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A Mini Review on Risk and Potential of Biogas Fed Solid Oxide Fuel Cell

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ABSTRACT

Solid oxide fuel cell (SOFC) can reduce the carbon footprint due to their flexibility of fuel usage by using hydrogen and light hydrocarbon as fuel to convert the chemical to electrical energy. This has made the SOFC an interesting device for renewable applications. SOFC which is able to convert the biogas produces from the water treatment plant directly to electrical energy is a reliable renewable energy application. The performance of SOFC itself can be greatly influenced by the characteristics of the biogas. This is caused by the impurities of the biogas that would degrade the internal reforming aspect of SOFC. Mainly on the anode side degradation due to the formation of carbon, sulfur poisoning, and mechanical instability. The commonly found biogas impurities from the wastewater treatment plant are Siloxanes. The compound is coming from sewage sludge digestion which is the common compound in household cleaning products and cosmetics. The presence of Siloxanes in internal reforming SOFC would lead to the formation of SiO_2 which degrade the anode layer and consequently reduces the power generation of SOFC. Hydrogen sulfide and ammonia were also present in the biogas fed from the wastewater treatment plant. These contaminations also showed degradation in the SOFC of the anode. Thus, this work will discuss the contamination compound and its effect on SOFC.

Keywords: Solid oxide fuel cell; biogas; contamination; degradation

INTRODUCTION

Global energy consumption is increasing tremendously with the increase of the human population per capita (Du & Xia 2018). Energy in the form of electrical has become part of life's necessity. The conventional way of providing electrical energy is through fossil fuel-based energy by burning coal and natural gas due to their availability and abundance. In recent years, global warming has reached an alarming state where the carbon emission of energy conversion through fossil fuel has increased the world greenhouse gas (GHG). It has caused harm to the environment and human life. A change in energy production is required to reduce the GHG effect whereas renewable energy could produce or convert energy to electrical energy by reducing the GHG effect(Viju & Kerr 2013; How et al. 2019; Nevzorova & Kutcherov 2019).

Waste management is one of the major issues faced around the world. Improper handling of waste would add effect to the GHG. Breakdown of waste in an improper manner would produce carbon dioxide which is released into the environment and indirectly causes environmental pollution (Thiruselvi et al. 2021). In Malaysia, waste can be categorized into two types which are solid and liquid waste. The solid waste could come from agricultural waste such as wood, coconut, paddy, palm oil and sugarcane, animal waste, and urban solid waste. On the other hand, the major contribution of liquid waste is sludge and wastewater from living. Improper handling of waste would lead to diseases and causes a major threat to humanity. Thus, converting the waste to renewable energy through biogas production could improve the GHG and reduce the creation of diseases in humankind (Yang et al. 2021). The solid and liquid waste would go through microbiological fermentation for biogas production. The biogas produced would consist of methane and carbon dioxide in a certain proportion depending on the types of waste (Hanafiah et al. 2016; Aziz, Hanafiah & Gheewala 2019). Methane which is a compound of hydrogen and carbon could be converted to electrical energy by an energy converter.

In recent years, renewable energy demand was increasing due to the awakening call by the nature on the GHG effect. Multiple natural disasters have shown the effect of GHG on environmental and human living. Biogas that was produced from waste could be converted to electrical energy by the fuel cell. Fuel cell an energy converter has shown efficiency in converting chemical energy to electrical energy. Moreover, the fuel cell is a renewable energy converter that produces almost zero carbon emissions. There were multiple types of fuel cells such as proton exchange membrane fuel cell, solid oxide fuel cell (SOFC), alkaline fuel cell, and molten carbonate fuel cell. Among them, the solid oxide fuel cell is the most suitable for biogas energy converter. This is because the SOFC has fuel flexibility, modular design, and high efficiency as compared to the other fuel cells(Ding, Lv & Weng 2019; Mantelli et al. 2019). Fuel cell energy converter has an energy converting efficiency of 45-60%.

Biogas that was produced from different waste would generate a different proportion of chemical compounds such as methane, hydrogen sulfide, nitrogen, ammonia, and carbon dioxide. The biogas that was useful for energy converters using SOFC was methane. To reduce the other impurities during the production of biogas, the researcher has improved the techniques and addition of a chemical compound to increase the production of methane during bio-gasification(Milad Beigzadeh et al. 2021). SOFC which converts the chemical energy to electrical energy produces minimal carbon dioxide during the process. Biogas that was produced from different biomass would affect the conversion efficiency of SOFC. Thus, this paper will discuss biogas resources, types of biogas contamination from solid and liquid waste, and their effects on SOFC efficiency.

BIOGAS RESOURCES

It was known that the major contributor to global warming and greenhouse gas (GHG) is contributed by the use of fossil fuel which produces carbon dioxide during energy conversion. However, the natural decay of living stands right after the fossil fuel in producing harmful gases to the environment. Anthropogenic activities of waste would produce a large amount of methane. Improper management of waste leads to the release of a large amount of methane into the environment (Liu et al. 2021). The emission of methane from decay activities contributed to about 50% of the GHG effect. Consequently, the ozone layer would be destroyed due to a large amount of methane.

Natural and sustainable waste such as wood, agriculture, palm oil, paper, municipal solid waste (MSW), and wastewater would release methane during the decay process. Trapping the methane produced from waste is a good source of biogas for renewable energy. This would improve the energy security on the dependence on fossil fuel and provide an alternative energy source using biogas. Moreover, capturing the methane for energy conversion would also reduce the GHG emission that causes a threat to the ozone layer.

Biogas productions are dependent on the country's waste supply. Different countries use different biomass or natural resources in producing biogas. For instance, in India, most of the population is in rural areas and the electricity grid is not possible. Thus, biogas is one of the alternatives to provide electrical energy to rural areas. The biogas is potentially produced from MSW, agriculture, and animal manure in rural Indian areas. The availability of biomass such as animal manure to produce biogas was seen as possible in India's rural areas. It was reported that almost 294 million animals were owned in rural areas and it was estimated that almost 17 KMm^3 of biogas could be produced daily (Kamalimeera & Kirubakaran 2021). Similarly in Vietnam, an increase in animal manure was seen due to economic development. Energy securities were developed by producing biogas from animal manure for farm usage and sold to public and private institutions.

In developing countries like China, a large amount of agricultural waste was produced such as straw. This was due to the food staple of the citizen where rice and wheat are mostly consumed in the country. Reports show China could produce almost 700 million tons of straw waste annually (Aziz, Hanafiah & Gheewala 2019). Thus, China has initiated to produce of biogas from straw waste, and this would improve the waste management of straw and also reduce the air pollution created by the straw dust. Moreover, implementing biogas energy could improve energy security in a developed country.

Malaysia as one of the palm oil exporters produces a large amount of palm oil mill effluent (POME) where almost seven times of POME is produced with every ton of palm oil extraction (Chin et al. 2013; Sadhukhan et al. 2018; Aziz et al. 2020; Ng 2021). POME is a liquid that is brownish with a gooey texture where it was a combination of complex organic pollution. The anthropogenic activities of POME could produce 70% of methane, 30% of carbon dioxide, and a small amount of hydrogen sulfide. Thus, inappropriate management of POME would lead to water and air pollution(Loh et al. 2017). On the other hand, the wastewater treatment plant was the second facility that capture the biogas to reduce the GHG effects during the water treatment process. The anaerobic digestion process of sludge would produce biogas containing the composition of 65% methane, about 35% of carbon dioxide, and other gases such as nitrogen, oxygen and water (Guilera et al. 2020). The impurities found in biogas produced from sludge were hydrogen sulfide, volatile organic compound, ammonia, siloxanes and minor residual aromatic hydrocarbon. Capturing the methane from POME and sludge anaerobic could produce renewable electricity through the energy converter SOFC.

BIOGAS COMPOUND

The major compound of biogas produced from the resources is methane and carbon dioxide. In addition, there was a minor compound found commonly in the biogas, which is nitrogen and oxygen. Other traces of sulfur compound, silicon compound, and volatile organic compounds could also be traced from different resources of waste supply(Syahri et al. 2022). Literature has reported that biogas composition varies from different resources depending on waste supply (Calbry-Muzyka et al. 2022). Table 1 shows a collection of data on the compound biogas produces from different resources(Papurello & Lanzini 2018a; Papurello, Silvestri & Modena 2021; Calbry-Muzyka et al. 2022).

TABLE 1. Biogas composition from different resources

Resources	Composition of Biogas Produce				Contamination Average Value of Compound		Ref.
	Methane (%)	Carbon Dioxide (%)	Oxygen (%)	Nitrogen (%)	Hydrogen Sulfide (ppm)	Siloxane (mg/m^3)	
POME	70	30	-	-	-	-	(A Aziz et al., 2020)
Wastewater	64	36	<0.1	0.2	600	1	(Guilera et al., 2020)
Animal Manure	58	41	0.5	2	160	Nil	(Ramos-Suárez et al., 2019)
Agriculture	56	39	0.6	3	661	0.02	(Aravani et al., 2022)
Landfill	54	35	1	5	437	3	(Villanueva-Estrada et al., 2019)
Waste	57	38	0.4	1	688	1	(Calbry-Muzyka et al., 2022)

The researcher has reported that POME produces a high composition of methane with a lower composition of carbon dioxide followed by wastewater. The other resources such as animal manure, agriculture, landfill and solid waste have shown an almost similar amount of methane produced. On the other hand, there was a minor compound of sulfur and silicon traces in the biogas from different resources. The wastewater and solid waste have been shown to produce a higher amount of Hydrogen Sulfide (sulfur compound) and Siloxane (silicon compound).

Sulfur compounds are commonly found in household waste which are shown in Table 1 where wastewater and solid waste has produces high sulfur compounds. The compound is commonly seen in cleaning agents in households where the sulfate is reduced to sulfide during the anaerobic digestion phase producing hydrogen sulfide during the production of biogas. Hydrogen Sulfide is colorless, poisonous and corrosive. Thus, the presence of hydrogen sulfide in biogas is harmful to the SOFC (Nurul Noramelya Zulkefli et al. 2019). Another biogas compound that was harmful to the operation of SOFC is the presence of Siloxane which is part of the silicon compound. It was also commonly found in the cleaning agent where the combustion of biogas at high temperatures would form silicon dioxide. Thus, affecting the life span of a SOFC. From Table 1, it was shown that resources that produce high methane compounds are linked to the higher contamination of sulfur and silicon compound. Thus, in-depth studies are required to know the limitation and process of contamination elimination are required to further enhance the usage of biogas fed SOFC. In literature, there were no data found for POME on the biogas contamination of sulfur and silicon compound. Multiple literatures has reported that the traces of sulfur and silicon in biogas would reduce the energetic use of biogas in SOFC. The effect of sulfur and silicon compound in biogas on SOFC will be discussed in the next section.

CONTAMINATION EFFECTS ON SOFC

SOFC application performance is affected by the contaminants in the biogas fed. Silicon-based contaminants are known to severely affect the anode SOFC. The effect of different biogas contamination on SOFC performance is shown in Table 2. Hydrogen sulfide is known to affect the mass transfer in SOFC and cause cell degradation. However, the effect of hydrogen sulfide is reversible when the contamination value is below 2 parts per million (ppm). On another hand, the presence of siloxane is more crucial as compared to hydrogen sulfide where the slight presence of siloxane would lead to the irreversible effect of the mass transport and electrochemical reaction in SOFC.

Multiple studies were carried out over the years to determine the acceptable range of contaminants to reduce the SOFC performance degradation. Papurello and Lanzini, 2018 have studied experimentally the raw biogas impurities produced from the water treatment and waste degradation. They reported that the threshold limit of biogas contamination for hydrogen sulfide is 2 ppm and hydrogen chloride is 40 ppm. Another study has reported that hydrogen chloride contamination at 20 ppm has led to an irreversible effect of small crack and reoxidation signal (Papurello, Silvestri & Modena 2021). The study has mentioned that the degradation of SOFC with the presence of hydrogen chloride is due to the corrosion near the manifold and single-cell configuration mainly on the sealant. Tian and Milcarek, 2020 have reported that the degradation of SOFC due to siloxane is less severe due to the presence of water. More silicon deposition on the anode is seen on the reactant fed containing hydrogen and siloxane as compared to a combination of hydrogen, water, and siloxane. Escudero et al., 2021 have investigated SOFC cells by first feeding clean biogas, then biogas containing hydrogen sulfide and siloxane. They reported that SOFC performance was stable during the clean biogas supply. The impurities of siloxane and hydrogen sulfide have degraded the SOFC performance, and an insignificant long-term degradation was seen after the removal of contaminated biogas. The study was carried out with a different anode material to overcome the irreversible performance degradation due to sulfur and silicone compound. It was shown that the anode material plays an important role in performance degradation due to biogas contamination substance, especially on siloxane. The commonly used anode material Ni-YSZ would increase the carbon deposition on the Ni surface due to the presence of silicon compounds. A study was also carried out on varying biogas compounds on the methane fraction over the carbon dioxide (Wang et al. 2021). It was reported that the system efficiency increases as the methane compound increase. However, this also leads to the increase of heat and the condition enhances the carbon deposition at the anode. The carbon deposition would cause stack degradation where it reduces the active area and permeability.

TABLE 2. Biogas Fed Contamination Effect on SOFC

Contamination	SOFC performance effect	Reversible or irreversible effect
Hydrogen Sulphide (H_2S)	Affects the mass transfer by forming nickel sulfide (Kamalimeera and Kirubakaran, 2021)	The reversible effect is when the H_2S value drop below 2 ppm, cell voltage increase. (Papurello and Lanzini, 2018)
Hydrogen Chloride (HCl)	Limit the electrochemical process on the electrodes. SOFC electrode degradation where small cracks and oxidation of HCl and glass-ceramic sealant were found near the manifold.	In contamination below 20 ppm, cell performance could be achieved (Papurello and Lanzini, 2018a).
Octamethylcyclotetrasiloxane (D4)	The formation of silicon dioxide on the anode porous area affects the mass transport and electrochemical reaction.	Irreversible effect by D4 with 1.19 ppm (Madi et al., 2015; Papurello and Lanzini, 2018a).
Tetrachloroethylene ($H_2S + C_2Cl_4$)	Chlorine affects the electrochemical reaction while sulfur compound causes the degradation of mass transport.	-
Methyl Ethyl Ketone (C_4H_8O)	Catalyst degradation and carbon deposition phenomena(Wang et al., 2021)	Irreversible effect of carbon deposition on porous area (Papurello, Silvestri & Modena, 2021).
Limonene ($C_{10}H_{16}$)	higher degradation compared to MEK due to the higher C/H ratio.	Irreversible effect of carbon deposition on porous area (Wang et al., 2021).
Thiols (CH_4S)	Causes anode deactivation due to sulfur content and carbon deposition. In long term, it would cause nickel deposition and fuel starvation.	Irreversible effect of carbon deposition on porous area (Papurello, Silvestri & Modena, 2021).
Phenol (C_6H_5OH)	Cell support erosion happen and causes an increase in the porosity.	The compound containing 8 g/Nm^3 and higher causes an irreversible degradation of the cell support (Geis et al., 2018).

BIOGAS FED SOFC APPLICATION

Multiple countries have started to adapt the application of biogas fed SOFC where the biogas produced was supplied to the SOFC for generating electrical current for the plant. For years, multiple applications and research were carried out to investigate the adaptability and biogas fed SOFC. A European industrial size biogas-fed 174 kW SOFC was studied on its capacity and performance as shown in Figure 1 (Gandiglio et al. 2020). The biogas SOFC was fed by sewage biogas produced from the wastewater treatment plant. The plant was reported to run since October 2017 and has been in a stable condition in providing electrical energy to the wastewater treatment plant. Another biogas-fed SOFC plant was reported in Vietnam where a sustainable energy application was built on a shrimp farm(Shiratori et al. 2019). Biogas produced from sludge and feedstock is fed to a 1kW SOFC to power the farm. The biogas fed SOFC was reported to have 53.1% of power generation efficiency. Another study was carried out by Langnickel et al., 2020 to determine the power efficiency of industrial SOFC fed by sewage biogas. They concluded that the power efficiency of SOFC is not dependent on the methane concentration produced from the sewage biogas. All the reported biogas-fed SOFC plants are equipped with the filtration process before feeding the biogas to SOFC. Studies were also carried out to optimize the methods of detecting silicon and sulfur presence along the filtration process. Calbry-Muzyka et al. (2021) have investigated to determine the suitability detection method for the presence of organic silicon compound along with the filtration process of the feeding biogas. They concluded that manual and online detection has shown similar results on the contamination compound.

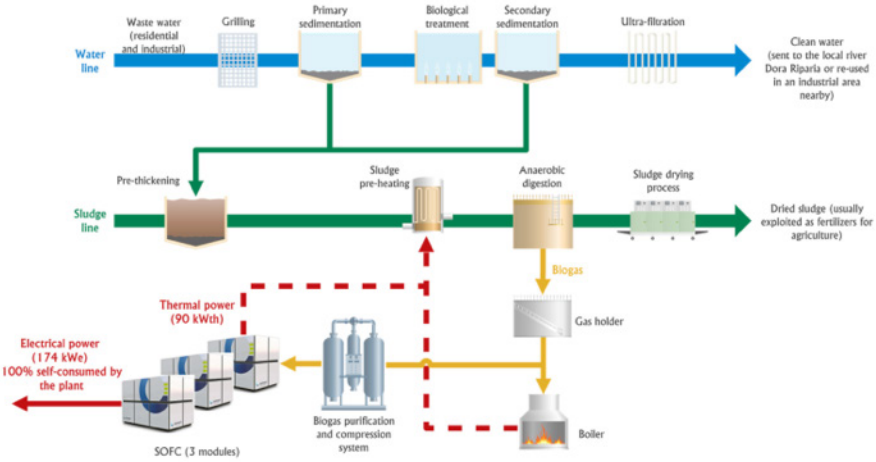

FIGURE 1. Biogas fed SOFC Demo plant (Gandiglio et al. 2020).

CONCLUSION

Biogas is seen as potential renewable energy to reduce the GHG effect and increase global energy security. The resources of biogas are varied from the national food supply waste to sewage, manure, and solid waste. The proper capturing of biogas gasification through all the resources could reduce the GHG effect and convert the gas to better use. Throughout the literature, SOFC which produces almost no carbon dioxide during energy conversion and fuel flexibility has shown to be suitable as a biogas fed energy converter. However, multiple recent research has stated on the contamination compound found in biogas from different resources. Among the contamination compound, silicon and sulfur originating in biogas would cause an irreversible degradation of the material and performance of SOFC. Thus, further research is required to improve the process of cleaning biogas, acceptable range of impurities in biogas, and produce SOFC material that is prone to impurities. The resources of biogas would contain different impurities. Malaysia has an abundance of POME are great resources of biogas to feed the SOFC. However, there was less data analysis on the impurities content of biogas produced from POME. Thus, further research on biogas compound from POME are required for Malaysia to enhance the renewable energy resources using biogas fed SOFC. As mentioned in the text, the neighboring country has developed a pilot plant on the potential of biogas fed SOFC and it has been shown to produce sufficient energy for a farm.

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DECLARATION OF COMPETING INTEREST

None

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