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Performance Analysis of Biogas-Fueled SOFC/MGT Hybrid Power System in Busan, Republic of Korea †

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Abstract: Biogas Plant is located in Busan, Korea and it has a facility to produce biogas through the anaerobic digestion of sewage sludge and food waste. But the generated biogas is recovered and used as fuel to increase the temperature in the digester and the rest is burned and dumped at the waste gas incinerator. In this study, we analyzed the performance of a biogas-fueled solid oxide fuel cell (SOFC) system, which is coupled with a Micro gas turbine (MGT) for a target biogas plant. The objective of this study is to clarify the relationship between the scale of a plant and the optimal size. The calculation results of the greenhouse gas emission due to power usage using biogas is decreased.

Keywords: performance analysis; biogas; SOFC; hybrid power system

1. Introduction

This study aims to conduct a performance evaluation of various hybrid systems such as SOFC and MGT using actual biogas operation data that processes food wastes and sewer sludge, analyzes thermal economic feasibility, and suggests data on greenhouse gas reduction in terms of power production viewpoints [1]. Biogas from the corresponding treatment facility is not used for the purpose of energy production and is incinerated only to raise the temperature of the digester [2]. Although a biogas upgrading and sales project started in 2015, it was temporarily suspended due to a gas leakage accident [3]. Thus, this study aims to generate power directly and to use this power as well and obtain thermal energy to raise the temperature in the digester in order to recover and employ waste biogas. The objective of this study is to clarify the relationship between the scale of a plant and the optimal size of the equipment. And built external-reforming SOFCs reflect as a power generation device the uniqueness and eco-friendly of a large sewage sludge and food waste treatment facility which uses biogas as hydrogen energy source [4]. In addition, the waste heat from the fuel cells was actively utilized in order to convert as much as possible the chemical energy possessed by hydrogen to electricity for the purposes, in order to use the waste heat we have built a hybrid system that combines MGTs [5].

Prior to practical application to a biogas plant, further studies on characteristics of SOFCs single or hybrid systems are required to answer the questions on whether the which is suitable to the loading characteristic of the biogas plant, which system can be built, what performance characteristic the system has, and whether the system is eco-friendly [6].

2. Biogas Plant in Busan, Republic of Korea

Biogas Production in 2014

In this chapter, the sewage sludge and food waste treatment plant uses MBR, MLE, and conventional activated sludge processes to treat sewage [7]. It also takes responsibility for the combined food waste-sewage treatment process, treating up to 452,000 m^3 of sewage and 120 tons of food waste a day. Moreover, it is proceeding with its biogas purification project to recycle methane gas generated in the process of sewage sludge digestion.

In this study, I designed and analyzed two CHP systems based on data collected from a biogas plant located in Busan, Republic of Korea. The plant was originally built in 1988 to handle the sewage produced by one million people, and it was renovated in 2013 to meet the enhanced discharge regulations by introducing a new membrane bioreactor [8]. As one of the sub-processes, the plant operates four 7000 m^3 capacity ADs to reduce the organic contents from the sewage sludge and to produce biogas as a profitable by-product. For the AD, organic-rich food waste is added to increase the digestion efficiency by providing a good nutrient balance for anaerobic bacteria [9].

Actual sewage sludge and food waste treatment plants were adopted as the model plants presented in Table 1. The analysis period is one year, from January 2014 to December 2014. The production decreases in summer due to the small amount of incoming waste (intrinsic seasonal variation). The plant produced a total of 7,231,294 Nm^3 of biogas for the period, and the plant used 28.5% of it to heat the digester. The rest of the gas was burned in the combustor without further use.

Four egg-shaped ADs with 7000-m^3 capacity (total 28,000 m^3) were installed to process a maximum of 220 tons of waste per day. The digestion temperature was controlled to 36.5 °C, which is one of the optimum temperatures for activating anaerobic bacteria, but it is not an economically optimal temperature due to the heat requirement [10]. In this plant, the major objective is cracking organic matter within 20 days and not producing biogas economically [11].

Table 1. Characteristics and operating conditions of the sewage sludge and food waste treatment plant.

Parameters	Unit	Value
Sewage sludge	tons/day	100
Thickener	m^3	672 × 6
Anaerobic digester	m^3	7000 × 4
Dehydrator	m^3/h	40 × 3
Gas tank	m^3	6000 × 1
Desulfurizer	m^3/h	800 × 2
Boiler	tons/h	2.5 × 4
Food waste	tons/day	120
Hopper	m^3	70
Crusher	m^3/h	7.5
Settling tank	m^3	6
Grinder	m^3/h	9
Storage basin	m^3	100
Transfer pump	m^3/h	30
Population coverage	People	1,094,000
Biogas production	m^3/month	105,954–718,748

3. System Modeling

3.1. Biogas Fueled SOFC Power System

The SOFC/MGT hybrid system must have MGT cooling due to its high TIT, and it is suitable for high-power systems [12]. However, it is difficult for low-powered SOFC/MGT hybrid systems to adopt a cooling device, as the output of the MGT itself is reduced, which requires a configuration that adopts a MGT system [13].

Figure 1 is a schematic diagram of an SOFC/MGT hybrid system for a methane fuel suitable for low-powered systems. This system installs an air preheater at two locations in contrast to the SOFC single system. The second air preheater at the stack outlet is to reduce the TIT, and the first air preheater at the back end of the MGT is to recover waste heat. The methane supplied to the system is mixed and preheated with recirculation gas whose steam concentration is high at the cell anode outlet and then sent to the reformer. Hydrogen is generated in the reformer as methane and steam are reacted, and the reformed gas includes carbon monoxide, carbon dioxide, steam, and a small amount of unreformed methane in addition to hydrogen. The reformed gas, with a high concentration of hydrogen gas, is supplied to the cell's anode. Air is used to supply oxygen for electrochemical reactions and cell cooling. It is sent to the cell's cathode through the air compressor and air preheaters 1 and 2. Hydrogen and carbon monoxide, which are reaction fuels supplied to the cell's anion, are reacted with oxygen ions. Then, the reacted gases are passed through the anion and electrolyte layer electrochemically to generate steam and carbon dioxide and emit electrons, thereby producing power from the chemical energy of the fuel. The air supplied to the stack absorbs the heat generated via the irreversible process of the reaction, and the waste heat is reutilized as a heat source in the reformer, air preheaters, and MGT. Unreacted hydrogen, carbon monoxide, and a small amount of methane included in the outlet gas of the cell's anion are combusted along with outlet air in the cathode in the combustor. Additional fuel is supplied to the combustor, since the waste heat in the system is insufficient to run the MGT. The amount of fuel is adjusted according to the required gas temperature at the combustor outlet (i.e., the inlet temperature (TIT) at the MGT). The limited maximum temperature of the TIT was set to 950 °C for turbine non-cooling, and the limited minimum temperature was set to 600 °C to run the MGT without additional power. The high-temperature outlet gas in the combustor was introduced into the MGT and adiabatically expanded, and the power generated at the MGT was used to compress the air and generate power.

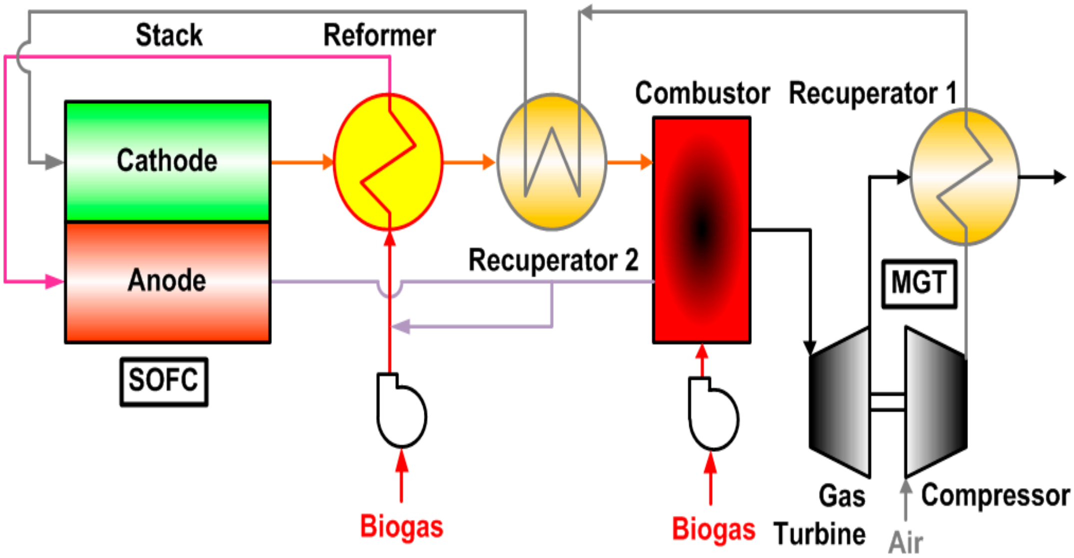

Figure 1. A model system including a SOFC, a bottoming MGT.

3.2. System Components

Air and fuel enter the tubular SOFC which is the heart of the cycle. Electricity and heat are produced due to electrochemical reactions that take place inside the cell. Steam-methane reforming is basically composed of the following reforming reaction and shifting reaction [14].

$$CH_4 + H_2O \rightarrow 3H_2 + CO \quad \text{(Reforming reaction)} \tag{1}$$

$$CO + H_2O \rightarrow H_2 + CO_2 \quad \text{(Shifting reaction)} \tag{2}$$

$$H_2 + 0.5O_2 \rightarrow H_2O \quad \text{(Electrochemical reaction)} \tag{3}$$

Assuming that the composition of mixed gas due to methane steam reforming at the given steam and carbon (S/C) ratio, temperature, and pressure has progressed until the main reactions reach equilibrium, a relationship between equilibrium constant (K) and Gibbs free energy (G) is calculated using the following chemical equilibrium equation:

$$K = \exp(-\frac{\Delta G}{RT}) \tag{4}$$

where R refers to a gas constant, and T refers to temperature (K). The equilibrium constant is different for each reaction equation. The equilibrium constant (K_r) in the reforming reaction and equilibrium constant (K_s) in the transition reaction are as follows:

$$K_r = \frac{P_{H_2}3 \cdot P_{CO}}{P_{CH_4} \cdot P_{H_2O}} \tag{5}$$

$$K_s = \frac{P_{H_2} \cdot P_{CO_2}}{P_{CO} \cdot P_{H_2O}} \tag{6}$$

where P refers to a partial pressure.

The electrochemical reaction of hydrogen and carbon monoxide in the cell anode and the cell's induced voltage (V) are calculated via the following equations:

$$H_2 + O^{--} \rightarrow H_2O + 2e^- \tag{7}$$

$$CO + O^{--} \rightarrow CO_2 + 2e^- \tag{8}$$

$$V = E - V_{act} - V_{ohm} - V_{trans} \tag{9}$$

where E refers to a theoretical open circuit voltage, and V_{act}, V_{ohm}, and V_{trans} refer to activation, resistance, and concentration overvoltage [15].

The electrical efficiency ($\eta_{e,sofc}$) is the fuel cell system (SOFC system) as given in Eq. (10). Here, $W_{aux,sofc}$ refers to the total required power for operation of auxiliary devices in the SOFC system

$$\eta_{e,sofc} = \frac{W_{e,sofc} - W_{aux,sofc}}{HC_{CH_{4,sofc}}} \tag{10}$$

The amount of air used for the purpose of the electrochemical reaction and cell cooling is calculated via the following energy balance equation at the stack:

$$(\Delta H_a + \Delta H_c) - HC_{H_2+CO} - W_{e,sofc} = 0 \tag{11}$$

where ΔH_a and ΔH_c refer to a difference in enthalpy between the inlet and outlet at the anion and cathode, respectively, and HC_{H2+CO} refers to the total low calorific value of hydrogen and carbon monoxide fuel [16].

4. System Performance Analysis Results

4.1. Thermodynamic Performance Analysis

Figure 2 shows the annual operating characteristics of SOFC/MGT. In the case of a 2150 kW SOFC/525 kW MGT, all available biogas is consumed. And the heat of the exhaust gas is enough for heating the AD, but the remaining heat shows large variation between different seasons.

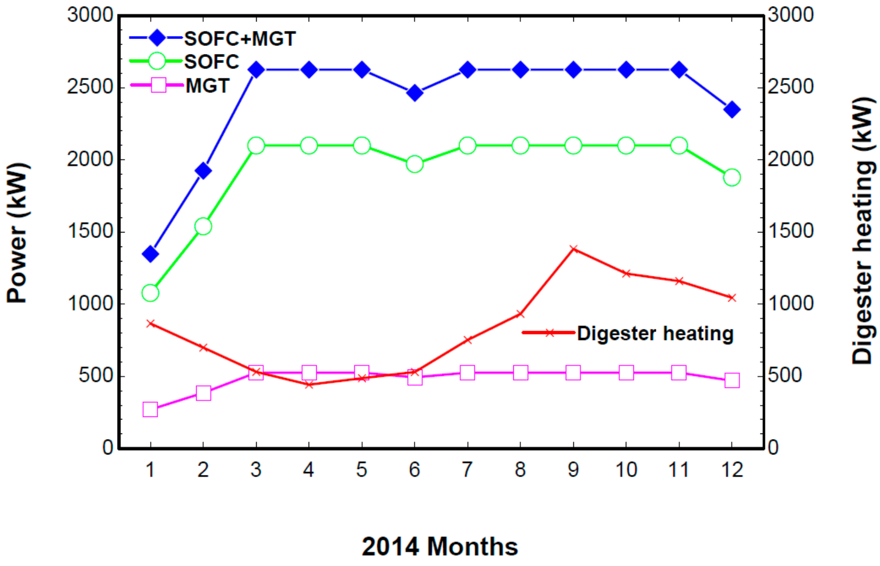

Figure 2. Operating characteristics of SOFC/MGT in 2014.

4.2. Thermoeconomic Analysis

Figure 3 shows the investment costs and payback period for different sizes of SOFC/MGT. The study showed that a SOFC/MGT system was sufficiently competitive due to short payback period 5.8 years and high Net present value 6,598,940 $. Currently, the price of SOFC is USD 7000 per kW, but the price of MW-grade fuel cells will drop to USD 3500 per kW due to mass production and technical advancement. The system prices are expected to become a competitive distributed power supply device within a few years.

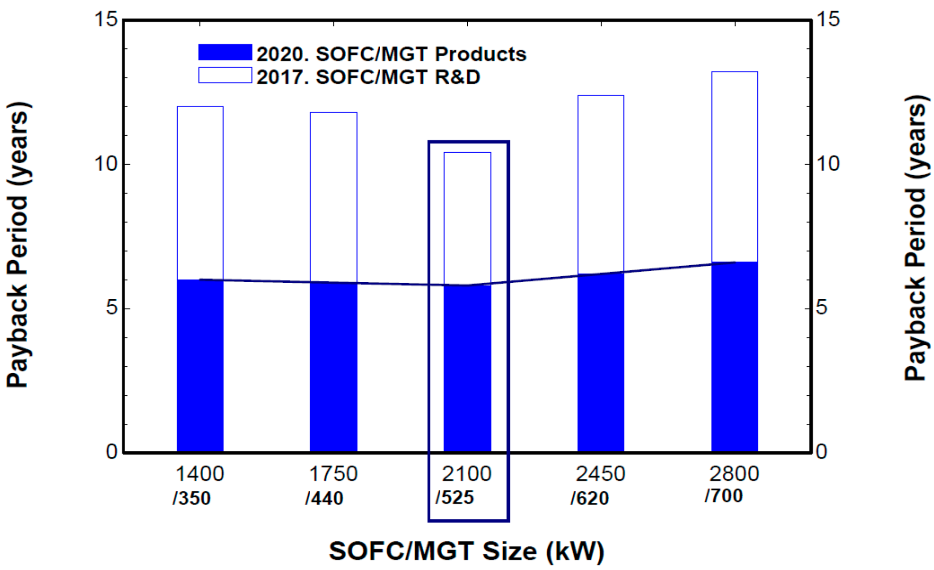

Figure 3. Payback period of the optimal SOFC/MGT system.

4.3. Green House Gases Reduction Analysis

Figure 4 shows the yearly dynamic supplied electricity requirements and GHG emissions considering biogas fueled SOFC/MGT. For this system, up to 55%–60% of the total power usage can be produced via biogas, and the 37% reduction goal of CO_2 (reduction of CO_2 by 50%) of the government could be satisfied.

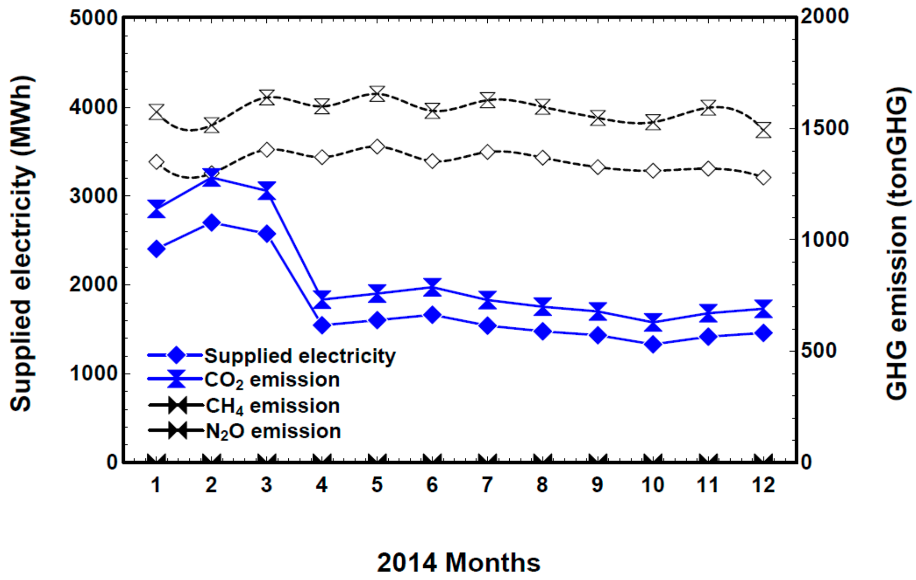

Figure 4. Electricity consumption and Greenhouse gas of SOFC/MGT in 2014.

5. Conclusions

The Sewage Treatment Plant is located in Busan, Korea and its annual capacity for sewage treatment is 132,601,000 m^3. It has a facility to produce biogas through the anaerobic digestion of sewage sludge. But the generated biogas is recovered and used as fuel to increase the temperature in the digester and the rest is burned and dumped at the waste gas incinerator. Therefore, in this study, biogas produced is then recovered and generates power through the gas micro-turbine and solid oxide fuel cell. The digestion gas power generation through biogas and the calculation results of the greenhouse gas emission due to power usage that is decreased as a result of power generated. The obtained results of SOFC/MGT reveals that overall electrical power of the SOFC/MGT is on average 2500kW. For this system, up to 50–55% of the total power usage can be produced via biogas, and the 37% reduction goal of CO_2 (reduction of CO_2 by 50%) of the government could be satisfied. The study showed that a SOFC/MGT system was sufficiently competitive due to short payback period 6 years. Currently, the price is USD 7000 per kW, but the price will drop to USD 3500 per kW due to mass production and technical advancement, and are expected to become a competitive distributed power supply device within a few years. For a hybrid system using biogas, its economic feasibility was very low compared to its sales. Thus, it is necessary to expand the subsidy of investment or assistance with operation cost from the central government in order to expand power production using biogas.

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