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Modeling and measurement of specific fuel consumption in diesel microgrids in Papua, Indonesia

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A R T I C L E   I N F O

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A B S T R A C T

Supplying electricity to populations without full access requires cost-effective, distributed sources of electricity generation. Diesel generators are a popular electricity source because of their low capital costs, but they can have high operating costs. Little data exist regarding the real-world behavior and operating costs of installed diesel microgrids. We report on the energy delivery and fuel consumption in three diesel microgrids in the Lake Sentani region of Papua, Indonesia. We found that these generators are operated below their capacity and that the fuel used per unit of electricity delivered can be over five times greater than expected based on published values. These estimations of specific fuel consumption suggest that nominally electrified areas are paying high costs for poor reliability, but cost-effective improvements are possible.

Introduction

Efforts to support the development goals of electricity access require affordable costs for sustainable operation. These efforts often require private capital in addition to available public support and funding. To attract these private-sector investments, microgrid electricity access projects must demonstrate business viability, which requires a focus on low generation costs (Williams, Jaramillo, Taneja, & Ustun, 2015) and sufficient revenue. However, many utilities in developing countries do not recover their costs (Kojima & Trimble, 2016), underscoring the need for improved financial viability. For microgrids beyond the reach of traditional grids, electricity production from diesel-powered generators is a dominant technology. Despite having a high fuel cost, diesel has a low upfront capital cost, which aids its popularity (Lazard, 2017). However, diesel-powered generators require maintenance and appropriate loads to maintain performance and keep fuel costs low.

Researchers have documented that existing diesel generators often suffer from problems related to elevated marginal costs. Schnitzer shows that these grids are underloaded with a peak load of 80 kW for a 149 kW generator and a 75 kW peak load for a 249 kW generator (Schnitzer, 2014). Casillas reports a microgrid in Nicaragua with a 45 kW peak load on a generator designed to deliver 110 kW (Casillas & Kammen, 2011). Casillas provides a simulation of a measured load on hypothetical 110 kW and 55 kW generators, showing 0.41 and 0.52 L/kWh of fuel consumption, which is well above the 0.30 L/kWh expected. It is also known that efficiency degradation can occur in diesel generators operating well below the peak load through wet-stacking and fuel polymerization (Hove & Tazvinga, 2012). These problems can lead to reduced power delivery because of generator failure or insufficient funds for diesel purchases due to higher marginal costs. These problems combine to lower the availability of electricity generation. Diesel grids struggle to operate in many places because of issues of cost and maintenance (Schnitzer, 2014). Schnitzer, who examined 36 municipalities that had microgrids with capacities ranging from 60 to 500 kW, noted that these microgrids either did not operate or operated infrequently. These systems are rarely operated 24 h a day, with some operating 12 (Casillas & Kammen, 2011) and some only 3–4 h per day (Schnitzer, 2014). Schnitzer further states that some of these grids do not operate well because of a lack of funds for fuel, underscoring the need to monitor these costs.

These prior studies modeled interventions to reduce the fuel consumption of these grids, but they lacked collected fuel data to calculate the observed costs and estimate the cost penalties of sizing and degradation. This work adds to the literature by estimating two types of fuel penalty: that of using oversized generators and that of degradation caused by oversizing. This work uses measured load data and fuel reports from three diesel microgrids in Papua, Indonesia along with a linear model of generator fuel consumption to estimate the fuel penalty on these grids. The generator fuel-use model, which is based on the specification sheets of several generators, estimates the fuel use per kWh for a generator of a given size at a given load. We estimate the fuel use of two generators: one that is currently installed in this region, in good condition, and one that is better suited to the

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observed load in the villages. We compare these two estimations and then compare them with the observed fuel use to estimate the cost penalties of sizing and degradation. This work calculates the specific fuel consumption (SFC; L/kWh) rather than the levelized cost of electricity (LCOE) to provide independence from fuel cost fluctuations. However, using a diesel fuel price of 1 USD/L, these consumption rates set a minimum levelized cost of electricity of the same magnitude. While Indonesia is a key location for studies on electrification, we find no data on microgrid performance in Papua, an area of low electrification, and this work adds to the geographic coverage of studied microgrids.

Site description

This work explores the diesel usage per unit of electricity delivered from three microgrids in the Lake Sentani region of Papua, Indonesia. Indonesia is executing a large electrification expansion to achieve universal access to electrical power (PLN, 2017). It has made significant progress in reducing the number of households without access to electricity over the past few decades. The electrification rate is over 80% in Indonesia but only 36% in Papua (Asian Development Bank, 2016). While these grids are a convenience sample, they are likely to be representative of other microgrids in (and beyond) Indonesia, and we are not aware of any published work showing the time series consumption of small-scale generators in Indonesia.

The villages included in this study have relatively dense household spacing and a modest daily electricity use of less than 1 kWh per household. These households are located in lake communities, either on islands or along a lakeshore. The households serviced by microgrids are built on stilts over water, positioned along the coastline at a center-to-center spacing of approximately 10 m. The community-run microgrids, Kensio and Atamali, are on islands that are approximately 100 m across. The Ayapo grid is run by the state utility, PLN, and is on a peninsula that extends over approximately 1500 m of coastline.

The three villages use diesel-powered electric generators to provide power in the evenings. As Table 1 shows, each of these grids is 10–17 years old and has between 20 and 100 users. We were unable to obtain the manufacturer specifications for the generators, but the rated power for each generator is shown in Table 1. The connected structures are mostly residential, along with a few businesses, and the connected loads are predominantly lights and electronics.

Two of these grids are located on islands and are operated by the community, while the third is located along the coastline of a lake and is operated by the local utility. Fig. 1 shows a typical load profile with relatively constant use in the evening and no availability in the daytime. The community-run micro-grids obtain fuel by rotating the responsibility for buying fuel among families connected to the grid. Operators keep records of the fuel volume added to the generator each night. The PLN microgrid charges a tariff of about 0.10 USD/kWh, which is consistent with the grid tariff.

Methods

We modeled and observed the fuel use per unit of electrical energy delivered (i.e., the SFC) for the three village microgrids. The metering data and fuel use observations were provided by Matt Basinger of Electric Vine Industries (EVI). We collected and cleaned

Table 1
Microgrid characteristics.

Village	Installation date	Connected households	Rated generator power (kW)
Atamali	2009	40	25
Ayapo	2000	103	40
Kensio	2007	20	35

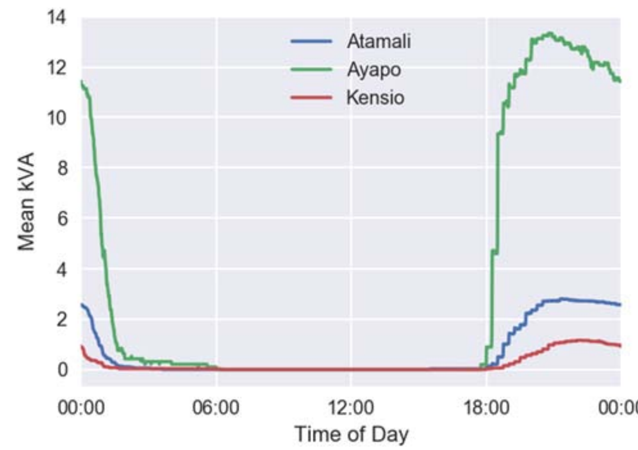

Fig. 1. The load profile shows the average nightly load of all observation days.

power and energy data using data-logging meters to determine the power and energy delivered daily by each generator. To estimate the expected fuel use of the current and potential replacement generators, we created a model of generator fuel consumption as a function of rated and delivered power based on the manufacturer specification sheets of comparable generators. We used the power observed during operation and this generator model to estimate the expected SFC for each of the three microgrids. To estimate the actual observed SFC, we used a ratio of the fuel use per day reported by the operator to the average measured energy use per day.

The energy data were compiled by EVI from late April to July 2015 as part of the company's work as a private microgrid provider in the area. The meters were placed at the main output of the generator and measured the amount of energy delivered to the village distribution system. The data logger measured power in volt-amps and accumulated energy in kilowatt-hours at one-minute intervals. Because the power factor of the household loads was close to one, we reported the power data in units of watts. The meters transmitted the measurements over a communication network to a database for storage.

We assembled a nearly complete time series record from the data loggers. There were three possibilities in terms of the data-recording process. First, the meter and generator were functioning properly, and data were stored at one-minute intervals. Second, the meter was functioning properly, the generator was dormant, and a data point was stored for the shutdown or startup of the generator. Third, the meter or communication networks were not functioning properly, and no data were recorded. We accounted for each of these possibilities as we assembled the time series of generator data.

To model fuel consumption, we used a linear relationship between the fuel rate and the delivered power and developed a statistical model of a representative generator using data from several current generator data sheets obtained from three manufacturers. This model allowed us to test hypothetical generators and establish a baseline for the existing generators for which we had no specification sheets. This linear model for the fuel consumption is used in other models of microgrid performance (Williams, Jaramillo, & Taneja, 2018).

$$F_{total} = F_{marginal} \cdot P_{load} + F_{no\ load} \quad (1)$$

In Eq. (1), F_{total} is the volume per unit time fuel consumption, F_{noload} is the fuel consumption for an unloaded generator, $F_{marginal}$ is the additional fuel consumption for each additional unit of power, and P_{load} is the power delivered by the generator. We have created