

Design, Sizing and Economic Analysis of Grid-Connected Solar PV (GCPV) System for an Electric Bus Depot in Malaysia

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Abstract- High maximum demand (MD) arising from electric bus charging results in increased operational costs and elevated carbon emissions. Therefore, this paper aims to design, size, and conduct an economic analysis of a grid-connected solar photovoltaic (GCPV) system for an electric bus depot in Malaysia, considering two key constraints: architectural and energy constraints. The architectural constraint is governed by the available installation area, while the energy constraint is based on the proportion of depot energy supplied by solar PV. Three solar energy contribution scenarios (25%, 50%, and 75%) and three PV module power ratings (low, medium, and high) were evaluated. Under the architectural constraint, a GCPV system with a capacity of 1,777 kWp demonstrated the most favourable economic performance, achieving the lowest payback period of approximately 8.7 years and net monthly savings of about MYR 68,153. This configuration requires approximately 3,774 PV modules rated at 470 Wp and seven inverters. In contrast, the energy constraint analysis revealed that a 1,588 kWp GCPV system supplying 75% of the depot's total energy yielded a payback period of 9.1 years, with net monthly savings of approximately MYR 58,448. This design requires about 4,823 PV modules rated at 315 Wp, along with seven inverters. Overall, the architectural constraint approach was found to be more feasible for sizing GCPV systems in the present electric bus depot. This study offers valuable technical and economic insights for stakeholders, supporting informed decision-making for sustainable infrastructure development and demonstrating clear economic and environmental benefits.

Keywords Solar energy, electric bus, maximum demand, grid-connected PV, Malaysia

List of Abbreviations

MD – Maximum Demand	MS – Malaysian Standard
GCPV – Grid-connected PV	NEM – Net Energy Metering
SEDA – Sustainable Energy Development Authority	IEC – International Electrotechnical Commission
BRT – Bus Rapid Transit	STC – Standard Test Condition
EBIM – Elektrik Bas Inovasi Malaysia	MPP – Maximum Power Point
EV – Electric Vehicle	MPPT – Maximum Power Point Tracking

PV – Photovoltaic

LSS – Large Scale Solar

PSH – Peak Sunshine Hour

DC – Direct Current

FiT – Feed-in Tariff

AC – Alternating Current

1. Introduction

The growth in world population with a drastic increase in industrial activities has led to significant consumption of energy. The fact is that globally 39% of the total electricity is produced from coal power plants that have emitted about 14 Gigatons of CO₂ in 2016 [1]. The electricity consumption of Malaysia has increased by almost 65% in the year 2016 (114 TWh) as compared to 2008 (92 TWh). However, most of this electricity is generated using fossil fuels such as coal (45%), and natural gas (40%). In contrast, the contribution from renewable sources remains very minimal (< 2%) in the recent decade [2]. Policymakers in Malaysia have taken major steps to reduce the dependency on fossil fuels and increase the contribution of renewable energy from 1.5% to 20% by the year 2025 in the energy generation [3].

Fig. 1 shows the energy consumed by various sectors in Malaysia for the past 40 years. The energy consumed by the Malaysian transport sector has increased dramatically in the past few years, and it heavily depends on fossil fuels. The transport sector alone generates about 75 million metric tons of CO₂ emissions per year [4]. Out of this, 85% carbon emission comes from road transport alone. For instance, diesel-powered buses emit a large number of air pollutants and global greenhouse gases. This has been estimated to be more than 45% of nitrogen oxides and 75% of particulate matter [5]. Therefore, measures are taken to develop a cleaner and sustainable transport system.

Battery operated electric buses have gained significant popularity across the world due to their unique advantage of zero emissions on the road or operating site. These buses are perfect for running within the short distances of the city area. About 98% of the world's battery-operated electric buses are deployed in China and the rest are adopted by Europe, India, the UK, the USA and South America [6]. Very recently, the UK has announced to ban petrol and diesel vehicles from the year 2035 to address the pollution issues. One such initiative by the Malaysian government was the development of the Bus Rapid Transit (BRT) Sunway transport line which is entirely based on electric buses and located in the Selangor region of Malaysia. These electric buses run on a 5.5 km (one-way) dedicated elevated corridor and connect two important train transit systems. Another Malaysian company named Sync R&D Sdn. Bhd. has developed the Elektrik Bas Inovasi Malaysia (EBIM) program under which they designed electric buses [7]. At present, electric buses are operated in Bandar Sunway, Selangor, Putrajaya, and Melaka city with future deployment in Kota Kinabalu, Kuching, Kota Bahru and other cities in Malaysia and the ASEAN region.

Although electric vehicles including buses are promising choice to achieve sustainable transport system,

however the source of energy to charge these vehicles is a matter of concern because countries like Malaysia are heavily depended on fossil fuel thermal power plants. For instance, one study reports that the power demands for charging 100,000 units of electric vehicle (EV) are ~3300 MW per 160 km travelling if a 33 kWh battery pack is utilised and that is considerably large [8]. Kunitz et al., 2014 reported energy consumption of about 2.3 kWh/km of an electric bus that can even reach 3.6 kWh/km in extreme temperature [9]. Therefore, electricity generation mix and power plant efficiency are the crucial parameters affecting the energy use and emissions of battery-operated electric vehicles [10, 11]. There are several concerns while charging electric vehicles from fossil fuel-based sources:

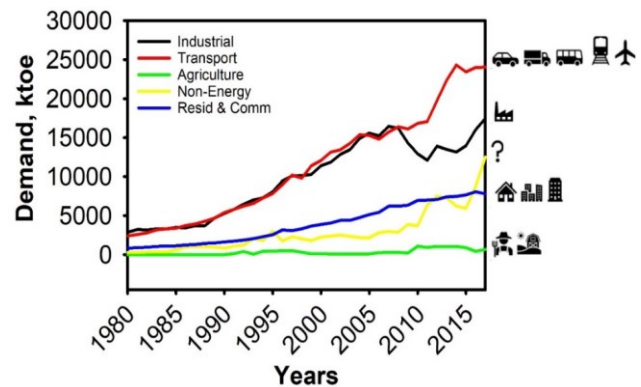


Fig. 1. Final energy demand by sectors in Malaysia.

- Charging electric vehicles consumes a significant amount of electricity
- This creates a spike in the electricity in the form of maximum demand (MD)
- Therefore, a transport company has to pay the high electricity bill for the MD (kW) besides their regular kWh consumption that increases the operational cost of the bus depot
- With the consumption of electricity, the power plant will generate a significant amount of carbon emissions
- Although electric buses are considered clean on the road, however, they are indirectly tied to the carbon emissions at the power plants
- For instance, in our case, electric buses indirectly could emit about 0.85 kg CO₂/km based on energy consumption of ~1.2 kWh/km

Recently, researchers have presented some additional challenges related to electric buses such as difficulties in charging a large number of electric buses and its impact on the grid and batteries. They also highlighted that charging simultaneously electric buses fleet could consume a

tremendous amount of power that can create a peak demand [12]. This results in oversizing of infrastructures, equipment and grid supply that could incur extra costs. According to another study, despite the significant advantages of the electric bus over the diesel-operated bus, energy consumption is one of the most focused parameters that would affect electric vehicles [13]. Further, traffic congestion and air conditioning are two factors that affect the energy consumption of electric buses [14]. Besides this, the major disadvantage of electric buses is that the operational range is not long enough [5]. Relatively expensive battery systems and charging infrastructure are other main challenges of electric buses [15].

Among the emerging renewable energy options, solar energy has shown a significant advancement and maturity for power generation [16]. The deployment of grid-connected solar PV (GCPV) has gained popularity over off-grid PV (OGPV) system, specifically where vast areas are accessible with the grid, and a significant amount of solar irradiation. For instance, Spain installed about 363 MWp new PV system, from which 96% were grid-connected [17]. Undoubtedly, there is a massive potential for solar energy in Malaysia, and it is snowballing as depicted in Fig. 2.

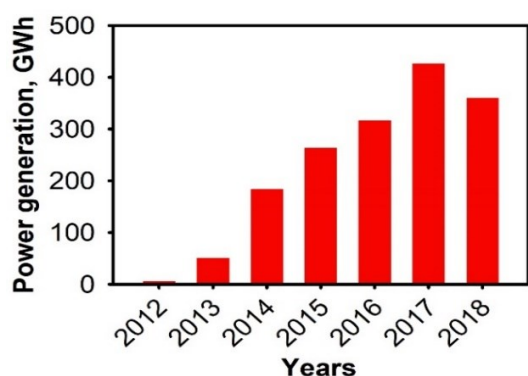


Fig. 2. Annual power generation from solar PV plants in Malaysia.

A growing body of literature has investigated the application of solar PV for battery electric vehicles. However, most of the studies have evaluated the techno-economic feasibility of applying integrated solar energy in the transport sector using various software such as HOMER, SAM, etc.

Two possible methods have been categorized; on-board and off-board PV systems for battery-operated electric buses. A feasibility study in China highlighted that solar PV modules have the potential to generate about 55% of the energy required for charging the bus resulting in the reduction of cost of energy per kWh. Almost half of the retail electricity price can be saved by utilizing solar energy because it eliminates transmission and distribution costs. Numerous researchers have proposed installing the on-board PV system to replace the battery in electric buses. For this, they developed the bus model and simulated it on a suburban bus drive cycle [18]. Another study by different authors in China, proposed a model of solar-powered charging stations for electric vehicles [19]. The integration of renewable energy, such as wind and solar energy into the

power system sources used by EVs is one of the excellent representation models [20]. Previous research findings have explored the synergies between renewable energy sources (specifically solar and wind) and electric vehicles [21]. The authors also presented the concept of solar panels providing shade and generating electricity to charge the parked electric vehicle. Another author published a comprehensive review article on the status and development of electric vehicles charging using solar PV [22]. An interesting study showed that the use of renewable energy for electric buses reduces operating cost and minimize CO₂ emissions. The authors modelled and simulated using HOMER software [23]. Very recently, literature suggested the feasibility of a modelled plug and played mobile solar photovoltaic power plant to charge electric vehicles (EVs) using MATLAB/Simulink software [24]. Other studies have also focused on the application of solar energy for charging stations of electric vehicles [25].

To the author's knowledge, there is no work reported on the design, sizing and economic analysis of a GCPV system for the electric bus depot, particularly in Malaysia. There are several articles on the application of a GCPV, but these are mostly for residential, commercial [26], and charging stations [27]. The GCPV plant in this study was designed and sized to reduce the MD occurring due to charging of electric buses as well as to provide ancillary services to the depot. Although this paper proposes a solution that has practical applicability and has been designed based on the Malaysian geographic characteristics of solar resources but can be developed anywhere in the world. Therefore, this paper presents for the first time, the design and sizing of the GCPV system for an electric bus depot in Malaysia. The specific objectives of the study are as follows:

- To evaluate the solar resource potential at the given site (Bus depot rooftop).
- To design a GCPV system for the electric bus depot considering the load data and different percentages of solar energy consumption scenarios.
- To analyze the economic feasibility of the proposed solar PV system designs.

2. Solar Irradiation Data and Site Information

The GCPV system is designed and sized according to two major constraints, namely; energy and architecture. Solar irradiation data is one of the crucial criteria for the design of a solar PV system, location or site selection and to determine the average peak sunshine hour (PSH). PSH is mainly used for 'energy constraints for PV system design' whereas site information is relevant to 'architectural constraints design' [28].

2.1. Site Information

The site selected for this study is situated in Selangor, Malaysia. It is an electric bus depot first of a kind in Malaysia and the ASEAN region. The electric buses run on lithium-ion phosphate batteries. There are in total, about 13 electric buses

that serve about 708,296 people in the region [29]. It connects major facilities such as hospitals, commercial offices, shopping centers and universities in the area. The battery-operated electric buses are charged overnight and during the morning time at the depot. Thanks to the huge space (~ 9000 m²) available on the rooftop of the depot building, as illustrated in Fig. 3.

2.2. Solar Irradiation Data

In order to design and size PV system, the average hourly solar irradiation data for each month in the year 2019 has been taken from Solar-Log 2000, a crucial equipment installed near the site location, which provides accurate solar irradiation data. This data is instrumental in determining the Peak Sun Hours (PSH), a key parameter used in the GCPV system design (Fig. 4). The electric bus depot rooftop receives a good amount of solar radiation around the year. The average daily irradiance varies from 3.61 kWh/m²/day to 5.52 kWh/m²/day with an annual average PSH of 4.15 h. Fig. 5 shows the average daily solar irradiation profile of Malaysia in different months and Fig. 6 presents the average solar irradiation in Malaysia for each month. The sunshine hour is generally from 8.00 to 18.30 in Malaysia throughout the year; however, considering the tropical climate and cloudy days, the PSH is typically taken as 4.15 hours (average) for GCPV design.



Fig. 3. Site location – Selangor, Malaysia.

Source: <https://earth.google.com>.

The lowest solar irradiation is measured in the month of November and December due to the rainy season whereas March to May can be considered as the highest solar radiation month.



Fig. 4. Solar-Log 2000.

3. Load Demand of the Electric Bus Depot

Fig. 7a presents the typical maximum demand (MD) data of the electric bus depot from January 2018 to July 2018. The daily MD (Fig. 7b) corresponds to the night and daytime peaks. The demand at night is higher than the day because about 6 buses are simultaneously charged in the night while 3 buses in a day. This daily MD patterns of bus depot are consistent all year round.

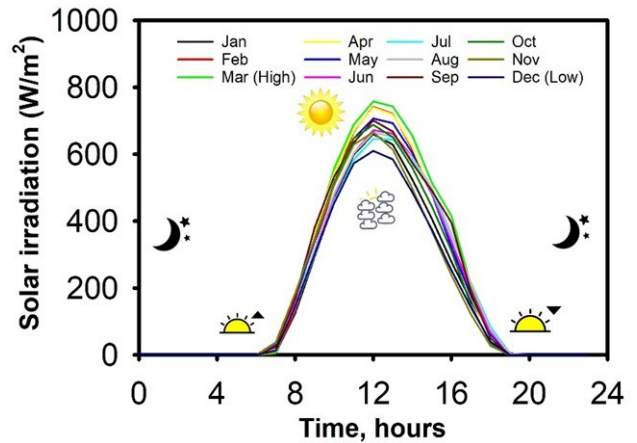


Fig. 5. The average daily profile of solar irradiation in Malaysia.

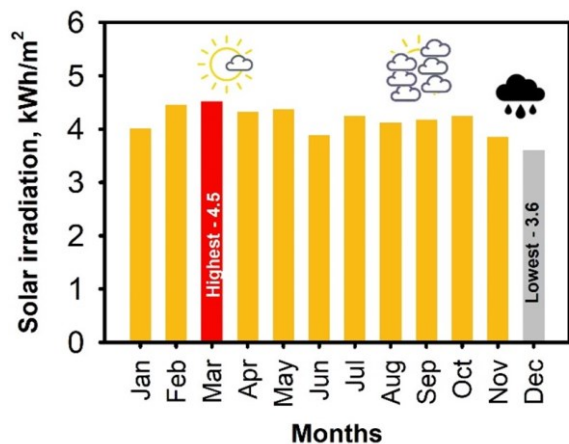


Fig. 6. Average monthly profile of solar irradiation in Malaysia.

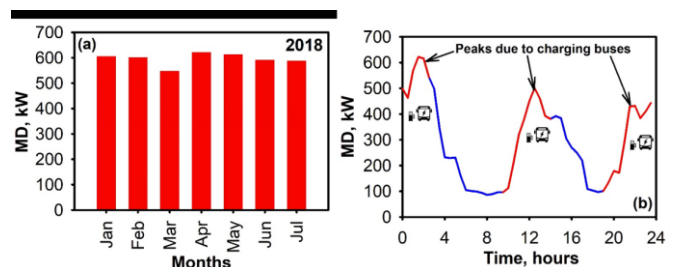


Fig. 7. (a) MD of the electric bus depot in different months of 2018 and (b) Typical daily MD profile of the electric bus depot.

Interestingly, the electric vehicle charging demand pattern for private cars and others could be different from that of present electric bus depot [30, 31]. The observed MD patterns,

characterized by pronounced night peaks, necessitate a tailored approach to the GCPV system design. This involves considering not only the capacity to meet peak demands but also the integration of energy storage solutions to ensure energy availability during nighttime charging. It should be noted that driving and charging patterns could have a significant effect on the load profile of the grid [32]. The load profile of the current electric bus depot showed similarities to that of the previous study with a difference in charging time [33]. The difference in charging time compared to the previous study could lead to variations in the load profile, potentially influencing both the peak demand periods and overall energy consumption patterns of the depot. The average total energy consumption of the bus depot is around 165,000 kWh, and the average maximum demand (MD) that occurs due to charging the buses is about 600 kW. Thus, the main aim to design and size the GCPV system is to reduce the electricity consumption and MD of the bus depot. This will result in the reduction of carbon emissions and the operation cost of the bus depot.

4. Methodology

4.1. Grid-Connected PV (GCPV) System Design and Sizing

Grid-connected PV systems (GCPV), as shown in Fig. 8 are the most preferred and used extensively in the residential and commercial sector because of easy grid access in urban areas. Further, GCPV is economically feasible to install since it does not require major cost associated with energy storage/batteries and charge controllers. The detail explanation for each component of GCPV can be found in the published review paper [34].

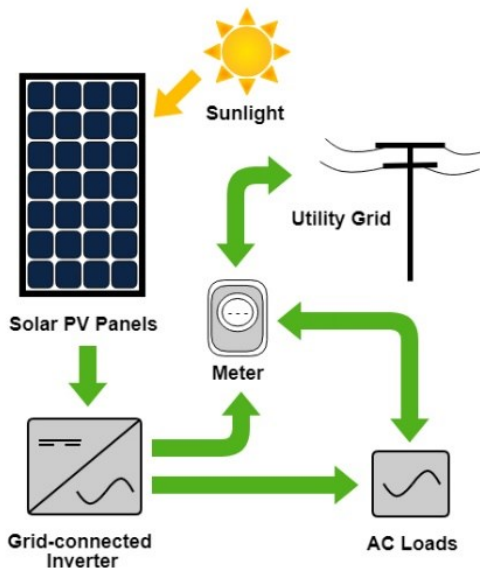


Fig. 8. Grid-connected PV system [35].

The main aim of GCPV is for self-consumption. If any excess electricity is generated, it could be exported to the main grid and consumers might obtain revenue based on “Feed-in Tariff (FiT)” or “Net Energy Metering (NEM)” mechanism. The final electricity yield production is highly depended on the proper and correct sizing of the GCPV system, and thus it is a very crucial step in designing. Moreover, it might also

affect the economic feasibility or cash flow of the solar project.

The GCPV in the present study was designed and sized according to the MS IEC standard designated by the Sustainable Energy Development Authority (SEDA), Malaysia. This method uses two approaches to design GCPV; architectural and energy constraints which are discussed in the following section. A detailed conventional GCPV system sizing steps were also presented in previous literature [36].

4.2. Architectural Constraints

According to this method, the number of PV modules that can be installed in an available area depends on the orientation of the PV modules. For instance, the PV modules can be installed in lengthwise across direction or lengthwise up adjustment, as shown in Fig. 9. The orientation that can accommodate the maximum PV module will be selected for the installation. There are several topologies available to connect the solar PV, but the PV-inverter topologies may differ depending on the rooftop area available [34].

Additionally, the selection of PV-inverter topology is crucial for optimizing system efficiency and accommodating spatial constraints. For example, centralized, string, and micro-inverter topologies offer varying degrees of flexibility and efficiency, impacting the overall performance of the solar PV system. Furthermore, the shading effect, which can significantly reduce the power output, must be considered when arranging PV modules. Innovative solutions, such as using optimizers or micro-inverters, can mitigate such losses by maximizing the output of each module independently.

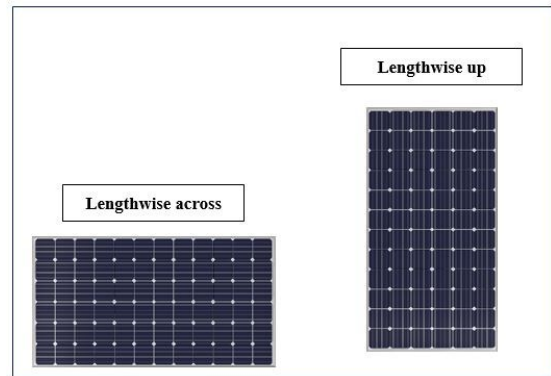


Fig. 9. Lengthwise across (left) and Lengthwise up (right) orientation.

Lengthwise-across: The maximum number of PV modules that can be installed lengthwise across is calculated as follow:

$$N_{max_module_across} = N_{across_up} \times N_{across_across} \quad (1)$$

Where, N_{across_up} and N_{across_across} is given by,

$$N_{across_up} = r.d. \left[\frac{W_{roof}}{W_{mod} + \Delta} \right] \quad (2)$$

$$N_{across_across} = r.d. \left[\frac{L_{roof}}{L_{mod} + \Delta} \right] \quad (3)$$



Fig. 10. Length and width of the bus depot rooftop using Google Earth.

Lengthwise-up: The maximum number of modules that can be installed lengthwise up is calculated as follow:

$$N_{max_module_up} = N_{up_up} \times N_{up_across} \quad (4)$$

N_{up_up} and N_{up_across} is given by,

$$N_{up_up} = r.d. \left[\frac{W_{roof}}{L_{mod} + \Delta} \right] \quad (5)$$

$$N_{up_across} = r.d. \left[\frac{L_{roof}}{W_{mod} + \Delta} \right] \quad (6)$$

Where r.d. is rounded down to the next value; $W_{roof} = 52 + 25 = 77 \text{ m}$ is the width of the utilisable area of the roof; W_{mod} is the width of the module; $\Delta = 0.01 \text{ m}$ is the allowed inter-module gap; $L_{roof} = 108 \text{ m}$ is the length of the utilisable area of the roof (Fig. 10), and L_{mod} is the length of the module.

4.3. Energy Constraints

In this method, the number of PV modules to be installed depends on the energy that will be supplied by the PV system. The following steps will determine the amount of energy that will be generated by the system, minimum power of the PV array and the minimum number of PV modules. The amount of energy to be supplied by PV (E_{req}) can be calculated as follow:

$$E_{req} = \frac{\varepsilon}{100\%} \times \frac{12}{n} \times \sum_{m=1}^{12} E_m \text{ (Wh)} \quad (7)$$

Where, ε = percentage of energy to be supplied using PV (%); E_m = energy consumption for month m (kWh); m = months with available data; n = number of months with available data.

The minimum power of the PV array required (P_{array_stc}) can be calculated as follow,

$$P_{array_stc} = \frac{E_{req}}{PSH_{poa} \times K_{deration} \times \eta_{sub_system}} \text{ (Wp)} \quad (8)$$

Where, $PSH_{poa} = 4.15 \times 365 \approx 1515 \text{ hours}$ is the Peak

Sun Hour received on the plane of array (poa) per annum, $\eta_{sub_system} = 0.8$ is the average subsystem efficiency, and $K_{deration}$ is the derating factor and is calculated as follow,

$$K_{deration} = K_{mm} \times K_{tem_p_ave} \times K_{dirt} \quad (9)$$

Where, $K_{mm} = 0.97$ is the mismatch factor, $K_{dirt} = 0.97$ is the dirt factor and $K_{tem_p_ave}$ is the derating factor of power due to the average maximum PV cell temperature given by,

$$K_{tem_p_ave} = 1 + \left[\left(\frac{\alpha_{power}}{100\%} \right) \times (T_{cell_ave_max} - T_{stc}) \right] \quad (10)$$

Where, α_{power} = is the power-temperature coefficient of specific PV module model that can be taken from PV module datasheet; $T_{stc} = 25 \text{ }^\circ\text{C}$ is the temperature at standard test condition (STC) [37], and $T_{cell_ave_max}$ is average maximum cell temperature given by,

$$T_{cell_ave_max} = T_{amb_ave_max} + T_{elevated} \text{ (}^\circ\text{C)} \quad (11)$$

Where, $T_{amb_ave_max} = 36 \text{ }^\circ\text{C}$ is the average maximum ambient temperature in Malaysia, and $T_{elevated} = 25 \text{ }^\circ\text{C}$ is the elevated temperature [38].

The minimum number of PV modules (N_{min_module}) required can be calculated as

$$N_{min_module} = r.u. \left[\frac{P_{array_stc}}{P_{module_stc}} \right] \quad (12)$$

Where, P_{module_stc} is the power rating of the specific PV module model at standard test condition and can be retrieved from the PV module datasheet.

4.4. Selection of PV Module and Inverter

In this study, three different power rating PV modules (SUNPOWER 470W, JINKO 315W and MITSUBISHI 110W) and one specific inverter (SUNG.-SG250HX) model was proposed to be used as presented in Table 1 and Table 2.

Table 1. Specifications of the selected PV modules [39, 41]

Parameters	Specification		
	SUNPOWER	JINKO	mitsubishi
Nominal power, P_{module_stc}	470 W	315 W	110 W
Open circuit voltage, V_{oc}	91.5 V	46.2 V	21.2 V
Voltage at maximum power, V_{mp}	77.6 V	37.2 V	17.1 V
Short circuit current, I_{sc}	6.45 A	9.01 A	7.16 A
Power-temperature coefficient, α_{power}	-0.29 %/°C	-0.41 %/°C	-0.478 %/°C
Voltage-temperature coefficient, $\beta_{voltage}$	-0.24 %/°C	-0.31 %/°C	-0.346 %/°C
Current-temperature coefficient, $\gamma_{current}$	0.045 %/°C	0.06 %/°C	0.057 %/°C
Efficiency of the module, η_{pv}	21.7%	16.23%	11.9%
Length of the module, L_{mod}	2.067 m	1.956 m	1.425 m
Width of the module, W_{mod}	1.046 m	0.992 m	0.646 m
Types of module	m-Si	p-Si	Thin film

Table 2. SUNGROW-SG250HX inverter specification [42]

Parameters	Specification
Nominal power, P_{nom_inv}	222.75 kW
Maximum power, P_{max}	247.5 kW
Maximum input voltage, $V_{max_inv_abs}$	1500 V
MPPT input voltage, V_{mppt_inv}	860 – 1300 V
Minimum input voltage, V_{min_inv}	600 V
Number of MPP input, n_{mpp}	12
Maximum input current, I_{max}	26 A × 12
Efficiency, η_{inv}	98.8%

4.5. Numbers of PV Modules Per Inverter

The nominal power rating of the inverter dictates the number of PV modules that can be connected to it and depends on several factors. Thus, calculating the number of PV modules correctly will ensure a proper state of health of the inverter. The range of numbers of PV modules that matches the nominal power rating of an inverter is given by,

$$N_{range_module} = N_{min} \cdot N_{max} \tag{13}$$

Where, N_{min} is the minimum number of PV modules per MPP

inputs of the inverter; N_{max} is the maximum number of PV modules per MPP inputs of the inverter and are calculated as follow,

$$N_{min_MPP} = r. u. \left[\frac{P_{inv_nom}}{k_1 \times P_{module_stc}} \right] \tag{14}$$

$$N_{max_MPP} = r. d. \left[\frac{P_{inv_nom}}{k_2 \times P_{module_stc}} \right] \tag{15}$$

Where, $k_1 = 1$ & $k_2 = 0.9$ are the derating factors, $P_{inv_nom} = 222.75$ kW is the nominal power of the inverter and P_{module_stc} is the power rating of the specific PV module model at standard test condition.

4.6. Voltage Limits of the PV Module

Input voltages to the inverter also play a crucial role in addition to the nominal power capacity of the inverter. The input voltages come in a range of values with an absolute maximum, an absolute minimum and an MPPT window. Operation of the inverter is optimum with these range of input voltages. Moreover, it ensures the safety and functionality of the inverter. These limits dictate the voltage outputs of the PV modules and thus the PV string, that is fed into the inverter MPP input.

The absolute maximum voltage of the PV module is allowed to generate or maximum open-circuit voltage from the PV module (V_{oc_max}) is calculated as follow,

$$V_{oc_max} = V_{oc_stc} \times \left\{ 1 + \left[\left(\frac{\beta_{voltage}}{100\%} \right) \times (T_{cell_min} - T_{stc}) \right] \right\} (V) \tag{16}$$

Where, V_{oc_stc} is the open-circuit voltage of the specific PV module at standard test condition; $\beta_{voltage}$ is the PV module voltage temperature coefficient; $T_{cell_min} = 20^\circ\text{C}$ is the minimum cell temperature [38]; $T_{stc} = 25^\circ\text{C}$ is the standard test condition temperature [37].

The highest voltage of maximum power from the PV module (V_{mp_max}) is calculated as follow,

$$V_{mp_max} = V_{mp_stc} \times \left\{ 1 + \left[\left(\frac{\beta_{voltage}}{100\%} \right) \times (T_{cell_min} - T_{stc}) \right] \right\} (V) \quad (17)$$

Where, V_{mp_stc} is the voltage of maximum power from the PV module at standard test condition.

The lowest voltage of maximum power from the PV module (V_{mp_min}) is calculated as follow,

$$V_{mp_min} = V_{mp_stc} \times \left\{ 1 + \left[\left(\frac{\beta_{voltage}}{100\%} \right) \times (T_{cell_max} - T_{stc}) \right] \right\} (V) \quad (18)$$

Where, Maximum cell temperature in Malaysia, $T_{cell_max} = 75^\circ\text{C}$ [38].

4.7. Limits of Modules Per PV String

The voltages generated by the PV string that will be fed into the MPP of the inverter must comply with the input window of the inverter. Thus, it is necessary to determine the number of PV modules that will be connected in series per PV string. This is to ensure that the operating input voltages are within safe and optimum limits of the inverter and its MPP inputs.

The maximum number of PV modules connected in a series string to match the maximum allowed input voltage of the inverter or the absolute maximum number of PV modules per string ($N_{s_oc_max}$) is calculated as follow,

$$N_{s_oc_max} = r. d. \left[\frac{V_{max_inv_abs} \times k_3}{V_{oc_max}} \right] \quad (19)$$

Where, The absolute maximum input voltage of each inverter MPP input, $V_{max_inv_abs} = 1500\text{ V}$ [42][40]; the standard safety margin, $k_3 = 0.95$ [36] and V_{oc_max} can be found from Equation (16).

The maximum number of PV modules connected in a series string to match the maximum MPPT input voltage of the inverter or maximum number of PV modules at MPPT ($N_{s_mppt_max}$) is calculated as follow,

$$N_{s_mppt_max} = r. d. \left[\frac{V_{max_mppt_inv} \times k_4}{V_{mp_max} \times k_5} \right] \quad (20)$$

Where, The maximum input MPPT voltage of each inverter MPP input, $V_{max_mppt_inv} = 1300\text{ V}$ [42]. The standard safety margin, $k_4 = 0.95$ and cable losses to be assumed, $k_5 = 0.95$ [38] and V_{mp_max} can be found from Equation (17).

The minimum number of PV modules connected in a series string to match the minimum MPPT input voltage of the inverter or minimum number of PV modules at MPPT ($N_{s_mppt_min}$) is calculated as follow,

$$N_{s_mppt_min} = r. u. \left[\frac{V_{min_inv} \times k_6}{V_{mp_min} \times k_5} \right] \quad (21)$$

Where, The minimum input voltage of each inverter MPP input, $V_{min_inv} = 600\text{ V}$ [40]; The standard safety margin, $k_6 = 1.1$ [38] and V_{mp_min} can be found in equation (18).

Therefore, the finalise range of numbers of PV modules connected in a series string that can safely and optimally match the input voltages of the inverter MPP, in other words, the range of number of PV modules connected in a series string (N_s) is given by,

$$N_s = N_{s_mppt_min} .. N_{s_max} \quad (22)$$

Where, N_{s_max} is chosen from the lowest value between $N_{s_oc_max}$ and $N_{s_mppt_max}$ from equation (19) and (20) respectively.

4.8. Parallel PV String

The MPP inputs of the selected inverter can take a certain amount of parallel PV strings. This is a critical step to ensure that the maximum input current is not exceeded. The maximum number of PV strings in parallel (N_{p_max}) can be calculated as follow,

$$N_{p_max} = r. d. \left[\frac{I_{dc_max_inv} \times k_7}{I_{sc_string_stc}} \right] \quad (23)$$

Where, The maximum input current to each inverter MPP, $I_{dc_max_inv} = 26\text{ A}$ [40][42]; Number of MPP inputs, $n_{mpp} = 12$ [42]; Safety factor, $k_7 = 0.8$ [38] and short circuit current of string that is equivalent to short circuit current of the specific PV module = $I_{sc_string_stc} = I_{sc_stc}$.

4.9. Array Configuration and Number of Inverters

After matching number of PV modules and PV strings from Equations (19 to 23), the appropriate array design is determined using the following equation,

$$N_{t_per_mpp_array} = N_p \times N_s \quad (24)$$

Where, the total number of PV modules in an array to connect to an MPP input of the inverter = $N_{t_per_mpp_array}$; The number of PV strings in parallel = N_p and the number of PV modules in series per string = N_s .

Therefore, the total number of PV modules to be connected to an inverter is calculated as follow,

$$N_{t_per_inverter} = N_{t_per_mpp_array} \times n_{mpp} \quad (25)$$

Where, the number of independent MPP inputs per inverter,

$$n_{mpp} = 12 \text{ [42].}$$

Finally, the number of inverters and inverter arrays (N_{inv_array}) can be calculated as follow,

$$N_{inv_array} = r.u. \left[\frac{N_t}{N_{t_per_inverter}} \right] \quad (26)$$

Where, the total number of PV modules required according to architectural or energy constraints = $N_t = N_{max_module_across}$ or $N_{max_module_up}$ or N_{min_module} [From equation 1,4 and 12].

4.10. Final Array Capacity Of Complete GCPV System

Final peak PV array capacity of the complete GCPV system ($P_{pv_system_stc}$) is given by,

$$P_{pv_system_stc} = N_{inv_array} \times N_{t_per_inverter} \times P_{module_stc} (Wp) \quad (27)$$

4.11. Economic Analysis

Three economic indicators are most important for a grid-connected solar PV system, namely; initial capital cost, monthly savings and simple payback period. One should do this general economic analysis before installing the solar PV system.

Initial capital cost: Typical market capital cost to install a solar PV system in Malaysia is provided as follow,

- Grid-connected PV system (GCPV) – 4000 MYR per kWp.
- Off-grid PV system without batteries (OGPV without batteries) – 3500 MYR per kWp.
- Off-grid PV system with batteries (OGPV with batteries) – 15000 MYR per kWp.

Hence, the initial capital cost equation is given by,

$$ICC = P_{pv_system_stc} \times 4000 (MYR) \quad (28)$$

Where, Initial capital cost = ICC and final peak PV array capacity = $P_{pv_system_stc}$.

The above capital cost includes the project expenses such as engineering, design, cabling, installation, testing, commissioning, procurement and logistics. The above price is provided at the time of writing this paper, and it can change according to the market demand and from one company to another.

Monthly savings: The proposed solar PV system can save up to a maximum of 75% of the total electricity used by the electric bus depot depending on the PV system capacity. The utility company levies the following charges,

- For all kWh – 0.365 MYR per kWh (Tenaga Nasional Berhad, 2019)
- For maximum demand (MD) – 30.3 MYR per kW [43]

Therefore, according to the average load data of the electric bus depot, the company had to pay a maximum of around 78,000 MYR per month as operational cost in form electricity bill. If the solar PV system can deliver up to 75% of the total electricity of the bus depot, 75% of the electricity bill (around 58,000 MYR) will be saved each month. Hence, monthly electricity cost savings by a solar PV system can be calculated by,

$$MS = [(E_{load} \times \varepsilon \times 0.365) + (MD \times \varepsilon \times 30.3)] (MYR) \quad (29)$$

Where, Monthly savings of electricity bill = MS ; Electricity consumption of the bus depot = E_{load} ; Percentage of energy to be supplied using PV (%) = ε and maximum demand = MD .

Simple Payback period: The simple payback period for a solar PV system is calculated as the total investment cost divide by the revenues from energy saved, displaced or produced from the initial years as given in Equation 30. Projects with short payback periods are perceived to have lower risks of investment.

$$PB = \frac{ICC}{YS-O\&M} (years) \quad (30)$$

Where, Payback period = PB ; Yearly savings of the electricity bill = YS and the operational and maintenance cost of the PV system per year = $O\&M$.

5. Results and Discussion

The GCPV system was designed and sized according to the architectural and energy constraint mathematical approach. The techno-economic analysis includes the total number of PV modules, number of inverters, PV system capacity and array configuration, the capital cost of the PV system, monthly savings and simple payback period.

5.1. Design, Sizing of the GCPV System According to Architectural Constraint

The allowable PV system capacity in the available area of the rooftop ranged from a minimum capacity of 1046 kWp with 8775 number of modules (model M110) to a maximum capacity of 1777 kWp with 3774 number of modules (model S470) as presented in Table 3. The required number of inverters, array configuration and economic constraints are depended on the PV capacity, as shown in Table 3. A study reported that about 4284 PV modules of 235 Wp each (model Yingli Solar YL235P-29b) were required for a typical 1 MWp plant in Malaysia [44]. In another study, about 44,448 solar PV modules each of 225 Wp was used for 10 MWp solar PV plant [45]. Similarly, about 54,000 number of solar panels were needed for 10 MWp solar PV plant [46]. Overall, the present findings seem to be consistent with a very recent study [47] that the number of PV modules is highly depended on the individual PV module power or capacity. It was obvious from their finding that even though the same model of PV module was used, but the difference in nominal power of individual module increased to ~2000 panels. The present study covers

most of the factors (budget, energy-saving target, available mounting space and the maximum penetration to the utility grid) that dictate the size of the GCPV [48]. Approximately 23,256 number of PV modules (each of 215 Wp) was installed for 5 MWp solar PV plant in Ethiopia [49]. This clearly shows that the capacity of solar PV plant to be installed is highly depended on the individual nominal power capacity and the type of PV modules.

The monthly savings of the electricity bill is proportional, and the payback period is inversely proportional to the initial capital cost of the solar PV plant. However, policies such as NEM and FiT can significantly reduce the payback period [50]. The standard lifetime of a solar PV system is 25 years

[38]. Therefore, large scale solar PV system may be more economical rather than small capacity [51]. However, according to architectural constraint, the current project can continue to save a significant amount of cost (7.5 million MYR- 1046 kWp) to 13 million MYR- 1777 kWp) on the electricity bill even after the payback period along the whole solar PV system lifetime, as presented in Table 3. Higher capital cost (7.1 million MYR) of SUNPOWER PV system is due to the high cost associated with PV modules and its capacity. The total cost of a solar PV system depends on the cost of selected PV modules, and further long-term implication of the selected module is based on their performance [47].

Table 3. GCPV sizing results according to architectural capacity

	Description	SUNPOWER 470W (S470), m-Si	JINKO 315W (J315), p-Si	mitsubishi 110W (M110), T-Film
Technical	Total number of PV modules	3774	4173	8775
	PV system capacity, kWp	1777	1316	1046
	Number of inverters	7	6	6
	Array configuration per inverter [$D_{mpp} \times (N_p \times N_s)$]	12×(3×15)	12×(2×30)	12×(2×66)
Economic	Capital cost, million MYR	7.1	5.4	4.2
	Monthly savings, MYR	68,153	46,767	38,966
	Payback period, years	8.7	9.7	9

5.2. Design and Sizing of the GCPV System According to Energy Constraint

In this section, the solar PV system has been designed according to three possible scenarios of energy requirement; 75%, 50% and 25% of the total energy coming from the GCPV system. Selecting specific energy constraints of 25%, 50%, and 75% for a PV system in a commercial building allows stakeholders to evaluate a spectrum of solar energy contributions, from supplementary to substantial. These scenarios cater to diverse goals, ranging from initial steps towards sustainability to achieving significant energy independence and potentially net-zero status. They provide a flexible framework to align solar energy integration with varying budgetary, spatial, and sustainability objectives of different commercial entities. Technical design results and

economic analysis have been shown in Table 4, Table 5 and Table 6, respectively. If the investing company can afford the high initial capital cost, it will be economically best to install the PV system according to the design in Table 4 ($\epsilon = 75\%$). Due to an outstanding amount of monthly savings that will end up a massive amount of operational cost savings at the end of every year. This design has a typical payback period between 8.8 and 9.1 years, considering the maintenance cost of the installed PV system to be 2000 MYR per year. The mentioned duration of the payback period is very much similar to the previous study conducted at an industrial park in Iran [52]. Acknowledging the standard lifetime of a solar PV system to be 25 years [38], the proposed design of PV system can save an average of 11.2 million MYR in its whole life for the investing company after paying back its initial capital cost.

Table 4. GCPV sizing according to energy constraints (75% of the total energy from PV system)

	Description	SUNPOWER 470W (S470), m-Si	JINKO 315W (J315), p-Si	mitsubishi 110W (M110), T-Film
Technical	Total number of PV modules	3076	4823	14218
	PV system capacity, kWp	1523	1588	1569
	Number of inverters	6	7	9
	Array configuration per inverter [$n_{mpp} \times (N_p \times N_s)$]	12×(3×15)	12×(2×30)	12×(2×66)
Economic	Capital cost, million MYR	6.1	6.4	6.3
	Monthly savings, MYR	58,448	58,488	58,488
	Payback period, years	8.8	9.1	9

Table 5. GCPV sizing according to energy constraints (50% of the total energy from PV system)

	Description	SUNPOWER 470W (S470), m-Si	JINKO 315W (J315), p-Si	mitsubishi 110W (M110), T-Film
Technical	Total number of PV modules	2051	3215	9479
	PV system capacity, kWp	1016	1134	1046
	Number of inverters	4	5	6
	Array configuration per inverter [$n_{mpp} \times (N_p \times N_s)$]	12×(3×15)	12×(2×30)	12×(2×66)
Economic	Capital cost, million MYR	4.1	4.6	4.2
	Monthly savings, MYR	38,966	38,966	38,966
	Payback period, years	8.7	9.8	9

Table 6. GCPV sizing according to energy constraints (25% of the total energy from PV system)

	Description	SUNPOWER 470W (S470), m-Si	JINKO 315W (J315), p-Si	mitsubishi 110W (M110), T-Film
Technical	Total number of PV modules	1026	1608	4780
	PV system capacity, kWp	508	681	523
	Number of inverters	2	3	3
	Array configuration per inverter [$n_{mpp} \times (N_p \times N_s)$]	12×(3×15)	12×(2×30)	12×(2×66)
Economic	Capital cost, million MYR	2	2.7	2.1
	Monthly savings, MYR	19,483	19,483	19,483
	Payback period, years	8.8	11.8	9

A significant recent study has designed and sized the GCPV system based on both architectural (available area) and energy constraint [53]. They designed the GCPV system based on the architectural constraint, which was 5 kWp while based on energy constraint it provided 9 kWp. However, according

to the author, 5 kWp can be installed on the available rooftop area. The architectural design constraint also considers the shadow from the surrounding region.

The capital cost to install GCPV system in Malaysia is higher (USD 850 per kWp) than India (USD 650 per kWp),

consistently the payback period of the former country is also slightly higher (7 to 8 years) than the latter country (6 years) [54]. Their studied GCPV system consists of 968 number of PV modules each of 310 Wp power. As evident from the above results, the capital cost associated with energy was lower than architectural constraint. The higher initial investment is perhaps one of the most severe obstacles for the uptake of solar PV systems. Therefore, it is essential to have reasonable capital cost with shorter payback period to attract the investor and implementation of the project. High initial capital investment would reduce the profit from sold PV generation [55]. Another study explained that the total cost for PV system installation would reduce to half (USD 15,000) as compared to typical original installation value of around USD 30,000 for the house due to tax credits, rebates and incentives. The capital cost of GCPV system in Ghana (USD 1400 per kWp) [47], China (USD 1740 per kWp) [55] was almost double than the present study. However, the payback period of 7 to 8 years from the present GCPV system agreed well with their study.

The GCPV payback period can be reduced with high saving in the electricity bills, which in turn is related to PV capacity and electricity selling price [55, 56]. It should be noted that the payback period for GCPV is usually lower as compared to the off-grid PV (OGPV) system [57]. As the former do not require energy storage systems such as batteries, charge controller and other related equipment. The influential factors that decide the economic feasibility (payback period) of the GCPV system are the electricity tariff of the site or location that varies from one country to another, incentives, tax exemptions, discount rate, PV yield and electricity mean present value [48, 58]. Very recently, researchers depicted how the payback period differs due to use of different types of solar PV modules (mono-crystalline, poly-crystalline, and thin-film) [59]. In contrast to their findings, the payback period for mono-crystalline PV module is lower in the current study as compared to poly-crystalline and thin film. Besides, the capital cost to install poly-crystalline modules is slightly higher in both architectural and energy constraint design as compared to mono-crystalline and thin-film modules. This finding is in contradict agreement with Allouhi et al. [60] findings which showed poly-crystalline technology has the lowest investment cost than mono-crystalline and thin film. The simple payback period was found [60] to be sensitive to the capital cost, PV module efficiency, interest rate and electricity sale price.

Overall, given the GCPV system lifetime of 25 years, the payback period (8 to 12 years) of the present study is highly attractive. The high profits and short payback period should be feasible for large scale GCPV investments in Malaysia. It should be noted that simple payback periods in the present study are lower even without any incentives such as FiT and

NEM and tax exemptions. Further, with continues drop in PV module prices and policies on incentives for renewable energy investments will have a significant impact on payback rates, thus making the project more attractive to the investor. According to a study in Jaipur, India, the payback period would vary before and after the inclusion of discounted cash flow and other tax payment [61]. It is also understood that the economic feasibility of the solar PV system is sensitive to the location of installation [62]. Even though mechanism such as FiT would provide much attractive economic package [49], [63, 64], however, FiT is not available for solar PV renewable energy in Malaysia. Thus, only options available are self-consumption, large scale solar (LSS) and NEM programs.

The monthly savings in the form of cost are depended on the installed capacity and amount of electricity saved, as shown in Table 3 to 6. The monthly savings (75%, 50%, and 25%) in the electricity bill is evident in energy constraint GCPV design. According to architectural constraint GCPV design, the monthly savings for mono-crystalline, poly-crystalline and the thin film is 100%, 70% and 50%, respectively. The present results are also consistent with the previous study [65] which reported more than 50% savings and about 32% reduction in electricity consumption by installing solar PV on the school building premise. A 450 kWp solar PV installation resulted in a monthly saving of approximately USD 2800 while the monthly average electricity amount without solar PV system was ~USD 16,000, a reduction of about 17.5% in monthly savings [66]. The energy bill savings contributed by solar PV-battery system was about 20% of net consumption when solar PV energy was self-consumed, and 3% of maximum demand [67]. This shows that a solar PV system with battery usually results in higher savings. However, it has a longer payback period due to high upfront capital cost of the energy storage system.

5.3. PV Module Voltage Limit and Modules Per String

The actual output voltage of the installed PV modules outdoor is reduced due to several factors, such as module temperature, mismatch etc. Hence, module sizing for an inverter should be designed concerning actual PV module voltage output [68]. Factors that have a significant influence on the module voltage output have been considered in this study (section 4.6). The open-circuit maximum voltage (V_{oc_max}), highest (V_{mp_max}) and lowest (V_{mp_min}) voltage at the maximum power of each type of PV modules has been calculated and is given in Table 7. The series connection between PV modules is responsible for increasing the voltage of the string, whereas, parallel connections between string increases the current in the array [69]. Besides, high power rating PV modules have a higher range of voltage limits.

Table 7. PV module voltage limit

Description	SUNPOWER 470W (S470)	JINKO 315W (J315)	mitsubishi 110W (M110)
V_{oc_max}	92.59 V	46.91 V	21.56 V
V_{mp_max}	78.72 V	37.96 V	17.5 V
V_{mp_min}	66.34 V	29.57 V	13.01 V

The minimum and the maximum number of PV modules per string are proportional to the input voltage capacity of MPP input of the selected inverter and inversely proportional to the power rating of the PV module. An inverter MPP input can accommodate a large quantity of PV modules of lower power rating since it has a smaller range of voltage limits. Many series-connected PV modules are treated as a single unit in the string of an inverter [70]. Table 8 presents the minimum and the maximum number of PV modules with a different power rating that the SUNGROW-SG250HX inverter MPP inputs can take per string. For example, the absolute maximum

open-circuit voltage of the SUNPOWER PV modules at faulty condition is about 93 V; hence a maximum of 15 PV modules can be connected in a series string to the SG250HX inverter MPP input that will lead to a total voltage of around 1395 V, which satisfies the absolute maximum DC input voltage range of the SG250HX inverter (1500 V). Similarly, the SG250HX model inverter can satisfy the nominal voltage requirement for JINKO and Mitsubishi PV modules. The appropriate inverter size is essential since it maximises the amount of energy generated from the PV system [71].

Table 8. Modules limit per PV string

Description	SUNPOWER 470W (S470)	JINKO 315W (J315)	mitsubishi 110W (M110)
$N_{s_oc_max}$	15	30	66
$N_{s_mppt_max}$	16	34	74
$N_{s_mppt_min}$	11	24	54
Minimum – Maximum	11-15	24-30	54-66

6. Conclusion

This is the first time that the design, sizing and economic analysis of the GCPV system for an electric bus depot were performed. The site is in Malaysia, and location resources such as solar radiation data, peak sunshine hour, load assessment data were used to perform the design and sizing of the GCPV system. The results from the present designed GCPV system and economic analysis can be applied to any location in Malaysia and similar geographical locations. The monthly average electricity consumption of electric bus depot is about 168,000 kWh and MD of about 600 kW. Thus, according to architectural design constraint, about 1.04 to 1.77 MWp GCPV capacity plant can be installed on the rooftop of the bus depot. The capital cost of such GCPV system will range from 4.2 to 7.1 million MYR with a simple payback period of 8.7 to 9.7 years. Further, the capacity of the GCPV system was highly depended on the amount (percentage) of energy harvested from solar PV plant. For example, if 50% of electricity is supplied by solar energy, then the GCPV capacity will range from 1.02 to 1.1 MWp. Accordingly, the capital cost of such GCPV system will range from 4.1 to 4.6 million MYR with a simple payback period of 8.7 to 9.8 years. Interestingly, the payback period of GCPV plant capital cost does not vary much when GCPV system is designed based on

energy constraint (75%, 50%, and 25% of electricity from solar energy). While the study provides comprehensive insights, however, it is important to consider that the analysis does not account for potential variations in solar irradiance due to unforeseen climatic changes or the evolving efficiency of solar PV technology, which could impact the projected outcomes. Furthermore, the economic analysis may not fully capture future changes in electricity tariffs or government incentives for renewable energy in Malaysia, potentially affecting the feasibility and attractiveness of the investment. Future research should explore the integration of energy storage systems and advanced grid management technologies to enhance the reliability and efficiency of GCPV systems in electric bus depots. Overall, the technical and economic results of this study show that the installation of the GCPV system will not only be technically feasible but also highly economically rewarding owing to lower capital cost and lower payback period. The GCPV systems may become more efficient since they will be installed on the rooftop of the bus depot that can minimise the losses due to long cabling. The present design results show that the investment can be a good decision from an economic and technical point of view under the Malaysian regulations. Integration of solar energy will not only decrease the operational cost of the electric bus depot but also reduce the carbon emissions in the long run. Lastly, this

study will help stakeholders of Malaysia to understand the techno-economic feature of a solar PV system for electric bus depot and invest in the project.

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