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EVALUATION AND ECONOMIC ANALYSIS OF 2MW SOLAR PV FARM IN MELAKA

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ABSTRACT

Photovoltaic (PV) plants in the world are presently subjected to the growing importance driven by the search for alternative resources of traditional fossil fuel. The development of photovoltaic energy in the last decade has brought to light the prediction of PV module performance under real outdoor operating condition. This paper presents a case study of installing 2MW solar power plant in Melaka. The case study discusses the key factors that could influence the power generation output of a solar plant, namely the environmental factors and the system factors. The environmental factors comprise of the effect from sun irradiance and temperature, whereas the system factors comprise of the effects of inverter and transformer efficiency, cable losses, dirt impact, mismatch and shading effect and degradation. The effects of the environmental factors on solar power plant were studied based on the historical meteorological data retrieved from the commercially available database, Meteonorm. In addition, economic viability was also analysed based on the system performance analysis. The key findings of the study suggest that despite the reduced power generation output caused by the environmental and system factors, it is still economically feasible to invest into the development of 2MW solar farm in Melaka under the current Feed-in Tariff scheme. .

Keywords: Photovoltaic, irradiance, system losses, PV power performance, economics.

1. INTRODUCTION

The rising number of PV installations throughout the world has witnessed the difference between the expected and the actual power production. The understanding of these differences is particularly important for the Photovoltaic (PV) system design and also the management of electricity grids. The uptake of solar PV installation in Malaysia has presently been given adequate attention by the government. This can be seen by the enactment of Renewable Energy Act 2011 and the establishment of The Sustainable Energy Development Authority (SEDA) Malaysia in 2011 to promote, stimulate and facilitate the development the renewable energy in Malaysia. Moreover, Feed-in Tariff scheme has been introduced under the Act to encourage the private investment into the renewable energy sectors.

This paper presents a comprehensive evaluation of a proposed 2MW solar PV farm at Melaka. Two types of PV module’s technology were considered, namely poly-crystalline and thin film modules. It is further assumed that each module would generate up to 1MW system to produce a total power of 2 x 1 MW solar farm. The estimated land size is of approximately 0.05 km^2, that house the solar farm, as well as the control and monitoring rooms.

PV cells are limited in efficiency due to losses; some of these are avoidable but others are inevitable to the system (Tiwari and Dubey, 2010). There are several causes for this loss, such as losses in cables, power inverters, the dirt on surface of the modules, the irradiance fluctuation impacts, ambient temperature, varying insolation levels, and so on (Sharma, 2011). There are various factors that may affect the PV system’s performance and efficiency. In this paper, these factors were divided into environment factors and system factors. One of the environment factors is the impact of sun irradiance that has positive correlation with the PV power output. On contrary, both ambient and module temperatures have an inverse correlation with the PV power output. The environment factors are related to the plant’s location. The location of the proposed solar PV farm has the geographic coordinates of 2.3° North latitude, 102.3° East longitude, and its altitude is approximately 70 m above sea level. Meteonorm is a meteorological database that contains extensive climatological data for solar engineering applications at every location on the globe (Remund et al. 2013). Therefore, Meteonorm was used to estimate the irradiance and temperature at the proposed plant location.

The second type of factors are the system factors which mainly includes losses due to (1) inverter efficiency, (2) transformer efficiency, (3) cables losses, (4) losses due to panels mismatch, dirt, sand, and shading, and (5) degradation effect of the panel.

2. THEORY AND FRAMEWORK

Ideally, the output of solar power plant is assessed by the summation of maximum output power of single panel, whereas the maximum output of single panel is calculated by the equation

$$P_{\max} = \eta_{sys} \times \eta_m \times G \times A \tag{1}$$

where η_{sys} is system efficiency, η_m is module efficiency, G is irradiance on the surface of module (w/m^2), and A is module's area (m^2). Efficiency of the PV system is related to the factors due to system components and therefore, it was calculated relative to single PV panel using the equation

$$\eta = \eta_{inv} \times \eta_{tr} \times \eta_{cable} \times K_l \times K_{\deg} \tag{2}$$

where η_{inv} is inverter efficiency, η_{tr} is transformer efficiency, η_{cable} is efficiency of DC and AC cables, K_l expresses the factor of losses due to mismatch, dirt, sand, and shading, and K_{deg} represents the degradation factor. It is worth mentioning that loss of batteries had not been considered in this case study as it will not be used.

Irradiance is defined as the measure of power density of sunlight received at a location on the earth, and is measured in watt per metre square (Jafari et al. 2011). The increasing of sun irradiance falling on PV panel surface lead to increase both open circuit voltage and short circuit current, and hence, the maximum power point varies.

Azimuth and tilt angles have significant roles in determining the sun irradiance of the module. Azimuth angle is the angle between the sun radiation and the south direction, and tilt angle is the angle between the module's surface and the horizontal line on the ground, as in Fig. 1. Furthermore, zenith angle is the angle between the beam and the vertical (Twidell and Weir, 2006). In order to satisfy high irradiance, sunshine has to be perpendicular on the PV panel surface which means the tilt angle should be equal to the zenith angle.

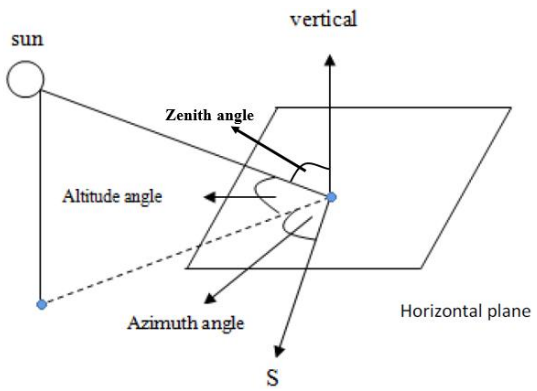

Figure 1 Azimuth and zenith angle relative to horizontal plane.

Meanwhile, operating temperature plays a central role in the PV conversion process. Both electrical efficiency and power output of a PV module depend linearly on the operating cell temperature (Tiwari and Dubey, 2010). In order to study temperature effect on PV performance, temperature coefficients should be presented. Temperature coefficients express the rate of change of PV performance parameters with respect to temperature (King et al. 1997). Normally, manufacturer gives three values of temperature coefficient, there are for P_{max}, V_{oc}, and I_{sc}. The correct method to present value of P_{max} at various temperatures is given by the equation

$$P_{\max}(Tc) = P_{\max}(T_{ref}) \times \left(1 - (Tc - Tc_{ref})\alpha_p\right) \tag{3}$$

where α_p is the temperature coefficient of P_{max}, $P_{max}(Tc)$ is the max output power at the actual cell temperature, Tc_{ref} and $P_{max}(T_{ref})$ are the cell temperature and the max output power at the reference temperature respectively. It is worth mentioning that $P_{max}(T)$ and $P_{max}(T_{ref})$ should be at same irradiance value.

On the other hand, cell temperature is given by the equation

$$T_{cell} = T_{amb} + (NOCT - 20) \times \frac{G}{800} \tag{4}$$

where T_{amb} is the ambient temperature, G is the sun irradiance, and NOCT is nominal operating cell temperature, which is given by the manufacturer. Besides, according to the mentioned clarification, the power output of a single PV panel could be presented as below:

- Determine the value of sun irradiance falling on the PV panel surface at certain values of azimuth and tilt angle.
- Calculate the system efficiency using Eq. (2), whereas the efficiency of PV module, inverter and transformer are determined by their manufacturers. As for K_{cable} factor of cables losses, K_l factor of losses due to mismatch, dirt, sand, and shading, and K_{deg} is the degradation factor. These factors will be estimated depending on prior works and researches.
- Evaluate P_{max} using Eq. (1), whereas this value at cell temperature of standard test conditions that equals 25°.
- Calculate the estimated value of P_{max} at actual ambient temperature by following Eq. (3).

Economic feasibility would be conducted according to value of actual power estimated in the evaluation process. The economic viability could be validated based on several financial models. Simple payback and levelized cost of energy are the models studied in this case study. Simple payback is calculated as follow:

$$SPP = \frac{initial\ capital\ \cos t}{Annual\ income} \tag{5}$$

Levelized cost of energy expresses the cost of generated power, and it is calculated as:

$$LCOE = \frac{\sum_{n=0}^{y} \frac{COF_n}{(1+i)^n}}{\sum_{n=0}^{y} \frac{E_n}{(1+i)^n}} \tag{6}$$

where COF_n is annual cash outflow over the year n, y is lifespan of the plant, n is year's number (0 to 21), i is discount rate, and E_n is energy generation over the years n (Lan et al. 2013).

3. METHODOLOGY

The solar power plant is planned to generate 2MW using two types of modules; NS-F130G5 and ND-R245A5, manufactured by SHARP. 1MW will be produced by PV arrays constructed using NS-F130G5 modules, and the other 1MW using ND-R245A5 modules. The data required for the case study was obtained from the modules' datasheets, as shown in Table 1 (SHARP, 2012). Other than that, the climatological data were exported using Meteonorm software.

Table 1 Characteristic data for NS-F130G5 and ND-R245A5.

Characteristic	NS-F130G5	ND-R245A5
Module efficiency	9.3 %	14.9 **%**
Maximum power (P_{max})	130 W	245 W
Voltage at maximum power (V_{mpp})	46.1 V	30.7 V
Current at maximum power (I_{mpp})	2.88 A	7.99 A
Nominal operating cell temperature	46 °C	47.5 °C
P_{max} temperature coefficient	–0.24 %/°C	–0.44 %/°C
Module area	1.4 m^2	1.642 m^2
Degradation rate	0.8 %/y	0.667%/y

3.1. Environment factors

Tilt and azimuth angles take some responsibility for determining the amount of solar energy received by PV panel surface. The optimum azimuth angle for solar power panel is usually 0° in the northern hemisphere or 180° in the southern hemisphere (Talebizadeh et al. 2011). Therefore, the azimuth angle of the PV panels in the plant was determined to be equal to 0°. On the other hand, the suitable tilt angle for Kuala Lumpur, away from the plant around 100 km, was obtained as 10° (Saadatian et al. 2012). In order to select the optimum tilt angle at the plant's site, the daily average incident energy on a PV panel at various tilt angles were compared using Meteonorm program, as shown in Fig. 2. It was observed that the optimum tilt angle is zero. However, unfortunately, at small values of tilt angle, like 0° or 5°, dust and water gather on the surface of PV panel, and thus, angles less than 10° were excluded. Therefore, 10° tilt angle was chosen as the optimum tilt angle.

According to the solar power plant location, the average incident energy kWh/m^2 falling on horizontal surface and tilt surface (10°) per month throughout the year was presented as shown in Fig. 3.

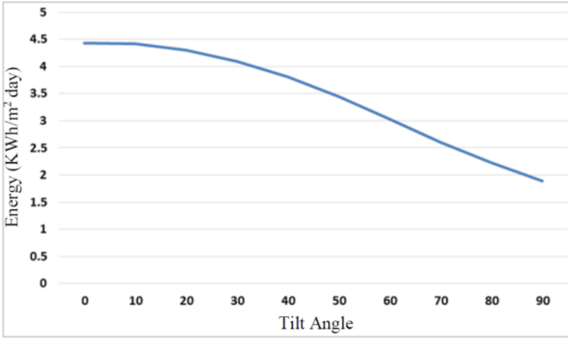

Figure 2 Average incident energy versus changing in tilt angle at the plant location.

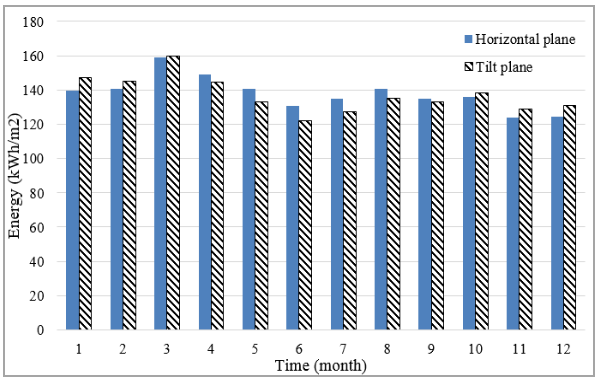

Figure 3 Monthly average incident energy KWh/m^2 on horizontal and tilted plane at the plant location.

The operating temperature plays a central role in the PV conversion process. In order to estimate the power produced by each module at the actual temperature using Eq. (3), the cell temperature is needed. Hourly average ambient temperature at the solar plant location was presented as shown in Fig. 4. Using Eq. (4), according to SHARP datasheet, the module NS-F130G5 has NOCT 46^{0}C and the module ND-R245A5 has NOCT of 47.5^{0}C. The average cell temperature per hour for the modules NS-F130G5 and ND-R245A5 were calculated and shown in Fig. 5.

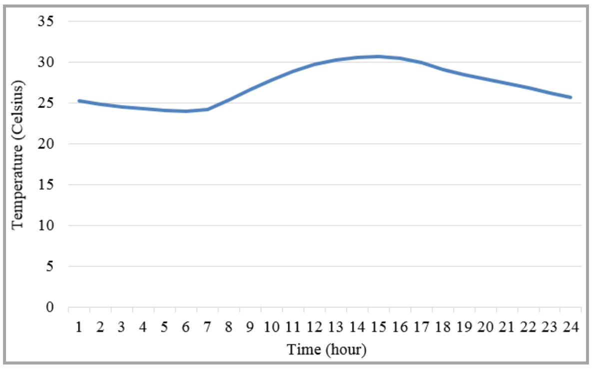

Figure 4 Hourly average ambient temperature at the plant location.

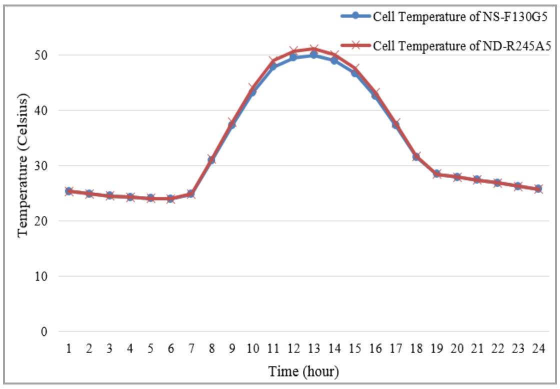

Figure 5 Hourly average cell temperature of thin film module and polycrystalline module at the plant's site.

3.2. System Factors

As mentioned, the system efficiency is related to several factors. Inverter and transformer efficiency in solar applications are commonly estimated as 98% and 99% respectively (EMERSON, 2013; SGB, 2007). Cables in this solar PV plant were divided into DC cables and AC cables. Malaysian Standard MS 1837:2010 determines that the maximum allowable voltage drop for DC cable in solar applications shall not exceed 5 %. On the other hand, 3% voltage drop in the AC system was adopted in the design process (DSM, 2010). On the other hand, mismatch, dirt, sand, and shading typically represents 10% of energy loss in PV system (Bhattacharyya, 2014). Therefore, $K_{DC\text{-}cable}$, $K_{AC\text{-}cable}$ and K_{mm} could be described mathematically as 95%, 97% and 90% respectively. As for the degradation factor K_{deg}, it is determined by the PV modules manufacturers. The degradation rates for NS-F130G5 and ND-R245A5 are 0.8%/year and 0.667%/year respectively [8-9], which means the power declines over one year by 0.8% and 0.667% of P_{max} in case of NS-F130G5 and ND-R245A5 module respectively.

From above, the system efficiency could be approximated using Eq. (2), the efficiency of the system in the first year of installation is shown in Table 2.

Table 2 Efficiency of the system in the first year of installation

System	η_{inv} (%)	η_{tr} (%)	$K_{DC\text{-}cable}$ (%)	$K_{AC\text{-}cable}$ (%)	K_l (%)	K_{deg} (%)	η_{sys} (%)
NS-F130G5	98	99	95	97	90	100	80.46
ND-R245A5	98	99	95	97	90	100	80.46

4. RESULTS

The maximum power generated by PV panel is deeply related to sun irradiance. Meanwhile, sun irradiance fluctuates during the day depending on the location, the average sun irradiance per hour at the plant location, 0° azimuth angle, and 10° tilt angle is shown in Fig. 6. It was observed that the highest sun irradiance falling on the target location occurs at (13:00-14:00) pm which matches the highest output power.

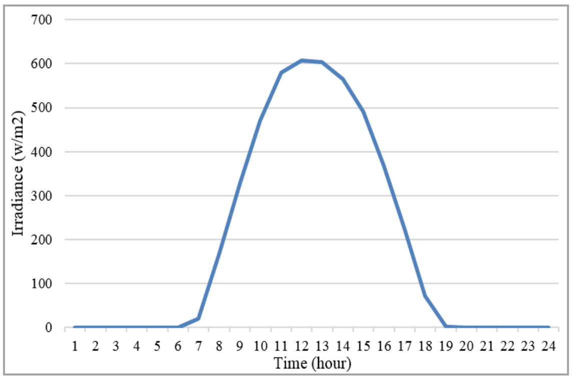

Figure 6 Hourly average Irradiance at the plant location, 0° azimuth angle, and 10° tilt angle.

The approximation value of the average maximum power produced by single PV module was calculated using Eq. (1). The surface area of module NS-F130G5 is 1.4 m^2 and its efficiency of 9.3%, the system efficiency was calculated previously and equals 80.46%. Fig. 7 shows the behavior of the power generated by single PV module NS-F130G5 throughout the day at cell temperature 25°C. On the other hand, the area and efficiency of module ND-R245A5 are 1.64m^2 and 14.9% respectively. Therefore, behavior of hourly power generated by module ND-R245A5 at cell temperature 25°C is shown in Fig. 8.

Power produced by single PV panel is influenced by cell temperature according to Eq. (3), whereas temperature coefficient of modules NS-F130G5 and ND-R245A5 are given by manufacturer as -0.24% and -0.44% respectively. The hourly average output power from single PV of modules NS-F130G5 and ND-R245A5 are estimated according to the target location and shown in Fig. 7 and 8 respectively.Therefore, maximum power produced by module NS-F130G5 at the target location occurs around 12:00 PM, being 60 W. As for ND-R245A5 module, the maximum produced power is 105 W occurs at 12:00 PM as well.

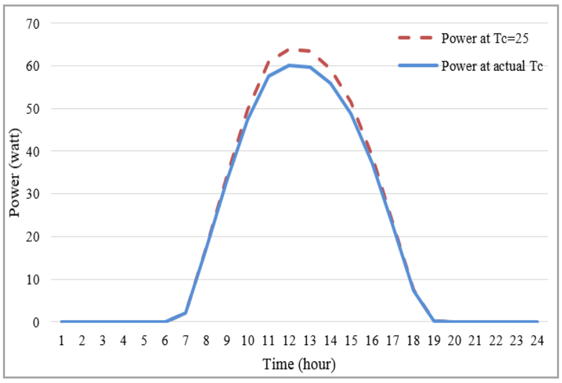

Figure 7 Hourly average power produced by NS-F130G5 module during the day at the plant location.

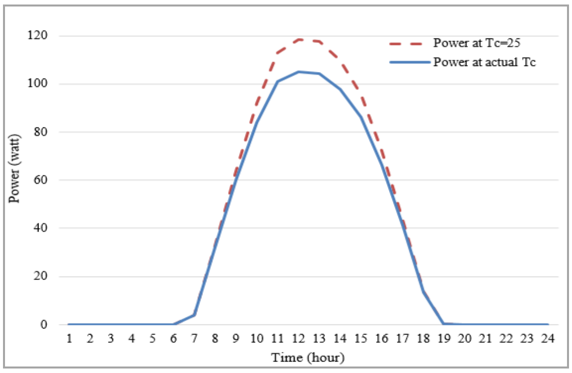

Figure 8 Hourly average power produced by ND-R245A5 module during the day at the plant location.

The monthly energy produced by NS-F130G5 and ND-R245A5 were estimated and shown in Fig. 9 and 10 respectively. Consequently, energy produced in the first year of installation by modules NS-F130G5 and ND-R245A5 are 163 kWh and 285 kWh respectively.

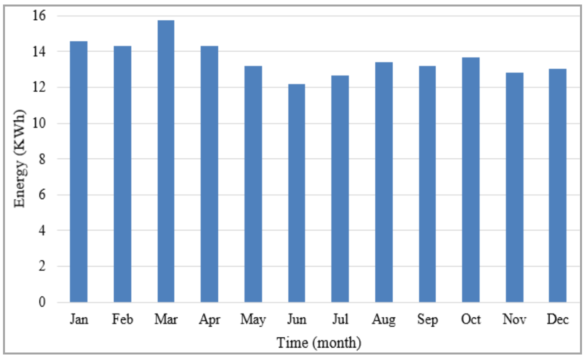

Figure 9 Monthly average energy produced by module NS-F130G5 at the plant location.

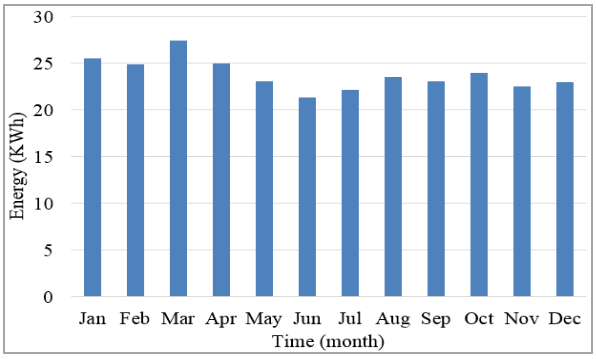

Figure 10 Monthly average energy produced by single ND-R245A5 module at the plant location.

The typical number of NS-F130G5 modules in the thin film system is 7695 modules with total power rating of 1000.35 kW. Meanwhile, the polycrystalline system requires 4100 ND-R245A5 modules with total power rating of 1004.5 kW to fulfil the desired energy. The annual average energy produced by the two systems of the plant was estimated and shown in Table 3. The monthly average energy produced by the two systems of the plant is shown in Fig. 11. Accordingly, the average energy produced by the designed solar plant as a whole per month is shown Fig. 12.

Table 3 Annual produced power by the modules

Arrays	Annual power production (MWh)
1MW by NA-E130G5	1254.2
1MW by ND-R245A5	1171.2

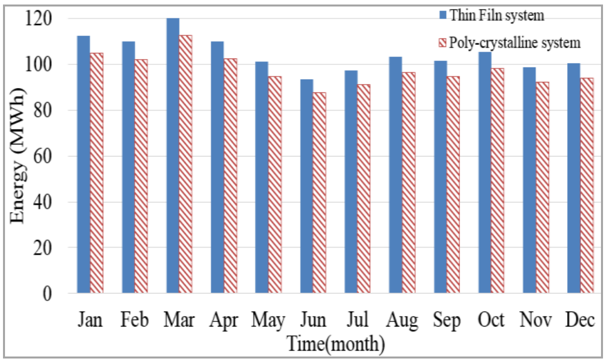

Figure 11 Monthly average energy produced by the two systems of the plant

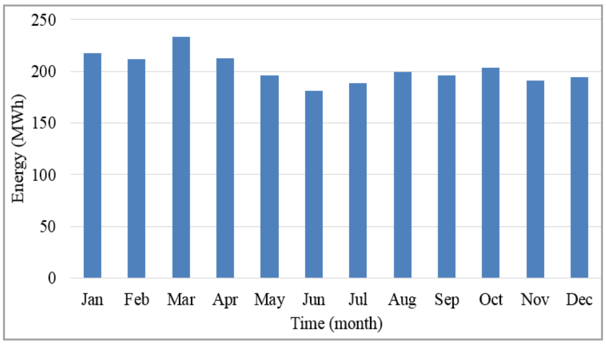

Figure 12 Monthly average energy generated by the plant as a whole.

According to the modules' datasheets, the degradation factor of NS-F130G5 and ND-R245A5 modules are 0.8 %/y and 0.667 %/y respectively. Fig. 13 illustrates the impact of degradation on performance of the two systems of the plant throughout its lifetime, a period of 21 years.

Initial capital cost required for installing the proposed PV plant was estimated at 14.35 million RM. The proposed PV plant complies with FiT rate of 0.8208 RM/kWh. The monthly average income of the plant was calculated based on actual generated power as shown in Fig. 14.

Simple payback of the proposed PV plant was calculated as referred in Eq. 5, and it equals 7 years and 3 months as shown in Table 4. It shows the value of levelized cost of energy of the plant based on lifespan of 21 years, and discount rate of 7.5%. The results are consistent with the findings reported in (Lau et al. 2014).

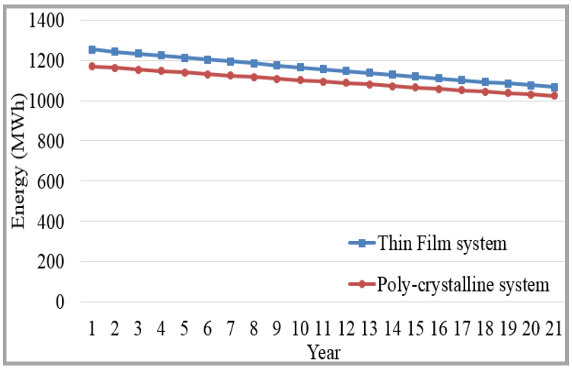

Figure 13 Impact of degradation on yearly average energy generated by the two systems of the plant throughout 21 years of lifetime.

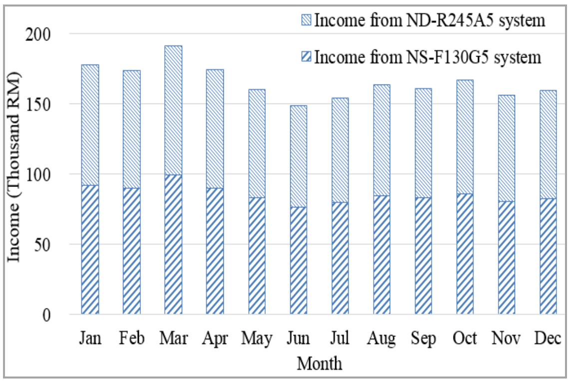

Figure 14 Monthly average income of the proposed PV plant in the first year of installation.

Table 4 Financial models of the Proposed PV Plant

Financial model	Value
Simple payback	87 months
Levelized cost of energy	0.76 RM/kWh

5. CONCLUSION

The results suggest that the PV datasheet given by the manufacturer is not sufficient for the detail design and evaluation of a large scale PV plant. Both the environmental factors and system components affect the PV system performance significantly. It can be concluded that two important weather conditions, *i.e.*, irradiance and temperature are the most crucial factors that impact the PV system performance. The presented study also suggests that according to the proposed PV plant's location, the highest annual average value predicted P_{max_avg} generated by NS-F130G5 is 60 W, as opposed to the P_{max} of 130 W. On the other hand, ND-R245A5 module, which was planned to generate 245 W, is expected to produce P_{max_avg} of 106 W. In addition, the degradation effect throughout the 21 years of module lifetime will reduce the thin film system performance by approximately 16.8%. As for the poly-crystalline module, the performance will reduce by 14%. Nevertheless, under the current Feed-in Tariff scheme, the presented economic analysis has demonstrated that it is economically feasibility to develop the proposed 2MW solar power plant in Melaka.

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