Performance analysis of a hybrid natural gas generator/photovoltaic system for residential use

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Abstract. Diesel generator sets are mostly used as the main electricity supply or as a backup for areas not connected to the main electricity grid. Natural gas can be used as an alternative fuel of generator set to replace diesel because of its abundant availability and is environmentally friendly. In addition to the generator set, the solar photovoltaic (PV) system is also suitable for implementation in remote areas since its primary energy sources are easy to obtain. The combination of these two types of power generation is expected to be reliable enough to supply the electricity for houses in remote areas. This study is conducted to observe the performance of the hybrid natural gas generator set/solar PV system in terms of specific fuel consumption (SFC) and power quality through a testbed, and further analyze the economic aspect. According to the result, the voltage and frequency generated by the natural gas generator set either integrated with a solar PV system or not is still within the allowable operating limits. Moreover, the SFC value of the hybrid system is higher than the one with natural gas generator set only.

1. Introduction

In Indonesia, the residential's need for electricity is commonly supplied by the utility grid, which consists of mostly coal-based generation systems. Whereas, in the remote areas, the need for electricity is fulfilled through off-grid generator sets, which are fueled either by a diesel or gasoline [1]. Coal, diesel, and gasoline are fossil-based energy resources which may cause the greenhouse gas effect and lead to the damage of the environment [2]. CO₂ emissions from the combustion of fossil fuels also are one of the main culprits to the problem of global warming whereas NO emissions contribute to smog and acid rain problems [3]. Furthermore, the availability of these fossil-based energy resources is also decreasing year by year [4].

Another fossil-based energy resource, such as natural gas, provides a lower emission compared to coal. It is estimated that carbon dioxide (CO₂) emission caused by natural gas is only 50-60% of coals [5]. Indonesia was the 13th country with the largest natural gas reserves in the world as of 2015, with 103,350,000 Million Cubic Ft of reserves [6]. On the other hand, the gas distribution network and even the gas tank refill stations are available in many areas in Indonesia. As per national gas company data, 325,773 gas distribution networks are spreading in 16 provinces in Indonesia, and 46 gas stations are installed in 7 areas [7]. The national gas company is also planning to increase the use of natural gas by 30% in 2025 [8].

The advantages of the natural gas as energy resources, such as low emission, comparatively low price, and the existence of the gas distribution network/refill stations, open an opportunity for the residents in the remote area to replace the diesel/gasoline with natural gas as a primary source of the
generator set. Diesel engines can be easily modified into natural gas engines without any significant modification [9].

Furthermore, the geographical condition of Indonesia raises the benefit of using solar energy through the photovoltaic (PV) system. The average level of irradiation throughout the year in Indonesia is 4.80 kWh/m², in theory, has more than 500 GW of potential solar sources[10]. Hence, this paper explores the configuration, benefits, and economic aspects of a hybrid system consisting of a gas generator set and a PV system installed in the residential houses. Hybrid Renewable Energy Systems is composed of one renewable and one conventional energy source or more than one renewable with or without conventional energy sources, that works in stand-alone or grid-connected mode [11]. When renewable energy sources do not produce enough energy for the user's electricity needs, the hybrid system will provide electrical energy through generators [12].

In this study, the hybrid system used is a hybrid PV-Natural Gas system intended for home use. The hybrid system will be compared with a stand-alone generator system with natural gas fuel. The purpose of this paper is to analyze the performance of a system with natural gas fuel only and a system with combined PV-Natural Gas. The parameters to be compared are the stability of the voltage and frequency produced, the Specific Fuel Consumption (SFC) of the generator, and the economic aspects. By using this system, it is expected to reduce the use of gasoline/diesel fuel for the generator.

This paper consists of four chapters, as follows: Chapter one contains an introduction that explains the background of this research based on previous studies. Chapter two contains a methodology that explains the equipment used in testing and testing procedures. Chapter three contains an analysis of the results of examinations that have been carried out. Chapter four contains conclusions from this study.

2. System configuration

2.1. Conversion of the diesel-fueled to the gas-fueled generator

The main component of the system is the generator, which has to be converted from the diesel-fueled to gas-fueled type by using some additional equipment. The additional equipment includes regulator, converter kit, and air and gas mixer, as shown in Figure 1. A regulator is a component of a hydraulic or pneumatic system that functions to regulate the amount of fluid pressure from a high-pressure source system to a low-pressure user system [13]. Converter kit is a mechanically controlled equipment used to respond to the change of the required power so that it can maintain a continuous supply of gas to the generator. A mixer is a device that converts the fueling system in the generator from diesel to gas, where it works by mixing the gas and air before transferred to the fire chamber.

![Figure 1. Supporting Components: (a) Regulator, (b) Converter kit, (c) Mixer](image)

2.2. Photovoltaic system

Photovoltaic is a device that can convert photon energy from the sunlight into electrical energy employing a semiconductor technology [14]. The smallest unit of photovoltaic is called a PV cell. A group of cells is assembled to form a PV module or PV panel. Whereas, some PV modules can be arranged and connected in series and in parallel to build a PV array [15]. The PV system is integrated with the gas-fueled generator. Since the PV system generates a DC power while the gas-fueled generator works in AC power, then it requires an inverter that converts DC to AC power.

Eastern Indonesia has the solar irradiance potential 5.1 kWh/m²/day with a monthly variation of around 9% [10]. The average daily demand for most households in the area is 7–12 kWh per day. Hence, it only requires the area of 2–3 m² at each house for the PV system, which can be installed at the rooftop [16].
2.3. Experimental testing circuit and measurement equipment

The testing circuit for the experiment in this study is presented in Figure 2. A gas meter is used to measure gas consumption during the operation. It is located right before the inlet to the gas-fueled generator. Whereas, the electrical variables such as energy, power, voltage, current, and frequency are measured by a power quality analyzer (PQA). The electrical measurement equipment is placed at the gas-fueled generator output and also at the output of the PV system.

![Testing circuit diagram](image)

**Figure 2.** Testing circuit diagram

2.4. Performance generalization using Least Square analysis

The performance of the proposed hybrid system, which is a converted gas-fueled generator and PV system, is evaluated by measuring some parameters through the least methodology. The least-square is a standard approach in regression analysis to estimate the pattern of the system performance. Hence, each parameter, namely the voltage, frequency, the specific fuel consumption (SFC), and the cost, is mapped based on the system loading percentage. The general form of the least-square equation is defined as

\[
\hat{Y} = ax + b
\]  

where \( \hat{Y} \) is a dependent variable such as voltage, frequency, SFC, and cost; \( x \) represents an independent variable such as the loading of the gas-fueled generator; \( a \) represents the intercept that indicates the slope, and \( b \) represents the bias or offset.

The generalization obtained from the least square equation then can be evaluated by calculating the Mean Absolute Percentage Error (MAPE) as follows:

\[
MAPE = \frac{1}{n} \sum_{i=0}^{n} \left| \frac{y_i - \hat{y}_i}{\hat{y}_i} \right|
\]  

(2)
where $y_i$ is the $i$-th actual measurement of the associated variable, $\hat{y}$ is its value based on the least square equation, and $n$ is the number of data.

3. Simulation and Results

3.1. Testing equipment specification

The generator used in this study is a Honda brand with type EP2500CX which has a rated AC power capacity of 2 kVA, the PV system used in this study is a Monocrystalline Canadian Solar CS6K-275P, and the inverter used in this study is Sunny Island 4.4 M, as shown in Table 1.

| Specification          | Generator | PV System   | Inverter       |
|------------------------|-----------|-------------|----------------|
| Type                   | EP2500CX  | CS6K-275P   | Sunny Island 4.4 M |
| Rated power            | 2.0 kVA   | 167.92 W/m² | 3.3 kVA        |
| Rated voltage          | 220 V     | 1000 V max. system voltage | 230 V/172.5 V to 264.5 V |
| Frequency              | 50 Hz     | -           | 50 Hz/40 Hz to 70 Hz |
| Speed                  | 3000-3600 rpm | -         | -              |
| Efficiency             | -         | 16.8% (peak) | 95.5%          |
| Current at maximum power | -         | 8.88 A      | -              |
| Voltage at maximum power | -         | 31 V        | -              |

3.2. Simulation Results

The simulation is performed by varying the loading of the system into 25% (0.5 kW), 50% (1 kW), 75% (1.5 kW), and 90% (1.8 kW), and each scenario is carried out five times.

3.2.1. Voltage Stability Test Results.

The results of the average voltage output of the generator using the stand-alone and hybrid system can be seen in Figure 3. The system voltage output is ranged from 217–232 Volt for the stand-alone system with the average value is 225.87 Volt. Whereas, the hybrid system results in the system output voltage range from 222–227 Volt with the average value is 224.93 Volt. The values of the voltage are still within the grid code limits in Indonesia (198–242 Volt) for both system configuration.

The MAPE is 0.76% and 0.31% for the stand-alone and hybrid system, respectively. Hence, the hybrid system provides a better least square model compared with the stand-alone system. It indicates that the hybrid system results in a better voltage variation in accordance with the system loading rather than a stand-alone system.

3.2.2. Frequency Stability Test Results.

The results of the average frequency output of the generator using the stand-alone and hybrid system can be seen in Figure 4. The frequency output is ranged from 49–51 Hz for the stand-alone and hybrid system with average value is 50.76 and 50.77, respectively. The frequency output when using a stand-alone system with 75% loading and 90% of the generator capacity is still within normal limits in Indonesia (49.5–50.5). The frequency output when using a hybrid system only at 90% loading of the generator capacity that still within normal limits in Indonesia.
Indonesia. Therefore, it is necessary to appropriately select the size of the generator that matches the size PV system that will be used.

The MAPE is 0.24% and 0.40% for the stand-alone and hybrid system, respectively. Hence, the stand-alone system provides a better least square model compared with the hybrid system.

3.2.3. Specific Fuel Consumption Test Results. The results of the generator SFC using the stand-alone and hybrid system can be seen in Figure 5. The SFC value is ranged from 0.41 – 0.75 m³/kWh for the stand-alone system with the average value is 0.53 m³/kWh. Whereas, hybrid system result in the SFC value ranged from 0.41–0.89 m³/kWh with the average value is 0.61 m³/kWh. It is shown that at a higher loading, both system result in similar SFC values, while at a lower loading, the hybrid system consumes more fuel than the stand-alone system since most of the loads can be supplied by the PV system.

The MAPE is 7.33% and 10.19% for the stand-alone and hybrid system, respectively. Hence, the stand-alone system provides a better least square model compared with the hybrid system.

3.2.4. Economic Aspect Analysis. Energy costs incurred at each level of loading using the stand-alone and hybrid system can be seen in Figure 6. Considering the gas price is Rp 3,350/m³ and the cost of production PV in Indonesia Rp 1,479 per kWh [17]. The energy cost value is ranged of Rp 1,500–Rp 2,800 for the stand-alone and hybrid system with the average value is Rp 2,003.54 and Rp 1,960.28, respectively. The hybrid system can provide a slightly lower cost compared to a stand-alone system. Moreover, the cost of production of PV shows a decreasing trend in the future, while the gas price may increase along with its scarcity. Besides, the hybrid system provides cleaner energy compared to a gas-fueled generator only.

The MAPE is 7.36% and 8.35% for the stand-alone and hybrid system, respectively, which indicates that the two systems provide an almost similar model for the energy cost.

4. Conclusions

The issue of electrification in some parts of Indonesia, especially in Eastern Indonesia, has raised some ideas to provide an affordable, clean, and reliable energy generation for residences in the remote area. This paper proposes a small system consists of a modified generator that uses gas as the fuel and a small PV system, which can be installed individually and off-grid at each household. The experiment applies the stand-alone system with solely the gas-fueled generator as well as the hybrid system with the combined configuration of gas-fueled generator and PV system.

The experimental results show that the output voltage of the system is within an acceptable limit allowed by the grid code. Whereas, the output frequency requires proper sizing of generator and PV system so that it does not operate in a lower system loading. The stand-alone system can be loaded as low as 75% of the system capacity, while the hybrid system must operate at 90% of the system capacity. The SFC, which leads to energy cost, also shows an affordable value for the residents. The cost of energy is Rp. 2,000.53 and Rp. 1,960.28 per kWh depending on the loading of the system for the stand-alone and hybrid system, respectively. In fact, it can reach Rp. 1,500 per kWh if the loading is at 90% of the system capacity.
This experiment has indeed shown the opportunity to increase the electrification in the remote area of Indonesia, where access to the utility grid is limited. However, the scope of improvements exists in this experiment, such as to optimize the size of the components and to enhance the frequency deviation, which can be executed as future works.

References
[1] Casson A, Ketut Y I, Muliastra D, and Obidzinski K 2014 Large-scale plantations, bioenergy developments and land use change in Indonesia 170 CIFOR
[2] Nanda S, Sarangi P K, and Vo D-V N 2019 Fuel Processing and Energy Utilization. (Boca Raton: CRC Press)
[3] Sunderan P, Singh B, Mohamed N M, and Husain N S 2011 Techno-economic analysis of an off-grid photovoltaic natural gas power system for a university in 2011 3rd International Symposium & Exhibition in Sustainable Energy & Environment (ISESEE) pp 129–135
[4] Abas N, Kalair A, and Khan N 2015 Review of fossil fuels and future energy technologies Futures 69 pp 31–49
[5] Fout T et al. 2015 Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3 Natl. Energy Technol. Lab. vol 1a doi: DOE/NETL-2010/1397
[6] British Petroleum Report 2018 67th edition Contents is one of the most widely respected Stat. Rev. World Energy pp 40
[7] Direktorat Jenderal Minyak dan Gas Bumi 2018 Laporan Tahunan Capaian Pembangunan 2018 Kementeri. Energi dan Sumber Daya Miner pp 43 [Online]. Available: https://migas.esdm.go.id/uploads/uploads/files/laporan-tahunan/Laptah-Migas-2018---FINAL.pdf
[8] Direktorat Jenderal Minyak dan Gas Bumi 2018 Neraca Gas Bumi Indonesia 2018-2027 Kementeran Energi dan Sumber Daya Mineral
[9] Azman P A, Fawzi M, Ismail M M, and Osman S A 2017 One dimensional modeling of a diesel-CNG dual fuel engine AIP Conf. Proc. 1831 020036
[10] World Bank Group 2017 Solar Resource and Photovoltaic Potential of Indonesia no. May
[11] Vladimir L, Notton G, Zarkov Z, and Bochev I 2005 Hybrid Power Systems with Renewable Energy Sources – Types, Structures, Trends for Research and Development ELMA
[12] Suchitra D 2013 Optimization of a PV-diesel hybrid stand-alone system using multi-objective genetic algorithm Emerg. Res. Manag. &technology 2 pp 68–76
[13] Mobley R K 2000 Fluid Power Dynamics (Amsterdam: Elsevier Science)
[14] Masters G M 2004 Renewable and Efficient Electric Power Systems (US: John Wiley & Sons)
[15] Darusalam R, Pramana R I, and Rajani A 2017 Experimental investigation of serial parallel and total-cross-tied configuration photovoltaic under partial shading conditions in 2017 International Conference on Sustainable Energy Engineering and Application (ICSEEA) pp 140–144 doi: 10.1109/ICSEEA.2017.8267699
[16] Bimantoro H, Ardita I M, Jufri F H, and Husnayain F 2019 Optimization of Rooftop Area on Building K Faculty of Engineering Universitas Indonesia for Grid-Connected PV IOP Conf. Ser. Earth Environ. Sci. 353 012005
[17] Kumarankandath A, Singh S D, and Singh M 2017 A Case for Solar Rooftop in Indonesia A centre for science and environment assessment Centre for Science and Environment [Online]. Available: https://cdn.cseindia.org/userfiles/case-for-solar-rooftop-in-indonesia.pdf

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