Indonesian Journal of Science & Technology

Journal homepage: http://ejournal.upi.edu/index.php/ijost/

Alternative Energy Options for a Thai Durian Farm: Feasibility Study and Experiments for the Combination of Solar Photovoltaics and Repurposed Lithium-Ion Batteries

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A B S T R A C T S

This research examines the viability of incorporating a second-life lithium-ion battery energy storage system with a solar photovoltaic power source to facilitate energy acquisition in two irrigation scenarios at a durian farm located in Thailand. The first option entails selecting the battery with suitable dimensions to effectively harness solar energy following morning irrigation, while the second option involves sizing the battery specifically for storing solar energy solely for the purpose of powering the motor pump. This study conducts an analysis on the degradation of the battery, focusing on the influence of specific environmental conditions and its specification. The degradation analysis employs polynomial functions as an alternative to exponential semi-empirical stress models for fitting stress models. This approach demonstrates a robust fit, as evidenced by a high R-squared value of approximately 1. The economic analysis considers various factors, including solar irradiance derating factors, battery deterioration rate, and photovoltaic power ratings for all scenarios. The sensitivity analysis evaluates the variations in irradiance and costs associated with the battery. When solar radiation levels surpass 500 W/m^2 and the cost of the battery remains below \$100/kWh, the estimated payback period is approximately 5 years over the duration of the 10-year project lifespan.

A R T I C L E I N F O

Article History:
Submitted/Received 26 Aug 2023
First Revised 16 Oct 2023
Accepted 22 Nov 2023
First Available online 23 Nov 2023
Publication Date 01 Apr 2024

Keyword:
Electric vehicles,
Hybrid energy storage systems,
Renewable energy,
Second-life batteries,
Solar photovoltaic.

1. INTRODUCTION

In a cropping system characterized by time constraints, such as a durian farm, the cultivation of the plant necessitates the implementation of an effectively regulated water supply at a precise timing, in conjunction with the application of soil amendments tailored to its carbon and macronutrient composition (Mutolib *et al*., 2023). This approach is crucial for the attainment of a high-quality crop yield. Durian requires irrigation every day from 7 a.m. to 10 a.m. during its 5-year growth before cropping, otherwise, the tree will not develop properly, which is critical for plant survival.

Electric water pump systems in farms have typically been powered by fossil fuels, either via grid power supply infrastructure or diesel generators (DG), although they may not be appropriate solutions for every environmental situation. DG can contaminate the farm through dust, noise, smoke, vibration, or lubricant leakage (Orts-Grau *et al*., 2021). Natural events such as landslides, strong storms, and animal invasions on the farm may disrupt the overhead or underground grid power supply system. In the absence of grid power supply infrastructure to the farmyard, requesting grid expansion may be difficult or non-economical to the farm owner. All of these have a negative impact on crop yields and, as a result, the farm owner's agricultural revenues (Sadi & Arabkoohsar, 2020).

Renewable energy sources are suitable viable options for use on agricultural farms because they are pollution-free, self-sufficient, and carbon-neutral emission (Shakeel *et al*., 2023). Solar photovoltaic (PV) technology presents itself as a viable and efficient alternative renewable energy source for the use of water irrigation in agricultural farms. As previously stated, durian requires water from 7 a.m. to 10 a.m., so the PV power supply system is designed to be oversized to harvest the low irradiance during that time. Aside from that, cloudy conditions may interfere with PV power generation.

On the other hand, during peak solar radiation hours, i.e., 10.00-14.30, the PV-generated power could not be properly deployed due to a mismatch between power production and consumption. One of the factors contributing to the necessity of a consistent power supply on a farm is the requirement for uninterrupted electrical equipment operation to support daily load demands. These are the challenges of using a solar PV power generation system in a remote and large area such as a durian farm. The installation of a solar PV power generation system with energy storage could be a feasible, profitable, and sustainable solution (Sutikno *et al*., 2022).

2. LITERATURE REVIEW

Solar PV hybridization with energy storage is becoming increasingly important in achieving net zero emissions. It implies that research into hybrid systems integrating renewable energy and energy storage will accelerate in the coming years. Among energy storage technologies, lithium-ion batteries (LiBs) are widely used and accepted for large-scale battery storage capacity. This is because they are suitable in terms of power and energy performance, affordability, lifespan, and acceptable safety (Han *et al*., 2019). Nevertheless, a significant obstacle hindering the widespread adoption of solar PV and battery energy storage systems pertains to the economic viability of the enterprise. This necessitates a meticulous examination of the business case on an individual basis (Mathews *et al*., 2020).

In one reference (Nikzad *et al*., 2019), the seal-lead acid battery bank is integrated with the solar water pump system to increase dependability and energy arbitrage. The study conducted a comparative analysis of the proposed system operating in both on-grid and off-

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

grid modes, concerning conventional diesel water pump systems. In contrast to conventional diesel water pump systems, the proposed system exhibits a higher initial capital outlay, approximately twice as much. However, it offers the advantage of lower ongoing operational and maintenance expenses, resulting in a significantly reduced total life cycle cost, estimated to be around eight times less. Additionally, the suggested system presents a noteworthy 20% decrease in total life cycle cost compared to standard diesel water pump systems. During the months when irrigation is not taking place, the revenue generated from the sale of power amounts to approximately USD 8,000 over the entire duration of its existence.

This analysis highlights the benefits associated with the utilization of a solar PV-battery hybrid power system in comparison to traditional fossil fuel-based power generation within contemporary renewable energy alternatives. The feasibility study conducted in this context exhibits a notable disparity in the attention given to battery degradation as opposed to solar PV array aging loss. Despite the latter being more frequently discussed, it is imperative to acknowledge that battery degradation surpasses PV array aging loss in terms of magnitude and significantly impacts revenue production. Consequently, the results could be employed with apprehension.

Rezk et al. proposed the utilization of a hybrid system comprising a lead-acid battery energy storage system integrated with a PV system to supply power to a desalination water facility. The study aims to enhance the efficiency of power sources through the utilization of HOMER software. However, it is important to note that the optimization technique employed in this research does not explicitly declare. The optimal energy cost is achieved when the price of PV arrays is at its minimum and the number of battery units is minimized. The study found that the power production of PV systems was not significantly affected by the high temperature, which reached approximately 50°C during specific months. Nevertheless, due to the influence of temperature on battery degradation, the projected battery lifespan may not be achieved.

Moreover, the DoD generally exhibits a 20% level of inefficiency, characterized by a varying SoC window ranging from 50 to 100%. This fluctuation leads to suboptimal utilization and a lack of cost-effectiveness. The lack of explicit disclosure regarding the interest rate, inflation rate, and project duration in the calculation of energy costs raises concerns about the validity of the techno-economic study conducted for a sustainable water supply. However, according to the research outcomes, carbon dioxide emissions have been effectively diminished, and the energy expenditure is comparatively lower in comparison to a diesel generator (Rezk *et al*., 2019).

According to Elkadeem et al., it was suggested that a hybrid power system consisting of various sources such as wind, solar PV, two diesel generators, lead-acid battery energy storage, and a converter, be employed for agricultural irrigation. This recommendation was made based on a techno-economic optimization study and the observed environmental advantages. The cost of the system is primarily determined by various factors, including the variability of solar radiation, wind speeds, and prevailing interest rates. In comparison to the reference scenario involving exclusively diesel generators, the analysis reveals a significant decrease in the levelized cost of energy, accompanied by nearly complete carbon emissions reduction and substantial fuel savings. The reason for this phenomenon is the considerable capacity of the area to generate energy from renewable sources, leading to the lowest energy costs compared to alternative scenarios. The discovery of energy expenditure aligns with evidence observed in numerous regions worldwide during the simulation of applications utilizing renewable hybrid power sources through the utilization of the HOMER software. (Elkadeem *et al*., 2019).

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

The authors, Kebir et al., suggest conducting a research investigation on the utilization of a hybrid power system consisting of PV technology supplemented by second-life lithium-ion batteries (SLiBs) specifically designed for elementary schools. The sizing of the systems is determined by considering variable solar PV sizes and SLiB capacities, which are dependent on cost factors such as local and import costs. When considering the minimum imported cost of SLiB, it leads to the lowest levelized cost of energy (LCOE) in comparison to the new battery hybrid power source and grid power supply. Consequently, this results in the shortest payback period. Indeed, battery life degradation is influenced by several factors, including the rates at which the battery is charged and discharged, the number of charge and discharge cycles it undergoes, the depth of discharge during each cycle, the average state of charge in each cycle, the operating temperature of the battery cells, and the duration of both the battery's operating and shelf-life. Consequently, it is impractical to assess the battery's rate of deterioration at a presumed constant value of 2.6% annually throughout the project's lifetime. Additionally, it should be noted that the SLiB lifetime of 5 years does not have a direct correlation with the suggested battery degradation rate of 2.6%. This degradation rate pertains to the initial capacity of the second life, which is 70%, and the final capacity, which is 40%, specifically in the context of utilizing the battery for single-building power supply purposes. Based on the observed rate of capacity loss, it can be inferred that the SLiB has the potential to remain functional for 10 years, until reaching approximately 40% of its original capacity, before requiring disposal.

Given these circumstances, the primary emphasis of the study centers around the techno-economic aspects of the hybrid power source, which consists of PV systems and batteries. The farm under consideration lacks access to grid expansion, however, it possesses favorable conditions for the generation of solar power. Moreover, the majority of previous endeavors focused on lead-acid batteries, which possess the potential to induce cumulative, detrimental, and chronic hemophilic, cardiovascular, and renal neurotoxic effects due to the presence of lead. Elevated levels of lead are associated with the development of anemia, hypertension, cerebral muscular weakness, and renal impairment. Children who have been exposed to lead toxicity exhibit symptoms such as hyperactivity, low attention span, susceptibility to boredom, reduced ability to concentrate on their environment, including educational material, and experience cognitive sluggishness in adulthood (Widyaningsih et al., 2024).

Therefore, it is crucial to repurpose and effectively utilize ironic battery waste before recycling it, to reduce the production of hazardous and toxic waste. Therefore, we propose a sustainable solution for repurposing SLiBs as a feasible energy storage system, owing to their capacity to decrease costs, minimize waste production, and mitigate carbon emissions. In the second section, we established the foundation for our study methodology, which involves the utilization of a solar-photovoltaic hybrid power system for the operation of an irrigation water pump system. The third section provides a techno-economic evaluation of hybrid systems in various applications. The present study integrates empirical data about solar irradiance, which is crucial for solar power generation, and ambient temperature, which affects the degradation of battery life. A sensitivity analysis is conducted to examine the impact of different input parameter tolerances on the cost of SLiB and the variety of solar irradiation available. The final section of the article presents a conclusion that emphasizes the importance of the farm owner gaining a comprehensive understanding of the project and implementing viable hybrid power sources for plant irrigation that effectively eliminates carbon emissions.

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

3. METHODS

The research methodology employed in this study is depicted in **Figure 1**. As previously mentioned, the literature review is provided to establish the background and address the identified obstacles. The hybrid power source is assessed and classified according to various application scenarios, such as utilizing solar energy during peak radiation periods to meet the energy demands of farms, or solely for powering motor pumps. The first scenario involves utilizing the current farm design to optimize solar energy generation, while the second scenario proposes an alternative solution involving a smaller hybrid power source. Both scenarios are evaluated using a techno-economic analysis that considers the impact of battery degradation caused by environmental conditions at the site, and thus the proposed system's yield is economically evaluated. Furthermore, this study examines the limitations imposed by battery costs and solar radiation to assess the viability of potential applications.

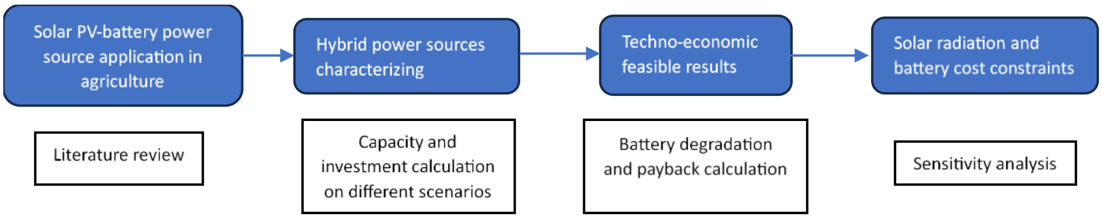

Figure 1. Research methodology of the study in hybrid power source for farm irrigation.

3.1. Solar PV-battery Hybrid Power Source for Agricultural Farm Loads

In this study, we examined a durian plantation located in the province of Trat, situated in the eastern region of Thailand at coordinates 12°12′25.7′′N, 102°24′45.7′′E. As depicted in **Figure 2**, the observed average daily irradiation received from the sun is approximately 5 kWh/m^2. Trat is situated at an elevation of 6 meters above the mean sea level. The region under consideration exhibits an average annual precipitation of 1942 millimeters, with a typical temperature of 28.4°C and a relative humidity of 78%. The climatic conditions of this particular region are classified as tropical (Okimoto *et al.*, 2013).

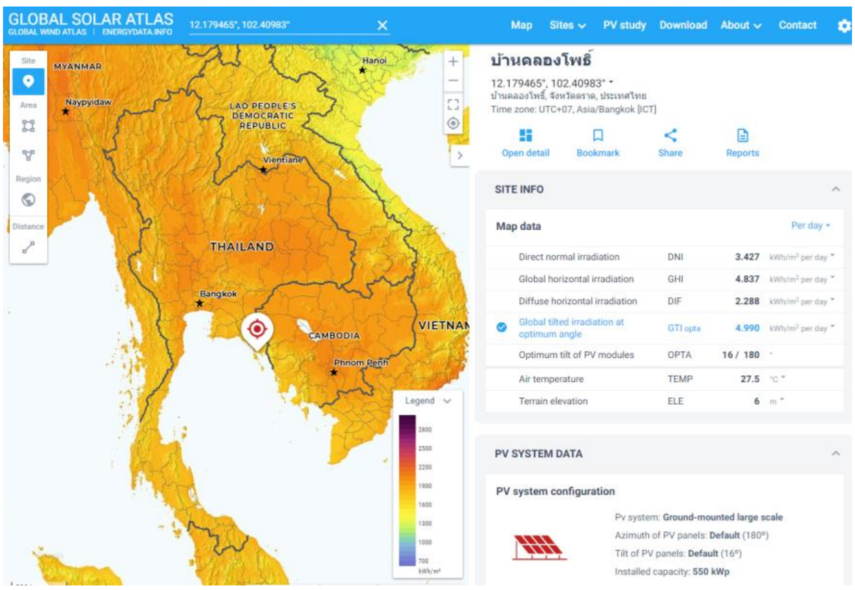

Figure 2. The location and solar information of Trat province. Data was taken from https://globalsolaratlas.info/map?c=12.179465,102.40983,11&s=12.179465,102.40983&m=site on November 2023.

This study aims to enhance a solar PV irrigation system to supply extra water to a growing durian farm that spans an area of 16,000 m^2, equivalent to 1.6 ha. As per the water pump system devised by the proprietor, the enhancement system comprises a 10-horsepower induction motor equipped with a variable speed drive unit, along with PV arrays consisting of 30 modules, each with a power rating (PV_{rat}) of 550 W. The integration of battery energy storage into the upgrading system is not currently foreseen, primarily due to a dearth of elucidation regarding its potential advantages in terms of energy and power applications. Consequently, the objective of this research is to address a knowledge gap by examining the viability of integrating a hybrid power source with battery energy storage systems, with a focus on the techno-economic feasibility.

As illustrated in **Figure 3**, the hybrid power source under consideration consists of a composite arrangement involving PV panels, an SLiB, and a hybrid inverter, as visually represented by the green-shaded region. The inverter can establish a connection with the DG system in the event of an emergency, as and when necessary. Furthermore, the utilization of the inverter primarily caters to the irrigation motor drive system, although it is feasible to establish connections with farm loads contingent upon the hybrid power source's capacity. The initial investment does not encompass the expenses associated with the DG and irrigation motor pump system, as the primary focus of this study is directed toward the hybrid power source.

The weather data logger, referred to as the Ambient Weather WS-5000-IP Smart Wireless Weather Station, recorded an estimated average irradiance during two-time intervals in September 2023. From 7.00 to 10.00 hours, the approximate average irradiance was evaluated to be around 300 W/m^2. From 10.00 to 17.00 hours, the approximate average irradiance was evaluated to be around 600 W/m^2, as depicted in **Figure 4**. The assessment is conducted utilizing weather data obtained directly from the farm, as opposed to relying on data sourced from external organizations.

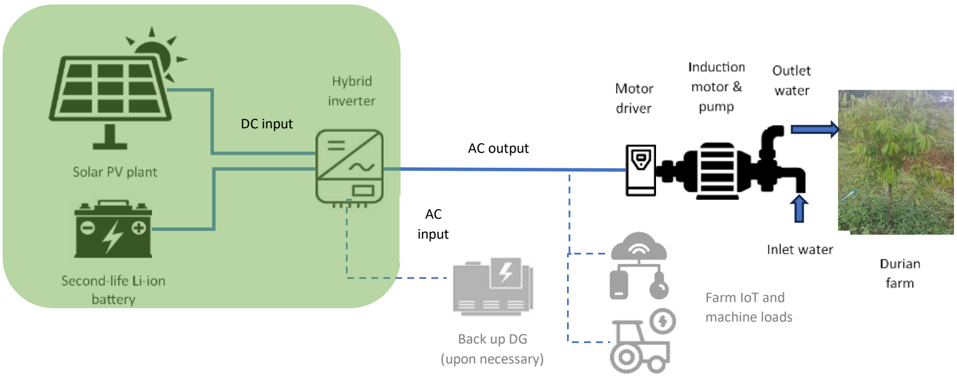

Figure 3. The architecture of the proposed hybrid power source (green shade) for the irrigation motor pump system.

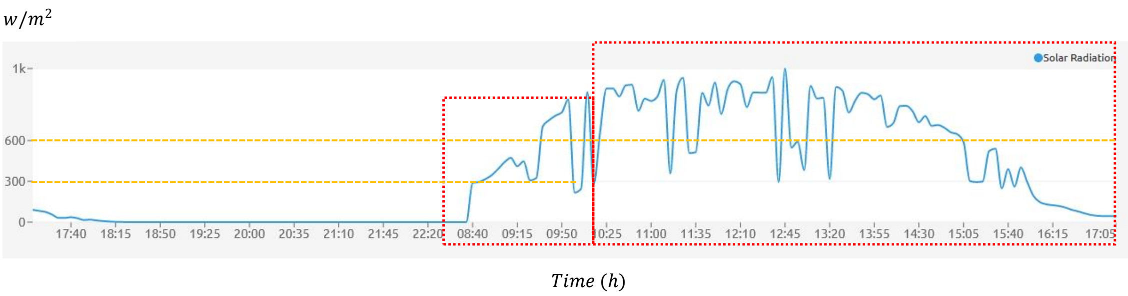

Figure 4. Solar radiation of the durian farm for a day in September 2023.

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

As previously stated, durian farms need watering in the early morning, between 7:00 and 10:00 a.m., which is when the PV power source is intended to harvest low amounts of solar radiation most effectively to feed the motor pump in real-time. As a consequence, the PV rating (PV_{rat}) exceeds the capacity designed for times of high solar ray intensity, i.e. after 10:00 a.m. If the solar energy produced by the PV is not used after the watering time, the power would be wasted due to the converter's curtailment. Furthermore, the farm's present location in Thailand's Trat province is outside of the energy trading zone; there is also no chance to sell the energy to the grid, though this may be feasible in the future. Therefore, to prevent the loss of electrical energy, SLiBs could be used for energy harvesting attributable to the possibility of technological and economic advancement (Wangsupphaphol *et al*., 2023).

The energy that is obtained from the harvest can be utilized to supply power to various farm loads including aerator pumps, submersible pumps, security systems, internet-of-things equipment, or agricultural machinery. These loads typically operate intermittently, adjusting their activity levels following fluctuations in solar radiation levels. Currently, these devices rely on solar PV hybridizing with new battery energy storage of limited capacity and high cost. Thus, the integration of SLiBs into a solar PV irrigation system would present a highly favorable amalgamation for sustainable and eco-conscious agricultural practices.

3.2. Investment and Tariff of The Hybrid Power Source

To determine the appropriate capacity of battery energy storage for agricultural loads, we analyzed data obtained from the weather data logger. This data specifically pertains to the levels of solar radiation recorded over eight months, from January to September 2023, as illustrated in **Figure 5**. The mean radiation (indicated by the solid blue line) typically falls within the range of approximately 100 to 400 W/m^2 with the highest and lowest values observed. The value denotes the average measurement taken over a 24-hour period, which includes both daytime and nighttime intervals. It is important to note that this average value may be significantly lower than the radiation levels observed solely during daylight hours. Upon examination of the spectrum of radiation values, specifically those depicted by the shade of light blue, it becomes apparent that the most significant fluctuations are observed within the range of 0 to 900 W/m^2.

Hence, the deliberate selection of solar radiations averaging 300 and 600 W/m^2 has been made to facilitate the computation of energy harvest and perform sensitivity analysis. This measure is implemented to mitigate the potential for either overestimation or underestimation. If the durian farm does not possess data for the forthcoming months in the year 2023, it would be appropriate to consider the utilization of this solar radiation prediction method. Farm owners in the local area generally hold a predominantly positive attitude towards the utilization of modern data concerning the phenomenon of global warming. This phenomenon is a result of the imperative for farmers to carefully oversee multiple factors, such as temperature, sunlight exposure, humidity, precipitation, and associated variables, to attain accurate crop cultivation (Teo & Go, 2021).

The analysis of the power output of the PV array involves examining the voltage and power curve of a 540 W bifacial dual glass monocrystalline PV module under standard test conditions. These conditions entail subjecting the module to solar radiation with an intensity of 1000 W/m^2. The graphical representation of this voltage and power curve can be observed in **Figure 6**. The relationship between intensity and output power is apparent, as the highest intensity is associated with the maximum output power. Conversely, as the irradiances decrease, the power gradually diminishes (see https://pages.trinasolar.com/DEG19C20.html).

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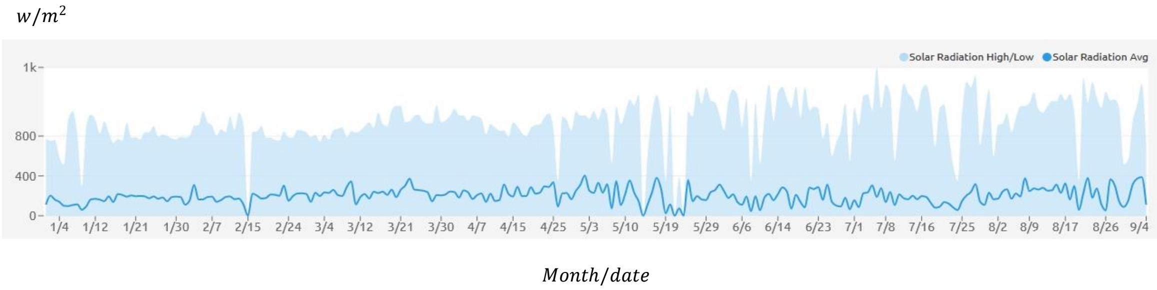

Figure 5. Solar radiation history from January to September 2023.

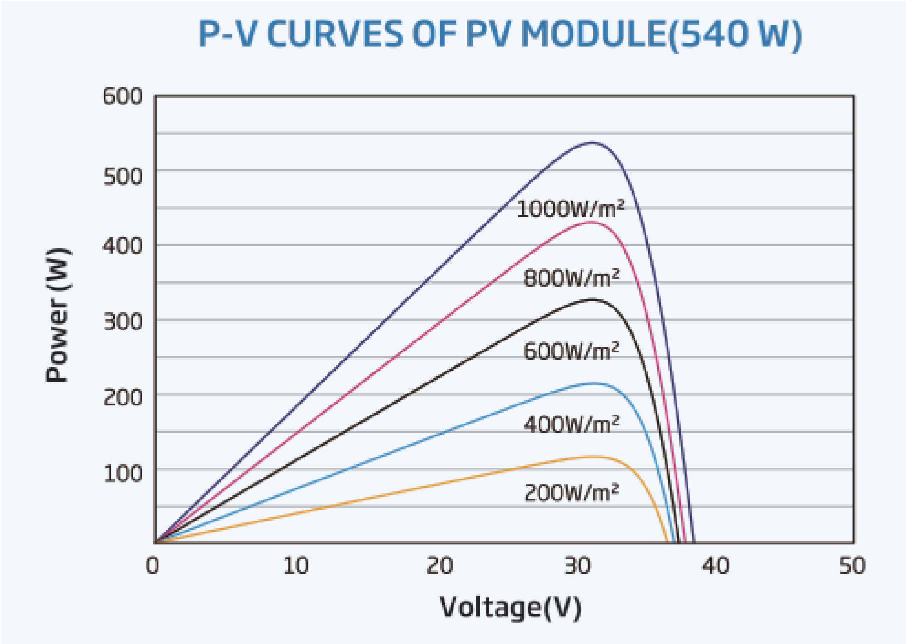

Figure 6. Power production of a PV module in this study.

The solar irradiation derating factor (SDF) is determined based on the average solar radiation observed over 8 months. The average solar radiation values of 300 and 600 W/m^2 corresponding to SDF values of 0.3 and 0.6 respectively were used in the calculation of the maximum output of the PV system. It also resulted in output powers of 162 and 324 W, respectively. This study does not incorporate the solar system derating factor, which encompasses wire losses, dust particle losses, high-temperature loss, or any other factor that causes deviations in output power. This ground-based, small-scale power plant can be easily maintained through its physical installation and the implementation of a suitable maximum power point tracking algorithm, thereby achieving optimal performance (Anang *et al*., 2021; Sutikno *et al*., 2022). Furthermore, the influence of temperature on the modeling of the microgrid system is deemed negligible, especially when the ambient temperature closely approximates the standard test condition (Sharma *et al*., 2022). Therefore, the power production period (P_{hr}) of 4.5 hours from 10:00 to 14:30 is implemented. This finding refers to the examination of the annual solar production's capacity factor, which was determined to be 19% as documented in the reference cited by Tran & Smith (2018) and of about the average practical potential hours of PV production in Thailand, 4.065 kWh/kW$_p$ (see https://globalsolaratlas.info/global-pv-potential-study). The total power output of 30 PV modules, taking into account only the SDF of 0.3 and 0.6, results in power outputs of 4.86 kW and 9.72 kW respectively. The daily energy production (E_p) for these configurations is calculated as 21.87 kWh and 43.74 kWh respectively.

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To harness viable solar energy after the irrigation phase for alternative purposes, the utilization of battery energy storage is imperative. This study focuses on the utilization of withdrawal rechargeable solid Li-Po batteries with nickel manganese cobalt (NMC) as the primary material. These batteries have been previously employed in traction applications before being selected for examination in this research. Due to the presence of incremental internal resistance, the current supplied by them is insufficient for torque generation in traction drives. However, it is important to acknowledge that the state of health (SoH) of the SLiB maintains a level of approximately 80% of its nominal capacity for light load applications, as indicated by Haram *et al.* (2021). Furthermore, a significant advantage of the SLiB is its highly cost-effective nature in comparison to a newly manufactured Li-ion battery, thereby enhancing the viability of the project. However, the implementation of battery management systems (BMS) is necessary for the use of SLiB in emerging applications. Hence, we conducted an assessment of the capital expenditure of SLiB, incorporating the BMS, utilizing the same value as referenced in Assunção *et al.* (2016) and Wangsupphaphol *et al.* (2023), specifically 42 USD/kWh. The technical details of the SLiB can be observed in **Table 1**.

The observation of outdoor temperature for 8 months is undertaken to assess its impact on the lifespan of batteries, as temperature is a significant factor in their degradation (Xu *et al.*, 2018). The battery degradation assessment involves selecting an average outdoor temperature of 30°C, as depicted in **Figure 7** (represented by the orange dot line). The study does not include the remaining data, such as the average feel-like temperature and dew point, in its analysis.

To sustain the heat generated during SLiB operation, it is possible to regulate the current rate of the battery (C) to a maximum of 1C, equivalent to 272 Ah, through the control of the hybrid converter. The achievement of this outcome can be facilitated through the utilization of a sequential arrangement of SLiB 16 units, specifically in the context of SDF 0.3. This arrangement can be combined with an additional string, resulting in a total of 16×2 units within the battery bank. The combined capacity of this battery bank amounts to 21.76 kWh, which is calculated based on the formula: 32x1 kWh x 0.8 SoH x 0.85 DoD. Hence, the charging current remains below 1C of the nominal capacity during a 1-hour discharge, specifically at 183 A [(21.76/2) kW/(16×3.7 V)]. This methodology can be applied to other SDFs, discharge hours, and the maximum input voltage of solar PV, specifically 60VDC. **Table 2** presents a summary of the initial investment along with the PV cost ($C_{cap,PV}$) and battery cost ($C_{cap,bat}$) specifically focusing on the SDF values of 0.3 and 0.6, as well as the SoH and DoD, which are recorded at 80 and 85% respectively.

Subsequently, the levelized cost of electricity for the hybrid power source is computed to assess the profitability concerning the diesel power generation tariff. The results of this calculation are presented in **Table 3**. The reason for this is the farm's geographical distance from the power supply of the grid, making DG a suitable alternative source for comparison. Based on the analysis conducted, it has been determined that the cost of hybrid power sources may become more economical than that of DG within ten years.

Table 1. Specification of NMC battery in this study.

Specifications	Value	Operating conditions	Value
Capacity ±3%	272 Ah/1000 Wh	Humidity non condenses	<90%
Normal voltage	3.7 V	Temperature	-20 to +60°C
Max. voltage	4.2 V	**Storage conditions**	**Value**
Min. voltage	3.0 V	Humidity non condenses	<90%
Charge mode	CC/CV	Temperature	20°C
Weight approx.	8 kg	Voltage	3.7-3.9 V

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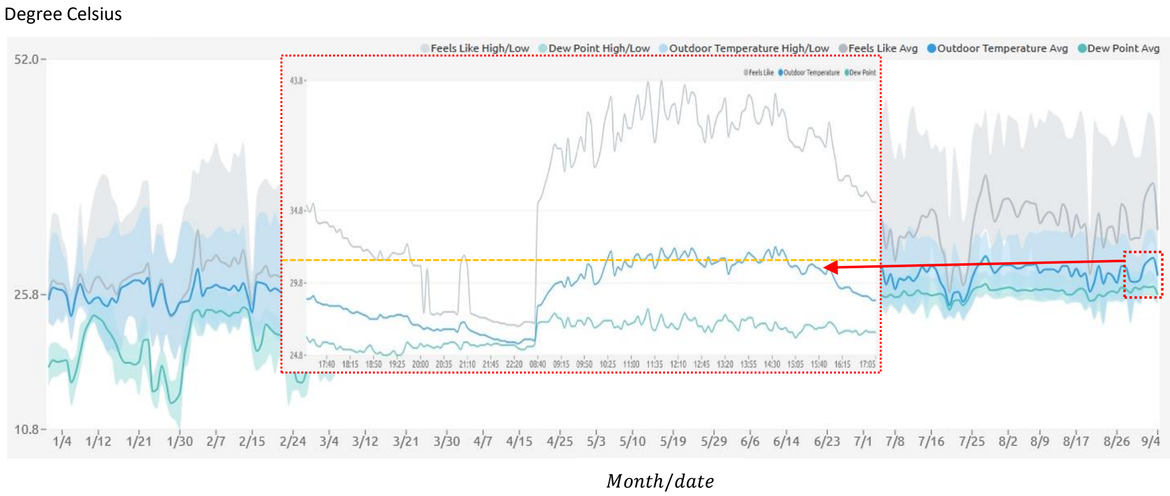

Figure 7. Average outdoor temperature between January and September 2023.

Table 2. Initial investment of the hybrid power source for harvesting energy for farm load.

Parameters	SDF= 0.3	SDF = 0.6	Unit
Installed PV rating (550 W), PV_{rat}	16.5		kW
Production hour, P_{hr}	4.5		hr
Energy conversion efficiency, E_{con}	0.94		-
Production energy, $E_p = PV_{rat} \times P_{hr} \times E_{con} \times SDF$	21	42	kWh
Approx. even value of battery rated, $B_{rat} = E_p/(DoD \times SoH)$	32	64	kWh
Initial investment, $C_o = \left[\left(PV_{rat} \times C_{cap,PV}\right) + \left(B_{rat} \times C_{cap,bat}\right)\right]$	11,970	13,314	USD

Table 3. Electricity tariffs of hybrid power source and diesel generator power generation.

Solar PV tariff	Year 2023	Unit	Source
Minimum loan rate + contingency value; r	8	%	(see https://www.bot.or.th/App/BTWS_STAT/statistics/BOTWEBSTAT.aspx?reportID=223&language=eng)
PV lifetime; n_{PV}	20	Year	(Bagalini et al., 2019)
Ratio of a constant annuity to its present value over time of PV; $CRF_{PV} = r(1+r)^{n_{PV}}/(1+r)^{n_{PV}} - 1$	0.102	-	(Tran & Smith, 2018)
Annual production hour of PV; CF_{PV}	19	%	
Capital cost of PV system; $C_{cap,PV}$	644.0	USD/kW	(Wangsupphaphol & Chaitusaney, 2020), 2 times China's engineering, procurement, and construction cost
Operation & maintenance yearly fix cost; $O\&M_{fix}$	25	USD/kW-yr	(https://www.nrel.gov/analysis/tech-lcoe.html)
Operation & maintenance varying costs; $O\&M_{vary}$	0.002	USD/kWh	
Levelized cost of electricity; $LCOE = \frac{(C_{cap,PV} \times CRF_{PV}) + O\&M_{fix}}{8760 \times CF_{PV}} + O\&M_{vary}$	0.057	USD/kWh	(Wangsupphaphol et al., 2023)

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Table 3 (Continue). Electricity tariffs of hybrid power source and diesel generator power generation.

Solar PV tariff	Year 2023	Unit	Source
Hybrid power source tariff			
Battery lifetime; n_{bat}	10	Year	(Wangsupphaphol et al., 2023)
Ratio of a constant annuity to its present value over time of battery; $CRF_{bat} = r(1+r)^{n_{bat}}/(1+r)^{n_{bat}} - 1$	0.149		(Tran & Smith, 2018)
Capital cost of SLiB system; $C_{cap,bat}$	42	USD/kWh	(Assunção et al., 2016), (Wangsupphaphol et al., 2023)
Operation & maintenance yearly cost; $O\&M_{year}$	6.9	USD/kW-yr	(https://www.nrel.gov/analysis/tech-lcoe.html)
Annual discharge hour of battery; CF_{bat}	19	%	Author's specified based on Ref. (Tran & Smith, 2018)
Solar energy conversion efficiency; E_{con}	94	%	(Wangsupphaphol & Chaitusaney, 2020)
Levelized cost of storage, $LCOS = \frac{(C_{cap,bat} \times CRF_{bat}) + O\&M_{year}}{8760 \times CF_{bat} - (P_c \times (1 - E_{con}))}$	0.00463	USD/kWh	(Wangsupphaphol et al., 2023)
Tariff of hybrid power source ($LCOE$+$LCOS$), $LCOE_{hyd}$	0.062		(Liu & Zhong, 2019)
Mean tariff of diesel power generation, DG	0.402		(Peerapong & Limmeechokchai, 2017)
Profit of hybrid power source; $DG - LCOE_{hyd}$	0.340		

4. RESULTS AND DISCUSSION

4.1. Technical and Economic Analysis of Hybrid Power Source for Farm Loads

The revenue generated by the energy availability of the battery throughout its life cycle. This study examines the linearized degradation of batteries to assess the decline in capacity, thereby providing evidence for the viability of the project. The present study incorporates the actual average temperature data of 30°C, along with the state of charge (SoC) limit ranging from 10% to 95%, state of health (SoH) at 80%, and depth of discharge (DoD) at 85%, as previously established in the research conducted by Wangsupphaphol *et al*. (2023). In contrast to our previous approach, where degradation stress models were implemented using quadratic and exponential equations, we have now employed 2nd order polynomial equations to fit the stress model of the battery (f_d), state of charge (f_{SOC}), depth of discharge (f_{DOD}), and temperature (f_T), This choice was made for the sake of clarity and practicality in application. It is evident that the variances of the dependent variables exhibit a strong correspondence with the independent variables, as indicated by the R-squared values of all models, which approach a value of 1, as depicted **in Figures 8, 9,** and **10**.

The equation representing battery aging is explicitly presented as Eq. (1). It is important to acknowledge that the first term pertains to calendar aging, which is dependent on the elapsed time (t in seconds, the average SoC, and temperature. The second term refers to cycle degradation, which exhibits variability based on the specific cycle of DoD, SoC, and temperature, and accumulates in conjunction with the number of cycles employed (i). The inherent symmetry of the charge and discharge cycles enables their daily counting to be consolidated into a single count.

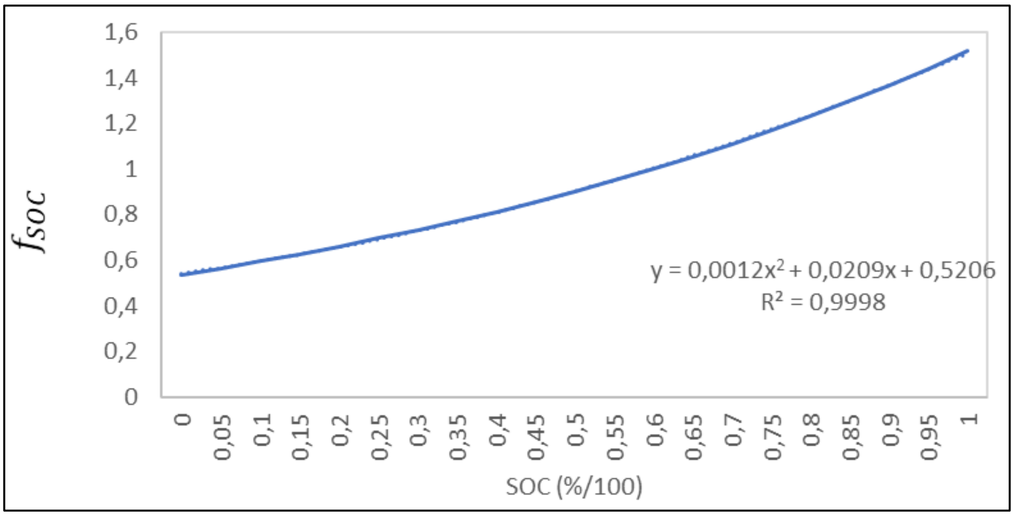

Figure 8. SoC stress model.

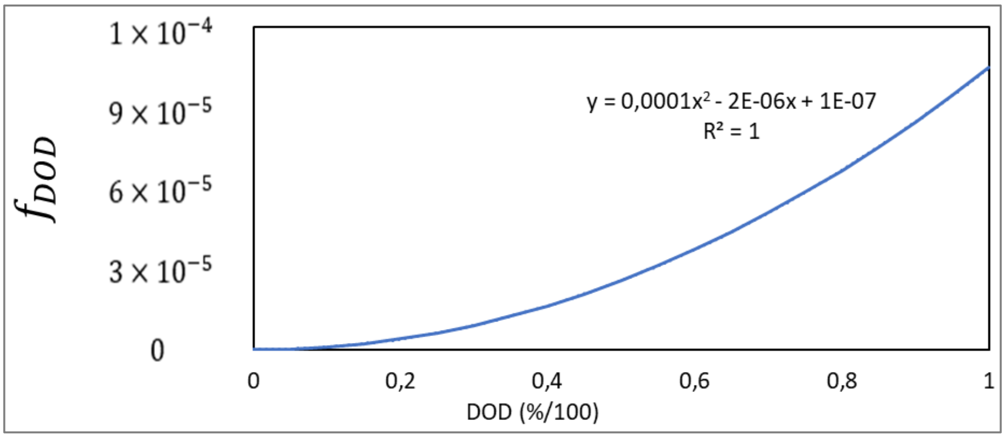

Figure 9. DoD stress model.

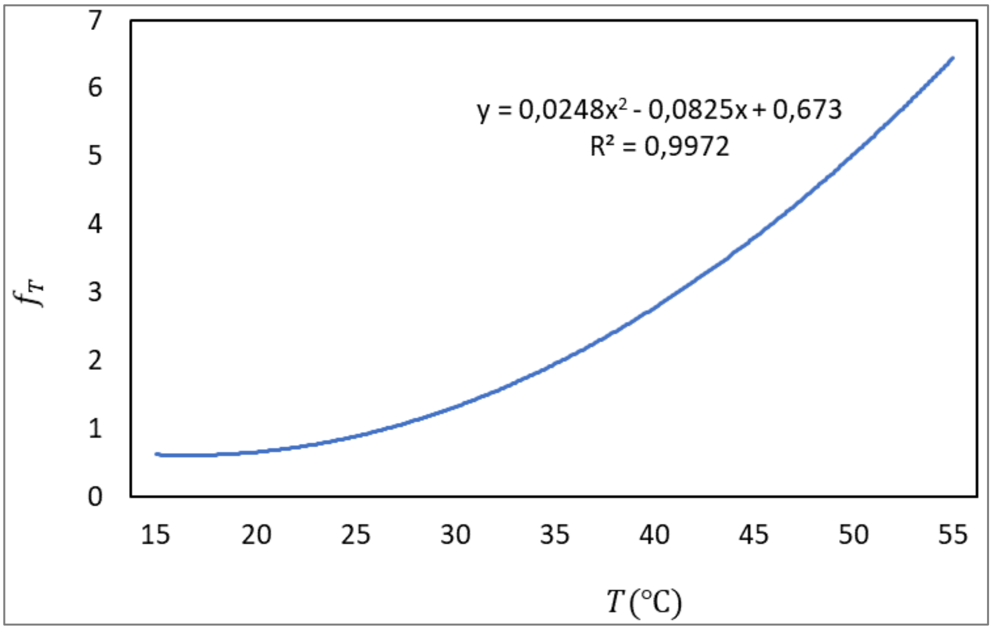

Figure 10. Temperature stress model.

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

$$\left.\begin{aligned} f_d &= f_t(t) f_{soc}(\overline{soc}) f_T(\bar{T}) + \textstyle\sum_{i=1}^{N} f_{DOD}(DOD_i) f_{soc}(soc_i) f_T(T_i), \\ f_t &= 4.1375 \times 10^{-10} t, \\ f_{SOC} &= 0.0012 soc^2 + 0.0209 soc + 0.5206, \\ f_{DOD} &= 0.0001 DOD^2 + 2 \times 10^{-6} DOD + 1 \times 10^{-7}, \\ f_T &= 0.0248 T^2 - 0.0825 T + 0.673. \end{aligned}\right\} \quad (1)$$

Due to the multifaceted nature of battery degradation and its varying rates of change over time, it is imperative to take into account this degradation to ascertain the feasibility of revenue generation. O&M is included as 0.1% of the initial investment to calculate cash flow. Subsequently, the project's feasibility is assessed by examining the net present value (NPV), internal rate of return (IRR), and payback (PB), as presented in **Table 4** based on our previous work in Wangsupphaphol *et al*. (2023). The investigation reveals that when the SDF is 0.3, the payback period amounts to 7.43 years. Conversely, when the SDF is increased to 0.6, the payback period is halved. The cost of the SLiB does not constitute a significant portion of the overall investment. Consequently, a larger battery capacity does not hold substantial relevance in terms of achieving a short payback period. The shorter payback period can be attributed to the increased revenue generated by the larger SDF), which necessitates a larger battery size. This larger battery size results in a shorter payback period when compared to the smaller SDF and corresponding battery size.

4.2. Technical and Economic Assessment of Hybrid Power Source for Solar Motor Pump

The evaluation of the energy supply to the solar motor pump involves assessing the energy production, denoted as E_p, during the period from 7.00 to 9.00. This energy production is estimated to be around 10 kWh, taking into account the utilization of 30 solar PV modules and a radiation level of 300 W/m^2. The storage of energy necessitates a capacity of 15 kWh in the SLiB, as determined by the SoH value of 0.8 and DoD value of 0.85. To effectively store solar energy generated during peak production hours (10:00-14:30) for subsequent use in powering motors, it is recommended to employ a battery system. Based on the SDF of 0.3 and 0.6, the required number of solar PV panels would be 14 modules (7.7 kW) and 7 modules (3.85 kW) respectively. This is derived from the computation presented in **Table 2**. Hence, the hybrid power source necessitates an initial investment of USD 5,589 for SDF 0.3 and USD 3,109 for SDF 0.6. From the techno-economic assessment as shown in **Table 5**, one can observe that the larger SDF (higher solar radiation) produces a smaller investment against the small SDF while the same revenue is achieved. Therefore, a faster return could happen where the payback period is short and motivated. However, the energy requirement for irrigation of about 10 kWh could not be maintained during its lifetime because of the gradual battery capacity reduction. It is recognized that the energy can be mandated by the hybrid inverter by taking assisting power from solar PV along with the battery during the irrigation time. Therefore, it would not trouble the operation of 10 years as desired.

Based on the techno-economic assessment presented in **Table 5**, it can be observed that a larger SDF, which corresponds to higher solar radiation, results in a reduced investment requirement compared to a smaller SDF, while yielding the same level of revenue. Hence, it is plausible for a more expedited reimbursement to occur in cases where the payback period is short and driven by strong incentives. Nevertheless, the energy demand for irrigation, which amounts to approximately 10 kWh, is found to be insufficient over the entire length of its operational lifespan due to the gradual decline in battery capacity. It is widely acknowledged that the hybrid inverter can regulate energy flow by utilizing supplementary power derived from solar PV systems and batteries, particularly during irrigation periods 7.00 to 9.00. Hence, it would not impede the intended operation over 10 years.

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

Table 4. Technical and economic evaluation of hybrid power source with 16.5 kW PV rated and different SDF-battery capacity for agricultural farm loads.

	Parameters	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Technical	State-of-health; $SOH = 1 - (1-0.2)e^{-f_d}$	80.00%	75.89%	71.99%	68.29%	64.78%	61.45%	58.29%	55.29%	52.45%	49.75%	47.20%
	SLiB degradation		4.11%	3.90%	3.70%	3.51%	3.33%	3.16%	3.00%	2.84%	2.70%	2.56%
Economics of SDF 0.3 and B_{rat} 32 kWh,	Battery available energy (kWh); $B_{avl} = B_{rat} \times \% \frac{SOH}{100} \times \frac{\%DOD}{100}$		20.6	19.6	18.6	17.6	16.7	15.9	15.0	14.3	13.5	12.8
	Revenue (USD); $R = [DG - LCOE_{hyd}] \times B_{avl} \times 365$		2559.4	2427.8	2303.0	2184.7	2072.4	1965.8	1864.8	1768.9	1678.0	1591.7
	O&M ($0.1\% \times C_o$)		-12.0	-12.0	-12.0	-12.0	-12.0	-12.0	-12.0	-12.0	-12.0	-12.0
	Investment (USD); C_o	-11970	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Yearly cashflow (USD); $C_y = R - O\&M - C_o$	-11970	2547.4	2415.9	2291.1	2172.7	2060.4	1953.9	1852.8	1756.9	1666.0	1579.8
	NPV each year (USD); $NPV = -C_o + \sum_{y=1}^{n} \frac{C_y}{(1+r)^y}$	-11970	-9611	-7540	-5721	-4124	-2722	-1490	-409.7	539.5	1372.9	2104.7
	**Payback (year);		1	1	1	1	1	1	1	0.43	0	0
	$PB = p + \frac{NPV_p}{NPV_p - NPV_{p+1}}$	7.43										
	IRR; $0 = -C_o + \sum_{y=1}^{n} \frac{C_y}{(1+IRR)^y}$	12.13%										
	NPV (USD)	2104.7										

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

Table 4 (Continue). Technical and economic evaluation of hybrid power source with 16.5 kW PV rated and different SDF-battery capacity for agricultural farm loads.

	Parameters	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Economics of SDF 0.6 and B_{rat} 64 kWh	Battery available energy (kWh)		41.28	39.16	37.15	35.24	33.43	31.71	30.08	28.53	27.07	25.67
	Revenue (USD)		5,119	4,856	4,606	4,369	4,145	3,932	3,730	3,538	3,356	3,183
	O&M		-13.31	-13.31	-13.31	-13.31	-13.31	-13.31	-13.31	-13.31	-13.31	-13.31
	Investment (USD)	-13314	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Cashflow (USD)	-13314	5105.5	4842.3	4592.7	4356.0	4131.3	3918.3	3716.2	3524.5	3342.6	3170.1
	NPV each year (USD)	-13314	-8586	-4435	-789.2	2412.5	5224.3	7693.5	9861.9	11766	13438	14906
	Payback (year)		1	1	1	0.25	0	0	0	0	0	0
		3.25										
	IRR	31.76%										
	NPV (USD)	14906.6										

**Remark: In the payback calculation, p is the number of years that have to pass before the NPV becomes positive, NPV_p is the NPV before it becomes positive, and NPV_{p+1} is the NPV after it becomes positive.

Table 5. Technical and economic analysis of a hybrid power source with a 15-kWh battery capacity and various SDF-PV ratings for only irrigation motor pump.

	Parameters	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Technical	State-of-health; $SOH = 1 - (1 - 0.2)e^{-f_d}$	80.00%	75.89%	71.99%	68.29%	64.78%	61.45%	58.29%	55.29%	52.45%	49.75%	47.20%
	SLiB degradation		4.11%	3.90%	3.70%	3.51%	3.33%	3.16%	3.00%	2.84%	2.70%	2.56%
Economics of SDF 0.3 and PV_{rat} 7.7 kW	Battery available energy (kWh)		9.7	9.2	8.7	8.3	7.8	7.4	7.0	6.7	6.3	6.0
	Revenue (USD)		1200	1138	1080	1024	971	921	874	829	787	746
	O&M		-6	-6	-6	-6	-6	-6	-6	-6	-6	-6
	Investment (USD)	-5589	0	0	0	0	0	0	0	0	0	0
	Cashflow (USD)	-5589	1194	1132	1074	1018	966	916	869	824	781	741
	NPV each year (USD)	-5589	-4483	-3512	-2660	-1911	-1254	-677	-170	275	666	1009
	Payback (year)		1	1	1	1	1	1	1	0	0	0
		7.38										
	IRR	12.24%										
	NPV (USD)	1008.9										

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

Table 5 (Continue). Technical and economic analysis of a hybrid power source with a 15-kWh battery capacity and various SDF-PV ratings for only irrigation motor pump.

	Parameters	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
Economics of SDF 0.6 and PV_{rat} 3.85 kW	Battery available energy (kWh)		9.7	9.2	8.7	8.3	7.8	7.4	7.0	6.7	6.3	6.0
	Revenue (USD)		1199.7	1138.1	1079.6	1024.1	971.4	921.5	874.1	829.2	786.6	746.1
	O&M		-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1
	Investment (USD)	-3109	0	0	0	0	0	0	0	0	0	0
	Cashflow (USD)	-3109	1197	1135	1076	1021	968	918	871	826	783	743
	NPV each year (USD)	-3109	-2001	-1028	-174	577	1236	1814	2323	2769	3161	3505
	Payback (year)	3.23	1	1	1	0	0	0	0	0	0	0
	IRR	31.91%										
	NPV (USD)	3504.9										

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

4.3. Sensitivity Analysis of The Hybrid Power Source for Farm Loads and Motor Pump

Based on the level of advancement in solar PV system engineering, procurement, and construction, it is feasible to pursue the development of a solar PV-battery hybrid power source. Nevertheless, the expense associated with SLiB is contingent upon several factors, including the origin of the battery, refurbishment costs, taxes, and other relevant variables. Consequently, the sensitivity analysis of battery costs concerning the SDF is conducted for various payback periods. The systems under study for sensitivity analysis are organized around two main aspects: (1) the utilization of a hybrid power source to harness solar energy for farm load supply following irrigation, and (2) the determination of the appropriate size for the hybrid power source solely dedicated to powering the irrigation motor pump. The SDF has been varied within the range of 0.3 to 0.6, with an increment of 0.1. Similarly, the SLiB cost has been adjusted from 50 to 200 dollars, with an increase of 50 dollars. Consequently, the calculation of PB follows the previously mentioned method.

The findings from the analysis of both examined systems reveal that when the SDF exceeds 0.5 and the cost of the battery is below 100 USD/kWh, the payback period is approximately 5 years. This duration represents half of the intended project lifespan, as illustrated in **Figures 11** and **12**. It is important to acknowledge that an SDF value below 0.5 may not yield advantageous outcomes for farmers contemplating an investment in a hybrid power source. Moreover, the current pricing of a new Li-ion battery, which is comparable to the cost of the SLiB at approximately 200 USD/kWh, serves as evidence that the implementation of a new hybrid power plant utilizing these batteries is currently not economically viable. The SLiB represents a viable solution for achieving a net-zero emission power supply across various applications, while concurrently prioritizing battery cycle longevity and sustainability.

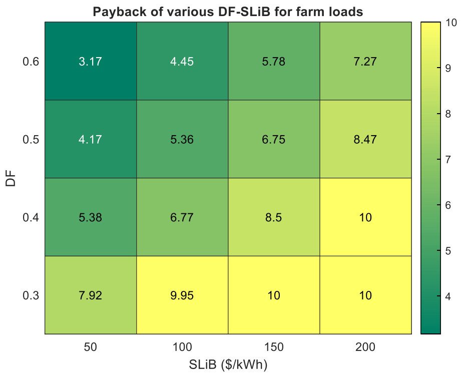

Figure 11. The payback period for SDF cost scenario for a hybrid power source in various applications.

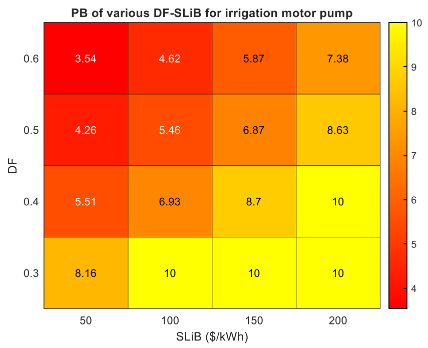

Figure 12. The payback period for SLiB cost scenario for a hybrid power source in various applications.

DOI: https://doi.org/10.17509/ijost.v9i1.64378
p- ISSN 2528-1410 e- ISSN 2527-8045

5. CONCLUSION

This research paper presents a comprehensive examination of the technical and economic aspects of utilizing a solar PV-SLiB hybrid power source to irrigate durian farms. The analysis is conducted by considering real-world conditions, historical data, and technical specifications. The farm's geographical positioning and environmental factors contribute to the battery's compliance with safety standards and operational requirements. The power output and life expectancy of solar PV systems and batteries are influenced by historical solar radiation and temperature data. The designs are specifically tailored for two purposes: (1) addressing the issue of electric loads on the farm, where the energy generated by solar PV systems is currently being wasted after irrigation, and (2) focusing on utilizing the irrigation motor pump. The preceding design exhibits an identical solar PV rating, albeit with a distinct battery capacity. Conversely, the succeeding design showcases an equivalent battery capacity for motor propulsion, albeit with a contrasting PV rating. Various considerations related to SDF are applicable in each of these instances. The impact of battery capacity on revenue is found to be insignificant in comparison to the size of the PV system. The utilization of a higher SDF leads to an expedited approach to capital recovery. This, in turn, results in increased power generation and a reduced payback period for the PV system of the same rating. The subsequent step involves performing a sensitivity analysis to examine the influence of changes in battery cost and SDF variations. The payback period for a project spanning 10 years is found to be approximately 5 years under the condition that the cost of the battery is below USD100 per kWh and the discount factor is higher than 0.5.

6. ACKNOWLEDGMENT

This research is supported by the Ratchadapisek Somphot Fund for Postdoctoral Fellowship and the Center of Excellence in Electrical Power Technology, Faculty of Engineering, Chulalongkorn University.

7. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the data and the paper are free of plagiarism.

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