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Biogas from Organic Waste - A Case Study

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Abstract

This paper presents a case study to investigate the potential for upgrade of a bio-waste treatment plant. The paper also discusses development potentials in order to optimize the plant for maximum energy and environmental benefits. Data gathered over two consecutive years about the production of biogas, energy and bio-rest were considered and mass balance analysis of inputs and outputs of the plant were carried out. An estimate of the energy and environmental impact of the plant were carried out, and it was observed that the plant had significant environmental benefits. However, the study demonstrates, through material balance analysis of the plant's operation, that the amount of produced methane and hence, generated electricity can be further increased by optimising the operation of the plant.

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Keywords: *Biogas, organic waste, anaerobic digestion (AD), municipal solid waste (MSW), biomethanation*

1. Introduction

The cost and security of energy and emissions of greenhouse gases (GHG) and other pollutants from the existing means of energy production are two main problems that have led to many technological developments in alternative energy sources. Using biomass to produce energy is one such alternative that has recently become attractive worldwide as a clean and sustainable source of energy. Another problem is effective disposal of Municipal Solid Waste (MSW), because the biodegradable part of MSW leads to unrestrained emissions of methane when dumped untreated. However, due to rapid urbanisation, landfill sites are becoming scarce and stringent legislations are in force, particularly restricting disposition of degradable waste in landfills.

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Nomenclature

GHG	greenhouse gases
MSW	municipal solid waste
AD	anaerobic digestion
ABP	animal by-products
LPG	liquid petroleum gas
WWS	waste water sludge
NMOC	non-methane organic compounds
LHV	lower heating value
THP	thermal hydrolysis process

It is recognised that biodegradable waste can be feedstock to produce useful energy, leading to waste minimisation at the same time. Therefore, waste treatment plants to produce biofuel and electricity are common in many countries.
Anaerobic digestion (AD) of MSW has advanced in Europe due to European regulatory pressures on waste disposal (EU landfill directive 2008). In July 2009, total ban on landfills was decreed in Norway. In addition, there has been increased focus on the implementation of Animal By-Products (ABP); regulation (ABPR EC 1774/2002), which resulted in building many waste treatment plants around Europe. This paper studies an AD biogas plant from Norway to investigate its development potential. The operation of the plant was monitored over a period of two years and data on production of biogas, energy and bio-rest was gathered. An energy and environmental balance were performed and parameters for optimization of the plant were discussed.

2. Anaerobic Digestion- Bio-Waste Treatment Technology

Anaerobic digestion (AD) is one of the preferred technologies for treating organic municipal solid waste (MSW) for the production of biogas and methane, which can be used as alternative fuel to liquid petroleum gas (LPG) and natural gas. The residue, after completion of the AD process, is a stabilized organic material that can be applied directly on agricultural land (without any maturing) as a bio-fertilizer, and thereby can replace artificial/mineral fertilizers and offer the possibility for recycling of nutrients (nitrogen and phosphorus). Thus, AD of bio waste combines the energy production with environmental benefits.
Digester design criteria and performance of AD process attracted te attention of many researches. For example, Igoni et. al. [1] investigated the designs of anaerobic digesters for producing biogas from municipal solid-waste and analysed the effects of various parameters such as temperature control, pH, C/N ratio, moisture content, waste particles and effects of mixing on biogas product characteristics. Zhang et. al. [2] compared the digestion efficiency of source segregated domestic waste and the mechanically recovered fraction of MSW. They concluded that higher percentage of biodegradability, leading to higher energy potential, can be achieved if the organic fraction of MSW is segregated at the source.
Banks et. al. [3] monitored the performance of an anaerobic digester receiving domestic food waste over a period of 426 days and showed that for each tonne of input material the potential recoverable energy was 405 kWh. Volatlie substance added with a methane content of around 62%. They observed high ammonia concentration in the digester, which could have been due to high nitrogen from the volatlie fatty acids in the food waste. In another study, Banks et. al. [4] monitored the bio-cycle anaerobic digester in South Shropshire, UK over a period of 14 months and again found that the source-segregated waste was readily biodegradable and produced a biogas with 60% methane. The process had a very favourable energy balance with around 400 kWh of energy recoverable from each tonne of waste processed. Those studies offer guidelines for the expected yield of biogas from the treatment of municipal solid waste.

3. Plant Specifications

The plant considered in this study is located in Nord Trøndelag County in central Norway. It's actual "waste-zone" covers an area of 98200 km2, with a population of 230000 inhabitants. Three organic substrates are treated in the plant: organic household waste, sludge from wastewater and a minor part of ensilage waste from fish farms.

The plant has a total capacity of 30000 to 45000 tons of organic waste. Due to high demand on waste flexibility, the original plan was based on 50 % of BDMSW and 50 % Waste Water Sludge (WWS). In addition, the plant was prepared to treat additional ABP category 2 waste (Category 2 ABP material includes high risk material) [5] , as well as Biological Degradable Industrial Solid Waste (BDISW).

4. Feedstock and Energy Balance

The primary sources of biomass, which we seek to utilize, are the organic fraction of municipal solid waste from residential, commercial and industrial sources. The fraction of the bio-waste in Norway can be assumed as 69.5 % of the total MSW, based on the characterisation of US MSW biomass materials, (i.e. paper, food and yard wastes, wood, leather, cotton and wool) and petrochemicals constitute another 15 % [6]. By using the atomic analysis of various types of wastes, and the atomic weights of the respective elements, it is possible to derive the composite molecular formulae corresponding to mixed food wastes and paper [7]:

Mixed food and green wastes: $C_6H_{9.6}O_{3.5}\,N_{0.28}S_{0.2}$
Mixed paper: $C_6H_{9.6}O_{3.54.6}\,N_{0.036}S_{0.01}$

It can be seen that sulphur and nitrogen are relatively minor components and occur principally in mixed and green food wastes. Moreover, if nitrogen and sulphur were ignored, the molecular structure of mixed paper is very close to cellulose, $(C_6H_{10}O_5)_x$. Furthermore, If minor elements were also ignored, the average molecular structure of organic compounds in MSW can be approximated by the molecular composition $C_6H_{10}O_4$ [7].
Biogas is a product of biodegradation of refuse in the AD process, and it contains primarily methane (CH_4) and carbon dioxide (CO_2), with trace amounts of non-methane organic compounds (*NMOC*) that include air pollutants and volatile organic compounds.
Anaerobic digestion, which is also known as biomethanation, or methane fermentation can be divided into four stages:

1. *Hydrolysis* or fermentation: where complex organic molecules (cellulose, proteins and fats) are broken down into simple sugars, amino acids, and fatty acids by hydrolase, an exoenzyme. Hydrolysis of carbohydrates takes place within a few hours while proteins and lipids take a few days to break down.
2. *Acidogenesis* or formation of organic acids: The monomers formed in the hydrolytic phase are taken up by acidogenic bacteria to be further degraded into short chain organic acids, alcohols, hydrogen and carbon dioxide.
3. *Acetogenesis*: In this stage, acetogenic micro-organisms further break down the hydrogen and carbon dioxide gas to produce mainly acetic acid and organic acids and alcohols which are subsequently converted into acetate. The acetate serves as a substrate for methane-forming bacteria and the acetogenic bacteria, which grows in a synergetic relationship with methane forming bacteria.
4. *Methanogenesis*: IN the final stage, bacteria known as methanogen, convert the acetic acid into methane, CO_2 and water under strict anaerobic conditions. A nutrient-rich by-product, known as the digestate, is formed during this process. The *pH* level should be maintained between 5.5 and 8.5 and temperature between 30-60 ^oC to maximize rate of digestion [8].

As explained, in the fourth and final stage of the anaerobic digestion (following fermentation and the formation of organic acids), methane is formed by methanogenic bacteria, either by breaking down the acids to methane and carbon dioxide, or by reducing carbon dioxide with hydrogen. Two of the representative reactions are shown below:

Acetogenesis

$$\boldsymbol{C_6H_{12}O_6 \xrightarrow{yields} 2C_2H_5OH + 2CO_2} \quad (1)$$

Methanogenesis

$$CH_3COOH \xrightarrow{yields} CH_4 + CO \tag{2}$$

$$CO_2 + 4H_2 \xrightarrow{yields} CH_4 + 2H_2O \tag{3}$$

The maximum amount of natural gas that may be generated during anaerobic decomposition can be determined from the approximate, simplified molecular formula [6]:

$$C_6H_{10}O_4 + 1.5H_2O = 3.25CH_4 + 2.75CO_2 \tag{4}$$

From equation (4), ignoring other minor constituents such as moisture and inorganic particles, the molar ratios of CO_2 and CH_4 in the product are 54% and 46% respectively. However, Angelidaki et. al. [9] suggested a different formula in which the molar amounts of CO_2 and CH_4 in the product are equal, this is shown in equation (5):

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \xrightarrow{yields} \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CO_2 \tag{5}$$

Ratio between CO_2 and CH_4 depends on the oxidation state of the carbon present in the organic material, which means that the more reduced the organic carbon content is, the more CH_4 will be produced [9].
Assuming that waste material contains 70% of biomass, and assuming that the dry organics amount to 60% of the biomass. Thus, the total mass of dry organic material $(C_6H_{10}O_4)$, is equivalent to 420 kg/tonne of waste material.
The molar mass of $(C_6H_{10}O_4)$ is 146 g/mole, which means that 420 kg of the material is equivalent to 2.56 kmol. From Equations 4 and 5, a yield of 3.25 moles of CH_4 for each mole of $(C_6H_{10}O_4)$ is obtained, in other words, the expected yield of methane is 8.32 kmol per tonne of waste material. In terms of mass, 133,5 kg or 0.1335 tonne of methane per tonne of solid waste is anticipated.
Modestly assuming that the thermal efficiency of electricity generation at the plant is 25%, and considering the Lower Heating Value (LHV) of methane (which is 50,000 kJ/kg), the total electricity produced per tonne of waste material will be according to equation (6):

$$133.5\ [kg/tonne]\ x\ 50000\ [kJ/kg]\ x\ 0.25\ =\ 1668750\ kJ/tonne \tag{6}$$

Hence, the expected theoretical output electricity from the solid waste = 463.5 kWh/tonne
This analysis is used in this work to evaluate the actual output of the plant against the theoretical expected output to investigate causes of lower productivity and potential for upgrade of outputs.

5. General Process Description

The AD process has four main stages: Pre-treatment, waste digestion, gas recovery and residue treatment. Pre-treatment of waste is very necessary to obtain homogeneous feedstock. The pre-processing involves separation of non-digestible materials and shredding. The plant under consideration utilises an anaerobic digester based on the technology of Thermal Hydrolysis Process (THP) at high temperatures combined with steam explosion, a schematic view of the waste treatment process is shown in figure 1.
In the THP process, the organic residues undergo both extreme disintegration, i.e. breaking up cells and dissolving organic solids into water, and complete pathogen, seed and helminthic (parasite) kill. The complex carbohydrate and protein substrates are reduced to single monomers of saccharides and amino acids, which rapidly acidify in the digestion process to give short chain volatile fatty acids. These fatty acids are rapidly converted to biogas in an anaerobic digester. The positive consequence is increased and accelerated biogas production during anaerobic digestion and improved dewater ability of the digested product [9]. Furthermore, in the THP process, hydrolysis occurs rapidly due to heating of the material to around 165°C under pressure and then releasing the pressure.

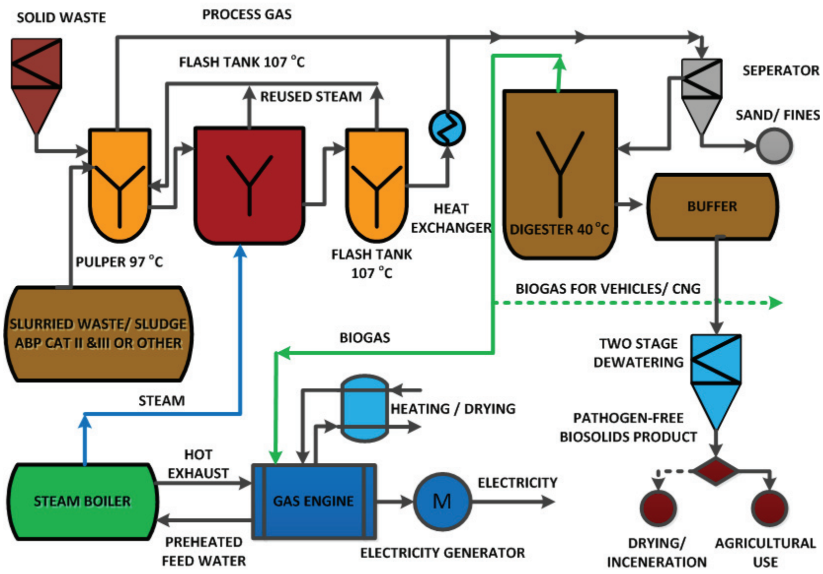

Figure 1. Schematic view of the waste treatment process

This increases the amount of biodegradable material available for biogas production. Another advantage is that all inputs to the digester are sterilized and therefore there is no risk of pathogen contamination in the digestate [9].

6. Analysis Of Plant Data

The data is comprised of monthly registers of raw material inputs and production of digestate at the plant as well as energy produced in the form of biogas, heat and electricity over two years of monitoring. Figure 2 below indicates the total inputs of sludge, municipal waste and ABP to the plant.

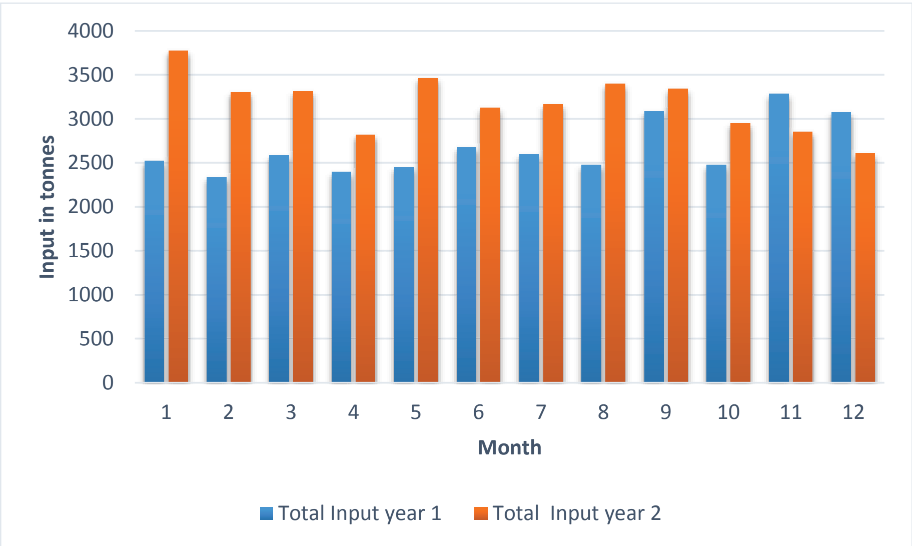

Figure 2. Total monthly inputs to the plant

The amounts received in year 1 are 17 % more than the total amounts received in the following year. As indicated by figure 2, plant inputs do not vary significantly during the year. While the total year round input in year 2 is higher than the input in the previous year, it is detected that the monthly inputs for November and December in year 1 were higher than the corresponding inputs in year 2. This could be attributed to the occurrence of a particular social occasion.
Figure 3 indicates the amounts of input materials for each category.
A dramatic increase in ABP is observed, which accounts mainly for the total increase in waste received by the plant, while the increase in other types of waste is not significant. The amount of ABP processed by the plant has almost doubled four times, which can result in the increase of fatty acids and ammonia and lead to operational problems. The increase in sludge is not so significant, while a decrease in the total amount of waste is perceived; however, this is compensated by the increased amount of ABP.

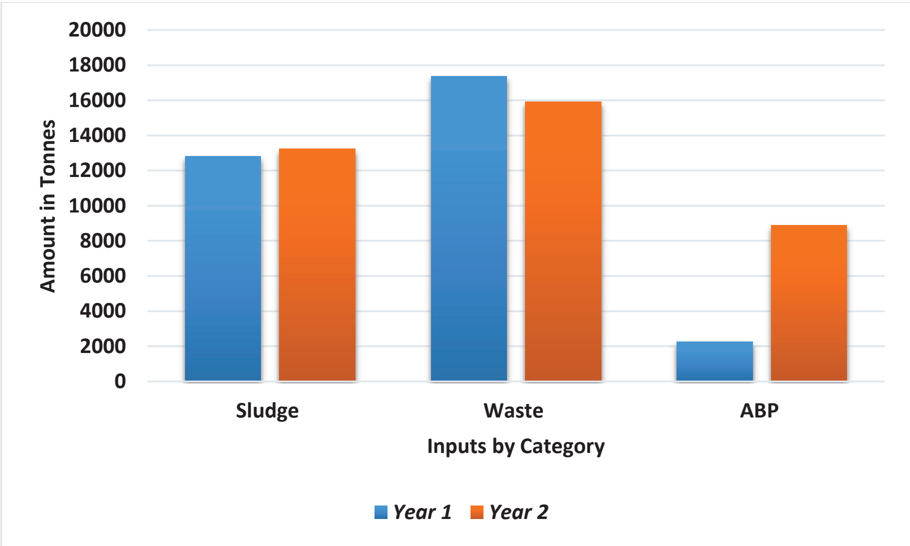

Figure 3. Comparison of inputs of waste by category in tonnes.

The major outputs of the plant are represented in figure 4. It is identified that product gas in year 2 is slightly lower than product gas in year 1. In spite of this fact, an increase in produced and sold electricity is noted. This could be due to an improvement in the quality of the product gas, which could be related to the higher percentage of ABP, as discussed earlier. Nevertheless, it should be carefully perceived that high concentrations of long-chain fatty acids and ammonia in the by-product could inhibit the biogas process at concentrations higher than 5g lipid/dm and 7gN/dm respectively [10].
The addition of ABP waste into the plant is occasional and cannot be predicted, for that reason it is obvious that the plant has to operate with a stable input of organic MSW and sludge. These sources of raw material are more or less stable from one year to another. On the other hand, the ABP waste represents a variable source of organic waste. However, it seems that this source has a positive effect on the produced biogas and digestate quality.
An increase of 14%, in the amount of digestate in year 2 as compared to year 1 is observed. When this value is related to the increase in inputs to the plant, which is 17%, it can be concluded that a greater amount of waste has been converted to useful biogases, but this cannot be absolutely confirmed as this percentage lies within the error limits of the measurements.

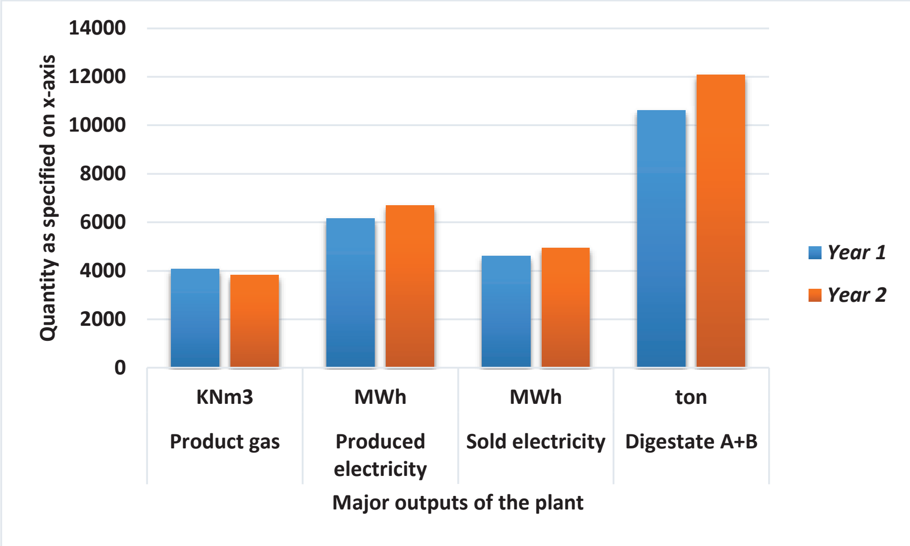

Figure 4. Comparison of Product gas, produced electricity and sold electricity

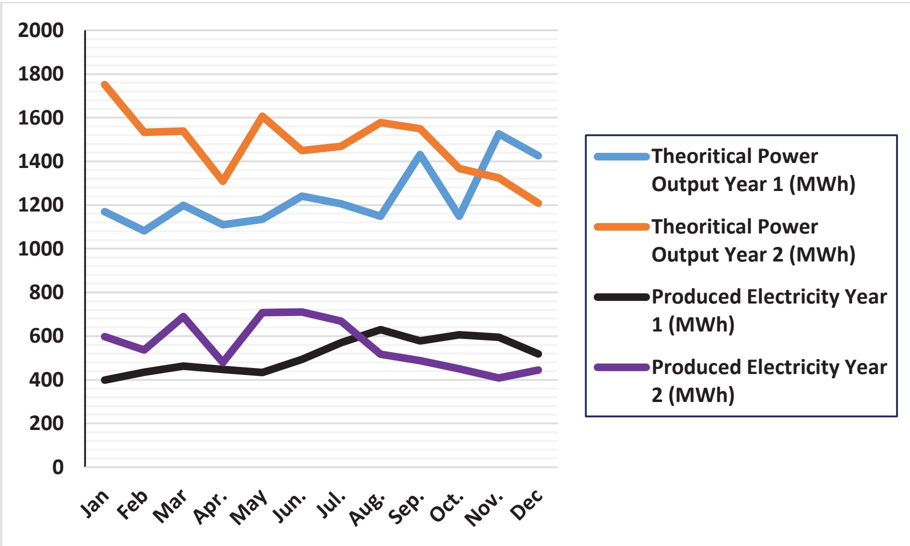

Figure 5 Theoretical and actual Electricity Generation of the plant for year 1 and year 2

The expected theoretical output electricity from input solid waste (considering the assumption of 25% efficiency of the thermal power generator) is plotted against the actual power generated at the plant in figure 5. It can be established from the graph that there is considerable potential for increasing the gas yield of the plant, and hence the power output, as the actually produced electricity is around 35% of the theoretical potential.

7. Conclusions

The types of inputs to a waste treatment plant were monitored over the period of two years to study the effects of various types of waste on the product of biogas and bio-rest. The following observations were concluded:

- An increased percentage of ABP reflects positively on the quality and amount of biogas produced, but of course, to the extent that does not inhibit the digestion process or lead to operational problems in the plant due to the accumulation of fatty acids and lipids.
- ABP contains high percentage of ammonia, and due to the susceptibility of the thermophilic digestion to ammonia, it would be better to use mesophilic digestion.
- The addition of controlled amounts of ABP will increase the methane yield and improve the quality of the produced biogas, which seems to be occurring in the process under consideration, but this needs further investigation to determine the appropriate dilution of the ABP and the optimum loading of the various products.
- The amount of methane produced by the plant could be increased significantly when comparing actual yield to the theoretical expected yield from the plant. The reduced production could be the result of inhibited anaerobic process or due to functional problems in the plant, which need to be further investigated and considered.
- Actually produced electricity was around 35% of the theoretical potential, which can be improved by optimising the process.

Acknowledgements

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