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GREENHOUSE GASES EMISSIONS ASSESSMENT OF A DIESEL-BIOGAS POWERED MICROCOGENERATION UNIT

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Abstract. *Electricity and heat requirements in Peruvian agricultural industries are often fulfilled by making use of diesel engines and boilers, respectively. The performance of these activities in a separate way, results in a higher demand of fossil fuels and higher emissions of pollutant gases to the environment; all of this, with a deficient use of the energy supplied by the fuel. Furthermore, these industries have started implementing anaerobic digesters to transform their organic residues into valuable biofertilizers, misspending the gaseous fuel generated in the process: biogas. Some companies free the so-called by-product and some others burn it in torches, polluting in both ways the environment, as well as casting away a possible increase of their profit, without harnessing the energy contained in the fuel.*
In this context, a microcogeneration unit was developed out from a 36 kW Diesel cycle generator set, a diesel-biogas conversion kit and a shell-and-tube heat exchanger with the objective of generating electricity and producing hot process water using biogas and diesel as fuels. The unit was evaluated for different electrical loads (from 5 to 30 kW), diesel substitution rates (from 15 to 75%), and water mass flows (from 0.03 to 0.15 kg/s). The results of the experimental tests allowed the development of a GHG emissions and economic assessment for different scenarios comparing three configurations for the obtainment of the amount of energy that fulfills the requirements.
With an increase of the efficiency of the system of nearly 10% and a diesel substitution rate of 63%, microcogeneration using biogas shows itself as an opportunity for an appropriate management of energy resources. The deployment of this technology in agricultural industries isolated from the electricity grid or with energy supply problems could benefit their operation. Cogeneration and the use of biofuels together, create favorable circumstances for reducing the GHG emissions while harnessing renewable energy sources.

Keywords: *biogas, diesel substitution, cogeneration, GHG emissions, electricity generation.*

1. INTRODUCTION

One of the greatest environmental problems that the world faces in these days is the climate change and the global warming originated by greenhouse gases (GHG) emissions. Among the GHGs, carbon dioxide (CO_2) is the most important, which is mainly released from the combustion of fossil fuels. The continuous growth of the world population and its corresponding energy demand results in increased emissions of CO_2. Of all of the human resource consuming activities, transportation and electricity generation are the ones that consume more fossil fuels and release more CO_2 to the atmosphere. Thus, the environmental impact of these activities could be certainly reduced by replacing the fossil fuels at present used with renewable energy sources. Uusitalo et al. (2012) affirm that biogas is one of the biofuels with the potential to attend part of the energy demanded by the two main consuming processes, since it is obtainable from any biomaterial digested anaerobically. When it comes to biogas generation, any residual material can be used, which production would not need a cultivation process that could result in a harmful effect on land use and feedstock economy.

The interest in reducing the GHG emissions and climate change is such that the European Union has declared that, by the year of 2020, 10% of the fuels used for transportation will have to be biofuels, which in 2009, were responsible for only 2% of the world consumption. In the same way, by 2020, 20% of the total EU energy consumption will have to be attended by renewable energy and the total GHGs emission will also have to be reduced by 20%. Facing this context, some governments have implemented feed-in-tariffs and other subsidies for electricity produced with biogas (Uusitalo et al., 2012). It can be clearly seen that biogas production is regarded as a sustainable practice that can ensure GHG emission savings (Masse et al., 2011). The interest in anaerobic digestion and biogas production has grown rapidly due to the increasing importance of renewable energy for reducing Europe's GHG emissions and for improving its energetic security (Boulamanti et al., 2013).

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Biogas can be produced from almost all kinds of feedstock and also from organic wastes. Anaerobic digestion is a worldwide used process to digest animal manure and slurries. The biofuel obtained from this process can be directly used as an energy source for heating, electricity generation and as a substitute for fossil fuels applications. Uusitalo et al. (2012) agree with the fact that petrol and diesel cars can be converted into dual using gas and the costs are relatively low; nevertheless, due to the local availability and ease of direct handling this source is commonly limited to stand-alone biogas plants (Chynoweth et al., 2001). Biomass is also widely used as a fertilizer, which production substitutes other mineral fertilizers that account for some other GHG emissions (Bougnom et al., 2012).

Some studies have been performed on the feasibility of biogas production without damaging the environment. Some authors have analyzed the methane output of different crops, evaluating single digestion and co-digestion (Bauer et al., 2010 and Kimming et al., 2011), the optimization of methane production (Amon et al., 2007), the energy consumption and emissions of the management of the substrates (Maranon et al., 2011), the end use of biogas (Chevalier and Meunier, 2005 and Kimming et al., 2011) and the environmental, agronomic and societal benefits of on farm production (Masse et al., 2011) depending on the regions and countries.

Boulamanti et al. (2013) concluded that the carbon footprint of biogas is strongly influenced by several factors. Their study evaluates the environmental performance of different scenarios of biogas to electricity conversion processes. They found two critical factors that may determine the impact of biogas production: the feedstock used and operational practices performed with the digestate, also affirmed by Uusitalo et al. (2012). The authors used maize and manure as substrates and co-digestion as the process for the research. While maize cultivation is responsible for 28-42% of the GHG emissions of the electricity production process, manure obtainment does not contribute to the GHG emissions of the electricity production process and also avoids methane emissions caused by its storage and later spreading as a fertilizer (aerobic digestion). As mentioned before, the reductions in GHG emissions depend significantly on the digestion process and the substrates. Anyway, some reductions of these emissions are obvious, as the ones obtained from the substitution of natural gas or diesel by biogas (Uusitalo et al., 2012).

In this context, Berglund and Börjesson (2006) gave a complete overview of a biogas system, confirming that the environmental impact of one of these systems varies significantly depending on the materials used (substrates). Different studies performed have focused mainly on the individual processes in biogas production chains and not in the complete potential impacts of different practices that could accurately show biogas sustainability. Different authors have also evaluated the impact of GHG emissions of biogas plants and their sustainability using Life Cycle Assessment (LCA) perspectives. Berglund and Börjesson (2006) also evaluated the impacts on human health, natural environment and resource depletion with a sensitivity analysis as a part of a major effort to compare the environmental impacts of several biogas pathways. The assumed content of biogas for many studies was 55% methane and 45% CO_2 in volume with some traces of H_2S.

Boulamanti et al. (2013) concluded that climate change can be lower if biogas is used for producing electricity, especially if it is obtained by anaerobic digestion. They found that when using maize as a substrate, the GHG savings were 35.8%; if it was produced from manure, the savings reached 332% and in the case of co-digestion the savings reached 92.4%.

At the moment, according to Uusitalo et al. (2012), the greatest reductions of GHG can be achieved if biogas is used as a transportation fuel or in natural gas CHP plants to generate power for electric cars and environmental effects could be smaller in the gas engine scenario. They affirm that in the future, biogas as a transportation fuel will also lead to reductions in particle and nitrous dioxide emissions.

In this background, this study was performed to evaluate the impact on GHG reductions obtained from the use of biogas in a Diesel cycle engine-generator, addressing only the effects of its transformation in electricity and heat (cogeneration) to attend the demand of an agricultural industry located in southern Peru.

2. BASE LINE CONDITIONS

The study was performed at an agricultural industry in Arequipa, Peru, dedicated to the food crops industry producing export quality vegetables and milk for the national market. The enterprise owns more than 500 cows, whose organic residues (manure) are fed into a 720 m^3 biodigester with the main objective of producing bio-fertilizers, with which the food crops are grown. Nevertheless, the harnessing of this residues is insufficient, since, the biogas, also produced in this process, is neither used or stored, being consequently burnt in torches or freed to the environment, polluting it in both ways.

As many other industries in Peru, this enterprise has a defined peak period for its electricity consumption: from 18 h to 21 h, the price of electricity is almost 10 times higher than the price out of this period. Since the bovines naturally start milk production at approximately 18 h, at this time, the enterprise has a high demand for electricity for its cooling processes. This demand is covered by a Diesel-cycle generator set, which feeds mainly industrial refrigeration equipment.

The energy requirements of the plant include 27 kWe for the supply of the electricity needs in the farm (milk refrigeration, lighting, water pumping, manure pumping, among others) and hot process water (around 50 °C) for the cleaning of the milking machines and storage tanks). In this context, an experimental device was built to meet the

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electricity and heat requirements of the plant, harnessing the energy stored in the biofuel, contributing to the environmental care and reducing the enterprise operating costs.

3. EXPERIMENTAL MODEL

The experimental model designed and built to address the requirements was made up by three sections described below. Figure 1 shows a schematic diagram of the experimental model.

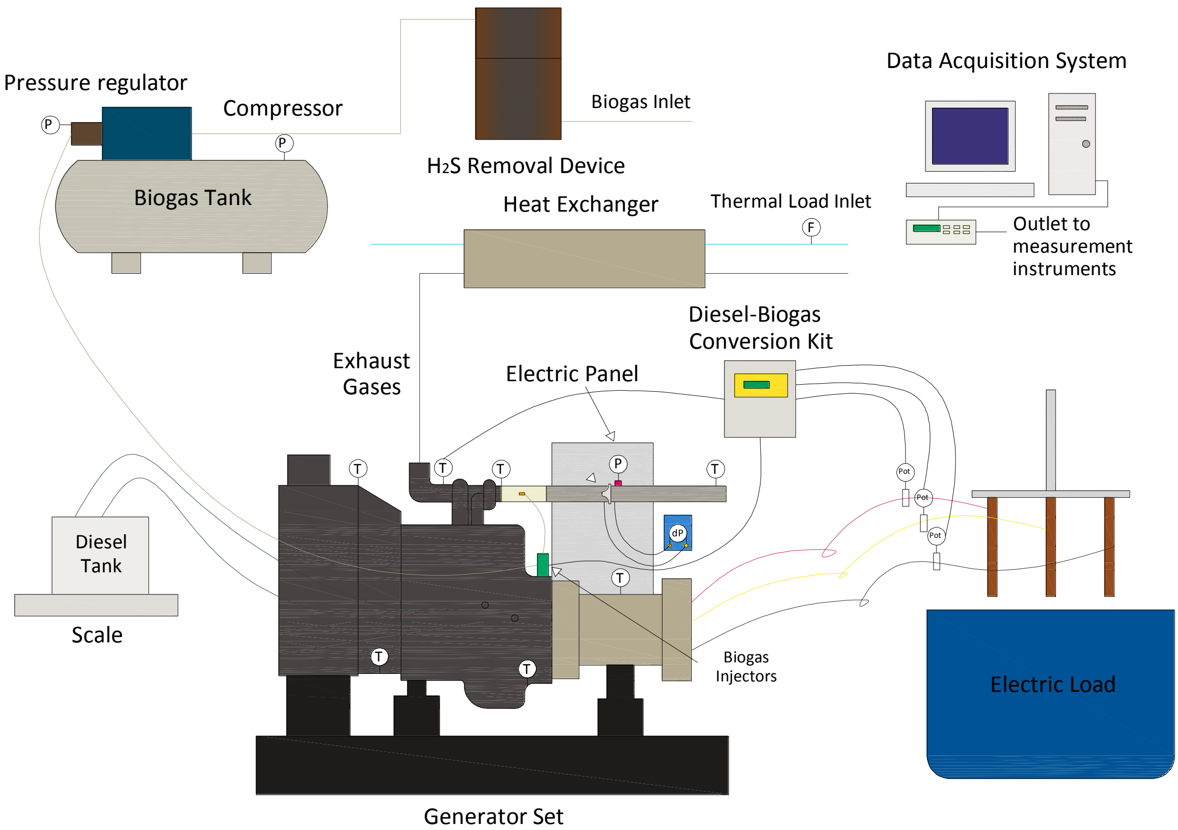

Figure 1. Schematic diagram of the experimental model.

3.1 Power generation section

This section involves the Diesel cycle generator set used as a prime mover for the cogeneration system and an electrical load to vary the power consumption of the system.

A 36-kW electrical generator coupled to a Diesel cycle engine (CUMMINS, 4BT3.9) was used to generate electricity. The equipment had 4 cylinders disposed vertically in line and a total displacement of 3.9 liters. The engine had a fixed speed of 1800 rpm and its regulation was performed electronically. The aspiration of air was performed using a turbocharger. The compression ratio of the engine was 16.5:1; this parameter was not modified for the later use of biogas. K type thermocouples (OMEGA, Chromel-Alumel) were installed in different points of the engine to monitor its adequate operation.

The electrical load for the different tests performed was simulated making use of an electric resistance. This device was formed by three copper bars of 25.4 mm of diameter, each of them connected to each phase of the generator through protected electric cable. This copper structure was submerged in salty water, while charged, to simulate the electrical load according to the submersion depth. The control panel of the generator set allowed the visualization and verification of the generated power and the engine temperature and speed.

To calculate the exhaust gases mass flow that would provide the heat to the thermal load, a nozzle and a differential pressure transducer (AUTROL) were used (Fig. 2). The nozzle outlet had 38.1 mm of diameter and the diameter ratio was 0.75 to avoid a high pressure drop from restricting the inlet of air to the engine. The nozzle was manufactured according to the NBR ISO 5167-1. The measurement device consisted of a PVC pipe with 50.8 mm in diameter, where the nozzle and the differential pressure transducer were installed. This device was placed in the engine inlet before the turbo compressor and the air-biogas mixer (explained later).

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3.2 Fuels supply section

For the development of tests using biogas, a hydrogen sulfide (H_2S) removal device was built. The biogas used for the tests was obtained from an anaerobic digestion process of organic residues. This biofuel contained around 50% of methane, 38% of carbon dioxide and 10% of carbon monoxide. The biogas also contained 7000 ppm of H_2S, concentration that would easily and quickly damage the inner parts of the engine and other metallic devices used. An activated carbon filter was built to reduce the H_2S content to 100 ppm, which is, according to IEA Bioenergy, the maximum acceptable limit for biogas use in stationary internal combustion engines.

A semi-hermetic compressor was installed after the H_2S filter to compress the biogas, since the biogas injectors required the supply of the biofuel at 0.3 MPa to ensure a more homogeneous mixture with the air that enters the engine. The compressor (DORIN, H200CS) had a maximum flow rate of 11.86 m^3/h. The biogas was pressurized to 0.5 MPa or more to guarantee that the pressure at the biogas injectors was the required one (taking into account the distributed pressure losses throughout the pipes). This is why a diaphragm type pressure regulator was employed. An electric-hydraulic control system was installed in the compressor for the protection of users and the regulation of the pressure in the tanks: a security pressostat activated and deactivated the compressor at previously established pressures, in most cases, between 0.3 and 0.5 MPa, respectively.

Figure 2. Biogas injectors.

Once the biogas was pressurized at the inlet of the injectors (Fig. 2), the supply of this fuel depended on the diesel-biogas conversion kit. This equipment was developed and configured to regulate the biogas mass flow rate into the engine according to three different signals: a three-phase power meter indicates the generated power, a K type thermocouple indicates the temperature of the exhaust gases at the immediate outlet of the engine and the electronic speed governor provides data about the diesel injection.

Figure 3. Cylindrical air-biogas mixing device.

The diesel-biogas conversion kit operates varying the injectors Duty Cycle, which refers to the fraction of time that the biogas injectors are opened. Using the data from the three signals, the conversion kit produces an electric signal that generates a variation of the Duty Cycle that governs the biogas injectors, which increase the quantity of biogas supplied

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to the engine. When this happens, the engine tends to produce more power. This increase is perceived by the electronic governor, which sends an electronic signal to the diesel injectors, reducing the quantity of diesel supplied. The opposite happens when the quantity of biogas supplied is reduced.

For the measurement of the diesel mass flow rate, an industrial scale (METTLER TOLEDO) with a capacity of 60 kg and an uncertainty of 0.1 g was used. The values obtained for this parameter, were later used for the calculation of the substitution rate.

Biogas was supplied to the engine through a mixer installed before the turbo-compressor and after the biogas injectors (Fig. 3). The tubular mixer was built in polyamide and had two connections on both opposite sides at 45° to facilitate the introduction of biogas in the air inlet and its mixing.

All of the instruments were connected to a Data Acquisition System (HP AGILENT), which received their signals and sent them to a personal computer for its later processing and analysis.

3.3 Cogeneration section

A shell-and-tube heat exchanger (Fig. 4) was installed in the exhaust gases pipe of the engine to recover the exhaust gases heat. The device was built with the objective of heating process water: the exhaust gases circulated inside the tubes while the water circulated in the shell.

Figure 4. Instrumented heat exchanger.

The thermal load of the heat exchanger (water at ambient temperature) was controlled using a flow meter (FLOWSTAT) with an operating range from 0 to 0.94 kg/s and a set of valves that adjusted this parameter according to the corresponding test.

The heat exchanger was instrumented with K type thermocouples (OMEGA): these sensors were placed in the inlet and outlet of the water circuit and in the inlet and outlet of the exhaust gases circuit.

A differential pressure transducer (AUTROL, APT3100) was installed in the gases circuit to evaluate the exhaust gases pressure drop caused by the presence of the heat exchanger.

The heat exchanger was covered with glass wool insulation with aluminum foil to prevent major heat losses.

4. EXPERIMENTAL PROCEDURE

The experimental procedure adopted for the tests included the development of tests varying the Duty Cycle and the water mass flow rate (thermal load of the heat exchanger). The Duty Cycle was varied from zero to the maximum possible attainable for each electrical load. The water mass flow rate varied from 0.03 to 0.15 kg/s for each electrical load. The power consumption was varied from zero (stand-by) to 30 kW, each 5 kW. The Diesel cycle generator set was designed to operate at 1800 RPM, which is why all the tests were performed at that engine speed.

Initially, tests were performed using only diesel as fuel, with the objective of determining the characteristic performance curves of the engine, so that they could be used as a base line for comparison.

4.1 Operation with diesel and biogas

For the operation in dual fuel mode, the H_2S content in the biogas was previously lowered and the biofuel was pressurized. The procedure to attain the maximum substitution rate possible for each load tested consisted in injecting the biofuel in a gradual and controlled way until noting an abnormal operation in the engine, for which there are two different states: ‘knocking’ and ‘miss firing’.

In dual-fuel operation, air enters the cylinder already mixed with biogas. As the piston begins the compression process, both the pressure and the temperature of this mixture begin to rise. In some cases, the biofuel finds suitable conditions for the onset of combustion, before reaching the top dead center. Thus, combustion does not occur in the optimal time, and the release of heat increases the pressure inside the cylinder before the appropriate time. This type of combustion causes a phenomenon known as 'knocking'. On the other hand, ‘miss fire’ occurs when the air/fuel mixture is too far from the stoichiometric balance to ignite, so the complete combustion does not occur. This may happen because the biofuel entering the engine with the air takes the space that air would have to occupy to guarantee combustion at the appropriate moment. So, when diesel is injected, it does not find the necessary quantity of air to promote an adequate combustion.

The tests were started without load and a Duty Cycle of 0, then, the load was incremented to 5 kW and when it reached a stable condition (within 5 minutes), the Duty Cycle was increased until noting any of the disturbances mentioned above. The Duty Cycle found was considered as the highest attainable for the corresponding load tested. After this, the load was increased and the procedure, repeated, until reaching 30 kW.

All of the modifications of the Duty Cycle were performed giving enough time to the electronic speed regulator to send the signals to the diesel injection system to reduce the quantity of fossil fuel supplied.

The diesel injection system was involved in the regulation process of the diesel supply when the engine operated with diesel and biogas. As mentioned before, when the biofuel is injected in the air inlet, the tendency of the engine is to increase the mechanical energy produced, since the biogas provides additional energy for the combustion. The electronic regulator perceives the variation and makes the diesel injection reduce to keep the generated power.

4.2 Operation performing cogeneration

For the cogeneration tests, the thermal load (i.e. water mass flow) was set using the Data Acquisition System: the flow meter sent the signal to the system, which allowed the lecture of the values on real time and the adjustment of the valves system for the test conditions.

Initially, the water mass flow was established and running through the heat exchanger. Then, the engine was started without electrical load and kept in that state until a stable condition was attained (within 5 minutes). Thereafter, the electrical load was increased by 5 kW and kept constant for 10 minutes, while the heat exchanger stabilized the temperatures (which are reflected in the water temperature). This operation was repeated each 5 kW until reaching 30 kW. The whole procedure was repeated for each water mass flow rate tested (0.03, 0.09 and 0.15 kg/s).

5. RESULTS

5.1 Performance evaluation

The tests carried out followed the experimental procedure indicated in the corresponding section. The first tests developed aimed the determination of the highest diesel substitution rates attainable. Figure 5 shows a curve with the highest substitution rates attained for the electrical loads tested. The highest substitution rate was obtained at the highest load tested: 63% at 30 kW.

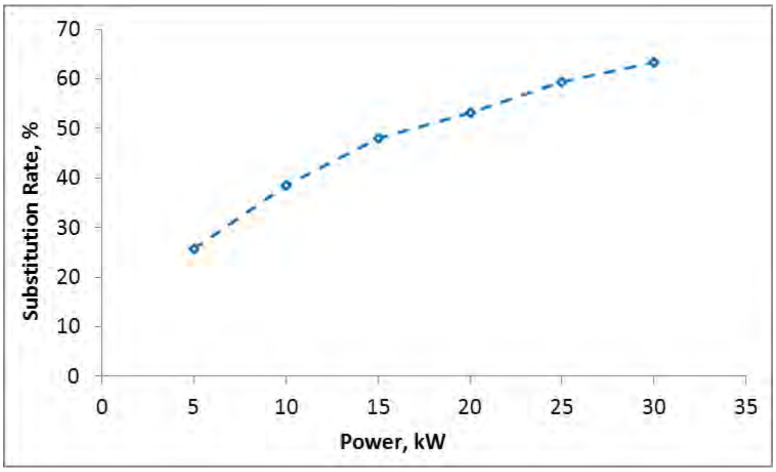

Figure 5. Diesel substitution rates.

Figure 6 shows the diesel consumption when using only diesel as fuel and when using diesel and biogas at the highest substitution rate for each load. As expected, the diesel consumption increases with the electrical load, since

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more fuel is required; nevertheless, it lowered drastically for all electrical loads tested when using biogas for its substitution. Apparently, the diesel consumption reached a lower limit due to the equipment design. At low partial loads, the electronic regulator is not capable of dosing the necessary quantity of diesel to start the combustion in the cylinders, since it was not designed for that range of loads, causing the 'miss firing' phenomenon.

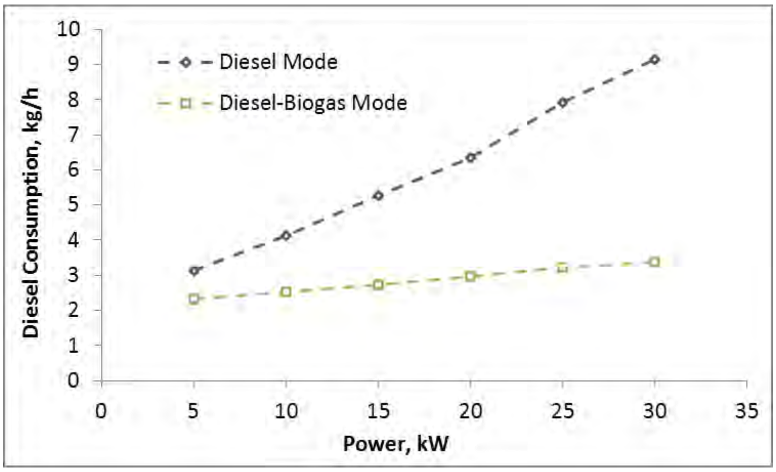

Figure 6. Diesel consumption in diesel mode and in dual mode.

Figure 7 shows a similar phenomenon: the specific fuel consumption is reduced with the increase of the Duty Cycle (consequent increase of the diesel substitution rate). Though, this parameter also reaches a lower limit, due to the same reasons explained above. The lower specific fuel consumption reached was 112 g/kWh.

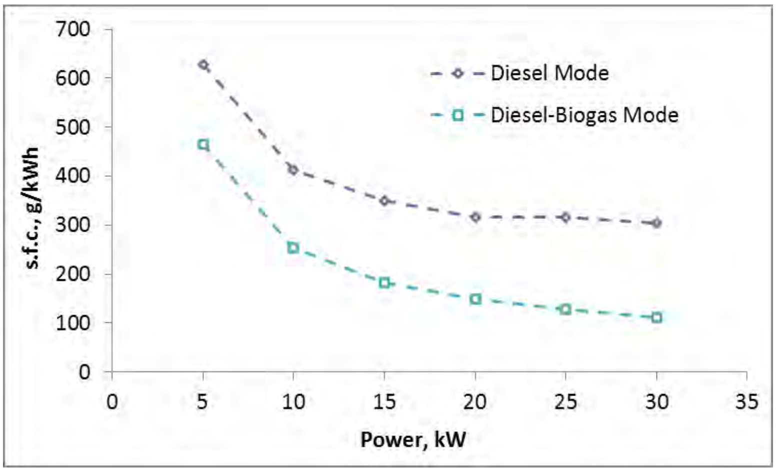

Figure 7. Specific diesel fuel consumption in diesel mode and dual mode.

The cogeneration tests were performed with three different thermal loads (i.e. water mass flow rates): 0.03, 0.09 and 0.15 kg/s (F1, F2 and F3, respectively). Figure 12 shows that the heat recovery from the exhaust gases was higher for the higher thermal loads. This may be due to the low contact between the water and the structure of the heat exchanger: The water flowed around the four tubes of the heat exchanger, but F1 did not flood all the device, but merely covered the lower part of it, recovering heat from the inferior tubes of the heat exchanger. Figure 8 also shows that with the increase of the electrical load, more heat can be recovered from the exhaust gases.

Figure 9 shows the increase of the system efficiency when cogeneration using diesel and biogas is performed. The power generation efficiency for the highest load tested reaches approximately 30%, a common value for Diesel cycle engines with the aforementioned characteristics and in the same conditions of the tests performed. Nevertheless, when performing cogeneration, the total efficiency increases around 10%.

The results of the pressure drop tests indicated that this parameter varied from 200 to 600 Pa. The maximum backpressure allowed for this generator set, according to the manufacturer is 10 kPa. This maximum limit allows the use of another type of heat exchanger that can recover a higher quantity of energy from the exhaust gases without reducing the performance of the engine.

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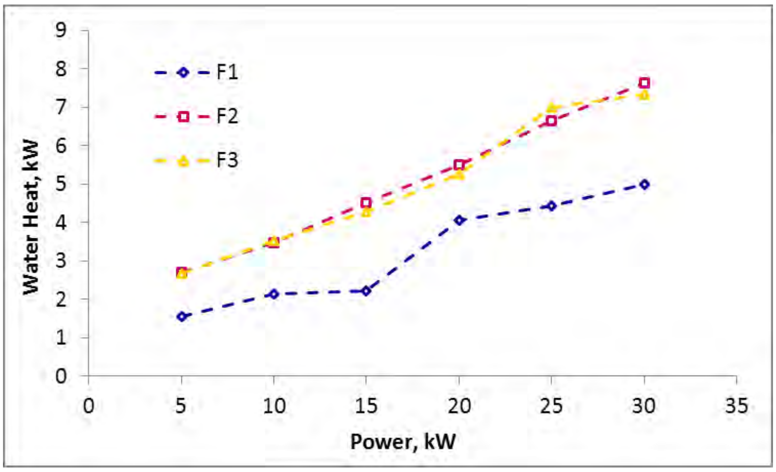

Figure 8. Energy recovered by the water from the exhaust gases.

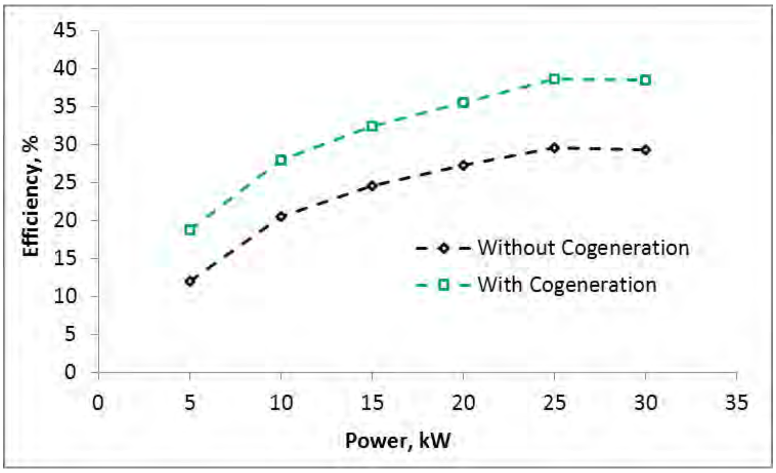

Figure 9. Power generation efficiency and total efficiency of the microcogenerator.

5.2 GHG emissions

With the performance results obtained from the experimental tests, the maximum diesel substitution rate and the maximum recoverable heat from the exhaust gases were determined. Based on these values, three scenarios were presented. The first one reflected the initial conditions of the enterprise: electricity generation using diesel fuel and release of the unused biogas to the environment. The second one involved electricity generation using diesel and biogas as fuels. It also included the processes needed to condition the biogas for its use in the internal combustion engine. The third one added the implementation of a heat exchanger at the end of the exhaust gases pipe for process water heating. This scenario also considered the use of diesel and biogas as fuels. Table 1 shows a summary of the values obtained for different sources of GHG emissions per evaluated scenario.

Table 1. GHG emissions per year and per kWh according to the source by scenario.

Source of GHG Emission	Scenario 1	Scenario 2	Scenario 3
Biogas release to the environment	105307.38	0.00	0.00
Electric consumption of biogas upgrading and pressurization	0.00	1561.28	1561.28
Electricity generation with generator set and diesel as fuel	37804.19	0.00	0.00
Electricity generation with generator set and diesel and biogas as fuels	0.00	22674.73	22674.73
Heat generation with engine exhaust gases heat	0.00	0.00	0.00
GHG emissions, $tCO_2eq/year$	**143.11**	**24.24**	**24.24**
GHG emissions, $kgCO_2eq/kWh$	**4.36**	**0.74**	**0.60**

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The impact of biogas released to the environment on GHG emissions was calculated considering the content of CH_4 and CO_2 in the biofuel: 50% and 38%, respectively. CO was not taken into account since its direct impact in global warming is very low.

Biogas compressing consumed 5.4 MJ/h. With a value of 92 gCO_2eq/MJ for the GHG emissions associated with electricity generation in Peru, a total value of 1 561.28 $kgCO_2eq$ was estimated to be produced per year.

The electricity generation in diesel mode involved the value of 87.64 gCO_2 per MJ available for combustion. When evaluating dual-fuel operation, the quantity of CO_2 in the biogas was taken into account, since it entered the engine and came out without being part of combustion.

Figure 10 shows the GHG emissions per kWh produced for each of the three scenarios. A considerable reduction in GHG emissions can be perceived when comparing the first scenario to the other two. The difference between Scenario 2 and 3 is caused by the addition of 7 kW of heat to the total energy produced, which correspond to the performance of cogeneration.

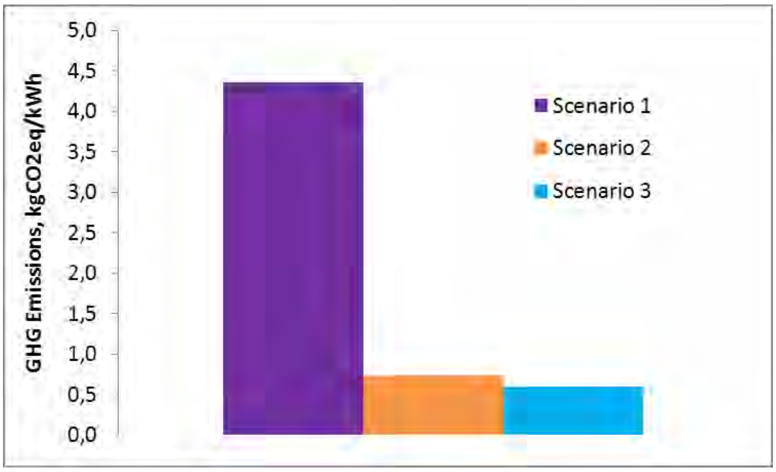

Figure 10. GHG emissions per kWh produced for the three different scenarios.

5.3 Economical results

The investments required and operational costs for each evaluated scenario were analyzed in a time horizon of 10 years. The annual energy production cost was calculated and it was found that lowest energy production cost per kWh was attained for the third scenario: microcogeneration.

The release of biogas to the atmosphere did not constitute any cost for the first scenario and was not considered for the second and third scenarios, since, instead of being freed, it would be used. Investment costs were determined for the biogas canalization, the upgrading system (only H_2S removal), the compressing system and the heat exchanger (only for the third scenario). The investment that a generator set would require was not considered, since the enterprise already owned one. The operational costs involved the activated carbon for the H_2S removal, the electricity for biogas compression, the diesel fuel for electricity generation and the maintenance (for the three scenarios).

The estimated price for H_2S removal and biogas compression were USD 0.07/kg and USD 0.008/kg, respectively. The price of diesel fuel was averaged in USD 1.33/kg. Table 2 shows the energy production costs for each evaluated scenario.

Table 2. Energy production costs per year and per kWh according to resource consuming activities by scenario.

Resource Consuming Activities	Scenario 1	Scenario 2	Scenario 3
Biogas liberation to the environment	0.00	0.00	0.00
Biogas canalization	0.00	295.05	295.05
Biogas upgrading system (H_2S removal)	0.00	68.09	68.09
Activated carbon	0.00	1031.74	1031.74
Compressing system	0.00	577.40	577.40
Electricity for compression	0.00	115.81	115.81
Diesel fuel	13261.05	4874.96	4874.96
Heat Exchanger	0.00	0.00	363.14
Maintenance	727.27	909.09	945.45
Energy Production Costs, USD/year	**13988.32**	**7872.13**	**8271.64**
Energy Production Costs, USD/kWh	**0.43**	**0.24**	**0.20**

Figure 11 shows the difference between the energy production costs attributed to each scenario. It can be seen that, when using diesel and biogas as fuels, the savings are approximately half of the initial price. Since more energy is produced with cogeneration, the cost is reduced.

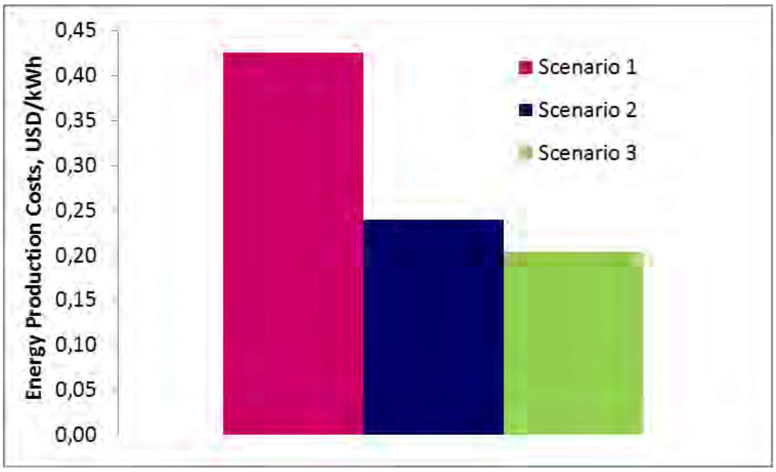

Figure 11. Energy production costs per kWh produced for the three different scenarios.

Figure 11 shows the difference between the energy production costs attributed to each scenario. It can be seen that, when using diesel and biogas as fuels, the savings are approximately half of the initial price. Since more energy is produced with cogeneration, the cost is reduced. Table 3 shows the savings in the GHG emissions and the energy production costs for Scenarios 2 and 3 compared with Scenario 1.

Using diesel and biogas for electricity production reduces the total GHG emissions in 83.06% with and without cogeneration, since the same pollutants are emitted with or without harnessing the exhaust gases heat. Recovering the energy available in the exhaust gases, would reduce the GHG emissions per kWh in 86.27%. When it comes to the energy production costs per year, there is a slight difference between the two scenarios, since cogeneration would require an investment on a heat exchanger; though, this would allow a reduction of 52.05% in the energy production costs per kWh. Anyhow, it can be clearly seen that the use biogas for the production of electricity and the utilization of residual heat generated in the same process, is environmentally and economically convenient.

Table 3. Reductions in the GHG emissions and the energy production costs for Scenarios 2 and 3.

	Per year		**Per kWh produced**	
Reductions	**Scenario 2**	**Scenario 3**	**Scenario 2**	**Scenario 3**
GHG emissions	83.06%	83.06%	83.06%	86.27%
Energy production cost	43.72%	40.87%	43.72%	52.05%

6. CONCLUSIONS

The objective of this study was to demonstrate the sustainability of biogas for the production of electricity and process heat. The feasibility of substituting fossil fuels with biofuels obtained from agricultural residues and of recovering part of the energy usually wasted to produce useful energy was proved. The flexibility of the technology proposed allows the use of two fuels for electricity generation, since the modifications for the use of biogas are external and do not interfere with the engine design.

Anaerobic digestion is a widely used technology in Peru and other developing countries, developed mainly with the objective of obtaining high quality biofertilizers. The possibility of using an almost free fuel generated in this process leads to the capacity of self-generating energy, reducing pollutant emissions and saving economic resources. It was shown that the use of biogas for the substitution of diesel in generator sets results in a 83.06% reduction of GHG emissions and a 43.72% reduction in operational costs for energy production.

On the other hand, using the rejected heat for different processes implies another opportunity for the users of this technology. Harnessing the residual energy of the electricity generation process, results in higher savings: 86.27% in GHG emissions and 52.05% in energy production costs.

The authors consider that many improvements still have to be made in the cogenerator, such as modifying the lower limit of diesel consumption and improving the design of the heat exchanger used to recover more energy from the exhaust gases.

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Anyhow, the combined power and heat production using diesel and biogas constitutes an opportunity for the facilities which have residues that can be converted into biogas and that need both forms of energy: power and heat. In this way, the total energy produced will be appropriately managed and savings in harmful pollutant emissions and economic resources will be attained.

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