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Techno-Economic of Residential Application for Grid-Connected Photovoltaic-Battery under Net Energy

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ABSTRACT

Nowadays, the demand for electrical energy is increasing due to the widespread use of electrical equipment such as air conditioners, refrigerators, televisions, computers etc. Grid-connected photovoltaic (PV) systems allow significant penetration of PV generated electricity into the national utility grid particularly under Net Energy Metering (NEM) incentive. However, it can cause grid instability and energy curtailment. The self-consumption (SELCO) program offers a solution by reducing the amount of PV energy fed into the grid through direct consumption of generated electricity and storage of excess energy in batteries. This paper presents a techno-economic analysis of a PV-battery system for grid-connected residential applications using PVsyst software. The self-consumption ratio (SCR), self-sufficient ratio (SSR), net present value (NPV), return on investment (ROI) and simple payback period are analyzed. The results show that the average monthly SCR and SSR are 85.8% and 68.8% respectively. The ROI is 17.8% with a payback period of 10.2 years, indicating that the investment in this project is financially viable.

Keywords:
Photovoltaic; grid-connected; net energy metering; PVsyst; self-consumption

1. Introduction

Energy is one of the essential resources that drives industrial and economic growth worldwide. The steady growth of industrialization has led to increase demand for electrical appliances [1]. Renewable energy sources (RES) such as wind and solar has become alternative energy sources due to the depletion of fossil fuel supplies [2]. Among RES technologies, PV systems have gained popularity because of abundant solar irradiation and ease of installation for small scales application compared to other RES [3].

At the beginning of PV technology was introduced, the installation costs were high, reaching $4808 per kW in 2010 [4]. Some of incentive introduced by government to encourage the installation of PV technology like Feed in Tariff (FiT). This incentive guaranteed the system owners to fed in the

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PV electricity generation into the grid with fixed rated price per kWh for specific period of time [5]. Over the years, PV installation costs have decreased, and alternative incentives such as net energy metering (NEM) have been introduced. Under the NEM scheme, system owner can export the excess energy back to the grid [6] and the electricity bills are calculated by offset the energy imported with the energy exported. Since the PV installation costs drop to \$857 per kW [4], some countries shifted to a self-consumption (SELCO) program. This program allows PV system owners to fully utilise the electricity generated to meet their own loads. Any insufficient energy needs are imported from the grid, while excess energy is stored in energy storage systems. In this scenario, PV installation is typically integrated with batteries to store surplus energy by PV generation [7].

The penetration of PV generation into the grid may lead to issues such as high energy export during periods of low demand, reverse power flow, increased power loss, and voltage fluctuations [8-10]. The integration of batteries into the aims to mitigate these challenges cause by the high energy penetration by PV [11]. However, several factors need to be considered regarding this system including technical, economic, and operational aspects such as the study by Aghamohamadi *et al.,* [12] and Bagalini *et al.,* [13]. Economic assessments have highlighted the significance of regional circumstances and incentives as seen in Sweden [14], Thailand [15], Brazil [16], Turkish [17] and the Dominican Republic [18]. However, predicting long-term economic developments is challenging due to the lack of long-term data and a dynamic policy implementation in different countries.

In Malaysia, studies by Halabi *et al.,* [19] and Ngan & Tan [20] have shown that hybrid PV systems combined with wind, diesel generators and batteries are economically viable. These systems can reduce diesel consumption, CO_2 emissions and demonstrate favourable NPV under various configurations. The studies focused on southern Malaysia and off-grid areas in Sabah utilizing HOMER software. Similarly, Khan *et al.,* [21] focused on the design of PV-battery systems for an indigenous school in Selangor, Malaysia, highlighting the practicality of PV systems in remote educational facilities. Meanwhile, Subramani *et al.,* [22] examined the financial benefits of grid-tied PV-battery systems for commercial and industrial customers in Malaysia. Their findings suggested that PV-battery systems can reduce electricity costs by lowering peak energy demands, contributing to a more economically viable energy solution under the Malaysian electricity tariff structure.

Therefore, this research aims to fill the gap by studying the implementation of a self-consumption design using a PV-battery system for households under the NEM incentive. The battery is designed to store excess energy generated by the PV system and provide power during high demand and low solar irradiance. Performance indicators such as the self-consumption rate (SCR), self-sufficient rate (SSR) and economic factor such as simple payback period and return on investment (ROI) are analysed for the system’s implementation.

2. Methodology

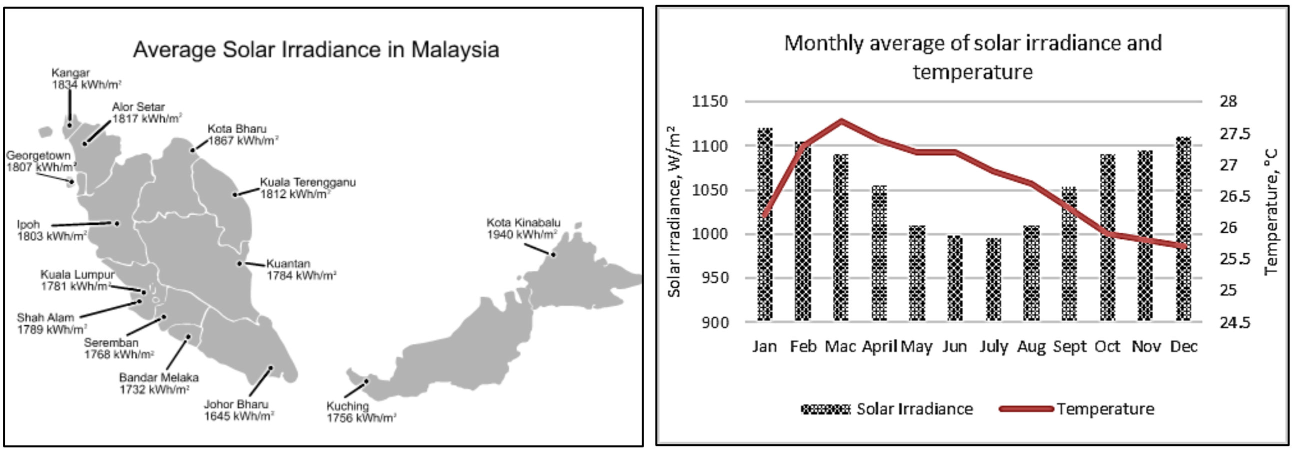
2.1 PVsyst Software

PVsyst is a widely used PV simulation software created by A. Mermoud and M. Villoz, favored by researchers and engineers for design and simulate PV systems in grid-connected, stand-alone or solar pumping system [23]. In this study, the PVsyst 7.3.1 version is used to simulate the grid-connected PV-battery grid.

2.2 Site Location

Malaysia is located in the equatorial region and received daily solar irradiation between 4.7 and 6.5 kWh/m^2 [24]. Perlis, a state in northern Malaysia has a latitude of 6.44°N and a longitude of

100.2°E. It received an average daily solar irradiance of 1061 W/m^2 with an average peak sun hour (PSH) of 5.01. Figure 1 provides solar irradiance data for Malaysia, where Figure 1(a) shows the yearly average solar irradiance in Malaysia and Figure 1(b) illustrates the monthly average solar irradiance and temperature in Kangar, Perlis, Malaysia as recorded by PVGIS provided in the PVsyst database.



(a) (b)

Fig. 1. Solar irradiance and temperature data collected in Malaysia

2.2.1 Load demand

The typical residential load demand in Malaysia is shown in Table 1 while 24-hour load profile is presented in Figure 2. The daily average load consumption is 22.6 kWh with a monthly average load consumption of 678 kWh.

Table 1
Daily average load consumption

Load	Power, W	Quantity	Average daily usage, h	Energy, kWh
Refrigerator	200	1	24	4.8
Television	100	1	6	0.6
Washing machine	300	1	2	0.6
Air conditioning	746	2	7	10.44
Water dispenser	150	1	24	3.6
Rice cooker	300	1	1	0.3
Iron	800	1	0.5	0.4
Ceiling fan	60	2	3.5	0.42
Fluorescent lamp	40	6	6	1.44
Total				22.6

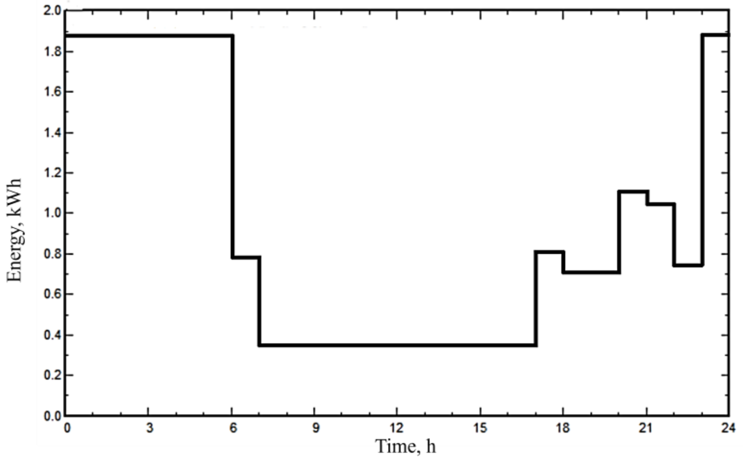


Fig.2. Daily average residential load profile

2.3 System Configuration

The system design is illustrated in Figure 3. This system consists of a PV array connected to a battery. The energy generated by PV charges the battery and supply power to the load. A solar charge controller manages the charging and discharging operations of the battery. The battery serves as energy storage and supplies power to load when the PV system generates insufficient power. Any excess energy from the PV system is fed into the grid while any shortfall in energy is imported from the grid.

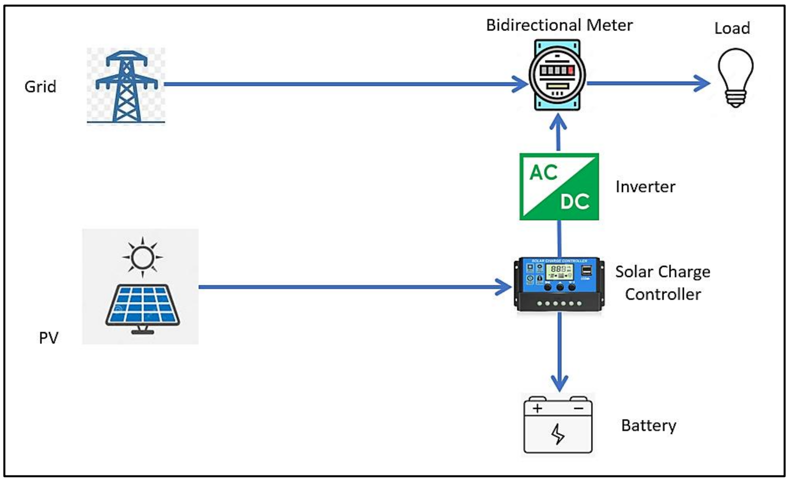


Fig. 3. System design of PV-battery grid-connected

2.3.1 PV generator

Energy generated by a PV system depends on the rated power of the PV module, peak sun hours (PSH), cable losses, and the efficiency of PV module, inverter, cable and temperature derating factor. This is represented by Eq. (1).

$$P_{PV} = \frac{E_{req}}{PSH \times \eta_{PV} \times \eta_{inv} \times \eta_{cable} \times f_{temp}} \qquad (1)$$

where P_{PV} is PV power generation, E_{req} is the daily average load required, PSH is peak sun hours, η_{PV} is PV module efficiency, η_{inv} is the inverter efficiency, η_{cable} is the cable efficiency and f_{temp} is temperature derating factor.

2.3.2 Inverter

In selecting the inverter, the inverter power rating should be more than 80% of the PV output and less than 120% of the PV output as shown in Eq. (2). The percentages are used to protect the inverter at high voltage and high current.

$$0.8\ P_{INV\_DC} < P_{INV\_selected} < 1.2\ P_{INV\_AC} \tag{2}$$

2.3.3 Battery

Battery is used to store the excess energy from the PV system. Battery sizing is based on the average load demand and battery's depth of discharge (DOD). DOD is an important parameter for designers to consider, as it affects the battery's life cycle. The DOD varies depending on the type of battery, whether nickel-cadmium, lead-acid or others. Consequently, the battery capacity, C_{batt} is calculated as shown in Eq. (3).

$$C_{batt}(Ah) = \frac{E_{load} \times sf}{\eta_{inv} \times V_{batt} \times DOD} \tag{3}$$

where E_{load} is daily average load demand, *sf* is safety factor, η_{inv} is the efficiency of inverter, V_{batt} is battery voltage and DOD is battery depth of discharge.

2.4 Performance and Economic Analysis

2.4.1 Self-consumption ratio (SCR)

Self-consumption ratio (SCR) is the ratio of energy consumed to the total energy generated. It can be measured daily, monthly, or yearly as shown in Eq. (4) [25].

$$SCR = \frac{E_{PV} - E_{export}}{E_{PV}} \tag{4}$$

where E_{PV} is the total energy generation by the PV system and E_{export} is the total energy exported to the grid.

2.4.2 Self sufficient ratio (SSR)

Self-sufficiency ratio (SSR) is the ratio of energy consumed to the total load as shown in Eq. (5) [25].

$$SSR = \frac{E_{PV} - E_{export}}{E_{load}} \tag{5}$$

where E_{load} is the total load demand.

2.4.3 Electricity billing

Under the NEM incentive, electricity bills are offset by the amount of energy imported compared to the energy exported as calculated in Eqs. (4) to (5) [26].

$$C_{bill} = (E_{import} - E_{export}) \times R \tag{4}$$

$$C_{saving} = C_{bill\_without\_PV} - C_{bill\_with\_PV} \tag{5}$$

where E_{import} is the amount of energy imported from the grid, E_{export} is the amount of energy exported into the grid, *R* is electricity tariff as shown in Table 2, C_{saving} is the money saved on the electricity bill, $C_{bill\_without\_PV\text{-}BES}$ is the electricity billing without the installation of PV-battery and $C_{bill\_with\_PV}$ is the electricity billing with the PV-battery. In Malaysia, the electricity tariff for domestic consumers is divided based on energy consumption rates as shown in Table 2.

Table 2
Electricity tariff rate for domestic consumer [27]

Rate	Energy, kWh	Rate, R (USD (RM)/kWh)
Rate 1, R1	First 200 kWh (1-200 kWh)	0.052(0.218)
Rate 2, R2	Next 100 kWh (201 – 300 kWh)	0.080(0.334)
Rate 3, R3	Next 300 kWh (301 – 600 kWh)	0.123(0.516)
Rate 4, R4	Next 300 kWh (601 – 900 kWh)	0.130(0.546)
Rate 5, R5	Next kWh (900 kWh onwards)	0.136(0.571)

2.4.4 Net present value (NPV)

Net present value (NPV) is a commonly used indicator to evaluate the investment decisions making. It can be expressed as shown in Eq. (6) [28].

$$NPV = PR - PC \tag{6}$$

$$PR = \sum_{n=1}^{t} \left(C_{saving} \times \frac{(1+inf)^n}{(1+dis)^n} \right) \tag{7}$$

$$PC = C_{ins} + \sum_{n=1}^{t} (C_{OM} + C_{rep}) \times \frac{(1+inf)^n}{(1+dis)^n} \tag{8}$$

where *PR* is the present worth of revenue, *PC* is the present worth of cost, *t* is lifetime of system, *n* is *n-th* year of the system, C_{saving} is the amount saved on electricity billing saving, *inf* is inflation rate, *dis* is discounted rate, C_{ins} is installation cost, C_{OM} is operation and maintenance cost and C_{rep} is replacement cost.

2.4.5 Return on investment (ROI)

Return on investment *(ROI)* is an indicator to evaluate the percentage profit or loss of investment product. The ROI can be calculated as shown in Eq. (9) [28];

$$ROI(\%) = \frac{(PR-PC)}{PC} \times 100 \tag{9}$$

2.4.6 Simple payback period

Payback period refers to the period of investor to recover their investment cost. Eq. (10) represents the payback period calculation [28]. The parameters used in this case study is shown in Table 3.

$$T_{SP} = \frac{C_{ins}}{C_{saving}} \tag{10}$$

where T_{SP} is the payback period.

Table 3
Economic parameter of system design

System	Parameter	Unit	Value
PV	Installation cost including BOS, C_{ins_PV}	\$/kWp (RM/kWp)	\$1,190(RM5,000) [29]
	Operation & maintenance cost, C_{OM_PV}	\$/kW/year (RM/kW/year)	2% of C_{inv_PV} [25]
	Degradation rate, f_d	kW/year	0.8% [30]
	Lifespan	year	25 [30]
Battery	Installation cost include BOS, C_{ins_BES}	\$/kWh (RM/kWh)	\$157(RM659.4) [31]
	Operation & maintenance cost, C_{OM_PV}	\$/kW/year (RM/kW/year)	2% of C_{inv_BES} [25]
	Lifespan	year	10 [32]
	Depth of discharge (DOD)	%	80 [32]
Other parameters	Project period, t	Year	25
	Discount rate, dis	%/year	7.4% [28]
	Inflation rate, inf	%/year	3.2% [28]
	Battery safety factor, *sf*	n/a	1.15
	Exchange rate, RM to \$USD		RM4.2 to \$USD1 [33]

3. Results

3.1 System Sizing

In this study, 14 of JAP60 S01-290/SC 290W JA Solar PV modules [30] and 18 of 648Ah 2V BAE Secura PVSM 880 [32] were selected to achieve a sizing of 4.06 kWp and 22.2 kWh capacity. Meanwhile, the Zeverlution 4000 by Zeversolar [34] was chosen with a 4.0 kW AC. The specifications used in this study are shown in Table 4.

Table 4
Specification of PV-battery system configuration

Parameter	Specification	Quantity	Rated design
PV module	JA Solar JAP60-S01-290-SC	14	4.06 kWp
Inverter	Zeverlution 4000	1	4.0 kW AC
Battery	Bae Secura solar 7PVV 688 Ah 2V	18	22.2 kWh, 12 V

3.2 Energy Produced

Figure 4 shows the simulation results of PV generation, load demand and energy import/export over the year using PVsyst software. The load demand remains consistent, close to 700 kWh for each month. However, the energy generated by PV fluctuates, peaking in January and decreasing significantly by December, reflecting seasonal variations in PV generation due to changes in sunlight availability. When PV generation is lower, such as in March, June, and December, there is a noticeable increase in energy import, indicating a reliance on grid electricity to meet load demand. For example, in March, the highest energy import occurs (304.1 kWh), while PV generation drops to 538.5 kWh. On the other hand, energy export, which represents surplus energy sent back to the grid, is highest in January (113.8 kWh), when PV generation exceeds the load demand.

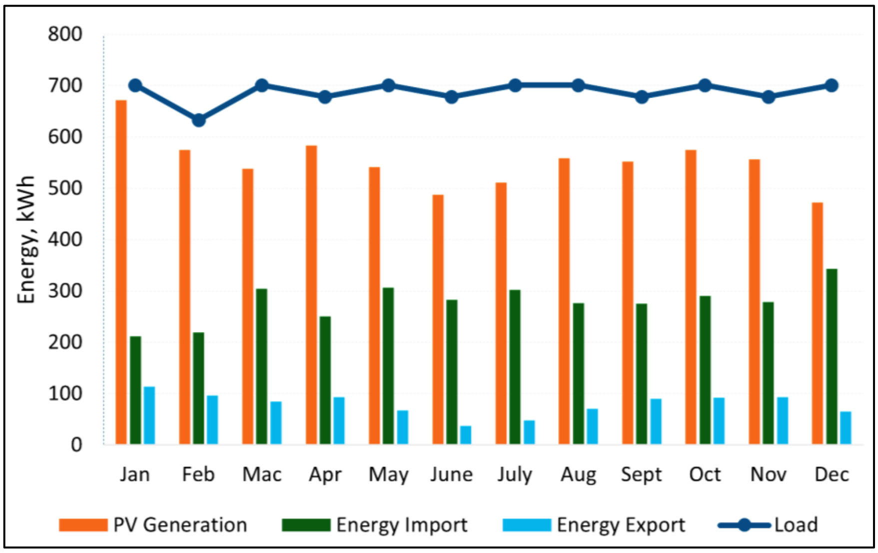


Fig. 4. Annual overview of load, PV generation, and energy import/export

Figure 5 illustrates the daily average interaction between PV generation, load demand, and battery charging and discharging operation over a 24-hour period. During the day, starting around 10.00, PV begins to generate the electricity and peaks between hours 12.00 and 14.00, gradually decreasing and stopping by hour 18.00, reflecting typical daylight solar energy production. The load demand is high during the early hours, particularly between 01.00 and 03.00, then drops significantly until PV generation begins. The load remains steady from 11.00 to 16.00, during which time the battery charges with the excess energy generated by the PV system. Once the PV generation diminishes around 16.00, the battery stops charging and begins discharging to meet the demand, especially as the load surges after 19.00 and again after 23.00. The battery also compensates for energy needs early in the day, between hours 01.00 and 04.00, when there is no PV generation. This system demonstrates efficient energy management by charging the battery during daylight hours when solar energy is abundant and discharging it during periods of high load demand or when solar energy is unavailable, ensuring a continuous energy supply.

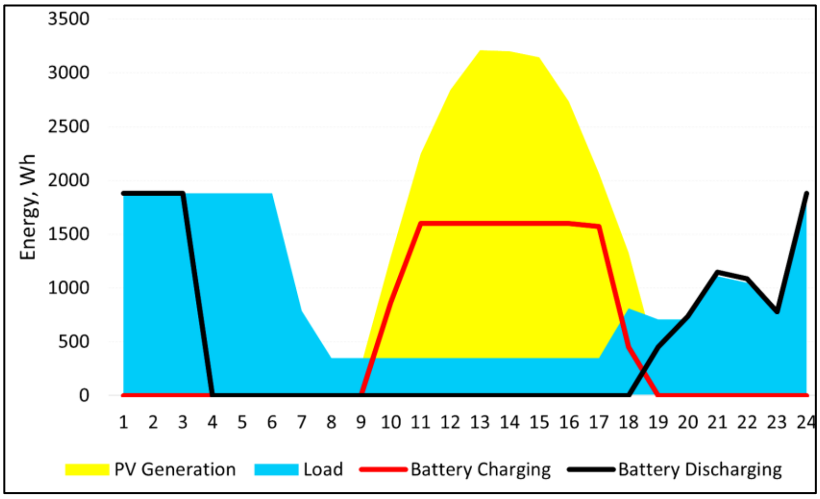


Fig. 5. Daily average energy generated-consume

3.3 Performance Analysis

In this case study, the SCR and SSR are calculated based on the Eq. (4) and Eq. (5) respectively and are shown in Table 5. SCR values remain consistently high, indicating that a significant portion of PV generation is directly consumed by the load, with the highest value in June (92.2%) and the lowest in January (83.1%). This suggests efficient energy usage throughout the year, with only minor fluctuations. In contrast, the SSR, which reflects how much of the total energy demand is met by the PV-battery system, shows more variability. It is highest in January (79.7%), indicating the greatest SSR during this month, and lowest in December (58.2%), when PV generation is low. The SSR gradually declines from January to June and fluctuates thereafter, suggesting seasonal variations in PV generation. Overall, the high percentages of SCR and SSR indicate that the integrating a battery into the PV design maximizes the utilization of energy generated by PV system.

Table 5
Monthly average of SCR and SSR

Month	Jan	Feb	Mac	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
SCR (%)	83.1	83.2	84.3	84.0	87.6	92.2	90.6	87.3	83.8	84.0	83.3	86.3
SSR (%)	79.7	75.5	64.8	72.3	67.7	66.3	66.1	69.6	68.3	68.9	68.4	58.2

3.4 Economic Analysis

The economic analysis is an indicator used to evaluate the performance of the system design and is shown in Table 6. It provides key economic performance indicators to evaluate the financial viability of the project. The NPV is $1926, indicating that this case study is expected to generate positive cash flow and be financially beneficial. The present worth cost (PC) is $10802, representing the total cost of the project, while the present worth revenue (PR) is $12728 showing that the expected revenue will exceed the costs, leading to profitability. The return on investment (ROI) is 17.8%, suggesting a moderate but healthy profit margin. The simple payback period (T_{sp}) is 10.2 years, indicating that it will take over a decade to recover the initial investment, which is typical for long-term projects.

Table 6
Economic performances indicator

Parameter	Value
Net present value, NPV	$ 1926
Present worth cost, PC	$ 10802
Present worth revenue, PR	$ 12728
ROI	17.8%
Simple payback, T_{SP}	10.2years

4. Conclusions

This paper investigates the performance and economic value of a grid connected PV-battery system for residential applications. The SCR and SSR are high, exceeding 83% and 70% respectively, due to the integration of the battery. The battery allows for the storage of excess energy, despite PV generation occurring only between 09.00 and 19.00 per day. The objective of this paper has been achieved through the economic and performance analysis of the PV-battery design. The ROI of this design is 17.8% and the simple payback period of 10.2 years. Furthermore, Malaysia is aiming to transition towards a self-consumption (SELCO) policy for grid-connected PV systems. The integration of batteries will enable the storage of excess energy, helping to mitigate grid instability and curtailment.

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