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A study on Agro-Hybrid Farm Vehicle with Small Onboard Solar Photovoltaic for Herbicide Spraying in Oil Palm Plantation

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Mohd Azwan Mohd Bakri[1,*], J. Salmah[1], S. Abd Rahim[1], K. Norman[1]

[1] Malaysian Palm Oil Board (MPOB), 6, Persiaran Institusi, Bandar Baru Bangi, 43000 Kajang, Selangor, Malaysia

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ABSTRACT

This study aims to investigate the performance of the agro-hybrid system incorporated in a utility farm vehicle for herbicide spraying in oil palm plantation operation. The novelty of the study lies in the proposed system and also methods to assess its performance. The study started with a simulation method using HOMER software after significant consideration of the prototype design, energy generation and utilisation has been identified. The result indicates that the energy requirement for herbicide spraying can be met by the system for the entire day operation without a capacity shortage. Thus, laboratory and infield test were implemented. The test provides excellent results in term of farm productivity, and the system could maintain the battery state of charge condition within an optimum level. Even though the contribution of the renewable energy source is small, but the incorporation of the hybrid power structure and photovoltaic eliminate the requirement of additional fossil fuel power. Thus, a cleaner energy system for oil palm mechanisation could improve the sustainability of oil palm plantation operation in Malaysia.

Keywords:
Hybrid power; farm mechanisation; renewable energy

1. Introduction

In general, a hybrid power system is pursued to improve reliability, speed or torque control and energy efficiency [1]. Although it is misinterpreted as a dual powertrain concept only, the hybridisation of the farm vehicle is also considering to power the implements [2,3]. Figure 1 depicts the applications of the farm hybrid technologies either for engine auxiliaries, traction drive, electric drive or implements electrification that surrounded by four main hybrid components. Thus, it implies that the hybrid power concept is almost similar to the hybrid vehicle but differed on its final intended

* *Corresponding author.*
E-mail address: azwan.bakri@mpob.gov.my (Mohd Azwan Mohd Bakri)

requirement. The main benefits of electric power farm implement are controllability and efficiency [3,4].

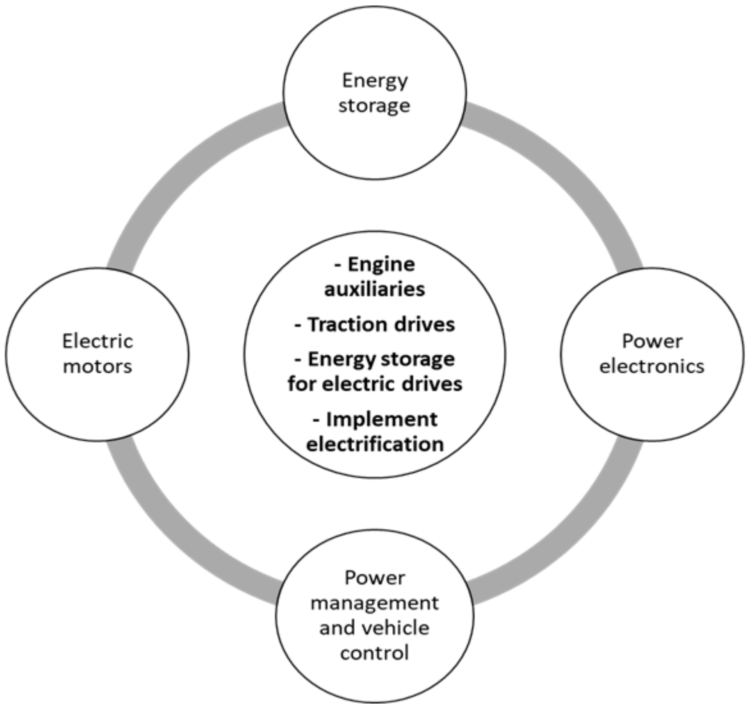


Fig. 1. Technology of hybrid farm vehicle that surrounds the potential applications [2]

One of the farm vehicle hybrid concept available is an agro-hybrid system. The system was introduced and demonstrated by Karner *et al.*, [3] on the fertiliser spreader attached to a tractor. The hybridisation structure was applied either on the chain speed drive or spreader disc or at the spreader drum itself. There are three types of agro-hybrid, which are parallel, mix and serial. They had found that serial agro-hybrid system was more flexible for the application in term of controllability and dynamic load compensation that could provide benefit in term of saving to the agriculture input or the fertiliser. The structure of serial agro-hybrid is by powering electric farm implements directly from a battery that recharge from the engine power itself. The system reduces additional energy requirement either from secondary engine or tractor's power take-off (PTO) to power the implement. Besides those advantages, the hybrid power system could incorporate a renewable energy source.
Electrification of the farm implements would also ensure less wastage to the farm input and provides significant productivity. A farm utility vehicle with sufficient power generation capability could embrace the advantages of the system. Thus, the sustainability of agriculture production, in general, is improving by balancing its input-output energy and decreasing its energy intensity [5].

Palm oil industry in Malaysia has always emphasised sustainability in its operation [6]. A study conducted in oil palm plantation operations revealed that the energy use efficiency of 62% was obtained based on the energy input to output ratio [7]. The study also found that diesel fuel consumption and machinery for mechanised operation contributed up to 12% of the energy input. The study also suggested that particular mechanisation practice should incorporate efficient energy technology in the process, especially for the low energy consumption activity such as herbicide spraying.

The current widely adopted practice of spraying activity is utilising knapsack sprayer [8]. This practice required regular refill and much idle time required for refilling. Furthermore, workers have to carry heavy knapsack on their back hence limit their walking distance. Thus, it reduces workers' productivity and field capacity for the activity. This situation can be improved by utilising farm machinery that attached to spraying equipment [9,10]

Several farm vehicles with spraying system technology have been adopted by the Malaysian oil palm plantation industry, as depicted in Figure 2. The machines are using secondary internal combustion engines for the operation and required more than two workers to conduct the activity [9]. Even though the system employed was successful in carrying out the duty based on their expectation, but absolute improvement could be made to improve the effectiveness of mechanised spraying system. Furthermore, advanced technology might reduce the total workers required and could also reduce chemical used to the targeted areas. It was reported that the 3-wheel type sprayer could effectively spray more than 9 ha per day with the diesel fuel used of 4 L/day for the vehicle transmission and the petrol fuel used of about 2 L/day for the water pump engine [10,11].

Fig. 2. A conventional 3-wheel type vehicle used in oil palm plantations for weedicide operation

Besides the utility type vehicle for herbicide spraying, oil palm plantation industries also employed tractor sprayer, shown in Figure 3. The sensor-based spraying system employed ultrasonic sensor and other auxiliaries as the detector to trigger the spraying mechanism. Once the ultrasonic sensor sensed the palm, it will trigger the solenoid valve that controls the herbicide sprayed. The technology is beneficial for flat topography area only, and it could achieve up to 40 ha per day with a single operator [11]. However, the system is expensive and could cost up to RM 50,000 for the automatic detection and spraying system only. Thus, an effective method to produce the desired solution for mechanised herbicide spraying operation in the field, especially for the undulating and hilly area is required.

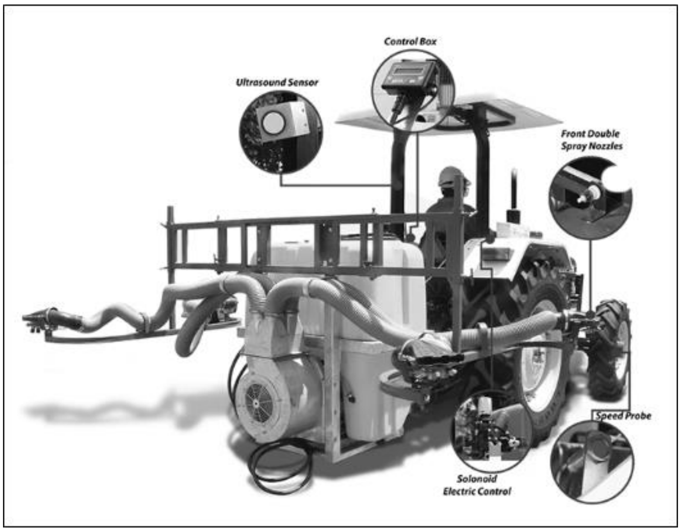


Fig. 3. A tractor sensor-based spraying system

Farm vehicle with capability such as the agro-hybrid system is one of the solutions towards adopting the electric power spray in a large plantation area and provides more effective results as compared by using mechanical control. Adopting hybrid power technology for particular oil palm plantation operation could provide advantages such as higher field coverage, improve the functionality of work, reduce fuel consumption and a few others [12]. Besides, an agro-hybrid farm vehicle could also incorporate renewable energy source to recharge the battery. The method allows the system to be more versatile and robust [13].

Solar energy technology onboard a farm vehicle in Malaysia can provide at least 25% of the energy to power an agriculture electric vehicle [14] for an oil palm plantation operation since Malaysia received about 4,000 to 5,000 W/m2 average solar radiation, with the average sunshine duration in between 4 to 8 hours a day [15]. However, for direct solar photovoltaic application onboard, only 20% to 35% energy from the sun penetrated the palm canopies, or a broadleaf tree in Malaysia can be captured [16]. Thus, making solar energy as the primary provider of the power is not adequate for oil palm mechanisation activity. Even though palm biofuel could be incorporated in the system, but a study indicated that renewable fuel has higher environmental impacts for the categories of acidification, eutrophication and photochemical oxidation [17].

A realistic approach is required to provide a solution in making the oil palm mechanisation more sustainable. The agro-hybrid concept is needed to be adopted into the farm vehicle system so that greater efficiency can be realised such as in the particular farm operation likes herbicide spraying to the targeted area. The fossil fuel engine could generate energy to recharge the battery and also the leading power for a vehicle transmission. The solar photovoltaic might support the battery charging at a specific condition such as during the rest time. Besides, the losses due to power conversion in mechanical and hydraulic drives are also eliminated [18].

This paper is aim to investigate the performance of the serial agro-hybrid system installed on a three-wheeled farm utility vehicle for herbicide spraying in oil palm plantation operation. The concept of three-wheeled farm vehicle with an energy-efficient component like belted continues variable transmission was fabricated and tested to assess its capability. The hybrid power system structure is expected to increase farm work productivity and improve energy application. The novelty of the research is not only on the proposed set up but also on the methodology used by incorporating simulation study from HOMER software to investigate the performance of the integration system.

2. Methodology

Integration of Agro-Hybrid System and HOMER Analysis

A three-wheeled utility farm vehicle was fabricated to assemble the proposed system in which including a belted continuous variable transmission, an air-cooled diesel engine with rectifier generator and electric starter, a solar PV system and as well as other electronic auxiliaries as depicted in

Fig. 1, in which also resembles the serial agro-hybrid structure. A seven-horsepower air-cooled diesel engine with electric starter and rectifier generator was selected since the power is adequate to cater for a proposed gross load of 300 kg based on the free force analysis [14]. The chassis of three-wheeled utility vehicle was selected since the vehicle concept is widely used in Malaysian oil palm plantation operation [19] and provide low cost of development. Another factor to consider the development of new farm utility vehicle chassis in this study was its weight consideration since the performance of the vehicle also depends on the engine capacity and its gross weight. Thus, a new chassis was developed and fabricated in considering those factors.

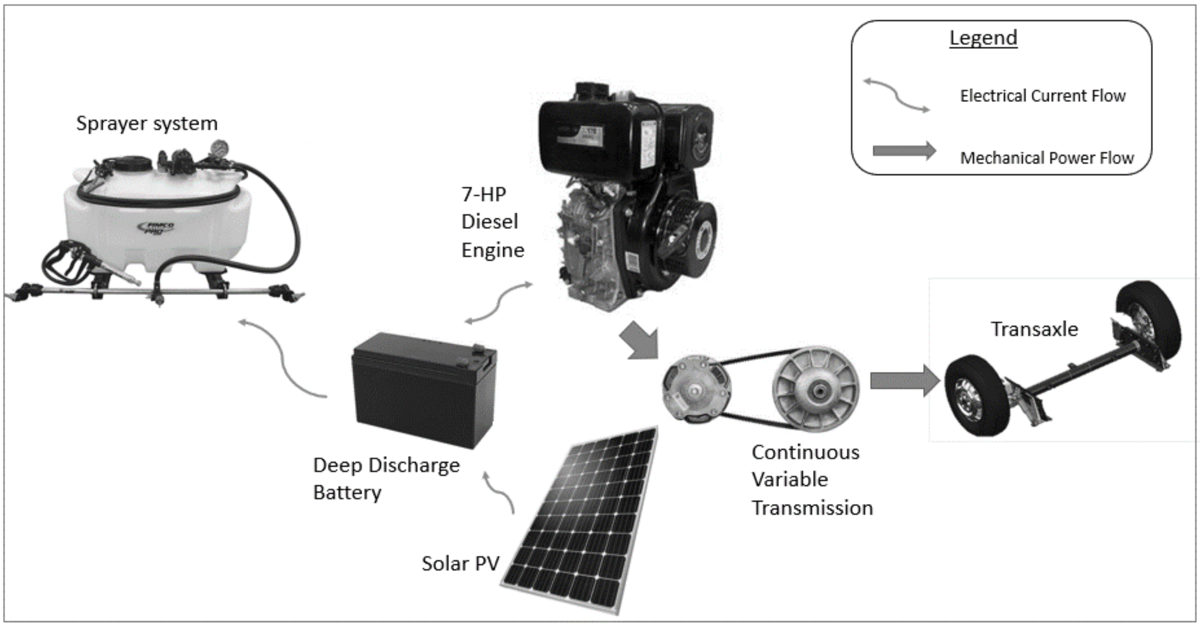


Fig. 1. Flow diagram of the proposed system

The herbicide spraying was considered in this study since the application could utilise electric farm implement such as the battery-powered sprayer. The system installed consists of a 12V-dc pump, a 180 L water tank, nozzles and also its auxiliaries. The system can spray both sides of the vehicle. Thus, either two water pumps or two electric water solenoid valves with one electric pump were considered in the trial as depicted in

Fig. 2.

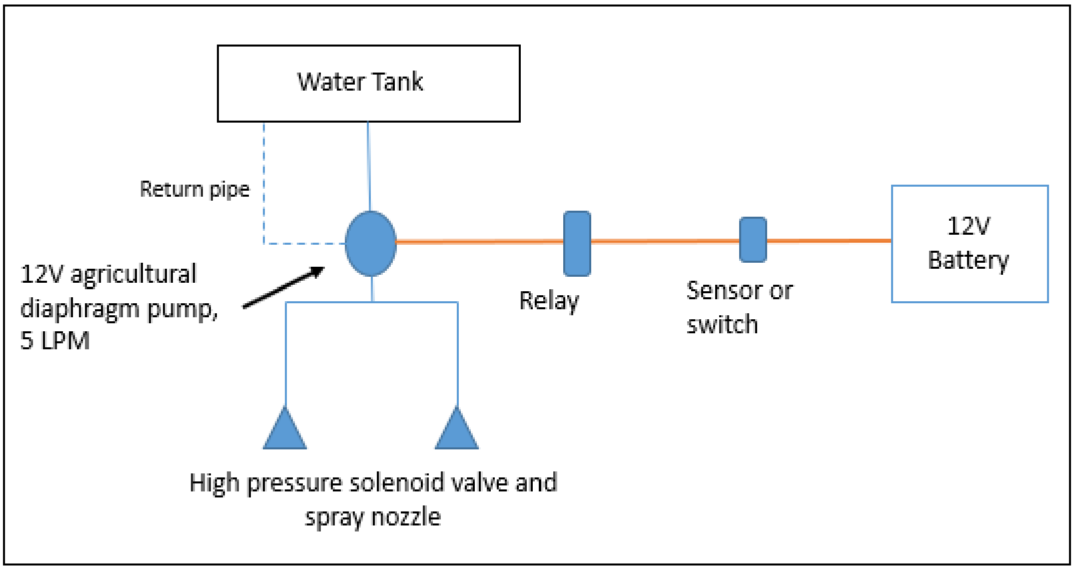


Fig. 2. Schematic diagram of the proposed spraying system

The system offered two power sources to charge a deep discharge battery. The rectifier generator is the primary charger. Meanwhile, the solar PV is the opportunity charging and its produce much lesser power as compared to the rectifier charger. If the dual power sources are similar in power capacity, each of the chargers striving to bring battery beyond its level and subsequently destroying the battery or any of the system. Thus, opportunity charging is just an effective method to improve the energy generation for this agro-hybrid system. However, a study on energy requirement is essential to determine the solar PV sizing.

An analysis by using HOMER software was carried out to determine the solar PV sizing based on particular input and assumption. The HOMER is a software produced by National Renewable Energy Laboratory (NREL) as a tool to analyse and optimise energy system [14]. The power requirement for the proposed system set up, as mentioned previously, was mainly for vehicle start-up and to provide the power for the battery-operated spraying system. Power requirement for the spraying system is about 100 Watt as the pump nominates the considerable percentage of the consumption. About 20 A power required for cranking purposes but the use is only on instantaneous second and suggested to ignore for this simulation since actual energy consumed for this particular application was hard to predict and it was only consumed a few times a day.

The input data illustrated in Fig. **3.** Load Profile as HOMER input, where the system was assumed to run for four working-hours in the field and only stopped for two hours in mid-day before resuming the work until late afternoon or another three working hours. Even though the actual spraying time taken was only 45 minutes for 180 L water as investigated, the assumption would at least consider the worst-case scenario. Meanwhile,

Fig. 4 depicts the overall set up of the proposed analysis. A DC-bus provides 12V system configuration where solar and generator are the power sources and back up by the battery to provide a load for spraying system. However, both power sources also required to recharge the battery by the excess power available.

In the HOMER, the energy was also investigated based on the baseline data. In this analysis, solar power was referred from a previous study conducted on the integration of solar photovoltaic onboard an electric vehicle in oil palm plantation operation [14].

Fig. **5** depicts the solar energy resource availability based on sky clearness index and daily radiation. Information on the diesel engine generator was only on the timing of the generator which replicated the working time of the vehicle, and another input was the sizing of the generator. The HOMER analysis was conducted based on the suitable photovoltaic size that able to install on the vehicle without interfering any other system involve onboard.

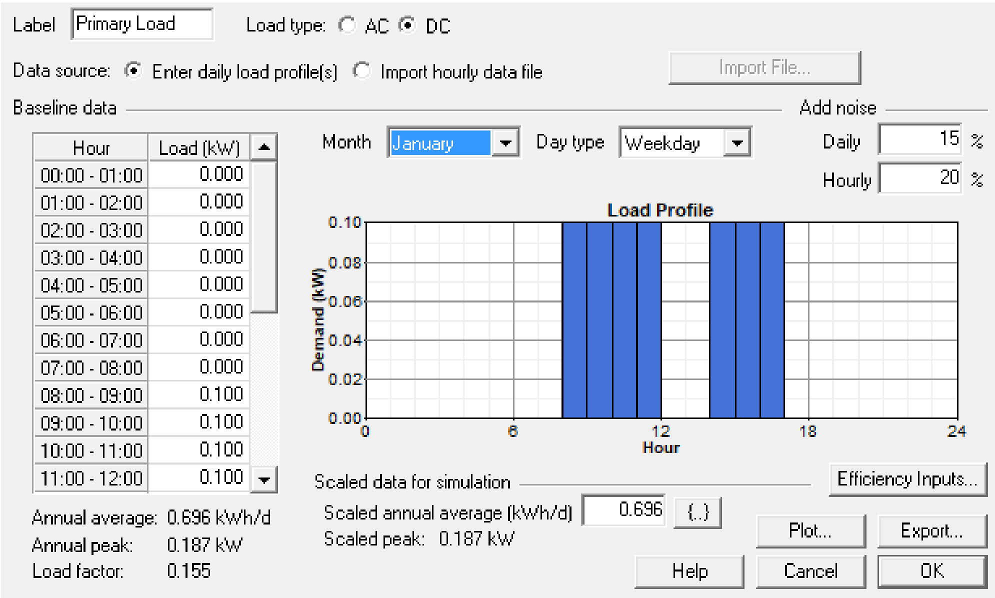


Fig. 3. Load Profile as HOMER input

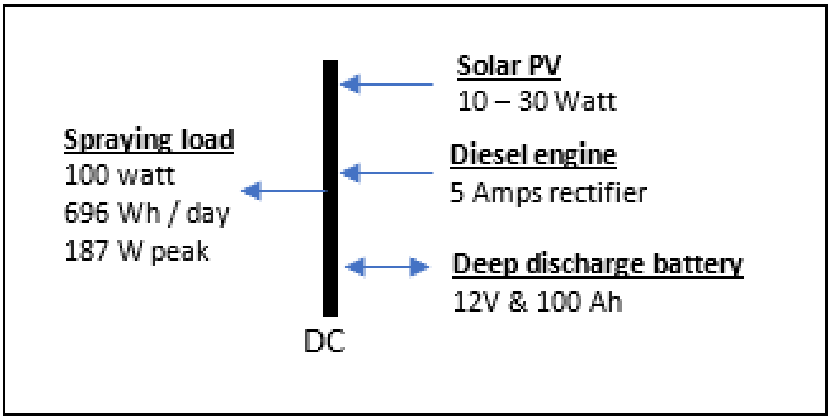
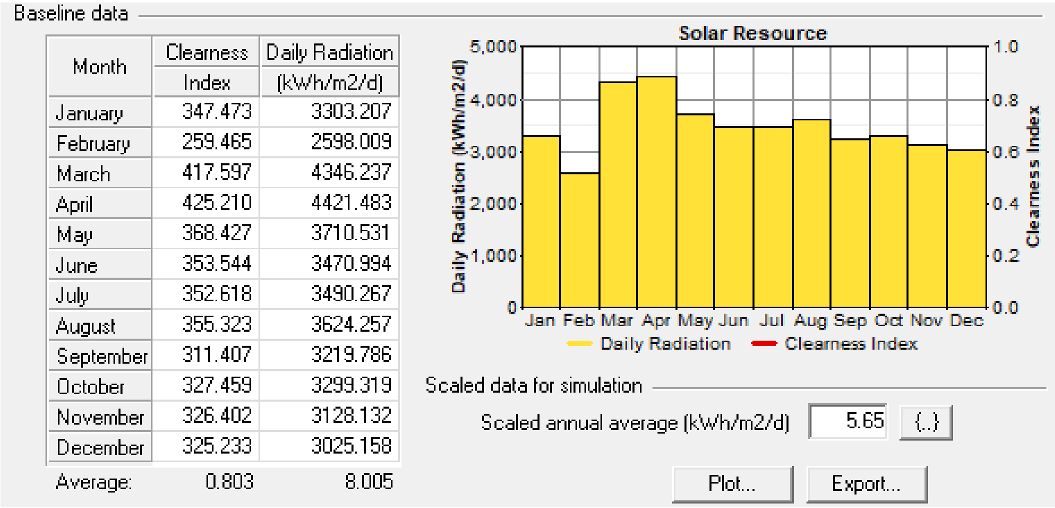


Fig. 4. Configuration of the proposed analysis



Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	347.473	3303.207
February	259.465	2598.009
March	417.597	4346.237
April	425.210	4421.483
May	368.427	3710.531
June	353.544	3470.994
July	352.618	3490.267
August	355.323	3624.257
September	311.407	3219.786
October	327.459	3299.319
November	326.402	3128.132
December	325.233	3025.158
Average:	0.803	8.005

Fig. 5. Solar radiation and sky clearness input

Performance Evaluation

For the second part of this study, laboratory and field test were conducted to evaluate the performance of the overall system. The prototype was also investigated based on the actual field data performed by farmworkers and in the real scenarios. Some of the findings also gathered through observation on the field trial. An undulating area of oil palm plantation with an area allocated for the test was about 100 ha.

Besides, several laboratory analyses carried out to determine a few indices such as generator charging characteristic and the energy consumption for the application. It was not conducted on-site since the measurement equipment could not adhere to rough travel condition in the field. A voltage divider, current sensor, hall effect sensors and Arduino microprocessor are the main components used as part of the measurement equipment.

3. Result and Discussion

Simulation and Prototype Development

Space for support structure was identified as significant constraints for the solar photovoltaic installation in a current three-wheeled type utility vehicle. Anticipates that only 50 -70 W of power required for the sprayer and its auxiliaries. Thus, smaller photovoltaic capacity is adequate to support the 60 W onboard generator. The HOMER had analysed the scenario based on input data mentioned in the previous section, and provides an indication on the energy consumption and generation for the spraying activity; either the energy is adequate for the whole period of time. The result of the simulation as in Fig. 6. The HOMER simulation found that the excess electricity generated was about 3%, with small renewable fraction and without capacity shortage. The result indicating that only small size solar PV was adequate to support the application discussed even though it was expected earlier that the power consumption was 100 W.

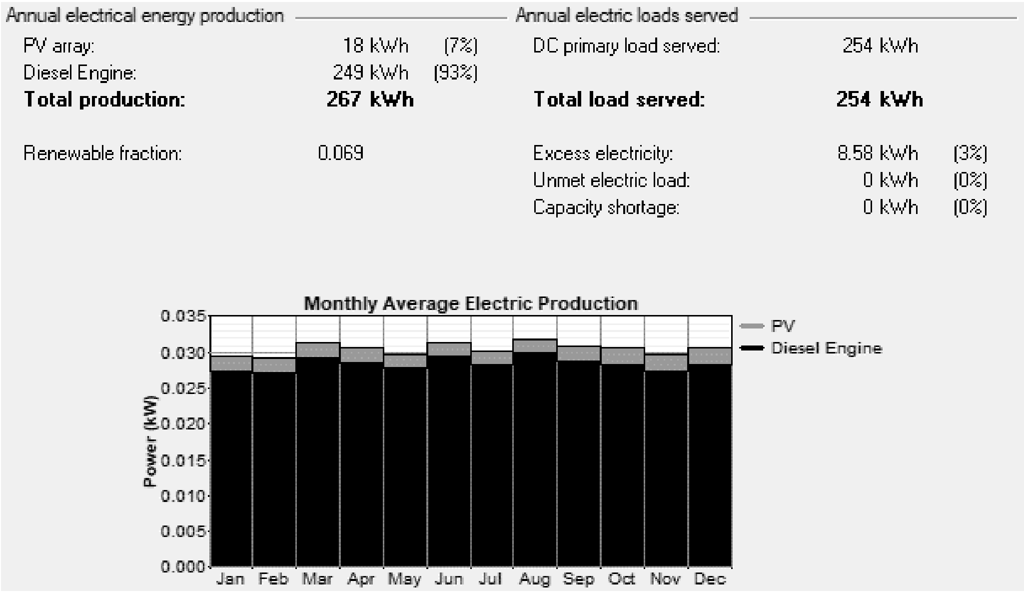


Fig. 6. HOMER analysis result of the rectifier generator and 10 W solar panel for the agro-hybrid application

Besides the energy production and utilisation, HOMER also can analyse the battery state of charge (SoC) condition. Thus, it could predict the power consumption of the system to recharge the battery and indicates its performance. Fig. 7 states simulation results indicating the battery state of charge condition is within 80% to almost full related to power consumption (DC load) and power produce (rectifier generator) in day to day operation. The result was preferable since the battery will not discharge too deep in order to ensure its life extended or within its economic life [20].

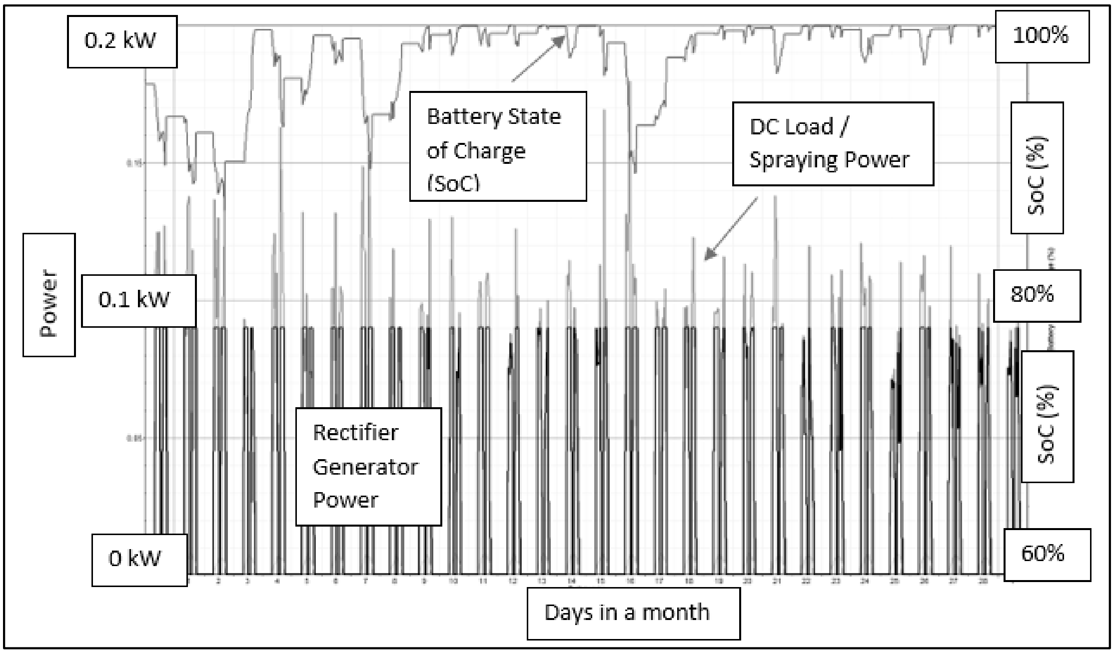


Fig. 7. Result of detail HOMER analysis on the system

The results above were significant in selecting the PV sizing since it also determines the area for installation of support structure requires, in which related to the PV weight.

Fig. 8 shows the CAD drawing of the prototype of the vehicle and location of the main components. The solar photovoltaic selected was 320mm x 290mm x 17mm in dimension and perfectly placed at the handlebar, supported with light structure since it only 1kg weight. It was placed horizontally with an inclined angle of about 20 degrees. Thus, it will able to capture solar radiation effectively if the vehicle park towards south-facing [7].

Fig. 8. A prototype of a three-wheel utility type machine for the study

Assessment on the power consumption and requirement

The hybrid power system was selected onboard the vehicle to provides adequate electrical power for the planned farm activity as justified in the previous section. Several investigations were made to provide scientific justification of the energy generation and consumption related to the 12 V electrical system. As mentioned, the overall electrical configuration indicates that the engine generator rectifier recharges the battery and supported by a solar panel. In total, almost 70 Watts power is available to charge the battery, as shown in **Error! Reference source not found.**. A small power solar panel is used since more substantial solar PV power of more than 50 W could damage the rectifier or its diode since the system is in parallel connection. The condition observed when similar size rectifier generators were installed in parallel to charge a battery, and either one of the rectifier diodes will destroy once the connection was triggered.

Table 1
Expected power produce to charge the battery

	Generator	Solar Panel
Maximum Current Flow	5 Amp	1.2 Amp
Power	60 Watt	10 Watt

The power from the rectifier generator is also can be used directly by the DC pump during the fieldwork, but any load variation produce in term of power consumption can only be supported by the battery. Thus, during the spraying, the electrical power is used by the DC pump, and the battery charging process takes place when the pump is shut off. This control strategy method was also used to predict the energy requirement for solar photovoltaic-based air conditioning system, and it was reported a successful demonstration of the study [21].

Energy for the pump was investigated by using the power meter logger. The result is depicted in Fig. 9. It was found that a constant power of about 50 Watt for a spraying rate of 2.3 L/min was consumed. Thus, the 60 watts rectifier generator alone is adequate to provide energy and to charge the battery. However, it was also learnt that, if other methods of spraying such as stripped and circle are used, then the power consumptions are increased. Therefore, it is necessary to incorporate solar photovoltaic in order to support higher power requirement. Anticipate that power generated from the solar PV and rectifier are adequate to power up to 200 watts if the application is not continuously running. Furthermore, during the lunch break hours, the system is still can generate energy from the solar PV if the vehicle is parked in an open area and produces numerous benefits [22].

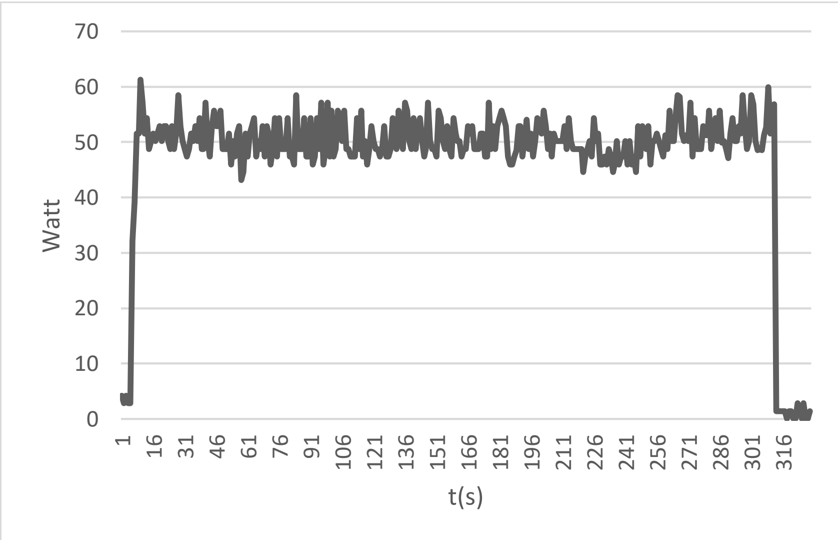


Fig. 9. Power consumption of the electric pump at the flow rate of 2.3 l/m

In term of energy generated from the rectifier generator, it is directly proportional to the ground speed of the vehicle as investigated. A power logger has been connected to the battery terminals, and the reading was logged based on various engine's RPM (revolution per minute) obtained from an RPM meter. It was found that the power produced while RPM is in between 1300 – 1500 and it is peaking at 1600 to 1700 RPM. The system will cut off power at 1800 RPM as in Fig. 10. The 1800 RPM reflected the ground speed of almost 10 km/h. The behaviour implies that the energy is not generated by the system while at high speed, especially travelling at the smooth road. Thus, additional power supported, such as from the solar PV, is an added advantage to charge the battery. The system will later be improved by incorporating added value such as vehicle to grid and better vehicle automation system [23].

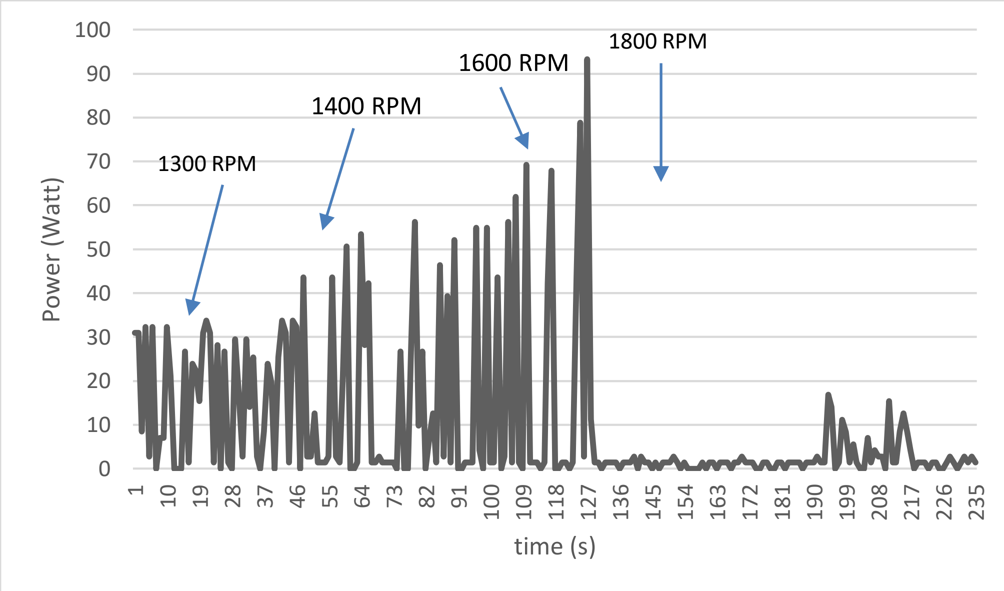


Fig. 10. Power at various engine speed

Even though solar PV could support the charging process, but the solar radiation was limited under the palm canopy. Thus, an investigation was carried out to determine the energy ratio in between open area to the under the canopy. The situation might be similar to PV partial shading effect, where mismatch might occur to interconnected PV modules [24]. The 10 W PV panel connected to a current meter and logged directly to a computer was set up. The investigation was carried out at noon, and the PV placed horizontally. The vehicle was run at a constant speed and passing through two harvesting paths. Between two paths and both ends of the paths was the open area, where the PV can capture maximum possible energy. The data logged as in Fig. 11, indicates two sets of information, under partial shading condition (below palm canopy) and no shading condition (open space area). Based on that information, an analysis was conducted for comparison.

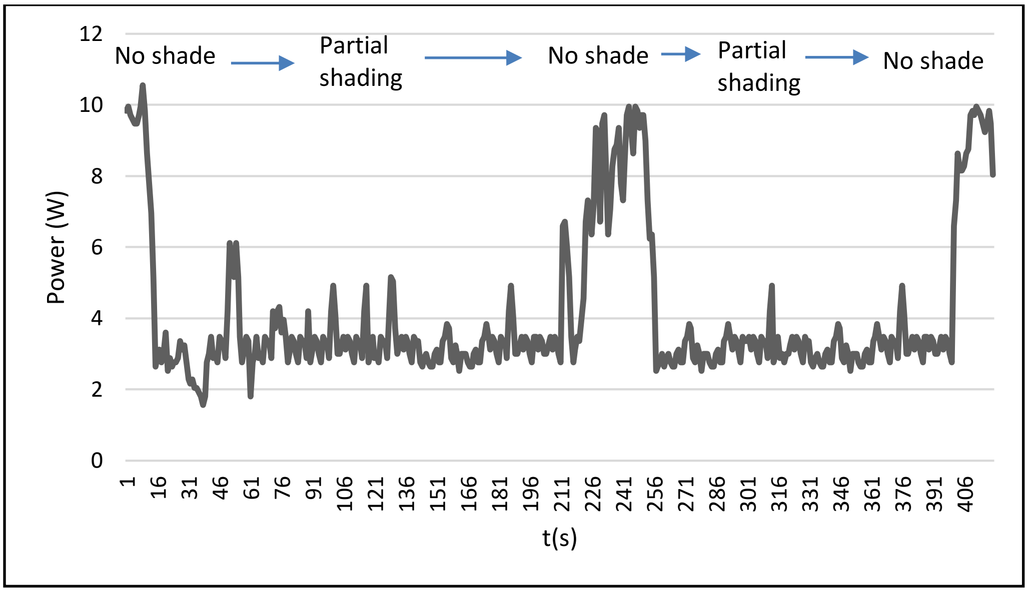


Fig. 11. Current vs time of the logged data

Result of the analysis as in **Error! Reference source not found.** indicates that about 36% difference of the maximum power received between those two conditions and with 70% difference in minimum value. Even though the average difference is about 63% but the comparison should consider maximum value only because the minimum value for open space reading might be unnecessary since no obstruction occurred, except that the cloud condition [25]. Therefore, 36% difference of solar irradiation penetration below the canopy in between partial shading and no shading is a justified situation under a broadleaf plant in Malaysia [16]. A yearly HOMER prediction of the solar energy captured by the 10 W solar PV system installed onboard the vehicle as in Fig. 6. The current result obtained has strengthened the previous argument.

Table 2
Difference of partial shading and no shading condition

	Partial Shading	No shading	Diff.
Max power (W)	6.7	10.6	36%
Min. power (W)	1.6	5.2	70%
Av. Power (W)	3.3	8.7	63%

Field Test Evaluation

A study on the prototype performance in the actual field was carried out in an actual oil palm plantation in Malaysia. The test period was about two months, from early May to the end of June. The study conducted in such a way that the prototype carried out a real task of herbicide spraying. A field contractor had been given the task by the estate’s management to utilise the prototype and fed the necessary information. The information required from the operator was the battery state of charge (SoC) and the productivity of the spraying activity.

During the test, the contractor had been given the task to clear the weeds along the mechanical path at an undulating area covering about 200 ha. Fig. 12 depicts the daily area covered with an average productivity of 8.75 ha per day per one operator.

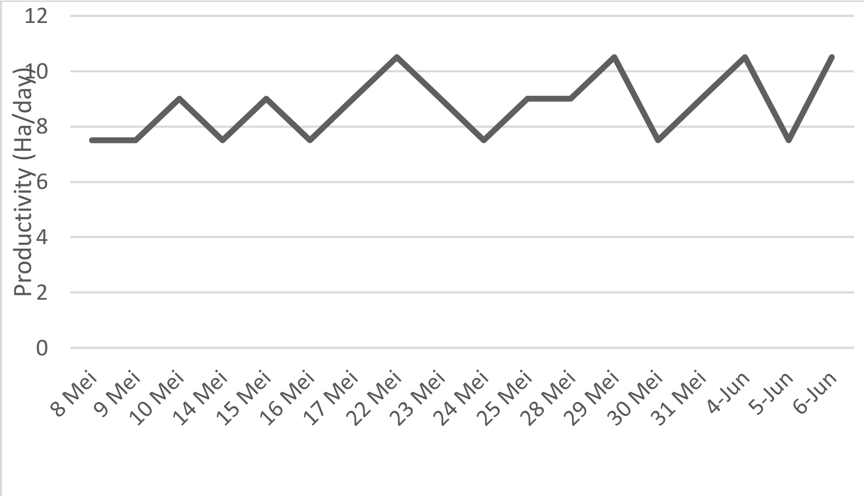


Fig. 12. Productivity of the chemical spraying activity

Performance of the battery during the field trial was monitored through the state of charge (SoC) battery meter. The operator logged the battery SOC before and after the work completed daily on the farm. The battery condition was monitored manually because unavailable networking facility to captured the data. Fig. 13 illustrates daily SoC reading during the actual field test. The data analysis as in

Fig. 14 indicates that the means different in between SoC start and finish was only 10% and it is consistent with the HOMER simulation result as in Fig. 7, where battery SoC usually felt up to only 15% of its original state. The condition will ensure longer battery life or less damaging to battery health [26,27]. The hybrid power system enables the battery to be charged even when the machine is idle or parked.

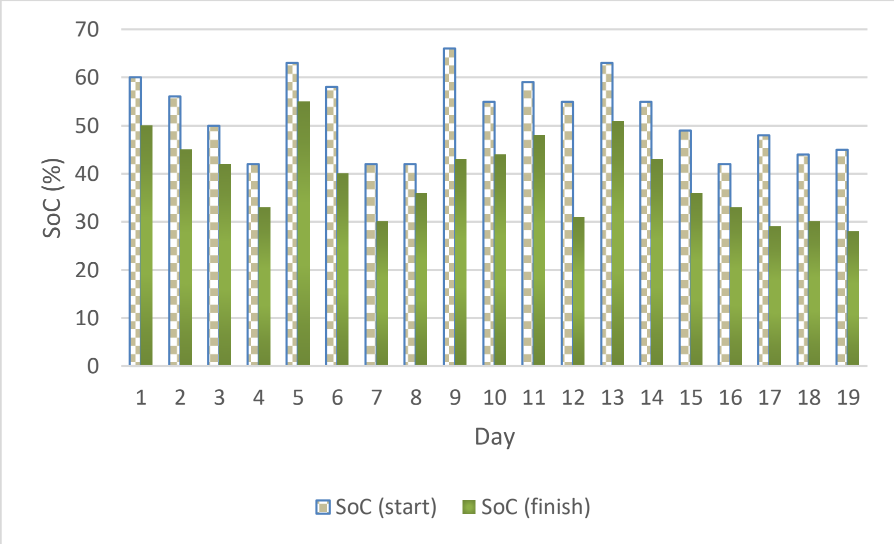


Fig. 13. Battery State of Charge (SOC) before and after work conducted during the field trial

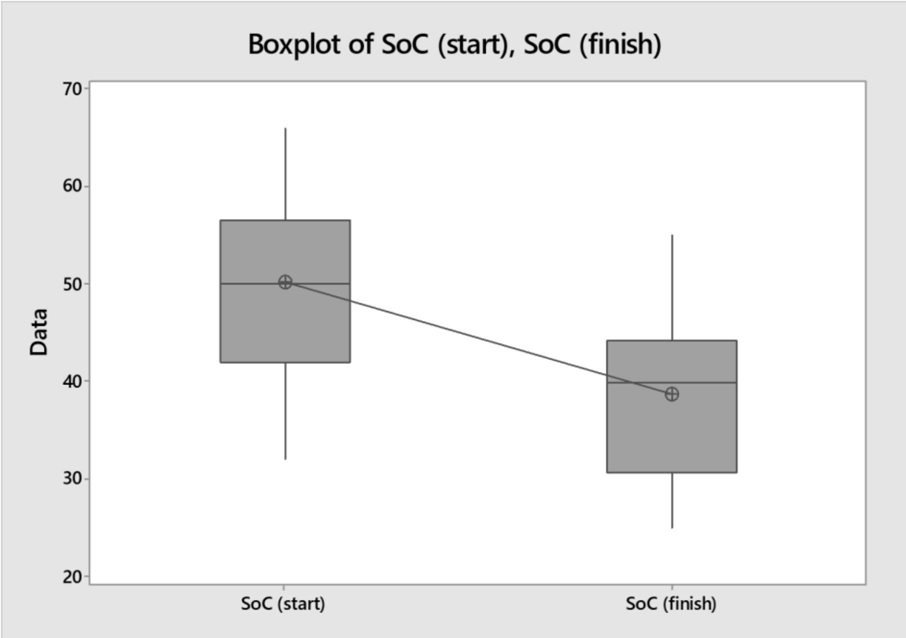


Fig. 14. Data analysis in between State of Charge conditions

In term of diesel fuel utilisation, it was found that a full tank of 400 mL diesel could provide a full day works. Based on a simple load carrying test in the field, a full weight load of 200 L water travel into the harvesting paths, utilise almost 100 mL of diesel per 290 palms or equivalent to the 2 ha of the area. The converted value to energy unit indicates the consumption is at 0.4 Wh/m. The methodology used was previously published to compare the energy consumption of farm work vehicles. The value obtained was lower as compared to the energy usage of about 1.44 Wh/m for a ten horsepower-diesel power vehicle, and almost similar with an electric vehicle that has been tested on almost the same terrain condition [28] as depicts in **Error! Reference source not found.**. The different occurred not only due to the engine sizing but also due to chassis design, transmission technology, weight and also other consideration.

Table 3
Comparison of energy consumption

	Full Electric Vehicle	Agro-Hybrid Vehicle	Utility-type farm vehicle
Power Capacity	48V 200 Ah	7hp air-cooled diesel engine and a deep discharge battery	10hp air-cooled diesel engine
Gross Weight	300 kg	190 kg	400 kg
Energy Consumption	0.3 Wh/m	0.4 Wh/m	1.44 Wh/m

4. Conclusion

In general, the study shows that the solar PV installed onboard the farm vehicle with the agro-hybrid system is technically and economically feasible for the mechanised spraying operation in Malaysian oil palm plantation. Even though the smallest PV capacity installed, but it could provide better advantages compared to without the PV installed. The advantages are such as higher excess electricity generated, more stables battery's state of charge condition, ease of installation and importantly the power produced from the solar PV could not do any harm to the rectifier generator since two power sources connected in parallel to the battery or the load.

The laboratory and infield test had justified the simulation test result that indicates the performance of the prototype. The onboard PV photovoltaic is supporting agro-hybrid structure in providing power to the spraying system and also to recharge the battery pack. All the system works in harmonised and more than 8 ha per day of productivity achieved during the test and in par with other technologies.

The prototype developed and tested based on the agro-hybrid structure provides environmental advantages as no additional power such as secondary internal combustion engines, or power take-off is required for the specific agriculture application. Thus, in conclusion, the sustainability of the oil palm plantation operation in Malaysia could be increased further by considering a sustainable or greener energy technology application.

Finally, the novelty of this research is found in the hybrid power structure and the methods to assess its performance. The proposed vehicle system structure that embeds greener technology has proven to improve the battery state of charge and making the system work for the entire day without capacity shortage. HOMER analysis has indicated that the solar PV can support the activity without additional power required from another internal combustion engine.

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