Performance analysis, techno-economic assessment, and optimization of Grid Connected PV (GCPV) system for commercial building

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Abstract

Commercial buildings consume about 48% of total generated electricity in Malaysia. Since most of the buildings adhere to commercial electricity tariffs, including the Monash Malaysia campus, building owners have to pay high electricity bills because of the maximum demand (MD). Moreover, the electricity supply in Malaysia majorly comes from fossil fuel-based power plants that further elevates the problem of carbon emissions that is not sustainable in the long term. Therefore, the Monash Malaysia campus has made an effort to reduce both the MD and carbon emissions by implementing an impactful solution of installing the Grid-Connected PV (GCPV) system on the buildings' rooftop, a journey towards a sustainable campus. Recently, the Monash Malaysia campus, in the first phase of the project, installed a 232.5 kWp GCPV plant on the rooftop of building B6. However, no performance analysis of this GCPV system has been done since its installation. In the second phase of the project, Monash Malaysia campus intends to expand and install more GCPV on other buildings' rooftops. However, management would like to have a techno-economic feasibility study prior to the implementation of the project. The main objectives of this research work are to carry out the target-oriented based performance analysis (according to Malaysian standard MS-IEC) of the existing 232.5 kWp installed GCPV system and to perform the techno-economic analysis of an extended GCPV system using HOMER Grid commercial software. The necessary load data of the building were collected from the facility management department of campus. The meteorological data were obtained from installed sensors with the GCPV system. The GCPV output data (for one the whole year 2019) was collected from a solar data logger that monitored and stored data at an interval of every 5 minutes interval. The solar irradiation and ambient temperature of the site (Monash Malaysia campus) fluctuate from 3 to 5 kWh/m^2/year and 28 to 31 ℃. The maximum PV module operating temperature of the GCPV system was 73 ℃ recorded in March. The GCPV system generated about 301.5 MWh of energy in 2019 that almost achieved the set target of 305.0 MWh. The Performance Ratio (PR), Capacity Utilization Factor (CUF), system efficiency, and Levelized Cost of Energy (LCOE) of Monash Malaysia GCPV plant was found to be 85.4%, 14.85%, 9.15%, and 0.396 RM/kWh, respectively. Interestingly, the PR of the present GCPV system was higher than other surveyed GCPV systems. A strong correlation between solar irradiation and AC yield and module temperature and AC power was observed using a statistical method, and a model was developed that can predict the output at a 5% level of significance. Approximately 177 metric tons of CO_2 emission is avoided over one year after installing the GCPV system. These findings would bring confidence in senior management and other stakeholders on how the GCPV installation performs with the set target. The techno-economic feasibility study was implemented on the highest electricity consumption building B3 (occupies School of Medicine and Health Sciences) and the lowest

electricity consumption building B7 (library). Depending on the input parameters, HOMER Grid simulated the options and recommended 866 kWp and 396 kWp as the optimal GCPV capacity for B3 and B7, respectively. At this capacity, the total net present cost (NPC), COE, and initial capital cost for building B3 are RM 12.1 million, 0.357 RM/kWh and RM 1.16 million, respectively. Whereas for building B7 it is RM 4.6 million, 0.373 RM/kWh, and RM 2.51 million, respectively. This capacity was enough to reduce the MD of the buildings significantly. However, according to the architectural constraint design, the rooftop area available on the buildings may not be enough to install the said capacity. Alternatively, a smaller capacity of the GCPV system has to be installed that would alter the techno-economic results. Overall, there is a high potential and feasibility to reduce the MD and carbon emissions by installing the GCPV on the rooftop of Monash campus buildings that can fulfill the sustainable development goals.

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Signature:

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Date: 30/10/2020

Publications

1. Mohammed Zeehan Saleheen, Arshad Adam Salema, Shah Mohammad Mominul Islam, Charles Raymond Sarimuthu "Target-oriented performanceanalysis of a 232.5 kWP grid-connected solar PV system for a commercialbuilding in Malaysia", Energy for sustainable development. Q2, IF – 3.610 (Under Review)

2. Mohammed Zeehan Saleheen, Arshad Adam Salema, Charles Raymond Sarimuthu "Techno-economic analysis of a grid-connected commercial photovoltaic system for different buildings at Monash University, Malaysia using HOMER Grid." Energy. Q1, IF – 5.5 (Under submission)

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List of Abbreviations

Capacity utilization factor – CUF

C-Si - Crystaline silicon

Feed-In Tariff – FiT

Green Investment Tax Allowance – GITA

Green Income Tax Exemption – GITE

Grid-connected solar PV – GCPV

Global Horizontal Irradiation - GHI

IRENA - International Renewable Energy Agency - IRENA

Levelized cost of energy – LCOE

Large Scale Solar – LSS

Mc-Si - Monocrystalline silicon

Net Energy Metering – NEM

Off-grid PV system – OGPV

Performance ratio – PR

P-Si – Polycrystaline silicon

Sustainable Energy Development Authority – SEDA

Self-Consumption – SLCO

STC – Standard Test Conditions

IRR – Internal rate of return

OECD - Organisation for Economic Co-operation and Development

MD – Maximum Demand

List of Symbols

$\boldsymbol{Y_{mea,AC}}$ - Measured AC yield

$\boldsymbol{Y_{mea,DC}}$ - Measured DC yield

$\boldsymbol{E_{AC(t)}}$ – Final AC energy output

$\boldsymbol{E_{DC(t)}}$ - Final DC energy output

$\boldsymbol{Y_{tar}}$ - Target Yield

$\boldsymbol{P_{array\_STC}}$ - Power of PV array at STC

$\boldsymbol{PSH_{poa}}$ - Peak sunshine hour

$\boldsymbol{k_{deration\_y}}$ - Deration factor of energy yield

η_{cable} - Efficiency of DC cable from PV to the inverter

η_{inv} - Inverter efficiency

$\boldsymbol{H}$ – Solar Irradiation

$\boldsymbol{G_o}$ - Solar Irradiation under STC

$\boldsymbol{SY_{mea}}$ – Measured specific Yield

$\boldsymbol{PR_{mea}}$ – Measure performance ratio

$\boldsymbol{PR_{tar}}$ – Target performance ratio

$\boldsymbol{CUF}$ – Capacity utilization factor

η_{sys} – System efficiency

$\boldsymbol{L_S}$ – System loss

$\boldsymbol{L_C}$ – Array loss

$\boldsymbol{LCOE}$ – Levelized cost of energy

$\boldsymbol{C_I}$ - initial capital cost

$\boldsymbol{C_{O\&M}}$ - Annual operation and maintenance cost

$\boldsymbol{P_{PV}}$ – PV array output

$\boldsymbol{\alpha_P}$ – Temperature coefficient

$\boldsymbol{\eta_{inv}}$ – Inverter efficiency

$\boldsymbol{L_{mod}}$ – Length of module

$\boldsymbol{W_{roof}}$ – Width of utilizable area of roof

$\boldsymbol{L_{roof}}$ – Length of utilizable area of roof

$\boldsymbol{NPC}$ – Net present cost

Chapter 1

Introduction

1.1 Background

Energy is a vital constituent of socio-economic development, and, in particular, electricity has become a necessity for social and industrial activities. Therefore, a continuous increase in electricity demand with global climate change has created significant concern for countries to sustain the economic development. In the past few decades, global electricity consumption has continued to increase at the faster rate, of course due to increasing population and industrial activities. According to the International Energy Agency [1], the world's annual electricity consumption rose from 10901 TWh to 23,106 TWh between 1990 and 2016. With an annual growth rate of 3.1%, electricity demand is expected to go up from 21,400 TWh to 73,000 TWh in 2010–2050 [2], which is shown in Fig. 1.1 (b).

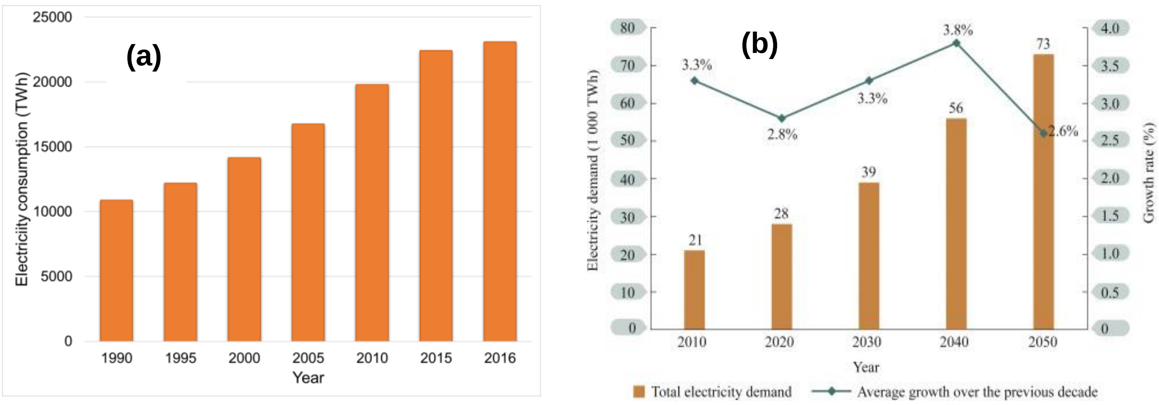


Fig. 1.1. Global a) electricity consumption during 1990–2016 [1]; b) World's total electricity demand and growth rates, 2010–2050 [2]

Simultaneously, electricity consumption has increased drastically in the commercial sectors, specifically in the buildings. Most of the electricity in commercial buildings is consumed by heating and cooling systems, lighting, computers, equipment used in universities, hotels, hospitals, etc. Fig. 1.2 shows that considerable growth in electricity consumption since 1974 has taken place in the commercial and public service sector [3].

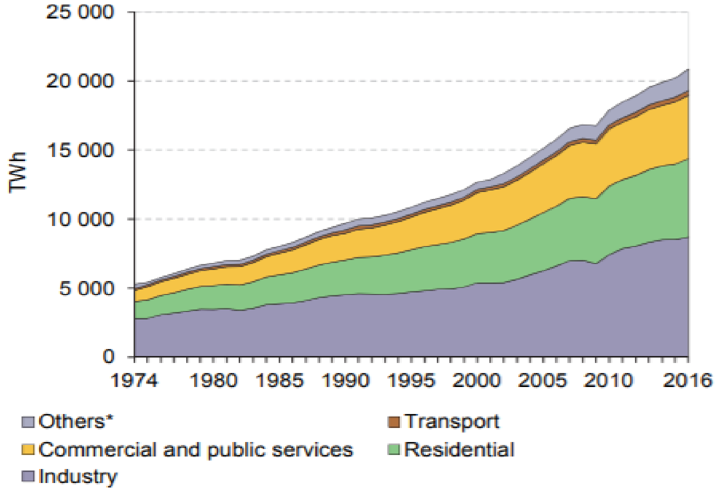


Fig. 1.2. World electricity consumption by sector [3]

Electricity consumption varies from one country to another and is dependent on the population growth, Gross Domestic Product (GDP), economic and industrial growth of a nation. For instance, along with the increasing global electricity demand, Malaysia's electricity demand is projected to increase by 4.7 percent per year to reach 274 TWh in 2030 [4]. The growing electricity consumption of Malaysia from 2010 till 2016 is shown in Fig. 1.3 (a) [5]. Comparatively, the population of Malaysia has grown from 28.5 million (year 2010) to 32.0 million (year 2017). While Fig. 1.3 (b) shows the electricity consumed by the different sector in Malaysia. Among these, the commercial sector consumes about 30.8% of the total Malaysian electricity [6]. According to Tenega Nasional Berhad (TNB), a electricity utility company in Malaysia, the commercial entity is defined as a consumer occupying or operating but not limited to office block, Hotels, service apartment, boarding house, retail complex, shop-house, carpark, workshop, restaurant, estate, plantation or farm (except those categories defined in the Specific Agriculture Tariff), port, airport, railway installation, toll plaza, street lightings at tolled highway including its bridges and tunnels, telecommunications installation, broadcasting installation, entertainment/recreation/sports outlet, golf course, school/educational institution, religious and welfare organization, military and government installation, hospital, waste treatment plant, district cooling plant, cold storage, warehouse, any other form of business or commercial activities which are not primarily involved in manufacturing, quarrying or mining activities [https://www.tnb.com.my/commercial-industrial/for-commercial/]. It is clear that the educational premises are under the commercial sector as defined by electricity provider

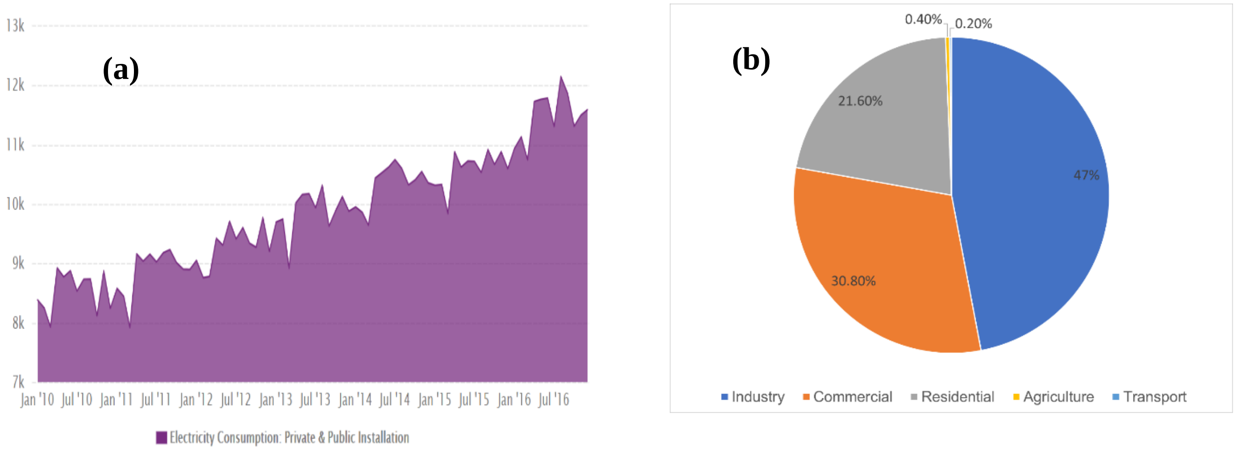


Fig. 1.3. (a) Electricity consumption of Malaysia between 2010-2016 [5], (b) Electricity consumption by sector in Malaysia, 2016 [6]

1.2 Motivation

As 90% of the human activities are carried out in buildings [7], the building sector has become the largest energy consumer, with 39% of the total global energy consumption [8]. Interestingly, electricity is the most consumed part of the buildings' energy for heating and cooling systems, lighting, and appliances [9]. According to the International Energy Agency, electricity accounted for one-third of building energy use in 2019 [10]. However, it is stated that, among buildings, commercial buildings responsible for around 32% of the final electricity consumption [11]. Researchers from the Preservation Green Lab reported that more than 40% of the commercial sector buildings comprise seven specific commercial building types such as retail, housing, main street, offices, strip malls, and educational institute, and accounts for approximately 680 TWh of energy annually [12].

However, to fulfill these hovering electricity demands, most of the electricity comes from thermal power stations that run on fossil fuels, mainly coal and natural gas. However, fossil fuel resources are limited [13]. Apart from the depletion of fossil fuel resources, the burning of these fossil fuels contributes to the increasing emission of greenhouse gasses (GHGs) including carbon dioxide (CO2) [14]. Emission of these greenhouse gases harms the environment and is one of the main reasons for global warming. Globally, the primary source of GHG emissions are from energy usage, and electricity represents over 31% of this energy, which can be viewed in Fig. 1.4 [15].

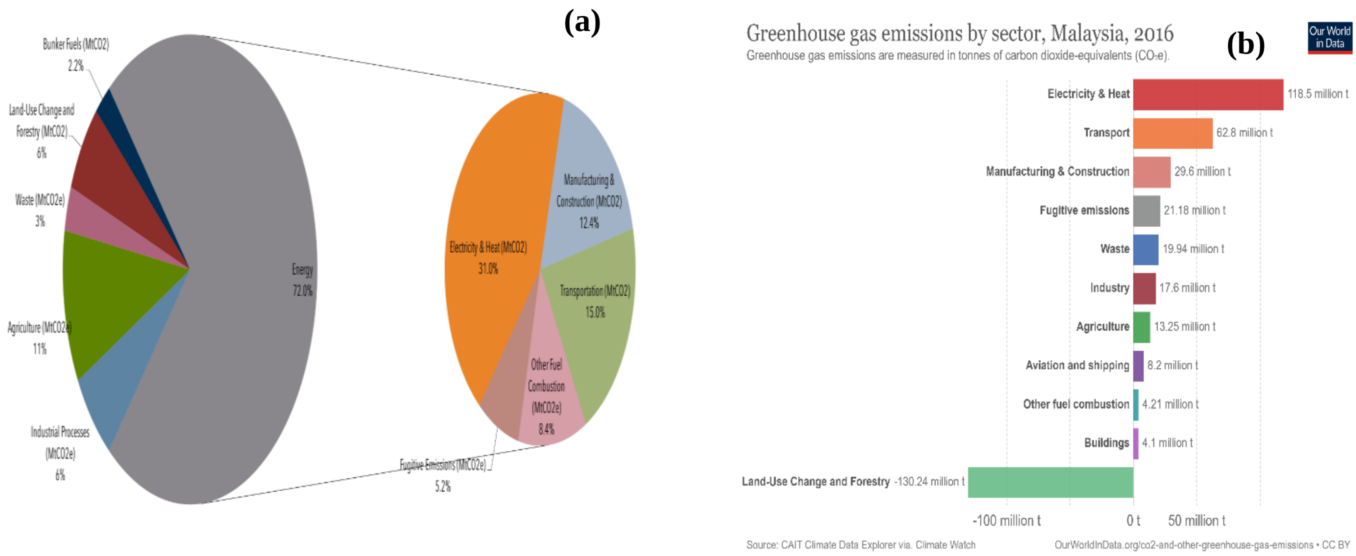


Fig. 1.4. (a) Global GHG emission by sector [15], (b) Greenhouse gas emissions by sector, Malaysia, 2016 [16]

The growth of commercial buildings in Malaysia has a great influence on country's development but it has also upsurge the electricity demand [17]. Like other countries in the world, most of Malaysia's electricity is generated from fossil fuels such as coal (45%) and natural gas (40%) [18], which is one of the main contributors to the carbon emissions. Fig. 1.5 shows that thermal power stations (coal and natural gas) are the main source of electricity in Malaysia. Therefore, electricity consumption in commercial buildings of Malaysia entails serious attention to ensure a sustainable future of the country.

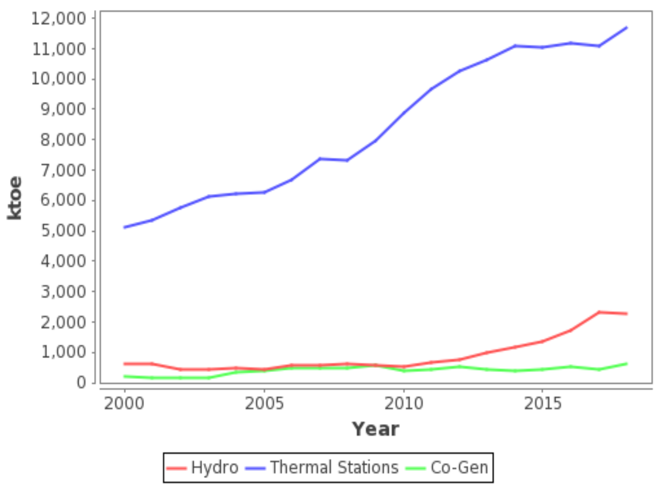


Fig. 1.5. Electricity generation sources in Malaysia (2000-2018) [18]

Hence, there is a powerful motivation to generate electricity from clean and renewable sources. Therefore, significant steps have been taken by the Malaysian policymakers to channel the current energy policy towards resource diversity to reduce the reliance on fossil fuels. Renewables such as solar, wind, biomass, and others are explored as an alternative and impactful resource to ensure the energy transformation towards sustainable development in Malaysia. In line with this effort, policy makers has set a goal to increase the contribution of renewable energy to 20% in the electricity mix by 2025, from the present 2% [19]. In view of this, solar energy is contributing greatly to the Malaysian sustainable development. Several business models and framework are developed to increase the solar energy fraction in Malaysia.

1.3 Solar energy

Remarkably, solar PV is at the forefront of this proclivity towards renewables in Malaysia due to the high amount of solar irradiance, ranging from 4.21 kWh/m^2/day to 5.56 kWh/m^2/day [20]. In addition, solar PV can be readily installed and can generate the power instantly as compared to other renewable energy systems subjected when the solar cells are exposed to sunlight. Besides this, it is considered renewable, environment-friendly (as it does not generate emissions while operation), the source (sun) is freely available, and almost everywhere [21]. The solar cells transform the sunlight into electricity that are connected in a solar panel or module. This solar cells are made up of semiconductor material, causing electron excitation [22]. Typically, solar PV generates DC power, which is then converted to AC for satisfying the load demand. It is estimated that PV modules installed on 4% of the world's desert area will fulfill the global current energy consumption [23]. According to IRENA, globally installed capacity for PV has reached 480.3 GW at the end of 2018. With around 274.6 GW installation, Asia holds the largest share of PV installation. According to Global Data’s recent report, solar PV installation is expected to reach 969 GW within 2025 as shown in Fig. 1.6 while it is estimated to provide 30% of the world's energy demand by 2050 [24].

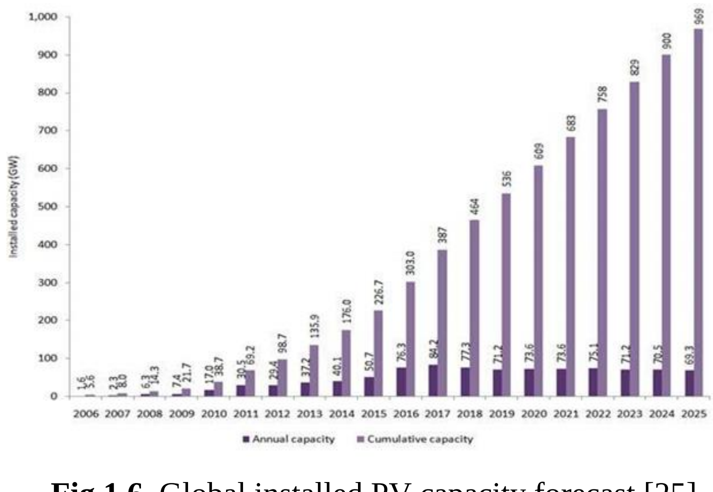


Fig.1.6. Global installed PV capacity forecast [25]

Solar PV systems are usually operated as a grid-connected (tied to grid) or off-grid (standalone) system [26]. Off-grid PV (OGPV) systems are operated without connection to the local grid. This system is beneficial in remote areas that are usually isolated from the power distribution network and is mainly used for self-consumption. This system also needs energy storage system such as battery banks and a backup system in form of generator due to unpredicted nature of sun and weather conditions in case when solar irradiation is unavailable or night time operation. On the other hand, the GCPV system is one of the fastest-growing PV technology designed to operate along with the utility power grid [27], which is expected to become a promising energy solution for maximum demand (MD) shaving worldwide. The mechanism of the GCPV system is shown in Fig. 1.7. Generally, energy storage is avoided in this type of system and grid itself can work as charge storage. Therefore, this system are comparatively less expensive than OGPV or standalone system because energy storage is expensive component.

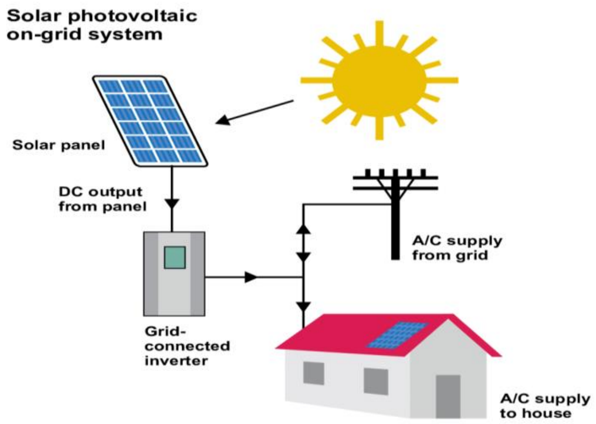


Fig.1.7. Schematic of GCPV system [28]

Due to the almost 100% grid accessibility, the rooftop GCPV systems have gained popularity in Peninsular Malaysia [29] as compared to the off-grid PV (OGPV) systems. The large amount of empty rooftop spaces in the urban areas have high potential and attracted the GCPV system to avoid the unnecessary land use. For example, according to Malaysian Ex-Minister Mrs. Yeo Bee Yin, Ministry of Energy, Science, Technology, Environment and Climate Change, there are over 4.12 million buildings with solar rooftop potential in the peninsular (West Malaysia) that can generate about 34 GW of electricity if they are fitted with solar PV systems. Therefore, to accelerate and promote the nationwide rooftop solar PV installation, Sustainable Energy Development Authority (SEDA), Malaysia has introduced various programs and incentives, such as; Net Energy Metering (NEM), Feed-In Tariff (FiT), Large Scale Solar (LSS), Self-Consumption (SLCO), Green Investment Tax Allowance (GITA), Green Income Tax Exemption (GITE), and Renewable Energy certification. However, the installation is based on the quota system. Driven by the implementation of these government-initiated incentives, a large number of rooftop GCPV systems of 1 kW to a few thousand

MWs for the commercial sector have been installed all over the country as shown in Fig. 1.8. Hence, recently, most research in electricity generation has emphasized the use of the GCPV system [30-40]. However, realistic techno-economic analysis before installing a GCPV system and performance analysis after installing the GCPV systems under actual climate conditions is necessary to anticipate the best economic and environmental outcomes, which is the main motivation of this thesis work.

Fig.1.8. GCPV system installed on the rooftop of Malaysian commercial building [41]

1.4 Problem statement and research questions

Monash University, Malaysia campus buildings falls under the commercial sector and hence the operational cost related to electricity consumption is high due to maximum demand (MD) Campus management has to pay the high cost related to MD (30.3 RM/kW) besides the normal electricity charges in kWh (0.365 RM/kWh). Further, on the environmental aspect, it contributes to high carbon footprint in form of emissions. Therefore, there is an effort to reduce the MD using optimum mix of energy sources with the inclusion of renewable energy to make a sustainable campus. Presently, the colossal electricity demand of the campus buildings is supplied mainly by the utility grid with a small amount of PV contribution (232.5 kWp) installed in November 2018. Since the installation of GCPV system, no performance analysis has been carried out. Another issue is that, Monash is willing to expand and install more GCPV system on the rooftop area of the buildings in the future. However, before such installation a techno-economic data is required for the feasibility of such project to take a decision based on the least cost method.

Based on the introduction and problem description, the research presented in this thesis aims to answer the following primary research question:

1) What is the performance of the existing Monash 232.5 kWp GCPV system after its installation?
2) Will the GCPV system be technically feasible and economically viable if it is extended to other buildings of the Monash campus?

1.5 Research objectives and scopes

The primary objectives of this research are as follow:

1) To evaluate the target-oriented performance analysis of the existing GCPV system of Monash as per MS IEC 61724:2010 developed by the Sustainable Energy Development Authority (SEDA).
2) To perform a techno-economic analysis of an extended GCPV system to reduce the MD of the Monash University, Malaysia buildings using commercial HOMER Grid software.

Following the research objectives, the dissertation's scopes are briefly listed below:

Based on objective 1: The performance of the current 232 kWp GCPV system will be carried out as per the per national Malaysian standard (MS IEC 61724:2010) and international standards. The parameters to be evaluated consists of yield, performance ratio, capacity factor, system losses, economic (cost saved) and environmental (CO2 emission offset) analysis. The performance will be evaluated with the set-target (calculated based on the solar irradiation data). The scope is further extended to develop a model based on the solar irradiation, module temperature and output power generated from GCPV system. The model is supported with statistical analysis.

Based on objective 2: The techno-economic feasibility study on the buildings that has potential to reduce the MD will be carried out using commercial HOMER Grid software. The technical feasibility of the GCPV system will include whether the modeled system can adequately reduce the MD of the defined building (two buildings were selected one with high energy consumption and other with low consumption). For this, two case study (with and without GCPV) will be analyzed. After examining all GCPV combinations, HOMER will optimize and rank the best option according to the least-cost options that will address the economic viability of the project. These economic parameters are net present cost, cost of energy, operating cost, etc.

1.6 Thesis structure and Organization

The thesis is structured as follows:

Chapter 1 begin with a brief discussion on the background of energy and electricity consumption. Subsequently, research motivation, problem statement and research questions, followed by the research objectives and scopes, will also be summarized in this chapter. Chapter 2 presents detail literature review on the GCPV systems and its application in the commercial buildings. Energy consumption in Malaysia, solar energy, and its Malaysian context will also be presented in this chapter. Literature on performance analysis and techno-economic analysis of the GCPV system using HOMER will also be included in this section. Chapter 3 covers the description of the site, data collection, and analysis method. The mathematical model used for performance analysis will also be described, followed by the in-detail discussion of methodology of techno-economic analysis done using HOMER software. Chapter 4 shows the results and discussion of the target-oriented performance analysis of the 232 kWp GCPV system of Monash University, Malaysia. In this result, the Monash GCPV system will be compared with other GCPV systems around the world. Further, a detailed techno-economic analysis of an extended GCPV system for specific buildings of Monash Malaysia campus will be presented in this section. Techno-economic analysis according to architectural constraint will also be included in this section. Finally, Chapter 5 summarizes the research work and provides future recommendations.

Chapter 2

Literature review

2.1 Energy and electricity consumption in Malaysia

Malaysia is a developing non-OECD (Organisation for Economic Co-operation and Development) country. Malaysia's primary energy supply has increased continuously over the last decade. Malaysia's energy demand is expected to reach 146.7 Mtoe in 2030, with an annual growth rate of 3.5% [15]. The primary energy supply of Malaysia by source between 1978 till 2015 is shown in Fig 2.1 [42].

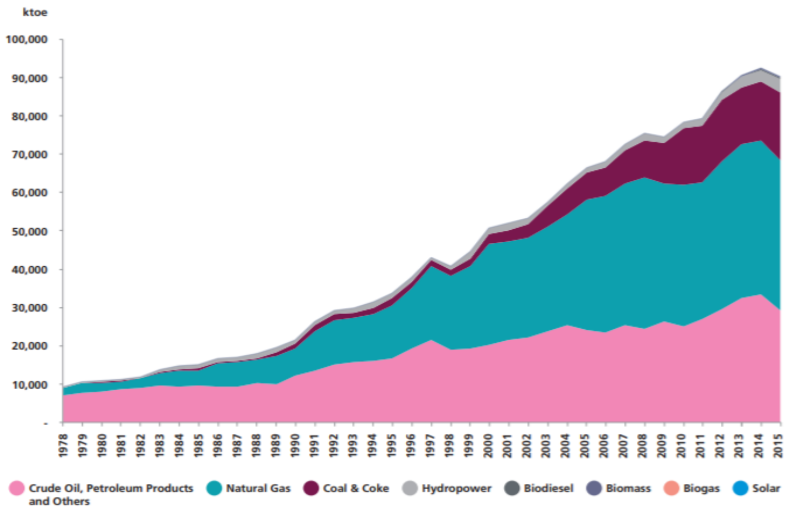


Fig. 2.1. Malaysian energy supply by source (1978-2015) [42]

Generation of electricity consumes most of Malaysian energy, about 45.6% of total end-use energy consumption [43]. Currently, Malaysia's total installed capacity is 24 GW [44]. Natural gas and coal are the primary source of electricity in Malaysia as shown in Fig. 2.2 [42]. Although there are enough natural gas reserves in Malaysia, their exhaustion is inescapable. At present depletion rate, reserves are predicted to last for 39 more years [45]. Therefore, renewable energies become increasingly popular in Malaysia.

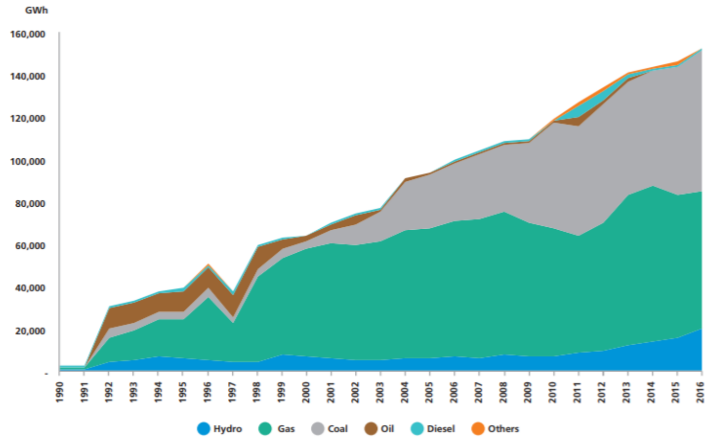


Fig. 2.2. Fuel consumption in electricity generation, 2016 [42]

2.2 Commercial building electricity usage and electricity tariff in Malaysia

Building sector consumes high amount of energy in Malaysia, and the maximum of it is attributed to electricity usage in commercial buildings [46]. Specifically, buildings in Malaysia consume about 48% of the country's total electricity [47]. Due to this high demand, the electricity rate increases in peak time, and commercial building owners have to pay a high electricity consumption cost. Usually most of this high demand is attributed to space cooling, lighting, and other official usage [48], as illustrated in Fig. 2.3. Under Malaysia's current electricity tariff, commercial consumers must pay the maximum demand (MD) charge apart from the net consumption charges every month, which is typically 20% of the electricity bill [49].

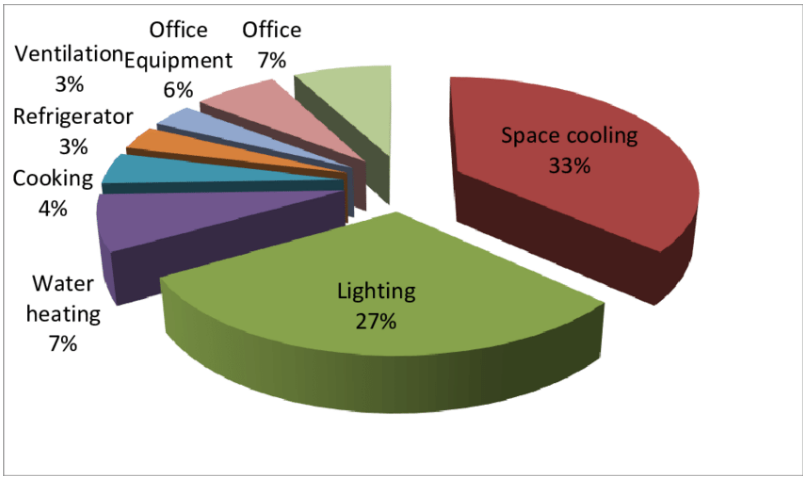


Fig. 2.3. Electricity consumption (by usage) in a typical commercial building [48]

MD is the highest level of electrical demand monitored in a particular period, usually for a month measured in Kilowatt (kW). For any month, MD shall be deemed to be twice the most significant number of kilowatt-hours (kWh) supplied during any consecutive thirty minutes in that month [49]. As Monash Malaysia campus falls under medium voltage general commercial tariff (C1), MD charges are calculated between 8.00 a.m. and 10.00 p.m., along with the regular kWh rates [49]. Consumption tariff rates for commercial users in Malaysia are shown in Table 2.1.

Table 2.1 Consumption tariff rates for commercial users

TARIFF CATEGORY	RATES
TARIFF B - LOW VOLTAGE COMMERCIAL TARIFF	
For the first 200 kWh (1 -200 kWh) per month	43.5 sen/kWh
For the next kWh (201 kWh onwards) per month	50.9 sen/kWh
The minimum monthly charge	RM7.20
TARIFF C1 - MEDIUM VOLTAGE GENERAL COMMERCIAL TARIFF	
For each kilowatt of maximum demand per month	30.3 RM/kW
For all kWh	36.5 sen/kWh
The minimum monthly charge	RM600.00
TARIFF C2 - MEDIUM VOLTAGE PEAK/OFF-PEAK COMMERCIAL TARIFF	
For each kilowatt of maximum demand per month	45.1 RM/kW
For all kWh during the peak period	36.5 sen/kWh
For all kWh during the off-peak period	22.4sen/kWh

Utility tariff rates differ between countries, and even within some countries, it can vary in different districts [50]. In Malaysia, most of the tariffs are designed to support the clients in giving alternative preferences to limit their electricity consumption during peak hours. If we look at the average electricity tariff rates for selected ASEAN countries [51] (Fig. 2.4), it is clear that Malaysian electricity tariff rates are still in the range of affordable rates compared to other countries.

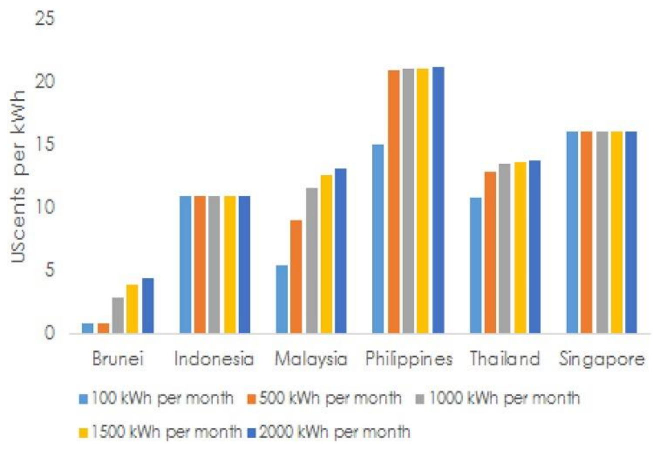


Fig. 2.4. Regular electricity tariff (based on kWh) rates in ASEAN countries [51]

As mentioned earlier, commercial buildings tend to have high energy consumption in the form of electricity due to the heavy use of electrical equipment. Therefore, several researchers have applied different techniques to reduce electricity consumption, ultimately reducing the energy bills and carbon footprints. Alajmi reports that investment in retrofit projects can save up to almost half of the commercial buildings' annual energy consumption [52]. Mbungu et al. [53] found that to minimize the overall electricity consumption of a commercial building, peak clipping is a more effective technique compare to valley-filling and load-shifting. This is because the energy demand's daily peak in a commercial building is typically from late-morning to early-evening. Again, demand-side management offers a dynamic behavior on electricity loads, which permits flexibility on the electrical system that can reduce the electricity consumption cost in commercial buildings [54].

Further, utility companies have introduced several price-based demand response such as time-of-use (TOU), real-time pricing (RTP), and critical-peak pricing (CPP) to encourage lower use of electricity during peak demand hours [55], which eventually will reduce the MD charges. Fakeha et al. [56] reported that synchronized control of building loads (i.e., demand response or DR),solar PV, and storage could substantially reduce commercial buildings' peak electricity consumption. This is because the integration of solar PV with storage system can help to move the building peak demand to off-peak periods.

Likewise, a large and growing body of literature has emphasized the concept of implementing solar PV to reduce energy consumption in commercial buildings [57-66]. In Poland [67], the GCPV system was implemented to reduce office buildings' peak load using different energy prices/tariffs. The results show that solar PV can reduce energy costs and MD irrelevant to the variety of tariffs. It was observed that in the case of that selected office building, the peak load reduction was almost 20%, with an electricity cost reduction of 1.2% up to 5.8%. Darghouth et al. [68] found that in comparatively high solar-resource, commercial building, day-peaking loads can have demand charge reductions of up to one third. They also argued that in locations with afternoon peak period designs, commercial consumers enjoy higher demand charge savings than residential consumers due to the load profile that matches quite well with PV generation.

2.3 Solar energy status in Malaysia and application of Grid-connected Photovoltaic system

According to the background study, to manage both the future energy demand and reduce the environmental impact [69], renewables such as solar play a vital role in becoming an alternative energy source. Malaysia, as one of the Southeast Asian countries, has taken the pace to increase the capacity of solar PV installation over the last few years. As the country has sunshine almost throughout the year, Malaysia is exceptionally suitable for the deployment of solar energy. The yearly typical quotidian solar irradiations for Malaysia were from 4.21 kWh/m^2 to 5.56 kWh/m^2 [20]. To utilize this great natural opportunity, the Malaysian government has been working hard on the development and implementation of green technology, primarily focusing on solar energy. As the electrification rate is almost 100% in Peninsular Malaysia, GCPV systems dominate the market as compared to the OGPV systems [29].

GCPV system is one of the fastest-growing PV technology designed to operate along with the utility power grid [27], which is expected to become a promising energy solution for MD shaving worldwide. Therefore, recently, most electricity generation research has emphasized the use of the GCPV system [30-40]. A comparison between the GCPV system and the single renewable or conventional system is presented in Table 2.2 [70].

Table 2.2 Comparison between GCPV system and single renewable or conventional system

Characteristic	**Off-grid system (Only PV)**	**Grid system (without RE)**	**GCPV System**
Reliance on natural resources	Extremely high	Autonomous	Fractional
Investment Cost	Very high	Low	Medium
O & M cost	Low	High	Low
Frequency of maintenance	Less frequent	frequent	Less frequent

Environmental impact	N/A	High	Low
Reliability	Dependent on the accessibility of natural resources	Dependent on availability of fossil fuel	Highly reliable due to balancing the nature of the resources

2.4 Performance analysis of Grid-connected Photovoltaic system

Driven by the implementation of the government-initiated incentives, many GCPV systems of 1 kW to a few thousand MWs for the commercial sector have been installed all over the country. These systems have been designed, installed, and commissioned following remunerative techno-economic approaches. However, realistic performance analysis of the installed GCPV systems under actual climate conditions is significant to evaluate the systems' performance as they are anticipated, to know the operational behavior of the GCPV systems in actual outdoor conditions. in order to calculate the economic reduction on total electricity cost, and to assess the environmental contribution. Besides technical specifications and system sizes, GCPV system's performance is site-specific and is depended on factors such as latitude, seasonal variation of solar irradiance, temperature, cloudiness, air pollution, etc. Therefore, an accurate, detailed study of GCPV system performance is a vital benchmark for commercial end customers to make future decisions.

Several researchers have carried out a performance analysis of solar PV installations in the past. In 2019, Sohouane et al. [38] investigated a 28 kWp GCPV system's performance under desertic weather conditions in Algerian Sahara and found that environmental parameters variation has a direct effect on the performance of solar PV. In the same year, Roumpakias et al. [39] analyzed the data of a grid-connected photovoltaic park after six years of operation, where the analysis results showed a minor decline of performance over the years, with a degradation rate varying from 1 to 4%. Halabi et al. [71] studied the performance evaluation of three different types of PV arrays connected to utility-grid in Malaysia and concluded that the PV performance depends directly on the solar irradiation and the surrounding environmental impacts. Performance assessment of a 20 kW_p solar PV system installed at the Indian Institute of Science, Bangalore, was done by Vasisht et al. [72], in which they reported that the performance ratio (PR) of the PV system is 85% and is inversely proportional to the module temperature. Chandrakant et al. [40] carried out a simulation-based performance analysis of a 6.4 kW grid-connected rooftop solar PV system using various simulation software. They reported a 41% reduction in the utility grid's energy requirement when the GCPV system with a 75% PR was implemented. According to Renu et al. [73], the performance of a PV system is sorted based on (i) Performance Ratio (PR) and (ii) Capacity Utilisation Factor (CUF).

From the aforementioned paragraph, it is evident that several studies [74-87] have carried out a performance analysis of GCPV systems worldwide. However, such studies are specific to regional conditions. Regarding Malaysia, environmental conditions vary from other countries, and only study [88] have attempted to analyze the long-term outdoor performance of GCPV systems. Further, no single study has been reported on target-oriented performance analysis of GCPV systems yet in the literature.

2.4.1 Performance Ratio

The performance ratio is one of the crucial parameters to assess the performance of a GCPV system and is accepted worldwide. The higher the system's PR, the greater its efficiency under comparable climatic conditions relative to other systems. Based on the report of an EU PERFORMANCE project, a PR of 0.8 and higher is an indicator of the excellent performance of GCPV systems [89].

In Belgium [90], PR was used as a critical indicator to analyze 993 residential GCPV systems' performance over two years. The average performance ratio was found to be 0.78, representing a decent performing system. The PR of a GCPV system in Algiers varied between 62% to 77%. [91]. Hussin et al. [92] reported that PR could be different for different PV module technologies. . In their study , they found different PR of 78.2%, 81%, and 94.6% for polycrystalline, monocrystalline, and amorphous silicon module, respectively, under the Malaysian climatic conditions Interestingly, PR can also be changed by time [93]. In a study carried out in India [94], the PR was less than 0.6 due to inverter failure for three months in the first year. However, in the next year, the average PR was 0.7 as the inverter problem was repaired. This indicates that PR's consistent monitoring would benefit the commercial consumer to improve system performance, leading to higher PR values.

Khalid et al. [89] report that for the GCPV system, PR reflects the actual performance as compared to the capacity utilization factor (CUF). It was reported by Stefan [95] that, for the identical meteorological condition or similar geographic region, PR is the principal tool to distinguish even trivial disparities in the performance of a GCPV system. Renu et al. [73] studied a GCPV system's performance installed in a university building and found the PR to be 0.78. The monthly distribution of PR was demonstrated by Kumar to assess the real performance of a GCPV system at Ramagundam, India [96], as shown in Fig. 2.5. The highest and lowest PR of 97.5% and 73.88%, respectively, in December and April, with an annual average of 85.15%. The authors mentioned that lower PR is attributed to the inappropriate operation of the system and inverter failure.

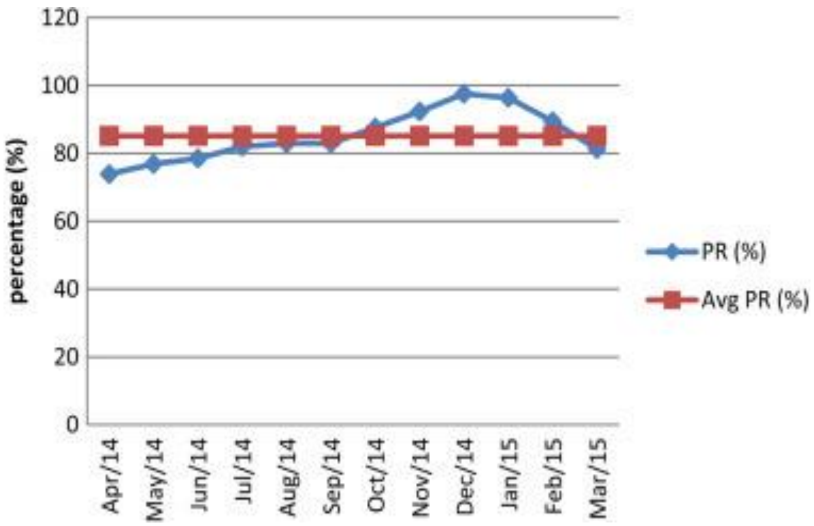


Fig. 2.5. Monthly and average PR over a monitored period of a study in India [96]

Recently, Kazem et al. [93] evaluated the effect of aging on the performance of a 1.4 kW GCPV system situated in Oman, as shown in Fig.2.6. It is evident that PR showed a minor degradation over seven years of operating, which was not observed for annual energy yield. In 2020, Rachit et al.[97] presented an overview of the performance of PV plants commissioned at different places in the world. They have found that almost all the PV plants exhibit a good performance ratio, and the average PR of all the solar PV systems was 73.21%. Interestingly, the highest PR was observed in Malaysia (94.6) due to implementation of modern PV technology and decent climate condition. Fig. 2.7 depicts the comparison of the PR at different location in the world. This confirms that the PR is very specific to the geographical region due to the respective weather conditions. They have also concluded that the PR of the solar PV system is improving with time due to the development in PV material technology and inverter topologies.

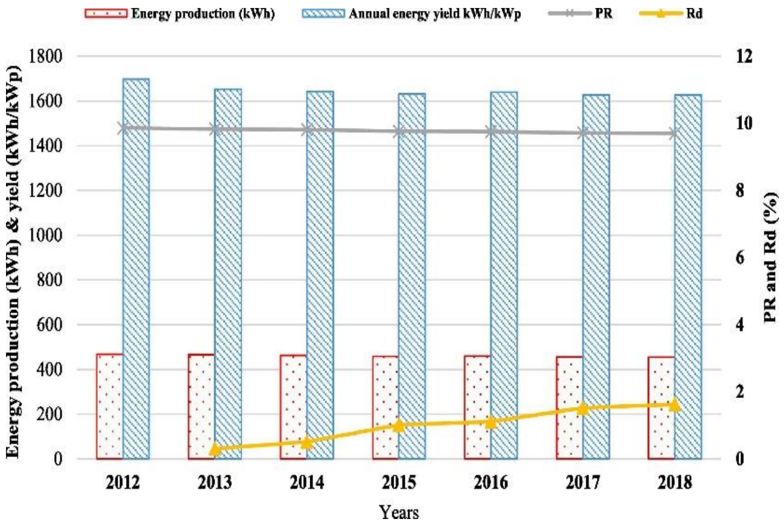


Fig. 2.6. Performance analysis after seven years of operation in Oman [93]

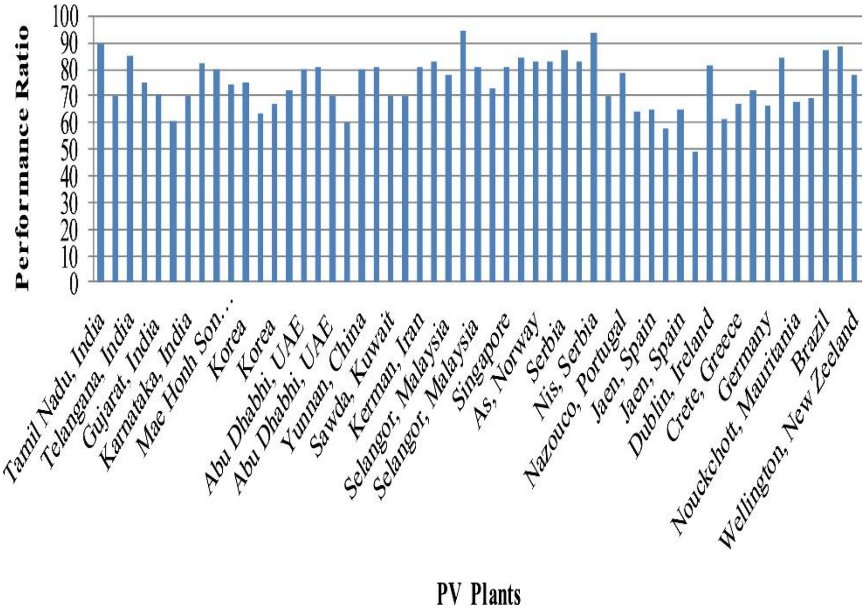


Fig. 2.7. Performance ratio of the PV plants at different places of the world [97]

2.4.2 Capacity utilization factor

CUF is considered one of the most important parameters to evaluate and compare the PV plants' performance at different locations. This is because CUF mainly depends on the global horizontal irradiance (GHI) of the installed PV systems' location. According to Chaudhari et al. [98], CUF is the relationship between the actual production of the installed PV capacity and the probable output which could be produced if the capacity was fully used. Moreover, they also found a strong positive correlation between CUF and solar irradiation.

Venkatesh et al. [99] claimed that CUF portrays the electricity cost, which means the higher the CUF, the lower the electricity cost. They also argued that the difference in CUF depends upon several aspects, such as losses in the system and climatic changes. Vasisht et al. [72] have argued that besides GHI, CUF of a GCPV system also depends on the solar PV modules' cell efficiency. In a performance assessment study, Sreenath et al. [100] found that the value of CUF fluctuates between 12.6% and 17.46% for a GCPV system installed in Kuantan airport, Malaysia. From their study, it has been observed that the CUF did not follow the same pattern as PR, as shown in Fig. 2.8.

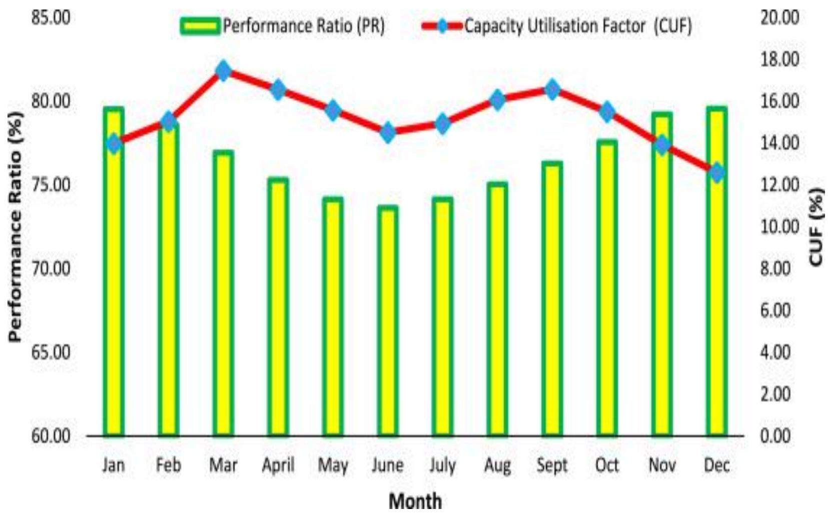


Fig. 2.8. CUF of a PV plant at Kuantan Airport, Malaysia [100]

In a performance analysis study [101], it was demonstrated that CUF usually varies from month to month due to the system losses. They found the annual average CUF for a GCPV plant in Timor LaRosae to be 14.83%, with a maximum of 19.44% in September and a minimum of 10.72 % in December. Similarly, Zoltan et al. [102] reported that CUF values varied significantly during eight years of operation between 13.15 to 14.5%. A study conducted by Attari et al. [79] on a GCPV system's performance analysis found the CUF annual average value to be 14.84%. They have reported that the PV system could generate full energy in about 55 days in a year. Ramanan et al. [103] evaluated the CUF for two different PV modules and found that for the CIS module, CUF is higher (19.57) than the P-Si module (17.99).

2.4.3 Yield

PV energy yield can be defined as the total AC energy generated by a solar PV system . It is one of the crucial parameters specified by International Energy Agency (IEA). According to Marios [104], PV energy yield is closely related to cost evaluations. Specifically, the payback period of a PV system and the investment level are linked with the PV energy yield. Usually, the energy yield of a solar PV system depends on many factors such as; PV module technology, solar irradiation, cell temperature, cloud, and other shading effects, inverter efficiency, dust, weather conditions, geographical location, cable thickness, etc. [105].

Ayompe et al. [106] studied the performance of a 1.72 kWp PV system in Dublin, Ireland and reported that despite high wind speeds, low solar insolation, and ambient temperature, the GCPV system had the highest annual average yield due to high PV module efficiency. The performance of a 20 kWp solar PV system was assessed by Vashist et al. [72] under different climate condition. They found annual yield of 28.9 MWh with an average daily yield of 80 kWh. Renu et al. [73] mentioned that the electrical behaviour of solar PV system has significant impact on cell temperature which ultimately affects the final energy output.

Edalati et al. [107] compared the energy yield of two different PV technology in Iran. Their findings revealed that the energy yield of polycrystalline (p-Si) PV modules was higher than monocrystalline (mc-Si) modules. However, Tahri et al. [108] compared the AC energy yield between mc-Si and CIS PV modules and found that mc-Si modules generate quite higher yield than CIS PV modules. Attari et al. [79] compared the final PV energy yield of several sites, as shown in Fig. 2.9. It is clear that energy yield was higher in some sites such as Oman, Kuwait, and Morocco (denoted as present study in Fig. 2.9.). According to authors, this was due to the high solar irradiation and maximum sunshine hours duration at the particular locations.

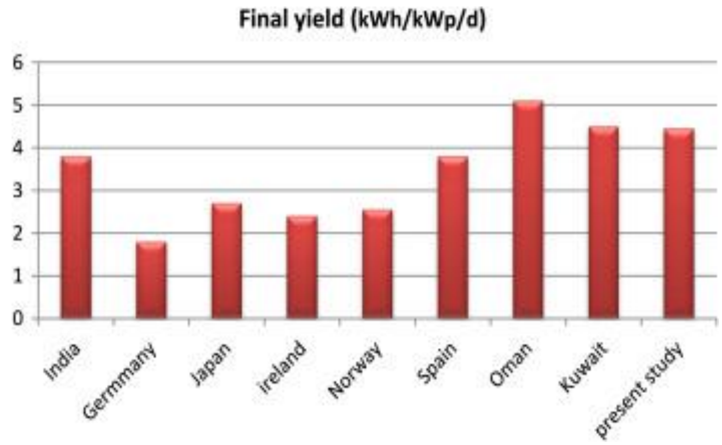


Fig. 2.9. Comparison of final energy yield in several sites [79]

Besides, PR, CUF, and yield, there are also some parameters such as; system efficiency, inverter efficiency, PV module efficiency, etc. to evaluate the performance of a PV system.

2.5 Techno-economic analysis of GCPV system using commercial HOMER software

Before implementing and installing a GCPV system, a realistic techno-economic analysis must be carried out to anticipate the economic and environmental outcomes. Several studies have been conducted on the feasibility of the GCPV system worldwide on homes, university campuses, schools, hotels, hospitals, etc. [109]. For instance, Zhang et al. [110] showed that solar PV with a grid connection would reduce cost of energy (COE) by 46% for commercial consumers in China. In southern France, a techno-economic feasibility study emphasized that the GCPV system would lower the electricity cost by 10% and minimize the GHG emission over 90% for an office building. A similar result has been observed for electricity generation for family farms in Algeria, where the GCPV system has lowered the electricity cost by 8% with a 68% reduction in GHG emissions [111].

On the contrary, Dalton et al. [112] found that the GCPV system would be less economical than the grid-only system due to a significant rise in total net present cost (NPC) for tourist accommodation in Australia. Interestingly, a feasibility study done by Ruben et al. [113] revealed that the GCPV system for university campus buildings in Indonesia is technically feasible but considered unfeasible economically due to the high value of NPC. The reason behind high NPC is that the Indonesian government subsidies the electricity cost to the educational institutions. Similarly, the techno-economic evaluation of GCPV systems for rooftop solar PV building in five climate zones in China was examined by Chong et al. [86]. They have reported that even though the GCPV system incurred a higher cost than the only grid system, in terms of both economics and emissions, the GCPV system was a better choice for all five regions than the other systems considered in that study. To install a 10MW GCPV system, Rehman et al. [114] carried out several techno-economic feasibility studies at different Saudi Arabia sites and select Bisha as the most suitable site due to its long sunshine hours and high amount of solar irradiance.

In recent years most research in GCPV systems has been carried out by using HOMER. Systematic literature review reveals that HOMER is one of the most used tools for system optimization by the researchers as it has a maximum combination of renewable energy systems and sensitivity analysis which makes it easier and faster to evaluate many possible system configurations [115]. Rabaza et al. [116] performed a techno-economic assessment of solar PV using HOMER and showed that the energy cost reduced by 37.2% in Spanish olive oil industry. Mohammed et al. [117], presented a HOMER based hybrid PV/fuel cell combination without battery storage, to prove a feasible alternative for conventional generators and reduced the total maintenance cost to meet the electrical load. In 2014, Adarmola et al. [118] analyzed the economic feasibility of six hybrid combinations of electricity generation by using HOMER in southern Ghana. HOMER was used to investigate the economic viability of a PV/diesel HPS in various climatic zones within Tamil Nadu (India), and this helped the government to invest in renewable energy to improve the rural electrification problem [119].

Table 2.3 Summarized literature review of using HOMER software on the commercial building

Author(s), year	Computational approach	System type	Commercial building type	Country	Outcome
Islam et al., 2018 [120]	HOMER	PV-Grid-Battery	Office Buildings	France	Lowered the electricity cost by 10% and minimizes the GHG emission by over 90%
Anand et al., 2017 [121]	HOMER	PV-HFC-Battery	Educational	India	Minimum NPC with 0% capital shortage
Sigalo et al., 2017 [122]	HOMER	PV-Grid	Educational	Nigeria	More cost-efficient than diesel-only PV system with COE $0.0386
Normazlina et al., 2016 [123]	HOMER	PV-FC-Battery	Hospital	Malaysia	Environment friendly with lowest COE 0.091 $/kWh
Zhang et al., 2016 [124]	HOMER	PV-Grid-Battery	Office building	China	Reduce the COE by 46%
Dalton et al., 2009 [125]	HOMER	PV-Wind-Grid	Hotel	Australia	50% lower NPC
Rachit et al., 2016 [126]	HOMER	PV-Grid	Educational	India	COE of $0.1/kWh with 37% renewable fraction and CO2 reduction 544t/year.

For hydrogen production in Saudi Arabia, HOMER was used to optimize renewables, which lead to a minimum cost of energy [119]. The outcome from Normazlina et al. [120], showed a cogeneration system of fuel cells and solar PV was profitable to meet the load of a Malaysian hospital building and at the same time reduce the effect of the emissions with the help of HOMER. In 2018, Gökçek, et al. [121], used HOMER and reported that hydrogen refueling station powered by renewable energy was economically cost-effective for Turkey. Recently, HOMER has developed a dedicated tool for grid system as HOMER Grid. However, this newly developed HOMER Grid has not been much applied to commercial buildings in particular to Malaysian region. A summarized literature review of using HOMER software for techno-economic analysis of renewable energy-based system is presented in Table 2.3. It is quite evident that HOMER is a powerful commercial tool to evaluate the techno-economic feasibility of the renewable energy hybrid system.

2.6 Summary

It is clear from literature review that GCPV system plays an important role in reducing the electricity demand of commercial buildings. It also revealed that performance analysis of installed GCPV is necessary to understand the efficiency and operation of the system. Therefore, several researchers from different locations in the world have presented the performance analysis of GCPV system. It not only provides a crucial information on the technical performance, but also on the economical aspect of the system that can benefit all the stakeholders; the consumer, investors and solar service company. Further, a commercial algorithm optimization software (HOMER, USA) has also been utilized to obtain decision on the techno-economic feasibility of the renewable energy. A range of literature covering performance analysis, and techno-economic approaches for investigating the feasibility analysis of GCPV systems for commercial building in Malaysia have been discussed. The main problem as highlighted in Chapter 1, is high operational cost associated to the consumption of electricity in the commercial buildings. In order to reduce the MD in the commercial building a GCPV system was installed on the rooftop of Monash Malaysia campus building whose description is provided in methodology Chapter 3. However, realistic performance analysis of already installed GCPV systems and techno-economic feasibility analysis of future GCPV system was not carried out until date. Clearly, till date very few or none have used newly developed HOMER Grid optimization tool to perform techno-economic feasibility study of GCPV system on the commercial building. In order to address the research questions and the gap of the present project, the following Chapter 3 provides a detail research methodology on the performance analysis and techno-economic assessment of GCPV system for commercial building of university campus.

Chapter 3

Methodology

3.1 Site characteristics and existing GCPV system description

Monash University, Malaysia, located in Bandar Sunway, Selangor, Malaysia, with a latitude of 3.0645° N and a longitude 101.6011° E, respectively, is selected as the site for this case study. As a tropical country with an average annual rainfall of ~2300 mm, Malaysia experiences substantial rainfall throughout the whole year. Individually, in Sunway city, the maximum temperature is around 27.4 ° C, and it ranges between 26.9 ° C and 28.0 ° C [127]. On a horizontal surface in Sunway city, Malaysia, the average global solar radiation is ~ 4.21 – 5.06 kWh/m^2/day [128]. Monash University Malaysia's architectural design and satellite view are shown in Fig. 3.1.

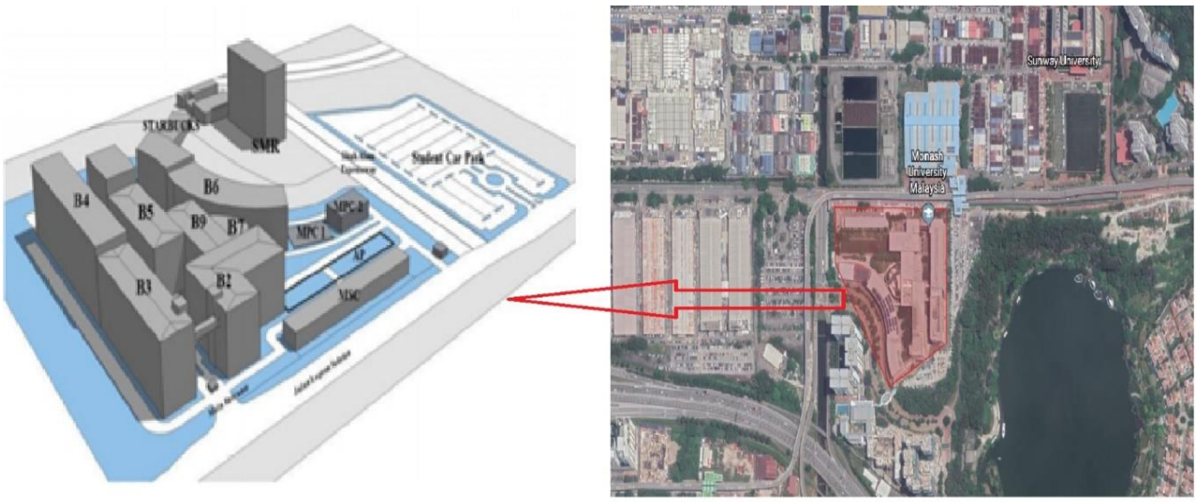
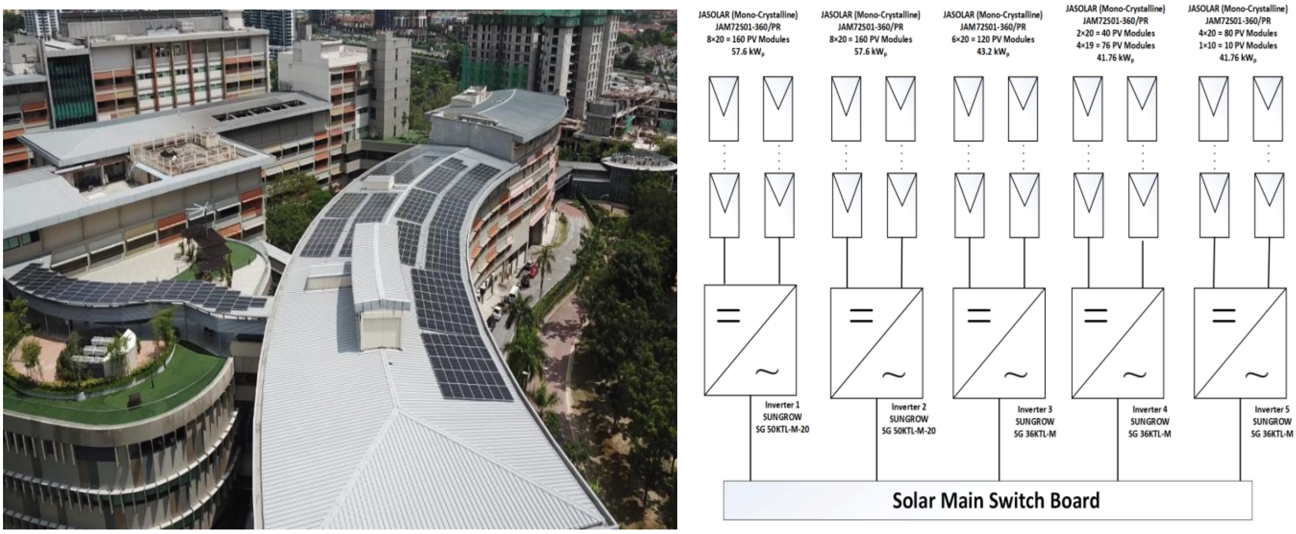


Fig. 3.1. Architectural design and satellite view of Monash University Malaysia

The existing GCPV system comprises of 646 monocrystalline PV modules (JA Solar), each of 360 Wp, covering an area of 2169 m^2, as shown in Fig. 3.2. The PV modules are accumulated into five units, and each unit is connected to an inverter. Two different models of inverters are used: inverters 1 and 2 are SUNGROW S50KTL (50,000 Wp), and inverters 3, 4, and 5 are SUNGROW S36KTL (36,000 Wp). The first two inverters (1 and 2) are connected to eight arrays, each consisting of a string of 20 PV modules, and six of which are connected in parallel with inverter 3.

Similarly, six arrays of PV modules are connected to inverter 4: the first two arrays each consist of 20 PV modules, and the remaining four arrays each consist of 19 modules. The final inverter is linked with five arrays, each consisting of 20 PV modules except one which has only ten modules. The inverter and PV module connection configuration are shown in Fig. 3.2.



(a) (b)

Fig. 3.2. a) Aerial view of the GCPV system installed on the rooftop of Monash campus building, b) Schematic layout of the GCPV modules and inverters connection

DC combiner boxes, an AC solar main switchboard, and a data logger were also installed. The orientation and the tilt angle of the GCPV system were based on the rooftop arrangement. The overall physical and technical specifications of the Monash GCPV system are summarized in Table 3.1.

Table 3.1 Physical and technical specification of the Monash Malaysia campus GCPV system

Commissioning date	November 2018	
System connection type	Self-consumption GCPV system	
Total area	2169 m^2	
PV module details and specifications	Number of PV modules	646
	Model	JAM 72 S01- 360/PR
	Cell type	Mono
	Rated maximum power (P_{max}) [W]	360
	Open circuit voltage (V_{oc}) [V]	47.66
	Maximum power voltage (V_{mp}) [V]	38.96
	Short circuit current (I_{sc}) [A]	9.81
	Maximum power current (I_{mp}) [A]	9.24
	Module efficiency (%)	18.5
	Temperature coefficient of I_{sc}	+0.060 %/ ˚C
	Temperature coefficient of V_{oc}	-0.300 %/ ˚C
	Temperature coefficient of P_{max}	-0.380 %/ ˚C

	Maximum system voltage	1000V/1500V/DC (IEC)	
	Operating temperature, ˚C	-40 ˚C ~+85	
	NOCT, ℃	45±2	
Inverter details and specifications	Model	SG 50 KTL-M-50	SG 36 KTL-M-20
	Number of inverters	2	3
	Maximum PV input voltage (V)	1000	1100
	Maximum PV input current (VA)	112	88
	MPPT voltage range (V)	300-950	200-1000
	Nominal AC output power (kW)	50	36
	Maximum AC output power (kW)	50	36
	Nominal AC operating voltage (V)	230/400	230/400
	AC voltage range (V)	310 - 480	310 - 480
	Efficiency (%)	98.9 – 98.5	98.5 – 98.3
Data Logger		Solar-Log 2000	

3.2 Data collection

A Solar-Log 2000) data logger was equipped with the Monash GCPV system to monitor and record, at 5-minute intervals, necessary energy production data and influential parameters such as: module temperature, solar irradiance, wind speed, ambient temperature, PV yield, and electrical parameters. The data logger is connected to a modem to capture a local wireless connection, where it transfers all the acquired data to the webserver. The results presented in this study consist of one year of data recorded between 1st January 2019 and 31st December 2019.

3.3 Meteorological data

The annual average solar irradiation of the Malaysian site is 4.15 kWh/m2/day, and ranges between 3 and 5 kWh/m2/day, with a high of 6.09 kWh/m2/day recorded in September 2019 and a low of 0.534 kWh/m2/day in December 2019 as shown in Fig. 3.3. Although the highest solar irradiation in 2019 was recorded in September, the maximum and minimum average daily peak sunshine hours (PSH) were recorded in March (4.52 h) and December (3.61 h), as illustrated in Fig. 3.4b. The PSH has a relation with solar irradiation. PSH is the ratio of solar irradiation (H) in kWh/m^2 to the standard solar irradiance (G) i.e. 1000 kW/m^2. The average monthly ambient temperature in March was 30.71 °C and in December was 28.34 °C (Fig. 3.4a). The highest monthly module temperature reached was 73 °C (in March, April, and October), and the lowest recorded was 21 °C (in April and June, at night)

(Fig. 3.4a). The average module temperature presented in Fig. 3.4a is a monthly average that includes both daytime and night time.

The ambient temperature was always found to be lower than the average module temperature, which may be due to thermal losses arising on power generation, as earlier reported by Sivasankari et al [129]. Usually, the wind speed is much lower in Malaysia, and the highest recorded was 1.42 m/s in May 2019. However, wind and its speed will affect the module temperature by taking away some of the heat through convection. Solar irradiation, module temperature, ambient temperature, PSH, and wind speed have a considerable influence on the performance of the solar PV system [130]. They concluded that even though PV technology prices have decreased and now offer a long service life with low operation costs, the energy production from PV systems is very much dependent on location and weather conditions. Solar irradiation is the most highly fluctuating and sensitive parameter, as depicted in Fig. 3.3. Santhakumari and Sagar [131] have addressed the effect of climatic and environmental conditions such as dust, ambient temperature, wind velocity, humidity, snowfall, hailstorms, lightning, ice, air-mass, clouds, the latitude of installation, module degradation, and sandstorm on PV efficiency, energy yield, and energy production. Four climatic factors (temperature, irradiation, humidity, and mechanical stress) are responsible for the degradation of the PV module. One of the most important of these was found to be hot and humid environmental conditions that allow moisture to permeate the back sheet of the PV module, which separates the PV cells from the metal, thus enhancing corrosion and causing leakage of current. This is scenario is highly possible in Malaysian tropical climatic conditions.

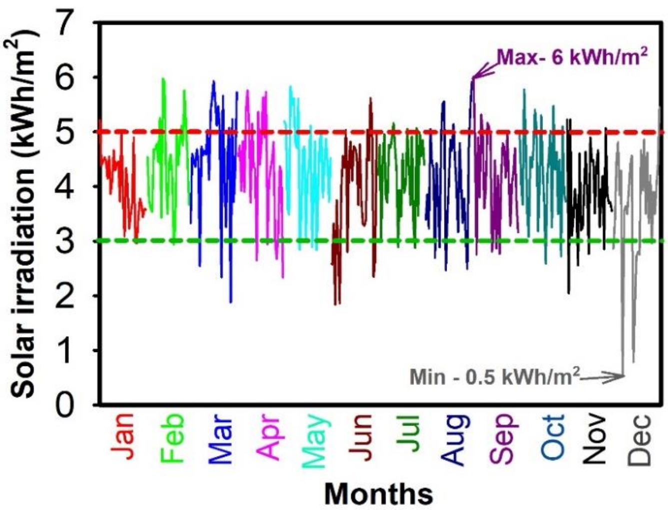


Fig. 3.3. Daily solar irradiation (kWh/m^2) for the year 2019 in Malaysia

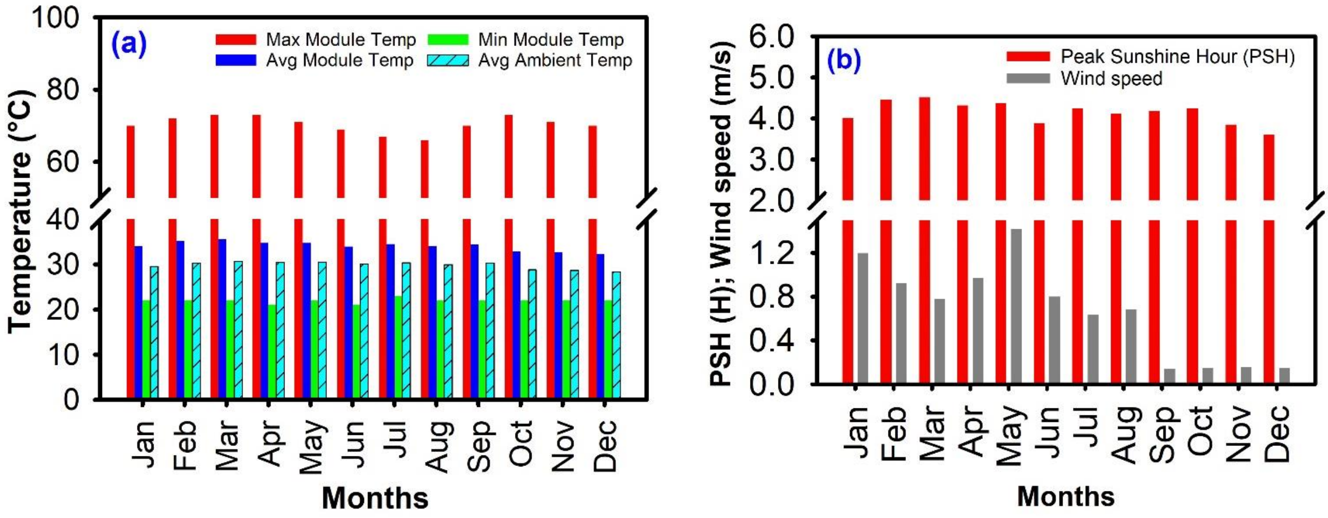


Fig. 3.4. (a) Monthly maximum, minimum and average PV module temperature, and ambient temperature; (b) PSH and wind speed (monthly average) of Monash GCPV site

3.4 Electricity load data

The monthly electricity consumption data of 2019 of the whole Monash University, Malaysia campus, was collected from Facility Management Department (FMD), as shown in Fig. 3.5. It can be observed that Monash has the highest electricity consumption during March to May, and August to October due to the peak operational time of the campus. During this time, semesters are running, and buildings are heavily occupied and used for teaching and learning activities. Besides this, the research activities are continuous that uses energy intensive equipment. The high amount of electricity is usually used to operate various building assets such as air conditioning, lighting, lifts, lab equipment, and other office electrical devices.

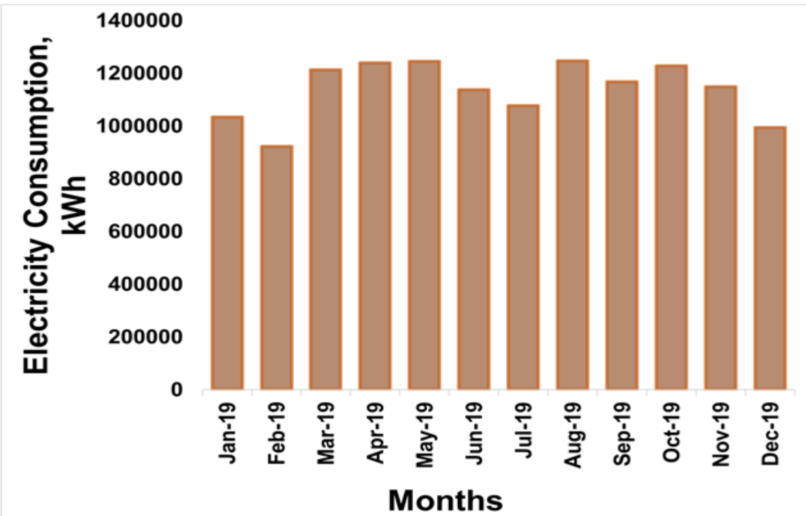


Fig. 3.5. Monthly electricity consumption of Monash University, Malaysia in 2019

Monash University, Malaysia, consists of seven buildings. However, the electricity consumption of these buildings are not the same. For techno-economic analysis, building with the highest and lowest load is selected for the present work as all the buildings show almost the same load pattern.

3.4.1 Load data for building with the highest load

The School of Medicine, Health Science and Science laboratories are situated in building 3 (B3) consumes the highest amount of electricity in the campus due to the continuous operation of lab equipment such as refrigerators, cold storage and sensitive equipment for 24/7. The average daily and seasonal profile of the electricity load of B3 is presented in Fig. 3.6. the highest consumption of about 250 kW in the morning till afternoon time is due to operation of teaching and learning activities in addition to research work. However, even after the office hours and during night-time the consumption is observed to maintain at 190 kW because of refrigerators operating for 24/7. In the seasonal profile, the highest bar refers to the maximum load consumption while the lower bar shows the minimum load consumption. The middle bar is the average and the box refer to the variation of load in the month.

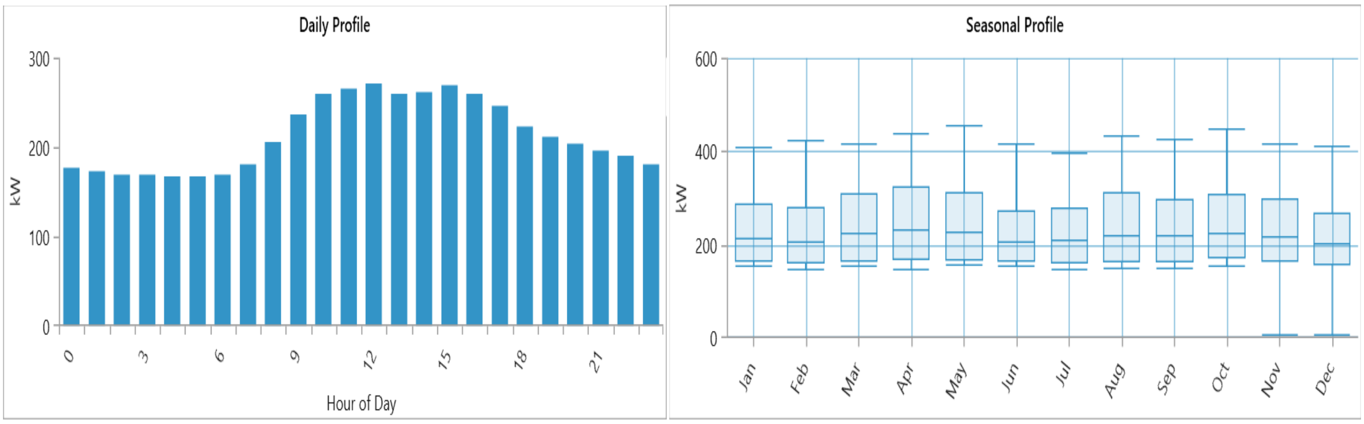


Fig. 3.6. Average daily and seasonal electricity load profile of B3 in 2019

From daily profile it's clear that B3 consumes significant amount of electricity throughout the 24 h of a day as compared to other buildings. The average MD was from 9.00 am to 17.00 pm, which is approximately between 250 kW - 300 kW. However, the highest MD of B3 in 2019 was 455 kW, which was recorded in May. It is clear from the seasonal profile that B3 has the highest electricity consumption during March-May, and August – October. The average hourly MD profile for B3 is shown in Fig. 3.7. B3 has almost similar MD profile throughout each month of the year.

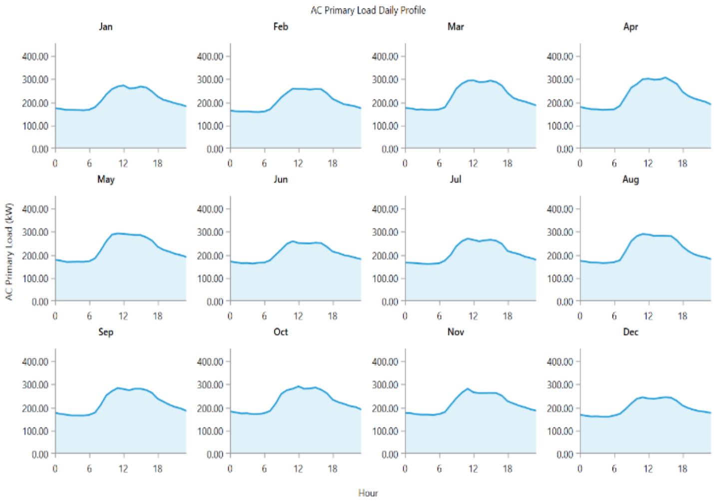


Fig. 3.7. Average hourly MD profile of each month at B3 in 2019

3.4.2 Load data for building with the lowest load

Building 7 (B7) consumes the lowest electricity in the Monash campus and this building occupies the library. The main electricity consumption in B7 is due to the lighting and air conditioning. The average daily and seasonal profile of the electricity load of B7 is presented in Fig. 3.8.

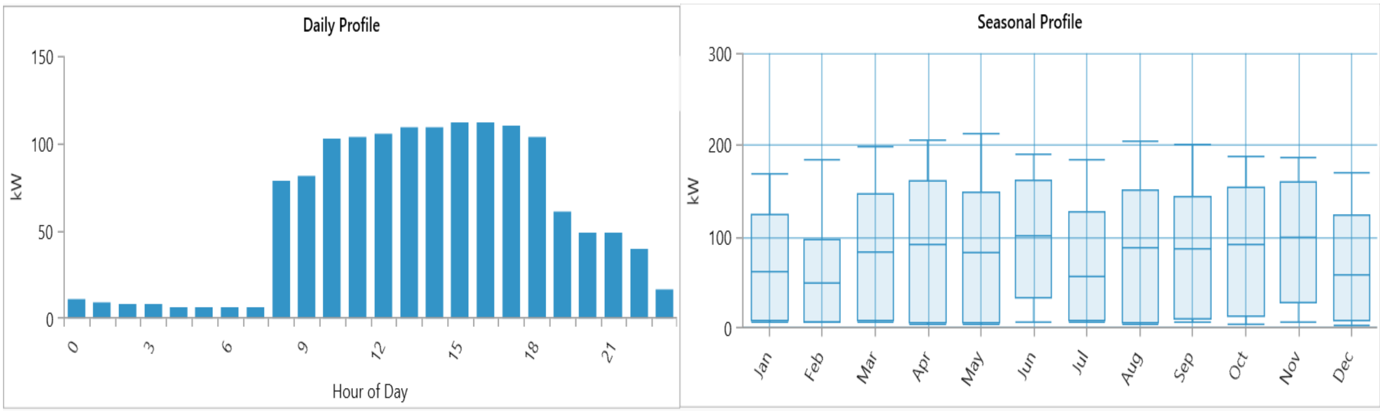


Fig. 3.8. Average daily and seasonal electricity load profile of B7 in 2019

The daily profile of B3 is quite different from B7, as the load for B3 drops below 10 kW in the night-time. The average MD was from 9.00 am to 17.00 pm, which is approximately between 70 kW - 120 kW which coincides with the library usual operating timings 9.00 am to 10.00 pm. The highest MD of B7 in 2019 was 212 kW, recorded in April and lowest in month of December and January (that has normal semester break). The seasonal profile illustrates the highest electricity consumption during March-May, and July – November, obviously corresponding to learning and teaching activities during running semester. B7 also has similar MD profile throughout each month of the year as shown in Fig. 3.9. However, May- June and Sep – Nov, there was a small spike in average MD during the beginning of the day.

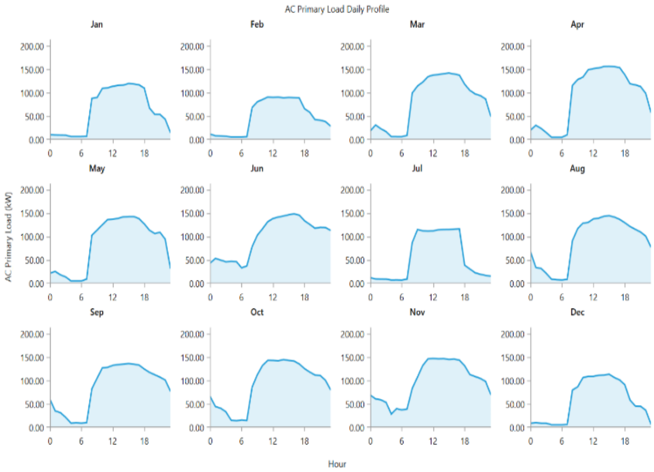


Fig. 3.9. Average hourly MD profile of each month at B7 in 2019

3.5 Mathematical methodology for the Performance Analysis of existing Grid-connected Photovoltaic system

To investigate the performance of the current GCPV system, several metrics were specified as per national (MS IEC 61724:2010) and international standards. The performance indices considered in this study are yield, PR, CUF, system efficiency. The economic and environmental performance has also been assessed.

3.5.1 Yield

Yield is the amount of energy generated by the GCPV system. It is one of the most critical performance metrics of a GCPV system that is directly related to PR and CUF.

The total measured AC yield generated by the GCPV system can be expressed as [132];

$$\boldsymbol{Y_{mea,AC}} = \sum_{t=1}^{N} \boldsymbol{E_{AC(t)}} \quad \text{[kWh]} \tag{1}$$

Where $\boldsymbol{E_{AC}(kWh)}$ is the measured final AC energy output at time t (can be in minutes, hour, or day), and N is the number of observations.

The total DC yield is given as [132];

$$\boldsymbol{Y_{mea,DC}} = \sum_{t=1}^{N} \boldsymbol{E_{DC(t)}} \quad \text{[kWh]} \tag{2}$$

Where $\boldsymbol{E_{DC}(kWh)}$ is the DC energy output at time t (can be in minutes, hour, or day), and N is the number of observations.

The target for AC yield evaluation is calculated as [132];

$$\boldsymbol{Y_{tar}} = \boldsymbol{P_{array\_STC}} \times \boldsymbol{PSH_{poa}} \times \boldsymbol{k_{deration\_y}} \times \eta_{cable} \times \eta_{inv} \text{ [kWh]} \quad (3)$$

where $\boldsymbol{Y_{tar}}$ is the target AC yield, $\boldsymbol{P_{array\_STC}}$ is the power of the PV array under standard testing conditions (STC), $\boldsymbol{PSH_{poa}}$ is peak sunshine hour, $\boldsymbol{k_{deration\_y}}$ is the deration factor of energy yield, η_{cable} is the efficiency of DC cable from PV to the inverter, η_{inv} is the inverter efficiency.

The peak sunshine hour was calculated as [132];

$$\boldsymbol{PSH} = \frac{\boldsymbol{H}}{\boldsymbol{G_o}} \quad (4)$$

where $\boldsymbol{H}$ is solar irradiation (kWh/m^2) and $\boldsymbol{G_o}$ is solar irradiation under STC, i.e., 1 kW/m^2.

Specific yield ($\boldsymbol{SY_{mea}}$) is the amount of AC energy generated by the system per unit capacity and is given by [132];

$$\boldsymbol{SY_{mea}} = \frac{\boldsymbol{Y_{mea,AC}}}{\boldsymbol{P_{array\_STC}}} \quad [\frac{\boldsymbol{kWh}}{\boldsymbol{kwp}}] \quad (5)$$

3.5.2 Performance ratio (PR)

The PR describes the quality factor that measures the performance of the PV system and specifies how closely its performance approaches the ideal performance during real-life operation independent of the location. It includes all design and installation parameters and gives a normalized indication of the system. The measured and target performance ratio can be calculated by Eq. 6 and Eq. 7 [132];

$$\boldsymbol{PR_{mea}} = \frac{\boldsymbol{Y_{mea}}}{\boldsymbol{P_{array\_STC}} \times \boldsymbol{PSH_{poa}}} \quad [\%] \quad (6)$$

$$\boldsymbol{PR_{tar}} = \frac{\boldsymbol{Y_{tar}}}{\boldsymbol{P_{array\_STC}} \times \boldsymbol{PSH_{poa}}} \quad [\%] \quad (7)$$

Where, $\boldsymbol{PR_{mea}}$, and $\boldsymbol{PR_{tar}}$, are the measured and target performance ratio, respectively.

3.5.3 Capacity utilization factor (CUF)

The CUF of a GCPV installation is defined as the ratio of the AC energy output ($\boldsymbol{E_{AC}}$) over a given period (usually one year) to the energy output that would have been generated if the system operated at full capacity for the entire period. It is calculated as [133]:

$$\boldsymbol{CUF} = \frac{\boldsymbol{E_{AC}}}{\boldsymbol{P_{array_{STC}}} \times \boldsymbol{A_h}} \quad [\%] \quad (8)$$

Where A_h is the total expected number of hours of operation in a given period, commonly a year (for a regular year which consists of 365 days, A_h = 8760 h).

3.5.4 System efficiency, η_{sys}

The system efficiency of the GCPV system is provided by Eq. 9 [134];

$$\eta_{sys} = \frac{E_{AC}}{H_t \times A_a} \tag{9}$$

Where, $\boldsymbol{H_t}$ is the total in-plane solar irradiation (kWh/m^2) and $\boldsymbol{A_a}$ is the module area (m^2).

3.5.5 Loss analysis

Energy losses occur in the GCPV system in several ways, the most significant of which are system losses and array capture losses.

System losses are due to the conversion of DC into AC by the inverters and are given by Eq. 10[132, 135]

$$L_S = \frac{E_{DC}}{P_{array_{STC}}} - \frac{E_{AC}}{P_{array_{STC}}} \tag{10}$$

Array capture losses are any losses due to the PV array and are given using Eq. 11;

$$L_C = PSH - \frac{E_{DC}}{P_{array_{STC}}} \tag{11}$$

3.5.6 Economic analysis

Metrics such as the payback period and the LCOE were considered to assess the financial viability of the GCPV system. The LCOE is the present value of the price of the generated electrical energy, considering the economic life of the plant and the costs of construction, operation, and maintenance. It is calculated as [133]:

$$LCOE = \frac{CRF * C_I + C_{o\&m}}{E_{AC}} \left[\frac{\$}{kWh}\right] \tag{12}$$

Where C_I is the initial capital cost, $C_{o\&m}$ is the annual operation and maintenance cost, and E_{AC} is the annual electricity generated by the installation. *CRF* is the capital recovery factor, which is given by Eq. 13 [133];

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{13}$$

where i is the interest rate, and N is the payment period (in years).

3.5.7 Environmental analysis

The environmental performance of the GCPV system was assessed using the CO_2 factor - the amount of carbon dioxide that can be mitigated by using solar PV in Malaysia. The average CO_2

factor in Malaysia is 0.585 tCO_2/MWh [136]. The annual carbon dioxide avoided was calculated using Eq. 14;

$$(CO_2)_a = 0.585 \times \boldsymbol{E_{AC}} \text{ (metric tons)} \quad (14)$$

3.6 Techno-economic assessment for an extended GCPV system using HOMER Grid

HOMER is one of the most used computational approach for system optimization as it facilitates the comparison of power generation technologies across a wide range of applications [137] with a maximum combination of renewable energy systems and sensitivity analysis. It evaluates the optimal size of hybrid energy systems by carrying out the techno-economic analysis [138]. HOMER Grid is an optimisation software dedicated in reducing the demand charge. A derivative-free Black Box algorithm is used for the optimisation mechanism. HOMER's optimisation and sensitivity analysis algorithms simplify the evaluation of many possible system configurations. Based on the project inputs given by the user such as load profile, grid tariffs, component specifications, economic parameters HOMER Grid runs hundreds of simulations, and it ranks the outcome of the simulations based on least cost of NPC (Net Present Cost) as show in Fig. 3.10. the input to HOMER consists of location, load profile, electricity tariff, economics and incentives and components (solar PV, energy storage, wind, generator, etc.). HOMER Grid uses all these inputs to run hundreds of simulations to provide an optimized hybrid combination solution.

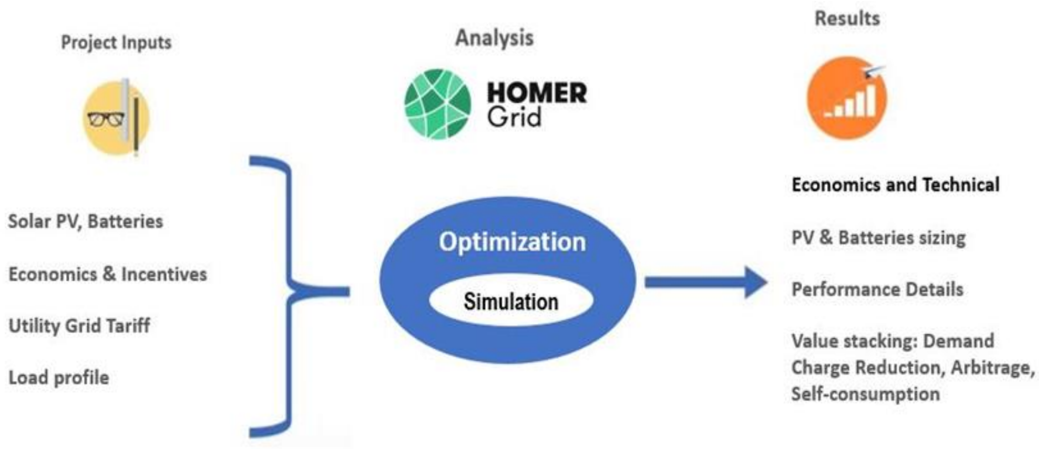


Fig. 3.10. Techno-economic analysis methodology of HOMER Grid

3.6.1 Technical parameters

Technical analysis plays a vital role in HOMER's simulation and optimization process due to many design options and the uncertainty in key parameters, such as load size. The modelling of the GCPV system configuration in HOMER Grid software consists of four main components, such as PV module, converter, battery and utility grid. However, batteries are expensive to install and also not feasible for the site location hence not included in the present study. 'Grid only' is the existing source of power supply (TNB) to satisfy the electricity load of B3 and B7 buildings. In the result section, the grid only system will be compared with the proposed GCPV system.

3.6.1.1 Solar PV system

A PV module is the core element of the solar PV system, which converts the sun's light or photons directly into electrical energy. HOMER calculates the output of the PV array using the following equation [139]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) [1 + \alpha_p (T_c - T_{c,STC}) \tag{15}$$

Where, $Y_{PV}(kW)$ is the rated capacity of the PV array, $f_{PV}(\%)$ is the derating factor, $\bar{G}_T \left(\frac{W}{m^2}\right)$ is the solar radiation incident on the PV array, $\bar{G}_{T,STC} \left(1 \frac{kW}{m^2}\right)$ is the incident radiation at standard test conditions, α_P is the temperature coefficient of power, T_C (°C) is the PV cell temperature, and $T_{C,STC}$ (°C) is the PV cell temperature under standard conditions. The derating factor is a scaling factor meant to account for effects of dust on the panel, wire losses, elevated temperature, or else that would cause the output of the PV array to deviate from that expected under ideal conditions. For the analysis purpose, JAM 72 S01- 360/PR solar PV module was selected in this study. The capital cost was set as 2500 RM per kWp, replacement and maintenance cost were assumed as 2500 RM and 1.5 RM per kWp/per year, respectively. These costs of the solar PV system were provided by local solar service company. The standard lifetime is 25 years.

3.6.1.2 Inverter

An inverter is a device that alters electric power from DC to AC in a process called inversion. The inverter size, which is a decision variable, refers to the inverter capacity, meaning the maximum amount of AC power that the inverter can produce by inverting. The following formula will be used for the inverter to convert DC electricity of PV panels to AC electricity with and efficiency η_{inv},

$$P_{inv,out} = \eta_{inv} P_{PV} \tag{16}$$

Where, $P_{inv,out}$ is the output power rating of the inverter. SG 50 KTL-M-50 has been modelled as an inverter in this thesis. The capital cost has been set to be RM 1000 per kWp, Replacement and maintenance cost has been assumed as RM 1000 and RM 1 per kWp, respectively. The standard lifetime of an inverter is 15 years. These costs were provided by local solar service company.

3.6.1.3 Utility

A Utility is an organization that supplies electricity to customers. For example, TNB is the only electric utility company in Peninsular Malaysia. In HOMER Grid, utility is one of the main components to design a GCPV system. A utility designs several tariffs to cover different types of services and customers. It typically has different tariffs for residential and commercial customers. Each tariff is a list of rate charges and describes a service.

3.6.2 Economic parameters

One of the main usages of HOMER Grid is to provide an economic analysis while meeting the system constraints. Two main economic parameters are calculated, such as; COE (cost of energy), TNPC (total net present cost). These costs are used by HOMER to determine the optimum system.

3.6.2.1 Cost of energy

The cost of energy (COE) is defined as the average cost per kWh of useful electrical energy produced by the system. The following equation will be used to calculate the COE,

$$COE = \frac{C_{ann,tot}}{E_{served}} \tag{17}$$

Where, $C_{ann,tot}$ is the total annualized cost and E_{served} is the total electricity served. The total annualized cost is the annualized value of the total net present cost. HOMER calculates the total annualized cost using the following equation:

$$C_{ann,tot} = CRF\left(i, R_{proj}\right). C_{NPC,tot} \tag{18}$$

Where, $C_{NPC,tot}$ is the total net present cost, i is the the annual real discount rate (%), R_{proj} is the project lifetime, CRF () is a function returning the capital recovery factor. The following equation will be used to calculate the operating cost,

$$Cop = C_{ann,tot} - C_{ann,cap} \tag{19}$$

3.6.2.2 Net Present Cost

HOMER's main economic output by which it levels all system configurations in the optimization results is total NPC. The NPC is calculated within HOMER using below equation

$$NPC = \frac{C_{ann.tot}}{CRF} \tag{20}$$

Where, $C_{ann.tot}$ is the total annualized cost and CRF represent capital recovery factor. The following equation defines CRF,

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{21}$$

Where i = real discount rate and N = number of years.

The objective function of HOMER Grid is to minimize the total NPC. Regarding the costs for each element, Equation (21) applies for all of the planning horizons,

$$C_{element,i} = \sum C_{capital,i} + C_{O\&M,i} + C_{replacement,i} + C_{fuel,i}\ (MYR) \tag{22}$$

Where, $\mathrm{C_{capital,i}}$, $\mathrm{C_{O\&M,i}}$, $\mathrm{C_{replacement,i}}$, $\mathrm{C_{fuel,i}}$ is the capital cost, operation and maintenance cost, replacement cost and fuel cost, respectively.

The PV fraction ($\mathrm{f_{PV}}$) can be calculated by Equation (2) below,

$$f_{PV} = 1 - \frac{E_{non-renewable}}{E_{served}} \tag{23}$$

Where, $E_{non-renewable}$ = The total amount of non-renewable energy produced and $\mathrm{E_{served}}$ = The total amount of energy served to the consumer.

It has now become apparent that the best system configuration would be the one that results in the lower total NPC at the start of the project while satisfying all constraints.

3.7 Environmental assessment

In HOMER, the environmental effect is calculated for direct emissions of CO2, CO, NOx, SO2, particulate matter, and unburnt hydrocarbons from fuel combustion technologies [140]. Calculating the emission in HOMER is slightly different between the generator and the grid. For the generator, before simulating the power system, emissions are studied in HOMER as the product of emission factor and annual consumption of fuel. An emission factor is kg of pollutant emitted per unit of fuel consumed. After the simulation, it calculates the annual emissions of that pollutant by multiplying the emissions factor by the total annual fuel consumption. However, in simulating a grid-connected system, HOMER calculates the net grid purchases, equal to the entire grid purchases minus the total grid sales. To calculate the emissions of each pollutant associated with these net grid purchases, HOMER multiplies the net grid purchases (in kWh) by the emission factor (in g/kWh) for each pollutant. If the system sells more power to the grid than it buys from the grid over the year, the net grid purchases are negative and so are the grid-related emissions of each pollutant.

3.8 Methodology for architectural constraint based on the SEDA standards

Based on 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. 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 [141].

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

$$N_{max\ \_module\_across} = N_{across\_up} \times N_{across\_across} \tag{24}$$

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

$$N_{across\_up} = r.d.\left[\frac{W_{roof}}{W_{mod} + \Delta}\right] \tag{25}$$

$$N_{across\_across} = r.d.\left[\frac{L_{roof}}{L_{mod} + \Delta}\right] \tag{26}$$

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

$$N_{max\ \_module\_up} = N_{up\_up} \times N_{up\_across} \tag{27}$$

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

$$N_{up\_up} = r.d.\left[\frac{W_{roof}}{L_{mod} + \Delta}\right] \tag{28}$$

$$N_{up\_across} = r.d.\left[\frac{L_{roof}}{W_{mod} + \Delta}\right] \tag{29}$$

Where, r.d. is round down to the next value; W_{roof} is the width of the utilisable area of the roof; W_{mod} is the width of the module; Δ= 0.01 m is the allowed inter-module gap; L_{roof} is the length of the utilisable area of the roof, and L_{mod} is the length of the module. Between lengthwise up and lengthwise across design, whichever accommodate maximum PV modules will be chosen for installation.

$$N_{max\ \_module} = max(N_{max\_module\_across}..N_{\max\ \_module\_up}) \tag{30}$$

Summary

The research methodology of the present project is outlined in Fig. 3.11. After the collection and analysis of required data in the first stage, all these data will be used for both performance analysis and techno-economic analysis. In stage 2, all the performance indices were calculated, and a realistic performance analysis has been carried out. The optimal sizes of GCPV system then will be determined in two steps, including simulation and optimization, in stage 3. The techno-economic analysis will be carried out based on total capital cost, net present cost. Finally, the results obtained from the present methodology are described in the next Chapter 4 with final conclusions in Chapter 5.

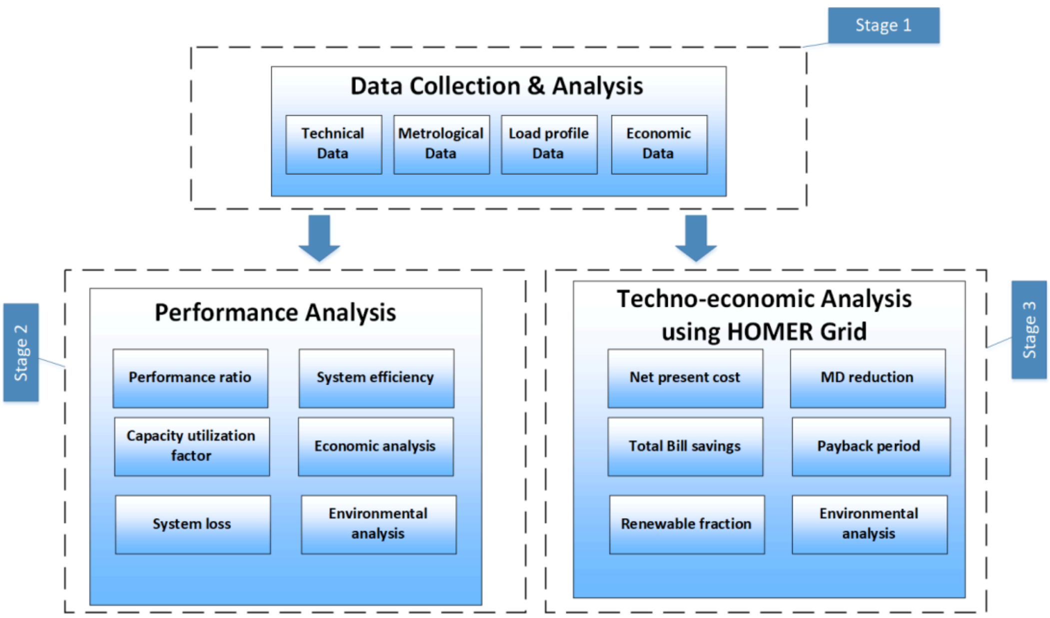


Fig. 3.11. Research methodology flowchart

Chapter 4

Results and discussion

4.1. Target oriented performance analysis of 232.5 kWp GCPV system

4.1.1 Yield analysis

The yield output was obtained from the solar data logger, which measures the energy generated from the installed GCPV system, after the DC/AC inverter, at 5-minute intervals. The total actual yield of the GCPV system achieved the set target yield for five months of the year (January, March, April, October, and November), as illustrated in Fig 4.1. The ratio of actual yield to target yield, as a percentage, was lower in the months in which the actual yield did not reach the target, leading to a reduction in the economic performance of the GCPV system. The highest yield of 29.70 MWh (due to the high number of sunny days with clear skies) was obtained in March, while the lowest yield of 21.15 MWh (due to cloudy days with frequent rain) was obtained in December, which corresponds with the highest and lowest PSH in March and December, respectively. Overall, in the year 2019, the total output yield was 301.55 MWh, only 0.78 MWh less than the target yield.

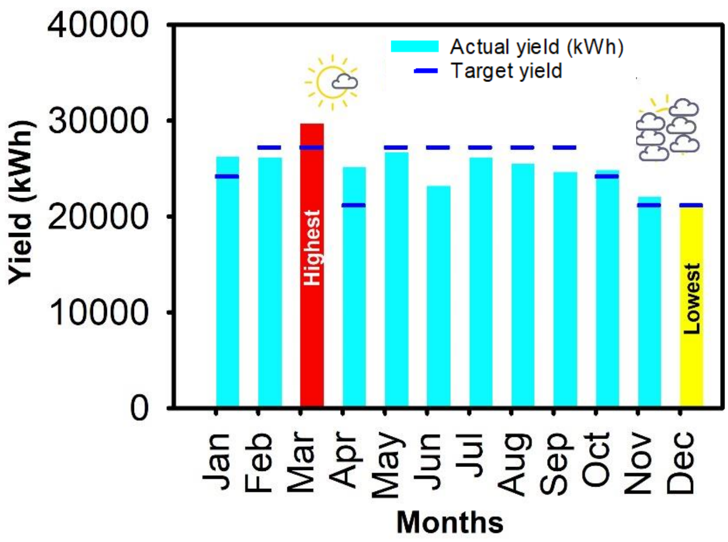


Fig. 4.1. Monthly solar yield production of the Monash GCPV system in 2019

It is striking to observe the relationship of output yield to solar irradiation for March and December, as shown in Fig. 4.2, which proves that the yield of the GCPV system is highly sensitive to solar irradiation. The highest and lowest daily energy yields were produced on 16th March (Fig. 6a) and 7th December 2019 (Fig. 4.2b), respectively. Further, the number of days that did not achieve the target yield was higher in December than March. This is due to the high amount of rain from the northeast monsoon and the frequent cloudy days between November and February. For some days, the GCPV system was shaded by clouds for the entire daytime. Thus, the weather conditions (cloud cover, rain, the position of the sun, etc.) are the most influential factors in the performance of the GCPV system, and the target yield cannot be the same for all months in a year. If the target yield for December had been the same as March, then the actual yield in December would have been far lower than the target yield. It is vital to set the target yield based on the weather conditions of that month. Therefore, the target yield for March is 27209.50 kWh as compared to 21162.95 kWh for December. Previous researchers [38, 142] have also agreed that there is a strong relationship between solar irradiation and energy production (yield) of the PV system. Recently, Allouhi et al. [143] reported that the most dominant parameter in computing the final yield is the solar irradiations falling on the panel surfaces.

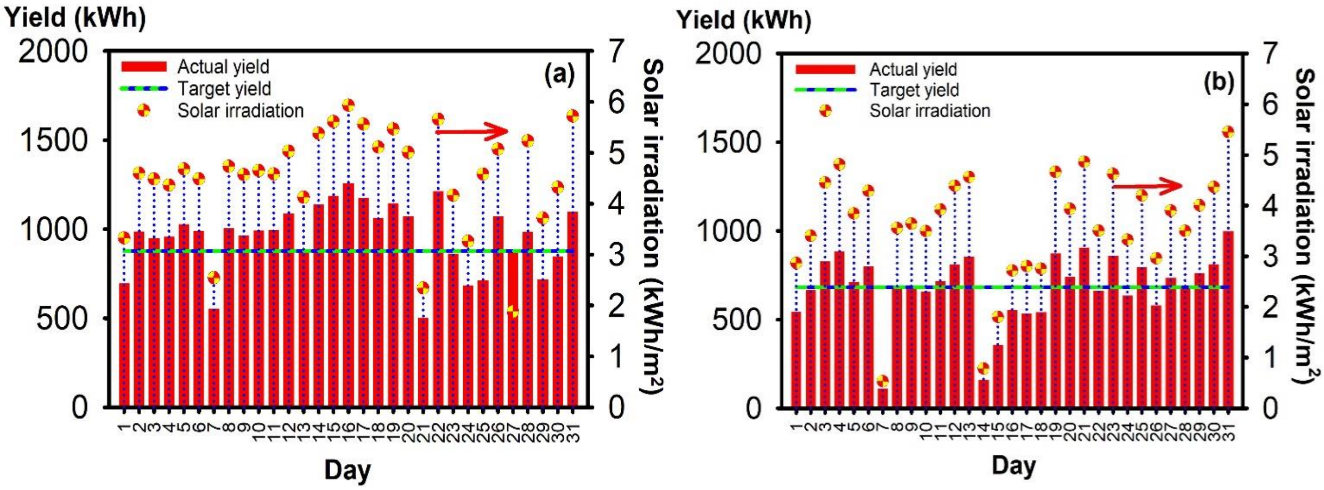


Fig. 4.2. Solar yield production of Monash GCPV system in (a) March 2019 and (b) December 2019

Fig. 4.3 depicts the highest and lowest hourly AC power output of the GCPV system on 11th February and 7th December 2019, respectively. The trend of AC power output (kW) from the GCPV system follows the profile of solar irradiance. The profile shown in Fig. 4.3a is a typical sunny clear day of the year 2019, and hence, the highest amount of power generation was recorded on 11th February 2019. Usually, the PV system starts generating energy at ~7:30 am, soon after sunrise, and it increases sharply till the sun reaches its peak at ~1.00 pm, after which it starts declining until sunset at around 7.30 pm. When the lowest AC power output from the GCPV system was recorded on 7th December 2019 (Fig. 4.3b), there were clouds and rain for the whole day. Despite the cloudy day, the solar PV plant was still able to produce energy, likely due to diffused solar irradiation that can penetrate the clouds. Nevertheless, the energy production on cloudy days is not consistent and does not show any specific pattern, unlike a clear sunny day (Fig. 4.3a Not all days of the year are the same, and consequently, the profile of the power generation from the GCPV system is also different for each day of the year. The solar cells are dependent on solar irradiation, and any slight shading decreases energy production. Khan et al. [144] found that the level of solar irradiance falling on the PV module is very sensitive to cloud thickness and patches of clouds. In their study, solar irradiance dropped between 300 to 600 W/m^2 due to a sudden patch of the cloud. However, the present study recorded even much lower solar irradiance (100 W/m^2) for the whole day, clearly signifying thick and heavy patch of clouds. The PV module temperature is usually similar to the ambient temperature on cloudy days since there is very low solar radiation. This results in very low power generation output from the GCPV system.

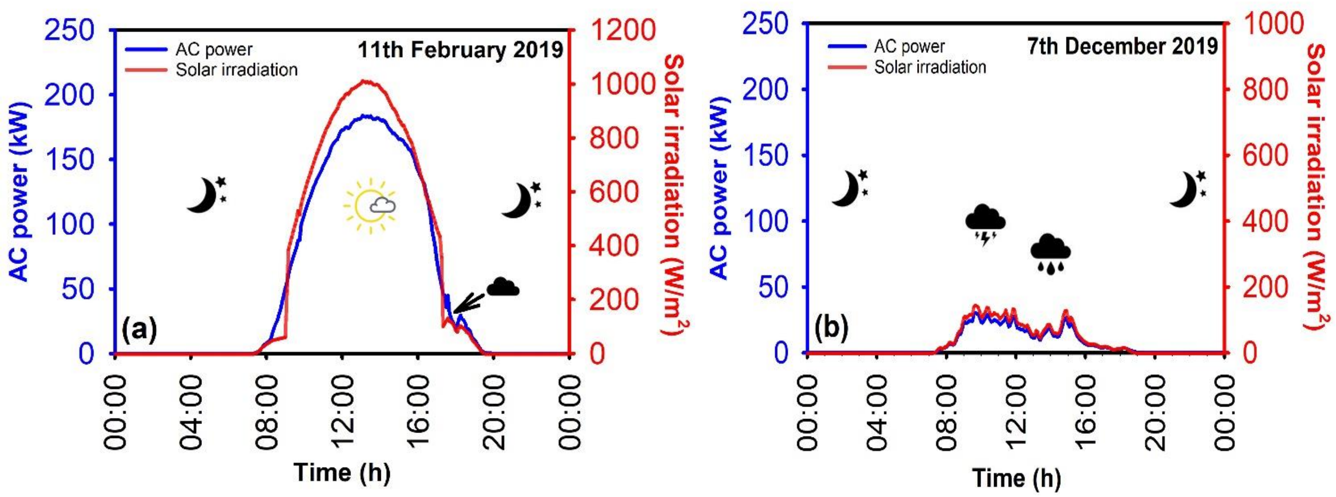


Fig. 4.3. Daily AC power output of the Monash GCPV system (a) highest in the year 2019 and (b) lowest in the year 2019

4.1.2 Performance Ratio (PR), Capacity Utilization Factor (CUF), and system efficiency

The average PR, CUF, and system efficiency of the Monash GCPV system for the year 2019 were 85.4%, 14.85%, and 9.15%, respectively, as presented in Fig. 4.4. The highest PR of 91% was observed in March and the lowest of 80% in October. The value of PR higher than 80% indicates the good performance of the GCPV plant, whereas below 75% designate problems [89]. The actual PR achieved the target values for January, March, April, October, November, and December, but was lower for the other months, mainly due to weather and climatic effects. This follows the same trend as yield production (Fig. 4.1). One of the ways to maximize the actual PR in order to reach or exceed the target PR is to reduce system losses, either by selecting the appropriate module technology (crystalline, CIS, CdTe, and thin-film) or by decreasing the module temperature.

However, there are minimal options to enhance a lower PR due to weather conditions, as these are beyond the control of operators, in particular, the shading created by clouds. Moreover, the climate can change very rapidly in a tropical climate like Malaysia. Therefore, the target PR was only reached or exceeded for half the months of the year. The PR from the present study is compared with other solar PV systems across the globe in a later section.

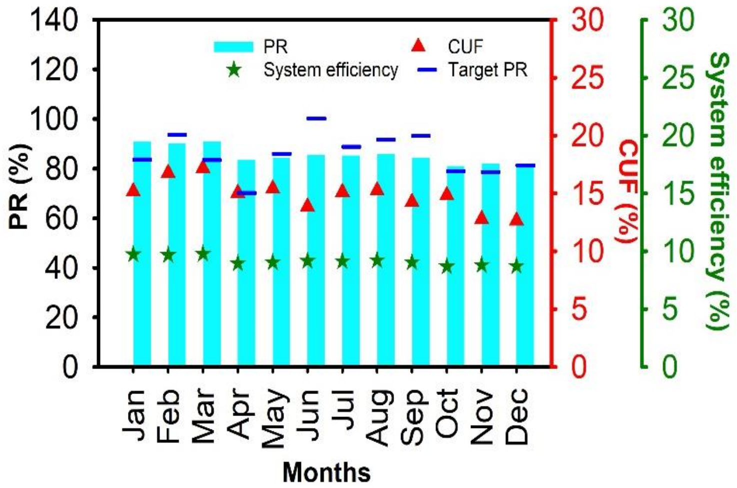


Fig. 4.4. Monthly average PR, CUF and system efficiency of Monash GCPV system

The average monthly CUF of the present GCPV system ranged from 12.6% (in December) to 17.1% (in March), with an average of 14.85%. These results are similar to those observed in earlier studies. [145] for a tropical climate such as Malaysia. According to Vasisht et al. [72], the CUF of the system is mainly dependent on the global horizontal solar irradiation at the specific location, and the PV module efficiency. Thus, there is a relation between solar irradiation and the CUF values. Again, CUF is very specific to the location and geographical conditions and may not necessarily indicate the performance of the solar PV system. For instance, the mean CUF for Slovenia (a region that faces long-existing snow barriers) was 11.85%, with very few solar PV systems reaching over 15% [146]. Another possible observation found by Kumar et al. [81] was that CUF varied between 15.25 and 16.33% based on the PV technologies (crystalline, CIS, and CdTe). The average CUF (14.85%) of the present GCPV system was close to their CUF (15.24%) value for crystalline PV technology and in the same location (Malaysia). As reported [87], in a hot and dry climate such as Oman, the CUF values ranged between 17% and 25.8%, with an average of 21.7%. Another study [114] presented a minimum of 12.1%, a maximum of 32.5%, and an average of 25.54% CUF corresponding to solar power plants in Saudi Arabia. Interestingly, the CUF in a temperate climate like New Zealand can be as low as 4.5% to as high as 21.0%, with an average of 12.5% [147].

The system efficiency in this study was found to be relatively stable, with minimal fluctuations throughout the year, as depicted in Fig. 4.4. The average was 9.15%, with a minimum in October (8.68%) and a maximum in March (9.76%). It was difficult to compare the system efficiency of the present GCPV system with prior studies [71, 88] because only two researchers have calculated the GCPV system efficiency in Malaysia. The first study [148] reported an average system efficiency of 8.05%, which is lower than the average system efficiency (9.15%) of the present GCPV system. This may be due to their higher average module temperature (~10°C) than the average module temperature recorded in the present study. The second study [149] reported system efficiency of eight different types of PV module technologies in Malaysia, and surprisingly it ranged from 6% to 14%. The combination of CdTe-Mono showed the highest efficiency. Notably, the system efficiency is very responsive to solar irradiation and module temperature [103, 150], which in turn depends on the sun's position. Therefore, system efficiency usually fluctuates along the time, even for each day. However, the fluctuation observed in our study is not that significant. Interestingly, the system efficiency of the present GCPV system was observed to be higher in January, February, and March may be due to clearer (sunny) days and lowest in October, November, and December, which could be owing to more cloudy days. In addition to this, the inverter efficiency is 98% throughout the year with negligible or no fluctuations.

4.1.3 System loss and array capture loss

The DC energy output data was not available for some days due to a malfunction of the data logger or connection errors. Therefore, the system loss and array capture loss for the day that produced the highest energy in a month is provided in Fig. 4.5. The system loss varied between 0.017 h/day in October to 2.980 h/day in February. It was also higher in January, February, and March, as was the energy yield. Interestingly, the system loss is comparatively stable from April to December but higher during the first three months of the year. This could be attributed in part to inverter error or to temperature losses from different components, particularly the PV modules, as a result of high temperatures.According to Trillo-Montero et al. [151], system losses are higher during the summertime. The trend of system loss and array capture loss of the present GCPV is similar to a previous study by Ayompe et al [106],], however, the system loss values are somewhat higher than they report. The array capture loss of the present GCPV system showed negative results from January to March, then improved from April and varied slightly until December. A previous study [38] also observed negative capture loss for solar PV systems, indicating a solar PV system will take less time to produce DC energy at its nominal power capacity.

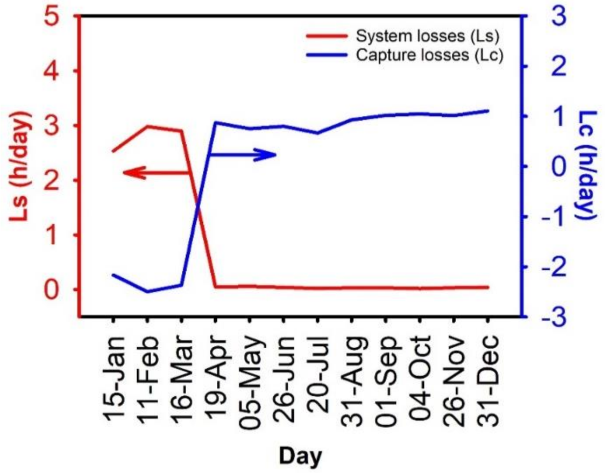


Fig. 4.5. System loss and array capture loss of the highest energy produced in a day of each month

Partial shading can also lower the capture loss to a negative value [152]. Similarly, the capture losses are also related to the temperature of the PV module, which in turn is dependent on the weather and wind speed [153, 154]. In the present case, the capture loss is relatively high with values of 1 h/d could be due to shading factor since there are months with no rainfall or El-Nino effect (large-scale ocean-atmosphere climate interaction linked to periodic warming in sea surface temperatures across the central and east-central equatorial region). During the El-Nino period, the weather becomes warmer for a more extended period or month with little or no rainfall. Therefore, the ambient temperature rises, and consequently, it might affect the PV module temperature. The correlation between system loss and capture loss is interesting because the GCPV system incurred more capture losses than system losses from April to December and vice versa from January to March. There are several reasons behind the capture losses, such as shading, soiling, maximum power point tracking errors, inverter failure, circuit breaker tripping, faulty PV modules, solar irradiation measurement errors, and prolonged grid power outages [154].

4.1.4 Statistical analysis on the effect of various parameters on PV output

Statistical analysis was performed to analyse and develop a model to predict and assess the performance of the GCPV system. A linear model (y=190.75×solar irradiation+33.44) between average solar irradiation (kWh/m2) and the amount of total AC yield (kWh) is shown in Fig. 4.6. It showed a high coefficient of determination R^2 of 0.916, indicating the measured data fit well with the linear model. This finding is consistent with the relationship witnessed by previous studies [84, 155, 156]. A strong positive linear relationship exists between the solar irradiation and AC yield with a Pearson correlation value of 0.957. Further, this correlation is highly significant since the p-value < 0.05. For the solar irradiation, the t-test statistics is 62.760 (p-value < 0.05). This concludes that at a 5% level of significance, solar irradiation is a highly statistically significant variable in predicting AC yield.

The data population was concentrated between 3 and 5 kWh/m2 of solar irradiation, corresponding to an AC yield production range of 600 to 1000 kWh. The total AC yield is 800 kWh at average solar irradiation of 4.15 kWh/m^2. The data population beyond 5 kWh/m^2 solar irradiation is sparse since the highest irradiation that can be achieved on an apparently sunny day is limited to 6 ± 0.5 kWh/m^2. The smaller data population below 3 kWh/m2 corresponds to a reduced total AC yield due to cloud and rainy days, while beyond 3 kWh/m2 shows a higher total AC yield when the days are clearer. Therefore, months that experience clear sunny days can easily achieve the target AC yield and PR compared to months with more cloudy days.

It was also found that PV module temperature also substantially affects the AC power output, as depicted in Fig. 4.7. The AC power output and module temperatures are linearly related ($y = 4.0741 \times module\ temp - 104.84$) with a coefficient of determination (R^2) of 0.914, indicating about 91% of the variation in AC power is explained by regression on the module temperature. This finding further seems to be steady with the result of [59]. They also found a linear relation with the R^2 of 0.8405. Like the previous model, the statistical analysis of PV module temperature and the AC power showed a strong positive linear relationship due to a high Pearson correlation value of 0.956 as well as this correlation is highly statistically significant (p-value < 0.05). For the PV module temperature, the t-test statistics are 1054.385 (p-value < 0.05), concluding that the module temperature is highly statistically significant in predicting AC power at a 5% level of significance.

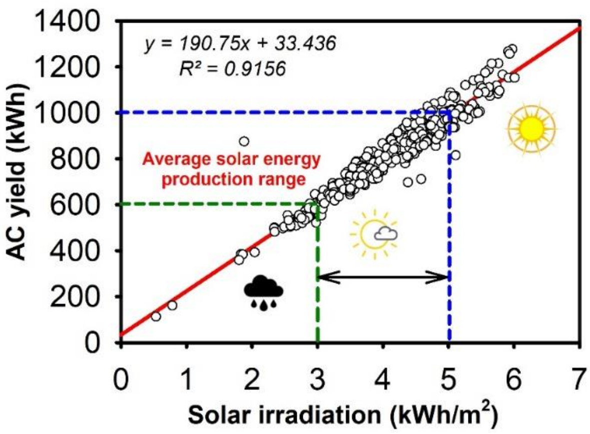


Fig. 4.6. Correlation between total AC yield from Monash GCPV and solar irradiation of the location

The total AC power produced from the GCPV system at average PV module temperature (40 °C) was about 58.00 kW, while at NOCT (45 °C) of the PV module, it is ~78.50 kW. This corroborates earlier findings [75, 157, 158] of a strong positive correlation between PV module temperature, solar irradiation, and PV mounting structure (freestanding or rooftop). However, for the present study, it is observed that solar irradiation has a more significant effect than the PV module temperature because statistically, the model suggests that with an increase in solar irradiation by 1 kWh/m^2, the value of the AC yield would increase on an average by 190.75 kWh. Whereas, for every 1 °C increase in PV module temperature, the AC power will increase by 4.074 kW.

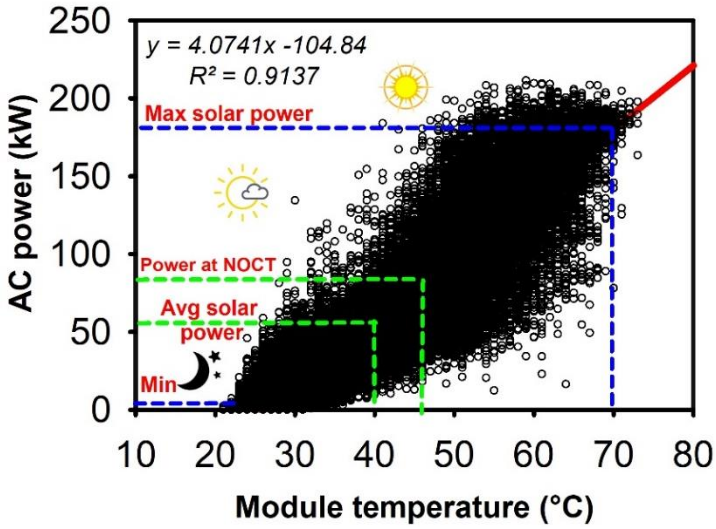


Fig. 4.7. Correlation between total AC power of Monash GCPV and module temperature (Minimum – 22 °C taken at nighttime; Average – 45 °C taken during the daytime; Maximum – 70 °C took during the daytime)

4.1.5 Economic analysis

The Monash GCPV system was installed through the self-consumption (SEL-CO) program; the electricity generated from the system is used by the campus building and any excess electricity cannot be sold back to the grid. For the LCOE calculation, factors such as the total lifespan of the solar PV system (25 years), the current interest rate (2.75%) [159], the discount and inflation rates (3.2% and 0.66%) [160], and and the average annual energy production, are considered. The Monash GCPV was installed at a capital cost of MYR 744,560 for a life span of 25 years. Based on this, the LCOE for the Monash GCPV installation is 0.396 MYR/kWh. This is considerably lower than the predicted LCOE for Malaysia in 2020 calculated by Matin et al. to be 0.49 MYR/kWh [161]. In their study, they also reported that BOS (balance of system) costs accounted for more than 30% of the LCOE in Malaysia. A previous study [162] reported a higher LCOE of 0.91 RM/kWh in 2014 due to higher interest and inflation rate at that time. They have also predicted that within 2029 Malaysia will achieve grid parity, which means the cost of PV system generation will be equal to or lower than the cost of conventional power plants. However, from the present study, it is evident that the current LCOE is very close to the per-unit electricity cost (0.365 RM/kWh) of the conventional fossil fuel-based power plants.

Using the commercial C1 electricity tariff (0.365 RM/kWh and 30.3 RM/kW for maximum demand) of TNB (Tenega Nasional Berhad) utility company, a significant reduction in the monthly electricity cost was observed (Fig. 4.8) by installing the present GCPV system in 2019. In total, about RM 110,067.00 (~USD 25,250.00 based on currency exchange when the paper was written) was saved by the present GCPV system in 2019, which was very close to the set target savings of RM 110,349 (~USD 25,315.00). As the energy output is assumed on an average to be constant for 25 years, the payback period is estimated at 6.7 years for the GCPV system, which is just one-fourth of the system life span. This shorter payback period is highly attractive since, after seven years of installation, the Monash campus can gain profit and significant savings until the GCPV lifetime. For the economic feasibility of a GCPV system, a payback period of 8-18 years is recommended [163]. Moreover, the payback period of the present GCPV system is quite lower than other studies done in Malaysia [145, 164]. Hence, the Monash GCPV system will significantly contribute to reducing the annual electricity cost.

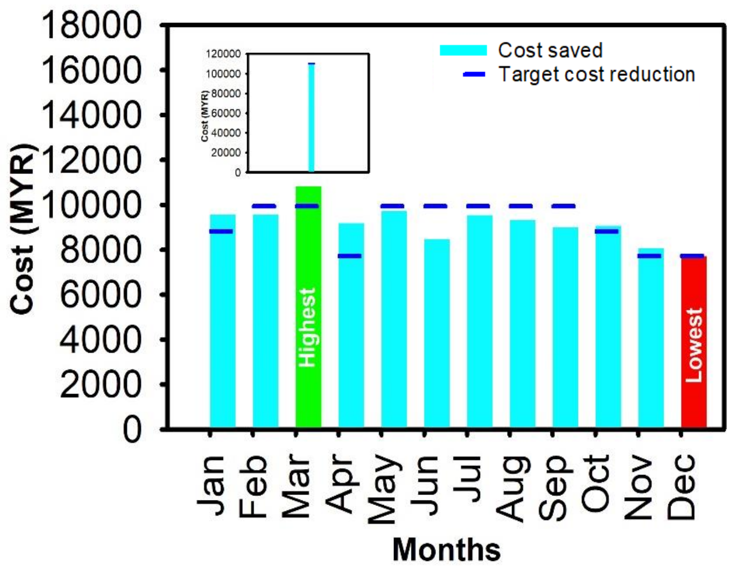


Fig. 4.8. Monthly cost reduction by Monash Malaysia GCPV system.

4.1.6 Environmental analysis

Based on the yield (301,554.2 kWh) generated by the Monash GCPV system, a total of approximately 177 metric tons of CO2 is avoided in the year 2019. The impact of this reduction is equivalent to a reduced oil equivalent to 228.42 barrels per year.

4.1.7 Comparison of Monash Grid-connected Photovoltaic with other Grid-connected Photovoltaic systems in the world

Table 4.1 presents a comparison of GCPV system (only Mc-Si) performance across the world. The primary focusing parameters of the comparison are PR, CUF, system efficiency, and inverter efficiency. Remarkably, the PR (85.4%) of the current GCPV system is higher than that of the other studies in Table 2, mostly due to the decent climate condition. Interestingly, a lower PR of 59% was also reported in Malaysia by Yacob et al. [165], due to the stochastic condition at site and the series configuration of the array. However, the reasons for the lower PR in India mainly attribute to dust as reported by Pritam et al. [166]. Typically, the CUF ranged from 15% to 40% [69]; however, with an average CUF of 14.85%, the present GCPV system has an acceptable level of productivity. The present study showed a moderate performance that is close to the reported studies In contrast to the CUF and system efficiency, the inverter used in the current study showed a higher efficiency (98%) than the other systems.

Table 4.1. Comparison of GCPV performance from different regions of the world

Location, references	PV technology	Installed capacity (kWp)	PR (%)	CUF (%)	System efficiency (%)	Inverter efficiency (%)
India, 2020 [99]	Mc-Si	50,000.00	79.94	24.65	N/A	N/A
Algeria, 2019 [38]	Mc-Si	28.00	71.89	18.58	10.99	96.46
Turkey, 2019, [167]	Mc-Si	84.75	72.90	N/A	N/A	N/A
India, 2018 [166]	Mc-Si	40.00	63.00	9.00	8.51	90.90
Ghana, 2017 [75]	Mc-Si	4.00	67.90	11.47	N/A	N/A
Morocco, 2016 [143]	Mc-Si	2.04	79.60	N/A	12.10	N/A
Abu Dhabi,2015 [168]	Mc-Si	111.60	80.00	16.00	N/A	97.30
Malaysia, 2016 [164]	Mc-Si	5.00	73.50	18.00	11.93	N/A
Malaysia, 2015 [145]	Mc-Si	3.00	77.28	15.70	N/A	95.15
Malaysia, 2014 [165]	Mc-Si	10.00	59.00	32.00	11	N/A
Present Study, Malaysia	**Mc-Si**	**232.50**	**85.40**	**14.85**	**9.15**	**98.00**

4.2 Techno-economic analysis of proposed Monash Grid-connected Photovoltaic system using HOMER Grid

In this section, the design of GCPV system to fulfil the electricity load demand of buildings B7 and B3 is presented. According to the given input parameters and constraints, simulation and optimization have been carried out using HOMER Grid software. Selling excess electricity to the grid has not been considered in the simulation as it is not the option available in Malaysia. Alternatively, the commercial sectors can opt for NEM where they can sell all the electricity produced from GCPV to the grid with displace cost of one to one. Therefore, the main objective is self-consumption and to find the optimum and most economically feasible GCPV system capacity to reduce the MD for B3 and B7.

4.2.1 Optimal sizing of the GCPV system to reduce the MD of Building 3 and Building 7 using HOMER Grid

As mentioned in chapter 3, B3 consumes the highest amount of electricity among all Monash buildings. If the GCPV is proposed for this building what will be techno-economic feasibility and the solution is provided by HOMER Grid. HOMER Grid eliminates all infeasible solutions (e.g., due to not having power sources, lacking converters, etc.) and ranks all feasible solutions according to total NPC, COE, O&M cost, as shown in Table 4.2. Based on these parameters, 866 kW capacity of the GCPV system is ranked #1 for building B3 to reduce the MD. HOMER Grid also optimizes the results based on yearly operating cost, initial capital, the renewable fraction (RF), emission and simple payback period. The layout design of the proposed GCPV system is shown in Fig. 4.9.

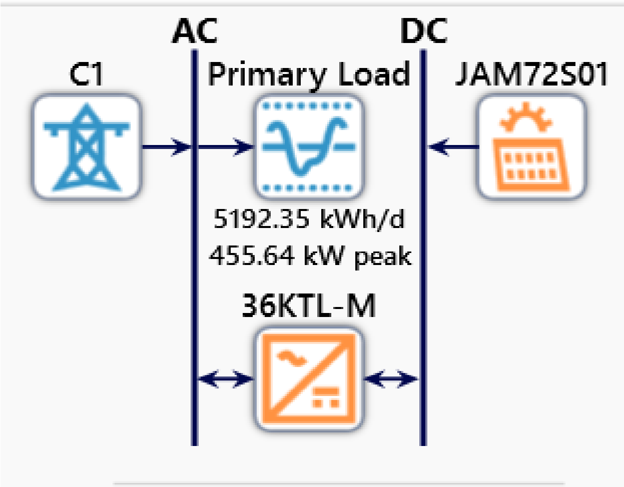


Fig. 4.9. Layout design of proposed GCPV system for building B3

Table 4.2. Ranking of different combinations simulated in HOMER Grid for building B3

Architecture			Cost			
JAM72S01 (kW)	C1	36KTL-M (kW)	NPC (RM)	COE (RM)	Operating cost (RM/yr)	Initial capital (RM)
866	1	342	RM12.1M	RM0.357	RM536,212	RM2.51M
838	1	346	RM12.1M	RM0.357	RM539,799	RM2.44M
866	1	349	RM12.1M	RM0.357	RM535,848	RM2.51M
866	1	335	RM12.1M	RM0.357	RM536,717	RM2.50M
811	1	342	RM12.1M	RM0.357	RM543,939	RM2.37M
865	1	356	RM12.1M	RM0.357	RM535,596	RM2.52M
811	1	349	RM12.1M	RM0.357	RM543,588	RM2.38M
811	1	335	RM12.1M	RM0.357	RM544,419	RM2.36M
865	1	328	RM12.1M	RM0.357	RM537,393	RM2.49M
920	1	342	RM12.1M	RM0.357	RM529,144	RM2.64M
920	1	349	RM12.1M	RM0.357	RM528,753	RM2.65M
1,731	1	228	RM13.8M	RM0.407	RM516,488	RM4.56M
2,596	1	342	RM14.7M	RM0.433	RM439,976	RM6.83M
2,596	1	570	RM14.9M	RM0.439	RM438,184	RM7.06M
	1		RM15.1M	RM0.446	RM845,815	RM0.00
	1		RM15.1M	RM0.446	RM845,815	RM0.00
3,462	1	456	RM16.7M	RM0.492	RM423,327	RM9.11M
3,462	1	684	RM16.9M	RM0.499	RM423,555	RM9.34M
3,462	1	228	RM17.5M	RM0.516	RM482,432	RM8.88M
5,193	1	456	RM20.8M	RM0.612	RM409,838	RM13.4M
5,193	1	684	RM21.0M	RM0.619	RM410,066	RM13.7M
5,193	1	228	RM21.7M	RM0.638	RM471,426	RM13.2M

It is estimated that the proposed system would save about RM 7.78 million throughout the project lifetime (25 years), with an NPC of 12.1 million, a simple payback period of 8.1 years, and an IRR of 12%. The integration of 866 kWp solar PV with the grid system would reduce the electricity bill by 63.3%. Similar reduction in utility bills of ~ 62.1% was reported by Fang et al. [162]. However, to achieve this reduction, they have integrated energy storage (battery) with the GCPV system. In our study, no battery is used due to the high capital cost, yet the electricity bill's savings are slightly higher than the saving reported by Fang et al. [169]. This could be because of tariff rates, solar irradiation resources, location and incentives available. Likewise, Subramani et al. [170] revealed that the solar PV-battery system's optimal sizing is subsidized to the electricity bill savings up to 20% of a university building's net consumption. Capital investment cost and O&M costs are used to evaluate the basic economic metrics of the self-consumption GCPV system. Indeed, the GCPV system requires a higher capital cost than only the grid system; while having the lowest O&M cost due to the least amount of grid purchase. Specifically, for MD, RM 36,971 will be saved annually by the proposed

GCPV system. The selected GCPV system offers the lowest COE of 0.357 RM/kWh. Interestingly, the COE offered by the proposed system was lower than other study done in Malaysia. For example, Ali et al. [171] performed a techno-economic analysis of the GCPV/T system in Malaysia and found the COE to be 0.81 RM/kWh. For the GCPV system in Oman, the COE was found to be 0.2258 USD/kWh (0.94 RM/kWh). This is due to the high electricity tariff rate in Oman, compare to Malaysia.

Further, the proposed system for B3 has a significant impact on the environment. It can reduce the CO2 emission up to 60%. The GCPV system is able to reduce the AC primary load and MD for each month of building B3 as shown in Fig 5.2. The major advantage is that the peak load profile (Fig. 4.10) of the building B3 (i.e. in daytime from 9 am to 5 pm) matches with the solar irradiation profile in the daytime (Fig. 4.3). this cause in significant reduction in the peak load from 250 kW to about 50 kW in the mid-day. This is because solar irradiation is at the peak during this time.

Further analysis was directed to building B7 that had a lowest electricity consumption compared to other buildings in Monash campus. For this building, 396 kW capacity of GCPV is enough to reduce the MD, as shown in Fig. 4.11. Likewise, in the previous building, during the simulation process, several feasible solutions were simulated and provided by HOMER as listed in Table 4.3. Apparently, the ranking was based on the main objective function of HOMER i.e. total NPC, followed by COE, operating cost and then initial capital cost. Among all the options, a GCPV system with capacity of 396 kW and converter rating of 176 kW was found to be the most optimized system for B7, since it results in a lowest NPC, and initial capital cost. Based on total NPC, COE, O&M cost, all feasible solutions' ranking is shown in Table 4.3.

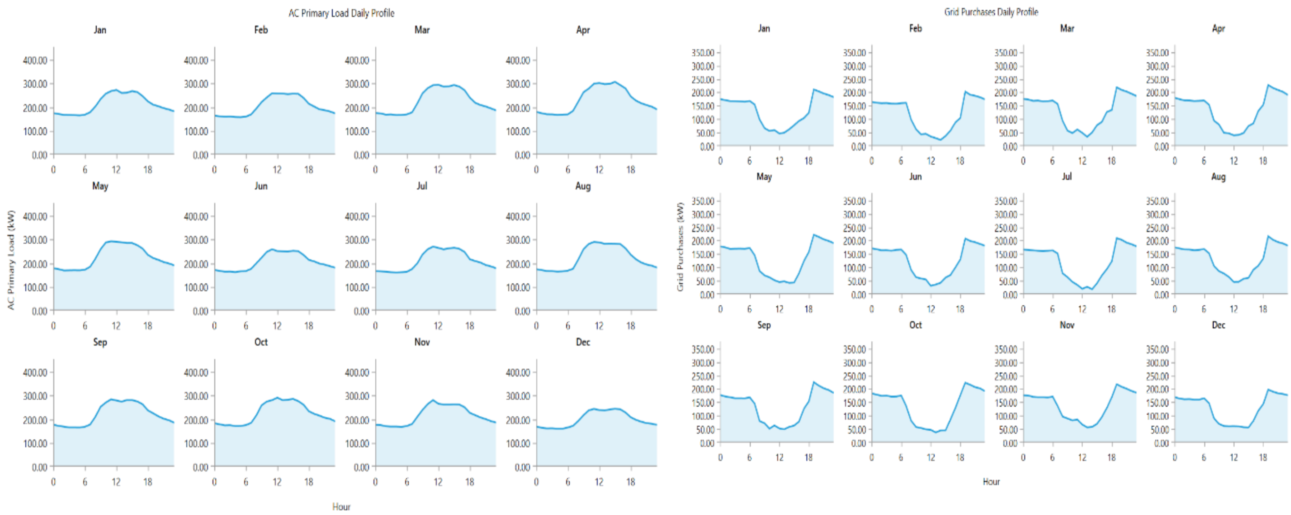


Fig 4.10 Average hourly MD, a) Before the proposed system, b) After the proposed system of building B3

Table 4.3. Ranking of different combinations simulated in HOMER Grid for building B7

Architecture			Cost			
JAM72S01 (kW)	C1	36KTL-M (kW)	NPC (RM)	COE (RM)	Operating cost (RM/yr)	Initial capital (RM)
396	1	176	RM4.63M	RM0.373	RM193,657	RM1.17M
405	1	178	RM4.63M	RM0.373	RM192,258	RM1.19M
396	1	181	RM4.64M	RM0.373	RM193,475	RM1.17M
396	1	170	RM4.64M	RM0.373	RM194,134	RM1.16M
371	1	174	RM4.64M	RM0.373	RM197,464	RM1.10M
368	1	178	RM4.64M	RM0.374	RM197,712	RM1.10M
424	1	178	RM4.64M	RM0.374	RM189,831	RM1.24M
422	1	174	RM4.64M	RM0.374	RM190,432	RM1.23M
396	1	187	RM4.64M	RM0.374	RM193,317	RM1.18M
355	1	170	RM4.64M	RM0.374	RM200,306	RM1.06M
356	1	185	RM4.65M	RM0.374	RM199,381	RM1.08M
158	1	187	RM5.10M	RM0.411	RM252,404	RM582,530
633	1	107	RM5.27M	RM0.424	RM199,755	RM1.69M
950	1	160	RM5.42M	RM0.436	RM160,933	RM2.54M
950	1	267	RM5.44M	RM0.438	RM156,360	RM2.64M
	1		RM5.78M	RM0.465	RM322,509	RM30.30
	1		RM5.78M	RM0.465	RM322,509	RM30.30
1,267	1	213	RM6.04M	RM0.487	RM148,746	RM3.38M
1,267	1	320	RM6.15M	RM0.495	RM148,853	RM3.49M
1,267	1	107	RM6.63M	RM0.534	RM187,290	RM3.27M
1,900	1	213	RM7.50M	RM0.604	RM141,369	RM4.96M
1,900	1	320	RM7.60M	RM0.612	RM141,476	RM5.07M

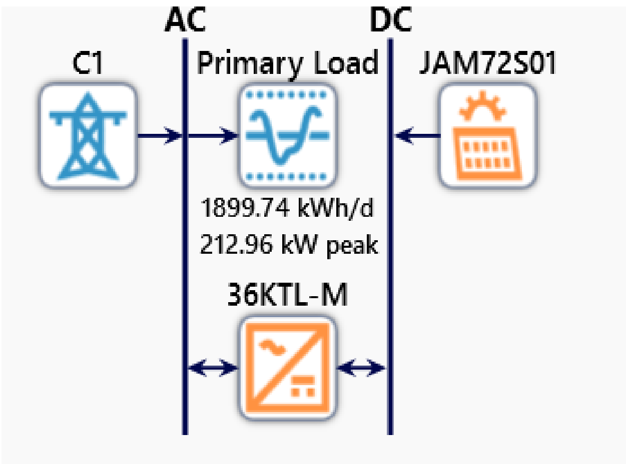


Fig. 4.11. Layout design of proposed GCPV system for building B7

The proposed GCPV (ranked #1 in Table 4.3) for B3 would result in a saving of about RM 2.32 million throughout the project lifetime, with a simple payback period of 9 years and an IRR of 10%. The NPC for the proposed system is RM 4.63 million. The COE of the proposed system for B7 is 0.373 RM/kWh, which is slightly higher than the COE for B3. This is because the pattern of electricity consumption in building B7 is different from other buildings. The main function of B7 is library and its operation hours are longer than other buildings in the campus. Usually, most of the buildings operation or activities are limited to at most 6.30 pm in the evening. However, library is opened until 10 pm in normal days and 11 pm during examination period. Therefore, both centralized air-condition system has to be operated for cooling purpose and lights for learning and reading activities. Even though the proposed system could reduce the MD during the daytime, a significant demand still exists in the night-time also as presented in Fig. 4.12. it is quite evident from the AC load profile, that the load demand extends beyond 6 pm. The reduction in peak demand after 6 pm is due to closing of certain offices and activities in this building. The daytime MD can be reduced by the installed solar PV system; however, night-time MD cannot be compensated with solar PV. This could have increased the COE for B7. Further, present system generates 50% less CO2 emission than the only grid system. Interestingly, during early morning the load is nearly 10-15 kW for the first seven months of the year except for June. However, this trend suddenly changed from August until November. A detailed techno-economic comparison of B3 and B7 is presented in Table 4.4. It is evident from this table that GCPV system perform better than only grid system for both buildings. Interestingly, for building B3, the solar integration is slightly lower than building B7. However, building B3 has higher annual savings of RM 311,243, which is RM 181,622 higher than building B7.

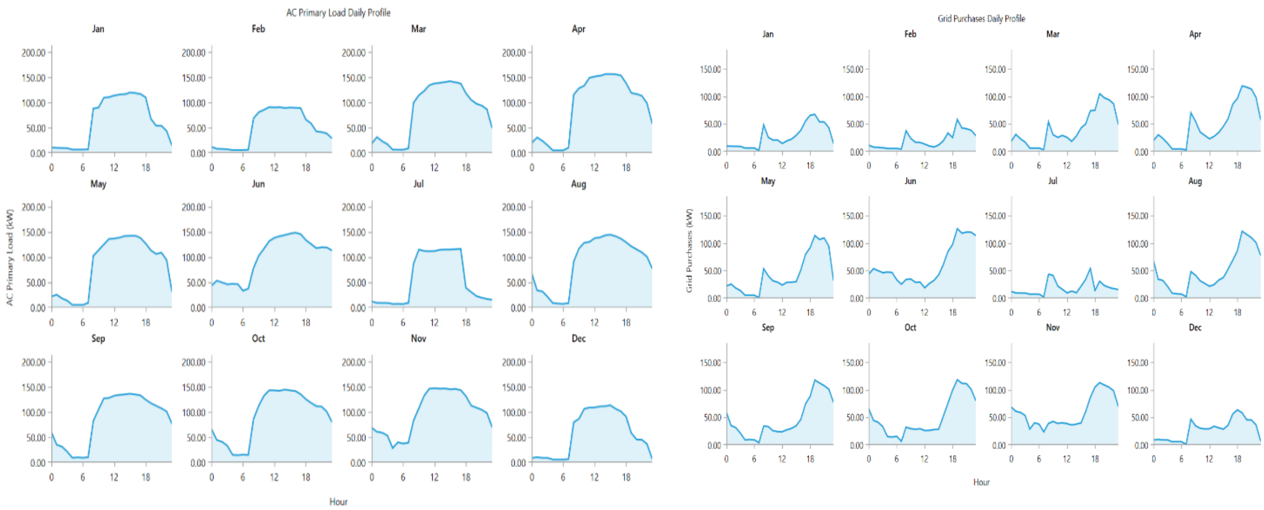


Fig 4.12 Average hourly MD, a) Before the proposed system, b) After the proposed system of building B7

Table 4.4 Detail techno-economic comparison between the current grid system and proposed system of building B3 and B7

Parameters	B3		B7	
	Grid	**GCPV**	**Grid**	**GCPV**
PV capacity, kW	0	866	0	396
CAPEX, RM million	0	2.51	0	1.16
OPEX, RM	**845,815**	**536,212**	**322,509**	**193,657**
Annual MD charges, RM/yr	154,064	117,093	69,446	61,128
Annual energy charges, RM/yr	691,751	417,479	253,093	131,791
LCOE, RM/kWh	**0.446**	**0.357**	**0.465**	**0.373**
Net Present Cost (NPC), RM million	**15.1**	**12.1**	**5.7**	**4.6**
Annual total savings, RM	0	311,243	0	129,621
CO_2 emission, t/year	**1197.8**	**722.9**	**438.2**	**228.2**
Renewable fraction, %	0	39.1	0	47.9
Grid purchased energy, kWh/year	1,895,208	1,143,779	693,405	361,070

4.2.2 Architectural constraint

Architectural integration of solar PV system in the rooftop area of any building is a major issue in the development and installation of the GCPV systems. The mechanical specification of solar PV panel is the major parameter to assess the architectural feasibility of any rooftop GCPV system. The mechanical specification for JA solar PV panel is –
$W_{mod} = 0.991$ m; $L_{mod} = 1.96$ m. Based on this specification and methodology mentioned in chapter 3, the total available area in Monash to install solar PV is given below in Table 4.5.

Table 4.5 Total no. of solar PV that can be installed on the Monash campus building rooftop as per the architectural constraint

Building No	W_{roof} [m]	L_{roof} [m]	Total number of PV modules that can be installed	PV system capacity (kWp)
Building 2	23.2	57.88	667	246.8
Building 3	15.01	86.39	602	222.74
Building 5	23.03	68.33	782	289.34
Building 9	22.36	36.67	396	146.52

Building 6	27.34	42.24	567	209.79
Building 7	0	0	0	0
Total	110.94	291.51	3014	1115.19

It is evident from Table 4.5 that building B3 does not have enough space to install the proposed solar PV system. Further, as the rooftop of building B7 is used for terrace garden, it is not suitable for PV installation. However, the allowable PV system capacity in the available area of the rooftop of whole Monash campus is 1115.19 kWp with 3014 number of PV modules. Therefore, only 866 kWp (for building B3) or 396 kWp (for building B7) can be installed on the rooftop of the available space (for 1115.19 kWp) on the campus. Recently, Manoj et al.[81] reported that 4284 PV modules of 235 Wp each were required for a typical 1 MWp plant in Malaysia. However, in our study 3014 modules are enough to set up a 1.15 MWp GCPV plant. This is because of the higher PV module power of the solar PV panel considered in this study. Similarly, Obeng et al. [172] found that the amount of PV modules is highly depended on the specific PV module power or capacity. It was apparent from their finding that the difference in nominal power of individual module can increase the number of modules to ~2000 panels. in Jordan about 54,000 number of solar PV panels were used to install a 10 MWp solar PV plant as reported by Ayadi et al [173]. For the present study, indeed, a solar PV capacity of 866 kWp would significantly reduce the electricity cost, and therefore, it is highly recommended.

Chapter 5

Conclusions and future recommendations

5.1. Main conclusions

In this thesis, a performance analysis of a 232.5 kWp GCPV system was studied to observe the system behaviour under specific real climate conditions. In addition to that, a techno-economic analysis of an extended GCPV system was also performed to reduce the excessive MD. A detailed literature survey was carried out on the GCPV systems and its application in commercial buildings. An in-depth literature review has also recommended that commercial buildings in Malaysia consume a large amount of electricity, which ultimately incurs a high electricity bill in the form of MD. Hence, the GCPV system is a promising alternative to the conventional power system. However, it was found that the implementation of GCPV systems in commercial buildings is still new in Malaysia and needs detailed research in terms of performance evaluation, technical feasibility, and economic viability. Monash Malaysia campus commercial buildings were selected for this study and based on this the main objectives and methodology of the thesis were defined. Based on the results, the following conclusions are summarized:

The performance analysis carried out on Monash's existing GCPV system indicates that it is favourable to install and expand the GCPV in the second phase. The existing 232.5 kWp capacity GCPV system's energy production was about 301.5 MWh electricity for year 2019 which was slightly lower than the set target of 305 MWh. This system helped to reduce the total electricity cost of RM 110,067.00 (~USD 25,250.00) in 2019. Interestingly, the PR of the Monash Malaysian GCPV plant was higher than other surveyed system of the world. While other parameters such as CUF, and efficiencies were comparable to other systems. Solar irradiation emerged as the most significant factor that affects the GCPV system's performance, besides module temperature. The total yield production and solar irradiation were highest for March (due to more sunny days) and lowest in December (due to monsoon climate, means more cloudy days). The actual yield of GCPV achieved about 90 % of the set target yield in the year 2019; similar was the case for PR. The array capture loss was higher than the system loss during most of the month. Based on economic data, a payback period of 6.7 years is projected with an LCOE of 0.396 RM/kWh. The total cost saved in 2019 was a shortfall of just RM 282.00 than the target cost reduction. In one year, the GCPV system was able to reduce about 177 metric tons of CO_2.

Overall, it will be technically viable, economically feasible and environmental impactful if Monash campus extends the installation of GCPV system on the rooftops of other buildings. The techno-economic study done on building B3 and B7 using HOMER Grid ranked GCPV system as number 1 in terms of least cost total NPC as well as can significantly reduce the MD of both buildings. For instance, in case of building B3, the proposed system would save about RM 7.78 million throughout the project lifetime (25 years), with an NPC of 12.1 million, simple payback of 8.1 years, and an IRR of 12%. Similarly, for B7, RM 2.32 million could be saved throughout the project lifetime, NPC of with a simple payback of 9 years and an IRR of 10%. The COE for B3 and B7 was 0.357 RM/kWh and 0.373 RM/kWh, respectively.

The findings from this thesis will serve as a base for future studies in the solar energy sector, and the method used can be applied elsewhere in the world. The target-oriented approach will benefit both the consumers and the solar service business to track the solar PV system's performance. The techno-economic approach can be used to install the GCPV system on similar conditions to the studied location. It is highly recommended that Monash campus senior management should continue with the plan to install GCPV system to other buildings.

5.2 Future recommendations

Following are the future recommendations to extend this research work:

- Performance analysis could be carried out for following years (i.e. beyond 2019) of operation to compare with existing year.
- The developed model using statistical analysis can serve as strong tool to predict the GCPV output in the future. The research work can be extended in this area.
- The system and capture losses can be evaluated in detail
- Techno-economic feasibility study can be extended to other buildings of Monash campus. More comprehensive and detailed study can be possible but with proper electricity load data of each building that needs to be monitored and stored.
- Simulation work using HOMER grid can be refined further to evaluate more feasible options.
- More variability and parameters can be considered in HOMER Grid
- The study can be extended by including sensitivity in the HOMER Grid and the techno-economic study can be carried out for whole campus buildings in the future. This was limited because of lack and inconsistency of load data in the present study.

- The architectural constraint design can be further analysed to refine the HOMER grid results
- Other energy efficient approaches would also contribute to the overall reduction in the MD of the buildings
- Techno-economic feasibility evaluation could be carried out for a grid-connected photovoltaic energy conversion system on the rooftop of a typical residential building in Kuala Lumpur, one of the major cities in Malaysia.
- Optimal configuration for a 1 MW GCPV plant in one of the major cities can be numerically discovered.
- Solar energy status in Malaysia Plans can be further investigated, and the techniques used in various techno-economic and economic feasibility studies on the implementation of solar energy system can be analysed in future.
- The potential energy generation and cost effectiveness for hypothetical 5, 8, and 10 kWh PV sizes under several financial scenarios can be carried out using Renewable Energy Project Analysis Software (RETScreen).

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