

Techno-Economic and Environmental Evaluation of Charging Strategy for the Harvesting Tools in Oil Palm Plantations Using HOMER Pro

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Received 15 January 2026, Received in revised form 21 June 2026

Accepted 21 July 2026, Available online 30 September 2026

ABSTRACT

The growing adoption of mechanised technologies in oil palm plantations presents a substantial opportunity to integrate electric-powered equipment or machinery that can deliver stable and durable energy solutions, enhance productivity and reduce environmental impact. A major challenge in this approach is the limited grid access in remote plantations, which requires continuous recharging during fieldwork. Current practice relies heavily on conventional diesel generators, resulting in high operational costs, complex fuel logistics, and severe environmental pollution. This study examines the techno-economic and environmental feasibility of hybrid energy systems for charging harvesting tools using Hybrid Optimisation of Multiple Energy Resources (HOMER Pro) software, modelling a 1.0 kWh/day deferrable charging load. Five system configurations were analysed based on Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and annual emissions. The optimal configuration identified was the Solar Photovoltaic + Battery system, comprising a 1.15 kW PV array and one battery unit with the lowest NPC of RM 14,310 and a reasonable LCOE of RM 3.51 per kWh. This system offers superior environmental performance, resulting in zero CO₂ emissions annually, and represents approximately 55 % reduction in lifetime cost compared to a conventional Genset-only baseline (NPC: RM 31,574; LCOE: RM 7.74/kWh). This strategy offers a reliable, cost-effective, and sustainable route for supporting mechanised oil palm operations in off-grid environments.

Keywords: Oil palm plantation; renewable energy; solar photovoltaic; HOMER Pro

INTRODUCTION

The total oil palm plantation area in Malaysia was approximately 5.61 million hectares in 2024, with Sabah and Sarawak being the two largest states, covering 1.48 and 1.62 million hectares of oil palm plantation area, respectively (MPOB 2024). Various methods are used to harvest, collect, and transport fresh fruit bunches (FFB). These depend largely on the operation's scale and the terrain's topography and is the most crucial part, involving about 60% of work operation in oil palm plantations. The problem with labor shortage impacts the operation and causes loss in productivity. Adoption of mechanization is a way to increase labor productivity by enhancing operational timeliness and task execution efficiency,

improving overall productivity (Azwan et al. 2017). The mechanization adaptation for oil palm varies from plantation to plantation, depending on the land conditions and field operations. In the past 20 years, machinery has been introduced to the oil palm plantation for harvesting and evacuation of FFB, which includes mechanical harvesters, wheeler grabbers, mini tractors, motorized cutters, loose fruit collectors, and others. These machines have simplified, sped up, and improved the efficiency of FFB harvesting and evacuation processes. An overview of mechanization in oil palm plantations was provided by Thaddeus et al. (2023), discussing how the adoption of advanced machinery has improved operations such as FFB harvesting and evacuation which allowed for faster and more efficient collection processes. This move towards

automation has improved productivity and reduced labor intensity associated with manual harvesting techniques.

Utilization of electric-powered tools and machines in agriculture has seen significant advancements in various agricultural operations that present numerous benefits, including increased work efficiency and enhanced ergonomics for users. For instance, Bakri et al. (2020) discussed the advantages of integrating electric systems into agricultural machinery, emphasizing improvements in control and reduced energy requirements, particularly in applications such as herbicide spraying using hybrid power vehicles. Another example is the electric vehicles designed to transport harvested fruits and other materials within the plantations. These vehicles can help reduce greenhouse gas emissions and support global sustainability goals. One significant development is the introduction of electric motorized cutters specifically designed for oil palm harvesting operations. This cutter, namely Cantas Electro, can double the harvesting output compared to traditional hand methods (Jelani et al. 2018). Moving from traditional fossil fuel sources to electric power is essential for modernizing agricultural practices. It offers not only economic benefits but also helps sustain the environment by lowering reliance on non-renewable energy.

Electric motorized cutters usually depend on grid-connected systems or diesel generator-based systems for charging. These systems provide consistent energy for electric equipment operations in well-developed areas with proper infrastructure. A major challenge in ensuring reliable energy supply for battery-powered tools and machinery in remote areas is that access to the national electricity grid is often limited or unavailable. A diesel generator can serve as dependable backup power source. However, its fuel consumption can be much higher, especially during long charging or continuous field operations. Diesel generators increase operational costs, carbon emissions, and maintenance needs, as well as fuel transportation and storage, making them unsustainable for long-term agricultural modernization.

Alternative charging methods, such as solar photovoltaic (PV) systems and portable batteries, are increasingly being used to address the limitations of grid dependency and fuel-based generation. Solar energy is an excellent renewable option for powering charging stations. This approach not only provides continuous power supply but also reduces operational costs and the plantation's carbon footprint. Mohammad et al. (2020) highlighted the versatility of solar panel installation for charging stations, emphasizing that solar panels can be installed close to electricity loads. This supports the design of solar-powered charging stations for equipment used in oil palm estates, enabling efficient and rapid recharging of machinery. Aji et al. (2023) explored the improvements in productivity

through solar energy solutions for electric vehicles. Although their focus is on electric vehicles, the principles of renewable energy applications can extend to solar-powered charging stations for machinery in oil palm estates. The adoption of portable batteries in agriculture is critical for enhancing efficiency and minimizing downtime. Harik (2021) studied the design and implementation of an autonomous charging station for agricultural electric vehicles, emphasizing how portable batteries can enhance operational efficiency within the agricultural sector.

Although solar PV systems and portable batteries are seen as effective off-grid solutions, there is insufficient study on the best design for off-grid solar PV charging station that can meet the continuous and energy demands of machines in remote plantation areas. Thus, this study aimed to use HOMER Pro to explore a suitable charging strategy for mechanized oil palm harvesting tools to identify the most economical and ecologically friendly setup.

MATERIALS AND METHODS

Studies were carried out in three phases. In the initial stage, the solar potential of the target area was investigated together with harvesting tools' load requirements. The HOMER Pro simulation phase involved designing the system configurations to optimize energy integration. Finally, the study concluded with economic and environmental performance analysis of the proposed systems.

HOMER PRO SOFTWARE

The main strength of Hybrid Optimisation of Multiple Energy Resources (HOMER) comes from its ability to perform detailed techno-economic analysis by combining different energy sources, such as solar photovoltaic (PV) systems, diesel generators, and portable battery storage. HOMER works by simulating a variety of possible system setups and optimizing them based on criteria such as net present cost (NPC), levelized cost of energy (LCOE), supply reliability, and emission output. This process helps the software to search for the best configurations by balancing technical feasibility, economic efficiency, and environmental impact. Halim et al. (2018) showed the way hybrid solar PV systems combined with diesel generators and battery storage can be effectively designed and sized using HOMER Pro. The software also optimizes configurations to discover the most cost-effective solutions for different operational situations (Alhousni et al. 2023). By integrating parameters such as load profiles and system

efficiencies with financial measures, including net present cost (NPC) and levelized cost of energy (LCOE), HOMER provides a clear framework for decision-making through detailed technical and economic input parameters.

HARVESTING TOOL

Cantas Electro is a battery-powered harvesting tool designed to enhance the efficiency of FFB cutting process (Figure 1).

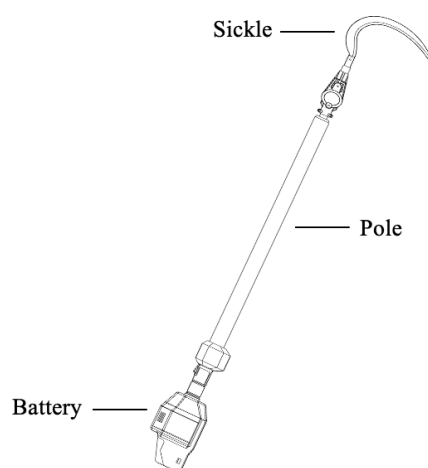


FIGURE 1. Cantas Electro

Harvesting rates of Cantas Electro's productivity were between 574 and 469 FFB/day, or 7.55 and 6.53 t/day, respectively (Ahmad et al. 2023). Two 18V 6.0A Lithium-ion batteries could last up to 2.5 hours on a single charge, whereby the harvester would require three replacements in an eight-hour workday. Harvester would need a backup battery, which could be charged off-site. Setting up battery charging stations powered by reliable alternative energy sources could help reduce labor and time, as continuous power is essential to reduce the number of batteries needed, which is costly and not environmentally friendly.

STUDY LOCATION, CLIMATE AND LOAD DATA

The key steps involved in the study started with data collection on solar radiation and load demand. The study area was in the southern region of Malaysia, specifically in Kulai, Johor (1.6986° N, 103.7340° E). This location was selected as it represents the second-largest oil palm-producing state in Peninsular Malaysia and experiences minimal seasonal variations with high solar irradiance. Weather conditions influenced the power generated by the solar PV array. The potential for average annual solar irradiation was obtained from the Jabatan Meteorologi

Malaysia at Senai Station. This solar resource data reflected the amount of solar radiation hitting the Earth's surface in a typical year. This information served as the Solar GHI Resource input parameter in HOMER Pro, where data was entered. The importance of precise solar irradiance data for assessing the performance of photovoltaic (PV) systems was highlighted in a previous study. These data can affect the expected energy production, which is crucial for running reliable simulations in HOMER Pro (Sunarso et al. 2023).

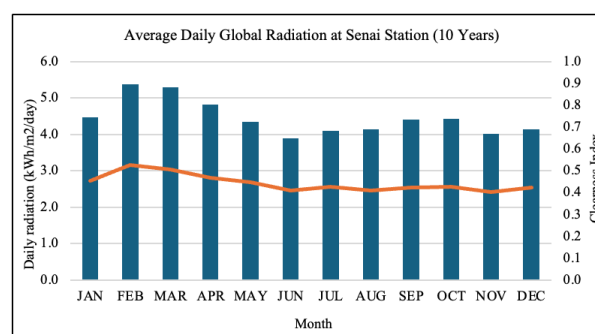


FIGURE 2. Monthly Average Solar Radiation and Clearness Index at Senai Station

10 years the highest average monthly solar radiation for 10 years in February and March exceeded 5.0 kWh/m²/day at the Senai Station (Figure 2). However, this trend changed from April to June where radiation gradually fell below 4.0 kWh/m²/day. From July to December, solar radiation remained steady between 4.0 and 4.5 kWh/m²/day. The overlaid line graph shows the clearness index, which measures the clearness of the atmosphere and is inversely related to cloud cover. A high clearness index indicates clear skies and higher solar radiation, while a lower value indicates cloudy skies or overcast conditions. It peaked in February at around 0.6 and hit its lowest point in June at around 0.45. This relationship suggests that cloud cover and atmospheric conditions have a significant effect on solar availability throughout the year. Despite some seasonal fluctuations, the consistent levels of solar radiation make it practical to implement solar-powered charging systems in the area. Minh et al. (2021) reported that solar irradiation levels greatly influenced system design and feasibility in photovoltaic-powered electric vehicle charging stations.

The primary load demand is important in simulating solar charging system with HOMER Pro as it has direct effect on the design, optimisation, and evaluation of the system. A reliable and consistent charging rate of the Cantas Electro's battery is essential to ensure that the photovoltaic (PV) size is appropriately designed. This data is fed to the HOMER Pro as the primary load demand. The time

required to charge the Cantas's batteries from 20% SOC to full takes about 1 hour (Table 1) (Ahmad et al. 2023). A nominal charging demand of 1 kilowatts (kW) was modelled for an 8-hour workday. This load is considered a deferrable load, which meant that charging can be flexibly

scheduled when power is most available. Deferrable loads, which can be optimally scheduled based on available energy resources, are crucial for enhancing energy efficiency, particularly when integrating renewable sources such as solar energy (Narimani et al. 2017).

TABLE 1. Estimated Power Requirement for Charging Two Batteries

Parameter	Value	Explanation
Battery Voltage (per unit)	18 V	Each lithium-ion battery has a rated voltage of 18 V
Number of Batteries	2	Two batteries are required for operation
Battery Capacity (per unit)	6.0 Ah	Capacity of each lithium-ion battery
Power Consumption Per Battery	0.216 kWh	Energy consumed per charge (calculated as Voltage x Capacity)

SIMULATION SETUP

The optimal solutions for potential energy used in oil palm plantations were analyzed using HOMER Pro software. The HOMER software was used to evaluate the possibilities of solar energy, diesel genset, and portable battery. The hybrid charging energy system comprises four major components i.e. PV panels, a diesel genset, a power converter, and a battery. Figure 3 shows a schematic diagram of the hybrid system. The HOMER software was

used to conduct a simulation for four units of Cantas Electro that were used in harvesting FFB, where two batteries were charged simultaneously, with a load requirement of 1.0 kWh/day. The system was assumed to run for eight working hours in the field and only stopped for one hour in the middle of the day before operation resumed until the afternoon. The simulation took into consideration elements such as resource allocation, load profiles and techno-economic variables of the model.

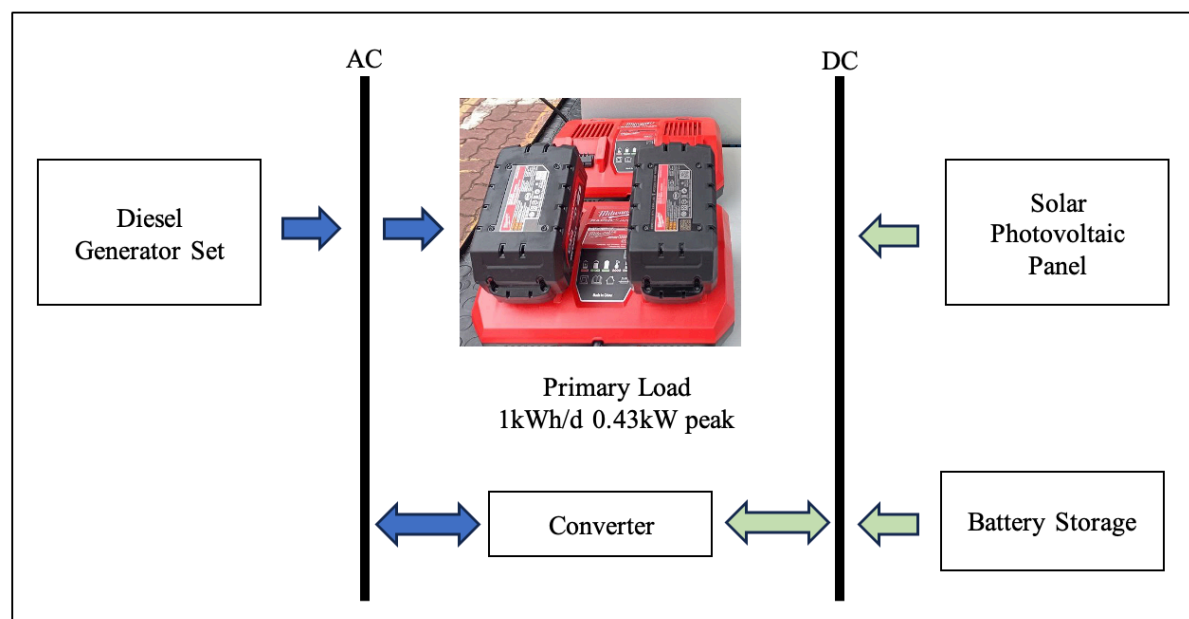


FIGURE 3. Schematic Diagram of Hybrid System Using HOMER Pro

Table 2 summarizes each component's lifetime and input cost i.e., capital, replacement, and operation and maintenance cost and Table 3 summarizes the economic

and battery storage input. This input was required to find the most technically feasible and economically optimal system design with the lowest life-cycle cost.

TABLE 2. Summary of the input costs for simulation

System component	Capacity	Capital Cost (RM)	Replacement Cost (RM)	O & M Cost (RM)	Lifetime
Solar panel	1 kW	4,000	4,000	50/ year	15 years
Generator Set	2kW	5,000	5,000	0.03/op. hour	15,000 hours
Portable Battery	1 unit	5,500	5,500	10/year	10 years
Converter	1 kW	1,800	1,800	Na	15 years

TABLE 3. Input Parameters Used in the Simulation

Input	Value
Project lifetime	15 years
Nominal discount rate	6%
Real discount rate	3.92%
Expected Inflation rate	2%
Battery storage efficiency	90%
Battery storage minimum state of charge (SOC)	20%
Battery storage Depth of discharge (DoD)	80%

ECONOMIC AND EMISSION ANALYSIS

System performance using economic indicators such as net present cost (NPC) and cost of energy (LCOE). The economic analysis evaluated and compared the production and operating costs, as well as the environmental analysis. NPC is the sum of all costs and revenues over the lifetime of the project and was calculated using the following equation,

$$NPC = \frac{C_{tot,ann}}{CRF(i,T_p)} \quad (1)$$

where T_p is the project warranty (year), $C_{tot,ann}$ is the total annualised cost (RM/year), i is the real interest rate (per cent), and CRF is the capital recovery factor, which was calculated using equation (2) where n refers to the number of years.

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

LCOE is the average cost per kWh of the total electricity that the energy system generates, given as,

$$COE = \frac{C_{tot,ann}}{E_{tot,ann}} \quad (3)$$

where $E_{tot,ann}$ represents the total annual electricity generated.

A significant feature of HOMER Pro is its ability to calculate emissions, specifically carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x) based on how much fuel is used and preset emission values for individual parts, especially generators. Lakhout et al. (2025) determined the amount of CO_2 and SO_2 released into the air, which is crucial for understanding the environmental impacts of integrating energy mix.

RESULTS AND DISCUSSION

HOMER SIMULATION ANALYSIS

Figure 4 shows changes in the load profile of the suggested solar system throughout the day, across seasons, and over the year. The proposed solar system is designed to produce up to 1 kWh per day, exceeding the required output to account for system inefficiencies, environmental variations, and to ensure reliable power availability. The Daily Profile showed that energy production is highest during the day, with short peaks between 9 AM and 5 PM. These charging intervals correspond well with periods of high solar irradiance, demonstrating that the system operation is aligned with solar energy availability and reducing dependency on additional backup energy sources. The Seasonal Profile showed that the output remained quite stable all year, with only minor monthly changes. This indicates that the charging demand for the harvesting tool batteries remains consistent despite changes in climatic conditions. The narrow variation in the monthly load distribution further suggests that the solar charging system

can maintain stable operational performance across different seasons in Malaysia's tropical environment. Meanwhile, the Yearly Profile heatmap illustrated that most energy was generated between 8 AM and 6 PM, which is highly suitable for daytime harvesting operations. The repeated daily charging pattern also demonstrates the suitability of the system for routine field deployment. Overall, the load profiles confirm that the proposed PV-based charging system is capable of supporting the operational requirements of mechanized harvesting tools while maintaining reliable daytime energy availability for remote plantation applications.

HOMER Pro returns simulated climatic, technical, and environmental results. Based on the inputs inserted,

the HOMER Pro program suggested a list of plausible configurations, accompanied by the NPC values from the lowest to the highest. The best configuration is often the one with the lowest NPC, but it can also priorities others based on renewability or emissions. Feroz Ali & Abdul Halim (2024) reported that the HOMER Pro ranks system configurations based on their total NPC. The software effectively identified solutions with the lowest NPC and can customize objectives to emphasize sustainability and emissions reduction (Feroz Ali & Abdul Halim, 2024). In addition, Mohseni et al. (2022) also found that the configurations analysed showed potential for lower emissions while remaining economically viable, supporting the idea that users might priorities renewability or emissions.

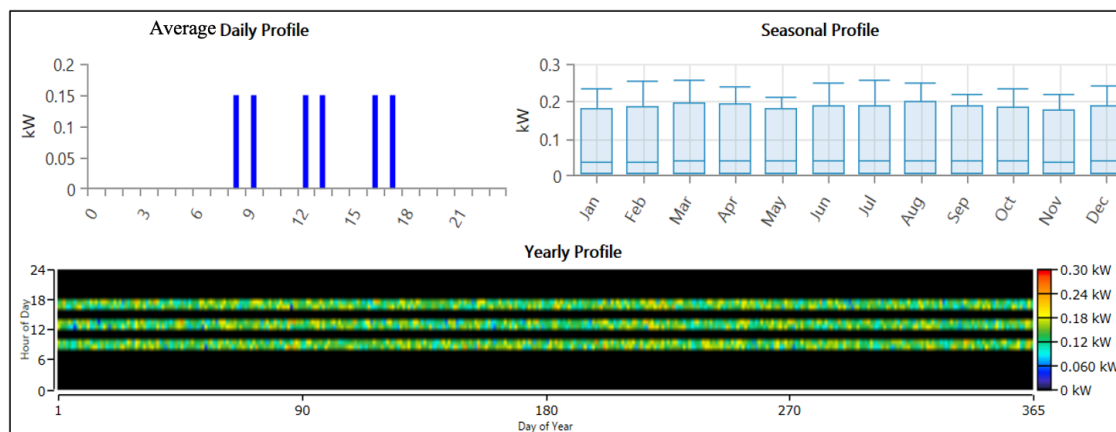


FIGURE 4. Daily, Seasonal, and Yearly Solar Load Profile for Charging the Harvesting Tools Battery

The HOMER Pro program generated a list of energy system configurations, combining various sizes of photovoltaic (PV) arrays, diesel generators, and battery storage. The table compares each scenario in terms of economic metrics, system performance, and simple payback period. The performance analysis of five system configurations generated from Homer Pro simulation (Table 4) showed a significant variation in renewable integration, backup capacity, and environmental impact. PV capacity ranged from 0.04 kW to 1.15 kW, resulting in annual energy production of 44 kWh to 1,646 kWh. Generator capacities remained 2 kW for hybrid designs, while one configuration operates without a generator. Battery storage remained at one unit for most configurations, mainly due to the relatively low load demand of the charging system, which only requires approximately 1.0 kWh/day. This indicates that the energy demand can be sufficiently supported using a small-scale battery storage system without requiring excessive storage capacity, thereby reducing overall system cost and complexity while

maintaining reliable operation. All genset-based systems had identical fuel consumption of 443 L/yr, leading to CO₂ emissions of 1,161 kg/yr. These results indicated that higher PV capacity and battery storage significantly enhance energy independence and environmental performance. Considering operational needs, sustainability, and the lack of grid access in remote oil palm plantations, the configuration of a PV + Battery system emerges as the most suitable option, offering a reliable supply without the use of fossil fuel, low maintenance, and environmental compatibility. Therefore, it is recommended that the charging system be configured for mobile use, with PV array suitably installed on the rooftop of a suitable vehicle as shown in Figure 5.

Besides that, while the current study prioritized the optimization of system configurations under static operating conditions, sensitivity analysis offers a more comprehensive perspective on system resilience within the variable environments typical of plantation settings. Parameters such as solar irradiance, diesel fuel price, and

load demand may significantly influence the technical and economic performance of the charging system. Future work should include sensitivity analysis to ensure that the

proposed system is truly reliable and stable when faced with the diverse operational challenges it will encounter in the field.

TABLE 4. Different Configurations of Charging Systems Generated by the HOMER Pro

Parameter	Hybrid (PV + Genset + Battery)	PV + Battery	Hybrid (PV + Genset)	Hybrid (Genset + Battery)	Genset
PV capacity (kW)	0.04	1.15	0.001	NA	NA
Genset (kW)	2	NA	2	2	2
Battery (units)	1	1	NA	3	
NPC (RM)	44,781	14,310	35,400	43,205	35,382
LCOE (RM/kWh)	10.97	3.51	8.68	10.59	8.67
OPEX (RM/yr)	2,431	299.90	2,270	2,477	2,270
CAPEX (RM)	17,605	10,958	10,018	15,512	10,000
Fuel use (L/yr)	443	0	443	443	443
Fuel Cost (RM/yr)	1,330	0	1,330	1,330	1,330
CO ₂ emissions (kg/yr)	1,161	0	1,161	1,161	1,161
Simple Payback (yr)	-	0.7	-	-	-
Energy Production (kWh/yr)	44	1,646	NA	NA	NA



FIGURE 5. Example of a Mobile Solar Charging System

ECONOMIC ANALYSIS

The comparison of NPC and LCOE for the charging strategies in Table 5 highlighted distinct compromises between economic viability, environmental impact, and operational practicality. The Hybrid system (PV + Battery) emerged as the optimal solution with low NPC of RM 14,310 paired with a competitive LCOE of RM 3.51/kWh. This system demonstrated its cost-effectiveness and operational efficiency throughout its lifetime. The hybrid (PV + Genset + Battery) configuration showed substantial elevated costs, with the highest NPC reaching RM 44,781 and LCOE of RM 10.97/kWh. This configuration is less cost-effective without complementary generation support.

Generally, high costs are mostly due to solar energy output not being always available, which means that more sources of energy are needed to keep the system reliable (Issahaku et al. 2022). On the other hand, the portable battery option had the lowest NPC cost of RM 7,045 and LCOE cost of RM 1.76. This metric did not account for the need to frequent off-site batteries recharge which may lead to operation downtime and reliance on external charging infrastructure. While the low upfront costs are attractive, portable batteries may not consistently support mechanized operations in isolated settings due to reliance on external infrastructure (Woldegiyorgis et al. 2025). Finally, the Genset-only system, despite its low capital cost (RM 10,000), had the highest NPC (RM 35,382) and LCOE

(RM 8.67/kWh), driven by high fuel and maintenance costs. These results showed that hybrid and battery-based systems offered more sustainable and economical options for continuous mechanized harvesting in remote oil palm plantations, as they can reduce fuel reliance and ensure consistent energy availability.

TABLE 5. HOMER Pro Cost Comparison for PV, Hybrid, and Portable Battery

System Configurations	CAPEX (RM)	NPC (RM)	LCOE (RM/kWh)
PV + Battery	10,958	14,310	3.51
Hybrid (PV + Genset + Battery)	17,605	44,781	10.97
Genset	10,000	35,382	8.67
Portable Battery	5,500	7,045	1.76

ENVIRONMENTAL IMPACT ANALYSIS

In addition to the economic considerations, each configuration was assessed for environmental impact. Table 6 compares the annual emissions across different system configurations, based on HOMER Pro's environmental modelling. The outcomes highlighted the substantial ecological benefits of incorporating renewable energy technologies. The findings showed that both PV and Portable Battery configurations had zero emissions, producing no CO₂, SO₂, or NO_x as the systems do not rely on combustion. Research has consistently shown that renewable energy alternatives promote sustainable practices and align with global emissions reduction targets. For example, Saurabh et al. (2025) reported that PV systems with battery energy storage systems (BESS) can enhance grid resilience and mitigate carbon emissions. This combination could shift fossil fuel dependence to cleaner solutions.

The Hybrid (PV + Genset + Battery) system was found to generate significant emissions, producing 1,161 kg of CO₂, 2.84 kg of SO₂, and 6.81 kg of NO_x annually as the genset component burns fossil fuels to supply power. Operation of diesel gensets can produce substantial yearly emissions, although the exact amount depends on operating parameters and system design (Madziga et al. 2018). Overall, the findings highlighted that the hybrid systems generate greenhouse gases and pollutants primarily due to fossil fuel reliance for energy production, while the renewable systems offer a cleaner alternative with minimal emissions during operation. A clear difference in environmental effect underscores the renewable energy technologies in reducing pollution and supporting sustainable energy development versus systems incorporating fossil fuel-powered generators.

TABLE 6. Comparative System Emissions (kg/year)

System Configurations	CO ₂ Emissions (kg/year)	SO ₂ Emissions (kg/year)	NO _x Emissions (kg/year)
PV + Battery	0	0	0
Hybrid (PV + Genset + Battery)	1,161	2.84	6.81
Genset	1,161	2.84	6.81
Portable Battery	0	0	0

CONCLUSION

HOMER Pro optimization platform was used to determine the most efficient off-grid charging strategy for electric harvesting tools in remote oil palm plantations. A combination of PV panels with battery storage is the best solution from both ecological and financial aspects. This configuration had the lowest NPC (RM 14,310) and competitive LCOE (RM3.51/kWh), making it the most practical strategy. The system's efficiency translated to an exceptionally simple payback period of just 0.7 years, offering a strong financial reason for industrial adoption. This system also generated zero annual carbon dioxide emissions, compared to the heavily polluting generator-only alternative. The diesel-only systems are cheaper in terms of capital expenses but lead to higher operating costs and increased pollutants. In addition, although the Hybrid (PV + Genset + Battery) system provided additional reliability, its higher cost and emissions reduced its suitability for small-scale or mobile applications. Other zero-emission alternatives such as the portable battery solutions, emerged as the most economical choice (NPC: RM 7,045.60, LCOE: RM 1.76/kWh), but was impractical for continuous mechanization due to logistic challenges and dependency on external support. The findings confirmed that integration of PV with battery storage offered a practical way to achieve sustainable energy independence for off-grid mechanized harvesting operations, minimizing fuel dependence and maintenance demands. To further strengthen these findings, it is recommended that a prototype of the mobile PV + Battery charging system be developed and tested in actual oil palm estate to gather crucial real-world data, including environmental parameters and operational metrics. This validation stage will allow for the optimisation of the design and fully confirm the commercial viability of this approach for greener and more efficient agricultural practices.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude and appreciation to the Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia (UKM) and Malaysian Palm Oil Board (MPOB) for their permission to publish this paper and support in the present work.

DECLARATION OF COMPETING INTEREST

None.

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