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J.J. Coble, A. Contreras

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Energetic, Exergetic, Thermoeconomic and Environmental Analysis of Various Systems for the Cogeneration of Biogas Produced by an Urban Wastewater Treatment Plant UWTP. (1)

J.J. Coble, Industrial Engineering Department, Nebrija University, Spain
A. Contreras, Chemistry Department, Industrial Engineering College, Spain

Abstract

General awareness that the world's energy resources are limited has meant that it is increasingly important to examine energy-saving devices and fuels more closely, in order to use our limited available resources in a more sustainable manner. With this in mind, we studied biogas from a UWTP, because it is a renewable fuel with a neutral contribution to CO_2 emissions. We compared two technologies for using biogas as an energy source: cogeneration using either motor-generators or phosphoric acid fuel cells. The comparison was made from the energetic, exergetic, thermo-economic and environmental points of view, internalizing all the costs involved in each case. We used data supplied by the UWTP at the City of Madrid Plant Nursery, which uses motor-generators, and the UWTPs in Portland, Oregon, and in Red Hook, New York, which use a phosphoric acid fuel cell. The joint work carried out has been divided into three parts for publication purposes, and we present here the first of these, which refers to the energy analysis.

Keywords: Cogeneration, UWTP, motor-generators, fuel cell, energy analysis.

1 Introduction

Wastewater treatment plants require large quantities of both electricity and heat in order to function properly. Cogeneration systems are ideally suited to these requirements, as they enable two or more useable energies (such as heat, electricity, industrial cold, etc.), to be employed simultaneously, using a single primary source. By using residual heat produced during the electricity generation process, this type of system improves the efficiency of fuel consumption [1].

Not all cogeneration systems perform and behave in the same way on site. It is therefore essential to compare systems in order to choose the most appropriate one. However, comparison would be incomplete if it were done solely in energetic terms. We therefore propose a methodology that involves not only energetic, but also exergetic, thermo-economic and environmental comparisons, as each of these on its own will not provide an adequate assessment of the system studies. This has been proven with the use of phosphoric acid fuel cells.

2 The Cogeneration Systems that Were Compared

As mentioned above, the cogeneration systems that were compared were motor-generators with subsequent heat recovery in a boiler, against cogeneration in phosphoric acid fuel cells. In both cases, the fuel employed was the biogas produced by the wastewater treatment plant in the study.

Motor-generation with heat recovery is a cogeneration system that uses an internal combustion engine connected to an electrical power generator and with a waste heat boiler that uses the waste heat from the process to heat up water. These systems are in widespread use because of their cost-efficiency, mobility and performance. However, with these systems, it is important to check the effective advantage of using internal combustion, as well as the real operating and maintenance costs [2].

Phosphoric acid fuel cells systems are cogeneration devices that do not function like a heater, but instead like an electro-chemical device, and their performance is not limited by their Carnot performance. The efficiency of these devices can be far superior to that of motor-generators. They are the ideal systems for stationary applications using cogeneration, due to the high temperature of the electrolytic medium (120-200 ºC) [3].

The results on the energy features of these two cogeneration systems - motor-generators, and phosphoric acid fuel cells - are presented in this study.

3 Biogas

The amount of biogas that may be produced during the anaerobic digestion process can be estimated by relating it to the chemical oxygen demand (COD) of the water or mud to be treated, providing an estimated value of 0.35 m3 CH4/kg CDO eliminated. The importance of its value as fuel is reflected in its large lowest calorific output: around 6000 kcal/STPm3 for a biogas with a composition o f 70% CH4 and 30% CO2.

Table 1 shows the average volumetric composition of the biogas that was studied, in which the presence of ammonia can be seen to be practically insignificant. It has therefore not been taken into account in the subsequent stoichiometric calculations.

Table 1: Average volumetric composition of the studied biogas, in %.

VOLUMETRIC COMPOSITION OF THE BIOGAS (In %).			
$\%CH_4$	$\%CO_2$	$\%H_2S$	$\%NH_3$
65.32%	34.67%	< 0.003%	< 0.0001%

The apparent molecular weight of the biogas can be calculated on the basis of the above data and the molecular weight of each species, as can its apparent density, which has values of 32.61 kg/kmol and 1.14 kg/STPm^3, respectively.

Calculating the highest and lowest calorific output level of the biogas is fundamental in order to find out its energy content, either per cubic metre (measured under normal conditions), or per kilogramme, so as to measure its potential for use as energy. Using the appropriate calculation correlations, therefore, we obtained the results show in Table 2.

Table 2: Approximate highest and lowest calorific output of the biogas per STPm^3 or per Kg.

APPROXIMATE HIGHEST AND LOWEST CALORIFIC OUTPUT (kJ/STPm^3, kcal/STPm^3, kJ/kg y kcal/kg)
P.C.S. = 25984.36 kJ/STPm^3 = 6236.25 kcal/STPm^3
P.C.I. = 23344.90 kJ/STPm^3 = 5602.78 kcal/STPm^3
P.C.S. = 22640.40 kJ/kg = 5433.70 kcal/kg
P.C.I. = 20340.60 kJ/kg = 4881.74 kcal/kg

From the results obtained, we were able to see the potential for use as energy of the biogas produced at the UWTP. The basic energy parameters for the operation of the WTP are as follows:

$$\eta = \frac{\text{ELECTRIC ENERGY PRODUCED}}{\text{ELECTRIC ENERGY CONSUMED}} = \frac{5.720.000\ \text{kWh}}{19.843.000\ \text{kWh}} = 28{,}82\%$$

$$\frac{\text{ELECTRIC ENERGY CONSUMED}}{\text{per head}} = \frac{19.843.000\ \text{kWh}}{451.643\ \text{per head}} = 43{,}93\ \text{kWh/per head}$$

$$\frac{\text{Biogas}_{\text{PRODUCED}}}{\text{per head}} = \frac{3.984.000\ \text{STPm}^3}{451.643\ \text{per head}} = 8{,}821\ \text{STPm}^3\text{/per head}$$

$$\frac{\text{ELECTRIC ENERGY PRODUCED}}{\text{per head}} = \frac{5.720.000\ \text{kWh}}{451.643\ \text{per head}} = 12{,}66\ \text{kWh/per head}$$

4 Energy Comparison of Both Systems

In this study, we defined new ratios that make it easier to compare the two cogeneration systems studied.

The ratios were defined as follows:

- FPE (EOF) is the electric output factor, which is obtained by dividing the electicity produce dby teh biogas consumed.
- FPT (TOF) is the thermal output factor, which is obtained by dividing the thermal energy produced by the biogas consumed.
- CII (ICI) is the cost of installation in terms of the electrical kilowats installed, which is obtained by dividing the cost of the installation by the electical kilowats installed.
- CIP (ICP) is the cost of installation in terms of electrical kilowats produced, which is obtained by dividing the cost of the installation by the electical kilowats produced.

4.1 The cogeneration system using motor-generators

With the motor-generators, we had to calculate and analyse the system on the basis of the balance of mass and energy for reactive systems. We used the following equations for this purpose:

$$\frac{\dot{Q}_{VC}}{\dot{n}_C} - \frac{\dot{W}_{VC}}{\dot{n}_C} = \sum_P n_P \left(\bar{h}_f^o + \Delta\bar{h}\right)_P - \sum_R n_R \left(\bar{h}_f^o + \Delta\bar{h}\right)_R \tag{1}$$

$$\Delta\bar{h} = \bar{h}\,(T, P) - \bar{h}\,(T_{ref}\ , P_{ref}) \tag{2}$$

By applying these to the control volume selected for the motor-generator system, and taking into account the principal factor of excess air (n) used for combustion, we were able to obtain the results with the EES programme [4]. If we take the results that refer to 50% of excess air as a standard working measurement in motor-generators using biogas, and taking into account the financial costs of the cogeneration system shown in Table 3, the results are as follows:

Table 3: Basic parameters and installation and operational costs for the Municipal Plant Nursery UWTP's biogas cogeneration system.

COSTS OF THE COGENERATION SYSTEM USING MOTOR-GENERATORS	
Power (3 motor-generators, 455 kW each)	1,365 kW
Investment/kW	1,502.53 €/kW
Lifespan	20 years
Cost of investment	**2,050,953.45 €**
Annual operating costs	
Fuel	93,878.1 €
General operation and maintenance	20,000 €
Labour	54,000 €
Total cost (investment and first year of operation)	**2,218,831.55 €**

$$\mathrm{EOF} = \frac{\text{ELECTRIC ENERGY PRODUCED}}{\text{Biogas}_{\text{CONSUMED}}} = \frac{5.720.000\ \text{kWh}}{3.984.000\ \text{STPm}^3} = 1{,}435\ \text{kWh/STPm}^3\ \text{Biogas}$$

$$\mathrm{TOF} = \frac{\text{THERMAL ENERGY PRODUCED}}{\text{Biogas}_{\text{CONSUMED}}} = \frac{9.533.333{,}33\ \text{kWh}}{3.984.000\ \text{STPm}^3} = 2{,}392\ \text{kWh/STPm}^3\ \text{Biogas}$$

$$\mathrm{ICI} = \frac{\text{System cost}}{\text{kWe installed}} = 1.502{,}53\ \text{euros/kWe}_{\text{INSTALLED}}$$

$$\mathrm{ICP} = \frac{\text{System cost}}{\text{kWhe produced}} = \frac{2.050.953{,}45\ \text{euros}}{5.720.000\ \text{kWhe}} = 0{,}3585\ \text{euros/kWhe}_{\text{PRODUCED}}$$

4.2 The cogeneration system using phosphoric acid fuel cells

In this case, it was necessary to use the data from a Pure Cell ™ Model 200 (200kW) phosphoric acid fuel cell, fed with reformed biogas [5, 6]. The differences in compositon of the two biogases have been adjusted by modifying the input flow. The results obtained for calorific power, electrical power, emissions, etc., once these modifications had been made, are shown in Table 4.

Table 4: Electrical and calorific performance of the phosphoric acid fuel cell, based on the data from the PureCell™ Model 200 (200 kW).

TEST	TEST CONDITONS	INPUT GAS FLOW (STP m^3/s)	INPUT CALORIFIC POWER (kW)	ELECTRICAL OUTPUT		CALORIFIC OUTPUT	
				ELECTRICITY (kWe)	EFFICIENCY (%)	HEAT (kWt)	EFFICIENCY (%)
1	200 kW required output	0.02366	524.88	193.1	36.79%	297.17	56.62%
2		0.02363	524.30	193.1	36.83%	294.24	56.12%
3		0.02360	523.71	193	36.85%	303.73	58.00%
AVERAGE VALUE		**0.02363**	**524.30**	**193.1**	**36.83%**	**315.95**	**60.26%**
4	150 kW required output	0.0180	399.74	152.3	38.10%	209.54	52.42%
5		0.0178	396.23	152.2	38.41%	202.21	51.04%
6		0.0179	398.57	152.3	38.21%	204.82	51.39%
AVERAGE VALUE		**0.01795**	**398.28**	**152.3**	**38.24%**	**205.23**	**51.53%**
7	100 kW required output	0.01198	265.87	101.5	38.18%	137.127	51.58%
8		0.01257	279.03	101.5	36.38%	151.194	54.19%
9		0.01221	270.91	101.5	37.47%	134.782	49.75%
AVERAGE VALUE		**0.01225**	**271.93**	**101.5**	**37.32%**	**140.644**	**51.72%**

The results for the parameters used in our comparison are as follows:

$$\mathbf{EOF} = \frac{\text{ELECTRIC ENERGY PRODUCED}}{\mathbf{Biogas_{CONSUMED}}} = \frac{\mathbf{5.867.400\ kWhe}}{\mathbf{2.496.256{,}4\ STPm^3}} = \mathbf{2{,}35\ kWh/STPm^3\ Biogas}$$

$$\mathbf{TOF} = \frac{\text{THERMAL ENERGY PRODUCED}}{\mathbf{Biogas_{CONSUMED}}} = \frac{\mathbf{9.533.333{,}33\ kWh}}{\mathbf{2.496.256{,}4\ STPm^3}} = \mathbf{3{,}82\ kWh/STPm^3\ Biogas}$$

$$\mathbf{ICI} = \frac{\mathbf{System\ cost}}{\mathbf{kWe\ \ installed}} = \mathbf{4.300\ euros/kWe_{\ INSTALLED}}$$

$$\mathbf{ICP} = \frac{\mathbf{System\ cost}}{\mathbf{kWhe\ \ produced}} = \frac{\mathbf{6.020.000\ euros}}{\mathbf{5.867.400\ kWhe}} = \mathbf{1{,}026\ euros/kWhe_{PRODUCED}}$$

It can be seen that FPE (EOF) is 61% greater in the fuel cell than in the motor-generator, and the FPT (TOF), is also 63% higher in the fuel cell. The set-up costs and one year of operation of this system are shown in Table 5.

Table 5: Basic parameters and installation and operating costs of the biogas cogeneration system using fuel cells.

COST OF THE COGENERATION SYSTEM USING FUEL CELLS	
Power (7 fuel cells, 200 kW each)	1,400 kW
Investment/kW	4,300 €/kW
Lifespan	20 years
Cost of investment	**6,020,000 €**
Annual operating costs	
Fuel	93,878.1 €
General operation and maintenance	12,512 €
Labour	54,000 €
Total cost (investment and first year of operation)	**6,180,390.1 €**

5 Conclusions

The energy analysis of the cogeneration systems studied has made it clear that the use of motor-generators is better suited in terms of installation costs and the first year of operation than phosphoric acid fuel cells. However, as we have already mentioned, this analysis alone is not enough to provide a realistic idea of each of the systems studied. It is therefore necessary to proceed with the energy, thermo-economic and environmental analyses, in order to get a precise idea of the behaviour of both these systems.

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