The Performance Analysis of a Three-Phase Grid-Tied Photovoltaic System in a Tropical Area

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***Abstract*— This paper describes the performance of a three-phase grid-tied 30.05kWp photovoltaic (PV) system on the rooftop of a high rise building in Singapore. The PV system consists of an array of 15.05kWp Mono-crystalline panels and another of 15kWp Poly-crystalline panels. They are arranged in 6 strings and are set up on the same roof top. This paper looks into the performance ratio and the capacity utilization factor CUF) over a 4 month period from March 2010 to June 2010. The PV system has achieved a high performance ratio of 81.8%. The remaining 18.2% of the incident solar energy in the analysis period that is not converted into usable energy can be attributed to factors such as pre-photovoltaic losses, module and thermal losses along the balance of system (BOS) and system losses. The CUF is calculated to be 15.32%. This paper discusses the PV system installation and the considerations taken during the design and installation phase such that a high performance ratio is achieved.**

Keywords-component; Solar energy, Photovoltaic, mono-crystalline, poly-crystalline, grid-tied, renewable energy, tropical

I. INTRODUCTION

Traditionally, the solar industry has placed their focus on the increasing energy conversion efficiencies at the cell level. However, the energy conversion efficiencies are not a good representation of the performance of a PV system. This is because the performance of a system seldom corresponds to the total capacity due to the real-world conditions interference. The energy losses of a PV system usually occur in 3 major areas, namely the module and thermal losses, pre-photovoltaic losses, and system loses. The energy conversion efficiency of the PV cell contributes only to the module losses. The temperature dependence of the PV module will also affect its performance. The pre-photovoltaic losses are caused by the shadows, dirt and reflection whereby the solar power density is reduced when it hits the panels. Therefore an ill-planned PV installation will reduce the total energy output of the system and thus lengthen the return of investment period. Last of all, the system loss occurs when the BOS components such as the wiring, switches and inverters contribute to certain level of losses in the system.

Nevertheless, the Photovoltaic (PV) system is still one of the most popular clean energy implementations today. It is safe and reliable without any noise and pollution. As it has no moving parts, the maintenance of a PV system is easy and convenient. PV systems are becoming increasingly popular in Singapore due to the encouragement and recognition from the government and various authorities such as the Building and Construction Authority of Singapore, BCA. The Green Mark Award which is an incentive for energy efficient buildings helps to increase the adoption of PV systems around the island. The drop in the price of PV modules and the increase in the public awareness of PV technology in the recent years also played a significant part in raising the number of rooftop PV systems on buildings.

Singapore, as a tropical country, enjoys a generous amount of sunshine throughout the year and is deemed as a suitable location for the installation of PV systems as alternative energy sources. Singapore has an annual average insolation of 4.56kWh/m^2/day [1]. This paper will discuss the installation of a 30.05kWp PV system on the rooftop of a high rise building. It will present the various considerations during the design and installation stage of the system in order to reduce the pre-photovoltaic losses. Pre-photovoltaic losses are attenuation of incoming light to the PV panels through shading, dirt and reflection before it hits the PV panels. This includes the selection of the building site, system and structure design, and data logging systems.

Silicon is the most commonly used material in PV as it has one of the highest efficiency rates with low production cost. The 3 main types of silicon-based PV are mono-crystalline, poly-crystalline and thin film. [2] The system presented in this paper consists of 15.05kWp mono-crystalline panels and 15kWp poly-crystalline panels. PV systems are usually implemented as standalone or grid-tied systems. The type discussed in this paper is a 30.05kWp 3-phase grid-tied system with no energy storage elements. High efficient inverters and low loss solar cables are used in this system to reduce the system losses over its BOS.

In addition to providing alternative energy source, the system was built to study the performance of the 2 different types of crystalline panels in a tropical country such as Singapore. High diffuse sunlight, humidity and ambient temperature are part of the typical weather condition in the country. These factors can affect the performance of the PV modules which are usually tested under the Standard Test Conditions (STC) of 25ºC and 1000W/m^2. [3] The amount of solar power density at the uppermost layer of Earth's atmosphere is approximately 1367W/m^2, the solar radiation on the Earth surface is reduced to approximately 1000W/m^2 on a clear day due to the absorption and scattering of solar radiation

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through the various layers of atmosphere. The data acquired will be used to study the trend and performance of PV systems. The effect of module and thermal losses will briefly be discussed in this paper. The result will be used to appraise the system based on the commonly used performance ratio and CUF. [4]

II. PV System Description

The installed system consists of 2 different types of crystalline PV that will deliver a total peak power of 30.05kW. It is grid-tied to the 3-phase system to provide secondary power to the building without the provision of any energy storage devices. Excess energy from the PV system will be fed into the power grid. In the event when there is insufficient or no sunlight resulting in low harvested power, the power grid will make up for the shortfall. Data acquisition systems are placed within the PV system for monitoring and analysis purposes.

One array of the system is made up of a 15kWp poly-crystalline array, consisting of 3 strings of 25 modules. Each poly-crystalline module can provide a maximum power of 200W under STC. The detailed specification of the poly-crystalline module is shown below:

ELECTRICAL PERFORMANCE UNDER STANDARD TEST CONDITIONS	
MAXIMUM POWER (Pmax)	200W (+10% / -5%)
MAXIMUM POWER VOLTAGE (Vmpp)	26.3V
MAXIMUM POWER CURRENT (Impp)	7.61A
OPEN CIRCUIT VOLTAGE (Voc)	32.9V
SHORT CIRCUIT CURRENT (Isc)	8.21A
MAXIMUM SYSTEM VOLTAGE	1000V
ELECTRICAL PERFORMANCE AT 800W/m2	
MAXIMUM POWER (Pmax)	142W
MAXIMUM POWER VOLTAGE (Vmpp)	23.2V
MAXIMUM POWER CURRENT (Impp)	6.13A
OPEN CIRCUIT CURRENT ((Voc)	29.9V
SHORT CIRCUIT CURRENT (Isc)	6.62A
CELLS	
NO. PER MODULE	52
CELL TECHNOLOGY	MULTICRYSTAL
CELL SHAPE	RECTANGLAR

Figure 1. Specification of the polycrystalline module used in the PV system

A 15.05kWp mono-crystalline array, made up of 3 strings of various numbers of modules is located on the other side of the rooftop. The maximum power capacity of each module is 175Wp under STC; therefore the 3 strings in the mono-crystalline array which consist of 28, 29 and 29 modules respectively has an maximum power capacity of 15.05kWp. Its detailed specification is as shown below:

ELECTRICAL PERFORMANCE UNDER STANDARD TEST CONDITIONS	
MAXIMUM POWER (Pmax)	175Wp
MAXIMUM POWER VOLTAGE (Vmpp)	35.8V
MAXIMUM POWER CURRENT (Impp)	4.89A
OPEN CIRCUIT VOLTAGE (Voc)	44.4V
SHORT CIRCUIT CURRENT (Isc)	5.30A
MAXIMUM SYSTEM VOLTAGE	1000V
ELECTRICAL PERFORMANCE AT 800W/m2	
MAXIMUM POWER (Pmax)	125.1Wp
MAXIMUM POWER VOLTAGE (Vmpp)	32.1V
MAXIMUM POWER CURRENT (Impp)	3.90A
OPEN CIRCUIT CURRENT ((Voc)	40.2V
SHORT CIRCUIT CURRENT (Isc)	4.38A
CELLS	
NO. PER MODULE	72
CELL TECHNOLOGY	MONOCRYSTALLINE SILICON
CELL SHAPE	SQUARE

Figure 2. Specification of the monocrystalline module used in the PV system

The 2 arrays are located side by side on the same end of the roof top. They are mounted on a structure with a height that ranges from approximately 500mm to 1000mm from the rooftop, and angled at 5º south facing. The 2 arrays occupy an approximate area of 218m^2.

Figure 3. Picture of the 30.05kWp PV system installed on the rooftop of a 7 storey building

The single phase inverter used in this system has an output AC power rating of 6000W and an absolute maximum voltage of 600Vdc. It has a wide operating ambient temperature range from -25ºC to 60 ºC with an enclosure that has an environmental rating of IP65. It can also operate in an environment with a condensing relative humidity from 0% to 100%. These specifications make it an ideal choice for use in a tropical region.

The converted AC power from the inverters is directed into the building AC Source Distribution Board (ACDB). The ACDB has dedicated double pole 20-Amp breaker rated at 230Vac which connect the inverter to the 3-phase power supply of the building.

Figure 4. Inverters used in the PV system

The inverters are also able to provide information on the power, voltage and current on both the DC input and the AC output sides. These data are logged with other useful information such as global solar irradiance from a pyranometer, ambience temperature and panel temperature. Data logging is done in 15 minutes interval.

The overall system is illustrated as below.

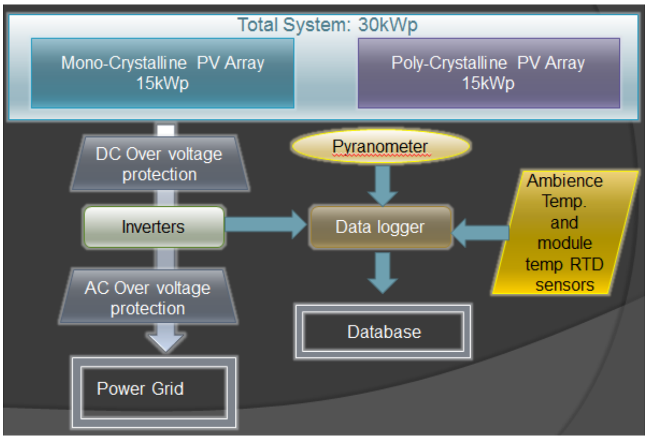

Figure 5. Overview of the PV system and the data acquisition system

III. DESIGN CONSIDERATION DURING THE INSTALLATION STAGE TO REDUCE ENERGY LOSS OF THE SYSTEM

This section of the paper will discuss the design considerations during the installation stage in order to reduce energy loss of the system. The paper will look into the site selection, system and structure design, as well as the selection and design of the data acquisition system.

A. PV location selection and considerations

The installation of a PV system is usually permanent and will not be moved after it is installed; therefore a good location has to be selected in order to minimize the pre-photovoltaic losses. This is particular important if the location of a PV system is in a built up area located in an urban region where there might be shadows from the surrounding buildings. The venue is to have minimum or no shading on the PV modules during most times of the day. This is to maximize the daily energy harvested and thus shorten the return of investment period. In tropical regions, partial shading due to nearby building, as seen in Figure 6 below, usually occurs during dawn or dusk. Hence, it is important to perform a site visit from 7 am to 9am and from 5pm to 7pm to ensure that the rooftop is not shaded by nearby buildings. The site visit is also important in identifying other facilities on the rooftop such as water storage tanks and communication antennas or dishes.

The PV system is to be installed on a rooftop that is within a cluster of 12 buildings having slightly different height. Buildings at the outer perimeter of the cluster are preferred so as to reduce the impact due to shadowing on the system. Site visit was done on these buildings during the early morning and late afternoon. The north side has been selected as it is not shaded and serves no other functions.

Figure 6. Example of shading casted by nearby building during the early morning

B. Design of 3 phase grid-tied PV system with 2 different types of panels

As mentioned in the previous section, the 30.05kWp system is made up of 2 arrays of crystalline modules. Each array consists of 3 strings of modules. In total, there will be 6 strings of modules, 3 strings of mono-crystalline PV modules and 3 strings of poly-crystalline modules. These 6 strings of modules are to be connected to 6 grid-tied inverters. In order to minimize the disturbance and unbalanced issues of the 3 phases in the power grid due to the power injected from the PV system, every phase will be served by 1 inverter from the mono-crystalline string and 1 inverter from the poly-crystalline string as illustrated below.

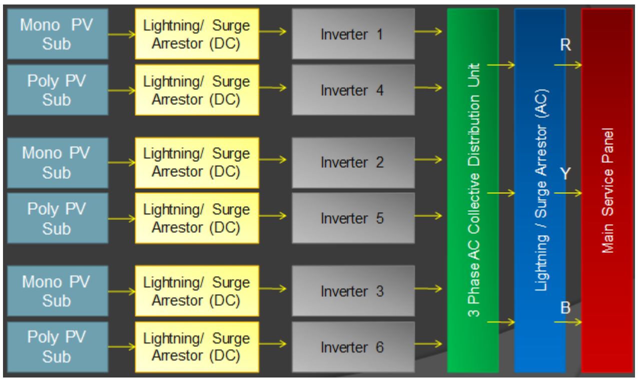

Figure 7. Block diagram of the grid-tied system

C. Structural design to reduce module thermal losses and pre-photovoltaic losses from accumulated dirt

The rooftop has a load capacity of 3kN/m^2 which sufficient to take the weight of the modules and the structure. However, this installation is to be made on an existing building where the rooftop has already been treated for water proofing, therefore drilling works are prohibited. In order to prevent movement of the modules in the event of strong winds or rain, the strings of the modules are bound together by aluminum fasteners. The legs of the structure are encased in cast cement studs that will hold down the PV arrays.

The arrays are tilted at an inclination angle of 5^o south facing. They are elevated at a height of 500mm at the lowest end and 1000mm at the highest end. The elevation is to allow air circulation, thus reducing module temperature. This helps to reduce module losses due to thermal losses when the temperature rises under the afternoon sun. It also allows easy maintenance of the PV system and the rooftop as the maintenance worker is able work underneath the panels.

As Singapore is located near the equator, the module inclination angle can be placed parallel to the floor for maximum exposure to the sunlight throughout the day. But the system is installed at 5º inclination angle to allow rainfall to drain off and clean the panels. This will prevent accumulation of dirt and dust on the panels and thus reduces the pre-photovoltaic losses. This also helps to reduce maintenance cost. The panels are oriented inwards as this helps to minimize the reflection of sunlight from the panels to surrounding buildings.

D. Data logging and User Interface

Data acquisition and logging is important in PV systems to evaluate their performance and output power quality. The data can be used to benchmark the system with various standards. In addition, data acquisition allows the user to identify faults or issues well in advance. [5][6]

In this 30.05kWp grid-tied system, data will be transferred to a Programmable Logic Controller (PLC) data logger every 15 minutes. The data logged includes:

- Input DC power of individual inverter, $P_{DC}^{Inv\#}$
- Input DC voltage of individual inverter, $V_{DC}^{Inv\#}$
- Input DC current of individual inverter, $I_{DC}^{Inv\#}$
- Output AC power of individual inverter, $P_{AC}^{Inv\#}$
- Output AC voltage of individual inverter, $V_{AC}^{Inv\#}$
- Output AC current of individual inverter, $I_{AC}^{Inv\#}$
- Irradiance W/m^2
- Ambient temperature, ºC
- Module temperature, ºC
- Total accumulative energy, kWh

Initially the information was transferred directly from the rooftop PLC data logger to a large user interface display at level 1 of the same building. The data source was in the form of a series of impulse transferred via an RS232 interface. An example can be seen below. However, there were losses of data packets due to the length of the cable, therefore the information shown on the large display became irregular over a certain period of time. This situation is further aggravated during thunderstorms and extremely hot days.

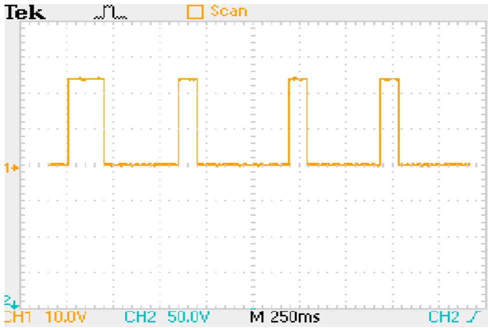

Figure 8. Sample data packet in impulses

The solution to the problem is to replace the ad-hoc connection between the data logger and the data display with an intranet network. The data from the PLC data logger is obtained from the intranet network and stored in the local server. The information from the server is then extracted and transferred to an industrial grade computer and displayed onto a LCD monitor located on level 1 of the building. The data on the monitor has been found to be consistent so far.

IV. OBSERVATONS OF THE DATA COLLECTED FROM THE SYSTEM

Singapore is located near the equator at 1.3520830 Latitude and 103.8198360 Longitude. It enjoys a generous amount of sunlight all year round, and has an annual average solar insolation of 4.5kWh/m^2/day. The table below shows the monthly average of solar insolation in Singapore. [1]

TABLE I. SOLAR INOSLATION IN SINGAPORE

Month	**Monthly average (kWh/m^2/day)**
January	**4.42**
February	**5.15**
March	**4.99**
April	**4.80**
May	**4.51**
June	**4.35**
July	**4.24**
August	**4.27**
September	**4.47**
October	**4.51**
November	**4.28**
December	**4.02**

Figure 9. Monthly solar insolation of Singapore

This section of the paper will explore the performance of the 30.05kWp grid-tied system. PV performance can be assessed in several areas, [7][8] this paper will also present some of the data collected from the system in the year 2010.

A. Irradiance and temperature effect

The pyranometer logs the irradiance data at 15 minutes interval. Below is an example of irradiance readings taken on 9 June 2010 over a period of a day. The data clearly shows that the peak of the solar energy collected occurs around noon and this value is approximately $1040 W/m^2$. There are 2 lowest points in the chart which occurred at 9am to 10am and at 2pm to 4pm. This could be due to brief sessions of rain or cloud overcast.

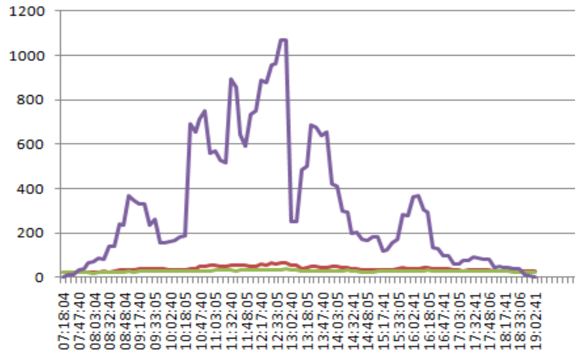

Figure 10. Irradiance of a day in Singapore

PV performance is tested under the STC where it is kept at 25ºC while receiving $1000 W/m^2$. However, in a tropical region, it is very challenging to satisfy these 2 conditions concurrently. The high solar energy density and irradiance will cause a corresponding increase in the temperature of the PV modules.

One of the factors that will affect the PV performance is the module temperature, which is the module thermal loss. This is especially true for crystalline panels. The PV performance will start to degrade when it exceeds a given temperature. The irradiance will have an effect on the module temperature and will in turn affect the performance of the module. A chart can be plotted to show the relationship between the module temperature and the irradiance. The data as shown below is taken from the PV system on 26 June 2010. The linear relationship between the module temperature and irradiance can be inferred from the graph.

$$y = x/30 + 25 \qquad (1)$$

where y = module temperature and x = irradiance

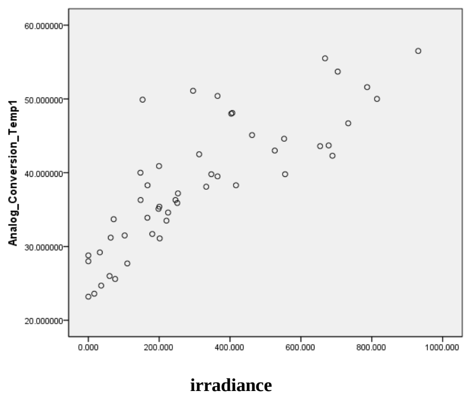

Figure 11. Relationship between Module temperature and irradiance

The chart below which was taken on 26 June 2010 combined the values obtained from module temperature, outdoor temperature, irradiance and power density harvested by the PV system. The power density is multiplied by a factor of 10 to make it more visible on the chart.

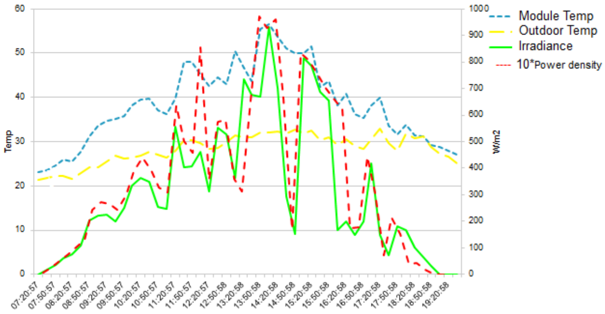

Figure 12. Relationship between temperature, irradiance and power density generated by PV system

It was observed that the peak module temperature occurs at peak irradiance. However this occurrence does not coincide with the peak power density generated by the PV system. At the peak irradiance of $931 W/m^2$ and peak module temperature of 55ºC, the power generated from the system is 21.312kW or $97.76 W/m^2$, which translates to an efficiency of 10.5%. This is not the peak power generated for the day.

B. PV performance and discussion

The data acquisition and logging system allows daily monitoring of the PV system performance. It can indicate or provide warning signals in anticipation of problems or issues with the PV system. It can also be used to analyze and evaluate the performance of the grid-tied PV system. Below is an example of the daily energy data extracted for the period from March 2010 to June 2010.

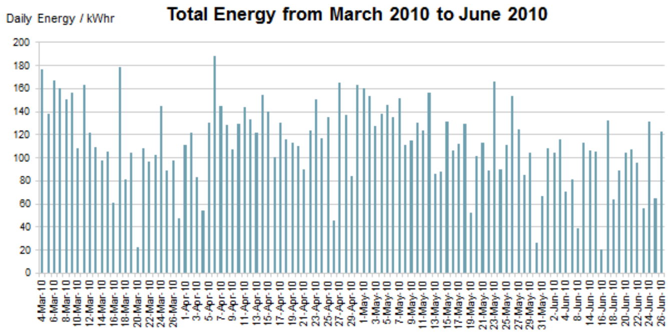

Figure 13. Daily energy yielded from March to June 2010

For a PV system, the capacity utilization factor (CUF) is the ratio of actual energy generated by the system over a period of time to the equivalent energy output at its rated capacity over the period. The period is usually a year, however, due to the limitation of the data collected, the period used in this paper will be 4 months. The rated capacity of the installed system is the total output of the solar cell measured in terms of Wp (Watt Peak) and refers to nominal power under STC.

$$CUF = \frac{Energy\ measured\ (kWhr)}{Installed\ Capcity\ (kW) * number\ of\ days * 24hr} \qquad (2)$$

The energy measured over the 118 days is 13035.46kWhr. The installed capacity is 30.05kW. Therefore the CUF is calculated to be 0.1532 or 15.32%.

Even though the CUF is used in performance indication of PV, but it does not take into account any external factors such as variation of irradiance and availability of grid. A better performance metric will be the performance ratio.

The table below relates the monthly average insolation in Singapore to the daily energy produced per square meter. The efficiency of the system with reference to the solar insolation is also calculated based on the data collected. The efficiency of the PV system is lower than the specified efficiency of the PV modules due to the pre-photovoltaic losses, module and thermal losses and system losses. Another reason for the discrepancy is because the modules are tested at STC condition which is different from the weather condition in a tropical country like Singapore.

TABLE II. MONTHLY DAILY ENERGY YIELD

Month of 2010	Monthly average ($kWh/m^2/day$)	Monthly daily energy yield ($kWh/m^2/day$)	Efficiency (%)
March	4.99	0.546	10.9
April	4.80	0.551	11.5
May	4.51	0.530	11.7
June	4.35	0.4	9.2

Performance ratio, PR, can be used as a measurement of the performance of the PV system. It indicates the overall effect of losses on the rated output due to array temperature, incomplete utilization of irradiation and system component inefficiencies or failures. The PR of a PV system is defined as the ratio of the final system yield, Y_f, to the reference yield, Y_R. [4]

$$Y_f = \frac{daily\ PV\ system\ energy\ output}{maximum\ PV\ system\ power} \quad (3)$$

$$PR = \frac{Y_f}{Y_R} \quad (4)$$

Y_f is the ratio of daily plant energy output (kWh/day) to the installed PV array peak power (kWp). The average daily output of the PV system was 110.47kWh/day. The PV system installed has a peak power of 30.05kWp. Therefore Y_f is calculated to be 3.68 hours/day. The reference yield Y_R can be calculated to be 4.5 hours/day by using the previously mentioned daily insolation of $4.5kWh/m^2/day$ and the STC reference in-plane irradiance is given as $1000W/m^2$. The PR of the system is thus calculated to be a respectable 81.8%. Approximately 18.2% of the incident solar energy in the analysis period is not converted into usable energy due to various reasons such as conduction and thermal loss from the Balance-of-System. The careful considerations during the design and installation phases of the PV system helped to enhance the overall performance of the system by minimizing the losses and implementing a good orientation with no partial shading. This allows the system to harvest more energy and thus shortens the return of investment.

V. CONCLUSION

This paper described the setting up of a 30.05kWp PV system that consists of 2 different crystalline modules, namely the mono-crystalline and poly-crystalline. It discussed the design and installation considerations such as the selection of the building and the rooftop. It also described the electrical connections and structural design. The data acquisition and logging system helped the user to monitor the daily performance of the PV system. This paper presented the collected data and discussed the observations made. It clearly showed the relationship between the irradiance and the module temperature. It has also shown that the peak irradiance does not necessarily lead to peak power generated by the PV system. In addition to the above, this paper presented 4 months of data on the energy generated, and calculated the performance ratio of the 30.05kWp system to be at a respectable 81.8%. In conclusion, this paper shows that the careful planning during the design and installation phase helps to ensure high performance ratio where the loss of usable energy can be minimized and will ultimately reduce the return on investment.

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