International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 03, March-2016

Technologies for Utilization of Biogas as Energy Source: A Review

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***Abstract*—Energy is fundamental to the quality of our lives. Energy growth is directly linked to well-being and prosperity across the globe. Meeting the growing demand for energy in a safe and environmentally responsible manner is always being a key challenge. Among so many alternative biofuels, there exists a clean and better fuel (biogas) that can help us cope up with the growing energy demand. Biogas is produced by anaerobic digestion of biodegradable solid waste, which is not only an environmentally sound and sustainable energy source but also provides a cleaner and safer route to dispose of the solid waste and make surroundings more hygienic. Raw biogas mainly consists 50-70% methane and 30-50% carbon dioxide with traces of some other impurities like, hydrogen sulphide and siloxanes etc. Biogas is considered to be a better alternative fuel as it is ecologically attractive, has considerable calorific value of 20-26 MJ/m^3, provides cleaner and reliable energy source, reduces greenhouse effect, a cheaper technology, and can have very compact design too. Despite of having number of benefits over other fuels and vast field of application, biogas is not that popularly accepted among common people because of many reasons such as lack of knowledge for substrate selection, pre-treatment and post-treatment cleaning requirement, and various routes/technologies available for its utilisation. Thus considering the capability of biogas to serve many energy industries, we need to emphasize on technological advancement to make this fuel an independent system. In this paper we have mainly focused on various gas-to-energy technologies to recover energy from biogas for its maximum utilisation.**

Keywords— Pretreatment, Anaerobic Digestion, Upgradation, Enrichment, Biomethane.

1. INTRODUCTION

With exponentially increase in population and explosively growing energy demand, there is a need to move from the non-renewable sources of energy (fossil fuels) to renewable energy source, as the whole world is now focusing on reduction of GHG emissions and use of cleaner reliable biofuel. Biogas can be the best alternative source of energy as biogas has following advantages over available and known renewable (wind energy, solar energy) as well as non-renewable (fossil fuels) sources of energy:

- It utilises organic waste that is easily available from agricultural waste and also the municipal solid waste (MSW) including waste from food industries.
- Serves dual purpose: energy source and waste management technology
- It is a more versatile renewable source of energy as its utilization is independent of the location, geographical conditions and season.
- It has a determinate energy value and is easy to store.
- It has a vast field of application such as heating, electricity generation and as a transport fuel [1].

The substrate used for biogas generation is organic matter which can be taken from number of sources such as waste from food industries, kitchen waste, agricultural waste, waste from slaughterhouses and waste from fish and vegetable markets. This feedstock undergoes anaerobic digestion and produces biogas (energy source) and digestate (organic manure).Biogas produced here has to be cleaned (upgraded) to make it compatible for maximum utilization where digestate can be directly spread over the arable land without treating only if the nutrient level of soil does not exceed the limits. Otherwise the digestate can be subjected to solid-liquid separation, and then dried to make biofertiliser to replace the chemical fertilizer.

The efficiency of the biogas system can be improved by refining (pre-treatment) feedstock, optimizing operating parameters and upgrading the process. Some post-treatment may also be required to clean the biogas (removal of impurities) and to increase the methane composition (enrichment) in it. There are number of routes available to extract energy from this energy source once the biogas is cleaned and enriched.

2. PRE-TREATMENT

The yield of biogas mainly depends on the quality of biomass used. The pre-treatment helps in improving the digestibility of substrate and increasing the production of biogas [2, 3]. Pre-treatment helps to kill the pathogens thereby taking care of sanitation [4]. The agricultural biomass or substrate used in the biogas plant to undergo anaerobic digestion must contain 40-50% cellulose, 20-30% lignin, and 20-40% hemicellulose by weight. Some plants (like cottonseed hairs) contain cellulose even more than 80% [2]. The factors affecting the bio-processing of the substrate are conversion of starch to glucose, proteins to amino acids, fats to fatty acids and glycerol, cellulose to cellulase and, fiber strength, lignin content, hemicellulose to hemicellulase, porosity and degree of polymerization and crystallinity of cellulose. The difficulty of the breakdown of the biomass depends on the bond between structural and non-structural carbohydrate content [2, 4]. The difference in these factors

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 03, March-2016

leads to the variation of decomposition of the biomass in the hydrolysis stage. The pre-treatment facilitates hydrolysis stage [3].

Different problems are reported with different substrates such as the higher content of lignin restricts enzymatic activity and microbial activity to degrade the biomass and crystalline cellulose limits the cellulase conversion rate as comparative to the amorphous cellulose which is easily converted [2]. The pre-treatment process helps to make a specific substrate suitable for anaerobic digestion; it can be broadly classified into three major categories which are as follows:

(i) Physical pre-treatment: This includes mechanical size reduction method such as milling, shredding, cutting, chipping etc. This method of pre-treatment helps to enhance the availability of the organic content, increase the surface area of the biomass, decrease the mass & heat transfer restrictions, decrease the degree of polymerisation and crystallinity of cellulose and increase the biodegradability rate of lignocellulose content [2, 4]. Some methods like milling produces high amount of biogas but is energy intensive.

(ii) Chemical pre-treatment: This pre-treatment uses various chemical species such as ionic liquids, organic solvents, alkalis and acids to breakdown the structure of the lignin in the substrate. Some alkalis like potassium hydroxide, sodium hydroxide, anhydrous ammonia, calcium hydroxide and hydrazine swells the substrate by increasing the internal surface of the biomass. This results in decrease in the degree of crystallinity and polymerization of the biodegradable substance. Dilute acid pre-treatment provides access to cellulose by hydrolysing the hemicellulose content to monomeric units [2].

(iii) Biological pre-treatment: This process includes the application of microorganisms to breakdown the biodegradable biomass containing polyphenols, lignin and hemicellulose. Generally fungal species are used for this purpose. The white rot and the soft rot fungal species are reported to breakdown the lignocellulose content of the substrate. While the brown rot fungi are good at degrading the cellulose content in the substrate. It has been concluded that the biological pre-treatment is inefficient for full scale biogas plant as it is very slow process [2].

3. BIOGAS PRODUCTION

Biogas is produced by the anaerobic digestion of biodegradable solid waste which requires environmental factors like temperature, pH, content of salts, available food, etc., to be maintained. Unlike other biological processes, the waste excreted by one microorganism is consumed as food by the next stage microorganism [4]. The production of biogas takes place via four stages of different biological reaction which are discussed below in detail:

(i) Hydrolysis:

This is the first step in anaerobic conversion process. In the hydrolysis the organic matter is depolymerized. The complex insoluble and longer unit substrates like polysaccharides are hydrolysed to smaller units. This is done by many hydrolytic microbes which secrete enzymes like cellulase, amylase, lipase, protease, etc. The colonies of facultative and anaerobic microbes (which release enzymes) cover the substrate particle and break it down to monomers. These monomers are then utilized by next stage microorganisms [4, 5].

(ii) Acidogenesis

This reaction is the fastest reaction in the anaerobic conversion process to convert the complex substrate to liquid form. In this reaction long chained fatty acids, sugars, and amino acids formed after the hydrolysis reactions are utilized by the fermentative bacteria. These substances are converted to short chained fatty acids, hydrogen, carbon dioxide, alcohols and various organic acids [5].

1. Conversion of glucose to ethanol

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$$

2. Conversion of glucose to acetic acid

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH$$

(iii) Acetogenesis

This is a slow reaction as the acetogens are slow growing organisms. These are very sensitive to oxygen, fluctuations in organic loading and require optimum pH of 6. After acidogenesis electron sinks (such as propionate, lactate ethanol higher volatile acids etc.) get developed due to the increase in hydrogen ion concentration, they are degraded by the acetogens and hydrogen is produced which is used by next stage microbes. One of the reactions is given below [5]:

Propionate conversion to acetate:

$$CH_3CH_2COO^- + 3H_2O \rightarrow 2CH_3COO^- + H^+ + HCO_3^- + 3H_2$$

(iv) Methanogenesis

The methanogenic bacteria produce methane as metabolic by product in the anoxic conditions. These bacteria use methylated C1 compounds, acetate, formate, hydrogen or carbon as a source of energy and for growth [5]. The methane is produced in two ways, either by the cleavage of the acetic acid molecules which generates CO_2 and CH_4 or by reduction of CO_2 by H_2.

1. Cleavage of acetic acid:

$$CH_3COOH \rightarrow CH_4 + CO_2$$

2. Reduction of CO_2

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

4. BIOGAS ENRICHMENT AND ITS UTILISATION

Raw biogas produced from digester is first cleaned in order to remove the impurities which may create various operational problems in energy recovery technologies. It is then upgraded for methane enrichment in order to achieve high efficiency from energy recovery processes.

At present the enriched biogas is very commonly used in combined heat and power system (CHP) to convert the biogas into electricity and heat, which can be utilized in the public grid system and district heating networks respectively. Apart from CHP, enriched biogas can also be used for various purposes such as substitute for natural gas and electricity production in fuel cell technology. Another emerging

International Journal of Engineering Research & Technology (IJERT)
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technology for utilization of enriched biogas is to utilize it as a substitute for transport fuel. All these technologies are discussed below in detail:

4.1 Conversion to electricity

A. Combined heat and power generation

In the CHP system (also known as cogeneration system), the biogas is combusted to run the internal combustion engine that drives a power generator [6, 7, 8]. This is the most commonly used gas-to-energy conversion technology which generates electricity using cleaned biogas having average concentration of 55% of CH_4, and then contributes in national electricity grid [9]. While the heat generated by the internal combustion is transferred via heat exchangers and used in the water heating, space heating, process steam recovering, small heating networks and some of the heat can be used in maintaining the temperature of process if required [1].

Presence of hydrogen sulphide in biogas is a major concern because of its highly corrosive nature which may cause many operational problems. H_2S should be removed before feeding the biogas to the CHP system, various biological or chemical cleaning processes are available to remove H_2S [10, 11, 12].

The energy produced in a CHP system is capable to satisfy the process energy requirements as it is usually very low as comparative to the energy produced by the system. It is reported that approximately 6.9% of totalenergy produced in a CHP system is utilized to satisfy internal energy demand such as energy for electrical components and computer support system in an agricultural anaerobic wet digestion plant [6]. In general, the electricity input for running CHP system varies dependent on the capacity of the system. Literature reveals that for a small scale biogas plant, 3% of total electricity is required for process requirement which may go upto 4.5% for a large scale biogas plant [1]. Therefore, usually there is no need to import energy to run a CHP system. It is an independent and self-capable system in terms of energy.

B. Fuel cell technology

Fuel cell technology uses a process to convert chemical energy of a fuel to electrical energy using chemical reaction between positive hydrogen ions and oxidising agent. This technology promises higher efficiency, lower emissions and possible use of multiple fuels like biogas, natural gas, water and different fluids containing hydrogen [13]. The different fuel cells can be basically grouped into two categories: High Temperature Fuel Cells (HTFC) and Low Temperature Fuel Cells (LTFC).

- High Temperature Fuel Cells (HTFC): The HTFC consist fuel cells that operate at temperature more than 873 K or 600^0 C, such as Solid Oxide Fuel Cells (SOFC) and Molten Carbonate Fuel Cells (MCFC) [14].
- Low Temperature Fuel Cells (LTFC): The LTFC consist fuel cells that work at temperature less than 473 K 200^0 C, like Phosphoric Acid Fuel Cells (PAFC), Alkaline Fuel Cells (AFC), Direct Alcohol Fuel Cells (DAFC), Biological Fuel Cells (BFC) and Polymer Electrolyte Fuel Cells (PEFC) [14].

For producing hydrogen or syngas, biogas can be reformed using the oxidants such as oxygen, steam or carbon dioxide. The various processes of reforming which provides flexibility to treat different raw fuels and has the capability to be merged with fuel cell technology are dry reforming, auto-thermal reforming, Catalytic Partial Oxidation, and steam reforming etc. [14]. As reported in literature [10, 14, 15, 16], at atmospheric pressure the sulfur-free biogas (60% methane and 40% carbon dioxide) undergo the following reactions:

Steam Reforming: $CH_4 + H_2O \rightarrow CO + 3H_2$; $\Delta H = 206.2$ kJ/mol

Dry Reforming: $CH_4 + CO_2 \rightarrow 2CO + 2H_2$; $\Delta H = 247$ kJ/mol

Catalytic Partial Oxidation: $CH_4 + ½\, O_2 \rightarrow CO + 2H_2$;

(Usually platinum is used as catalyst) $\Delta H = -36$ kJ/mol

The partial oxidation is a two-step mechanism.

In first step, the full oxidation of CH_4 yields carbon dioxide and water.

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ [5]

In second step, syngas is produced via reaction of unreacted methane with H_2O or CO_2.

Another reforming method is the auto-thermal reforming (ATR) which combines partial oxidation and steam reforming processes. In this type of reforming exothermic and endothermic reactions take place together. Due to such integrated process the heat required for the endothermic reaction of the steam reforming is directly provided by the exothermic partial oxidation reaction [14]. The equation of auto-thermal reforming process as given in the literature [14] is given below:

$CH_4 + x^{½}\, O_2 + yCO_2 + (1 - x - y)\, H_2O \rightarrow (y+1)\, CO + (3 - x - y)\, H_2$

After this, steam is introduced in presence of the catalyst and Water Gas Shift Reaction (WGSR) occurs in which the carbon monoxide reacts with the water to produce H_2 and CO_2 as given by the following equation:

WGSR: $CO + H_2O \rightarrow CO_2 + H_2$, $\Delta H = -41.2$ kJ/mol [14]

The overall reaction of the fuel cell is mentioned below:

Overall cell reaction: $H_2 + ½O_2 \rightarrow H_2O$ [15].

Although the fuel cells are widely accepted, these can be easily damaged by the impurities present in the biogas. LTFCs have higher sensitivity towards CO, CO_2, CH_4, H_2S, NH_3, while the HTFCs the catalytic processes have sensitivity towards H_2S as sulphur is a poison for catalysts present in the anode of fuel cell [10, 11].

To remove this H_2S from the Biogas various gas cleaning units can be integrated in the fuel cell systems, such as biological cleaning system, absorption in various liquids, membrane separation, and activated carbon adsorption etc. [10, 11, 12]. As referred in the literature [11], Biological gas cleaning unit operated at constant inlet of H_2S concentration, showed a reduction from 500 ppm to 5 ppm. In one of the Chemical gas cleaning method (using zinc oxide bed at 673 K or 400°C), H_2S content was reduced to less than 0.1 ppm in outlet gas stream [10].

The catalytic biogas reforming process is hindered by undesired reactions, such as methane cracking and Reduction of CO etc. [14]. These reactions form carbon on the electrodes and reducing the hydrogen yield. Carbon deposition is a severe problem as it deactivates the catalysts and sometimes blocks the pipelines.

C. Stirling engines

The main advantage of Stirling engine is that it is an external combustion engine, capable to use different kind of fuels to burn. This allows utilization of biogas to run this engine and to combine with a CHP system. As the engine has an external chamber for combustion of fuel, the fuel can be used as it is and does not require refining. This saves cost and energy as purification of biogas may not be necessary [1]. Also the fuel under goes complete combustion which results in less emission of unburnt hydrocarbons [17]. Presently, Natural gas based Stirling engine is commonly used because it has higher power output as comparative to the biogas based Stirling engine. The main reason of this variation in power output is difference in the concentration of methane in both the fuels, which is 96.4% in natural gas and 62% in the biogas [17]. As the major reason to switch to alternative fuels is to reduce the harmful emissions, the Stirling engine integrated with CHP unit operated by biogas instead of natural gas will help achieve the goal. This is because the biogas based Stirling engine reduces CO_2, CO and nitrogen oxide emissions. As reported in literature [1], the overall thermal and electrical conversion efficiencies of these engines are 72% and 24% respectively which makes heat utilisation through Stirling engine an attractive option. Stirling engines have been proved to better due to low maintenance [1].

D. Micro gas turbines

The gas turbines having size lesser than 1 MW, are defined as micro gas turbines. It is an attractive gas to energy technology as it has low environmental impact and less operation and maintenance cost, and biogas can be utilised to operate this technology [13]. The MGT system is small, lightweight and compact. It comprises of components like high speed magnetic generator, radial turbine, and single stage centrifugal compressor. It is important to provide a pre-treatment to biogas before using it in the MGT. Owing to the fact that, purified biogas and compressed air in the process is necessary, the technology becomes energy intensive.

In the MGT system the air is compressed using centrifugal compressor and sent to the regenerator. Here the compressed air is preheated by the exhaust gas from the micro gas turbine [18]. The preheated compressed air is then used for combustion of fuel in the combustion chamber till inlet temperature requirement of turbine is achieved. The hot gases then expand in the turbine and conveyed to the regenerator for heating the compressed air [18]. As the temperature of these exhaust gases coming from the turbine exit unit can be as high as 593°C, can be used to recover the heat using heat recovery boilers and water as a working fluid. This way cogeneration can be done by integrating MGT with a CHP unit to increase the fuel energy conversion efficiency and also achieving thermal efficiency greater than 70% [18].

The power generated in MGT can be converted to 1600 Hz alternating current using a high speed magnetic generator and the AC can be transformed to 50-60 Hz which can be utilised in the electricity grid system. The power generated by the modular MGT can range from 30-200 kW [1]. MGT provides low NOx emissions as the system is operated at low combustion temperature [1, 18].

4.2 Heat generation

Biogas is used as fuel and combusted to obtain energy in form of heat which is then utilised for various purposes discussed in detail in the following sections.

A. Process energy requirement in biogas system

Along with the production of electricity, heat is also generated after combusting the biogas which is depicted in figure 1.The heat generated from CHP or any other technology can be used to maintain the temperature conditions for the process of anaerobic digestion in the biogas system.

The internal thermal energy requirement for maintaining the temperature of digestion chamber in the biogas system can be achieved by the heat produced via CHP unit [6, 8]. This heat can also be utilized to fulfil the thermal requirements of certain feedstock pre-treatments such as sterilisation of slaughter house waste and the food residues [1]. As revealed in literature [6] the thermal efficiency of the Austrian facility working on wet anaerobic digestion system is 39%.

Typically the CHP unit can be operated using biogas as fuel for combustion which results in biogas losses of 0.5% [6, 7]. The CHP thermal efficiency for small scale biogas plant (having 10,000 tonnes capacity of waste) can reach upto 50% and for large scale biogas plant (having 20,000 tonnes capacity of waste) it is reported around 48% [1].

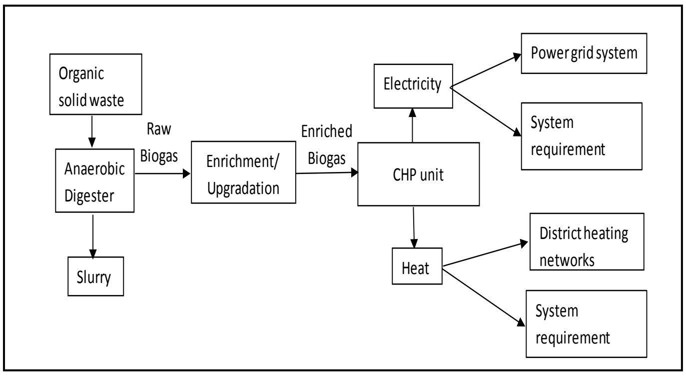

Fig: 1 Utilisation of biogas to generate heat and power.

B. Heat utilisation by heating networks

The biogas serves as a fuel for the plants/technologies producing heat for various applications such as space heating or water heating [19]. The heat generated by the biogas plant integrated with CHP or any other technology can be applied to the district heating networks is a centralised system to generate and distribute heat to the residential, institutional and commercial sections [19]. A report has mentioned that the

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 03, March-2016

heat required by the houses, commercial and industrial sector results in 49% of energy demand and carbon emissions of 47% [19]. The heat demand varies with change in the season [1]. Biogas powered heating networks are used for heating nearby greenhouses, animal stalls, horticulture houses, public amenities and houses [1]. The district heating networks can be:

1. Two or more building connected to one heating source
2. Only one building having 10 or more customers connected to single heating source [20].

A major advantage of biogas is that the infrastructure established to use natural gas for heat production has the capability to accommodate biogas to serve the same purpose which will reduce the capital investment [21].

C. Organic Rankine Cycle Generators

The organic Rankine cycle (ORC) technology which is small size and low temperature generator, work on the principle of Rankine thermodynamic cycle in which organic fluids such as alkyl benzene, refrigerant fluid, siloxanes etc. are used as the working fluid [22]. The conventional steam cycles work on the same principle but with a difference in the use of working fluid as steam. The steam cycles are not as flexible as the ORC which allows the use of variety of working fluids and provides an innovative solution for heat production and conversion to electricity.

Biogas from the digester and compressed air are fed in the combustion chamber. The gases from the combustion chamber drive the generator to produce electricity. The heat transferred by cooling the compressed air and the motor can be used for heating the anaerobic digester to satisfy the input energy requirement. The exhaust gases which leave the motor around temperature of 490°C are conveyed to a heat exchanger to heating up the thermo-oil. This thermo-oil then provides heat for the preheating, evaporation and superheating of the organic fluid also called as working fluid. Then the superheated organic fluid is expanded in the expansion machine which can be either a turbine or a screw type expander. This expansion machine is connected to a generator. The vapour is then desuperheated and condensed by a condenser. Then it is cooled down in a cooling tower and pumped again through the heat exchanger by a feed pump [23].

The efficiency of ORC units varies between 5-17% but average assumption is 12% [1]. It is recommended for the biogas system because the ORC utilizes low temperature heat sources of the biogas system to convert thermal energy into electricity using organic fluids having high molecular mass.

D. Utilisation of heat in absorption chillers

Biogas can be utilised in the process of trigeneration of energy. Trigeneration means combination of cooling, heating and electricity generation. This is often referred as combined cooling, heat and power (CCHP). Trigeneration occurs mainly via two technologies: Production of heat and power by a CHP unit referred to as cogeneration, and utilization of the heat for cooling processes using an absorption chiller. The combustion of biogas produces heat required by the absorption chiller for cooling process [1, 24].

In this process the purified biogas is fed in the combustion chamber of internal combustion engine. The engine produces electricity using power generator (power generation). The exhaust gases from the engine exit unit are conveyed to the absorption chiller which generates chilled water for cooling purposes (cooling). The waste heat present in the exhaust gases from the absorption chiller exit unit is conveyed to heat exchanger to produce hot water (heating) [24].

Thus absorption chiller or refrigerator helps to convert the heat generated from the CHP for combined heat, power and cooling [1].

4.3 Other uses

Biogas can be purified to biomethane and if regulations allow then it can be injected with natural gas for further utilisation in the gas networks. The application of biomethane can be extended for its utilization as a transport fuel. It can also be compressed and stored in the gas cylinders in place of LPG cylinders [1].

A. Utilisation of biogas as a Transport Fuel

The biogas produced from digester is conveyed to upgrading unit to remove all the impurities of the biogas and makes it rich in methane (CH_4> 95%), generally named as biomethane [25, 26, 27]. Then the gas is transferred to the compression unit where it is compressed to a pressure of 200 bar to make it suitable for the distribution systems [6, 7], it can also be filled in gas cylinders [29]. This upgraded and compressed gas can be used as a transport fuel in the vehicles. The requirement of the input energy (operation of the digester, upgrading unit and compression unit) of this technology can be supplied directly from grid system or one of the above discussed technologies present on-site.

As reported and estimated in literature [6] the electricity required for upgradation and compression systems is 0.35 kWh per m^3 of biomethane transformed from biogas in the process. A study indicates that the capital costs of production of biomethane are 19% more than that of a CHP unit. However, the operational costs for the production of biomethane are 26% lesser than the CHP unit. This is due to the use of biomethane in the captive fleet replacing the use of diesel [28]. In order to make the bio-methane facilities economically feasible, the facility must be scaled up from small-scale plants to medium-scale plants as the small-scale facilities do not have the capability to cope with the economics of biomethane technology [6].

B. Utilisation of biogas in gas grid systems.

After necessary purification, there are possibilities of injection of biogas in the natural gas grid system [6, 7]. This process of feeding the biogas in the gas grid system can be an energy efficient solution. The upgraded gas is compressed using a compressor which increases the pressure of biomethane and makes it compatible for the pressurised lines of the gas grid system. If the gas is to be injected in the grid system, the biogas has to be free of impurities, dried and enriched to high CH_4 content (usually >95%), so that it does not damage the gas pipeline networks [6].

This approach is already being used in many countries including Germany, France, Austria, Ireland and the USA.

C. Utilisation of biogas for cooking purposes

In many developing nations where small scale biogas plants (2-10 m^3 capacity) are operated the end use of biogas is as fuel for cooking [30]. In country like India where 60% of energy consumption is for cooking, biogas can prove to be a sustainable alternative as it has heating value of 21MJ. Biogas is far better than the solid fuels used in many parts of the world which provide only 5-15% of thermal efficiency. But the biogas based cooking stoves can achieve thermal efficiency upto20-56% [30].

5. CONCLUSIONS

Biogas is a better and versatile fuel as it produces less emission, reduces GHG emissions, reduces the organic waste and has vast area of application. To increase the yield of biogas generated by anaerobic digestion, pre-treatment of the substrate is necessary. Raw biogas requires cleaning (upgradation) before feeding it to any gas-to-energy technologies. Among the various technologies discussed in this paper CHP appears as a promising technology for biogas utilization. Its efficiency may again increase by integrating it with some other technologies such as with micro gas turbines, ORC unit or absorption chillers.

ACKNOWLEDGMENT

Author is thankful to Shroff S. R. Rotary Institute of chemical technology Ankleshwar (Gujarat), India for providing all necessary facilities to undertake the work.

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