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Comparison between Solar-Powered and Diesel-Driven Water Pumping Systems for Oil-Palm Irrigation Plantations

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Abstract: This paper presents a comprehensive comparative study between solar-powered and diesel-driven water pumping systems for irrigating oil palm plantations in the dry regions of Malaysia. The study aims to address the need for sustainable and efficient water pumping systems in these areas, considering the costs and environmental impact associated with traditional diesel-driven systems. The research specifically focuses on evaluating the feasibility and effectiveness of solar-powered systems as an alternative to diesel-driven systems in the context of Malaysian oil palm plantations. The study employs the HOMER software to evaluate the feasibility and performance of solar-powered water pumping systems in comparison to conventional diesel-driven systems. The research methodology involves collecting data on oil-palm plantations in dry regions and obtaining relevant meteorological data. Subsequently, solar-powered water pumping systems are modeled and simulated using the HOMER software. A comparative analysis is then conducted, considering factors of electrical and economic performances, to evaluate the feasibility and benefits of solar energy for irrigation in Malaysian oil palm plantations. The findings of the study indicate that the configurations of the system without a battery is the most satisfactory, as it demonstrates decent electrical generation, and economic attractiveness with an internal rate of return (IRR) of 17% and a payback period of 5.72 years. Implementing this configuration of the solar-powered water pumping system offers various advantages, including providing adequate water for boosting plantation production, enhancing sustainability, offering environmental benefits, achieving cost savings, and ensuring economic viability. These findings can assist decision-makers in considering the implementation of solar-powered irrigation systems in Malaysian oil palm plantations.

Keywords: Diesel-driven systems, environmental sustainability, Homer software, oil palm irrigations, solar-powered water pumping systems

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1. INTRODUCTION

Solar-powered water pumping systems have emerged as a viable alternative to conventional diesel-driven systems for irrigation. These systems utilize PV panels to convert sunlight into electricity, powering the water pump. Compared to diesel-driven systems that have been used for a long time for irrigation purposes, associating with some negative factors such as rising oil prices, harmful emissions, high maintenance costs, and short lifetimes have compelled researchers to explore alternative options. Renewable energy, particularly solar-powered water pumping systems, holds promise in reducing reliance on fossil fuels and addressing these challenges [1-3]. solar-powered water pumping offers advantages such as reduced operating costs, lower greenhouse gas emissions, and enhanced reliability in remote locations. Many studies have concentrated on evaluating the economic viability of solar-powered water pumping systems when contrasted with their diesel-driven equivalents. For instance, a World Bank Group study highlighted the operational, financial, and environmental sustainability of solar water pumping as a viable alternative to diesel-powered systems [4]. Similarly, research conducted by Green Coast revealed the economic benefits of solar-powered pumps, including reduced operation and maintenance expenses and lower environmental impact compared to combustion engine-driven pumps [5]. Beyond economic advantages, solar-powered water pumping systems also contribute to environmental preservation. Solar Magazine's study emphasized the global shift towards renewable energy considering the current energy crisis [6]. Another study by Yuvraj Siddharth examined the fundamental component of PV panels, the solar cell, within the broader context of solar-powered systems [7, 8].

The feasibility analysis conducted on irrigation implementation economics has shown that irrigation can increase yields by 5-6 tons per hectare per year, which is economically viable. To effectively irrigate oil palm plantations, a substantial water source is required [9,10]. Solar-powered water pumping systems have been constructed and analyzed in different agricultural contexts, showcasing the use of HOMER software to study system performance [11]. Two solar-powered water pump systems to micro-irrigate a 14.7-hectare Iranian wine garden. One uses a battery bank, while the other uses a water tank. The first installation uses Lorentz compass3 software and a 6-inch 18.5 KW submersible pump. HOMER Pro software modeled the second system, which had a 6-inch 11 kW submersible pump, 44.4 kW PV modules, and 144 kWh battery bank. The results show that battery banks are cheaper than water tanks. Another study has explored the integration of solar energy into a diesel pumping system for cotton farms in remote areas of Australia [12]. The findings indicate that integrating solar PV systems into off-grid scenarios can accomplish both economic and environmental goals concurrently, particularly when irrigation water can be stored. The solar installation reduces emissions and costs, mitigates exposure to future diesel fuel price fluctuations, and optimizes pumping capacity during the crucial summer growing months when crop water demand peaks. The economic evaluation of the baseline scenario determined the internal rate of return (IRR) of 23% to be satisfactory, indicating the project's viability. However, when considering the modified internal rate of return (MIRR), the return decreases to 10% when profits are reinvested at a finance and market reinvestment rate of 5%. The hybrid installation demonstrated a notable decrease in CO_2 equivalent emissions by replacing diesel fuel with energy from the solar PV system. The calculations indicate a decrease of 35 kg CO_2 equivalent per bale of cotton and the displacement of nearly one million litres of diesel over the project's lifespan [12].

This study evaluated the technical, economic, and environmental aspects of solar water pumping systems compared to conventional diesel systems in Egypt [13]. The findings reveal that solar water pumping emerges as a financially efficient and effective alternative for agricultural crop irrigation compared to electric and diesel water pumps. The study used HOMER software to perform system optimization in terms of minimum net present Cost (NPC), cost of energy (COE), and CO_2 saving. The study discovered that the NPC of a solar water pumping system in on-grid mode is three times higher than that of a PV-battery off-grid system and four times higher than that of a conventional diesel system. The COE of a solar water pumping system is 0.07 /kWh, while it is 0.332/kWh for a PV-battery system and 0.434 $/kWh for a diesel system. These studies offer valuable insights into the feasibility and advantages of solar-powered water pumping systems across various settings.

Reference [14] conducted socio-economic and environmental analyses in the Philippines, revealing that solar irrigation offers significant environmental benefits. These benefits include a reduction in greenhouse gas (GHG) emissions by up to 26.5 tons CO_2 eq/ha/year and the avoidance of air pollutant emissions such as carbon monoxide, nitrogen oxides, sulfur oxides, and particulate matter. The energy savings range from 11.36 to 378.54 L/ha of diesel per year, resulting in a net present value of -USD 1255/ha to USD 68,582/ha, returns on investment ranging from 30% to 2958% with an average of 315%, and payback periods ranging from 0.3 to 30 years with an average of 2.88 years. Despite a relatively low awareness of environmental sustainability, the study found that a majority of farmers (69%) expressed interest in investing in solar irrigation systems. However, 26% of farmers indicated a lack of interest due to their minimal fuel consumption, which hinders their ability to recover the high investment costs through cost savings.

Reference [15] introduced a design for a PV-powered DC water pump system aimed at irrigation and examines the techno-economic feasibility of utilizing solar Photovoltaic (PV) systems as a substitute for diesel engines and electric pumps. PVSyst simulation software was employed by the author for ease of use and cost considerations. The findings indicate that solar PV water pumping is economically more viable than diesel or electric water pumping systems in various regions of Palestine, including rural, urban, and remote areas. The investment payback period for PV water pumping systems as an alternative to diesel is approximately one year, while the replacement of conventional electric pumps takes around 7 years.

Reference [16] explored the technical-economic feasibility of various solar pumping solutions for an irrigation system in Ethiopia. The study concludes that the direct solar irrigation system is the most efficient and cost-effective solution, but emphasizes the need for proper evaluation based on specific water needs and weather conditions. The study highlights the potential of smaller and simpler systems as a foundation for off-grid, modular, scalable, and replicable solutions in developing countries. The economic analysis done in [17] demonstrated in their study of photovoltaic water pumping system (PVWPS) for rice paddy irrigation in northern Iran that the operating and maintenance costs, as well as the total life cycle cost, of PVWPS were significantly lower compared to conventional diesel pumping systems (CPS). Selling excess electricity generated by PVWPS to the grid during non-irrigation months proved to be a profitable venture, reducing costs by 189.2% when compared to CPS. Furthermore, the environmental analysis showcased the substantial environmental benefits of PVWPS, including a significant reduction in CO_2 emissions and diesel fuel consumption. These findings underscore the economic viability, environmental advantages, and potential for income generation associated with PVWPS in rice paddy irrigation.

Reference in [18] found that CO_2 production for off-grid PVWPS during the project lifetime is 190-201 times lower than that for CPS. Sharon presented a step-by-step process to assess the economics and environmental impacts of solar PV water pumping units, along with recent research findings in these areas. It recommends the use of solar PV water pumping units in regions with a rainfall of at least 300-400 mm per year and located 2 km away from the local grid power supply. The operation of solar PV units in on-grid mode significantly reduces the payback period. The study reveals that the pumping costs associated with diesel units are 300.0% higher than those of solar PV units, highlighting the effectiveness and sustainability of solar PV water pumping for farmland irrigation. The article also discusses the advantages, limitations, and strategies to enhance the acceptance of solar PV water pumping systems among farmers [19].

Economic feasibility of large-scale photovoltaic (PV) irrigation systems has been examined in the ECOWAS region [20]. The study compares the substitution of diesel-powered and grid-powered systems with PV systems in seven countries, considering two irrigation operating modes. The findings reveal that the NPC values range from 0.33 to 41.5 × 10^5 dollars, IRR values range from 8 to 47%, and Payback Period (PBP) values range from 2.1 to 10 years. Additionally, the evaluation of Levelized Cost of Energy (LCOE) demonstrates that PV irrigation systems have LCOE values ranging from 4.5 to 17.4 cents/kWh, resulting in percentage savings of 30-84% compared to diesel-powered and grid-powered systems. These findings emphasize the potential economic benefits of PV irrigation systems as cost-effective alternatives in the ECOWAS region. Reference in [21] examined two different climatic conditions and employed a life cycle cost (LCC) analysis to evaluate the systems. The findings indicate that photovoltaic irrigation pumps with batteries for energy storage are comparable to systems powered by transmitted electricity through private lines for pump capacities of 4.5 kW and 5.5 kW in a citrus orchard and vineyard, respectively. It is concluded that private power transmission lines are more cost-effective for irrigation pumps exceeding 3 kW, as long as the transmission line length is less than 2 km. For power requirements below 4.5 kW, photovoltaic energy is relatively comparable to fossil fuel. Given Iran's dependence on subsidized fossil fuels, the successful financing of solar irrigation projects necessitates supportive policies and regulations.

This paper aims to address the gap in research specific to oil palm plantations in dry regions of Malaysia. The importance of having proper irrigation for dry areas of Malaysian oil palm plantations is highlighted in [9]. By comparing the feasibility and effectiveness of solar-powered water pumping systems to traditional diesel-driven systems, this study aims to meet the growing demand for sustainable and efficient irrigation systems. The research methodology involves collecting data on oil palm plantations in dry areas and gathering meteorological data. Subsequently, solar-powered water pumping systems will be modelled and simulated using the HOMER software. A comparative analysis will be conducted, considering factors such as electrical performance and economic performance. This research is crucial in addressing the pressing need for sustainable and efficient water pumping solutions for irrigation, contributing to enhanced agricultural productivity and environmental sustainability.

Section 2 discusses on the Homer simulation modelling, while section 3 describes the findings of the simulation. Finally, conclusion is drawn in Section 4.

2. HOMER SIMULATION MODELLING

The research methodology for this paper adopts a systematic and structured approach to comprehensively compare and evaluate the feasibility and effectiveness of solar-powered water pumping systems as an alternative to diesel-driven systems for irrigation in the dry areas of Malaysian oil palm plantations. The methodology involves several key steps to gather data, analyze system performance, and assess economic and environmental factors. The HOMER software, a widely recognized and powerful tool for optimizing and analyzing renewable energy systems, plays a central role in the methodology. Figure 1 provides a flowchart illustrating the modelling process conducted using HOMER.

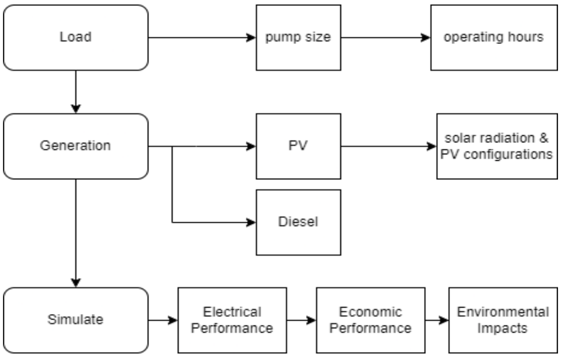

Figure 1. Flowchart of HOMER modelling

The research methodology consists of several key steps to systematically evaluate and compare the feasibility, performance, economic viability, and environmental implications of solar-powered and diesel-driven water pumping systems for irrigation in dry areas of Malaysian oil palm plantations. The selected location for this study is Serting Hilir, Malaysia as based on [9]. Mean daily irradiation and mean daily temperature are illustrated in Figure 2 and Figure 3.

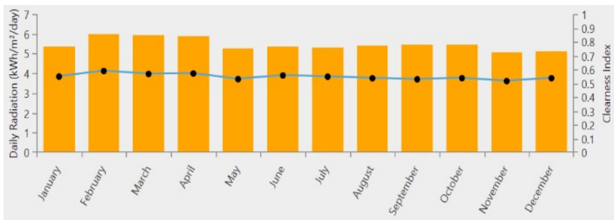

Figure 2. Mean Daily Irradiation of Serting Hilir, Malaysia

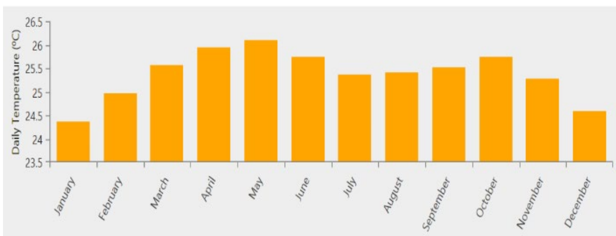

Figure 3. Mean Daily Temperature of Serting Hilir, Malaysia

The first step involves determining the pump size depending on the daily water requirements and operating hours. This includes inputting the load profile that represents the energy consumption of the pump and selecting an appropriate pump size to meet the water demand. Next, The options considered for generation are photovoltaic (PV) /diesel generator (DG). The system configuration entails determining the PV capacity, DG capacity, and battery storage requirements. Figure 4 illustrates the network topology considered in this study. The size of the system is calculated using the formula provided in [11].

Once the system is set up, the performance results are evaluated. This includes assessing the electricity production from the PV system, evaluating the electricity consumption of the pump, and identifying any capacity shortage situations that may arise. Additionally, the capacity factor, which serves as a measure of system efficiency, is calculated. The economic performance of the system is then assessed. Parameters such as the internal rate of return (IRR), net present value (NPV), simple payback period (SPB), discounted payback period (DPB), and capital cost are evaluated to determine the financial viability of the system. The value for the capital cost used in this study is based on [17].

The NPV is the sum of the present values of all cash flows (inflows and outflows), discounted at a specific rate, r as shown in equation 1. IRR represents the discount rate, r at which the NPV equals zero. The SPB is the time it takes for cumulative cash flows to equal the initial investment as stated in equation 2. The DPB considers the time value of money. It is the time required for the cumulative discounted cash flows to equal the initial investment as illustrated in equation 3.

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \quad (1)$$

$$SPB = \frac{Initial\ Investment}{Annual\ Net\ Cashflow} \quad (2)$$

$$cumulative\ DPB = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad (3)$$

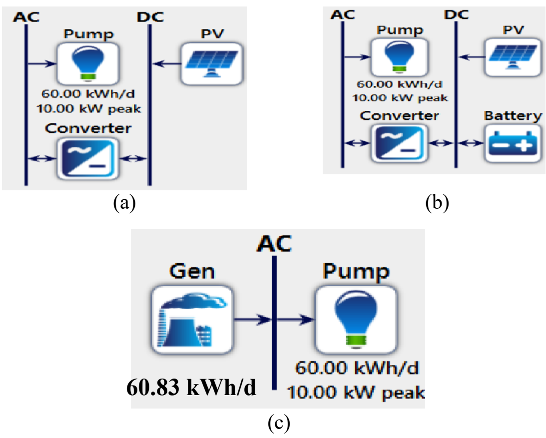

Figure 4. Network Topology (a) PV without battery (b) PV with Battery (c) Diesel

3. RESULT AND DISCUSSION

To evaluate the performance of different network topologies, electrical performance, and economic performance are compared between PV without battery, PV with battery, and diesel systems.

3.1 Electrical Performance

HOMER Pro simulation results provide a comprehensive assessment of the proposed systems by analyzing various performance aspects. These aspects include electricity production, electricity consumption, excess energy, capacity shortage, capacity factor, and hours of operation. The simulation evaluates the amount of electricity generated by the systems, taking into account the available renewable energy resources and system configurations.

3.1.1 PV without Battery

The study revealed intriguing findings regarding the performance of the PV system without battery storage. It was observed that the system exhibited surplus electricity generation of 9,882 kWh/year, indicating its capacity to generate more electricity than the load necessitates. However, a small unmet electric load of 6.82 kWh/year was identified, implying that the system may not be able to fully meet electricity demand during certain periods. Furthermore, a capacity shortage of 9.54 kWh/year was noted, indicating instances when the system falls short of providing the required electricity capacity. These findings shed light on some limitations and drawbacks associated with this configuration. One such drawback is the possibility of temporary disruptions or limitations in the electricity supply, potentially leading to inconveniences or interruptions in the energy supply. Additionally, inefficiencies in the system may result in unused or lost electricity, which could be addressed with improved design and optimization. The lack of energy storage capability in this configurations also poses a challenge, as it may lead to potential energy wastage. Moreover, the system's performance is susceptible to fluctuations in sunlight availability, which can affect electricity generation and overall system performance. These factors should be carefully considered when assessing the practicality and reliability of the PV system without battery storage.

3.1.2 PV with Battery

In contrast, the PV system with battery storage demonstrated a remarkable potential for substantial power generation, reaching 46,304 kWh/year, indicating its ability to generate surplus electricity of 22,629 kWh/y. Despite this electricity surplus, the system suffers periods of capacity shortages of minor value of 21.8 kWh/year. which can be considered negligible compared to the amount of electricity generated. These outcomes highlight the effectiveness and reliability of the PV system with battery storage, providing a robust solution for mitigating intermittent electricity generation and ensuring a steady and uninterrupted energy supply.

3.1.3 Diesel System

The system maintained a balance between the electrical output of the generator and the load requirements, with no surplus electricity or unmet electric load. This consistency indicated appropriate generator sizing. Also, the diesel systems operate less hours annually due the nature of diesel generators that can be switched on when needed. This justified the 0 kWh on excess and unmet load. The system capacity factor is 22.7%.

3.1.4 Comparative Study

PV configurations show excess electricity generation which could be considered as a safety net against unexpected changes in electricity demands. As it can be used in periods of low or no generation, whereas the PV with battery comes out superior to the other configurations. But if the excess electricity is not utilized it can be disadvantageous, and the diesel system could emerge as the superior one with 0 kWh excess and unmet load, and higher capacity factor than the PV configurations. 22.7%. Table 1 summarizes the electrical performance of all proposed configurations..

Table 1. Electrical performance comparison

Parameter	PV without battery	PV with Battery	Diesel System
Excess Electricity (kWh/yr)	9,882	22,629	0
Unmet Electric Load (kWh/yr)	6.82	15.6	0
Capacity Shortage (kWh/yr)	9.54	21.8	0
Production (kWh/yr)	20,204	46,304	21,900
Consumption (kWh/yr)	9,542	21,884	21,900
Hours of Operation (hrs/yr)	4,319	4,319	2,190
Capacity Factor	17.0 %	17.0 %	22.7 %

3.2 Economic Performance

This study analyzes two sensitivity scenarios, alongside the existing configurations, to demonstrate the impact of fluctuations in fuel expenses on the system's economic viability. The first scenario will feature a diesel price of \$0.5/L, while the second scenario will involve a diesel price of \$1/L.

The economic analysis unveiled insightful findings regarding the water pumping systems, highlighting the Diesel Generator system as the most economically viable investment among the five systems evaluated. With a fuel cost of \$0.5 per liter, this system demonstrated a lower capital cost of \$10,092 and exhibited a positive NPV of \$20,487.75, indicating potential profitability. Furthermore, the investment yielded a healthy IRR of 32% and boasted a relatively short payback time of 2.79 years (simple payback) and 3.29 years (discounted payback). These economic metrics showcase the Diesel Generator system as a prudent financial decision.

For higher fuel prices, for instance \$1/L the economic viability is vulnerable. As the operations & maintenance costs go double by \$86,527 and it cannot be recovered within the project life, hence the IRR and SPB cannot be calculated. Figure. 5 and Figure 6 illustrates the Diesel system cost summary with both diesel prices, \$0.5/L and \$1/L, respectively. The same goes for the PV with the battery. As the battery increases the capital cost by 47% making it impossible to be recovered within project lifespan. Figure. 7 shows the cost summary for the PV with battery system. On the other hand, the PV without battery is very successful, showing a very high NPV of \$34,292.29. High IRR and relatively low payback period (5.72 years). Figure. 8 shows the PV system without battery cost summary. Considering the sustainability goals, a PV system without a battery emerges more attractive than the diesel generator (\$0.5/L).

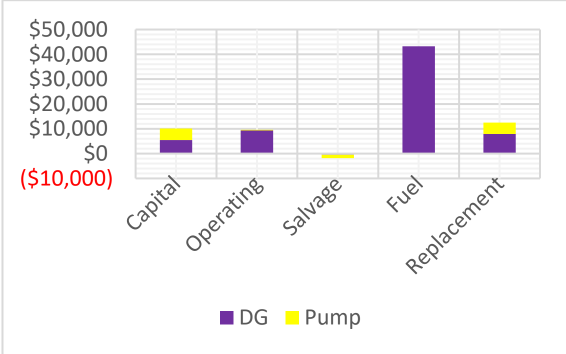

Figure 5. Diesel System \$0.5/L

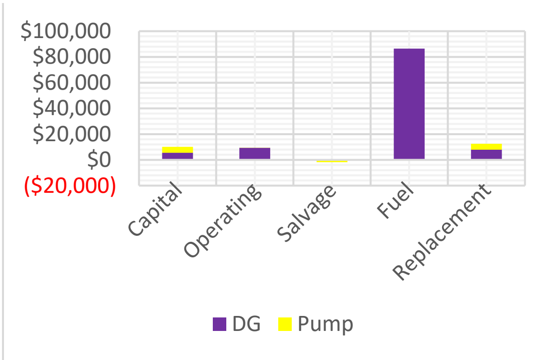

Figure 6. Diesel system \$l/L

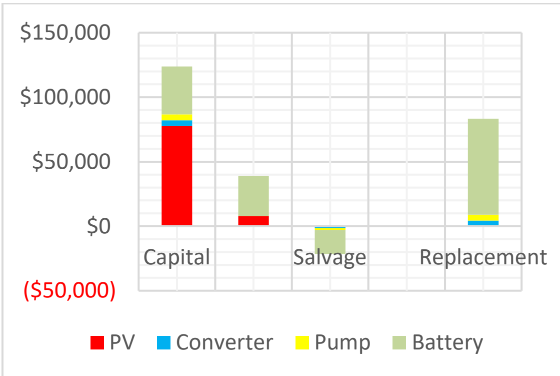

Figure 7. Cost summary for the PV with battery

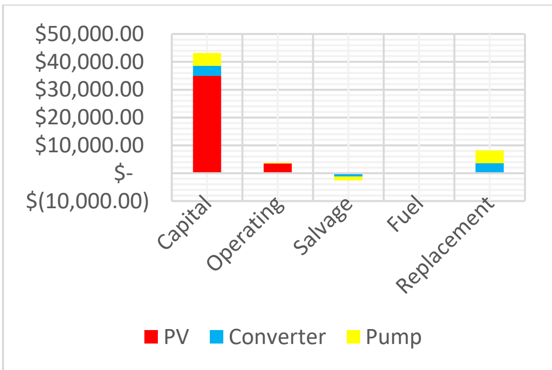

Figure 8. Cost summary for the PV without battery

Nevertheless, it is imperative to consider environmental impact and long-term sustainability when making investment decisions. While solar photovoltaic (PV) systems may entail higher initial investment costs, they align with sustainability goals and offer renewable energy benefits. Therefore, the cost breakdown between the different system configurations. is presented in Table 2.

Table 2. Cost comparison between each configurations

configurations	Capital ($)	NPV ($)	IRR (%)	SPB	DPB
Diesel $0.5/L	10,092.00	20,487.75	32	2.79	3.29
PV	43,162.26	34,292.29	17	5.72	7.88
PV-Battery	123,887.00	84,206.85	-2	NA	NA
Diesel $1/L	10,092.00	15,240.72	NA	NA	NA

The cost comparison between the different configurations highlights significant trade-offs between economic viability, sustainability, and sensitivity to external factors like fuel costs. The Diesel $0.5/L configuration emerges as the most financially attractive option, with a low initial capital requirement ($10,092), a high Net Present Value (NPV) of $20,487.75, and a rapid payback period (SPB of 2.79 years and DPB of 3.29 years). This configuration benefits from low operating costs due to the low diesel price, resulting in a high Internal Rate of Return (IRR) of 32%. However, its dependence on fuel prices makes it vulnerable to fluctuations, as evident in the Diesel $1/L configuration. With doubled fuel costs, the NPV drops significantly to $15,240.72, and no meaningful IRR, SPB, or DPB can be achieved, highlighting the financial risks associated with rising fuel costs.

On the other hand, the PV configuration offers a more sustainable alternative with an NPV of $34,292.29 and a moderate IRR of 17%. Despite requiring a higher capital investment of $43,162.26, the PV system provides long-term profitability and eliminates dependency on fluctuating fuel prices. However, the longer payback periods (SPB of 5.72 years and DPB of 7.88 years) may deter investors seeking quicker returns.

The PV-Battery system, although environmentally appealing and capable of providing energy independence, is not financially viable within the scope of this analysis. With a high capital cost of $123,887 and a negative IRR of -2%, it fails to recover its investment within the study period, as evidenced by the lack of SPB and DPB values. This highlights the challenges of integrating battery storage, which, while crucial for addressing intermittency issues in renewable energy, significantly increases upfront costs.

It is worth highlighting that, while the Diesel $0.5/L configuration is the most economical in the short term, it is highly sensitive to fuel price volatility. Meanwhile, PV systems strike a middle ground, offering long-term profitability and environmental benefits, albeit with higher upfront costs and longer payback periods. The PV-Battery system, while future-oriented, requires cost reductions in battery technologies to become a competitive option. This analysis underscores the need to consider not just financial metrics but also external risks and sustainability goals when evaluating energy configurations.

3.3 Overall System Performance

The findings of the study suggest that the optimal configuration for water pumping is the PV system without battery, directly linked to the pump. This configuration showcases a satisfactory power generation capacity, meeting the requirements for efficient water pumping. From an economic standpoint, this PV system demonstrates favorable feasibility with a reasonable capital cost, positive net present value, and a relatively short payback period. These economic indicators suggest the potential for profitability and a sound investment decision. In addition to its economic viability, the PV system without batteries is also environmentally sustainable. By relying solely on solar energy, it eliminates the need for fossil fuels and contributes to reduced greenhouse gas emissions. This translates to a positive impact on the environment by minimizing carbon footprint and enhancing air quality. Embracing such a sustainable approach in water pumping aligns with the broader goal of reducing our carbon footprint and promoting environmentally friendly practices.

Table 3 presents a breakdown of the differences based on this study, advantages, and disadvantages of all the proposed configurations, effectively highlighting the strengths and weaknesses inherent in each system.

Table 3. Result Summary

Configuration	Performance	Economic Viability	Environmental Impact	Advantages	Disadvantages
PV	Excess generation	Viable, Attractive, High IRR & low PBP	Environmentally friendly	Simple, low cost	Unreliable
PV - Tank	Excess generation used to store water in the tank	Not viable, negative NPV	Environmentally friendly	Highly reliable, Robustness	Higher capital cost compared to direct connection
PV - Battery	Storing excess generation in the batteries	Highest capital cost, not viable	Environmentally friendly	Provides energy storage for consistent water pumping	Highest capital cost, replacement costs
DG ($0.5/L)	Efficient, no excess & shortage	Viable, shorter PBP than PV, higher IRR	Emissions and pollutants from diesel fuel	Lower capital cost compared to PV systems, efficient & sufficient	High O&M, maintenance breakdowns
DG ($1/L)	Efficient, no excess & shortage	Not viable	Emissions and pollutants from diesel fuel	Low capital, efficient & sufficient	Very high O&M costs, maintenance breakdowns

4. CONCLUSION

In conclusion, this paper aimed to develop a water pumping system for oil palm irrigation by exploring various configurations and conducting a comparative study. The findings highlight the overall satisfactory performance, economic feasibility, and environmental sustainability of the PV system without battery. The electrical performance analysis revealed that the PV system without battery storage generated a surplus of 9,882 kWh/year, while having a small unmet electric load of 682 kWh/year. In terms of economic performance, this configurations displayed attractive indicators compared to other configurations, including a capital cost of $43,162.26, positive NPV of $34,292.29, an IRR of 17%, and a relatively short payback time of 5.72 years. Regarding environmental impacts, the PV systems emerged as a sustainable alternative with zero emissions, while diesel systems exhibited significant pollutant emissions. The study's achievements signify the provision of an alternative irrigation method that demonstrates decent performance, economic success, and minimal environmental impacts. To further validate the accuracy of these findings, future research is recommended utilizing more precise and up-to-date data. This would enhance the understanding of the system's performance and facilitate the advancement of sustainable and efficient water pumping systems for oil palm irrigation

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