Biogas Technology: Current Trends, Opportunities and Challenges

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***Abstract*—**

***Keywords*—**Advancements, Anaerobic Digestion, Biogas Technology, Biomass

I. INTRODUCTION

THE history of the anaerobic digestion of biomass for energy production can be traced back to the 10th Century B.C with the earliest available record being around the 19th century. The first anaerobic digester was set up in the town of Bombay, India around the year 1859. On the other hand, in England, the first remarkable application of biogas as a fuel was also recorded in the same year 1859 [1]. Over the years, farm based manure has been the most extensively used feedstock for biogas production. However other sources have gradually been adopted as alternatives [2]. During AD, biomass (organic matter) is broken down by microorganisms in the absence of air. Therefore, the process can artificially be set up within airtight vessels also known as anaerobic biodigesters or it can occur naturally at the bottom of ponds or marshes where there is successful air-deprivation [3].

Biogas is currently used in many developing countries as an alternative and renewable source of energy for wide spread range of applications. In contemporary times, biogas has been used most extensively in India and China. Currently in Germany, biogas technology is in advanced stages and being used to produce green electricity in the Mega Watt range. Economic production of biogas can be economically achieved for both large and small scale applications. Hence it can be designed to fit into rural, urban as well as regional and nationwide energy needs [2]. The quality of raw biogas can be further improved via various upgrading techniques to remove the non-combustible components and as a result increasing the methane content to approximate natural gas quality (75-98% methane). The biomethane produced from the enrichment and subsequent compression processes can be used as vehicular fuel among other applications. Currently Sweden and Germany have invested heavily in biomethane distribution infrastructure. Biogas has lower emission rates than natural gas or any other fossil fuel hence possesses much less environmental pollution potential compared to fossil fuels as shown in TABLE 1 [4].

TABLE 1
COMPARISON OF GASEOUS EMISSIONS FROM HEAVY VEHICLES

g/kg	CO	HC	NO_x	CO_2	Particulates
Diesel	0.20	0.40	9.73	1053	0.100
Natural Gas	0.40	0.60	1.10	524	0.022
Biogas	0.08	0.35	5.44	223	0.015

On the other hand, the growth of biogas technology in South Africa still lags behind [5]. Over 86% of the country's energy demand is derived from fossil fuels such as coal, oil and natural gas. Primary energy supply is dominated by coal at 67% because its abundance and low cost. However these are all non-renewable fuels associated with high CO_2 emissions [6]. This high dependence on fossil fuels as over time led to rising energy costs and environmental concerns in the recent past that have in turn sparked sustained interests in biogas as a potential clean energy alternative. However, the penetration of the technology is still low and some of the factors leading to this slow growth are, among others, generally limited experience in biogas technology and lack of biogas specific standards in the country [5]. Efforts to address the growing issues have seen the formation of organisations such as the Southern African Biogas Industry Association (SABIA) tasked with the responsibility of streamlining knowledge transfer and policies which are all still a work in progress [5], [7].

Recent advancements in biogas technology have led to the development of more efficient AD systems incorporating such modifications as feedstock pre-treatment techniques, techno-economic gas upgrading, bioprocess improvements and advanced digester technologies among others. This paper discusses the current state of biogas technology highlighting the recent advancements in its applications as well as production. Fig 1 shows the distribution of biogas plants in the

This work is funded by the South African National Energy Development Institute (SANEDI).

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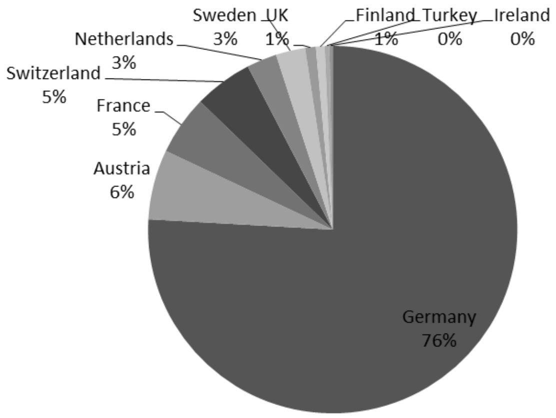

Fig 1: Distribution of biogas plants in Europe[8]

A. Microbiology of Anaerobic Digestion

Anaerobic digestion of biomass for biogas production is a complex microbiological process carried out by large complex set of bacteria that work in a symbiotic environment. It is broken down into three (3) stages, that is: hydrolysis, acidification and methane formation [9];

1. Hydrolysis

At this stage, the biomass is externally enzymolysed by microorganisms using their extracellular enzymes to decompose the long and complex molecular chains of the biomass into shorter and simpler intermediate products [10].

2. Acidification

In the second step, the simple intermediates from the hydrolysis are converted into molecules of carbon dioxide (CO_2), acetic acid (CH_3COOH) and hydrogen (H_2). These bacteria at this stage utilise the dissolved oxygen or bounded-oxygen in the solution and carbon to produce acetic acid. By doing this, they create an anaerobic environment that is conducive for methane formation [9].

3. Methane Formation

This stage is controlled by methanogens. These bacteria are responsible for the breakdown of the carbon dioxide, acetic acid and hydrogen that are produced during the acidification stage to produce methane and carbon dioxide. Chemical reactions during methanogenesis can be summarised as in (1) and (2) [10], [11].

$$CO_{2(g)} + 4H_{2(g)} \longrightarrow CH_{4(g)} + 2H_2O_{(l)} \quad (1)$$
$$CH_3COOH_{(aq)} \longrightarrow CH_{4(g)} + CO_{2(g)} \quad (2)$$

The in-depth knowledge on the microorganisms involved in the biochemistry of anaerobic digestion is still lacking and there is a lot of ongoing research to try and isolate the various families of bacteria involved in anaerobic digestion. This inadequacy of knowledge has resulted into several unexplainable AD system failures [12]-[14].

The complexity of the biochemistry of the anaerobic digestion regarding the involved array of microbes alongside the reaction determining factors such as pH, temperature and enzymes among others make it increasingly hard to establish a clear understanding of what exactly takes place during anaerobic digestion [15], [16]. However, there have been several attempts at the determination of the complex kinetic models to describe this seemingly mysterious process for both mesophilic and thermophilic digestion. Work by Manher (2007) in an attempt to model the process showed that the organic solids degradation can be represented as a first order reaction assuming maximum biogas yield [17]. The quantification of methanogens as well as various feedstock microbial assessments have successfully been attempted and achieved via the use of the fluorescence in-situ hybridisation techniques [18].

B. Conditions for Anaerobic Digestion

Various factors affect biogas production from anaerobic digestion. Some of the key factors have been elaborated in detail below;

1. pH

Methanogens thrive best under neutral and slightly alkaline environments. They are killed by acidic conditions. Upon stabilisation of the AD process, the optimum pH values in the system will be in the range of 7 and 8.5 [10], [19], [20].

2. Temperature

Optimum performance of an AD system is influenced greatly by the operating temperatures of the digester. The various temperature ranges within which optimal AD performance occurs are classified as; Psychrophilic (< 30°C), Mesophilic (30 – 40°C) and Thermophilic (50 – 60ºC) [21]. Previous studies have however shown that anaerobic bacteria exhibit the highest activity within the mesophilic and thermophilic ranges [2]. Extreme cases of either very high or very low temperatures kill the anaerobes hence inhibiting the whole AD process. The optimum temperature is 35°C [3], [19].

3. Feedstock Composition and Nutrients

Several varieties of biomass feedstocks can be utilised by AD systems such as agricultural crops, animal manure, human waste, municipal sewerage and biowaste among others. The nature of the feedstock used determines the quality and quantity of the biogas yield [2]. In addition to the biogas yield, biomass produces carbon and essential nutrients that facilitate the sustainable growth of the microbes. [2], [22].

4. Carbon/Nitrogen (C/N) Ratio

Anaerobic digestion ideally occurs at C/N ratio ranges between 20:1 and 30:1. Methanogenic bacteria use nitrogen to meet their protein requirements. Therefore in cases of high C/N ratios higher than the optimum ranges, the nitrogen will be depleted rapidly by the bacteria and hence will not react on the excess carbon in the feedstock thereby reducing the biogas yield. For cases of lower ratios than the desired range, the excess Nitrogen will result into Ammonia (a strong base) formation hence raising the working pH over the desired 8.5 inhibiting the microbes and ultimately dropping gas production rates [2].

4. Substrate Particle Size

The substrate for anaerobic digestion should be composed of digestible particle sizes. Smaller particles increase surface area for the microbial action of the methanogens thereby increasing the rate of biogas production as well as biodegradability of the feedstock. And the reverse is true for large particles which can clog the digester [23], [24].

II. Biogas Applications

A. Merits and Demerits of Biogas Utilisation

Economic production of biogas can be achieved for both large and small scale applications. Hence it can be designed to fit into rural, urban as well as regional and nationwide energy needs making it a versatile source of energy. In addition, the production of biogas can be controlled fully without relying on the forces of nature as the case with solar and wind energy that are seasonal dependent [2]. The production of biogas from biodegradable wastes over the years has provided implicit potential in improving waste management practises worldwide. As an integrated solid waste management strategy, AD will reduce the costs associated with landfilling while simultaneously harvesting the biomethane produced as a clean energy source which is a potential greenhouse gas. In addition, the by-product of anaerobic digestion of biomass produces a valuable organic agricultural fertiliser in the form of a digestate which is of great economic value [25].

Notwithstanding, biogas production and its subsequent use as an alternative energy source are associated with a multitude of limitations such as the characteristic limited lifespan of AD plants at an average of 20 years, negative perception in areas where there is low functionality of existing plants, inability to perform at all temperature conditions, association with poor hygiene especially in systems where biowaste is the primary feedstock and high initial operation and maintenance costs relative to income of most potential users among others [10].

B. Advancements in Biogas Applications

Worldwide, Europe has recorded the highest growth of biogas usage with a remarkable 18% increase recorded between 2006 and 2007. Germany and Sweden have recorded the highest growth levels with Germany leading boasting over 4000 biogas plants, most of them set up on farms for electricity and heat cogeneration [10].

Traditionally biogas in its raw form has been used as a domestic fuel for open flame applications as a heat source such as cooking, heating, lighting and to some extent in combined heat and power (CHPs) internal combustion engines. However, raw biogas contains equipment-damaging trace gases such as hydrogen sulphide (H_2S) and volatile organic compounds (VOCs) that have always limited its application at industrial scale. The precise concentration of these gases in any particular biogas sample depends on the source of substrate and operating process conditions, however, the reported range is typically 40-70% by volume of methane (CH_4) while carbon dioxide (CO_2) and other trace gases takes up the remaining percentage. Upgrading biogas to fuel grade biomethane involves two major processes; cleaning and CH_4 enrichment. The cleaning of the biogas consists of removal of acidic gases and impurities, while the enrichment process is for separation of CO_2 from biogas. The removal of these harmful components and other non-combustible gases makes biogas a more viable and economical alternative renewable energy source [26]. Current technologies for cleaning of biogas and its subsequent CH_4 enrichment are physiochemical processes which can be grouped as follows;

- Absorption process (physical and chemical absorption)
- Hybrid solution (mixed physical and chemical solvent)
- Physical separation (adsorption on solid surface; membrane; cryogenic).

All of these techniques have been reported to yield biomethane typically containing 95-99% CH_4 and 1-3% CO_2. At this quality, the spectrum of applications for biogas widens, it can be used to serve the same applications as natural gas. Usually the compressed biogas (CBG) is fed into existing natural gas service lines infrastructure to serve higher grade applications. The most recent application of CBG is its use as a transport fuel. Sweden and Switzerland in Europe are already applying biogas as a green fuel for public transport. CBG has been found to reduce CO_2 emissions greatly as compared to any fossil transport fuel and hence making it the preferred choice as a transport fuel.

By the end of 2013, there were over 700 filling stations across Europe dispensing blended CBG with CNG for vehicular fuel use and another about 300 stations dispensing pure CBG. The use of biogas for heat production is also on a rapid increase being used primarily in CHP plants in developed countries and relatively small amounts used in heating plants only. The application of biogas for power generation also is rising rapidly in Europe. By the end of 2012, more than 13,800 biogas power plants, with a total installed capacity of 7.5 GW, were in operation [27]. Fig. 2 shows the trend in growth of biogas upgrading plants in Germany [28].

III. Feedstock for Biogas Production

The amount and nature of feedstock to be used in AD systems for biogas production is the single most important factor to be considered in the system design. The volumetric yield of the gas per unit weight of the substrate added varies from one type of substrate to another depending on the composition as well as nature of the substrate. In addition, the percentage of methane obtained from the resultant biogas also varies independently according to type of biomass material. Therefore, to run an efficient biogas digester, a keen interest should be drawn on the availability and quality of biomass [10]. The yield of biogas in litres per kg of various materials is summarised in

TABLE 2 alongside the percentage of methane production per raw material [26].

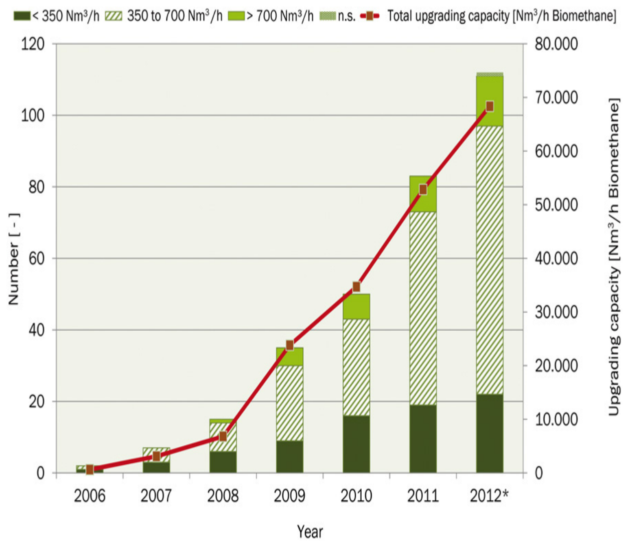

Fig 2: Development of biogas treatment plants in Germany [28]

TABLE 2
BIOGAS PRODUCTION POTENTIAL FROM DIFFERENT SUBSTRATES

Raw Material	Biogas Production Litres/kg	Methane Content In Biogas (%)
Cattle Dung	40	60
Green leaves	100	65
Food Waste	160	62
Bamboo Dust	53	71.5
Fruit Waste	91	49.2
Bagasse	330	56.9
Dry Leaves	118	59.2
Non-edible oil seed cakes	242	67.5

A. Substrate Parameters

For efficient biogas production, a clear understanding of the nature of the input substrate has to be made because the properties of the substrate have a direct bearing on the resultant volume of the biodigester, the quantity/quality of biogas output and hence the project cost. Among the substrate parameters that should be ascertained are: Substrate Input Flow Rate, Substrate Dryness, Total Solids (TS) and Total Volatile Solids (VS).

1. Total Solids

This is the total amount of solid matter present in a given substrate. The Total solids' content of a substrate is obtained by weighing the residue or dry material left after drying it for 48 hours at 105°C. The mass obtained is the raw estimation of both the organic and inorganic content of the substrate [29], [30]

2. Volatile Solids

Volatile solids (VS) also referred to as the organic fraction of the total solids represent the digestible portion of the total solids normally expressed as a percentage. It is determined by heating the TS to 550°C for 24 hours. The balance of the process is the inorganic fraction of the TS [29], [30].

3. Biomethane Potential

This is the measure of the volumetric yield of methane from a given substrate often expressed as cubic metre per tonne of volatile solids (m^3/ton VS) of a given feedstock stream. This gives a direct indication of the suitability of the feedstock for biogas production via anaerobic digestion [31]. Fig 3 shows a comparative analysis of biogas yields from various substrates.

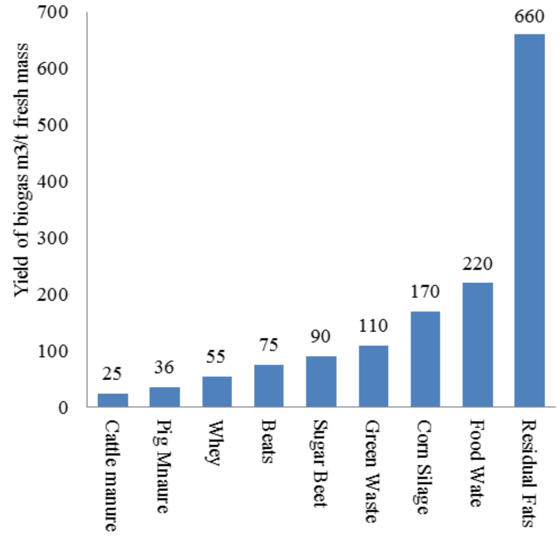

Fig 3: biogas yields of various substrates in m^3/tonVS [32]

Biogas production from anaerobic digestion can be achieved by use of any source of biomass such as biowaste, food crops and wood among others. However, a report by the Food and Agricultural Organisation (FAO) of the United Nations (2008) indicated that increased use of food crops for bioenergy production in a bid to increase its supply will lead to increased food prices. This in the short run will help agricultural economies to grow significantly but in the long run will lead to food insecurity in developing nations [33]. Therefore, to prevent the risk of increased global food insecurity, alternative types of biomass for biogas production should be introduced other than food crops [34]. In this context, other energy crops have been proposed such as Jatropha to suit the purpose. But just like food crops, all planted biomass requires resources such as land and water so as to meet the requirements of a reliable and sustainable substrate supply and yet both land and water are also very vital resources for the global energy balance. This therefore disqualifies planted biomass as the most preferred feedstock source [35]. This then leaves biowastes as the most viable feedstock sources [10]. The possibility of bioenergy production from biowastes represents a scenario where an alternative source of clean energy is obtained, space for composting waste is saved and GHG emissions are reduced while simultaneously improving waste management. Hence currently biodegradable waste is the future of biogas production [2]. The biowastes used anaerobic digestion differ significantly in both their qualities and quantities depending on their sources [36]. Germany, Austria and Denmark still obtain the largest amount of anaerobic digestion feedstock from agricultural by-products and manure [25].

To improve the economic viability of AD systems, centralised systems have been recommended that handle a spectrum of wastes from various sources. In addition, studies have indeed proved that the overall biogas yield is directly linked with the type of interaction within different waste streams that interfere with digestibility of wastes in AD processes [25]. This has in turn resulted into numerous research works to try and establish the best combination of waste streams for optimum biogas production also referred to as the concept of co-digestion. These studies have concluded that the co-digestion on sewage sludge, the organic fraction of municipal solid waste (OFMSW) and agricultural crops give the best biomethane yield in terms of quality and quantity. However, the most used basic substrate in agriculture is pig or cow manure in co-fermentation with biogas crops [37]-[39].

Beside co-digestion of feedstocks, studies have also shown that certain pre-treatment techniques can improve the overall yield per unit weight of substrate. This involves all the processes that the feedstock undergoes prior to use in anaerobic digestion. These processes range from physical ones such as sorting and particle size reduction to chemical processes like alkali treatment and metal addition among others [29]. Pre-treating feedstock for AD can result into increased biogas production rates as well as volatile solids reduction [40]. The various performance enhancers are as elaborated as follows [41];

1. Seeding

Seeding is a way of kick-starting a newly commissioned biogas plant by feeding it with previously digested material from another established set up. Alternatively, materials such as animal manure or municipal sewerage are often used to seed a newly commissioned biogas digester, so as to reduce the plant start-up time. The method aims to introduce inoculum into the system [19].

2. Particle Size Reduction

The particle sizes of the substrate directly affect digestion as it has direct indication on the available surface area for hydrolysing enzymes especially with plant fibre. Methane yield and fibre degradation have been found to improve with decreasing particle sizes within the feedstock from 100mm to 2mm [23].

3. Alkali Pre-treatment

A study by Taherdanak and Zilouei (2014) found that addition of controlled doses of alkali solutions in AD substrates was found to enhance biogas yield and at the same time reducing cellulose production especially when using plant material as feedstock [42]. Clarkson and Xiao (2000) proved that the rate of degradation of paper waste in AD systems increases by addition of optimum amounts of Sodium hydroxide (NaOH) solution [43]. However, alkali solutions often lead to saponification reactions in continuous plants. These reactions tend to yield generate compounds leading to tremendous drops in acetate and glucose degradation rates [44].

4. Addition of Metals

Kumar et al (2006) studied the impact of adding Cadmium (Cd^{2+}), Nickel II (Ni^{2+}) and Zinc (Zn^{2+}) in the anaerobic co-digestion of a combination of cattle manure and potato waste. The results showed the biogas yield was enhanced greatly with the highest increases recorded with Cd^{2+} to Ni^{2+} and lastly Zn^{2+} [22].

5. Thermal/Thermochemical Pre-treatment

Pre-heating of substrate before anaerobic digestion has proved to improve methane production as well as volatile solids reduction. Studies have also shown that pre-heating of substrate that has been treated with chemical additives (thermo-chemical) even gives better results [45]. Ardic and Tarner (2005) showed that pre-treatment of chicken manure with pre-heated sodium hydroxide at 100°C enhanced both the bio-methane yield as well as the biodegradability of the feedstock [46].

6. Ultrasonic Pre-treatment

Commonly used in sewage sludge treatment, the feedstock is treated using ultra sonic sound waves. Generally the method has been found to improve biogas production from anaerobic digestion. This technique introduces ultrasonic cavitation into the system that in-turn builds up mechanical shear forces that ultimately aid the sludge dis-integration as well as the collapse of cavitation bubbles which improve the feedstock's physical properties [40].

IV. Performance Monitoring of AD Systems

Research on the performance of various feedstock combinations vis-à-vis the pre-treatment techniques to predict biogas yields have also over the years become increasingly easier and quicker. Currently there is equipment on the market that can give instant biomethane potentials of a given choice of feedstock as well as biogas prediction models. In 1952 Buswell and Mueller in 1952 developed a theoretical model that can be used to predict the molar proportions of the various products of anaerobic digestion of a given substrate whose CHNOS elemental compositions are known [47], the value of the biomethane yield obtained from the model was theoretical and the model did not consider the solubility of the gases and ignored any AD inhibition factors such temperature and pH. Furthermore, the equation assumed 100% biodegradability of the organic matter and maximum HRT; hence to get reasonable results, the obtained results have to be corrected by the degradability factor of the substrate (usually 40-65% for OFMSW) [31].

Over the years, there have been several developments of computer models to try to model biochemical anaerobic digestion. Remarkable breakthroughs have since been made depending on the current advancements in computer technology like the Activated Sludge Model #1 (ASM1) by the International Association on Water Pollution Research and Control (IAWPRC) in 1987 for characterisation of waste sludge which was followed by more refined versions to produce the ASM2 in 1995, ASM2d in 1999 and ASM3 in 2000 [48], [49]. In 2002, to incorporate the latest development in computer technology as well as the better comprehension of AD systems into the ASM family of models, the International

Water Association (IWA) developed the Anaerobic Digestion Model #1 also known as the ADM1. Owing to its improved accuracy in determination of methane yields, the ADM1 is the most commonly applied model in recent times for analysis of AD systems because of its improved accuracy. The model uses laboratory determined parameters of the substrate that are input using computer languages like C and environments like Matlab-Simulink [31], [50].

V. BIOGAS DIGESTER TECHNOLOGY

Biogas digesters are specifically designed air-tight bioreactors for the anaerobic digestion of biomass to produce biogas [51]. A basic biogas plant unit is made up of four (4) major components namely [2];

- Reception tank for receiving feedstock,
- Digester or fermenter where anaerobic digestion takes place,
- Gas holder for holding the produced gas from the digester,
- And an overflow tank for tapping the digestate.

Fig 4 shows the major components of a typical biogas unit [52].

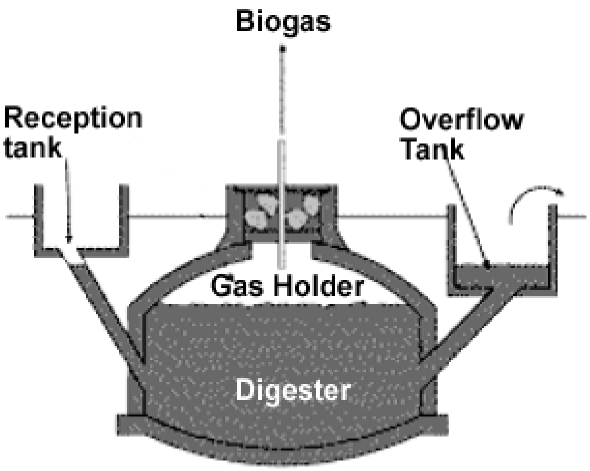

Fig 4: General layout of a Chinese fixed-dome biogas unit

The development of anaerobic digestion technology has gone through similarly a series of advancements over the years since the first Indian digester built in 1859. In the beginning biogas digesters were built to perform under rather uncontrolled conditions mostly emphasising air tightness. The more basic models built at the time were the fixed dome type built as one unit with a fixed dome gas-holder made out of brick masonry and floating drum the floating drum digesters made with a movable steel drum as a gas-holder. These were however faced by several challenges and system failures such as the unstable gas pressures from the fixed dome digester and the excess scum formation leading to high maintenance costs with the floating drum [1], [53]. Most recently there has been a new digester type developed by the Shenzhen Puxin Science and Technology Company (Puxin) of China to combine the qualities of all existing designs in a bid to improve gas production efficiency known as the Puxin digester [54].

With the ever changing trends in biogas technology in terms of feedstock types and an increasing range of applications in various parts of the world, robust plant designs have been developed to respond to the ever changing horizon in terms of capacity and functionality. For large scale applications such as biogas production for vehicular fuel use, the sizes of digesters constructed has grown to such capacities as 5000 m^3 from the smaller domestic 6m^3 plants earlier designed [10], [19].

At such large scales, biogas plant designed have to be modified to work in a more automated manner to prevent system failures. Such modifications incorporated today into digesters are mechanical agitators for substrate agitation, heating accessories, temperature regulators and performance monitoring systems (SCADA). Some plants have been developed that include the entire feedstock pre-treatment processes such as screening and particle size reduction in cases where complex feedstocks are used such as the organic fraction of municipal solid waste (OFMSW) [10], [19].

VI. GENERAL OUTLOOK

Biogas as a potential alternative to fossil based fuels is a growing trend world over with highest growth levels recorded in Europe most notably Germany and Sweden. Other parts of the world are gradually following suite. There have also been several remarkable technological advancements with regard to biomass feedstock optimisation as well as the entire anaerobic digestion process. Biogas is currently still mostly applied as a heating and electricity fuel but gradually find more advanced applications as a vehicular fuel especially in Europe where the technology is in its advanced stages.

The growth of the technology is still undermined in some parts of the world such as South Africa due to stringent non-supportive energy development polices as well as lack of enough plants, research facilities for knowledge transfer as well as perceived slow economic returns but with considerable works in progress. However, there are remarkable efforts to implement the technology through formation of bodies to simplify the complex policies among other things.

The technology should not be viewed as competition to the already existing fossil fuel based energy sources but rather a compliment to what is already existing and a sustainable environmental management strategy for the future. In addition, more demonstration plants should be set up to improve awareness.

Governments and policy makers should have supportive policies such as subsidisation of biogas projects to support the growth of the technology in places where its growth is still undermined. More research should be done on advanced bioreactor design and feedstock performance enhancement to improve AD economic viability.

ACKNOWLEDGMENT

The authors are grateful to the South African National Energy Development Institute (SANEDI) and the Technology Innovation Agency (TIA) through the Process Energy and Environmental Technology Station (PEETS) at the University of Johannesburg for supporting this study.

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