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A Comparative Study on the Reduction Effect in Greenhouse Gas Emissions between the Combined Heat and Power Plant and Boiler

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Received: 31 May 2020; Accepted: 22 June 2020; Published: 24 June 2020

Abstract: The purpose of this study is to compare the effect of a reduction in greenhouse gas (GHG) emissions between the combined heat and power (CHP) plant and boiler, which became the main energy-generating facilities of "anaerobic digestion" (AD) biogas produced in Korea, and analyze the GHG emissions in a life cycle. Full-scale data from two Korean "wastewater treatment plants" (WWTPs), which operated boilers and CHP plants fueled by biogas, were used in order to estimate the reduction potential of GHG emissions based on a "life cycle assessment" (LCA) approach. The GHG emissions of biogas energy facilities were divided into pre-manufacturing stages, production stages, pretreatment stages, and combustion stages, and the GHG emissions by stages were calculated by dividing them into Scope1, Scope2, and Scope3. Based on the calculated reduction intensity, a comparison of GHG reduction effects was made by assuming a scenario in which the amount of biogas produced at domestic sewage treatment plants used for boiler heating is replaced by a CHP plant. Four different scenarios for utilizing biogas are considered based on the GHG emission potential of each utilization plant. The biggest reduction was in the scenario of using all of the biogas in CHP plants and heating the anaerobic digester through district heating. GHG emissions in a life cycle were slightly higher in boilers than in CHP plants because GHG emissions generated by pre-treatment facilities were smaller than other emissions, and lower Scope2 emissions in CHP plants were due to their own use of electricity produced. It was confirmed that the CHP plant using biogas is superior to the boiler in terms of GHG reduction in a life cycle.

Keywords: biogas; biogas utilization; GHG emissions; CHP

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1. Introduction

Korea is one of the OECD (Organization for Economic Cooperation and Development) countries with a rapid increase in greenhouse gas (GHG) emissions, rising about twofold between 1990 and 2014 [1]. The Korean government established a goal in 2016 to reduce GHG emissions by 37% against the forecast of the country's total GHG emissions by 2030, and submitted the first basic plan for responding to climate change to the UNFCCC (United Nations Framework Convention on Climate Change). According to the 2030 National GHG Reduction Roadmap in Korea, the portion of renewable energy generation will be increased from 6.2% in 2017 to more than 20% in 2030, and 0.4 million tons of GHG will be reduced by improving livestock manure treatment efficiency and biogas production efficiency [2,3].

While the expansion of renewable energy to reduce GHG emissions has been considered as a major means of reduction, policies for the proper disposal of organic waste have also been developed. Since 2005, organic wastes, including food waste, livestock excreta, and sewage sludge, have been banned from direct landfill and must be treated in the interim before reclamation, and marine dumping of organic wastes was prohibited under the London Convention from 2013. The Ministry of Environment established an implementation plan for organic waste resources and biomass energy measures in 2009 and plans to newly expand and install domestic organic waste energy facilities at 28 locations, 5638 tons/day by 2020 [4]. Under this policy of vitalizing organic waste energy, the volume of biogas produced by domestic waste water treatment plants (WWTPs) also increased, producing 321 million m^3 of biogas per year in 2017—up 1.8 times from 179 million m^3 in 2012. Of the total, 268 million m^3 of biogas, or 83.5%, were used for energy production [5,6]. Although the main composition of biogas is CH_4 like natural gas, the lower heating value of biogas (23 MJ/Nm^3) is lower than that of natural gas (40 MJ/Nm^3) [7]. However, biogas can reduce greenhouse gas emissions by replacing natural gas because biogas is produced from biomass.

The use of biogas as a renewable energy source overseas is becoming more active [8–12]. As of 2018, the world's biogas-driven power generation capacity was 17,692 MW, of which 136 MW was in Korea and 12,252 MW was in Europe [13]. In Europe, which accounts for 69% of the world's biogas-based power generation capacity, the most modernized WWTPs have energy facilities that produce electricity and heat using anaerobic digester-producing gas. In the past decade, primary energy production by biogas has more than tripled in Europe. Biogas can be divided into landfill gas, sewage sludge gas, anaerobic digestion gas, and thermal process gas depending on the source, and the biggest contribution to the increase in biogas use was energy production using anaerobic digestion gas [14]. A study of sewage digestion, landfill gas, and farm biogas in Finland found that sewage digestion had the highest methane concentration and the lowest contamination of benzene, hydrogen sulfide, and nitrogen [15]. These findings support the sharp increase in energy production using anaerobic digesting gas compared to other biogas. The biogasification of organic waste is expanding worldwide to reduce GHG emissions and secure renewable energy sources. Renewable energy, in particular, is recognized as an important source of energy due to Korea's heavy energy dependence on the outside world and the increase in GHG emissions. In this context, this study attempts to analyze the greenhouse gas reduction effects of each biogas energy facility.

2. Research Scope

The Korean government established the 4th Basic Plan for Renewable Energy (2014–2035) in 2014 and plans to expand the supply of renewable energy to 11% of total primary energy consumption by 2035 [16]. Power generation by biogas in Korea increased from 3363 MWh in 2008 to 138,600 MWh in 2016 [17], and biogas use was investigated in the order of self-use (34.8%), external supply (31.3%), and generation (17.4%) as of 2017 [6]. Due to its high concentration of methane, biogas has the advantage of being able to be used in various energy facilities, thus, it is being used in various places in WWTPs.

In this study, combined heat and power (CHP) plants and boilers were selected as targets for analysis among facilities for biogasification of organic waste resources. Firstly, this study collected actual operation data using the biogas generated from the anaerobic digester tank of each facility—CHP plants and boilers—and calculated the GHG reduction effect of each facility. Rehl et al. (2013) derived GHG reduction potentials for each biogas conversion technology and analyzed that GHG reduction potentials are greater when produced simultaneously in electricity and heat than when biogas was used only in the heat production of CHP plants [18].

Accordingly, in this study, the amount of GHG reduction due to the substitution effect of fossil fuels in domestic biogas energy facilities was calculated for the CHP plants and the boilers. The method of calculating the reduction was applied using the Clean Development Mechanism (CDM) Small Methodology (AMS-I.C., AMS-I.D.) approved by the UNFCCC. Based on the estimated reduction, we estimated the amount of GHG reduction for each scenario of replacing domestic biogas energy facilities. Secondly, this study conducted an analysis of the preprocessing GHG generated from an anaerobic digester when using them in CHP plants and boilers. There is a big difference between the biogas preprocess facility because of regulations for emissions of air pollutants from power generation facilities and boilers. The main ingredient of siloxane included in the biogas is SiO_2, which is used in a wide range of products such as lubricants and cosmetics, and will be partially discharged into sewage upon disposal. The siloxane contained in the biogas is decomposed in the combustion chamber during hot combustion inside the engine and forms a silica layer on the combustion chamber surface and causes the engine to suffer [19]. Accordingly, CHP plants will be required to install pre-treatment facilities to remove SiO_2 to protect the engine.

3. Data and Methods

This study collected one year's operational data for similar capacity CHP plants and boiler facilities among biogas energy facilities to calculate GHG reduction and emissions (Table 1). CHP plants produce 3 MW of electricity and 3 Gcal of heat per hour by receiving biogas from sewage treatment facilities that conduct merge treatment, while boilers receive biogas from food waste disposal facilities and produce 5 Gcal of heat per hour. The pre-treatment facility had additional siloxane removal devices installed at the CHP plant, and SCRs were installed as exhaust gas treatment facilities to comply with regulations on air pollutants. In order to compare GHG emissions under the same possible conditions, the survey period was set at a time when the fuel consumption in the two facilities was as similar as possible.

Table 1. Characteristics of biogas utilization plants.

	CHP(Combined Heat and Power) Plants	Boiler
Target facility	Sewage treatment facility (mixed treatment)	Food waste disposal facility
Waste type	Food waste (409 tons/day) + Sewage sludge (2734 tons/day)	Food waste (250 tons/day) + Livestock manure (10 ton/day)
Capacity	[1.5 MW(electricity)+1.5 Gcal/h (heat)] × 2 facilities	5 Gcal/h (heat) × 1 facility
Pretreatment facility	Dehumidifier-Desulfurizer-Siloxane remover	Dehumidifier-Desulfurizer
Exhaust gas treatment facility	Selective catalytic reduction apparatus	None
Efficiency	Power generation efficiency (40.8%), Heat recovery rate (46.1%)	85.9%
The amount of fuel hour	1083 Nm^3/h	1050 Nm^3/h
Survey period and fuel quantity	2016.01~12 (4,553,000 Nm^3)	2018.07~2019.06 (4,905,000 Nm^3)

The purpose of calculating GHG emissions in the entire process, such as carbon footprints, is to open the results of calculating the amount of GHG generated per product to the public to induce sustainable consumption and production and to respond to climate change. The organizational boundary included the activities of exhaust gas being properly treated and released into the atmosphere after being burned through an energy-generating facility through a pretreatment process for receiving and using biogas produced in an anaerobic digester tank as fuel. Functional units, which became production units of the products produced, were determined by the amount of GHG generated when 1 GJ of heat was produced by biogas.

The GHG emissions of biogas energy facilities were divided into pre-manufacturing stages, production stages, pretreatment stages, and combustion stages, and the GHG emissions by stages were calculated by dividing them into Scope 1, Scope 2, and Scope 3 [20].

Scope 1 emissions are direct emissions, which are those of GHG caused by fuel combustion and mobile combustion within the organizational boundaries. Scope 2 emissions are indirect emissions, which are GHG emissions from external energy use, such as electricity use and steam within the organizational boundaries. Scope 3 emissions are other indirect emissions from the use and disposal of raw materials or products, not those generated or managed within the organizational boundaries.

The emissions of Scope 1 and Scope 2 were obtained in accordance with "The Administrative guidelines for the GHG and energy target management" (No. 2016-255 of the Ministry of Environment, Republic of Korea). According to the Certification Guide for domestic carbon footprints (Korea Institute of Environmental Industry and Technology, 2015), carbon dioxide emissions of Scope 1 from combustion of biomass, such as biogas, were not included in the calculation of GHG emissions, but non-carbon dioxide emissions were included in the calculation. Each GHG emission activity can be classified by Scope, as in Table 2.

Table 2. Greenhouse gas (GHG) emissions by category.

	Emission Activities	
Scope 1	Biogas combustion	
Scope 2	Power usage of biogas energy facility	
Scope 3	Assembly stage	Biogas production
	Preprocessing stage	Use, transport, and disposal of activated carbon
	Emission processing stage	Use and transport of diesel exhaust fluid (DEF)

The emission coefficients and sources used for calculating GHG emissions for each emission activity of Scope 3 are shown in Table 3.

Table 3. Emission factors for Scope 3 activities.

Activities	Emission Factors	Source
Biogas production	0.104 $kgCO_2e/Nm^3$	J.-Y. So (2012) [21]
Use of activated carbon	1.05 $kgCO_2e/kg$	Certification guide for the domestic carbon footprints (2015) [22]
Waste reclamation	0.178 $kgCO_2e/kg$	
Use of ammonia	0.415 $kgCO_2e/kg$	
Trucking transport	0.249 $kgCO_2e$/ton km	

In the case of Scope 2 emissions, the CHP plant had a separate watt hour meter, so it was possible to obtain the actual measurement data for electricity usage, but the boiler facility did not have a separate watt hour meter, so actual measurement data could not be used. Therefore, the equivalent boiler electricity usage calculation was obtained by multiplying the ratio of heat production. If there was more than one product produced, such as a CHP plant, an allocation of GHG emissions was required. Products produced in CHP plants are electricity and thermal energy (hot water or steam), and boilers produce only thermal energy. Electricity and heat can be converted into the same unit as J or MWh, but even if the energy is the same size, the ability of electrical and thermal energy to work is different. Considering this quality aspect of energy, the concept of Exergy was introduced in 1953 by Rant [23]. When the exergy of electrical energy is 100 the steam is marked as 60 [24]. Therefore, we did not add units of electricity and heat production of CHP plants when calculating the intensity of GHG emissions, but allocated emissions from electricity production and heat production, respectively. In order to compare the emissions of the two facilities, the functional unit was set at 1 Gcal of thermal energy, a product commonly produced in both CHP plants and boilers, and GHG emissions of the CHP plants were allocated to electricity and heat, respectively. An alternative generation method reflects both thermal and electrical benefits from CHP. This method allocates emissions or raw materials to heat and electricity production as a percentage of the fuel required to produce heat or electricity in a separate energy production facility [25]. In this case, the alternative facility uses the same fuel used in CHP.

As shown in Table 4, there are many types of allocation methods for GHG emission of CHP facilities, and for allocations related to CHP, an "alternative generation method" and a "power bonus method" that meet the two requirements are mainly applied. The energy method is easy to use and used in some studies, but other allocation methods reflect the physical situation better [25]. In this study, GHG emissions were allocated using the Alternative Generation method, and the efficiency of alternative heat production facilities and alternative electric production facilities were applied with 0.8 heat production efficiency and 0.35 electricity production efficiency, respectively, in accordance with the guidelines for GHG and energy target management operations [26].

Table 4. Allocation method and criteria.

Allocation Method	Is the Physical Condition of the Energy System Well Reflected?	Is it Well Known and Accepted during the Preprocess Evaluation?
Energy method	(○)	(○)
Alternative generation method	○	○
Power bonus method	○	○
Exergy method	○	
200% method	○	
Economic method		○
PAS 2050 method	○	

Source: IEA DHC (2011) [25].

4. Results and Discussion

Monthly biogas generation and heat generation changed according to the operation conditions of sewage treatment facilities and food waste disposal facilities, as shown in Figure 1.

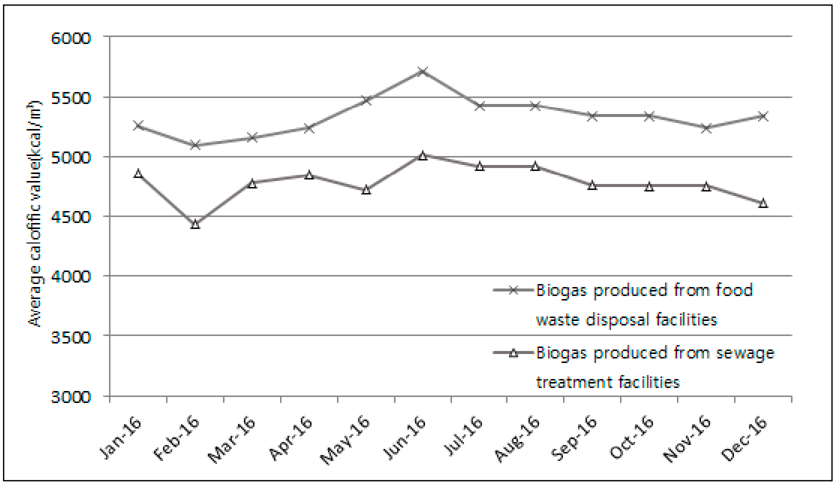

Figure 1. Average calorific value of biogas.

During the survey period, the biogas fuel consumption was 4,533,000 Nm^3 in CHP plants and 4,905,000 Nm^3 in boilers. Due to the nature of biogas generation, the amount of heat generated by biogas is not constant, so the total amount of biogas generated per year was calculated by weighted average of the monthly average calorific value of biogas and the amount of biogas. The results showed that the total amount of biogas used in CHP plants was 90,893 GJ, with 109,011 GJ in boilers. The calculation of GHG reduction using a small-scale CDM methodology resulted in a 9883 $tonCO_2e/yr$ GHG reduction in CHP plants and a 6379 $tonCO_2e/yr$ GHG reduction in boilers (Figure 2). In the case of CHP plants, out of the total GHG reductions, the amount of GHG reductions by electricity production was 7167 $tonCO_2e/yr$, and 73% of the total reductions by heat production was 2716 $tonCO_2e/yr$, 27% of the total reductions. Despite the higher amount of biogas calories used in boilers, GHG reductions were 1.55 times larger in CHP plants.

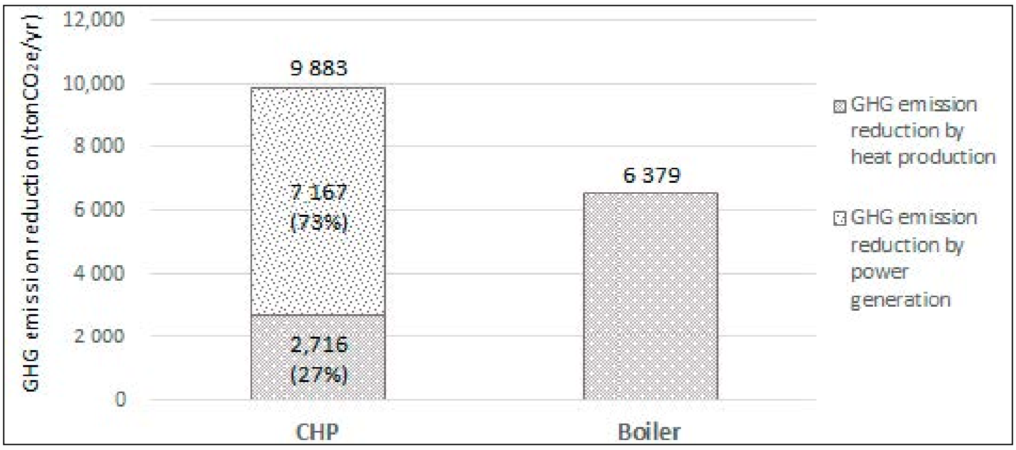

Figure 2. GHG emission reduction in the combined heat and power (CHP) and boiler (LNG alternative scenario).

In the case of heat production, the amount of GHG reduction was calculated on the assumption that only LNG that emits relatively less GHG was replaced, but in the case of GHG reduction by electricity production, CM emission factors were multiplied by various power mixes using solid fuel and liquid fuel. For this reason, the GHG reduction effect appears to have been higher in electricity production, and the amount of GHG reduction resulting from heat production may vary depending on which fossil fuels are applied in the alternative scenario. Assuming the scenario of using BC oil, a liquid fuel, for boilers, the calculation of GHG emissions from heat production showed that the reduction by heat production, as shown in Figure 3, was higher than that of LNG because the GHG emission coefficient of BC oil is higher than that of LNG. However, the reduction by electricity production was the same because it did not affect the reduction by electricity production.

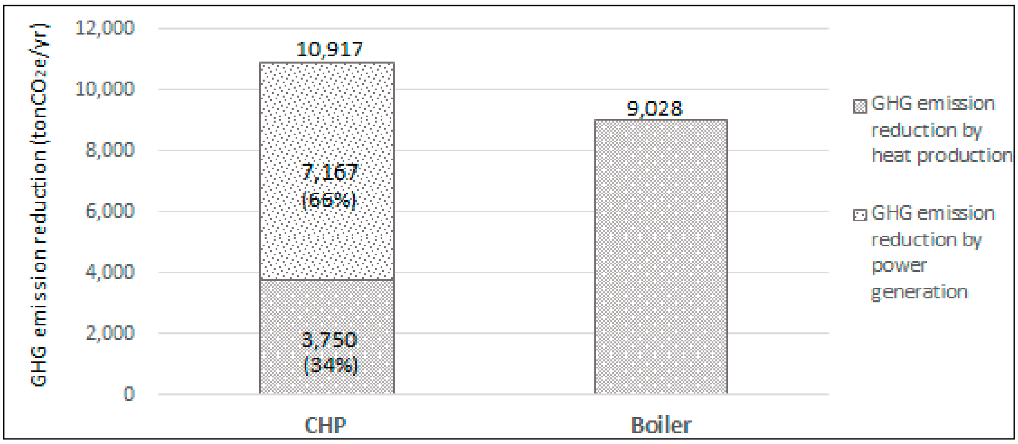

Figure 3. GHG emission reduction in the CHP and boiler (Bunker C oil alternative scenario).

Even if the amount of GHG reduction was calculated based on BC oil as an alternative fossil fuel, power generation facilities showed larger GHG reductions than boilers. This is because CHP plants also included heat production units, which resulted in an increase in the amount of GHG reduction. However, the GHG intensity was compared based on the LNG alternative scenario for conservative calculations. When the GHG reduction during the survey period was divided by the weighted average amount of heat generated by biogas, the unit of GHG reduction in power generation facilities was 108.73 $kgCO_2e/GJ$ and the boiler was 58.52 $kgCO_2e/GJ$, 1.86 times larger than the boiler (Figure 4).

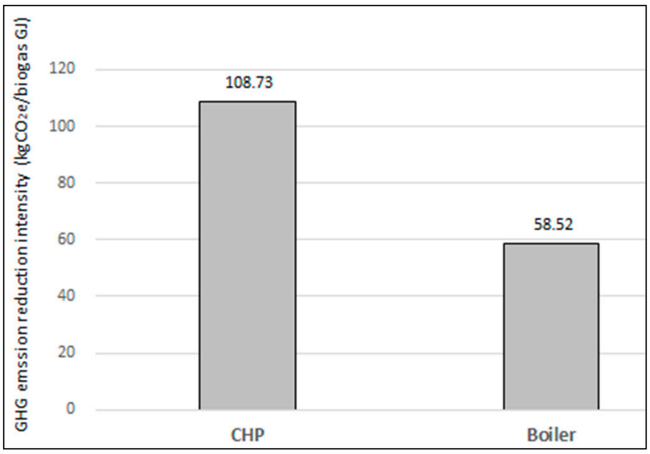

Figure 4. GHG emission reduction for 1 GJ of biogas (LNG alternative scenario).

Based on the GHG reduction intensity of the CHP plant and the boiler, we estimated the amount of GHG reduction by dividing the same amount of biogas used for the heating of the anaerobic digester into the following assumed conditions: (A) using all of the biogas for a boiler, (B) using all of the biogas for the CHP plant and using local heating to heat the anaerobic digester, (C) using all of the biogas for the CHP plant, and (D) using 50% each for CHP plants and boilers for heating the anaerobic digester, with insufficient calories replenished through LNG boilers (Figure 5).

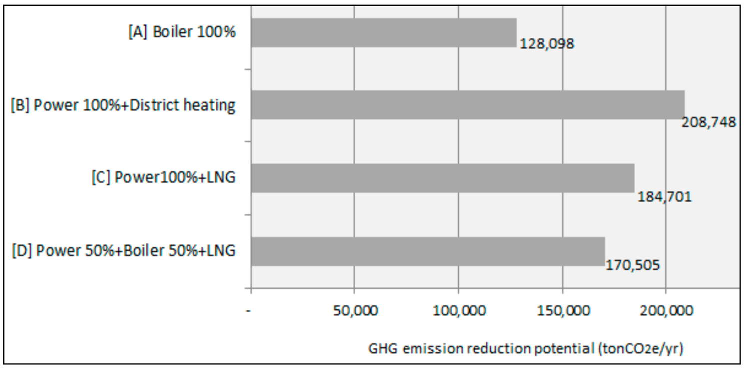

Figure 5. GHG emission reductions by scenario case.

Estimating that, as of 2014, the amount of biogas produced for the heating of the anaerobic digester through boilers at WWTPs across the country accounted for 92% of its own use, or 102,521 m^3, GHG reductions were 128,098 $tonCO_2e/yr$, and this is a scenario (A). If the same amount of biogas was used in CHP facilities, not boilers, and the district heating system was used to heat the anaerobic digester, the GHG reduction (B) was the highest at 208,748 $tonCO_2e/yr$. Among the four scenarios, it can be seen that using biogas for CHP had a higher GHG reduction effect than using boilers alone.

Scope 3 emissions of CHP plants and boilers were analyzed and are shown in Table 5. Since emissions at the biogas production stage are proportional to biogas usage, there was not much difference between the two facilities. In the pre-treatment stage, emissions from CHP plants were greater depending on the operation of siloxane removal facilities. The emission from the use and disposal of activated carbon from the siloxane removal facility was 11,789 $kgCO_2e/yr$ and 456 $kgCO_2e/yr$ from the transport of activated carbon, indicating that the effect of the use and disposal of activated carbon was greater. In the exhaust gas treatment stage, emissions from the use of the DEF (Diesel

Exhaust Fluid) were 12,021 $kgCO_2e/yr$, and emissions from the transport of DEF were 1724 $kgCO_2e/yr$, which was estimated to be the result of the frequent replenishment of DEF.

Table 5. Scope 3 emissions from CHP plants and boilers in ($kgCO_2e/yr$).

		CHP Plants	**Boiler**
Biogas production stage		471,463	510,100
Preprocessing stage	Desulfurization facility	24,416	27,441
	Siloxane removal facility	12,265	-
Emission processing stage		13,745	-
Subtotal		50,425	27,441
Total		521,888	537,541

The emission in the pre-treatment stage and exhaust gas treatment stage of the boiler was 54% compared to the CHP plant. Even though emissions at the biogas manufacturing stage, i.e., fuel consumption at power plants, were lower than boilers, it can be analyzed that the additional operation of preprocessing facilities and exhaust facilities resulted in greater GHG emissions.

As Table 6 shows, compared to CHP plants, boilers were 18% higher for Scope1 direct emissions, while they were 3% higher for Scope3 other indirect emissions, due to higher emissions at the pre-treatment and exhaust treatment stages in the CHP plants.

Table 6. GHG emissions in a life cycle ($kgCO_2e/yr$).

	CHP Plant		**Boiler**
	Electricity + Heat	**Heat**	
Scope 1	4712	1505	5761
Scope 2	74,436	23,777	164,636
Scope 3	521,888	166,705	537,541
Total	601,036	191,987	707,938

The biggest difference among the emissions by Scope was the Scope2 emissions, with the boiler 2.21 times higher than the CHP plant. The power usage of CHP plants is larger than that of boilers due to the operation of preprocessing and emission processing facilities, but since CHP plants produce electricity and use it for internal power, the amount of electric power reception is found to be lower than that of boilers. Since GHG indirect emissions are come from the use of electric power which is supplied from an electrical grid, Scope2 emissions from electricity use showed lower results in power generation facilities.

The GHG emissions in a life cycle are shown in Figure 6 with a division into those from the use of raw materials and those from the assembly process. Biogas production and combustion accounted for the highest proportion in the emissions from the use of raw materials, and power consumption accounted for the highest proportion in the assembly process. As previously analyzed, CHP plants produce electricity and use it for its own facility, so use from external electricity was lower than boilers, resulting in lower emissions from the assembly process. However, in the case of boilers, the actual operation data were not available, so GHG emissions were estimated through the electricity use of boiler facilities with a similar capacity, but given that most of the electricity used in CHP plants is covered by itself, the amount of emissions from the manufacturing process was inevitably larger than that of boilers.

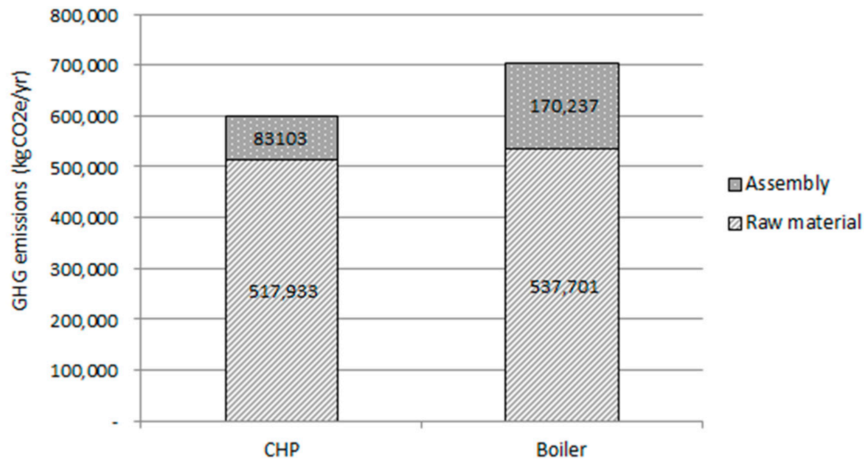

Figure 6. GHG emissions in raw material and assembly.

GHG emissions from the CHP plants were allocated as electricity and heat, and the intensity of GHG emissions generated per 1GJ of heat production was calculated and compared with boilers. As shown in Figure 7, for GHG emission intensity in a life cycle, the boiler was 1.53 times higher than the CHP plants, which means that the GHG emissions in a life cycle were 1.53 times higher than the boiler when producing 1GJ of heat by using biogas.

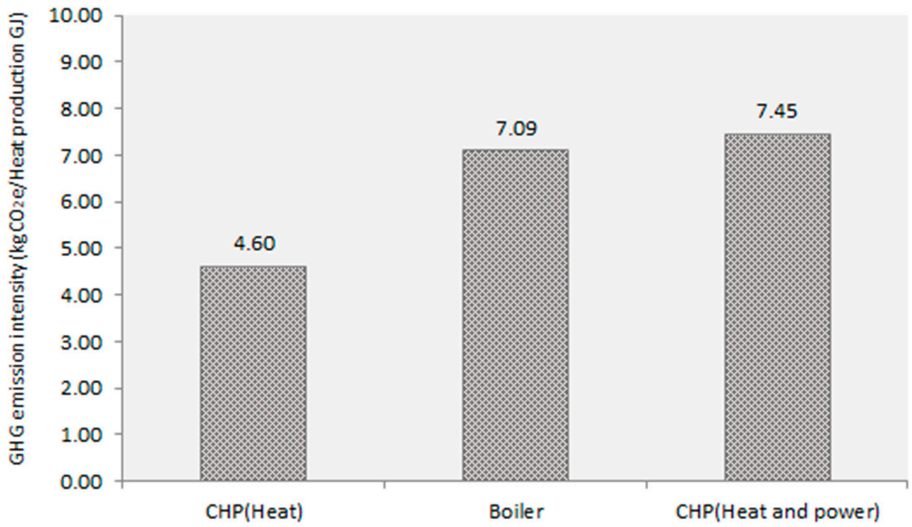

Figure 7. GHG emissions intensity by 1GJ of heat production.

5. Conclusions and Implication

This study collected actual operation data of CHP plants and boilers, which are mostly used as biogas energy facilities in Korea to estimate GHG reduction effects based on a CDM methodology, and to calculate GHG emissions in a life cycle. The amount of GHG reduction was calculated as an alternative effect when produced using biogas by replacing fossil fuels. The amount of GHG reduction was higher in CHP plants than in boilers, and 1.86 times higher than that in CHP plants when the intensity of GHG reduction per GJ of biogas fuel was calculated. Based on the calculated GHG reduction intensity, we estimated the amount of GHG reduction by scenario, assuming that biogas used as boiler fuel for the domestic anaerobic digester heating system was used in CHP plants. The reduction in the scenario of using all biogas in CHP plants and using district heating for the anaerobic digester was the highest at 208,748 tonCO_2e/yr, and the reduction in GHG in the scenario of using all biogas in boilers was the lowest at 128,098 tonCO_2e/yr, as it is now. In theory, a comparative analysis of GHG reductions showed that the scenario of using all biogas in CHP facilities was better than other scenarios.

In practice, however, other factors such as the size of individual sewage treatment facilities, the possibility of securing investment costs, maintenance personnel, and biogas generation characteristics should be considered for the alternative application of boilers in sewage treatment facilities. Since Scope3 emissions for all inputs to the process are not considered when calculating the amount of GHG emission reduction, the total emissions of CHP plants and boilers were calculated and compared. Unlike natural gas, biogas contains a large amount of impurities such as silica. Silica forms layers inside the engine during the high-temperature combustion of CHP plants, leading to degrading efficiency, so the preprocessing process is essential. Scope3 emissions in the preprocessing stage and exhaust gas post-treatment stage were more than twice as high as those in the boiler, but the emissions in that stage were relatively less than those in the other assembly stage. Scope2 emissions from the use of external electricity in CHP plants were much lower than those of boilers because the CHP plants generate and use their own electricity inside the facilities. At this time, differences in Scope2 emissions offset additional GHG emissions from the Scope3 preprocessing stage and the exhaust gas post-treatment stage of the CHP plant. When calculating the GHG emission intensity based on heat, which is a common product of the two facilities, the CHP plant was 4.6 $kgCO_2e/GJ$ and the boiler was 7.09 $kgCO_2e/GJ$. Based on the results of this study, it was confirmed that the CHP plant using biogas is superior to the boiler in terms of GHG reduction and GHG emissions in a life cycle.

Considering Korea's policy to expand renewable energy and global moves to reduce GHG emissions, it is deemed necessary to invest in facilities that take into account long-term GHG reduction effects and energy efficiency rather than short-term convenience in comparing and selecting energy-generating facilities that use biogas generated from organic waste disposal facilities. Despite the above achievements, this study has some limitations, including the insufficient number of survey samples in the course of investigating the biogas-energy facility and the limitation of the survey period to one year. It is hoped that further research will complement the limitations of our study.

Author Contributions: D.K. developed the conceptualization and methodology of the study. K.-T.K. and Y.-K.P. provided the valuable research insights into the study, helped in the review and editing of the manuscript, and helped in publishing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was support by the National Research Foundation of Korea (NRF) grants funded by the Korean government (MSIT) (NRF-2019R1A4A1027795).

Conflicts of Interest: The authors declare no conflict of interest.

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