for the small-scale plants. A problem mentioned for straw combustion is catalytic reduction of NOₓ due to large uncombusted particles in the flue gas that block the catalyst. There are examples on plants where this has been solved by using nets for collecting the particles before the catalyst.

The incineration directive sets emission limits for both combustion and co-combustion of waste. For the co-combustion of pre-treated waste the so-called mixing rule is applied. This means, that the joint emission limit for the situation of co-combustion is based on the weighted average of the emission limits for the co-combusted fuels. The weighing is based on the flue gas volume resulting from the combustion from the secondary and regular fuel. (European Parliament and Council, 2000)

The emission limits for the regular fuel principally follow from the emission limits for the considered installation (national or other legislation). At all times the total emission limits for the most relevant heavy metals (Hg, Tl and Cd) and for dioxins for the joint co-combustion operation should be the same as for mono-combustion. For combustion plants and cement kilns additional regulations are valid. Values for the emission limit share of the regular fuel in combustion plants (here only large plants mentioned, >300MWth) are:

- SO₂: 200 mg/Nm³
- NOₓ: 200 mg/Nm³ for solid and liquid fuels, 300 mg/Nm³ for biomass
- dust: 30 mg/Nm³
For some emissions total limits for the joint co-combustion operation are set:

- other heavy metals: as for mono-combustion
- dioxins: as for mono-combustion

For cement kilns total emission limits for the joint co-combustion operation are set:

- SO₂: 50 mg/Nm³, if the emission does not stem from the waste input, exemptions are possible.
- TOC: 10 mg/Nm³, if the emission does not stem from the waste input, exemptions are possible.
- NOₓ: 500 mg/Nm³ for new plants
- dust: 30 mg/Nm³
- other emissions, apart from CO: as for mono-combustion

Waste combustion operators do not like the situation in which co-combustion of waste has emission limits deviating from those for mono-combustion of waste. The Confederation of European Waste-to-Energy Plants (CEWEP) pleads for a ‘level playing field’ for all thermal waste treatment operations. On a national level, the differences in emission limits may be more outspoken (BMLFUW, 2010).

Waste water that needs to be cleaned can be formed in the flue gas cleaning system. Other residues from the waste combustion plant are ashes and solid residues from the flue gas cleaning system.

Among the identified development areas of the process for combustion of waste reducing dioxin emissions, reducing ash volumes, improving ash quality and stabilising solid residues from flue gas cleaning can be mentioned. Suggested solutions include combustion control, bed temperature changes, addition of oil scrubber, recirculation of ash and ash treatment. (European Commission, 2006).

Concerning combustion of straw Hinge (2009) also mentions the use of the ash together with emission control, plant efficiency and pre-treatment of the straw as areas of interest for further development and research.

### 3.2.2 Other aspects

The development of the technique for combustion of waste is towards limiting the costs and improving environmental performance. (European Commission, 2006)

Fendel and Friege (2010) have compared RDF power plants with mixed municipal solid waste power plants and conclude that RDF plants might be more profitable if the energy prices increase even though it might not be more competitive if the pre-treatment costs are included. However, RDF plants have the disadvantage of not being as flexible concerning what waste fractions can be used as fuel compared to municipal solid waste power plants.

In a comparison of two waste combustion plants in Sweden the plant with less pre-treatment of the waste showed higher maintenance costs (Johansson et al., 2009). According to Johansson et al (2009) waste combustion plants often have unique technical solutions and strategies for operation and maintenance and very few comparisons between different plants.
therefore exist. This also results in little knowledge about improvement possibilities. Compared to combustion of other types of fuels, waste combustion plants have higher operation and maintenance costs due to more advanced handling but the existing studies on waste combustion plants only give general estimated costs for operation and maintenance (Johansson et al., 2009).

Fendel and Friege (2010) discuss the problem with overcapacity due to competition between several possible waste-energy concepts, e.g. the combustion of mixed municipal waste, co-combustion of waste with other fuels, production of RDF followed by combustion and the use of waste fractions in cement kilns. They estimate an overcapacity of about 18% in Germany and they suggest that an explanation to this can be different actors on the market driven by different aims with the public sector increasing the municipal waste combustion capacity to decrease the lack of waste treatment capacities and the private sector increasing the RDF combustion capacity and waste use in cement kilns with the aim to reduce energy costs and using the possibility to sell electricity to the grid.

### 3.3 Pyrolysis of waste

Pyrolysis of biomass (including waste) can be described as the direct thermal decomposition, or degassing, of the organic matrix in the absence of oxygen to obtain an array of solid, liquid and gas products. Pyrolysis consists of a very complex set of reactions involving the formation of radicals. The pyrolysis method has been used for commercial production of a wide range of fuels, solvents, chemicals and other products from biomass feedstock. There are two major distinctions between combustion processes and pyrolysis. Firstly, combustion processes are exothermic, whereas pyrolysis is an endothermic process. Secondly, products of combustion processes are CO₂, water, and ash, whereas with pyrolysis the products are char (carbon rich solid residue), oil or tar, and fuel gases. These products can be used as fuel in a combustion process or as intermediate products for synthesis and the production of chemicals. Generally, for a high yield of gas products high temperature, low heating rate and long gas residence time should be applied (Cheremisinoff and Rezaiyan, 2005; Yaman, 2003; European Commission, 2006).

Types of wastes that are used in pyrolysis processes are municipal wastes, RDF, sewage sludge, synthetic waste and used tires. The process can also be used for decontamination of soil and for material recovery from cable tails and metal and plastic compound materials. (European Commission, 2006)

The heating value of the pyrolysis gas is related to the composition of the gas which depends on various parameters, such as the constituents of the pyrolised material, temperature, heating rate and residence time. Karayildirim et al. report on a calorific value of 2.55 MJ/Nm³ for pyrolysis gases, containing combustible gases of 19 vol%, from sewage sludge while according to the European Commission the heating value of gas from pyrolysis of municipal waste is in the range of 5-15 MJ/ Nm³ and from RDF 15-30 MJ/ Nm³. A study by Bridgwater and Peacocke showed that gas produced in a fast pyrolysis process had the higher
heating value of 4 MJ/kg and bio-oil produced had a higher heating value of 19 MJ/kg. (Karayildirim et al., 2005; European Commission, 2006; Bridgwater and Peacocke 2000)

3.3.1 Process design and operation

Slow pyrolysis has traditionally been used for the production of charcoal. Short residence time pyrolysis (fast, flash, rapid, ultrapyrolysis) of biomass at moderate temperatures has been used to obtain high yield of liquid products. Fast pyrolysis is characterized by high heating rates and rapid quenching of the liquid products to terminate the secondary conversion of the products. Among the fast pyrolysis technologies applied for wood and biomass conversion into liquid fuels, the bubbling fluidised-bed reactor is used to a large extent at both laboratory and industrial scale (Yaman, 2003; Di Blasi, 2007)

Pyrolysis of waste is often combined with combustion of the produced gas and sometimes also of the solid carbon rich fraction and oil. By including a pyrolysis step the flue-gas amounts are reduced and with that the requirements of flue-gas cleaning. The same techniques as used for combustion can also be adapted to be used for pyrolysis, e.g. the use of different oxygen levels and temperatures. The European Commission mention in their report systems using rotary kiln and grate furnaces for pyrolysis of waste. Usually the pyrolysis is carried out in the temperature range 400 to 700 °C but lower temperatures (250 °C) can also be used for sewage sludge. The pyrolysis plant for waste usually has the following basic steps:

- preparation and grinding
- drying
- pyrolysis
- secondary treatment
  - condensation of gas for extraction of oil mixtures or combustion of gases
  - combustion of coke

(European Commission, 2006; Malkow, 2004)

Japan is mentioned as a country with interest in pyrolysis of waste. One of the first facilities built for the disposal of municipal solid waste, located in Yoshii, Japan, was commissioned in 1999 and processes up to 24 ton/day of MSW in a single reactor. It produces a syngas that is utilized in a waste-heat boiler to generate steam. Another facility in Utashini, Japan is similar to the Yoshii plant but uses two 83 ton/day trains. It is designed to process automobile shredder residue and MSW. This plant was commissioned in late 2002. Other wastes of interest for pyrolysis in Japan are waste cooking oil and waste lubricating oil. There are also reports on several plants in operation in Austria, Germany, Italy, Korea and Switzerland during the end of the 1980’s and 1990’s where municipal solid waste are pyrolysed followed by combustion. (Malkow, 2004; Cheremisinoff and Rezaiyan, 2005; European Commission, 2006; Singhabhandhu and Tezuka, 2010)

Panda et al. (2010) report on producing hydrocarbon fuels from plastic waste by catalytic pyrolysis and that several research activities have been initiated to test different catalysts and process conditions. They also give examples of use of the process in UK, Germany, China and India in plants with capacities ranging from 1000 to 40 000 tons per year. The company Ener-G (2011) is developing a process for pyrolysis of waste where the gas is then used in a
gas engine and the solid residues (char and tar) can be sold as fuel. They state that development of capacity, gas and by-product quality is needed to make the technique commercial. They aim at a capacity of 1 ton of waste per hour. The waste can be municipal solid waste, shredded rubber, clinical waste, sewage sludge, wood wastes or chicken litter.

During recent years several studies investigating the influence of different process conditions on the quality of the products from pyrolysis of waste can be found. Parameters that are investigated are temperature, residence time and different atmospheres. For example in a study by Karayildirim et al. (2006) pyrolysis of mixed sludge and oil sludge was investigated at temperatures between 450 and 800 °C. Smets et al. (2011) investigated pyrolysis of rapeseed cake at 350-550°C, Puy et al. (2011) have studied the pyrolysis of forestry waste at temperatures from 500 to 800 °C and residence times from 1.5 minutes to 5 minutes, Önal et al. (2011) studied pyrolysis of potato skin in different atmospheres, Brown et al. (2010) compared profitability of pyrolysis of crop residues in processes with different residence times and Hossain et al. (2011) investigated the influence of temperature (300-700 °C ) on the pyrolysis of waste water sludge . The different parameters influence both the yields and the quality of the different products and increasing the yield and quality of one product might decrease it for another. Among the mentioned use of the products are using the char as soil amendment (providing both carbon and nutrients), as a solid fuel, as activated coal or as adsorbent, using the pyrolysis oil as transportation fuel, or for heat and/or power production and the use of the gas for heat and/or power production.

3.4 Gasification of waste
Gasification is a thermo-chemical process where a solid material is converted to a gas. The process is usually done by air, oxygen or steam and at temperatures between 600 -1000°C and at oxygen- carbon ratios lower than 1. The medium and temperature used influence the composition of the produced gas which is also dependent on the feedstock and the reactor used. According to Ptasinski (2008) the choice of medium depends on which gas composition is required. However, the main components of the gas are CO₂, CO, CH₄, H₂, H₂O and small amounts of C₂-hydrocarbons and char. For the possibility to use the produced gas in natural gas networks, that is to produce synthetic natural gas (SNG), the content of methane is increased in a methanisation step where steam is added. To be able to operate this step efficiently the gas should not contain nitrogen. (Valleskog et al., 2008; Ptasinski, 2008) In a report the European Commission (2006) mentions municipal waste, certain hazardous wastes and sewage sludge as possible waste feedstock for gasification where the municipal waste often needs to be pre-treated.

3.4.1 Process design and operation
In the same way as for pyrolysis of waste, gasification of waste can be combined with combustion of the produced gas and the same techniques as used for combustion can be adapted to other oxygen levels and temperatures for gasification. (European Commission, 2006)
Kopyscinski et al. (2010) present a review of the development of processes for gasification of coal and biomass from 1950 to 2009. They divide the process from the raw material to synthetic natural gas (SNG) into the steps gasification, gas cleaning, gas conditioning, fuel synthesis and fuel upgrading. The focus in the review is on the fuel synthesis step, which is the methanisation step.

There are three main types of gasifiers: fixed bed, fluidised bed, and entrained suspension bed gasifiers (also called entrained flow gasifiers). According to McKendry (2002) the entrained type is not suitable for biomass gasification since the feedstock needs to be very finely divided which is difficult to do with fibrous materials such as wood compared to coal. However, there have been successful attempts to use entrained suspension bed gasifiers for biomass. Zhou et al. (2009) made a successful experimental setup using rice husk, sawdust and camphor wood as feedstock. In the report by the European Commission (2006) it is mentioned that pre-treated municipal wastes is possible to use in entrained suspension bed gasifiers and also that hazardous wastes in liquid, pasty or granulated form can be used. The entrained suspension bed gasifiers are operated at high temperatures and give a gas with low char and methane content. Usually oxygen is used as a gasification medium. Fixed bed gasifiers are classified according to airflow and are called updraft, downdraft and cross-flow. In general fixed bed gasifiers have the advantage that the design is simple but the gas they produce is of low calorific value and the tar content is high. In the updraft gasifier the feed is introduced at the top and the air at the bottom of the gasifier. The gas leaving the gasifier has a low temperature and therefore the overall energy efficiency of the process is higher than for the other configurations. The particulate content is low since the gas is filtered through the feed. It is also difficult to maintain a uniform radial temperature and problems with local slagging for large installations (Li et al., 2004; McKendry, 2002). An example of waste that has been gasified in an updraft gasifier is salmon waste (Rowland et al. 2009). In the downdraft gasifier the feed and the air flow are in the same direction. The gases leaves the gasifier at a high temperature making the overall energy efficiency low and particulate content is high but the tar content of the product gas is lower than for an updraft gasifier since the gas passes the hot zone before leaving the gasifier. Examples of wastes that have been gasified in a downdraft gasifier are hazelnut shells and wood waste (furniture). (Dogru et al., 2002; Sheth and Babu, 2009; McKendry, 2002).

In a fluidised bed reactor a carrier material (e.g. sand) is used, which, being flowed through by a gas, shows liquid-like behaviour. Compared to fixed bed gasifiers, fluidised bed gasifiers have the advantage of having a uniform temperature distribution in the gasification zone. There are three main types of fluidised bed gasifiers in use: Circulating Fluidised Bed (CFB) gasifier, Bubbling Fluidised Bed (BFB) gasifier and the Internal Circulating Fluidised Bed (ICFB) gasifier. In the CFB gasifier the bed material is circulated between the reaction vessel and a cyclone separator where ash is separated. One example of a waste that has been gasified in a CFB gasifier is sawdust (Li et al., 2004). The BFB gasifier consists of a vessel with a grate at the bottom through which air is introduced. Above the grate there is a moving bed of fine-grained material. The biomass is then added to this moving bed. The ICFB gasifier consists of two separate interconnected chambers which are normally operated with gasification in one of the chambers and combustion in the other. The major difficulty in operation of fluidised bed gasifiers is the possibility of slagging of the bed material due to the
ash content of the fuel. Alimuddin et al. have reviewed gasification of lignocellulosic biomass in fluidised beds. Among the mentioned feedstock are those that could be considered as waste such as wheat straw, saw dust and olive oil residues. According to Alimuddin et al. many researchers have been looking into gasification of lignocellulosic biomass and fluidised beds are very able to conduct the gasification process even though more research is required for significant progress in the area. (McKendry, 2002; Alimuddin et al., 2010; Miccio et al., 2008). In Figure 3.4.1 the different types of gasifiers are illustrated.

Valleskog et al. (2008) mention three different gasification processes that can be used for gasification of biomass pressurized gasification in a fluidised bed, indirect gasification in a gasifier and combustor, and hydrogen gasification. Data for those processes is presented in Table 3.4.1. Indirect gasification means that the heat for the process is supplied from outside, usually by burning coke separated from the gasified fuel. In the project GoBiGas (Gothenburg Biomass Gasification Project) forest residues will be gasified in an indirect gasification plant combined with an existing biofuel CFB boiler. The gasification process will be based on technology from the Austrian company Repotec. The first stage of the plant is planned to be ready in 2012 and is then planned to produce 20 MW gas. A second stage producing 80 MW gas will then be built to 2016. (Göteborg energi, 2011). Another gasification plant being built, using waste as resources is a plant in Lahti, Finland. Here 250000 tons of waste from businesses and households in Lahti and Helsinki will be used to generate 90 MW of heat and 50 MW of power per year. The plant is planned to start in 2012. (European Investment Bank, 2011). The supplier of the gasification process both to the GoBiGas project and to the Lahti plant is Metso (2011).

The company Energos has built several plants with waste as feedstock. The process is based on a two-step thermal conversion of the fuel with gasification on a grate in one chamber followed by high temperature oxidation in a combustion chamber. The heat is used to produce steam for a steam turbine. MSW, residual MSW, RDF and commercial waste are used as feedstock. The first plant was commissioned in Norway in 1997 and currently six plants are in operation in Norway, one in Germany and one in United Kingdom. The fuel capacities of the different plants are from 10 000 to 78 000 tons/year with a thermal energy production of 25 to 256 GWh/year. (Energos, 2011)

Foster Wheeler Energia Oy develops gasifiers for gasification of RDF. The process is based on pressurized oxygen-steam fluidised-bed gasification. A lot of effort is also put on cleaning the gas and catalytic reformation to a clean syngas. They also have a system for stand- alone power plants using the produced gas in a gas-fired boiler. Foster Wheeler has already delivered atmospheric fluidised bed gasifiers using waste as feedstock. They have also tested straw as feedstock with good results but economic studies done in 2001 for a plant in Denmark showed that the straw price was too high to make it profitable. (Palonen et al., 2006)
Figure 3.4.1 Different types of gasifiers. Other gasification medium than exemplified with here is possible. a) Fixed bed gasifiers, up-draft to the left and down-draft to the right, b) Fluidised bed gasifiers, bubbling bed to the left and circulating bed to the right, c) entrained suspension bed gasifiers (also called entrained flow gasifiers) (Belgiorno et al., 2003; Palonen et al., 2006; Naqvi et al., 2010)
Table 3.4.1 Typical process data for some gasification processes used for biomass gasification (Valleskog et al., 2008). MC= Moisture Content

<table>
<thead>
<tr>
<th>Process</th>
<th>Reactor</th>
<th>Temperature [°C]</th>
<th>Pressure [bar]</th>
<th>Media</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurised gasification</td>
<td>Fluidised bed</td>
<td>850-950</td>
<td>20</td>
<td>Oxygen</td>
<td>MC of feed &lt; 15% Sand in bed</td>
</tr>
<tr>
<td>Indirect gasification</td>
<td>Gasifier and Combustor</td>
<td>800-900</td>
<td>1</td>
<td>Steam</td>
<td>Ungasified carbon combusted in combustor, heat transferred with sand</td>
</tr>
<tr>
<td>Hydrogen gasification</td>
<td></td>
<td>800-850</td>
<td>30</td>
<td>Hydrogen</td>
<td>MC of feed &lt; 5% Feed in small sized particles High content of methane and low content of CO in gas</td>
</tr>
</tbody>
</table>

According to an Italian study more than 100 plants with gasification of waste can be found in Japan and most of them are using untreated waste as feedstock (Panepinto and Genon, 2010). However, Kirkels and Verbong (2011) point out that most of these plants are focused on waste handling and not energy recovery.

One type of waste that has been of interest for gasification since the 1990’s is black liquor from pulp production. Besides producing gas for further use the process is also designed for recovering of cooking chemicals for the pulp process, where reduction of sulphate to sulphide is important. This process has been studied both experimentally and theoretically. Several technologies have been developed and tested for this application. Some operate at low temperatures, 600–850 °C, below the melting point of the inorganic material in the waste, and other at high temperatures 900–1000 °C. In the first group fluidised bed based processes can be found, for example a process developed by Manufacturing and Technology Conversion International (MTCI) using an indirectly heated bed of sodium carbonate and steam as gasification medium and another developed by ABB with direct causticization using a circulating fluidised bed of titanium dioxide. The gasification medium in the second process is air and the pressure is 5 bar. An example of a high temperature process is the one developed by Chemrec based on entrained flow gasification. Here the gasification medium is oxygen and the process pressure is 30 bar. Catalytic hydrothermal gasification is also a technique that has been suggested for black liquor gasification. (Dahlquist and Jones, 2005; Naqvi et al., 2010). In Table 3.4.2 some examples of waste gasification plants are given.

Kirubakaran et al. (2009) have identified some variables affecting the gasification process of biomass; size, shape, structure, environment, flow of medium, heating rate, temperature, type of ash (catalytic or not). The size of the feedstock material affects the heat transfer, the smaller the size of the feedstock particles the better the heat transfer. The shape also has an impact; biowaste is most often found in powder form. Therefore the biowaste needs to be pelletized before gasification to reduce the needed size of the gasifier and pelletization is a power consuming process. If the biowaste instead of turning to powder forms into lumps
Table 3.4.2 Some examples of waste gasification plants. (European Commission, 2006; Palonen et al., 2006; Energos, 2011)

<table>
<thead>
<tr>
<th>Plant (year built)</th>
<th>Process</th>
<th>Temperature [°C]</th>
<th>Pressure [bar]</th>
<th>Feedstock</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>?</td>
<td>Packed bed, steam and oxygen</td>
<td>800-1300</td>
<td>25</td>
<td>Coal and waste plastics, dehydrated sewage sludge, contaminated soils (up to 85 % waste)</td>
<td></td>
</tr>
<tr>
<td>Japan (2001 and 2002)</td>
<td>Fluidised bed + cyclonic high temperature step, steam and oxygen</td>
<td>700-1400</td>
<td>8</td>
<td>Plastic packaging</td>
<td>Demonstration plants, capacity 30 and 65 tons per day gas used for ammonia production</td>
</tr>
<tr>
<td>?</td>
<td>Bubbling fluidised bed, air</td>
<td>580</td>
<td>1</td>
<td>Shredding residues, waste plastics, shredded MSW</td>
<td>Combined with melting chamber with combustion of the gas</td>
</tr>
<tr>
<td>Isle of Wight, United Kingdom (2009)</td>
<td>Fixed horizontal oil-cooled grate</td>
<td>?</td>
<td>?</td>
<td>RDF</td>
<td>Combustion of gas in high temperature oxidation chamber Capacity: 30 000 tons/year 1.8 MW electricity</td>
</tr>
</tbody>
</table>

these lumps need to be chipped if they are larger than 6 cm. When it comes to structure, if the biomass is highly porous the surface area for reaction is very high and the diffusion of reactant/product will be facilitated. Furthermore uniform temperature can be achieved throughout the biomass feedstock resulting in continuous reactions at all parts of the biomass making the composition of the product gases homogeneous. When the biomass is less porous the reaction will only take place at the exterior surface and the product gases will not be uniform. A reactive environment (air/oxygen) results in complete gasification of the biomass while inert environment (nitrogen/argon) benefits pyrolysis resulting in more char. On the subject of flow of medium, secondary degradation of char to gases can be prevented by sweeping away devolatilized gases by using inert gases. If the medium is static then there is a possibility of secondary degradation which may result in complete gasification. However,
According to Kirubakaran et al. no attempt has been reported so far on the effects on biomass gasification when using static inert or static reactive medium. Formation of char is minimized by using high heating rates. Temperature also affects the gasification process; according to Kirubakaran et al. (2009) two temperature ranges are normally selected above and below 500°C. However other temperatures have been reported by other authors, Ptasinski states that temperatures below 600°C should not be selected due to kinetic limitations (Ptasinski, 2008). The processes used for biomass gasification presented by Valleskog et al (Valleskog et al., 2008) are all operated at temperatures between 800 and 950°C (see Table 3.4.1). The last variable mentioned by Kirubakaran et al. as an important parameter for biomass gasification is ash which can also affect the process since impurities can catalyze or inhibit the gasification even in small concentrations. (Kirubakaran et al., 2009)

As mentioned in the beginning of this chapter, air and oxygen are not the only media which can be used for gasification. Ordinary gasification using steam has difficulties with char formation, which reduces the gasification efficiency. Near- and supercritical water gasification offers a solution to this problem according to Matsumura et al. (2005). There are two types of near- and supercritical water gasification: low-temperature catalytic gasification and high-temperature supercritical water gasification. In the low-temperature application temperature ranges from 350°C to 600°C and in the high-temperature application from 500°C to 800°C. In the low-temperature catalytic gasification catalyst are used to improve the reactions even though full gasification is still hard to achieve. At the high temperatures the biomass is highly reactive allowing for high gasification efficiency but when concentrations of organic material are increased the gasification efficiency is decreased. Biowaste has been tested for this application. According to Matsumura et al. researchers at the University of Hawaii have tested using potato waste as feedstock and have received good results. The conclusion of Matsumura et al. is that supercritical water gasification can become an important process for conversion of wet biomass or organic waste. There are still technical problems but it can be competitive with biomethanation. The syngas produced through steam gasification contains mainly methane and carbon dioxide while gas produced through air gasification mainly consists of hydrogen, carbon dioxide and nitrogen. In a review on the thermodynamic efficiency of gasification Ptasinski (2008) concluded that the carbon boundary point is the optimum point for air-blown gasifier and that the exergetic efficiency at this point is 80.5%. For steam gasifiers the optimal gasification occurs when the steam-to-biogas ratio is 1.30 kg/kg and the resulting exergetic efficiency is then 87.6%. Ptasinski also points out that while the steam gasification exergetic efficiency is at a first glance higher the difference decrease when exergy losses at the steam production is considered. Furthermore Ptasinski points out that the feedstock affects the chemical composition of the gas and the process. Biomass contains more oxygen than coal which previously has been the main feedstock for gasification. The optimal point for biomass containing more coal, from exergetic efficiency point of view, is above 800°C. However, for the majority of biomass feedstock the optimum temperature is instead between 620°C and 660°C. For sludge and manure it is even lower, below 600°C. Nevertheless higher temperatures than these are practically suitable due to kinetic limitations and therefore methods have been developed to increase the optimal temperature. One way is co-
gasification with coal and another is thermal pre-treatment. Ptasinski also compares the gasification efficiency of coal, vegetable plant, straw, treated and untreated wood, grass/plants, sludge and manure. Sludge and manure exhibit lower efficiencies than the other feedstocks. Otherwise there are small differences in gasification efficiencies based on lower heating value. (Ptasinski, 2008)

Another possible technique for gasification of waste is using thermal plasma. Gomez et al. (2009) made a review of using thermal plasma for treatment of waste. In this process an electrically generated plasma arc torch is used for the gasification. Thermal plasmas can reach temperatures up to 20,000 °C. Among the advantages with this technique are 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 treatment has been used for hazardous wastes such as ashes from combustion plants, healthcare wastes, asbestos waste, waste from steelmaking, and chlorine containing wastes. The process gives a vitrified slag that can be reused for example for roadbed and concrete aggregates. The conclusion of Gomez et al. is that the technical feasibility has been demonstrated for the thermal plasma technology but the economic viability is unclear. Lemmens et al. (2007), investigated the gasification of pelletized RDF, from carpet and textile waste, in a thermal plasma pilot plant. Due to a non-optimal test reactor they were not able to assess the stability of gasification but still they conclude from their test results that it is possible to achieve a suitable syngas quality from plasma gasification. In Japan a plasma gasification plant using MSW as feedstock has been running since 2003. Also mixtures of 50 % MSW and 50 % auto shredder residues are treated. The capacity of the plant is up to 220 tons/day of MSW or up to 165 tons per day of the mixture. (Willis et al., 2010). Clark and Rogoff (2010) have studied the economic feasibility of a plasma gasification plant, using MSW but also other waste material as feedstock, in Iowa, USA. Different waste capacities, 150 to 600 tons/day, and output configurations were evaluated. The output configurations included using the syngas for electricity production, using the syngas as substitute fuel, using the slag for rock wool production, and using the syngas for production of ethanol fuel additive. They found that a plant with the largest capacity selling the syngas for direct use could be economically feasible.

### 3.4.2 Process modelling

Better understanding of the thermal gasification process and its optimal working conditions can be gained by modelling of the process just as for biogas production in biological processes.

According to Nemtsov and Zabaniotou (2008) even though the processes are different, modeling approaches that are used for gasification of coal could also be applied for gasification of biomass. A number of different types of models have been created for gasification; two examples are kinetic models and equilibrium models. Nemstov and Zabaniotou identify two categories simulation of discrete biomass particle (DPM) and simulation of the reactor. Different models have different applications. Kinetic models can predict the progress and product composition at different positions in the reactor and an equilibrium model can be used to predict maximum achievable yield of the product gas.
According to Di Blasi, equilibrium models can also, given the solid composition and equilibrium temperature, predict exit gas composition. However Di Blasi also stresses the limitations of equilibrium models stating that “they cannot be used for reactor design”. (Di Blasi, 2000; Li et al., 2004; Nemtsov and Zabaniotou, 2008)

Huang and Ramaswarmy suggest a different way of classifying gasifier models and divide them into 0-D, 1-D, 2-D and 3-D models (D is representing dimension). The 0-D is the space independent models which are the thermodynamic equilibrium models. 1-D, 2-D and 3-D models are models that contain space variables that consider local heat/mass transfer. The equilibrium models can be furthered divided into stoichiometric models, which are based on stoichiometric reactions and non-stoichiometric equilibrium models, which are based on minimization of Gibb’s free energy. (Huang and Ramaswarmy, 2009)

Regarding 0-D models or equilibrium models, there are some discussions regarding the accuracy and suitability of such models in relation to the gasification process. Melgar et al. (2007) mention two other studies on coal gasification that has concluded that equilibrium fits the gasification process well and states that similar conclusions have been made by researchers on downdraft biomass gasification (Melgar et al. 2007). In a study by Ramanan et al. (2008) equilibrium modelling is used for modelling the downdraft gasification of cashew nut shell char and the authors conclude that the equilibrium modelling works well for predicting the effect of equivalence ratio, moisture content and reaction temperature. At the equivalence ratios less than 0.15 the model due to pyrolysis fails to predict the gas composition correctly but otherwise the model predictions correspond to experimental values. Another study states that it is important to have a “fairly simplified method” that is at the same time reliable and accurate and that equilibrium models fulfils these demands. Furthermore, the authors mean that kinetic models are very complex and hard to implement on a computer. (Altafini et al., 2003).

In contrast Roy et al. mean that thermodynamic equilibrium never occurs in reality in the gasification process and can only be approximated in the high temperature zone of the downdraft gasifier. Roy et al. instead uses different techniques for modelling the different zones of the downdraft gasifier. The pyro-oxidation zone was solved using chemical equilibrium while finite rate kinetics was used for the reduction zone. (Roy et al., 2009). Huang and Ramaswarmy (2009) found a mismatch between their non-stoichiometric equilibrium model’s result and result from experiments but by modifying the model using real experimental data they created a better match. Li et al. (2004) also tried using a non-stoichiometric equilibrium model to model a circulating fluidised bed gasifier but they also found that the result of the model deviated from the result of the real gasifier. According to the authors earlier work has also reported a difference in gas composition from equilibrium calculations. The greater the deviation the further the system is away from chemical equilibrium. They define something called the best fit temperature, which is “the temperature that minimizes the sum of square of the deviations for five principal gas species (H2, CO, CO2, CH4, N2)” (Li et al., 2004). At full chemical equilibrium and the best fit temperature the actual temperature should be the same and therefore the best-fit temperature could be used as a measure of approach to chemical equilibrium. Examples of non-stochastic
equilibrium models implemented for waste are Mountouris et al. (2006) who implemented a model for plasma gasification of solid waste and Jarunghammachote and Dutta (2007) who created a model of a downdraft MSW gasifier. This model was also modified using experimental data to make it fit reality better.

An example of a 3-D model is presented by Fletcher et al. (2000). They have created a detailed CFD model for an entrained flow biomass gasifier feed with a mixture of seeds, cotton and pieces of stalk. The authors assume that the biomass can be represented as spherical particles. The output of the model is outlet gas composition and temperature. The authors mean that simple mass and energy balances can be used to describe what would happen under equilibrium conditions but when using such models no account is taken to finite rate processes or of variation over space. A CFD model allows for determination of local information and inclusion of finite rate chemistry effects. (Fletcher et al., 2000)

Another approach to gasification modelling is Artificial Neural Networks (ANN). One study created an ANN model consisting of three layers; one input layer with seven nodes, one hidden layer with five nodes and one output layer with three nodes. The feedstock used was five types of waste to simulate MSW: wood (discarded chopsticks), paper (paper cartons), kitchen garbage (from a refectory), polyethylene plastics (from a petrochemical factory) and textile (from a tailor’s shop). The input parameters are percentage of the five feedstock, equivalence ratio and temperature. The output parameters are LHV of gas, LHV of gasification products and gas yield. When the model was tested against an industrial sample the relative error was less than 25% which according to the authors is adequate for industrial demand. (Xiao et al., 2009)

Computational modelling tools that has been reported as used for gasification are Glacier Computational fluid dynamic (CFD) code REI Models, CFX package, MFIX (Multiphase Flow with Interphase eXchanges), ASPEN (Advanced System for Process Engineering), Matlab Neural Network Toolbox and FORTRAN (programming language) (Nemtsov and Zaniotou, 2008; Faaïj et al., 1997, Fletcher et al., 2000; Xiao et al., 2009; Altafini et al., 2003)

3.4.3 Gas cleaning

Particles, char, ammonia and sulphur usually needs to be removed from the gas produced in a gasification process using biomass as feedstock. The particles are removed with cyclones and filters in a two-step process where the gas usually is cooled before entering the filtering step. Char and also ammonia can be removed in a scrubber using water as the scrubber media. For removing the char also oil can be used as scrubber media. The char can also be removed chemically either by reactions at high temperatures (over 1000°C) or with the help of catalysts that can be supplied to the gasifier bed material or in a separate reactor. If the gas will be used as SNG, high temperature removal is not suitable since the methane content of the produced gas is reduced. The sulphur in the gas can be removed by adsorption to active coal or Zink oxide, where the use of Zink oxide is the most efficient process reducing the content to below 100 ppb with operation at 250-300°C. (Valleskog et al., 2008)
At the Kymijärvi power plant of Lahden Lämpövoima Oy in Lahti, cleaning of the gas from waste and biomass gasification to syngas has been tested in a so called slip stream pilot plant. That is, only a small part (about 5%) of the produced gas from a full-scale atmospheric CFB gasifier is cleaned. Tests on gas from gasification of both 40% waste and 60% biomass based fuel and 100% waste were done. In this pilot plant the gas was first cooled and then passed through a hot gas filter. Ash was removed in both the cooler and the filter. The outline of the plant is shown in Figure 3.4.2. Glass fibre bag filters with ceramic coating, low-density candle filter elements of calcium silicate, and filter of aluminium silicate were tested in parallel. The temperature was 320°C to 400 °C during the tests. The plant was running for one year, 2003 to 2004, with good results without any damage to the filters and dust contents of the cleaned gas below 10 mg/Nm³. Tar deposit was kept low in the gas cooler with adjustments of the temperature of the cooling water and with spring hammers. With addition of limestone 80% of the chlorine was removed and with calcium hydroxide 95% was removed. 99.9% of the fuel content of heavy metals was possible to remove with the ash. However, mercury and most of the sulphur will be in the gas phase. (Palonen et al., 2006). Also Göransson et al. (2011) mention dry hot gas cleaning in combination with catalysts as a promising technique for gas cleaning.

3.4.1 Uses of the gas

Produced syngas can be either directly combusted to produce heat or electricity. Another option is the use of the syngas in chemical industry. Also combinations with existing installations are known, e.g. a RDF (Refuse Derived Fuel) gasifier as an upstream fuel production unit of a power plant.

The resulting syngas can be used to produce Fischer-Tropsch (FT) hydrocarbons, methanol and hydrogen. Sewage sludge is a waste product that is suitable for production of methanol. Ptasinski evaluated the sewage sludge to methanol process and found the overall exergetic efficiency to be 56%. A process of producing FT fuel from sawdust was also evaluated and the overall exergetic efficiency was found to be 36.4%. In addition, a process to produce hydrogen from wood (not waste wood) was evaluated and the efficiency was found to be
65.7%. Ptasinski explain some of these large differences in efficiency with that the processes differ in how by-products are used and the degree of energy integration in the process. (Ptasinski, 2008)

To produce SNG the content of methane has to be increased. This is done by reaction of hydrogen with carbon monoxide and carbon dioxide, when also water is produced. Nickel is used as catalyst for those reactions. The reaction is more efficient at temperatures below 300 °C and at high pressures. Three common process designs are; the re-circulated reactor where the temperature is kept low with the help of recirculation of cooled product gas; cooled reactor where the catalyst is placed in heat exchanger tubes and reactor in several steps with addition of steam, where reactors with fixed bed at gradual decreasing temperature is used. After the methanisation carbon dioxide and water are removed from the gas. Carbon dioxide can be removed by membrane separation (operation pressure 25-40 bar), by pressure swing adsorption (using zeolit or active coal) or by scrubbing for example with polyglycolether. The water is usually removed by condensation by cooling the gas to 40 °C. (Valleskog et al., 2008)

3.4.2 Other aspects
In a market analysis by Vallskog et al. (2008) it is concluded that SNG is not competitive to natural gas in Sweden today. Further, the markets of greatest interest for SNG is said to be industry and vehicle fuel, due to the dependency on continues demand for the product as the processes should be run continuously and also due to efficient use of a high quality energy product as SNG. The production cost for SNG is calculated to be 390 SEK/MWh compared to the price for natural gas of 250 SEK/MWh. Vallskog et al. also shows that the production cost for SNG production starts to level out at a size of about 80 MW fuel feed to the process.

To lower the costs for ash disposal there is an interest for ash treatment and to up-grade the ash for further use. (Palonen et al., 2006)

Among the development areas of gasification of biomass, including also waste, are gas cleaning, tar reduction, process operation conditions and increasing system energy efficiency. (Kirkels and Verbong, 2011; Kumar et al., 2009)
4. Biorefinery and integrated systems

Biorefinery systems include the production of several products such as, for example, heat, electricity, ethanol and biogas. By recirculation of mass and energy flows within the system, higher efficiencies can be achieved for the whole production process.

Processes with microbes as production organisms are often called biorefinery operations, especially if they are adding to or replacing petrochemical processes. As an equivalent to an oil refinery, a biorefinery can be used for manufacturing environmentally friendly biofuels and combustible gases as well as industrial chemicals, plastic monomers, synthetic rubber etc. The scope of industrial biotechnology and microbiology is strongly broadening to new areas such as medicine and other products with relationally small volumes. Biotechnology can utilize many sources of biomasses in the production of heat, power, fuels and chemicals, such as different types of waste. Combined biotechnical use of biomasses enables local and even mobile energy production and furthermore produces logistical benefits, economical waste treatment, co-operatives, ecological city planning and other multiplied benefits. Also the biorefinery’s water management can be renewed in order to remove toxic substances, minimize environmental impacts and produce pure, clean water. Finnoflag Oy has developed a technology that converts waste materials into e.g. fuels, chemicals, plastic and rubber via low-energy routes. The Finnoflag technology is based on the PMEU (Portable Microbe Enrichment Unit) which is a new innovative instrument for use in the microbe detection process and that is designed to create an optimal growth environment for microbes. (Hakalehto, 2010).

At present, the economic competitiveness of bio-ethanol strongly depends on the amount of needed energy in the production process besides the feedstock cost. In order to improve the economic performance and increase energy efficiency of bio-ethanol production the concept of integration is of growing interest to satisfy the requirements of economic and technical development, especially when dealing with small-scale bio-ethanol plants. (Kirk, 1984; Starfelt et al., 2009; Pfeffer et al., 2007; Reith et al., 2001; Starfelt et al., 2010; Song et al., 2010).

The results of Starfelt et al. (2009) show that integration of bio-ethanol production with an existing CHP plant can be beneficial from both an energy and economic point of view. For example, it is shown that the integration can give a reduction in biomass feedstock consumption and an increase of power production compared to two stand-alone plants. An integrated system of bio-ethanol and solid fuel production is described by Sassner et al. (2008). If a new small-scale CHP plant can be installed for integration with an existing bio-ethanol plant, the residual energy from the production process can be utilized as much as possible while reducing production costs and CO₂ emissions (Eriksson et al., 2010).

Cherubini and Ulgiati (2010) made a life cycle analysis of a biorefinery using crop residues as feedstock producing ethanol, biogas, heat, electricity and biochemicals. Their conclusion is that a biorefinery reduce the greenhouse gas (GHG) emissions with 50 % compared with a fossil fuel based system.
Also the gasification process is of interest for biorefineries. One example is the GoBiGas project described in Chapter 3.4. The process is here integrated with power and heat production and the produced gas will be used as transportation fuel. Vallskog et al. (2008) show that combination of the production of SNG with power, heat and also liquid fuels can be favorable from an economic point of view. Panopoulos et al. (2006) presents a concept where a solid oxide fuel cell is integrated with biomass gasification.

An example of a new integrated system including waste to energy is the system described by Cheung et al. (2009). They suggest a system combining waste combustion with biofuel production from algae. They see this as a promising system for remote hybrid energy management systems. The waste combustion plant provides heat and \( \text{CO}_2 \) from the flues gases for cultivation of algae. The algae are then used for production of biofuels. As mentioned in Chapter 3.2.1 combustion of waste can also be integrated with a gas turbine to improve the efficiency. Udomsri (2001) has also studied the possibility to combine thermally driven cooling with a waste combustion plant.
5. Comparisons of different conversion processes

Several studies comparing alternative processes for waste to energy utilization can be found in literature. Different methods and approaches are used and also different countries or regions have been studied. Finnveden et al. (2007a) presents an overview of different methods for assessment of waste management systems and some of those methods have been used for evaluating different possibilities for waste to energy systems. Pires et al. (2011) presents a review of system analysis techniques applied on systems for municipal solid waste handling. Some examples of studies, found in literature, comparing different waste-to-energy systems are given below.

Cherubini et al. (2009) have made LCA of three different options to treat MSW, all including energy recovery. The studied options were landfill with landfill gas recovery, sorting using one fraction for upgraded biogas production and one fraction for electricity production by combustion, and the third case producing electricity from combustion of the unsorted waste. The second alternative showed to be the best option with an energy efficiency of 52% and also a low ecological footprint. The energy efficiency for the first alternative was 13% and for the third 22%. Kirkeby et al. (2006) presents LCA of two different alternatives for the MSW system in Aarhus, Denmark. The two alternatives are similar to the second and third alternatives in the study by Cherubini et al. with the difference that the biogas is not upgraded but used for power and heat production and also with the difference that heat production is included in both alternatives. Contrary to the result of Cherubini et al., Kirkeby et al. find the combustion alternative more favourable even though they point out that the difference between the two alternatives is small. Also Fruegaard and Astrup (2011) have made LCA analysis of some waste to energy options for Danish conditions. They compare three options (combustion with and without energy recovery and co-combustion with coal) for RDF fuel and four alternatives for organic waste (combustion with and without energy recovery, anaerobic digestion using biogas for transportation, and anaerobic digestion using biogas for CHP production), where both the RDF and organic waste are from municipal waste. Their conclusions are that co-combustion and combustion of RDF with energy recovery show similar results and for organic waste combustion with energy recovery is a better alternative than anaerobic digestion. LCA of different waste-to-energy scenarios in England are presented by Tunesi (2011). The analysis includes different numbers, locations and types of waste management plants including combustion, gasification and anaerobic digestion. Her conclusion, concerning comparing different energy recovery options, is that a system with combustion performs similar or slightly better than a system with gasification.

Kimming et al. (2011) presents a LCA comparison of two different energy (electricity, heat, fuel) agriculture self-sufficiency systems in Sweden using agriculture residues as energy resource. The first system use straw for energy production and the second use ley, grown as green manure. In the system using straw, ethanol is produced for covering the fuel demand for field operations on the farm, burning straw for heat production and using lignin residues from ethanol production for electricity and heat production in a CHP plant. In the second system biogas is produced from ley that is then used both for electricity and heat production.
in a CHP plant and also upgraded for use for field operations on the farm. Their conclusion is that the system based on using ley needs less farm area to be used to cover the energy demand and it also gives higher emission saving although the results are sensitive to assumptions about soil carbon content and by-product handling.

Gómez et al. (2010) have studied the economic potential for generating electricity from MSW, sewage sludge and manure in Spain. The three conversion routes landfill gas utilisation, anaerobic digestion, and combustion are considered. Their conclusion is that the potential range from 3 to 7% of the electricity generated in Spain. The highest potential and most economical alternative is found to be combustion of MSW.

Münster and Lund (2010) compared eight different waste-to-energy technologies in the Danish energy system from a fuel efficiency, CO₂ emission and economic point of view. The studied technologies are combustion of unsorted waste, combustion of RDF, co-combustion of RDF with coal, biogas from organic household waste and manure used in CHP, biogas from organic household waste and manure used for transportation fuel, gasification of MSW for production of syngas used either as fuel in transportation or for CHP, production of biodiesel from animal fat, and production of bioethanol from straw, grass and paper waste and also production of biogas from fermentation residues. They found that the most attractive alternatives were the one including production of biogas and the one including gasification, which is the opposite to what Gómez et al. found and also different from the LCA analysis of Fruergaard and Astrup. However, Gómez et al. only consider electricity production costs, while Münster and Lund have done a more complex energy system analysis including different possible energy products and also CO₂ emission reduction. The two studies also represent different parts of Europe where Münster and Lund have studied Denmark where heat demand and CHP is important factors in the energy system while those factors are of minor importance in Spain studied by Gómez et al. The studies by Fruergaard and Astrup and Kirkeby et al. also consider Denmark but the studied alternatives are slightly different. Finnvveden et al. (2007b) point out that it is difficult to compare combustion and anaerobic digestion of waste because they have different advantages and disadvantages and that the environmental impact of digestion is dependent on many factors that vary with the studied situation. However, they conclude that anaerobic digestion is a good alternative for some waste fractions such as manure, waste from food industry and some fractions of household waste.

Dornburg et al. (2006) and Dornburg and Faaij (2006) studied different possibilities for the Dutch waste treatment system including several energy conversion processes such as anaerobic digestion, gasification, pyrolysis, and different options for combustion. They optimized the system in terms of primary energy savings and their costs for future scenarios for the year 2020. Their conclusion is that gasification and hydro-thermal upgrading are the most attractive energy conversion technologies and that electricity production is more favourable than transportation fuel production.

The use of MSW for energy purposes in Ireland was studied by Murphy and McKeogh (2004). Combustion, gasification, anaerobic digestion using the gas for transportation and
anaerobic digestion using the gas for CHP production were studied. They found that gasification was more favourable than combustion mainly due to that the market for thermal energy is difficult in Ireland. Further anaerobic digestion using the gas for transportation fuel was found to be the economical most favourable option.
6. Conclusions

In the above description of the state-of-the-art of the waste-to-energy area several different waste categories and conversion processes have been addressed. In Table 6.1 the characteristics of and products from the different conversion processes are summarised and in Table 6.2 identified development areas are given. Further, in Table 6.3 the different waste categories considered for the different types of conversion processes can be found.

Sludge from waste water treatment, municipal solid waste (MSW) and refuse derived fuels (RDF) are all used as feedstock both in anaerobic digestion, combustion, pyrolysis and gasification. Most experiences can be found for combustion and anaerobic digestion of waste and for these conversion processes there are commercial and well-proven technology. However, the focus has so far mostly been on waste management and further development is needed to improve the energy efficiency. For fermentation of lignocellulosic waste, and pyrolysis and gasification of waste the basic techniques need to be further developed and tested to be fully commercial as energy recovery processes. The development areas are different for the different conversion processes but pre-treatment of the waste is one area that is of interest for several conversion processes. Common areas of interest for the thermal conversion processes are gas cleaning/emission control and ash handling/by-product quality and use. Some more unconventional processes for gasification, such as plasma technology and supercritical water gasification have lately also been suggested for waste.

<table>
<thead>
<tr>
<th>Conversion process</th>
<th>Conversion characteristics</th>
<th>Main products</th>
<th>By-products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic digestion</td>
<td>35-55 °C (for hygienisation 70 °C), anaerobic, reactor size 10-10 000 m³</td>
<td>Gas (main components CH$_4$ and CO$_2$)</td>
<td>Fertiliser</td>
</tr>
<tr>
<td>Fermentation</td>
<td>20-400 °C (different for different process steps and configurations)</td>
<td>Ethanol</td>
<td>Solids of lignin (use for pellets production or as fuel in combustion) Stillage (use for biogas or animal feed production)</td>
</tr>
<tr>
<td>Combustion</td>
<td>Steam data 40-110bar/400-540 °C, thermal capacity 5-120 MW (smallest only for heat production)</td>
<td>Heat, Electricity</td>
<td>Ash</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>250-700 °C, absence of oxygen</td>
<td>Char, Oil or Tar, Gas (CO, CH$_4$, hydrocarbons, H$_2$, CO$_2$ (content dependent on feedstock and process conditions))</td>
<td>Char (use as soil amendment, as activated coal, as sorbent)</td>
</tr>
<tr>
<td>Gasification</td>
<td>350-1800 °C, air, oxygen or steam medium, 1-30 bar</td>
<td>Gas (CO, CH$_4$, H$_2$, CO$_2$, H$_2$O, N$_2$(content dependent on feedstock and process conditions))</td>
<td>Ash</td>
</tr>
</tbody>
</table>
Table 6.2 Development areas for different conversion processes

<table>
<thead>
<tr>
<th>Conversion process</th>
<th>Development status</th>
<th>Development areas</th>
</tr>
</thead>
</table>
| Anaerobic digestion | Well-proven technology for waste treatment | Feedstock pre-treatment  
Avoidance of inhibition  
Mixing  
Monitoring and control |
| Fermentation       | Mature and well-proven technology for sugary waste  
Research stage for lignocellulosic waste | Increasing the yield  
Process design  
Energy efficiency/integration |
| Combustion         | Mature and well-proven technology for waste treatment | Emission control  
Plant efficiency  
Ash handling (reducing volumes and increasing quality) |
| Pyrolysis          | Used for waste treatment  
development stage for waste-to-energy | Gas and by-product quality  
Plant efficiency |
| Gasification       | Used for waste treatment  
premature technology for waste | Feedstock pre-treatment  
Process design  
Process operation  
Gas cleaning and separation  
Ash handling |

Anaerobic digestion, fermentation, gasification and pyrolysis give products that can be used as fuel in further energy conversion. Ethanol from fermentation is usually used as fuel in transportation. The gas from anaerobic digestion can also, after upgrading, be used as fuel for transportation but it can also be used directly in an oven, gas engine or gas turbine for heat and power production. The gas from gasification can be used in a similar way as the gas from anaerobic digestion but it can also be further reformed for production of other types of transportation fuels. Most interest in pyrolysis of waste has concerned pyrolysis in combination with combustion with the aim to reach a more efficient emission control. However, during recent years an increased interest for studies on pyrolysis of waste for production of fuels and other products can be seen.

Process modelling can be a usable tool for understanding complex energy conversion processes and optimisation of operation conditions. Process modelling also offers the possibility to control the process and predict its outcome. For biogas production in biological processes and for thermal gasification there exist different modelling approaches. For modelling of the anaerobic digestion process models describing the biological and physical processes but also models based on statistical analyses are used. The main problem with the first approach is to get the right input data. For thermal gasification discussions are going on concerning what approaches are best suited for different purposes. Both kinetic and equilibrium models are available and used. Also statistical models have been suggested. Most modelling work can be found for coal and biomass but there also exist a few studies with applications on waste.

Of the available comparisons of different waste-to-energy systems found, most concerns MSW. The results of the comparisons are dependent on the conditions chosen for the study.
Table 6.3 Summary of conversion processes for different waste categories.

<table>
<thead>
<tr>
<th>Waste</th>
<th>Conversion processes</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge from waste water treatment</td>
<td>Anaerobic digestion to biogas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyrolysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td></td>
</tr>
<tr>
<td>Grease trap sludge</td>
<td>Anaerobic digestion to biogas</td>
<td></td>
</tr>
<tr>
<td>Manure</td>
<td>Anaerobic digestion to biogas</td>
<td></td>
</tr>
<tr>
<td>Biowaste</td>
<td>Anaerobic digestion to biogas</td>
<td></td>
</tr>
<tr>
<td>Municipal solid waste(MSW)</td>
<td>Anaerobic digestion to biogas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyrolysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td></td>
</tr>
<tr>
<td>Food wastes</td>
<td>Anaerobic digestion to biogas</td>
<td>From restaurants and industry</td>
</tr>
<tr>
<td>Waste cooking oil</td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyrolysis</td>
<td></td>
</tr>
<tr>
<td>Refuse derived fuel (RDF)</td>
<td>Anaerobic digestion to biogas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyrolysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td></td>
</tr>
<tr>
<td>Lignocellulosic wastes</td>
<td>Fermentation to ethanol</td>
<td>For example straw, wood wastes, sugar cane bagasse, corn stover</td>
</tr>
<tr>
<td></td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td></td>
</tr>
<tr>
<td>Sugarcane molasses</td>
<td>Fermentation to ethanol</td>
<td></td>
</tr>
<tr>
<td>Industrial waste water</td>
<td>Anaerobic digestion to biogas</td>
<td>From distilleries, food processing</td>
</tr>
<tr>
<td></td>
<td>Fermentation to ethanol</td>
<td></td>
</tr>
<tr>
<td>Waste lubricating oil</td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyrolysis</td>
<td></td>
</tr>
<tr>
<td>Packaging waste</td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td></td>
</tr>
<tr>
<td>Product specific industrial waste</td>
<td>Combustion</td>
<td>Plastic and paper industry</td>
</tr>
<tr>
<td>Bulky waste</td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td>Shredder light fraction (SLF)</td>
<td>Combustion</td>
<td>Furniture etc.</td>
</tr>
<tr>
<td></td>
<td>Pyrolysis</td>
<td></td>
</tr>
<tr>
<td>Clinic waste</td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td>Hazardous waste</td>
<td>Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td></td>
</tr>
<tr>
<td>Synthetic waste</td>
<td>Pyrolysis</td>
<td></td>
</tr>
<tr>
<td>Used tires</td>
<td>Pyrolysis</td>
<td></td>
</tr>
<tr>
<td>Cable tails, metal and plastic</td>
<td>Pyrolysis</td>
<td>For material recovery</td>
</tr>
<tr>
<td>compound material</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As for example where the system is located and what combinations that are included in the options compared. No clear conclusions about what waste to energy technology that is most favourable can be drawn from the studies found in literature.
7. References


Juvonen, M. (2011). Biokymppi Oy, Personal contact


SEKAB (2010b). Personal contact.


Svensk Växtkraft (2007). The Växtkraft project in Västerås


