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Economic Utilisation of Biogas as a Renewable Fuel for Fuel Cell

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Abstract: In recent years focus has been changed towards using of biomass derived fuels in the fuel cells such as usage of syngas derived from gasification, coal mine gas derived from abandoned coal mines, biogas derived from biomethanation, methanol produced from renewable biomass feed stock and etc., in combination with the process of reforming. The problem lies in the poisoning effect of some of the components of syngas and biogas and other gases onto the catalyst and other components of fuel cell. This paper intends to address some of these problems and gives an idea to the usage of biomass derived fuels in the fuel cells for power production. In this study, worked out a gas cleanup mechanism and established a layout plan, where almost all the unwanted components are removed from biogas. The conclusion of the study states that the cost of fuel cell technology itself is very high at present when compared to the conventional CHP systems. Also biogas must be cleaned to a greater extent for its successful usage in power generation through fuel cell application

Keywords: Biomass, Biomethanation, Biogas, Fuel cell, Economic Utilisation, Levelised Cost Method

Introduction

The effect of greenhouse gas emitting infrastructure on climate change is also a growing concern, especially agricultural activities. While bio-energy as a power source has become more popular, it addresses many of these concerns and has a few drawbacks. Burning biogas generates photo reactive ozone precursors such as volatile organic compounds (VOCs) and nitrogen oxides (NO_x). NO_x also contributes to photochemical smog and acid rain. The environmental management and treatment of waste is going to be a question and it has to be done in a well-planned and managed method. If degradable components of the waste are let out to the open environment, under anaerobic conditions lead to the release of methane which is a potential green house gases (GHG) and is one of the curtailed

GHGs under Kyoto Protocol. In the process of biomethanation, the organic portion of the waste is being converted anaerobically by bacteria into a mixture of mostly methane (CH_4) and carbon dioxide (CO_2), which is called biogas. These two major components of biogas are potential GHGs. Although these are neutral emissions, by using an efficient technology could be converted into energy.

This case study is a comparison of these two technologies wherein biogas is used. One is conventional Combined Heat and Power (CHP) technology and the other is fuel cell technology. There are various kinds of fuel cells and the one considered in this study is Molten Carbonate Fuel Cell (MCFC). Both these technologies have their advantages and disadvantages in using biogas to generate energy. In CHP motor application CO_2 is considered as a non-energetic component and often removed from biogas using various techniques. Else 30-40% of this GHG would emit into environment. Fuel cells could also use biogas to generate electricity and heat at 40% and higher efficiency than combustion route with less noise and emission of environmental loads such as NO_x and VOCs. In fact MCFC technology uses 30-40% of CO_2 in biogas as fuel in internal reforming reactions.

However biogas also has other components and these would be in part per million (ppm) range. Although these impurities are in ppm range – poisonous to catalyst that is used in the MCFC. Hence cleanup of biogas is very essential before use as a feedstock in MCFC. The biogas quality requirement is not that stringent for CHP motor technology.

Fuel cell has a potential advantage to be an integral part of Renewable Energy (RE) systems. This case study addresses that fuel cell technology itself is expensive when compared to CHP motor technology wherein biogas is used as feed stock. In arriving at this conclusion - second section of this paper presents the methodology adopted, third section would address the biogas cleanup requirement along with economic analysis of clean up system, fourth section would integrate the whole system for CHP motor technology as well as MCFC technology with economic analysis. The last section would addresses the conclusions drawn from this case study.

Methodology

Analysis of biogas cleanup system

The characteristics of the biogas are shown in the table 1. The composition, rather constituents would vary from place to place. These values have been compiled from various literatures. Biogas has to be thoroughly analysed before designing a cleanup system. The biogas samples could be derived in different seasons of a year and at an average two samples per month from bioreactor before making a decision on which type of cleanup system to be implemented and what level of biogas purity is required for the system. It could be seen from the following sections that the cost of cleanup would add to the cost of electricity generated

Table 1 Typical average composition of reactor biogas [1]

Substance	Vol %*	1**	2***	3****	4*****	Landfill gas******
Methane, CH_4	55-75	55-65	55-70	50-70	65-75	57
Carbon dioxide, CO_2	25-45	33-43	30-45	30-40	25-35	37
Carbon monoxide, CO	0-0.3					
Nitrogen, N_2	1-5	2-1	0-2	Small		6
Hydrogen, H_2	0-3			Small		
Hydrogen sulphide, H_2S	0.1-0.5	<2000 (ppm)	~ 500 (ppm)	Small	<5000 (ppm)	
Oxygen, O_2	Traces;					
Ammonia, NH_3		<1000	~ 100 (ppm)		<1	
Water, relative moisture		80				

Units are in Vol%, unless mentioned
*[2]
**Paper BP-12 20th World Gas conference
***Combined utilisation of Biogas and Natural gas, J.Jemsen, S Tafdrup, and Johannes Chrisensen, Paper BO-06, 20th world Gas
Conference. 1997
****Renewable energy World, March 1999, page 75
*****Caddet renewable energy newsletter, July 1999 pages 14-16
******Caddet renewable energy Technical Brochure No.32 (1996)

Various technologies were analysed for removal of unwanted components of biogas for MCFC such as NH_3, H_2S, traces of halides, moisture and siloxane from biogas. H_2S must be removed from biogas whatever the technology one would use. However the purity level required for biogas varies with the technology. Table .2 shows the components of biogas and their use, effect of H_2S and cleanupclean up standard required for fuel cell (i.e. MCFC). Table .3 details the impact of other constituents of biogas.

Table 2 Major constituents of biogas and their use/impact on MCFC [3]

Biogas components	MCFC
CO	Fuel[a]
CH_4	Diluent[b]
CO_2 & H_2O	Diluent[b]
S as (H_2S & COS)	Poison fuel processor reforming catalyst (<0.5 ppm)

[a] In reality, CO, with H_2O, shifts to H_2 and CO_2, and CH_4, with H_2O, reforms to H_2 and CO faster than reacting as a fuel at the electrode.
[b] A fuel in the internal reforming MCFC.

Table 3 Some more details on constituents and their impact on MCFE {3}

Some more constituents in Biogas in general	Ammonia (NH_3)	Halogens (F, Cl, Br)	Siloxane	H_2O	DUST
Fuel cell power plant requirements*+	< 1 ppm	< 0.1 ppm	No data	?	< 0.5 µm
Issue/concern	Fuel cell stack performance	Corrosion of fuel processor	Obstruct the catalytic and chemical processes	Damage to fuel control valves	

Economic analysis

For all the processes the economic analysis was conducted by using levelised cost method. The case study analyses the biogas clean up system required for use of gas in CHP motor technology as well as MCFC, as the quality of standards required would vary for both the technologies. The brief analysis was performed by considering the data from Department of Defence (DoD-US) website [4] for MCFC and real data of CHP motor technology was obtained from a farm located near Oldenburg, Germany [5]. The optimal gas cleanup system was designed and applied levelised cost method to arrive at €/ m^3 of biogas cleaned. Then €/ m^3 is divided by energetic value of biogas for specific technology, as this number would vary from technology to technology. This helps to analyse the cost of energy that is produced from specific technology in terms of cost (i.e. €) per kWh. This analysis would suggest which technology is best in terms of economics and where there is a possibility to reduce the cost. However analysis of reducing the cost is beyond the scope of this paper, the study could conclude with recommendations.

Biogas Cleanup Requirement and Economic Analysis

Biogas cleanup system for CHP motor technology

There are various constituents present in the biogas and those must be cleaned to use biogas as feedstock in the CHP motor technology. The components that are essential to be removed are:

Hydrogen sulphide (H_2S)

The sulphur that is present in the biogas would be minimised using biological sulphur removal (with air/oxygen dosing to the biogas system) process. This technique is based on the biological aerobic oxidation of H_2S to elemental sulphur by a group of specialised microorganism and is called thiobacillus bacteria. The following reaction occurs in the biogas:

$$\mathbf{2H_2S+O_2 \rightarrow 2\,S + 2\,H_2O}$$

The small amount of oxygen (approximately 5-10 %) is introduced in the biogas system e.g. by using an air pump. As a result, the sulphide in the biogas is oxidised into sulphur and the H_2S concentration of the biogas is lowered. The results obtained with this method to date are very promising. A reduction of H_2S - levels down to 20-100 ppm H_2S which equals 30 - 150 mg/m^3 H_2S, and removal efficiency of H_2S between 80-99 % have been achieved depending primarily on the duration of stopover and the specific surface. The H_2S removal obtained with this method is sufficient for a direct use of biogas in gas engines. If excess air gets blown into the fermentor than the required stoichiometry, the formation of sulphuric acid will be enhanced. Hence one has to be careful while inducing oxygen and advised to have a separate chamber for this process by having a special biological filter through which biogas is passed. Also in order to have the bacteria developed in the biogas system, liquid-manure-wetted surface is required as this is a stand alone system [6].

Moisture

The presence of moisture would reduce the calorific value of biogas. This aspect has to be taken into consideration when biogas is used in combustion technologies. To remove few unwanted components (for example H_2S) often activated carbon would be used. The moisture presence in the biogas would restrict the free movement of gas by blocking the permeable area as well as reducing the surface area required. In any case moisture must be removed before passing through other cleanup processes. There are various techniques that could be used to remove moisture from biogas. However the process of condensation is a best technique to remove moisture as well as silicon based compounds. The process of condensation (at -22°C) is placed after biological cleanup process (refer Fig. 1). The power required to cool the gas (assuming a difference of 12°K in cooling machine – input gas is at 30°C and output gas is at 18°C) is 1.59 kW and electrical power is twice to that power (assuming heat transfer in heat exchanger is 30°C is possible) and is 3.18 kWel [7]

Economics of the clean-up plant

The processes mentioned under section 3.1 could be summarised as mentioned in the Fig. 1.

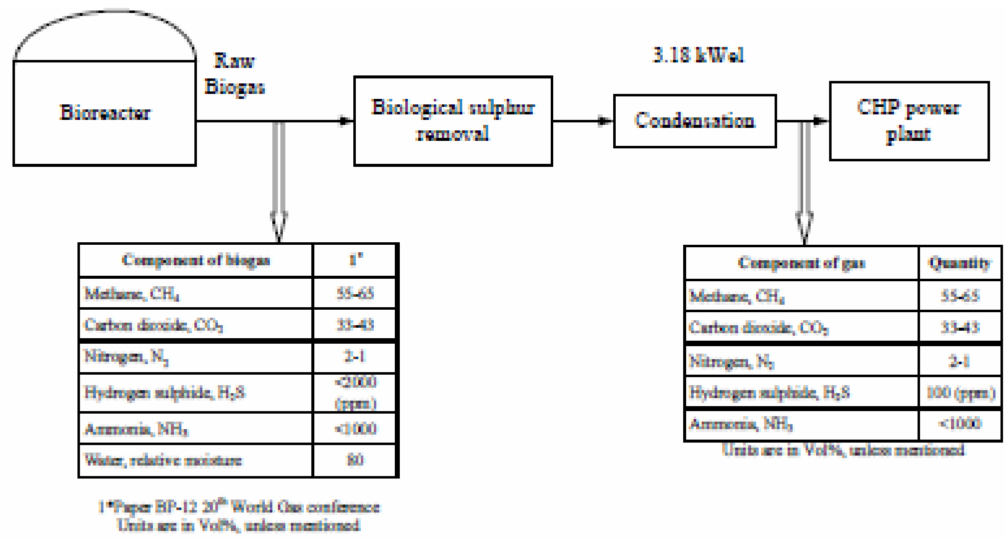

Fig. 1 Schematic of biogas cleanup system for CHP motor technology

The economic analysis was performed to arrive at cost (i.e. €) per m^3 raw biogas cleaned and Table .4 show the details.

Table 4 Levelised cost analysis for cleanup of raw biogas for CHP motor technology

System components	Levelised cost (€/m^3 raw biogas cleaned)
1. Investment cost for biological clean-up from ATZ EVUS	0.0024
Maintenance for biological clean-up	0.0005
2. Condensation process for Silicon compounds and water	0.0008
3. Insurance @ 2% of investment	0.0006
TOTAL	0.0043

Biogas cleanup system for MCFC

MCFC has more stringent requirements on the quality of biogas required as feedstock. In addition to the two processes that are mentioned under section 3.1.1 and 3.1.2, NH_3 must be addressed first followed by the fine tuning of H_2S content is very much essential (refer section 2.1 for details on the tolerance limit of these gases). In the removal process of these gases halogenated hydrocarbons would also be addressed in directly. The final system layout could be seen in the Fig.2.

Ammonia

In industrial large-scale cleaning processes, ammonia is often removed from the gas by a washing process with diluted nitric or sulphuric acid. However, the use of such acids requires equipment constructed with stainless steel, which is expensive for small-scale applications as biogas cleaning. Ammonia can be removed with activated charcoal units and can be removed in some upgrading processes, such as adsorption processes and water scrubbing [8]. The acid-impregnated activated charcoal will adsorb NH_3. When using a H_2SO_4 impregnation, the following reaction takes place:

$$\mathbf{2NH_3+H_2SO_4 \longrightarrow (NH_4)_2SO_4}$$

An appropriate reaction to ammonium phosphate takes place with the impregnation of H_2SO_4 onto activated charcoal. The active charcoals supplied can not be regenerated, but loaded coals must be disposed off. With both kinds of activated charcoal the NH_3 removal should be prior to desulphurisation, since ammonia contents worsen the adsorption-catalytic process. Activated carbon processes for fine tuning of H_2S content and halogenated hydrocarbons Catalytic oxidation (adsorption catalysis with activated charcoal), with this procedure H_2S is catalytically oxidises to elementary sulphur. Activated charcoal is the designation, for a group of porous carbon structures, which consist of mixtures of smallest graphite crystals and amorphous carbon. The adsorption of hydrogen sulphide on activated carbon is catalytic and the carbon acts as catalyst. The carbon is often impregnated with potassium iodide (KI) or sulphuric acid (H_2SO_4) to increase the reaction rate. The chemical reaction is:

$$\mathbf{2\ H_2S+O_2 \xrightarrow{\text{Catalyst}} 2S+2H_2O}$$

The condensation process would eliminate most of moisture and there by avoids the saturation of H_2O onto activated charcoal. Usually the used or deposited loaded activated charcoal is exchanged and can be regenerated externally [9]. Halogenated hydrocarbons, particularly chloro and fluoro compounds are predominantly found in landfill gas and can cause corrosion. They can be removed with impregnated activated carbon. In this process small size molecule like methane, carbon dioxide, nitrogen, and oxygen pass through, whereas larger molecules are adsorbed. Regeneration of these could be carried out externally [8].

Economics of the clean-up plant

The processes mentioned under section 3.3 and 3.1 could be summarised as shown in the Fig. 2.

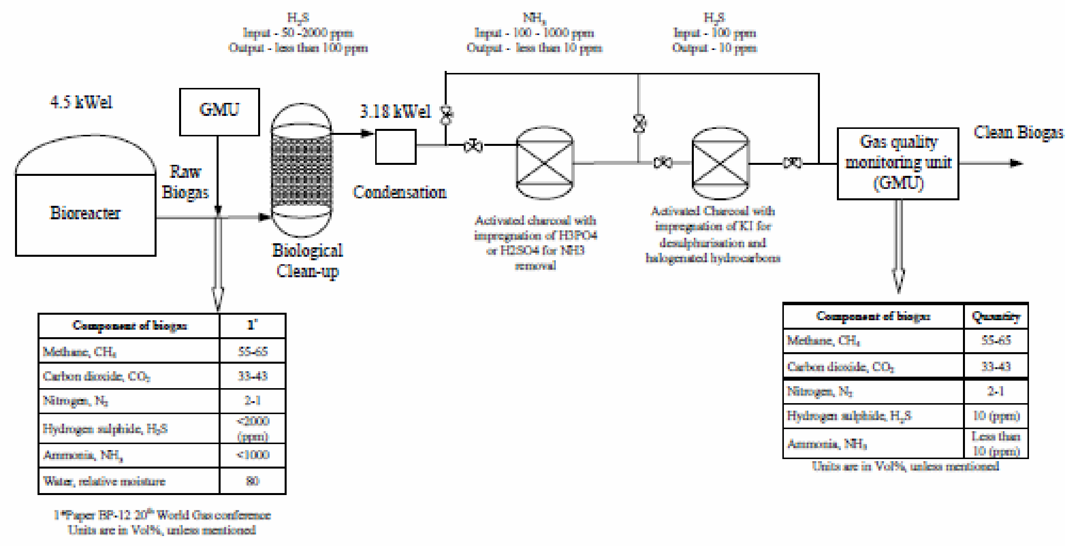

Fig.2 Schematic of biogas cleanup system for MCFC

Based on the Fig.2, the economics of biogas cleanup system is shown in Table 5.

Table 5 Levelised cost analysis for cleanup of raw biogas for MCFC

System components	Levelised cost (€/m^3 raw biogas cleaned)
1. Investment cost for biological clean-up from ATZ EVUS	0.0024
Maintenance for biological clean-up	0.0005
2. Condensation process for Silicon compounds and water	0.0008
3. Activated charcoal for H_2S removal	0.0070
4. Activated charcoal for NH_3 removal	0.0004
5. Investment cost for the setup (H_2S & NH_3)	0.0009
6.Operation cost for the setup (H_2S & NH_3)	0.0001
7. Insurance @ 2% of investment	0.0006
TOTAL	0.0127

Analysis of integrated system for chp motor technology and MCFC

The advantage of fuel cell is that it will not under go Carnot cycle and is purely based on chemical energy. There is also a fundamental advantage using biogas as feedstock in MCFC. Both CH_4 and CO_2 acts as diluents and are converted as fuel in the internal reforming reactions of MCFC. In fact water is required in the reforming process of biogas to hydrogen. Although the moisture present in the biogas is initially removed because of its presence would be a disadvantage to other cleanup processes. The theoretical energetic value of biogas with 60% methane content is 5.56-6.64 kWh/m^3; in general the value can be taken 6.5kWh/m^3. If this energetic gas is used in CHP-motor, then the conversion process efficiency must be taken into account. The overall process efficiency can be taken as 30% and the energetic value of biogas in terms of electrical energy is 1.95 kWh/m3.

To produce 200kW power the amount of biogas flow rate that is required for MCFC is 81.4 m^3/h. From this data it can be stated that the energetic value of biogas is 2.5 kWh/m^3 in case the electrical energy is generated from MCFC by using biogas as feedstock. Both heating energy and environmental effects are not considered in the analysis.

The case of CHP motor technology

If biogas is used as feedstock in CHP-motor, there are no stringent regulations on the biogas quality when compared to standards required for MCFC. The rated life time of the CHP-motor considered in the analysis is 70,000 hours.

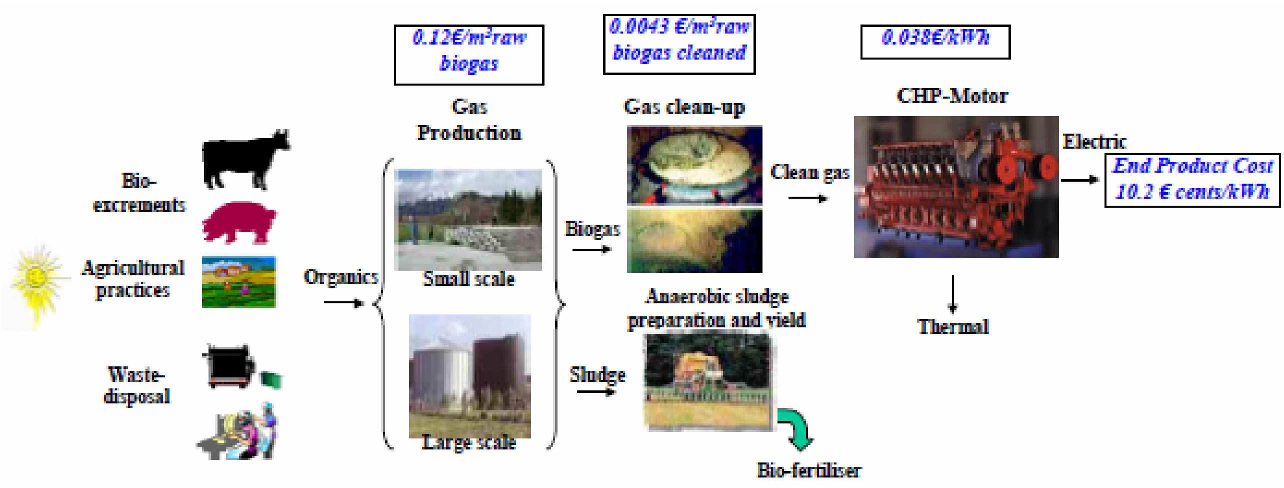

Fig. 3 Integrated system analysis shows the levelised cost at each stage-for CHP motor technology

Levelised cost for biogas production assuming energy content of 1 m^{3}of biogas as 1.95 kWh/ m^3

$$= \frac{0.12\text{ €}/m^3}{1.95\ kWh/m^3} = 0.062\text{ €}/kWh$$

Levelised cost for biogas cleanup by desulphurisation and removal of silicon compounds

$$= \frac{0.0043\text{ €}/m^3}{1.95\ kWh/m^3} = 0.002\text{ €}/kWh$$

$$= 0.038\text{ €/kWh}$$

$$= 0.102\text{ €/kWh}$$

Levelised cost of energy production from CHP-motor

Total levelised cost, energy produced in case of CHP system

The case of MCFC

Cost of fuel cell was considered 3750 €/kW [4] and there has been reports, which says that 4000-4500$/kW. Life of fuel cell assumed 40,000 hours and i.e. about 5 years. There is low grade heat which is released in the process and is not considered in the economic analysis - the reason being, that the reforming reaction will consume a lot of heat that is being produced

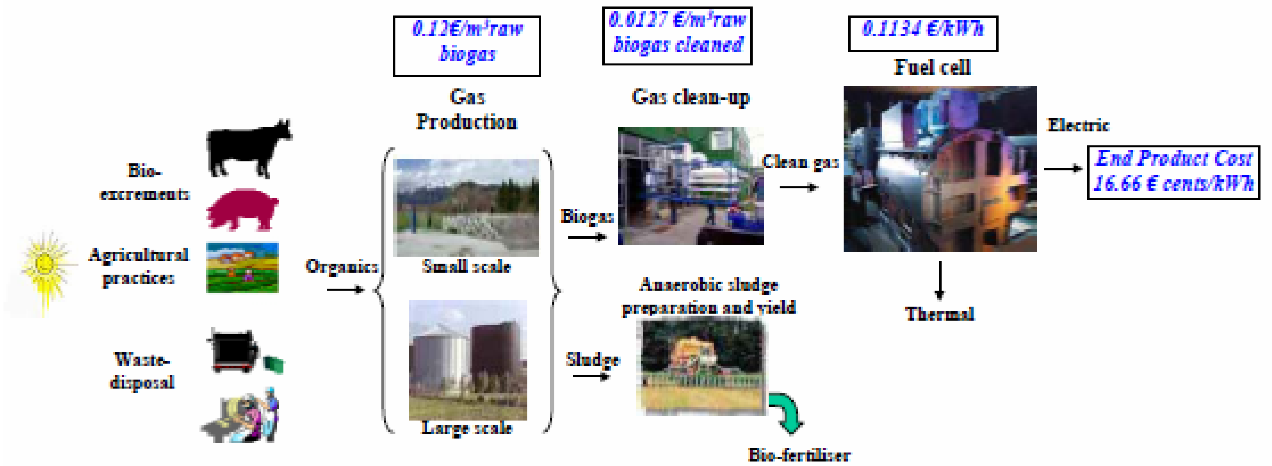

Fig.4 Intergrated system analysis shows the levelised cost at each stage-for CHP motor technology

Levelised cost for biogas production assuming energy content of 1 m^3 of biogas as 2.5 kWh/ m^3

$$= \frac{0.12\ €/m^3}{2.5\ kWh/m^3} = 0.048\ €/kWh$$

Levelised cost for biogas cleanup from section 3.4

$$= \frac{0.0127\ €/m^3}{2.5\ kWh/m^3} = 0.0051\ €/kWh$$

Levelised cost of energy production from fuel cell

$$= 0.1135\ €/kWh$$

Total levelised cost, energy produced in case of fuel cell system

$$= 0.1666\ €/kWh$$

Conclusions

In the next 20 to 30 years, deployment of decentralised power generation technologies is going to be increased. Such distributed and decentralised power systems should involve energy generated from natural gas, biogas from agricultural and residential wastes, syngas derived from gasification, gas derived from coal gasification and landfill gases. Efficiency and environmental compatibility will remain crucial areas that need optimisation. Fuel cell technology in particular has a major potential for decentralised power generation and it is conceivable that, larger plants will be seen with a generating capacity ranging from 200 kW to 2 MW. With this longing, this case study is based on use of biogas as a renewable feedstock to MCFC. However fuel cell used in the case study failed in the economic analysis to compete with CHP motor technology. The conclusions from the study are as follows:

- The production of energy from MCFC is more efficient than from CHP motor
- Fuel cells are not economically viable in the present context unless cost could be reduced further. This could only be achieved with the support from R&D.
- No utility will be capable of purchasing energy at 16.7 € cents/kWh, whereas the cost of the energy that can be purchased from the grid is much lesser than this amount (the situation of Germany).
- In most cases it might not be possible to prevent the above mentioned compounds entering the digester. They will get converted along with the process of biomethanation into H_2S, ammonia, siloxane and halogens.
- The case of siloxanes, these can be removed by freezing the gas at -30°C [7]. The process of freezing consumes power and will add-up to economics in addition to replacement of active charcoal beds. In the reference [10] it is stated that siloxane compounds can be freezed at 0°C. There is a need for experimental proof in order to state the freezing temperature of siloxane.

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