IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 2 (2026) 340-348
https://publisher.uthm.edu.my/ojs/index.php/ijie

Towards a Sustainable Campus: Performance and Economic Analysis of a Rooftop Solar Power System for an IIUM Campus Building

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DOI: https://doi.org/10.30880/ijie.2026.18.02.027

Article Info

Received: 15 November 2025
Accepted: 31 March 2026
Available online: 6 July 2026

Keywords

Solar power system, grid-connected, PVsyst, shading analysis, levelized cost of energy (LCOE), economic analysis, PV

Abstract

This study presents the design and techno-economic analysis of a grid-connected rooftop solar photovoltaic (PV) system for an IIUM campus building using PVsyst software. The system modeling accounts for key loss factors, including temperature effects, shading, soiling (dust accumulation), and inverter inefficiencies. To validate the simulation approach, results were replicated from a reference study involving a 16.2 kWp PV system. For the IIUM campus building, nine configurations were assessed, combining three rooftop areas (1,200 m^2, 1,400 m^2, and 1,600 m^2) with three PV module power ratings (535 Wp, 575 Wp, and 615 Wp). Among these, Design 7 (535 Wp modules with a 1,600 m^2 area) demonstrated the best overall performance, delivering an annual energy output of 362,151 kWh, a payback period of 7.4 years, and the lowest levelized cost of energy at RM 0.14 per kWh.

1. Introduction

Malaysia's push toward renewable energy highlights the role of solar PV as a clean and scalable energy solution. With high solar irradiance levels, favorable government incentives, and declining technology costs, solar PV adoption has expanded, particularly for institutional and commercial applications. However, system performance depends heavily on local design parameters such as tilt angle, orientation, and shading effects. In Malaysia, grid-connected solar PV systems for educational institutions remain underutilized despite the government's National Energy Transition Roadmap (NETR), which targets 70% renewable energy capacity by 2050. Studies show that small-scale PV rooftop systems under the NEM scheme are financially viable for residential users, offering reasonable payback periods and long-term savings [1].

Recent studies have demonstrated the technical suitability and environmental benefits of rooftop solar power systems in Malaysian educational buildings [2]. Malaysia's location near the equator means it gets a lot of sunlight consistently (4.21–5.56 kWh/m^2/day) throughout the year, which is great for solar panels. Research shows that Malaysia enjoys between 2,200 and 3,000 hours of sunshine each year, more than many other countries in Asia [3]. Solar power generation in urban areas faces several challenges, such as efficiency losses of 3-8% due to dirt and air pollution, and limited roof space in densely built environments [4]. New studies suggest that using passive cooling methods, like raising the solar panels, can help deal with Malaysia's hot temperatures (28-32°C), which can otherwise lower the efficiency of the panels by 0.4–0.5% for every degree above standard testing conditions (STC) [5]. Government initiatives such as the Net Energy Metering (NEM) program, Green Investment Tax

Allowance (GITA), and Sustainable Energy Development Authority (SEDA) incentives have driven adoption among homeowners and institutions [6].

Solar PV systems connected to the grid are now the most common setup for businesses and institutions around the globe. Recent research shows that systems with a capacity of between 100-500 kWp usually have performance ratios (PR) ranging from 75-85% under ideal conditions [7]. However, systems in institutions encounter specific issues - a 2023 study on university systems in Southeast Asia revealed that their average PR values were 8-12% lower than those of commercial systems, due to inconsistent load patterns and limitations from building designs [8]. Furthermore, studies in Malaysia have assessed the performance of rooftop PV systems on university buildings, providing valuable insights into their energy generation and economic viability [9], [10].

Research also extends to the design and simulation of such systems in specific university contexts to cover electricity demand. At Taylor's University, a study on a 433 kWp grid-connected rooftop solar PV system indicated a significant reduction in electricity consumption, supporting sustainable energy goals. The system is projected to deliver substantial annual savings with an estimated payback period of eight years [11]. Theres's also a 56.7 kW on-grid photovoltaic system designed for the Engineering Faculty at Mu'tah University can cover its 96 MWh annual electricity demand, with a capital cost of $117,000 and an estimated payback period of 5.5 years [12]. The design and assessment of rooftop solar photovoltaic systems are crucial for achieving sustainable campuses and evaluating their performance, even for secondary schools [13], [14]. A design and feasibility study by Sujoy Barua [13] demonstrated that a grid-connected rooftop solar photovoltaic system for an academic campus in India could generate 590 MWh annually, covering about 11% of the total energy consumption and saving three tons of carbon dioxide. Geospatial and aerial imaging techniques have also been applied to evaluate rooftop solar potential in Malaysian universities.

A study conducted at Universiti Kebangsaan Malaysia (UKM) using UAV and GIS-based analysis confirmed high solar suitability on campus buildings, reinforcing the viability of campus-wide PV deployment [15]. The techno-economic analysis of solar PV systems is crucial for evaluating their financial viability and broader adoption, particularly within the Malaysian context. Recent studies have investigated the economic feasibility and performance of grid-connected rooftop solar PV systems, including those implemented at educational institutions like UiTM Shah Alam [16], and commercial-sized installations under schemes such as NEM 3.0 [17]. Furthermore, research extends to specialized applications, assessing the techno-economic potential of solar energy implementation in critical sectors like hospitals in Malaysia, highlighting the diverse applicability and economic benefits across various building types [18]. A recent study using the UTAUT2 framework in the Malaysian context found that public interest is significantly influenced by price perception, performance expectations, and environmental concerns [19].

This study presents a techno-economic analysis of a rooftop solar PV system for the E0 building at the IIUM Kulliyyah of Engineering, utilizing PVsyst software. Various system configurations are evaluated to identify the optimal balance between energy production and financial feasibility. Although the results are specific to the site, the methodology offers a useful framework for similar future assessments.

2. Methodology

2.1 Simulation Setup

The simulation-based assessment of the rooftop solar PV system begins with a comprehensive data collection phase. This included acquiring site-specific information such as the building's rooftop dimensions, tilt angle, azimuth orientation, and local meteorological data using PVsyst 7.4 software. Meteonorm 8.1 weather data specific to the IIUM Gombak location (3.252°N, 101.735°E) is demonstrated in Fig. 1. Global Horizontal Irradiation (GHI), totaling 1773 kWh/m^2/year, includes both direct and diffuse solar radiation received on a horizontal surface. In contrast, Diffuse Horizontal Irradiation (DHI), totaling 955 kWh/m^2/year, accounts solely for the scattered (diffuse) component of the incoming solar radiation. The P50 probability method is used to estimate the energy production scenario, based on average weather conditions. This method implies an equal 50% likelihood that the actual energy production will be either higher or lower than the simulated estimate, making it a reliable baseline for the design study. The P50-GHI is used to compute the solar energy on the solar panel's plane according to orientation and tilt angle. All key system losses, including those from temperature, shading, dust accumulation (soiling), and inverter inefficiencies, are accounted for in the analysis.

Subsequently, the solar power system specifications are determined, including the choice of PV modules and inverters, the location and area of the solar panels, their tilt and azimuth, as well as key installation parameters. The simulation is executed to estimate the annual energy output and assess overall system performance using key performance indicators such as energy yield, performance ratio (PR), and specific production. The financial and environmental evaluation followed, including calculations of the payback period, levelized cost of energy (LCOE), and return on investment (ROI). Finally, all results were compiled into a comprehensive report summarizing the system's technical and economic feasibility for the selected university building.

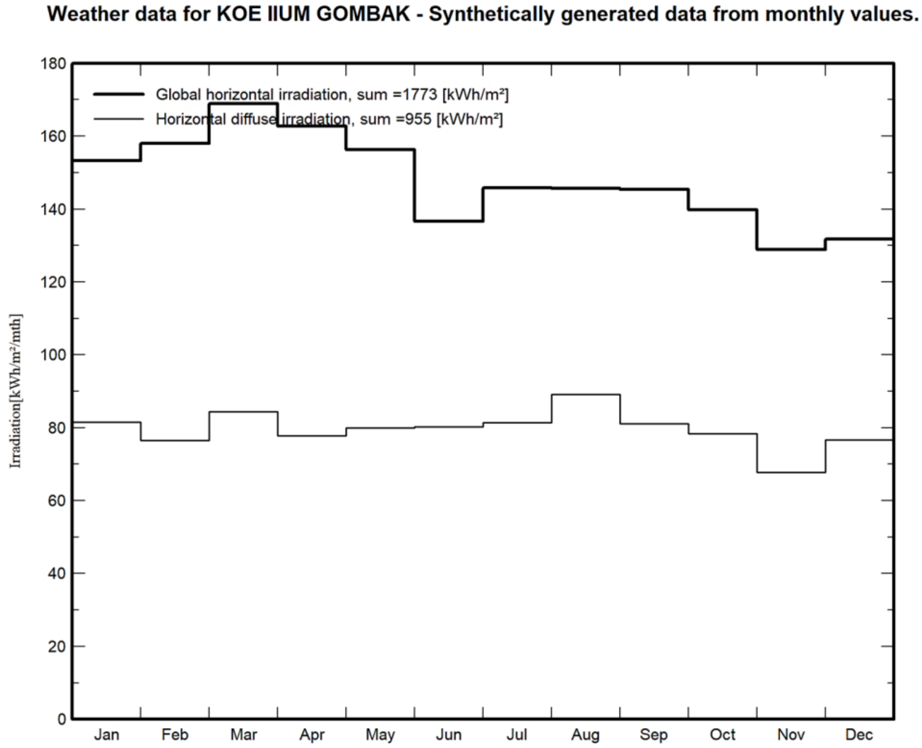

Fig. 1 *Weather data for KOE IIUM Gombak*

Fig. 2 illustrates the locations of the rooftop solar panels on the targeted campus building (E0 building, Kulliyyah of Engineering, IIUM, 3.252°N, 101.735°E) as viewed in Google Earth Pro. The solar panels are installed with a fixed tilt of 45° to match the rooftop slope, while the azimuth varies based on the orientation of each building side (0° for south, 90° for east, 180° for north, and 270° for west).

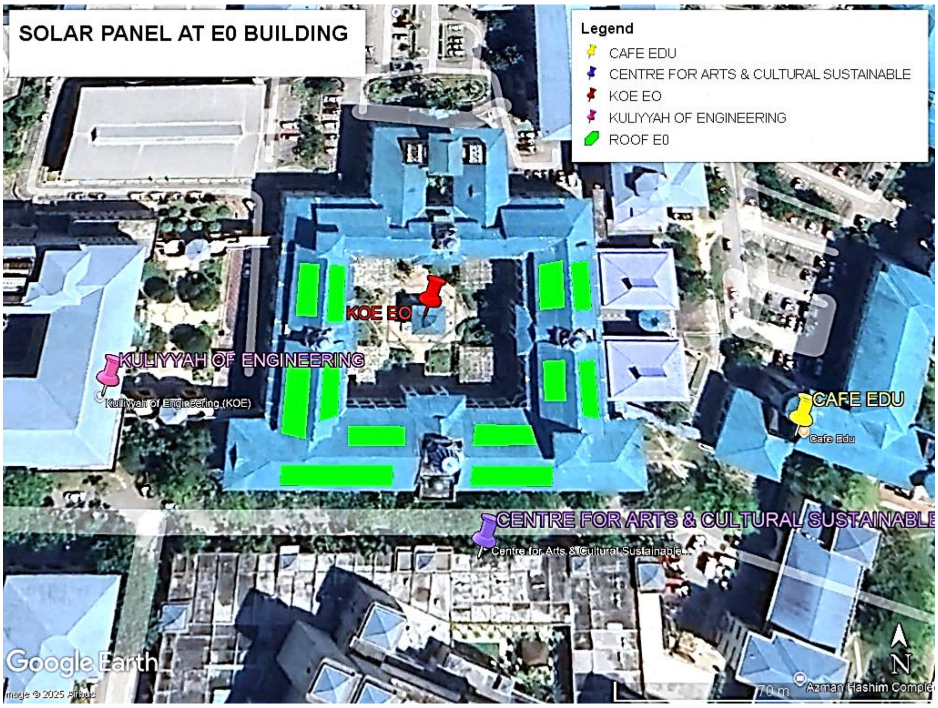

Fig. 2 *Solar panel locations on the rooftop of KOE E0 building as viewed by Google Earth Pro*

A full-factorial design approach was used to evaluate multiple design scenarios by considering three different solar panel areas (1,200 m^2, 1,400 m^2, and 1,600 m^2) with three PV module power ratings (535 Wp, 575 Wp, and 615 Wp). This resulted in a total of nine unique system configurations as listed in Table 1. The purpose of this variation is to analyze how changes in module efficiency and panel coverage area would impact energy output and financial performance, enabling the identification of the most optimal design in terms of both technical and economic viability.

Table 1 Solar power *system configurations*

Design	Solar panel area (m^2)	PV module rating (Wp)
Design 1	1200	535
Design 2	1200	575
Design 3	1200	615
Design 4	1400	535
Design 5	1400	575
Design 6	1400	615
Design 7	1600	535
Design 8	1600	575
Design 9	1600	615

Monocrystalline solar panels are selected for their high efficiency and better performance under Malaysia's high-temperature conditions. A suitable inverter, Huawei SUN2000-33KTL is selected based on matching the DC system size and ensuring optimized performance under partial shading conditions also known for their high efficiency and grid compliance [20]. Nine configurations are simulated by combining PV Module Power Ratings: 535 Wp, 575 Wp, 615 Wp (Jinko Solar JKM series). All nine designs are simulated under 3D shading conditions as illustrated in Fig. 3.

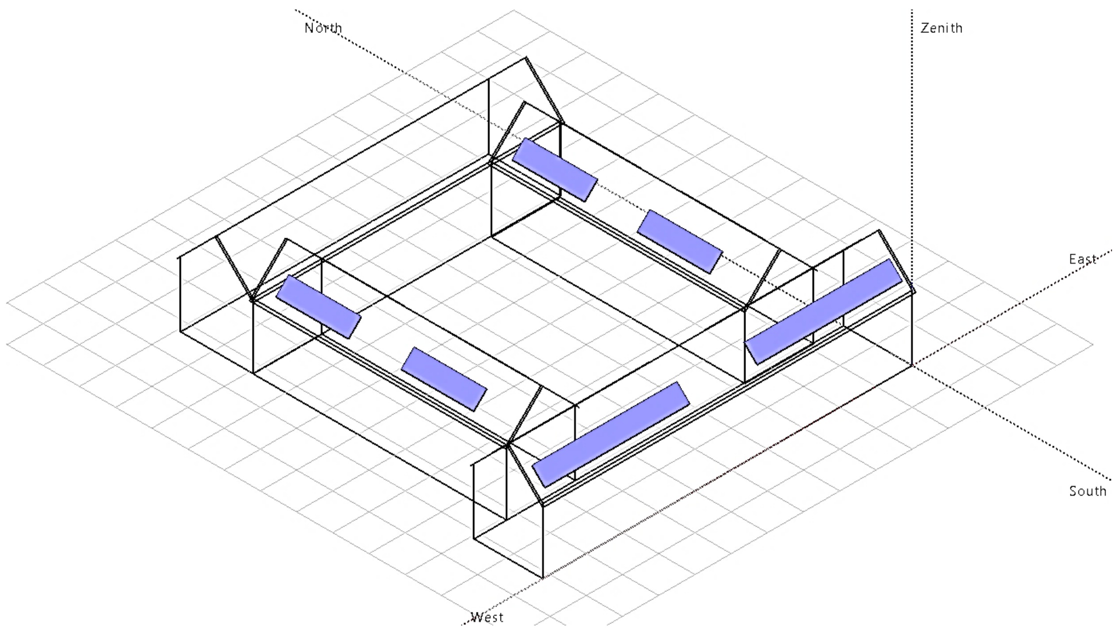

Fig. 3 *3D scene construction of shading scenario*

Performance metrics are calculated as:

$$\text{Performance energy yield (kWh/year)}, E = G\ A\ \eta_{total} \tag{1}$$

where G is Solar irradiance on the module plane (kWh/m^2/year), A is the total area of the PV module (m^2), η_{total} is the overall solar power system efficiency (including all losses and shading effect).

$$\text{Performance ratio}, PR = \frac{E}{E_{ideal}} \tag{2}$$

PR is a key metric used to evaluate the efficiency and overall quality of a solar power system. It expresses the ratio of actual energy output to the theoretical energy output under ideal conditions. The ideal energy output (E_{ideal}) is calculated by multiplying the incident solar energy by the system's rated power. A well-designed rooftop system typically has a PR between 75% and 90%. For financial analysis, the lifetime of the solar power system is assumed as 20 years. The economic performance of the solar PV system was evaluated by estimating:

$$Payback\ Period\ (years) = \frac{Total\ System\ Cost\ (RM)}{Annual\ Savings\ (\frac{RM}{year})} \tag{3}$$

$$\text{Levelized cost of Energy}, LCOE = \frac{\sum_{t=1}^{n}(\frac{C_t}{(1+r)^t})}{\sum_{t=1}^{n}(\frac{E_t}{(1+r)^t})} \tag{4}$$

where C_t is the total cost in year t, E_t is the energy generated in year t, r is the discount rate, and n the system lifetime. Generally, a lower LCOE is preferable as it indicates a more cost-effective energy source. LCOE is calculated by dividing the total cost of building and operating the solar power system over its lifespan by the total electricity generated.

$$\text{Return on Investment}, ROI(\%) = \left(\frac{Total\ Profit}{Total\ Investment\ Cost}\right) \times 100 \tag{5}$$

3. Results

3.1 Validation

A validation study was conducted by replicating the system setup from a published case study of a 16.2 kWp rooftop solar PV installation in Bukit Tinggi (6.21°N, 100.43°E) [21]. Solar panels area is 81 m^2, tilt angle is 25°, and azimuth angle is 140°. Silicon Monocrystalline PV solar cells with 405 Wp power rating were used along with 4 dual Maximum Power Point Tracker (MPPT) inverter. Table 2 shows the validation results, with a maximum deviation of less than 5% in energy output, performance ratio, and specific yield. This minor variation is primarily attributed to differences in PVsyst software versions and updates in weather data.

Table 2 *Validation results*

Performance metric	Reference [21]	Present work	Difference [%]
Annual energy output (kWh)	21,590	22,282	+3.21
Performance ratio (%)	80.21	82.68	+3.07
Specific yield (kWh/kWp/year)	1333	1375	+3.15

3.2 IIUM Campus Building

3.2.1 Performance Analysis

The results for the nine system configurations are presented in Table 3. The Performance Ratio (PR) across all designs ranged from 80.8% to 82.1%, reflecting strong technical performance. Specific yield values exceeded 1170 kWh/kWp/year for all configurations. Design 6 (1400 m^2, 615 Wp) achieved the highest annual energy output at 374,756 kWh, followed by Design 9 (1600 m^2, 615 Wp) with 374,301 kWh, and Design 7 (1600 m^2, 535 Wp) with 362,151 kWh. Among these top-performing systems, Design 6 achieved both the highest PR and the highest specific yield.

Table 3 *Comparison for multiple designs*

Design	Solar panel area (m^2)	PV module rating (Wp)	Capacity (kWp)	Energy output (kWh/year)	PR (%)	Specific yield (kWh/kWp/year)
Design 1	1200	535	240	282,625	80.8	1179
Design 2	1200	575	248	294,422	81.21	1185
Design 3	1200	615	266	318,401	82.12	1198
Design 4	1400	535	289	340,731	80.81	1179
Design 5	1400	575	276	326,522	81.06	1183
Design 6	1400	615	315	374,756	81.55	1190
Design 7	1600	535	308	362,151	80.52	1175
Design 8	1600	575	294	347,206	80.81	1179
Design 9	1600	615	315	374,301	81.45	1189

3.2.2 Economic Analysis

Table 4 provides the economic parameters necessary for conducting financial analysis. The objective is to assess the financial feasibility and determine the most cost-effective rooftop PV system design among the nine configurations. Financial viability is evaluated using key indicators, including payback period, Levelized Cost of Energy (LCOE), and Return on Investment (ROI) as shown in Table 5. We are looking for the shortest payback time, the minimum LOCE and the maximum ROI.

Table 4 *Economic parameters*

Parameter	Value
PV Module:	
535 Wp	RM 550/Unit
575 Wp	RM 750/Unit
615 Wp	RM 950/Unit
Inverter	RM 15388/Unit
Installation cost	RM 1000/Unit
Maintenance cost	RM 3078/Year
Permitting	RM 3000/Unit
Feed-in-tariff	RM 0.365/kWh
Discount rate	0
System expected lifetime	20 years

Table 5 *Financial analysis*

Design	Energy output (kWh/year)	PR (%)	Specific yield (kWh/kWp/year)	Initial cost (MYR)	Payback period (years)	LCOE (MYR/kWh)	ROI (%)
Design 1	282,625	80.8	1179	758,952	7.6	0.15	163.0
Design 2	294,422	81.21	1185	820,552	7.9	0.15	153.7
Design 3	318,401	82.12	1198	906,952	8.0	0.15	148.9
Design 4	340,731	80.81	1179	901,552	7.5	0.14	168.4
Design 5	326,522	81.06	1183	904,552	7.8	0.15	156.1
Design 6	374,756	81.55	1190	1,062,952	8.0	0.15	151.0
Design 7	362,151	80.52	1175	957,352	7.4	0.14	169.1
Design 8	347,206	80.81	1179	960,552	7.8	0.15	156.9
Design 9	374,301	81.45	1189	1,062,952	8.0	0.15	150.7

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 340-348

Design 7 emerged as the most financially favorable option, offering a 7.4-year payback period, a 169.1% ROI, and the lowest LCOE at RM 0.14/kWh. In comparison, although Design 6 achieved the highest energy output, it had a longer payback period of 8 years and a higher LCOE of RM 0.15/kWh, primarily due to its greater capital investment. The cumulative cashflow for design 7 over its 20-year lifespan is demonstrated in Fig. 4. The project finance breaks even (zero cashflow) in 2032 after 7.4 years (payback time). After this payback period, the cashflow keeps increasing, representing real financial benefits from energy savings. The cashflow after the payback indicates consistent growth, proving the system's long-term economic feasibility. In contrast, less effective designs experience a slower increase and reach their break-even points later, highlighting how crucial it is to choose the right system size and components to maximize returns on investment. Design 7 provides the optimal balance between technical performance and economic feasibility, making it the recommended configuration for rooftop solar implementation at the IIUM Kulliyyah of Engineering building.

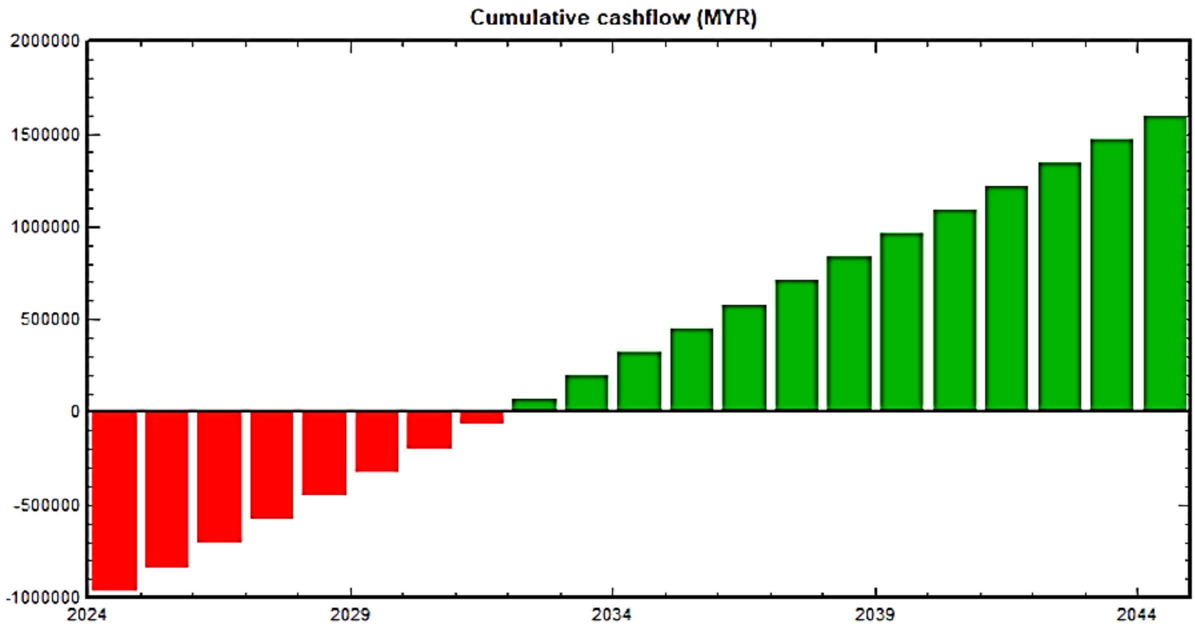

Fig. 4 *Cumulative cashflow for Design 7*

4. Conclusions

Technical and economic analysis of a grid-connected solar power system is conducted for an IIUM campus building. PVsyst software is utilized and key system losses, such as temperature effects, soiling, shading, inverter losses, are incorporated into the analysis. Nine configurations with different solar panel areas and module ratings are evaluated. Design 7 (1,600 m^2, 535 Wp) produced the most balanced results, generating an annual output of 362,151 kWh/year, with a payback period of 7.4 years, and it had the lowest levelized cost of energy at RM 0.14/kWh. This shows the importance of including financial analysis with technical analysis in the decision process. Future research may include real-world monitoring and storage integration to support enhanced system design.

Acknowledgement

The authors would like to acknowledge Kulliyyah of Engineering, International Islamic University Malaysia, for providing the laboratory facilities and technical support necessary to carry out this research.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Aiman Hakeemi, Moumen Idres; **data collection:** Aiman Hakeemi, Moumen Idres; **analysis and interpretation of results:** Aiman Hakeemi, Moumen Idres; **draft manuscript preparation:** Aiman Hakeemi. All authors reviewed the results and approved the final version of the manuscript.*

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