BIOGAS, AS A RENEWABLE ENERGY SOURCE, PRODUCED DURING THE ANAEROBIC DIGESTION OF ORGANIC WASTE

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Abstract

Identifying alternative sources of energy is a matter of urgency, since conventional energy sources are becoming exhausted. Renewable energy sources, such as biogas, can be generated from organic waste, through the anaerobic digestion (AD) technology. Investigations were undertaken at the CSIR to study biogas potential derived from the anaerobic digestion of organic waste. The results of the study showed that biogas was generated when initially 100% kitchen waste was degraded and later kitchen waste combined with primary sludge in different concentrations in a laboratory scale anaerobic digester (Volume: 5L), which was operated at 35ºC. The results of the study showed that with increasing loading rates to the reactor as well when the percentage primary sludge increased (70%), a higher volume of biogas was obtained. Furthermore, the results showed a clear relationship between the loading rate and the gas production rate. This paper will provide recommendations as to the possible applications for the generation of heat and power. Possible applications are to fuel microturbines to generate electricity and process heat.

1. INTRODUCTION

Identifying alternative sources of energy is a matter of urgency, since conventional energy sources are becoming exhausted. With the increasing population, the demand on energy is growing accordingly (Kalyuzhnyi, 2008). Renewable energy sources, such as biogas, can be generated from organic waste, through the anaerobic digestion (AD) technology (Gosselink, 2002). Not only will the population and the economic growth cause a demand on the energy supply, it will also contribute to the generation of waste. The production of biogas, operating anaerobic digesters, has been used worldwide as a source of renewable energy (Kalyuzhnyi, 2008; Hartmann & Ahring, 2006). Van Nes (2006) describes that in the rural areas of China and India, biogas produced from organic waste, e.g. kitchen waste, animal dung and human excrements, is used as energy for lighting and cooking. So far only a few examples of biogas production from organic waste, mainly manure, for the generation of light and cooking gas have recently been identified in South Africa (Agama, 2008; personal communication, J. Van Ierland, 2008).

Anaerobic digestion (AD) is a process in which micro-organisms break down biodegradable material in the absence of oxygen. The digestion process begins with bacterial hydrolysis of the input materials in order to break down insoluble organic polymers such as carbohydrates and make them available for other bacteria. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids, where after acetogenic bacteria convert these resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide. Methanogenic bacteria finally are able to convert these products to methane and carbon dioxide, (Hartmann and Ahring, 2006).

Anaerobic digestion can be applied to treat various organic waste streams - waste water (sewage), agricultural waste (manure), food waste and the organic fraction of municipal solid waste (OFMSW). Globally, landfilling of waste was practised; however, this way of disposing waste has been banned and thus discontinued in a number of countries (Jewaskiewitz, 2008). In South Africa landfilling is still considered the most practical waste management method, although many of the active landfill sites in

South Africa are currently under pressure to close (Jewaskiewitz, 2008). The middle class in South Africa generates in the order of 2.7 million tonnes/year of domestic waste (DEAT, 2006). This translates to about 0.7 kg waste/day produced per person, comparable to 0.73 kg/person/day produced in developed countries such as the UK (Austin *et al*., 2006). The biological treatment of organic waste (40% by mass) has become an established technology in many European and Asian countries. This way of organic waste treatment should also be implemented in South Africa, for two main reasons: firstly, less waste will find its way to landfills, which are running out of space, and secondly, the organic waste has the potential to generate biogas, as a renewable energy source. Eskom, the local energy supplier in South Africa had a shortage in electricity supply in the first few months of 2008, which resulted in many power outages and in subsequent economic losses for a great number of businesses.

The anaerobic digestion process was and in some cases still is an established technology as a way to reduce the amount of sludges produced at sewage plants in South Africa (Ross et al., 1992). Sadly, many of these digesters are presently not operated properly or are even entirely non-operational or simply not in use. The study by Snyman *et al.* (2006) revealed that at sewage plants in South Africa, the main challenges relate to operation and maintenance of infrastructure. This is not unique for South Africa, since Kalyuzhnyi (2008) revealed similar situations for the former USSR, where the first full scale implementation of the AD technology happened in the 1950’s at a waste water treatment plant (WWTP) in Moscow. The biogas was used for heating the digesters, similarly as occurred in South Africa in those days. Nowadays, the authorities in Moscow and surroundings have realised the potential of biogas resulting from animal manure and the waste generated by the Russian agro-industrial complex and are thus revisiting the utilisation of the many existing digesters for the generation of renewable energy.

Considering that many municipalities in South Africa still have digesters on site, which could be used for the co-digestion of sludges generated at the WWTP with organic waste, produced at restaurants, the Russian example could be followed in South Africa. Therefore, revitalising the digesters on WWTP sites by adding organic wastes to the sludge degrading digesters to generate alternative energy should be encouraged.

The objective of the study presented here was to investigate the biogas generation potential from the co-digestion of kitchen waste with primary sludge in different ratios.

2. EXPERIMENTAL

In order to achieve the objective, a 5 L closed glass bottle was used as a stirred anaerobic batch reactor. The reactor (M) was operated at 35°C (mesophilic range). The reactor was filled for about 50% of the volume with sieved (0.5 cm x 0.5 cm) anaerobic sludge, of which the volatile solids (VS) was 20 g/L, obtained from the anaerobic digester at Daspoort, Pretoria, sewage plant. Heating the reactor to the required temperature was achieved by way of a hot plate stirrer system. The reactor was fed with organic waste, obtained from the kitchen of a CSIR-campus restaurant. This waste (VS: 150 g/L) was minced in a “Sinkmaster” (an organic waste disposer, normally build into kitchen sinks to remove table scraps) and added to M, to start the digestion process. Sample taking and gas emission took place through two separate openings at the top of the reactor. From day 1 to day 40, M received only kitchen waste in different concentrations to stabilize the reactor process and to initiate the biogas production. From day 41-57, the reactor received kitchen waste (KW). During this period the loading rate was increased steadily from 1.7 to 2.5 to 3.7 g VS/L.d^{-1}, with the aim to investigate whether the gas production rate would increase accordingly. From day 58-77 the KW was added to the reactor in combination with primary sludge (PS) in the ratio of KW 75: PS 25. Thereafter (day 79-90) this was changed to a ratio of KW 50: PS 50, while from day 90-105, the ratio became KW 30 and PS 70. The loading rates of the reactor are presented in Figure 1.

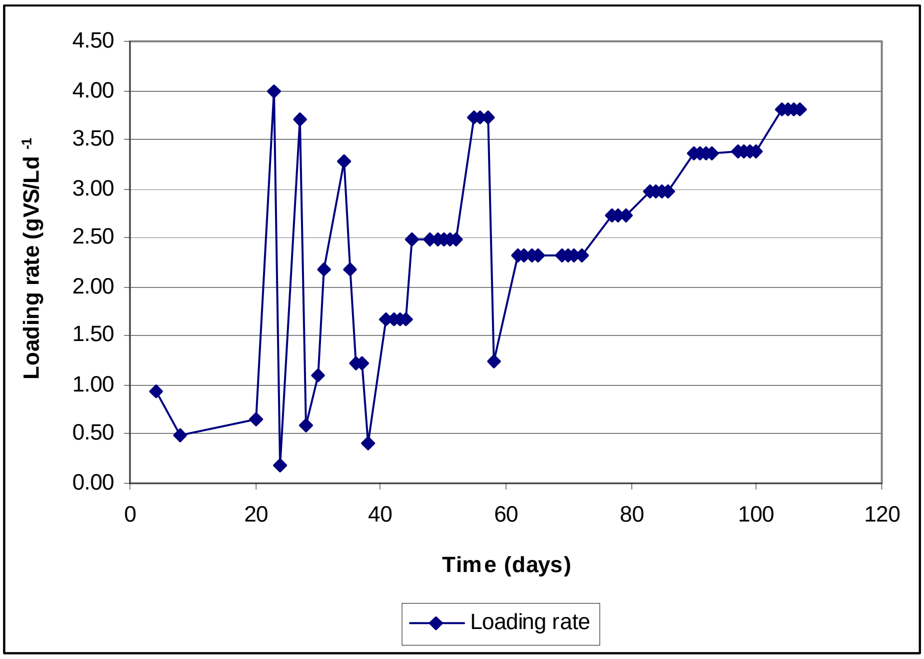

Figure 1: The loading rate of the reactor M.

It can be observed from Figure 1 that the loading rate to the reactor during the first 40 days of operation was irregular, which corresponded with the stabilisation of the process. Once it was noted that the gas production and thus the reactor operation became stable, the loading rate was increased step wise (day 41-57). Figure 1 furthermore shows that the loading rate during third part of the experiment (day 58-105), being the co-digestion period was performed in a controlled manner, with regular small increases in the loading rate.

3. ANALYTICAL METHODS

Daily samples (125 ml) were taken from M for pH measurement and for the determination of the Ripley ratio. The Ripley ratio is a function of the volatile fatty acids (VFA) and alkalinity concentrations, which were determined by titrating a reactor sample to pH values of 5.75 for the VFA concentration and to 4.3 for the alkalinity concentration with 0.5 M HCl (Ross *et al*., 1992). The Ripley ratio is an important parameter to monitor the degradation process in the digester as it represents a measure of both the VFA and the alkalinity concentrations; two important parameters in the AD process. An excess in VFA production can usually be ascribed to reactor overload. The methane producing bacteria become inhibited when the reactor pH decreases to values lower than 6.8. During the operation of M the pH was measured daily and when the reactor pH was < 6.8, the pH was manually corrected by adding a saturated solution of $NaHCO_3$, such that the pH increased to > 6.8. When the Ripley ratio was lower than 0.3, the anaerobic digester is functioning optimally, with the required ratio of VFA and alkalinity in the reactor. The produced alkalinity buffers the VFA concentration in the reactor maintaining the ideal reactor pH for the methanogenic bacteria to produce methane gas.

The daily gas production was measured by the water replacing method. The gas volume produced in the anaerobic reactor was captured in a bottle filled with water, which was kept under pressure. When a gas bubble entered the bottle with water, the gas replaced the water, which was then forced out of the bottle into a measuring cylinder. The volume of water in the measuring cylinder thus resembled the gas production in the reactor.

The determinations of pH as well as for the total solids (TS) and volatile solids (VS) were carried out according to standard analytical procedures as described in *Standard Methods* (APHA, 1985).

4. RESULTS

As already indicated, the AD process is highly complex biological system, where microbiological, bio-chemical and physio-chemical aspects are closely linked. The stability of the process is dependent on the balance between symbiotic growth of the different groups of bacteria, such as the acid forming bacteria, obligate hydrogen producing acetogens and methanogens (Angelidaki, et al., 2009). This symbiotic relationship can be monitored by the pH and measured in the reactor by the Ripley Factor and the biogas production. Thus the three most important parameters to monitor the digestion process in an anaerobic reactor are the pH, the Ripley Factor and the gas production.

pH

The average pH value in M during the experimental period was 6.98. Ideally, the anaerobic digester pH should be between 6.8 and 7.2. When the organic waste is added to the digester, the acid-producing bacteria produce VFA. When the methanogens can not degrade the VFA fast enough, the reactor pH becomes < 6.8 (Ross et al., 1992). At a pH < 6.5, the methanogenic bacteria will die, resulting in an acidified reactor, which leads to failure. The operating pH in M of an average of just lower than 7 was perfect for a well balanced reactor process.

Ripley Factor

The Ripley ratio results in M (Figure 2) showed that over the total experimental period of 105 days, the ratio was mainly > 0.3. It started to decrease around day 58, when the loading rate to the reactors was increased, while feeding KW. After day 58, the feeding and thus the loading pattern changed, which resulted in a higher Ripley Factor for M, however at the end of the experimental period, when the loading rate was increased again during the co-digestion of KW and PS, the Ripley Factor slightly decreased again in M.

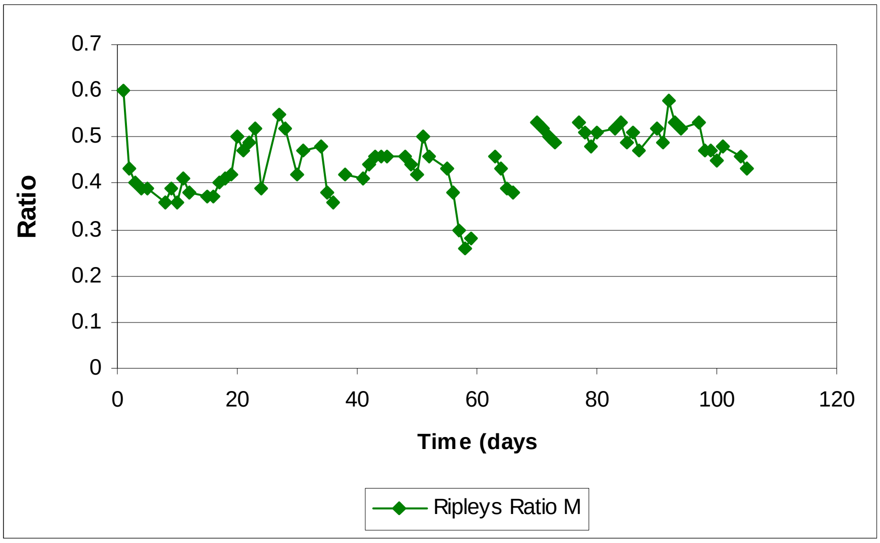

Figure 2: The Ripley factor in M

Gas production

Anaerobic digesters at WWTP are nowadays not only considered because of the treatment efficiency, but also in terms of their energy efficiency. As indicated before, the main source of energy generated at a WWTP is the biogas, which is produced in the anaerobic digester when the sludge is stabilised. The gas can be earmarked for gas engines to produce electricity or the gas can be used on site (Schwarzenbeck et al., 2008). Ross *et al.*, (1992) described that approximately 1 m^3 gas can be produced from the degradation of 1 kg sewage sludge at a HRT of 20 days and at a temperature of 35°C.

The gas production from reactor M is presented in Figure 3. It can be noted that initially (day 10-20) the gas production was < 500 ml/day. This low gas production coincided with a low loading rate of 1 g VS/L.day^{-1}. When the loading rate increased (albeit irregular) throughout the first experimental period, the gas production increased as well. From day 40 onwards, the increase in loading rate became more regular (Figure 1), to which the gas production responded accordingly, showing a clear relationship between the increased organic mass to the digester and the improved gas production. This observation is in accordance with the results of Angelidaki et al., (2006), who described that loading a reactor at progressively increasing rates as compared to a fixed feed rate showed superior process performance. The relationship between the loading rate and the gas production rate for the experimental periods day 41 to day 57 and day 62 to day 105, are depicted in Figures 4 and 5, respectively.

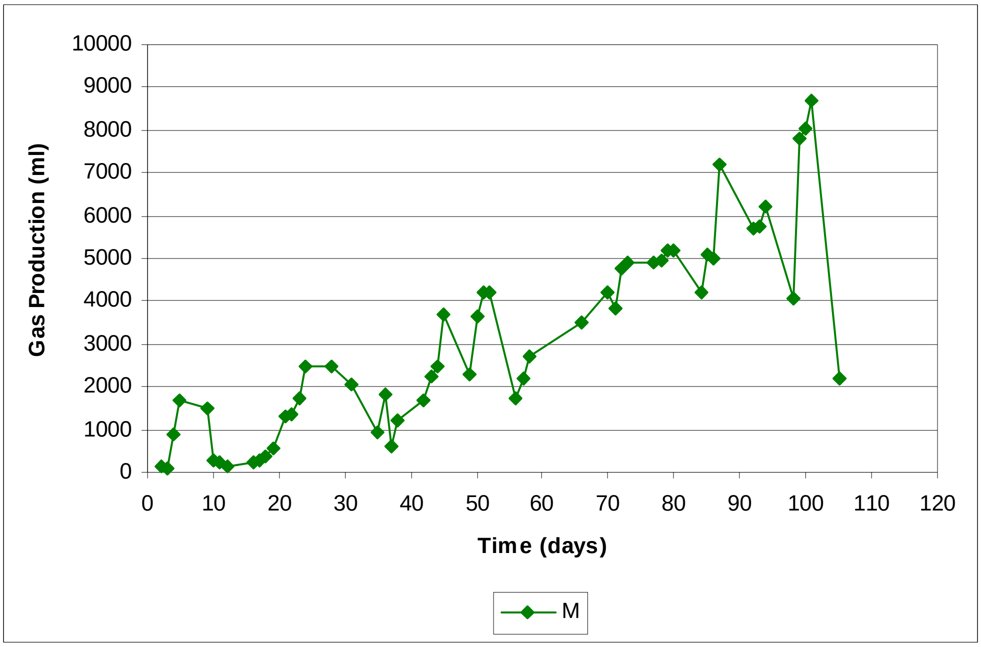

Figure 3. The gas production over the total experimental period in M

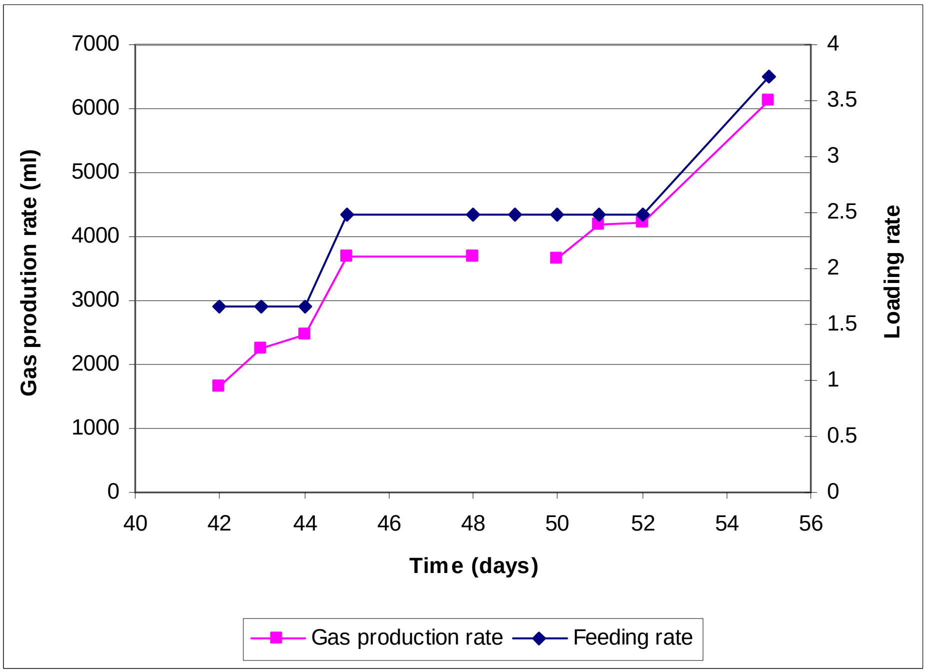

Figure 4. The loading rate and the gas production rate from day 41-57

It can be observed from the graphs in Figure 4 that the loading rate and the gas production rate follow the same trend, as was also indicated by Angelidaki et al., (2006). When the loading rate was increased, the gas production rate responded similarly. The same trend, as indicated by the trendlines, can be observed from Figure 5, depicting the data generated during day 62 to day 105.

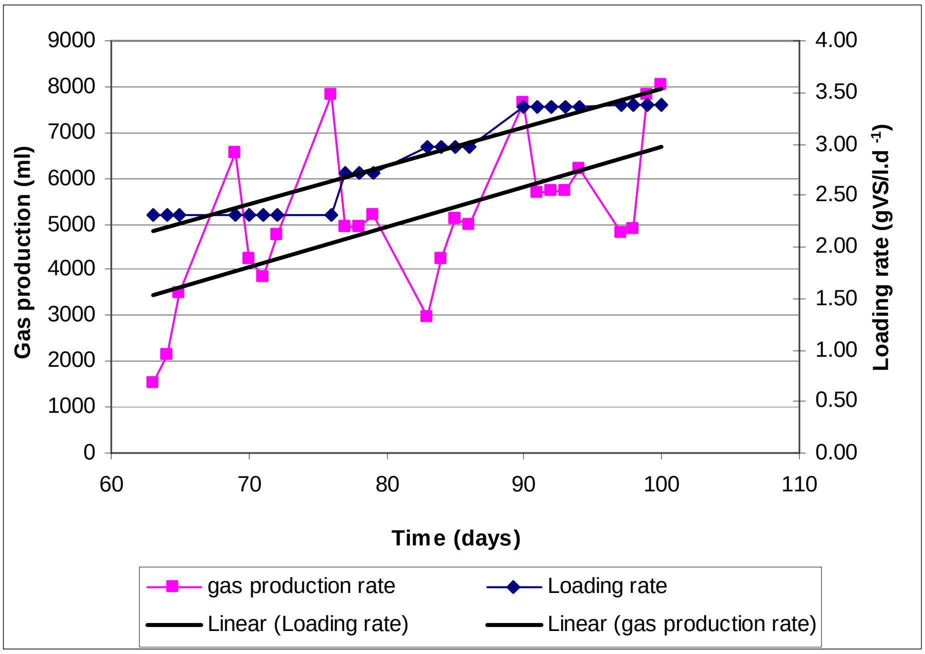

Figure 5. The loading rate and the gas production rate from day 62-105

Co-digestion

During the experimental period day 62 to day 105, two different feed stocks were added to M as opposed to during the previous periods when only KW was added. The feedstock changed from a mainly KW base to KW combined with PS as indicated under experimental. As can be noted from Figures 1 and 5, not only the feed stock changed, but also the loading rate increased. At the same time the gas production rate increased. However, the microorganisms in M needed to adapt to the change in feed stock, since when the percentage PS increased, the gas production initially decreased, but once the microorganisms were adapted to the increased amount of PS, the biogas production increased again. The results (Figure 5) seem to indicate that the co-digestion and the increase in loading rate have a favourable influence on the gas production.

Co-digestion is defined as anaerobic treatment of a mixture of at least two different organic waste types. With the large volumes of sewage sludge (SS) produced at wastewater treatment facilities and the large number of existing anaerobic digesters at these facilities to stabilise the sludge, the anaerobic co-digestion of KW with PS is especially attractive (Hamzawi et al., 1998). The substrate characteristics of KW and PS are complimentary and therefore co-digestion is beneficial towards the anaerobic digestion treatment process and biogas generation. The KW typically has high solid concentrations while PS is low in total solids (TS), but contributes high microbial concentrations. Moreover, the higher concentration of macro- and micro nutrients in the sludge will compensate for the lack of nutrients in KW contributing to a mutually beneficial co-digestion system (Rivard et al., 1990; Kayhanian and Rich, 1995). While digested sludge has a stabilising effect on the digestion process, PS increases the methane yield. Moreover, the addition of PS significantly decreases imbalances during the start-up of digesters (Demirekler & Anderson, 1998). The optimal mixture of KW and PS is dependant on the specific waste characteristics and the process concept used. Several researchers observed the best performance with a volume of 25% KW and 75% sewage sludge, respectively (Diaz et al., 1981; Demirekler & Anderson, 1998; Hamzawi et al., 1998). From the observations made during the experimental period in the study presented here, when

M received 30% KW and 70% sewage sludge (day 97 to day 105), the biogas volume was high at > 7 L/d and even at approximately 8 L/d towards day 98 and 100, respectively.

Co-digestion can also be applied at existing WWTP without excessive investment costs, thereby combining the treatment of the two largest municipal waste streams. There are several advantages to co-digestion, namely an increase in methane yield, improvement of the process stability, combining different waste streams, with diverse characteristics in one common treatment facility and the treatment of larger waste amounts in centralised large-scale facilities (Ahring, 1995; Bozinis et al., 1996; Angelidaki and Ahring, 1997; Hamzawi et al., 1998; Gavala et al., 1999). There are a great number of anaerobic digesters at many different WWTP in South Africa, presently under-utilised or not in use at all and considering that South Africa is producing high volumes of organic waste, efforts should be concentrated on the utilisation of these anaerobic digesters. This would result in less waste to landfill, thus less stress on existing landfill sites, and moreover in the production of biogas, to be used as an alternative energy source. Furthermore, when the anaerobic digesters can be put to use for co-digestion of the main waste streams, it can be envisaged that it may results in additional jobs for trained operators at WWTP.

5. APPLICATIONS FOR BIOGAS

Biogas can basically be used in all applications that have been developed for natural gas. It has the advantage that it can be stored relatively easily and that it can be used where it has been generated. Alternatively it can be transported to the site where it is needed. There are four basic ways of biogas utilisation – production of heat and steam, electricity generation/co-generation, use as a vehicle fuel and (possibly) production of chemicals. The various utilisation pathways are illustrated in Figure 6 (adapted from Appels et al. 2008)

Without any treatment such as the removal of sulphur, biogas can only be used at the place of production. By increasing the energy content of biogas, such as through compression, the biogas can be transported over larger distances in pressure tanks. The enrichment and enhancement of the use of biogas can be achieved after removing the CO_2 and other contaminants. Strachan et al., (2007) described the use of landfill gas in the Durban area to fuel a microturbine thus generating power, which is added to the electrical grid. Applying this technology reduced the emission of greenhouse gases (GHG), for which carbon credits were earned. This technology has since then has also been applied to other landfills, however, this way of using biogas should not advocate landfilling as the best waste treatment option, since the present-day trend is towards waste minimization rather than towards waste disposal.

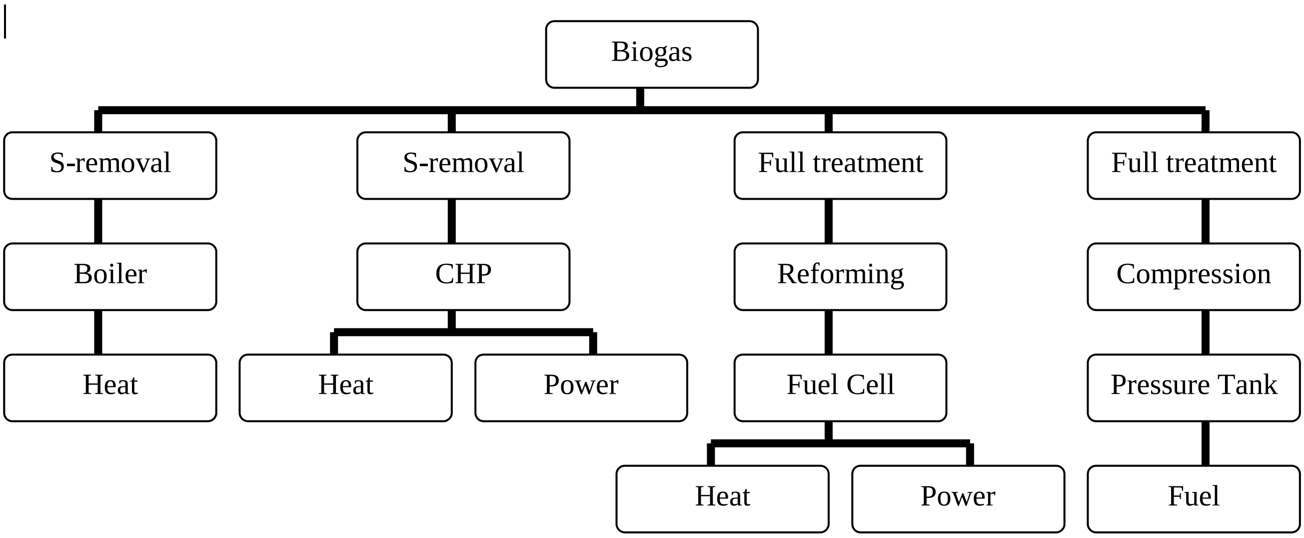

Figure 6. Biogas utilisation options

5. CONCLUSIONS

The results of the investigation showed that biogas production from the digestion of organic kitchen waste was feasible. It was furthermore shown that an increased loading rate resulted in an increased gas production rate. Co-digestion of kitchen waste with primary sludge seemed to improve the gas production rate. When the loading rate increased and when co-digestion was practised simultaneously, the biogas production increased. Since both parameters occurred concurrently, the determining factor for the biogas increase could not be established. However, co-digestion of PS and KW has been described as beneficial for biogas production.

It is anticipated that conventional energy sources are becoming exhausted and the world is focussing on renewable energy such as biogas (Kalyuzhnyi, 2008). In South Africa, where energy shortage has been experienced in early 2008, the municipalities should consider applying the AD technology to the OFMSW to generate biogas as an alternative energy source. Moreover, this waste to energy process has potential for the rural areas of the country, using cattle manure as a source for biogas, which can replace the burning of wood and paraffin, which are causing respiratory heath problems. Waste to energy has potential for the future as has been shown from this research study as well as from the examples globally.

6. REFERENCES

Agama Energy, (2008). http://www.agama.co.za

APHA, (1985) "Standard Methods for the Inc. Examination of Water and Wastewater" 16th Edition, Washington DC.

Angelidaki, I., Chen, X., Cui, J, Kaparaju, P. and Ellegaard, L (2006). "Thermophilic anaerobic digestion of source-sorted organic fraction of household municipal solid waste: Start-up procedure for continuously stirred tank reactor." *Water Research*, **40**, 2621-2628.

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, J.L., Campos, L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P. and Van Lier, J.B. (2009). "Defining the biomethane potential (BMP) of solid organic waste and energy crops: a proposed protocol fro batch assays". *Water. Sci.Technol.*, **59** (5), 927-934.

Appels, L., Baeyns, J., Degrève, J. and Dewil, R., (2008) "Principles and potential of the anaerobic digestion of waste-activated sludge" *Progress in Energy and Combustion Science*, **34**, 755-781

Austin, G., Gets, L.E., Liphoto, C., Nissing, C and von Blottnitz. (2006). "Energy recovery from Municipal Solid Waste in South Africa". A pre-feasibility study for the Department of Science and Technology, pp 206.

Demirekler, E. and Anderson, G.K. (1998). "Effect of sewage sludge addition on the start-up of the anaerobic digestion of OFMSW". *Environmental Technology*, **19** (8): 837-843.

Department of Environmental Affairs and Tourism (DEAT) (2006). "South Africa Environment Outlook: A report on the state of the environment" (Department of Environmental Affairs and Tourism, Pretoria). ISBN 0-621-36422-3.

Diaz, L.F., Savage, G.M. Trezek, G.J. and Golueke, C.G. (1981) "Biogasification of municipal solid wastes. Transactions of the ASME". *Journal of Energy Resources Technology*, **103** (2): 180-185

Gosselink, J.W. (2002). "Pathways to a more sustainable production of energy: sustainable hydrogen – a research objective for Shell". *Int. J. Hydrogen Energ.*, **27** 1125-1129.

Hamzawi, N., Kennedy, K.J. and McLean, D.D. (1998). "Technical feasibility of anaerobic co-digestion of sewage sludge and municipal solid waste". *Environmental Technology*, **19** (10): 993-1003

Hartmann, H and Ahring, B.K. (2006). “Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview”. *Water Sci. Technol,*. **53**(8) 7-22.

Jewaskiewitz, S. (2008). “Waste to Energy: Are we ready for it in South Africa?” *Waste Management, IIESA, February 2008* 69-77.

Kalyuzhnyi, S.V. (2008). “Energy potential of anaerobic digestion of solid wastes generated in the Russian Federation”. *Water Sci. Technol.,* **58**(9) 7-22

Kayhanian, M. and Rich, D. (1995). “Pilot-scale high solids thermophilic anaerobic digestion of municipal solid waste with an emphasis on nutrient requirements”. *Biomass and Bioenergy,* **8**(6): 433-444.

Rivard, C.J., Vinzant, T.B., Adney, W.S., Grohman, K. and Himmel, M.E. (1990) “Anaerobic digestibility of 2 processes municipal solid waste materials”. *Biomass,* **23** (3): 201-214

Ross, W.R., Novella, P.H., Pitt, A.J., Lund, P., Thomson, B.A., King, P.B. and Fawcett, K.S. (1992) “*Anaerobic Digestion of Wastewater Sludge”*. WRC Project no 390, TT 55/92, Pretoria, South Africa.

Schwarzenbeck, N., Bomball, E. and Pfeiffer, W. (2008). “Can a wastewater treatment plant be a powerplant? A case study”. *Water Sci. Technol.,* **57**(10) 1555-1561

Snyman, H., Van Niekerk, A.M. and Rajasakran, N. (2006). “Sustainable wastewater treatment - What has gone wrong and how do we get back on track?” *Proceedings of the WISA 2006 Conference,*

Strachan, L.J., Wright, M., Broomfield, M., Couth, B and Pass, J. (2007). Using landfill gas. *Resource,* **9**: No 1.

Van Nes, W.J. (2006). “Asia hits the gas: Biogas from anaerobic digestion rolls out across Asia”. *Renewable Energy World*. January/February, 2006: 102-111.