ENERGY RECOVERY FROM RESIDUAL WASTE BY MEANS OF ANAEROBIC DIGESTION TECHNOLOGIES

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1. ABSTRACT

Anaerobic digestion (AD) is a natural process, spontaneously taking place in natural surroundings, such as marshes, bogs, paddies, or in cesspits, landfills, and dedicated digesters, used for the conversion of organic waste into a rich gas. Typical AD substrates are: manure, sewage sludge, high BOD wastewater, and – more recently - the organic fraction of Municipal Solid Waste (MSW), which is at the heart of this survey. Anaerobic digestion thus converts moist materials that would not sustain combustion into flammable biogas, either used as a boiler or motor fuel, or upgraded to pipeline quality.

Anaerobic digestion is largely based on a sequence of biochemical steps (hydrolysis, formation of volatile fatty acids and acetic acid, conversion into methane and carbon dioxide) and is hence a relatively slow process that can be seriously retarded by inhibitors and toxicants. Moreover, part of the organics (plastics, rubber, wood, lignin in board & paper…) do not degrade and, depending on process conditions, the bacteria responsible for various stages in the process show quite distinct growing rates, yet must still cohabitate harmoniously. Large molecules and hydrophobic substrates either require special pre-treatment for rendering digestion possible, or remain almost unchanged in a moist residue, the digestate.

Treatment technology is subdivided into batch and continuous processes, continuous single step and double or multiple step (staged) digestion, vertical and horizontal treatment units, with various flow arrangements and mixing methods, meso- and thermophilic processes, and also into 'dry' (high solids) and wet' (low solids concentration) digestion. Changes in feed or operating conditions can either disturb equilibrium or result in intermediaries that may inhibit the overall process or shut it down altogether. It is crucial to use adequate designs, enhancing stability, as well as control technologies to continually monitor and adjust the environment to prevent such occurrence.

Anaerobic digestion has been promoted for three decades by National as well as E.U. subsidies, destined for financing R&D and demonstration plants, resulting sometimes in successful process demonstration. However, both technical difficulties and poor economics have hampered a more widespread application. The promise of Green Energy subsidies will somewhat influence upon decision making. Hence, the more promising fields of application of energy recovery by AD are to be identified, as well as subsisting economic challenges. Several processes successfully demonstrated AD of organics from MSW. Unfortunately, only part of fuel values available can be converted by AD and the moist residue still leaves most of the original waste for final disposal by either landfill or thermal techniques. Thus, technical opportunities are limited to those cases in which the digestate can be recycled, i.e. when the fractions to be treated are sufficiently pure and exempt of heavy metals, plastics, and other undesirable contaminants!

2. SURVEY

2.1 Definitions

Digestion is a process by which food is dissolved and chemically converted so that it can be absorbed by the cells of an organism and used to maintain vital body functions. Thereby, complex carbohydrates (e.g. cellulose and starch), fats, fibres, and proteins, are converted into simpler compounds (e.g. sugars, glycerine and fatty acids, amino-acids) before being assimilated into cells. During digestion, these organic compounds are reduced by hydrolytic enzymes, such as
cellulase, protease, and lipase, secreted by bacteria and glands, which split the long molecular chains into monomer units.

The process of **Anaerobic Digestion** (AD) employs specialised bacteria to break down organic waste, converting it into **biogas**, a mixture of carbon dioxide and methane, and a stable semi-solid (**digestate**). Digestion and fermentation processes have been observed and practised ever since prehistoric times, but their study and development on a scientific basis only could start after the discovery of micro-organisms and of enzymes secreted by bacteria on the one hand, the application of chemical engineering concepts in fermentation on the other hand. In most cases complex populations develop that are capable of conducting consecutive processes capable to break down organic waste. The latter follow a sequence of hydrolysis, acidogenesis (formation of fatty acids), acetagenesis and eventually methanogenesis in a balanced, steady, and controllable fashion. These four consecutive steps normally proceed side by side, but the first and last step are sometimes singled out, since they may require specialised conditions, controls, and auxiliaries.

**Hydrolysis** may be conducted using separate aerobic, thermal, chemical, or enzymatic means. Acidogenic bacteria then turn the products of hydrolysis into simple organic compounds, mostly short chain (volatile) acids, e.g., propionic, formic, lactic, butyric, or succinic acid, or alcohols, e.g., ethanol, methanol, glycerol, and acetone. The specific concentrations of products formed at this stage vary with the type of bacteria as well as with feed and conditions, such as temperature and pH. **Acetagenesis** occurs through carbohydrate fermentation and other metabolic processes with acetate as the main product. Long chain fatty acids, formed from the hydrolysis of lipids, are oxidised to acetate or propionate and hydrogen gas is formed. Under standard conditions, the presence of hydrogen in the solution inhibits oxidation, so that hydrogen scavenging bacteria are required to ensure the conversion of all acids.

The transition from organic material to organic acids causes the pH of the system to drop. This is beneficial for acidogenic and acetogenic bacteria, but problematic for methanogens, which prefer neutral or slightly alkaline conditions and are very sensitive to abrupt changes. If the pH falls below 6, they cannot survive. Since they are slow to develop, they may fail to adapt to changes, e.g., in inlet temperature, concentration, or other conditions. Therefore, for the digester to remain stable an equilibrium based on complex interactions of several varieties of bacteria is required; the kinetics of the entire process can best be described by that of methanogenesis.

A simple introduction (in German) is given in: [http://www.fnr-server.de/cms35/Biogas.304.0.html](http://www.fnr-server.de/cms35/Biogas.304.0.html).

### 2.2 Anaerobic Digestion Processes

Anaerobic digestion is conducted in a variety of modes: batch or continuous, single, double or multiple step (staged digesters), vertical or horizontal treatment units, static units or others, using various mixing methods, and 'dry' (high solids) or 'wet' digestion (low solids concentration). A simple digester consists of a single, suitably shaped, static or mixed digester, in which the most desirable operating conditions are carefully maintained, yet in a robust manner.

In the **batch process**, substrate is sealed in the digester for the complete retention time. When unmixed, the content of the digester stratifies into layers of gas, scum, supernatant, an active layer, and stabilised solids at the bottom. Retention times range from 30-60 days, with typically an organic loading rate between 0.5 and 1.6 kg TVS/m³ reactor volume/day. Disadvantageous are the long retention times, the low organic loading rates and the formation of a scum layer. The production of biogas ideally follows a bell curve with time.
In the **continuous process**, fresh material either continuously or periodically (e.g., daily) enters the tank and an equal amount of digested material is removed. Ideally, all processes occur at a fairly steady rate, resulting in a constant biogas production. Because of flow, there is some movement, material is somewhat more mixed and does not become stratified so easily inside the tank. The removed effluent is, however, a mix of completely and partially digested material. Hence, some of the more successful designs dictate the path of the digestate inside the chamber, or use either plug-flow or a cascade of consecutive units. Some designs take advantage of the successive phases of digestion, optimising each one under distinct conditions.

In a **single stage** digester, all bacteria inhabit the same volume and their relative growth rates are kept in balance. The operating conditions are not necessarily optimal for any bacteria, but are acceptable to all. The most crucial parameter is pH, kept close to neutral in order to ensure the survival of methanogens.

In a **multiple stage** digester, the substrate passes progressively through sequential chambers, where AD occurs in a staged approach. If two tanks are used, the first tank features hydrolysis, acidogenesis and acetogenesis, while the second optimises methane forming conditions from volatile acids. The first tank is heated to a uniform temperature and mixed and fed continuously. The pH is allowed to fall. The residence time in this chamber is 10-15 days. The second tank must maintain a higher pH and provide capacity for gas collection or storage. Two-stage digesters can be more efficient because the micro-organisms have specific nutrient needs, growth capacities, and abilities to cope with environmental stress. In more complex, multiple stage digesters each tank has a unique purpose and living environment. The need to construct multiple tanks, however, may offset cost savings.

Digestion is subdivided into two categories of solids content: **dry digestion**, with a typical dry solids (DS) content of 25-30% and **wet digestion**, with a DS-value of less than 15%. When the feedstock is MSW, both systems require adding water to the feedstock to lower the total solids (TS) content. A higher TS contents leads to smaller, less costly digesters, yet requires more expensive pumps needed to move denser material, as well as more maintenance. Systems with lower TS tend to have much better mixing, and are amenable to co-digestion with dilute feedstock, such as sewage sludge or manure. Dense particles, such as sand and glass, tend to settle to the bottom for lower TS-values.

There are also multiple stage systems with different criteria for solids and liquids. Incoming waste is pulped, and the liquid, which contains soluble organics, is sent immediately to a methane-producing tank. The remaining solid is hydrolysed under more drastic operating conditions in a different tank, dewatered, and the liquid from that tank is also sent to the methane production tank. This system can take advantage of the significantly lower retention time required of liquids compared to solids.

For many waste streams, large amounts of water must be added to reduce the solids content, thereby adding to cost of dewatering the digestate to reuse the process water. In a **gravity driven system**, the material is fed from the top into a vertically chamber and effluent is removed at the bottom, with gravity being the only driving force to bring the waste through the bacterial population living in the chamber. For this system, the ideal solids content is 2-10%. A **plug-flow** digester is suitable for a higher solids content, because the more viscous material may move as a plug through the tank.
Mixing can take place as a result of the pathway the waste must travel before its removal. Some systems have interior walls that increase (static) mixing. More intense mixing results through the use of mechanical, hydraulic, or gas mixers to keep solids in suspension. Mechanical mixing is less common because of a difficult maintenance. Also, mechanical mixers get wrapped with solids or entangled. Recirculating heated digested waste inoculates the fresh waste, improves mixing and ensures temperature control. Biogas is bubbled through the digester for mixing.

2.3 Anaerobic Digestion Technology

Digesters range in complexity from simple, empty cylindrical cans with no moving parts to fully automated and integrated industrial facilities. The simplest are easy to design and maintain, but require consistent monitoring and are less efficient. The most complex, on the other hand, are designed to detect subtle changes in conditions, such as may occur with small changes in feedstock feed rate, concentration, and quality.

Design and feedstock considerations dictate technical choices, such as batch or continuous flow, vertical or horizontal orientation, capacity, total solids content, number of stages, mixing and pre-treatment. Digester processes are designed and optimised for specific conditions, locations, types of waste, and the desired degree of autonomy and complexity. Vertical tanks are gravity driven, the material flowing generally downward, though the path can vary, depending on interior boundaries in the chamber. In other cases, material is pumped into the bottom of the tank and removed from the top, causing general upward flow accompanied by a lesser, downward, gravity driven flow. Horizontal tanks require greater space and are closer to plug flow than to perfect mixing. See also: http://www.soton.ac.uk/~env/research/wastemanage/anaerobic.htm#top

The digester provides optimal physical and chemical conditions for a balanced or differentiated development of micro-organism colonies, taking into account the numerous Control Parameters (Table 1) whereas both toxicity and malfunction problems (foaming, elutriation of cell material) are carefully to be avoided:

<table>
<thead>
<tr>
<th>Physical</th>
<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature, mixing, space loading rate,</td>
<td>Redox potential, pH, Carbon/Nitrogen Ratio,</td>
</tr>
<tr>
<td>food to micro-organisms ratio</td>
<td>Nutrient Balance, Alkalinity</td>
</tr>
</tbody>
</table>

Several factors within the digester affect the physical environment and therefore the rate of digestion and biogas production. Facility managers must monitor and maintain the following parameters within acceptable ranges: pH, temperature, C/N ratio, retention time, organic loading rate (OLR), bacterial competition, nutrient content, the presence of toxicants and solids content. Digestion and fermentation processes must be closely maintained under steady-state conditions. The following parameters are typically monitored: Table 2.

<table>
<thead>
<tr>
<th>Physical</th>
<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, pressure, residence times,</td>
<td>pH, volatile fatty acids, alkalinity, hydrogen</td>
</tr>
<tr>
<td>flow rates, biogas production</td>
<td></td>
</tr>
</tbody>
</table>
A practical difficulty is that the substrate in some cases is available only on a cyclic basis (e.g. in case of an annual harvest). In most plant feeding occurs once a day whereas residence times vary from at least ca. 10 days to rather long time periods, of the order of one or more months. AD is hence a slow process and the reactor concept and operating conditions are carefully adjusted towards the feed or the mix of feedstocks employed.

2.4 Potential Feedstocks

The first substances ever to be digested anaerobically were human and animal waste (e.g. in a cesspool). According to some reviews such operations already appeared in the Antiquity and countless small units have been operated both in India and China, as well as in Western farms.

The first industrial operation evolved in the wake of sewage treatment: smelly and pathogen-rich sewage sludge can conveniently be stabilised using AD, generating a flammable gas and leaving an odour-free, pathogen lean and hence sanitised residue with still some nutrient value for gardens and agriculture. Digested sludge is no longer putrescent and much easier to dewater.

The introduction of industrial breeding of animals locally leads to huge concentrations of dung, far in excess of what could be used on attached land. Anaerobic digestion hence was widely introduced to treat effluents, reduce concomitant nuisances (odour, soil pollution), and also to generate useful products (fermentation gas, humus). However, initiatives have been hampered by the relatively high investment levels, associated with the long residence times required, as well as by the difficulties of mastering digestion processes on a steady and technical basis and of making the best use of the fermentation gas (biogas) and residual solids.

Table 3 cites some potential feedstocks in Digestion processes.

<table>
<thead>
<tr>
<th>Origins</th>
<th>Agricultural Origin</th>
<th>Industrial Origin</th>
<th>Municipal Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult Waste</td>
<td></td>
<td>Wastewater</td>
<td>Sewage Sludge</td>
</tr>
<tr>
<td>Crop Waste</td>
<td></td>
<td>Sludge</td>
<td>Municipal Solid Waste</td>
</tr>
<tr>
<td>Dedicated Energy Crops</td>
<td>By-products</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

However, some pre-treatment and post-treatment is often required, as is summarised in the next table 4:

<table>
<thead>
<tr>
<th>Operations Upstream and Downstream of the Digester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Storage and Pre-treatment</td>
</tr>
<tr>
<td>Biogas storage, treatment, and upgrading</td>
</tr>
<tr>
<td>➢ Sorting</td>
</tr>
<tr>
<td>➢ Chopping</td>
</tr>
<tr>
<td>➢ Warming</td>
</tr>
<tr>
<td>➢ Acidification</td>
</tr>
<tr>
<td>➢ Mixing</td>
</tr>
<tr>
<td>➢ Recycling</td>
</tr>
<tr>
<td>➢ Storage at low, medium, or high pressure</td>
</tr>
<tr>
<td>➢ Elimination of water and sulphur and nitrogen compounds</td>
</tr>
<tr>
<td>➢ Removal of carbon dioxide</td>
</tr>
</tbody>
</table>

Source of Tables 1 to 4: LIOR CD-ROM Collection – Renewable Energies Series
Similar reasons eventually led to the treatment of organic fractions from MSW, supplied either by selective collection of garden waste and kitchen waste, or by mechanical sorting of residual MSW. Such pre-treatment processes vary with the characteristics of the incoming waste and the effects desired. The most common treatment is separation and shredding. Separation of metals, glass and plastic is similar to the practices usual in recovery facilities and may be conducted in many different ways, each method resulting in recovery of some ‘valuables’ (solid fuel, metals, glass…) and in removal of contraries (ash, dust, salts …). Size and solids content reduces entering waste increases the amount of soluble organics. Shredding and pulping gives bacteria access to a greater surface area, reducing retention time.

Diluting waste with water improves mixing and pumping, and also allows bacteria to move more freely inside the digester. In a hydrapulper the recovery of recyclable materials is combined with preparing organic suspensions. Also the availability of useable substrate can be enhanced by a wide variety of pre-treatments, such as rupturing bacterial cell membranes, forming soluble waste, by boiling under pressure and subsequent pressure release, via wet and dry mechanical methods of grinding, ultrasonic action, or freezing. Such chemical or thermal treatment reduces particulate organic matter, yielding more soluble, lower molecular weight compounds. Biomass waste, contains components that are not readily available as substrates for anaerobic digestion. Consequently, a substantial portion of potentially available carbon is not converted into methane and the incompletely digested residues require additional processing prior to their return to the environment. In the particular case of the organic fraction from MSW the yield is estimated by considering MSW-composition, and the dry solids (DS), Volatile Matter (VM), and – more importantly - the potential biologically generated Volatile Matter (bVM) content of each fraction.

For MSW management the smallest digester that is still economically viable is about 50,000 tons per year. The size of individual chambers ranges from 70 m3 to 5000 m3. Larger plant makes use of multiple chambers, to avoid incomplete mixing as well as-short circuiting, as normally occurs when individual chambers get too large. Potential operating problems include corrosion, clogging of ducts, foaming, fouling of surfaces and loss of methanogenic organisms by their elutriation, etc.

2.5 Process Parameters

The rate of digestion is measured by gas production, microbial growth, and substrate degradation rates. Temperature is the most critical process parameter. Anaerobic bacteria survive from freezing to 70°C, but thrive best in either a mesophilic (25-40°C, preferably 35 °C) or a thermophilic range (50-65°C, preferably < 55 °C). Thermophilic digestion allows higher loading rates and achieves a more complete pathogen destruction and degradation efficiency of the substrate, yet it is more sensitive to toxins and changes in the environment and less attractive from an energetic point of view. Furthermore, thermophilic cultures require a month or more to establish a population. Mesophilic bacteria tolerate greater changes in their environment, including temperature. The stability of the mesophilic process makes it more popular in current AD facilities, albeit at the expense of longer retention times.

Temperature is carefully monitored at various locations in the digester and maintained through insulation, circulation and solar heating. Temperature fluctuations can be extreme in smaller or poorly insulated digesters or in digesters in cold climates. Digester heat is lost through heat transfer to the surroundings or through formation of water vapour. Heat is added by preheating the recycled slurry or by direct steam injection into the digester.
pH is a major variable to be monitored and controlled. The range of acceptable pH in digestion is theoretically from 5.5 to 8.5. However, most methanogens function only in a pH range between 6.7 and 7.4. A falling pH can point toward acid accumulation, which typically occurs if there is an overload of volatile solids in the digester. The acidogenic bacteria then thrive, producing more organic acids and lowering the pH to a level lethal to methanogens. A declining methanogen population leads to further acid accumulation and action to restore process stability is required, such as recycling more water. Conversely, prolific methanogenesis may result in a higher concentration of ammonia, increasing the pH above 8.0, which will impede acidogenesis. This is opposed by adding fresh feedstock, spurring acidogenesis and acid formation.

Maintaining pH is especially delicate at start-up because fresh waste must undergo acid forming stages before any methane forming can begin. Operators may add chemicals to the system, such as calcium carbonate or lime, also when the pH drops due to increased loading rate, signifying an increase in VFAs and decreased activity with methanogens.

Gas production is the only parameter that shows digester instability faster than pH monitoring.

The Carbon/Nitrogen Ratio may be either monitored explicitly or simply by keeping track of the waste types entering the facility, knowing the relative make-up of each. If a feedstock is high in carbon, manure or sewage sludge can be added to increase nitrogen. A high C/N ratio will lead to a rapid consumption of nitrogen by the methanogenic bacteria and lower gas production rates. A low C/N ratio, or too much nitrogen, can cause ammonia to accumulate which would lead to pH values above 8.5. Additionally, the quality of the compost resulting from the digestate lowers with ammonia production. As with composting, the optimum C/N ratio is between 20-30.

The retention time is the average time taken by organic material to digest. The longer a substrate is kept under appropriate reaction conditions, the more complete degradation will be. The rate of reaction, however, decreases with rising residence time, so that there is an optimal in cost effective digestion, depending on feedstock, conditions and use of the digestate.

Lower retention time reduces the size of the digester, resulting in cost savings and leads to higher production rates per reactor volume unit, but also to a lower level of degradation and gas yield. The retention time ranges between 14 and 30 days for most dry processes, and can be as low as 3 days for wet-only processes. The optimal value varies according to technology, process details, temperature and waste composition. For a specific digester, it may even change from day to day with changing feedstock or from season to season with changing temperatures.

Most digesters perform some sort of mixing in order to minimize settling within the tank and to ensure that conditions are consistent throughout the digester and that bacteria have rapid access to digestible surfaces. A poorly mixed digester will form stratified layers, reducing useful volume and longer retention times. In case of poor mixing short-circuiting may occur and undigested material may exit an unmixed digester. One method is stirring, another to recirculate water and/or biogas into the digester.

Decreasing solids content also reduces required retention times, because bacteria more easily gain access to the liquid substrate; also, the relevant reactions require water. Moreover, mixing is more complete and easier when the solid content is lower. The solids content is generally
adjusted adding significant quantities of recycled water. For feedstocks with variable solid content, such as MSW, the ISKA technology uses percolation to control organic loading.

The **organic loading rate** (OLR) determines how much volatile solids are put to the digester. A higher OLR feed rate may cause crashing of AD if the acidogenic bacteria would multiply and produce acids rapidly. An early indication is lower biogas production and eventually a lower pH.

Other parameters are methane formation, partial pressure of H₂, bacterial competition, solids and nutrient content, the presence of toxicants.

Research into reducing retention time in the AD process historically has focused on:

- Separating the consecutive stages of digestion so that the bacteria population is optimised for its purpose.
- Improving internal circulation and mixing patterns.
- Introducing surfaces, such as foam or other porous carriers, on which the bacteria can live permanently, reducing their washing out with the effluent.
- Closer control of operating conditions.
- Pre-treating waste to increase digestibility.

### 2.6 Major Output Flows

The AD processes generate two types of outputs: a gas phase, and a moist liquid or semi-solid digestate. The gas phase can be characterised by means of the following quality criteria or options of further usage:

- **Gas Phase - quality criteria:**
  - Biogas formation rate and amount of main compounds (methane and carbon dioxide) in the biogas.
  - Level of fatty acids (VFA), of acetic and formic acid.
  - Level of impurities, such as sulphur and nitrogen compounds, mainly as hydrogen sulphide and ammonia.

- **Gas Phase: options of usage**
  - Substitute Natural Gas (upgrading to pipeline quality).
  - Power generation (spark ignited and Diesel engines, gas turbines normally necessitating larger gas flows).
  - Motion of motor vehicles.
  - Combined Heat & Power (CHP) generation.

- **Effluents**
  - Solid (can it be handled with a spade) or Liquid?
  - Quality?
  - Liquid for fertilising and/or irrigation
  - Solids, to be used as a soil structure improving substrate
  - Advantages?
  - Markets?

Energy recovery clearly focuses on the gas phase, a mixture of mainly methane and carbon dioxide. In simple applications such fermentation gas can be used as it comes, without further purification or upgrading. A more sophisticated usage requires separation of entrained droplets...
and of condensable water vapour, using cooling, condensers and demisters, and also of corrosive
gases. Techniques for removal of organic acids, ammonia and hydrogen sulphide are well-known
e.g. from manufacturing synthesis gas, but these methods become quite expensive in small-scale
applications. Sometimes simple absorption beds or modular Pressure Swing Adsorption units will
be preferred. Such techniques are strictly required to avoid undue corrosion in downstream
equipment. Before upgrading to pipeline quality the pressure will be raised, generally to 1 – 3
MPa, rendering the treatment operations more efficient and compact.

The different substrates and processing methods (wet or dry A.F.) also produce distinct solid or
liquid effluents (digestate). Part of it is recycled with process water, with the aim of reducing the
volume of effluent liquids; however, there are limits to recycling, since toxic or undesirable
compounds, such as salts and heavy metals, should be sluiced out continuously or periodically!
Success stories on a prosperous application of the resulting solids as a soil structure improving
substrate are rather scarce and relatively less documented in AD literature.

The digestate after aerobic post-treatment is a stable, organic humus-like material, the subsequent
use of which depends on market conditions for compost and on the feedstock characteristics of to
the AD process. In the case of MSW the digestate will be contaminated with sand, plastics, and
heavy metals, severely limiting the scope of its eventual application.

2.7 Balances

The material balance in Table 5 shows a typical flow of materials for an anaerobic MSW
digestion system (courtesy of O.S.W.).

Table 5 Material balance for an anaerobic MSW digestion system (courtesy of O.S.W.).

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Flow Weight %</th>
<th>Flow Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW</td>
<td>Pre-sorting</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Process water</td>
<td>Separation of RDF and metals</td>
<td>28</td>
<td>23</td>
</tr>
<tr>
<td>Steam</td>
<td>Biogas</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Poly-electrolytes</td>
<td>Digestate cake: of which</td>
<td>3.5</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>- sand</td>
<td></td>
<td>(5)</td>
</tr>
<tr>
<td></td>
<td>- coarse inert material</td>
<td></td>
<td>(8)</td>
</tr>
<tr>
<td></td>
<td>- moist cake (DScontent of 43.7 %)</td>
<td></td>
<td>(54)</td>
</tr>
<tr>
<td>Process cake</td>
<td></td>
<td></td>
<td>25.5</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>133.5</td>
<td>133.5</td>
</tr>
</tbody>
</table>

The moisture content of raw waste is normally too low, and water must be added so that it can be
pumped. Generally this is provided by dewatering the final solid digestate and re-circulating the
water back to the mixing tank. However, some salt and toxicants should be sluiced out, in order
to avoid their accumulation. Most plants thus use a combination of fresh and recycle water.

Biogas is the energy carrier derived from the process. Typical values for biogas production range
from 80-130 m3 per ton of waste feedstock. The methane content of biogas ranges from 50% to
as high as 75%, though most plants report values of 60%. The remainder is predominately carbon
dioxide, with trace elements of other gases, such as hydrogen sulphide, ammonia and water
vapour. These play a critical role in its potential uses.
The energy balance shows that large plant combining heat & power is self-sufficient on its biogas. Because heat is a by-product of power generation, it makes less sense for a large AD plant to burn biogas in a boiler.

2.8 Social and Economic Factors

The production of biogas generally has had a very favourable mediatic outlook, because - as a 'green' treatment method - it has at times been successfully opposed to the thermal techniques (cf. Greenpeace), especially to process those wet organic effluents that would not sustain combustion. Also, it has historically been subsidised by many a National and E.U. R&D project. Moreover, in several E.U.-countries it can claim Green Energy as well as combined heat & power (CHP) subsidies and possibly also other financial benefits.

Nevertheless, the expectations that have been fostered for more than 30 years, at first as a consequence of the first oil shock, never completely materialised. The reasons for this sad state of affairs are multiple: some are technical or economic, others relate to institutional factors and to culture or convenience. The occurrence of technical and operating difficulties, the necessity of adapting processes or specific operational factors to various substrates, the variability in available techniques and the largely empirical approaches in process development and selecting optimal operating conditions have been one major stumbling stone.

Being a slow process, AD requires relatively large plant, to be maintained under moist and corrosive conditions. This seriously hampers process economics. Biogas sources, coming from agricultural or from landfills, are often situated in the middle of nowhere, far from potential users of heat & power. Connecting to the grid may be quite expensive and local needs ill-adapted to local potential of heat & power generation. Such an 'island' configuration is markedly different from one in which all outputs supply a district heating & power grid, as is traditional practice in Denmark. These shortcomings are possibly less so when MSW serves as an AD-feedstock.

Nevertheless, Investment & Operating Costs must be evaluated on a strict case-by-case basis, taking into account the market Value of the Biogas, that associated to the Effluent Cleaning and Disposal realised, and possibly to the financial subsidies and associated benefits earmarked for Green Energy. Substrates derived from MSW are rather less predictable in composition and value and in pollutants load than animal dung or sewage sludge, which is a rather unfavourable factor for applying AD as a method of energy recovery from the organic fraction of RDF!

Salient factors in decision-making are:

- The availability of separately collected or otherwise separated moist organic fractions, e.g., during green waste collection or Refuse-Derived Fuel (RDF) production.
- Possibilities for marketing heat & power. In Denmark, the availability of district heating is a favourable factor. Depending on local regulations and possibilities, the ease of access to the power grid may be an asset, or a barrier.
- Possibilities for using the dewatered digestate, after an aerobic post-treatment, as a soil amendment.
- Conditions for discharging a liquid bleed stream from AD
- Nuisances associated with each particular solution or waste management strategy.
- Presence of political or institutional forces militating actively for green solutions.

Nevertheless, it is desirable that the community decisions would be based on a sound technical & economic basis, rather than on political propaganda.
3. CASE STUDIES

In what follows, several case studies are presented, with the aim of comparing various substrates and processing methods, as a first step in assessing their feasibility. An Australian survey study is related in: http://www.greenhouse.gov.au/challenge/methane/mwbapp4.html. An important factor is in differences in raw materials and associated context.

3.1 Manure – Sewage Sludge

Manure and Sewage Sludge is the oldest field of application of AD. Those traditional substrates show a number of potential strategic advantages, e.g.

- Less greenhouse gas emissions, especially with respect to methane,
- Environmentally sound recycling of organic waste,
- Reduced nuisance from odours and insects,
- Pathogen reduction,
- Improved fertiliser efficiency,
- Savings for the farmers (http://www.ecop.ucl.ac.be/aebiom/articles/biogas/biogas.htm),

and, above all in this particular context, a free energy production.

Nevertheless, experience shows that the level of implementation has remained low, only at a level of few percent. A positive exception is Denmark, a country with a strong agricultural tradition, ad hoc governmental initiative, and an easy delivery of heat & power to the grid!

3.2 Landfill

Landfills are still widely used for the disposal of MSW and organic waste, especially in countries with a low population density and/or lenient technical Standards! The operation of a Sanitary Landfill also involves a necessity of controlling landfill gases: the uncontrolled evolution of methane has an important safety as well as Greenhouse Impact, so that flaring is a simple, cheap and expedient measure to control odours and methane emissions. Obviously, using such landfill gas is much more sustainable! Technically, the system required is composed of the following unit operations:

- Gas collection – Maintaining pressure gradients from the origins of the gas to the points of suction.
- Separating condensation water at an early stage, in order to avoid obstructions in piping.
- Operating a flare, for safe disposal of excess gas.
- Leachate collection, treatment and effluent monitoring.
- Land reclamation – considering all possibilities.

One of the major incentives for the development of Mechanical/Biological plant for treating MSW has been the EU - Landfill Directive, prohibiting the landfill of organic waste. Prior digestion holds the promise of decreasing both leaching and landfill gas and is highly recommended by Greenpeace in its campaigns against incineration or other thermal treatment.

According to estimates related to the current Belgian MSW composition sorting roughly eliminates ¼ of the feed for recycling, as RDF + wood (19 wt. %) and metals (3.6 wt. %),
whereas up to 16 wt. % arises as biogas from digesting the organic fraction. However, the bulk of
the input (67 %) subsists as a moist (DS of 54 %) digested substrate. Thus, AD of the organics in
MSW mainly makes sense as a pre-treatment to landfill, but fails producing the type of volume
reduction provided by the major alternative, i.e. a thermal treatment.

3.3 Current processes for the organic fraction of MSW

The website of Davis University http://cbc1.engr.ucdavis.edu/conv/suppliername.asp offers a
broad survey of new techniques in waste management amongst which 55 different entries on AD!

The first recorded example of anaerobic digestion of fractions, separated from MSW, was active
in the early eighties at Pompano Beach, Florida (capacity 100 tpd of MSW, RefCom). The
concept was sponsored by DOE and due to Prof. Pfeffer, University of Chicago. A plant visit was
made 25 years ago, showing good pre-treatment to provide an organic fraction, after primary &
secondary shredding, ferrous metal removal, trommelling, and air classification. The resulting
organics were mixed with sewage sludge, nutrients, and water, and digested in mechanically
agitated digesters. Mechanical stirring was a severe source of operating problems, plastics and
textiles winding around the shaft until moving it became impossible!

The first full-scale EU-process, Valorga, at Amiens, was designed to treat organic solid waste as
a one-step, plug-flow continuous AD process. The process dilutes and pulps the organic fraction
to about 30% solids content, considered to be "dry", i.e. of high dry matter content. Steam is used
for heating and maintaining temperature in the digester. Mesophilic or thermophilic systems are
used, depending on feedstock, technology, and economics. The digester consists of a vertical
outer cylinder, with an inner cylinder of about the 2/3 diameter of the outer one. Material enters
at the bottom, on one side of the inner cylinder, and must flow up on this side and down the other
side of the inner cylinder before it moves to exit. The retention time is ca. 3 weeks. Biogas is
injected at the base of the digester and the bubbles serve as a means for mixing and keeping
solids suspended. The digestate is dewatered and can then be composted (http://www.valorgainternational.fr/index.htm).

The Dranco process (http://www.ows.be/) was developed by O.W.S. as a high solids, single
stage, anaerobic digestion system operating at thermophilic temperatures. Feed is introduced
daily on top of the reactor and digested material at the same time is removed from the base. Part
of the digestate is recycled as inoculation material, while the balance is dewatered to an organic
compost material. There is no mixing within the digester, other than that brought about by the
downward, plug-flow movement of the waste and some gas bubbling upwards. The technology is
commercial with nine full scale plants in operation throughout Europe, the first opening in 1992.
From a ton of processed waste 0.3 MWh/y of electricity is produced from utilizing the biogas and
0.06 kg/h of steam generated.

CiTec (http://www.citec.fi/lang/eng/enviroment/Waasa_process/Ref_biogas.pdf) offers the
Waasa process, a single stage, wet anaerobic digestion system. The organic fraction of MSW is
shredded, homogenised, and diluted in a pulper, using recycled process water and some make-up
water, to reach the desired concentration of total solids (10-15% TS). Steam is injected into the
pulper to pasteurise the feed for one hour at 70 °C. A pre-chamber is used to ensure that all
material has a guaranteed minimum of few days retention time. The resulting slurry is further
digested in a well-stirred reactor, featuring mechanical impellers and injection of biogas. The
plant at Vaasa has both thermophilic and mesophilic modes running in parallel (retention time of
10 and 20 days respectively). The gas production is in the range 100-150 m³/tonne of bio-waste added, and a volume reduction of 60%, and a weight reduction of 50-60% is achieved, at a 20-30% internal consumption (heat) of biogas. The digestate can be further treated by aerobic composting, but this depends on input quality. There are several plants operational in Europe and Japan based on the Waasa process. Capacities range from 3000 - 90,000 tonnes per annum.

The ISKA Percolation process (U-plus Umweltservice AG; www.iska-gmbh.de/) addresses the putrescible organics fraction of the waste stream. It involves mechanical sorting, as well as hydrolysis and digestion, with dewatering of the digestate. Biodegradable material is separated from MSW and subjected to a hybrid aerobic/anaerobic degradation process. The ISKA process uses aerobic hydrolysis (percolation) of insoluble organic material to reduce the overall retention time. After this step, the material passes to standard anaerobic methods for production of biogas and reduction of mass. The digestate is eventually dewatered and sent to aerobic composting or conversion by thermal means to energy or other products. The energy available from biogas production is roughly sufficient to power the process. The ISKA process was chosen for a new facility near Sydney, Australia (170,000 metric tons/yr). The demonstration plant at Buchen, Germany was expanded to 150,000 metric tons/yr.

Other process descriptions can be gathered from the references given at the end of this paper.

3.4 Evaluation and Outlook

At EU level all major promotional measures affecting AD were taken in the framework of either Biomass activities (R&D and Demonstration) or Renewable Energy activities at large. Another action with a major impact on AD was also the Landfill directive (Directorate General Environment), influencing upon the recovery or flaring of biogas for strictly environmental reasons. Many R&D and Demonstration AD projects have been supported, e.g. by the former DG XVII (Energy), but all such support to projects has eventually been abandoned since many years, taking into account the fact that AD was considered to be a mature industrial technology, and that there was hence no need for further demonstration of its feasibility and applicability. The economy of the AD process has always been somewhat questionable, and only environmental constraints could justify its application, with or without subsidies. Projects involving AD of the organic fraction of MSW have been supported in few cases (Valorga process, OWS process) but the economic viability of specific technology has never been proved from an energetic point of view alone: AD can only be considered as one of the possible treatment options (i.e. associated with an efficient sorting at source that generates green waste streams) in the framework of an integrated MSW treatment concept.

At present DG TREN (A combination of formerly DG Transport + DG Energy) supports Demonstration projects concerning Clean Vehicles and Fuels (EU Directive on the use of biofuels as well as other renewable fuels for transport of May 2003 requiring a 2% use of biofuels by the year 2005 and up to 5.75% by 2010). In this context Biogas is considered an interesting possibility, especially in the public transport sector (buses, trucks, taxis, city distribution and refuse collection, etc.). This is still an emerging technology; yet, there are already many examples of such use in public transportation in many EU countries: Ex. Lille and Chambéry (France), Trollhättan and Stockholm (Sweden), Jyväskylä (Finland), etc. Biogas for transport is included into the priorities of the 6th EU Framework Program within the topic of Alternative fuels. Biogas sources considered are Agricultural Wastes, Municipal Wastes, Water Purification.
In Sweden the price of compressed Biogas is about 15% lower than for petrol, per unit of energy, and comparable to that of diesel for commercial traffic. The extra gas tanks render the vehicles more expensive, but with a reasonable driving distance and considering other benefits it is still cost-neutral to choose biogas as a fuel. In Sweden > 2,700 light vehicles and ca. 700 heavy vehicles run on biogas, with > 30 filling stations available for biogas. A reasonable estimate is that biogas could replace ± 3% of the total fuel consumption in Sweden. In Finland a recent study reveals that biogas production for transport use in the region of Jyväskylä could satisfy the fuel consumption of 2,260 passenger cars/year (Personal communication from Dr. Gianluca Ferrero).

4. CONCLUSIONS

The growing awareness of problems originating in an inappropriate treatment of organic waste has stimulated worldwide research, development, and demonstration efforts of new concepts and processes, to convert these principles into practise. Anaerobic Digestion is such a technique, which also has been demonstrated as a technically feasible process, duly deserving further consideration in any integrated waste management concept addressing MSW. The conversion of a sizeable part of organic waste into a convenient source of energy, i.e. biogas, is a precious asset, not in the least in times of oil scarcity and of economic support for renewable forms of energy. The simultaneous generation of digestate, which can be turned into a soil amendment, may be an added advantage. However, as for aerobic compost, it is unlikely to satisfy specifications if based on sorted residual waste.

Implementing AD also encounters several obstacles that must all be overcome. The first is simply perception. AD treats putrescible waste, which when leaking into the surroundings spreads unpleasant odours. The NIMBY principle is strongly developed for AD treatment plants, despite the controlling of odours with negative pressure and biofilter treatment. A second obstacle is a lack of knowledge and information dissemination. Various methods of generating green energy can conveniently be studied from a series of CD-ROMs, available from LIOR (http://www.lior-int.com/). Useful homepages are also found at http://www.biogasworks.com/, for actual biomass works, http://www.biogas.ch/ a Swiss and http://www.biogas.org/ a German biogas works homepage. There are very few companies manufacturing facilities, little research being done outside of the farming community, and no professional trade organisations promoting the technology specifically for MSW. The BioCycle Journal of Compost and Organics Recycling is a good source and also organises US-conferences, currently focusing on farming applications.

Municipalities rightly are very hesitant to try out new MSW technology. Anaerobic digestion of MSW was considerably confronted with mechanical problems in the handling and preparing of the feedstock and a need for specially designed digestion systems for this purpose was identified. At present, there are perspectives (http://www.ecop.ucl.ac.be/aebiom/articles/biogas/biogas2.htm) for combining AD and composting on selected MSW fractions. Nevertheless, if the main output digestate cakes, have no other outlet but landfill or incineration, there is little logic in combining three processes, with concomitant cost factors and potential problems in an integrated plant.

A major attraction of AD today resides in the Green Energy subsidies that are granted by EU Member Countries. There is no specific subsidy related exclusively to Biogas or energy from Biogas. The Communication from the Commission “EU Policies and Measures to Reduce Greenhouse Gas Emissions: Towards a European Climate Change Programme (ECCP)” states that one of the proposed measures in the area of waste is the promotion of the biological treatment of biodegradable waste. Indeed, even the most optimistic sources do not predict a
reduction in the volume of organic waste, a stream contributing disproportionately to landfill gas emissions and odour. Processing waste locally reduces truck traffic and associated air emissions. However, an AD facility requires land allocation, a valuable commodity in urban areas. Hence the need arises to make the process more efficient, reducing retention time and space requirements. Another need is to identify markets for the impure compost produced. The future of AD treatment units at present clearly depends on policies with respect to energy, environment, and agriculture!

**ABBREVIATIONS USED**

AD = Anaerobic Digestion  
DS = dry solids  
MSW = Municipal Solid Waste  
TS = total solids  
TVS = Total Volatile Solids

**ACKNOWLEDGEMENT**

Useful and interesting discussions are acknowledged with Dr. Gianluca Ferrero, formerly with DG XVII, ir. Peter Van Acker (OVAM) and Mr. Luc Duysens (LRM), further also with technology suppliers, such as O.W.S., U-Plus and Valorga.

**LIST OF REFERENCES**