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Study of an Indirect Injection (IDI) Diesel Engine Using Pure Coconut Oil, Pure Tamanu Oil and B-20 for Smart Microgrid Applications Part II: Pilot Testing

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Novelty: This paper shows that biofuels (pure coconut oil and pure tamanu oil) can be used to replace commercial diesel fuel (B-20) for smart microgrid applications in remote areas; as was shown in the Karimunjawa Islands. This can be significant because, in accordance with the first part of this twin paper regarding laboratory testing, it was found that the engine performance of these two biofuels were nearly the same as B-20 diesel fuel, but with much lower engine emissions; in particular, pure tamanu oil. It was also shown that pure tamanu oil has 2-3% higher thermal efficiency compared to B-20 in a pilot test.

Highlights:

- Pure tamanu oil and pure coconut oil were found to have higher thermal efficiency compared to B-20 in pilot testing.

Abstract. The Smart Microgrid (SMG) can be used as a solution to overcome problems with electrical distribution on remote islets. The SMG system allows for a combination of conventional and renewable energy for power generation. Biofuel was chosen as a renewable energy source because of its abundant availability and ease of mobilization. This study examined the performance of B-20, Pure Tamanu Oil (PTO), and Pure Coconut Oil (PCO) in an IDI diesel engine that acts as a backup for SMG systems in the Karimunjawa Islands. The entire SMG system consists of: diesel engine, stabilizer, inverter, PV, batteries, ice maker, and a channel to the electrical grid. The results show that PTO has the highest value of thermal efficiency, that of 17.38%, but with a higher BSFC of 0.54 kg/kWh when compared to B-20 usage (14.69% and 0.51 kg/kWh). According to performance test results, their performance can be compared to the first part of this twin paper, which is laboratory testing, with a range of 2400-3200 W loads. Therefore, it can be said that biofuels are feasible for replacing B-20, as shown in pilot testing.

Keywords: *B-20 diesel fuel, coconut oil, smart microgrid, tamanu oil.*

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1 Introduction

There are many challenges regarding convenient access to energy for local people living in islets. Fuel and electrical distribution are examples of this. Diesel power plants as the main power source have been built on most islets in the Indonesian archipelago [1]. However, the accessibility of diesel fuel, which serves as the primary energy source for power plants, is occasionally hindered by delayed or belated shipments.

Smart Microgrid (SMG) can be used as a solution to overcome these fuel shipment problems. SMG refers to a set of loads and power sources which provide power for a designated area at a lower voltage level and which can be operated in an islanded-mode or grid-connected with a modernized network [2]. Renewable energy sources have shown potential advantages as an additional contribution to conventional power generation systems [3]. The SMG system allows for the combination of renewable energy and conventional power generation. This system is also known as the Hybrid Renewable Energy System (HRES) [3].

Many studies regarding the SMG system have been conducted in the past [4]–[10]. One such study shows that the SMG system can improve energy utilization efficiency due to its ability to control and optimize power in several interconnected power plants. Therefore, the SMG system allows for grid acceptance of different distributed generators [5]. A literature-based test [11] was conducted on an SMG prototype based on renewable energy with 1 kW solar panel and a 3 kW lister engine, using biofuels as the energy source. A comparison of diesel fuel and two kinds of biofuels, Pure Coconut Oil (PCO) and Pure Palm Oil (PPO), showed that the SMG system could work well using both diesel fuel and biofuels. Inverter efficiency for all kind of fuels averaged around 87%.

An application of the SMG system is available in the Karimunjawa Islands and is being used as an electrical supplier for an ice maker [12]. Considering that local people in Karimunjawa are fishermen, an ice maker plays an important role in their livelihood as fishermen need ice to preserve their catch, since ice keeps fish moist and prevents dehydration [13]. Other than an ice maker, the SMG system in this area is also connected to batteries and has another source of electrical energy from the PV array, electrical grid, and a diesel engine. This system has a bi-directional inverter and a monitoring system to ensure that the ice maker always has enough power to be able to operate. Since blackouts are very common in the Karimunjawa Islands, the diesel engine is used as the last power backup for the ice maker.

Past studies on the use of biofuels in SMG are available, including design simulations and prototype testing. The first part of this twin paper explained the positive laboratory test results and comparisons between the use of B-20, PTO, and PCO in an IDI diesel engine before and after endurance testing. Therefore, in this paper, a pilot test on the SMG system available in the Karimunjawa Islands was done to ascertain the results of the on-site application. There is still a lack of studies on the comparison of biofuel usage on an IDI diesel engine with an SMG system connection; therefore, this study attempts to complete those gaps.

2 Materials and Methods

2.1 Tested Fuels

Table 1 Tested fuel specifications

Parameter	Unit	Testing Result Value		
		B-20	**PTO**	**PCO**
Viscosity @25°C	cSt	2.168	34.965	40.262
Calorific Value	J/g	48,154	38,142	37,951
Density @25°C	g/cm^3	0.84	0.91	0.92
Cetane Number	CN	48 [14]	59[15]	51 [16]

The pilot test was done in Kemojan Village in the Karimunjawa Islands. This study was done using B-20, PTO, and PCO as the tested fuels. The properties of each fuel are shown in Table 1.

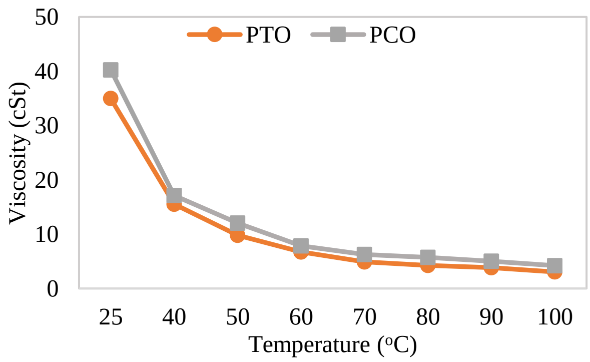


Figure 1 Pure oil viscosity versus temperature

Viscosity was affected by temperature, to prevent clogging in fuel lines it is necessary to heat PTO and PCO as shown in figure 1. The values were obtained from laboratory tests in the Physical Chemistry Laboratory, ITB.

2.2 Preheater Specification

A preheater was added to the installation of the pilot test, as was done in the first part of this twin paper, which is the laboratory test. The purpose was to reduce the viscosity of the pure biofuels by transferring heat from the exhaust gas to the biofuels. As in the first paper, the preheater used in this study was the same as the one used in a literature experiment [17]. It was made of spiral-shaped copper with a diameter of 75 mm containing15 loops. The biofuels were heated to 70-100°C to obtain the standard value as commercial fuel, which is between 2-4 cSt [14]. The working principle of the preheater is shown in Figure 2.

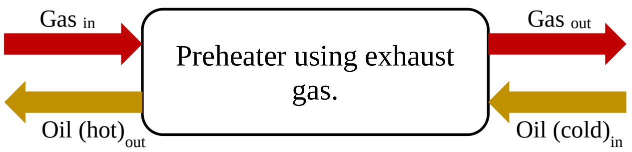


Figure 2 Preheater working principles

2.3 Engine and Generator Specification

The specifications of the engine being used in the pilot test are shown in Table 2. This engine has the same characteristics as the one used in the laboratory test in the first part of this twin paper, except for the displaced volume of the piston. This engine was also modified by adding a preheater that utilized the exhaust gas of the engines to heat the biofuels.

Table 2 Engine specifications

Parameter	Specifications
Power	16 HP
Rated speed	2200 rpm
Cylinder	1
Displaced volume	903 cc
Injection system	Indirect injection
Starting system	Electric and mechanic
Cooling system	Water cooled

The diesel engine was connected to an AC generator with a belt transmission (pulley ratio 1:1). The specifications of the generator are shown in Table 3.

Table 3 Generator specifications

Parameter	Specifications
Power	5000 VA
Voltage	220 V
Electric current	22.7 A
Frequency	50 Hz
Rated speed	1500 rpm
Phase	1

2.4 Pilot Test

The experimental scheme for the pilot test is shown in Figure 3. The rate of fuel consumption was measured by a measurement tube. The right side of Figure 4 is an SMG system consisting of stabilizer, inverter, PV, batteries, ice maker (with a load of around 2900 W), genset, and one channel to the electric grid. An additional bypass valve was used to control the amount of exhaust gas that passed through the preheater. There was a valve in every outlet of the fuel, which is the same as in the laboratory test. The diesel genset was used as a supporting electricity producer in case the other electricity producers had a problem; for example, if the PV could not provide enough electricity and the national electrical company, PLN, was out of service. An ice maker and batteries were used as the load of the diesel engine. Aside from supplying electricity to the ice maker, the diesel engine also needed to supply a minimum of 10 Ampere electricity to the batteries.

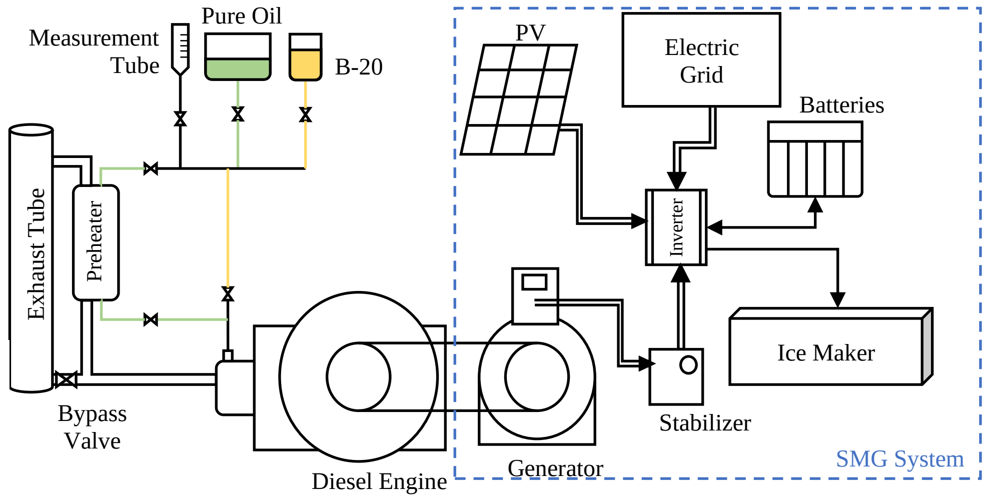


Figure 3 Pilot test scheme

For the purpose of a back-up emergency, two scenarios were done in the pilot test of each fuel testing:

1. When the battery is low because the electrical grid is off and the PV is off (night time)
2. When the battery is low because the electrical grid is off with a PV drop (usually at noon when there is not enough sunlight)

Each test was done in a six-hour interval after the inverter gave a signal for AC power to start charging the batteries with a voltage of 46 V. The first test was the the grid off-PV off with a duration of six hours, and the last test was the grid off-PV drop. Before the next type of fuel was tested, the lubricant in the diesel engine were changed .

3 Results and Discussion

Brake Specific Fuel Consumption (BSFC) is the ratio of the rate of fuel consumption to power output. BSFC results for the pilot test are shown in Figure 4. The average of each fuel test was: 0.51 kg/kWh, 0.54 kg/kWh, and 0.57 kg/kWh for B-20, PTO, and PCO, respectively. The results show that B-20 has the lowest BSFC compared to other fuels; this is in line with the laboratory test results in the first part of this twin paper, which showed that B-20 has the lowest BSFC. B-20 has the lowest average value of BSFC, which means less fuel mass is needed to produce 1 kWh; this is likely because B-20 has the highest calorific value compared to other fuels, as shown in Table 1.

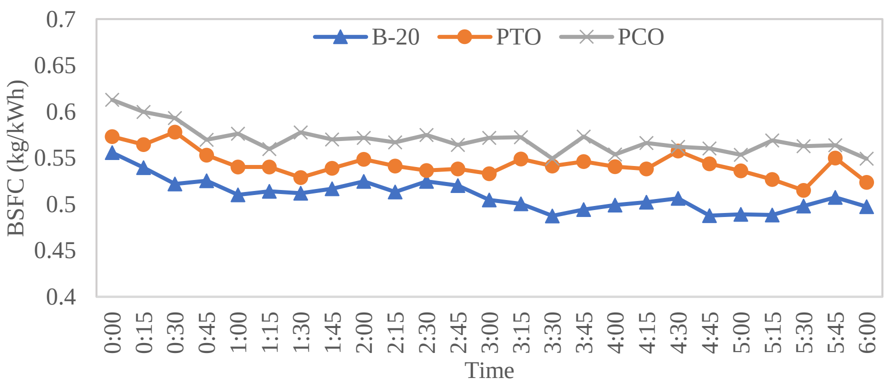


Figure 4 BSFC versus time from pilot test

From Figure 4, it can be seen that PCO has the highest BSFC value compared to other fuels, which is caused by its high viscosity value. Higher viscosity results in worse fuel atomization during fuel injection, so fuel consumption is also raised.

When PCO leaves the preheater, there is a temperature drop which causes higher viscosity, resulting in worse fuel atomization from the fuel injector to the combustion chamber. This is also proven by the deposit measurement that was done in the laboratory test; i.e., the use of PCO results in thicker deposits forming on the cylinder head and pistons. On the other hand, PTO has the second highest BSFC, which is in line with the viscosity order shown in Table 1; it is also known that PTO is second in high viscosity value. PTO has a lower BSFC compared to PCO, which is probably due to its better fuel atomization considering that it has lower viscosity compared to PCO. Better atomization results in better mixing with oxygen inside the combustion chamber.

Figure 5 shows the results of thermal efficiency for each fuel test. Thermal efficiency is the ratio between the measured brake power and the calorific value of fuel times the mass of the fuel; it is basically a parameter that shows the effectiveness of the conversion of fuel energy to useful work. The average value of B-20, PTO, and PCO are: 14.7%, 17.4%, and 16.7%, respectively. The results in the graph below show that PTO has the highest thermal efficiency compared to other fuels, which is the same as the results obtained in the experiment done in a laboratory.

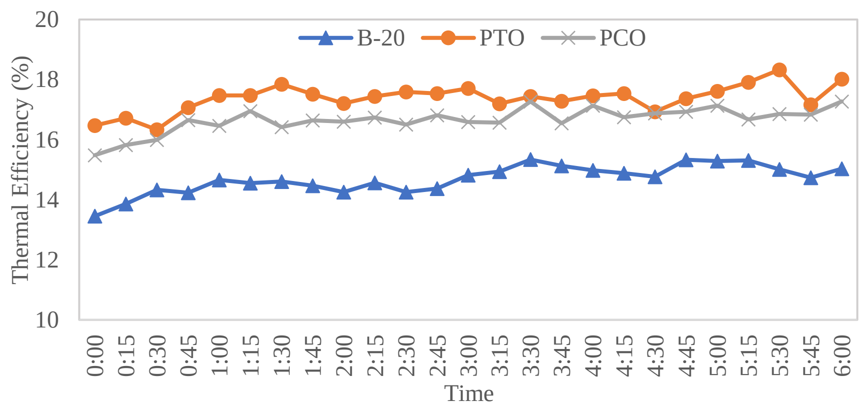


Figure 5 Thermal efficiency versus time from pilot test

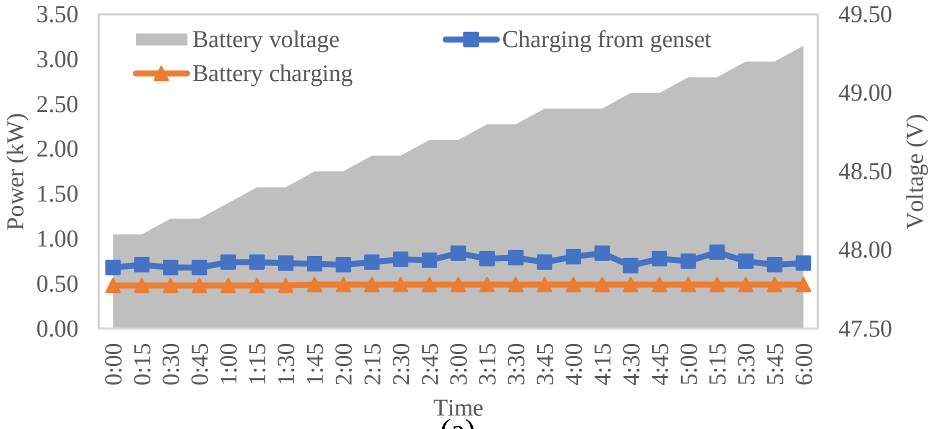
Despite its positive BSFC value, B-20 has the lowest thermal efficiency; this is because of its worse lubrication, which is shown in the first part of this twin paper. From the first paper, it is known that B-20 has the highest dimensional (fuel injector nozzle needle, and pump plunger) decrement compared to PCO and PTO usage. On the other hand, PCO, which has the highest BSFC, has a higher value of thermal efficiency compared to B-20. This could be caused by better lubrication which results from its higher viscosity, compared to B-20. However, PCO has lower thermal efficiency than PTO because its high viscosity results in bad fuel atomization in the fuel injector. PTO has the highest value of thermal efficiency due to better lubrication and higher oxygen content in the fuel, which leads to a better combustion reaction, when compared to PCO.

Figure 4 shows that the results of the pilot tests can be compared with the average results from a laboratory test with loads of 2400 W and 3200 W. This is because the ice maker load is around 2900 W. It can be seen from Table 4 that the results of the pilot test compared with the average results of the laboratory test (before endurance testing) are nearly the same. The difference between the laboratory and the pilot test results are reasonable, considering the unstable load of the ice maker and the difference in test ambients, as well as the influence of the age of the engine components.

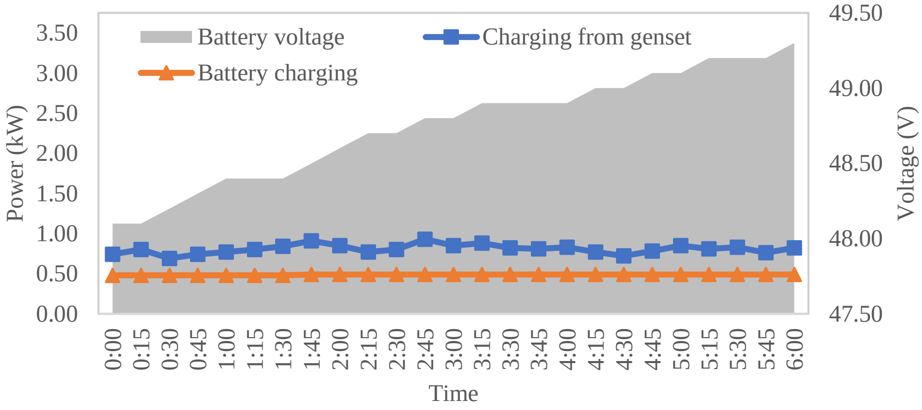
Table 4 Comparison of laboratory and pilot test results

Test	B-20		PTO		PCO	
	Thermal Eff. (%)	**BSFC (kg/kWh)**	**Thermal Eff. (%)**	**BSFC (kg/kWh)**	**Thermal Eff. (%)**	**BSFC (kg/kWh)**
Laboratory Test*	14.15	0.53	17.64	0.54	13.56	0.71
Pilot Test	14.69	0.51	17.38	0.54	16.66	0.57

*Average of data result with loads of 2400 W until 3200 W before endurance test



(a)



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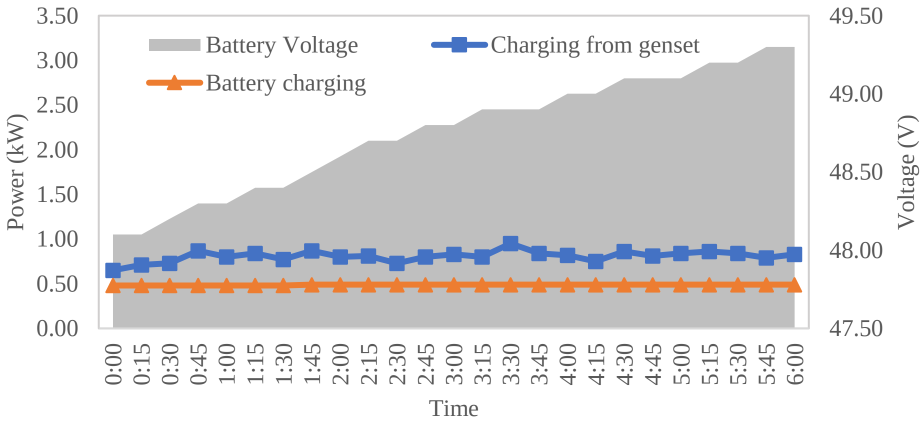
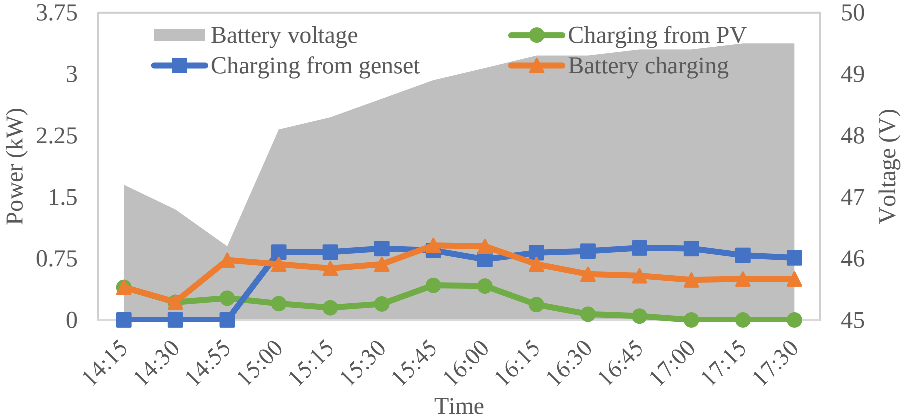


(c)

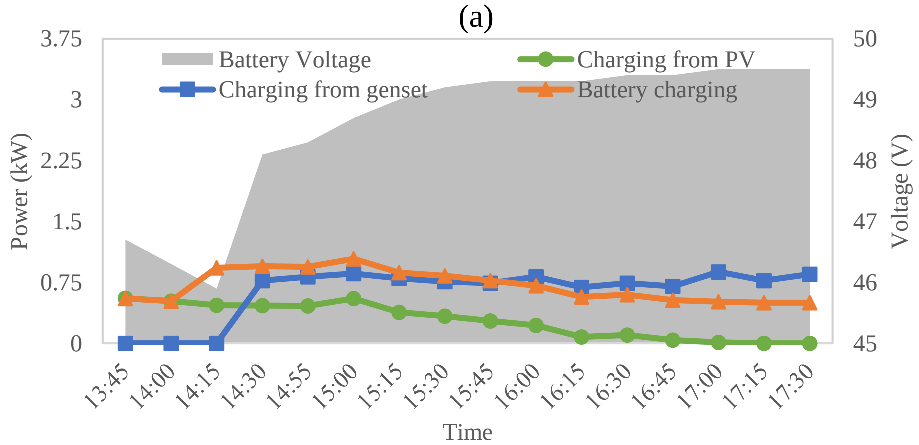
Figure 6 Generated power versus time and voltage using (a) B-20, (b) PTO, and (c) PCO, with scenarios of grid-off and PV-off

Figure 6 shows a graph of battery power charging using genset in each tested fuel with the grid-off PV-off scenario. This scenario was assumed to occur at night when blackouts happen; battery voltage then reaches the minimum level, and batteries should be recharged. Under these circumstances, genset was used as a backup power generator to maintain the stability of the ice maker power input and also recharge the batteries at the same time. It can be seen from Figure 6 that the input power from genset is not very stable due to the fluctuating condition of the ice maker; however, battery charging remained stable because it is regulated by the inverter. Each tested fuel shows that the graph of power input from the genset has a similar pattern. This shows, therefore, that in a pilot testing, PTO and PCO were capable of replacing B-20 in maintaining charging stability.

Figure 7 shows a battery power charging using genset with grid off-PV drop scenario. This scenario was assumed to occur during the day when battery voltage is at a minimum level; and that the electric grid is off at the same time because of a blackout. Power generation from PV dropped because the sun's radiation was not optimum due to bad weather. Thus, battery voltage reached its minimum level as the power input from PV decreased, so the generator started to turn on as a backup power for battery charging. It can be seen from each of the graphs in Figure 7, that the lines of "charging from genset" show the same pattern. Hence, it can be said that PTO and PCO have the same capabilities as B-20 in terms of power fulfillment for the SMG system.



(a)



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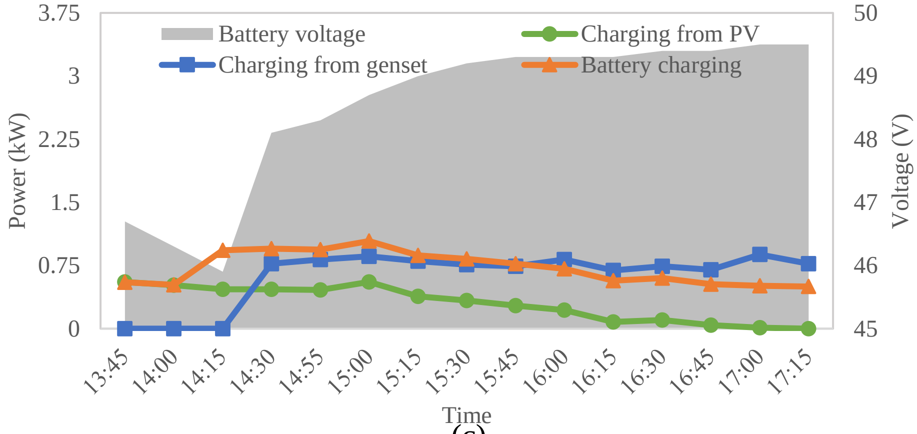

(c)

Figure 7 Generated power versus time and voltage using (a) B-20, (b) PTO, and (c) PCO, using a scenario of grid-off and PV-drop at noon

4 Conclusions

The SMG system allows for the combination of conventional and renewable energy for power generation. B-20, PTO, and PCO were tested on an IDI diesel engine with SMG system integration. Engine performance tests were conducted in the Karimunjawa Islands for a duration of six hours.

The pilot test results show that PCO has the highest value (with an average of 0.57 kg/kWh) of BSFC compared to the other fuels; this is because PCO has the highest viscosity. A decrease in temperature when PCO exits the preheater causes higher viscosity, resulting in worse fuel atomization from the fuel injector to the combustion chamber. B-20 also has the lowest value (0.51 kg/kWh on average) of BSFC; this is the same result as that of the laboratory test in the first part of this twin paper.

The results of thermal efficiency are different from the BSFC. PTO showed the highest average yield (17.4%) compared to other biofuels tested, which is the same as the results of the laboratory test. In contrast with BSFC, B-20 has the lowest average yield (14.7%) of thermal efficiency; this is because of bad lubrication; this is similar to the results obtained in the first part of this twin paper.

According to the data derived from the pilot testing, it can be seen that, overall, PTO and PCO engine performance with SMG connection has positive results; therefore, it can be concluded that PTO and PCO can be used as alternative energy providers for the SMG system, as shown in the Karimunjawa Islands.

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Nomenclature

BSFC	=	Brake Specific Fuel Consumption
CO_2	=	Carbon dioxide
CO	=	Carbon monoxide
NOx	=	Nitrogen oxides
PCO	=	Pure Coconut Oil
PPO	=	Pure Palm Oil
PTO	=	Pure Tamanu Oil

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