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PERFORMANCE OF DIFFERENT ENGINES IN BIOGAS-BASED DISTRIBUTED ELECTRICITY GENERATION SYSTEMS

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KEYWORDS

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ABSTRACT

Different mechanical configurations of diesel engines, when powered by biogas, can influence engine performance and efficiency. Consequently, this study aims to evaluate various generator engines to determine the optimal configuration for a distributed generation unit at a swine farm. In this study, we assess the biogas consumption, specific consumption, and efficiency of five biogas generator engines. Three engines (A, D, and E) were provided by Biogás Motores Estacionários, while the remaining two (B and C) were provided by Electro Hager models and MWM, respectively. The biogas used was produced in plug flow biodigesters (piston flow) by the treatment of swine waste. Engine A, provided by Biogás Motores Estacionários, exhibited specific consumption at a power of 30 kW (low load) similar to engines B and C. However, engines B and C displayed higher efficiencies at high loads compared to engines A, D, and E, attributed to their advanced fuel injection and control systems.

INTRODUCTION

Biomass, as highlighted by Gongora et al. (2022), stands as one of the most significant energy sources accessible within rural areas and agroindustries. This energy form bears the potential to drive development in rural regions, as indicated by Souza et al. (2013), Gupta et al. (2023), and O'Connor et al. (2021). Notably, biomass emerges as a compelling alternative energy option, distinguished by its superior reliability compared to solar and wind energy sources. Furthermore, its unique attribute of a "null balance" of CO2, meaning the carbon dioxide released during biomass combustion is subsequently reabsorbed during the plant's following life cycle through photosynthesis (Avcıoğlu et al., 2019), underscores its environmental advantages.

The biomass derived from animal and plant waste readily available in rural areas or agroindustries offers a valuable avenue for electricity generation. This is achieved through the utilization of biodigesters, which facilitate both electricity production and the conversion of waste into biogas via anaerobic digestion (Khiari et al., 2019; Huang et al., 2019; Kabeyi & Olanrewaju, 2022). It's worth noting that just a few years ago, animal waste was indiscriminately dumped into rivers and springs, with little consideration for the resulting environmental repercussions. However, the current approach mandates the pre-treatment of manure before its introduction into the ecosystem (Ström et al., 2018).

In Brazil, certain properties equipped with facilities like swine and cattle farms, starch producers, and animal slaughterhouses, are actively constructing biodigesters. Notably, the focus often lies on the implementation of pig flow (specifically piston flow), tubular, or piston model biodigesters (Freitas et al., 2019; Werncke et al., 2023). The primary aim here is to harness biogas production for self-sustaining energy generation using engine generator sets. These systems are capable of being integrated into the grid using Distributed Generation (DG) mode. The key objective is to meet the energy demands of the rural property while also potentially exporting surplus energy to the grid, thereby functioning within the domain of Grid Distribution (GD).

The majority of engines employed are generator engines, typically possessing an average power. Initially designed as diesel cycle engines, they have undergone a conversion to operate on the Otto cycle using biogas. This

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conversion involves adjusting the compression ratio, modifying the ignition timing, and incorporating a biogas/air injection system (Aguiar et al., 2021). To date, much of the research concerning the performance assessment of biogas engines centers around pinpointing particular sources and rates. Nevertheless, only a limited number of studies have concentrated on evaluating distinct types of biogas-fueled engines.

In Brazil, various mechanical configurations of diesel engines have been converted to biogas by specialized companies. Our hypothesis was that not all of these configurations possess a sufficient level of efficiency in converting biogas to energy. As a result, the aim of this study was to assess the performance of biogas engines across different engine setups.

MATERIAL AND METHODS

The experiments were conducted across various electricity generation plants utilizing the biogas distributed generation mode and employing distinct generator engine technologies. These assessment endeavors took place in facilities situated within the cities of Toledo and Ouro Verde do Oeste – PR, Brazil. Five generator engines were subject to evaluation (Fig. 1), showcasing differing volumetric displacements, cylinder counts, and power outputs ranging from 35 to 75 kW (Table 1). Notably, engines A, D, and E were operated with an ignition advance setting of 25 degrees and an air-fuel ratio (lambda) maintained at 1.45.

FIGURE 1. Engines used in the tests.

TABLE 1. Technical specifications of engines.

Description	Engine A	Engine B e C	Engine D	Engine E
Model	Ford 4.9	MAN 0836 E	MWM 4.12	Mercedes Benz OM 352
Cylinders	6 in line	6 in line	4 in line	6 in line
Cycle (times)	Otto 4 stroke	Otto 4 stroke	Otto 4 stroke	Otto 4 stroke
Diameter of cylinders	101.60 mm	108.00 mm	10.00 mm	97.00 mm
Piston stroke	101.09 mm	125.00 mm	137.00 mm	128.00 mm
Total cylinder capacity	4.90 L	6,90 L	4.80 L	5.60 L
Compression ratio	8.8:1	13:5	12:01	12.5:1
Maximum power	3500 rpm	1800 rpm	2200 rpm	1700 rpm

The load was adjusted across a range of 10 to 75 kW. The generator set was fine-tuned to a constant load, ranging from 10% to 100% of its nominal capacity, achieved by modifying the energy fed into the utility. Following this adjustment, measurements were taken for load readings, specific consumption, and biogas composition.

The biogas flow was quantified utilizing a mass dispersion volumetric biogas flow meter, specifically the TA2-A1B0-K30/TFT-141A-000 model from the Magnetrol brand. The measurement was expressed in cubic meters per hour (m^3 h^{-1}). The methane (CH4) percentage was determined using a gas analyzer known as the GEM 5000, manufactured by Landtec. Through the methane concentration data, it becomes feasible to calculate the lower calorific value of the biogas consumed by the generator engine, presented in kilowatt-hours per cubic meter (kWh m^{-3}).

For biogas consumption measurement, we employed a mass thermal flow transmitter of the Magnetrol brand, specifically the TA2 model. This instrument facilitates mass flow measurement utilizing thermal dispersion principles. Its flow measurement range spans from 0.05 to 100 m^3 h^{-1} with an accuracy rated at ±1% of the reading plus 0.5% of the calibration. The equipment was strategically positioned within the gas line in close proximity to the engine's intake, enabling it to gauge the flow utilized by the engine during its operation. This device provides instantaneous flow readings in cubic meters per hour (m^3 h^{-1}).

Specific fuel consumption was derived from real-time biogas consumption data (measured in m^3 h^{-1}) and the concurrently generated active power (in kW) (Çengel & Boles, 2013). Equation (1) outlines the methodology for computing specific consumption (SC), expressed in cubic meters per kilowatt-hour (m^3 kWh^{-1}).

$$\mathrm{SC} = \frac{\mathrm{Q}}{\mathrm{P}} \tag{1}$$

Where:

Q is the biogas consumption in the generator set (m^3 h^{-1});

P is the generated active power or generator load (kW).

To measure the consumption of biogas in the generator engine, a thermal flow transmitter was used, which was installed in the biogas feed pipe to the generator engine.

The conversion efficiency of biogas into electrical energy (η) is given by the following [eq. (2)] (Mitzlaff, 1988):

$$\eta = \frac{\mathrm{P}}{\mathrm{Q} * \mathrm{PCIbiogas}} \tag{2}$$

Where:

PCIbiogas is the lower calorific value of the biogas (expressed in kilowatt-hours per cubic meter, kWh m^{-3}), which depends on the biogas composition;

Q the biogas consumption in the generator set (measured in cubic meters per hour, m^3 h^{-1}), and

P denotes the generated active power or generator load (kW).

To determine the lower calorific value of the biogas in kilowatt-hours per cubic meter (kWh m^{-3}), methane content data within the biogas was acquired using the Infralyt ELD analyzer manufactured by Saxon Junkalor GmbH.

RESULTS AND DISCUSSION

Higher loads led to increased consumption. Motor B exhibited lower consumption compared to the other motors, particularly under heavy loads. At lower loads, engine A demonstrated minimal biogas consumption. Generator engines B and C utilized a distinct fuel injection control system, contributing to their reduced biogas consumption (Fig. 2). In conventional engines, the injection system primarily regulates the air/fuel ratio through a lambda sensor and a butterfly valve. In contrast, engines B and C employ a fuel injection control mechanism based on piston combustion pressure and temperature, elucidating the positive outcomes observed in these engines.

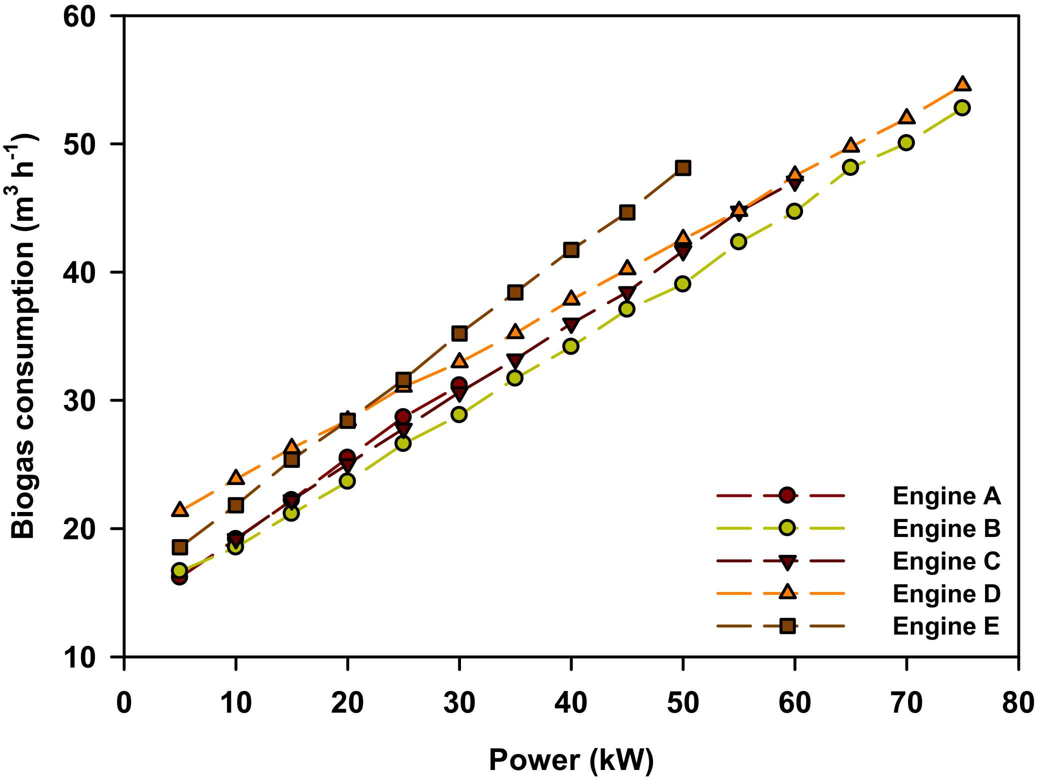

FIGURE 2. Biogas consumption of engines.

Specific consumption decreased with the load on the generator engine (Fig. 3), a trend consistent with findings by Verma et al. (2017) and Silva et al. (2018). As the load increased, consumption decreased due to enhanced combustion efficiency (Deheri et al., 2020). At maximum power, engines B and D exhibited specific consumptions of 0.70 and 0.73 m^3 kWh^{-1}, respectively. These values are notably below the 0.89 m^3 kWh^{-1} reported by Silva et al. (2018) for an engine similar to the D model operating at full power. The superior combustion control of engines B and D contributed to their lowered specific consumption and consequently greater efficiency.

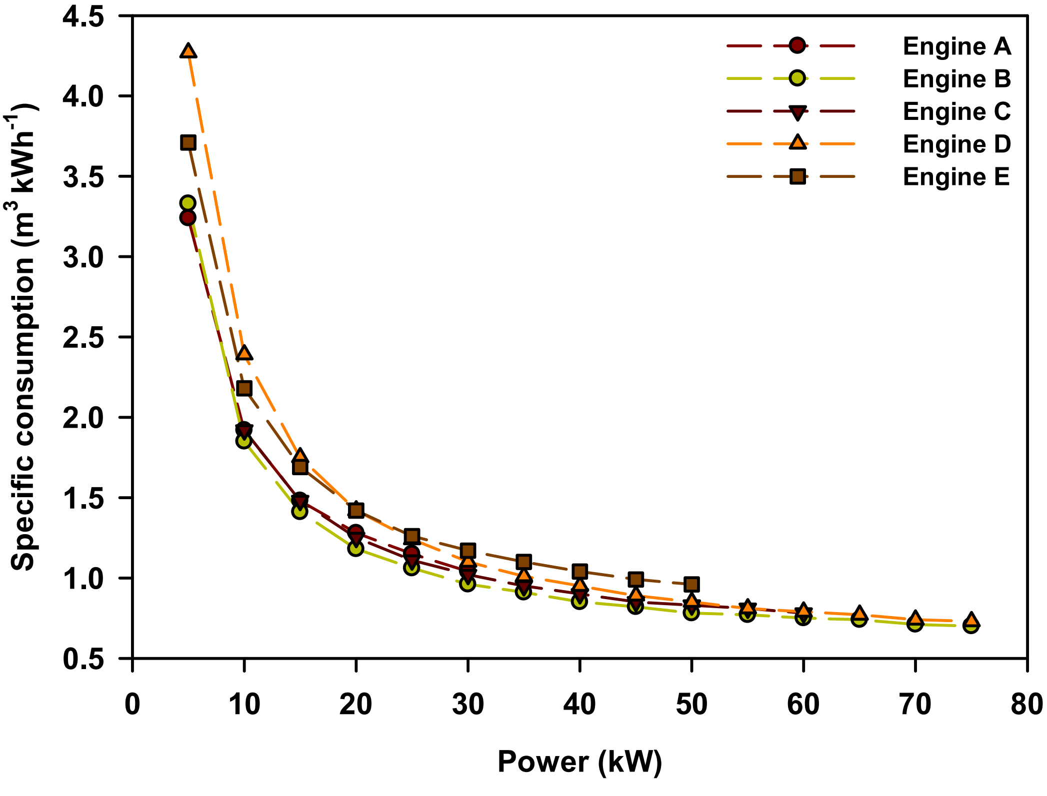

FIGURE 3. Specific consumption of engines.

At maximum power, engine A showcased a specific consumption of 1.04 m³ kWh^{-1}, which closely aligned with engine E specific consumption of 0.96 m³ kWh^{-1} under similar conditions. In contrast, the smaller-scale biogas engines (with lower power) exhibited elevated specific consumption levels at their respective loads or maximum power settings. Nevertheless, these generator sets possess advantages in the form of reduced capital costs and maintenance expenses. Notably, the specific consumption of Motor A was akin (~1.04 m³ kWh^{-1}) to that of motors C, D, and E, all operating at a 30 kW load. This insight holds significance for operational scenarios constrained by limitations of the electric power grid and variations in biogas production, where sustained high-load operation for 24 hours might not be feasible. Consequently, the employment of smaller generator engines operating continuously at maximum power could be a pragmatic alternative to larger engines with lower power output. As posited by Jatana et al. (2014), low-power motors find particular suitability in remote rural areas, where individual households typically exhibit lower energy requirements. Additionally, the implementation of certain modern engine configurations presents challenges in remote areas.

Engines D and E lack the precision of combustion control evident in engines B and C, resulting in diminished efficiency (Fig. 4). Conversely, the engine generator B, which incorporates German technology (imported), exhibited superior efficiency across various loads. Nevertheless, the elevated cost associated with the B engine could constrain its adoption on smaller farms.

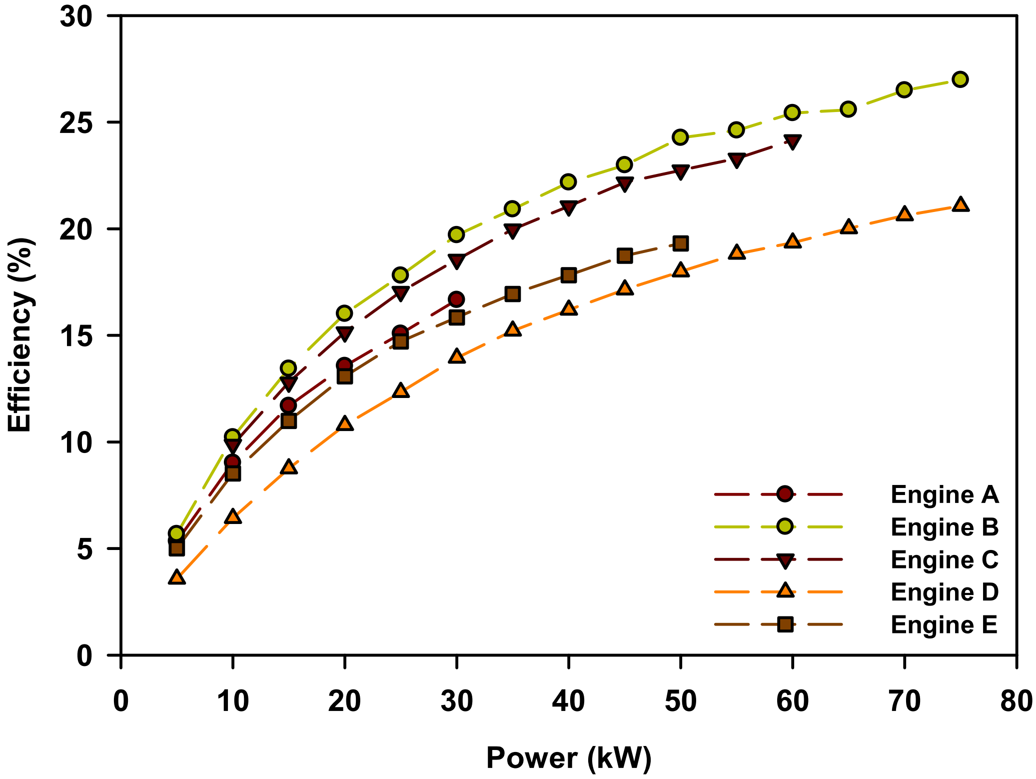

FIGURE 4. Efficiency of engines.

The conversion efficiency showed improvement with escalating engine loads, aligning with observations by Verma et al. (2017). Engine B, benefitting from advanced combustion technology, achieved an efficiency of 27% at full load (75 kW). Souza et al. (2016), employing two 100 kW generator engines—one at a pig fattening facility and the other at a chicken slaughterhouse—attained an efficiency of 21.8% (equivalent to 1.4 m³ kWh^{-1} of biogas). Silva et al. (2018) reported an efficiency of 17% (equivalent to 1.1 m³ kWh^{-1}of biogas) for a 100 kW generator engine operating at maximum capacity.

CONCLUSIONS

Engine A exhibited a specific consumption at a 30 kW power level akin to that of engines B and C. Nevertheless, engines B and C demonstrated elevated efficiencies compared to engines A, D, and E, particularly at high loads, owing to their advanced fuel injection and control systems in contrast to the others. Therefore, engines provided by Electro Hager (B and C) displayed higher efficiencies and can be recommended.

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