Life-cycle assessment of 5MW grid-connected photovoltaic system in east coast of Malaysia

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Abstract: The technical and economic feasibility of photovoltaic (PV) power plants throughout their lifetime must be evaluated prior to their development and operation such that the sustainability of the project can be justified. This paper presents the Life Cycle Assessment (LCA) of energy and the LCA of economics for a 5 MW grid-connected photovoltaic (GCPV) power plant located in the East Coast of Malaysia. Firstly, an LCA of energy was conducted to evaluate the expected energy yield, energy payback period and energy return of investment throughout the project lifetime. Later, an LCA of economics was performed to determine several economic performance indicators such as the net present value, internal rate of return, payback period and return of investment.

1. Introduction

Grid-Connected Photovoltaic (GCPV) systems is one of the most important renewable energy-based power generations. The rapid growth of photovoltaic (PV) systems is mainly driven by the falling prices of PV modules and increasing efficiency of solar cell technology. Besides being used as distributed power systems, the application of GCPV systems is now extended to large-scale centralized power systems. Therefore, the GCPV system’s role is enhanced in improving the overall energy mix in electricity generation. In Malaysia, the implementation of GCPV systems is supported by the government through the feed-in tariff (FiT) scheme. The scheme has attracted numerous power plant developer to invest in developing large-scale GCPV power plants in the range from 1 MW up to 5 MW. However, the development of a large-scale GCPV system usually involves various types of cost involving financing, land acquisition, installation, operation and maintenance of the system throughout the FiT tenure. Improper costing and expenditure may lead to poor economic feasibility of the investment. Apart from that, the energy generation and consumption resulting from the operation of GCPV power plant must be evaluated to justify its operation as a feasible power plant.

A Life-Cycle Assessment (LCA) was commonly used for assessing the technical, environmental and economic aspects and potential impact associated with a product throughout its life-cycle [1]. In relation to GCPV systems, an LCA study was conducted to evaluate the energy payback time (EPBT) of a 2.7 kWp mono-crystalline GCPV system in Singapore [2]. The study found that the EPBT and GHG emission are 4.5 years and 165 gCO2 equivalent per kWh respectively. In addition, the study also showed that the values of EPBT and GHG emission are site dependent. Another study showed that EPBT and GHG for a mono-crystalline based residential GCPV system are 8.9 years and 61 g CO2 equivalent per kWh respectively [3].
Besides that, a 100 MW GCPV system installed in Gobi desert in China yielded EPBT and GHG of 1.7 years and 12g CO2 equivalent per kWh respectively [4]. Apart from that, an evaluation of EPBT and GHG emission for roof-top based GCPV systems discovered that the EPBT and GHG emission for monocrystalline silicon, polycrystalline silicon, amorphous silicon, micro-morphous silicon, cadmium telluride and CIGS modules are 1.96, 1.24, 1.39, 0.92, 0.68, and 1.02 years and 38.1, 27.2, 34.8, 22.8, 15.8, and 21.4 gCO2 equivalent per kWh respectively [5].

This paper presents a Life-Cycle Assessment (LCA) of energy and economic performance for a large-scale GCPV system. Several energy and economic performance indicators will be evaluated for a large-scale GCPV plant located in east coast of Malaysia. The results of this study are expected to serve as benchmarks for large-scale GCPV system developers in Malaysia.

2. Methodology

The study was conducted in two major parts, i.e. the LCA of energy and the LCA of economics. This section provides an overview of the site and the GCPV system being installed, the determination of final yield, energy payback period and economic analysis of the project.

### Site description

The GCPV system under study is located in East Coast of Malaysia. It consists of 5.184 MW PV array which are connected to 160 string inverters. The site is expected to have an annual irradiation of 1,755.4 kWhm-2 with the PV array mounted at 10° tilt angle and facing South. The PV array consists of 17,280 poly-crystalline modules installed on free-standing ground-mounted structures. The installation of the array occupies approximately a flat land. Each PV string contains 18 modules and there are 6 strings which are connected to a 27.6 kW string inverter. The inverters produce rated AC outputs of 400 V and 50 Hz while the AC output of every group of 4 inverters is then connected to an AC combiner. Then, all AC combiners are connected directly to the main switch board inside a power house. The 400 V AC is later stepped up to 33 kV via a transformer and transmitted via a 33 kV overhead lines to the nearest substation approximately 3km away from the site. A summary of the system specifications are shown in table 1.

| Parameter                  | Specifications                        | Number of units |
|----------------------------|---------------------------------------|-----------------|
| Type of PV module          | Poly-crystalline, Hanwha SolarOne     | 17,280          |
| Type of Inverter           | ABB TRIO-27.6-TL-OUTD                 | 160             |
| Mounting structure         | Aluminium                             | 5               |
| Type of mounting           | Ground mounting                       |                 |
| PV array configuration     | 960 strings (18 modules per string)    |                 |
| Rated power of PV array    | 5.184 MWp                             |                 |

Apart from that, a PV monitoring system is installed to monitor the electrical parameters such as voltage, power and current while two environmental monitoring stations are installed to monitor environmental parameters such as solar irradiance, ambient temperature, cell temperature and wind speed. The system has been consistently monitored since its inception in 2014. The solar irradiation profile for the site is tabulated in table 2.
Table 2. Specification of GCPV system under study.

| Month     | Irradiation, in kWhm² |
|-----------|-----------------------|
| January   | 156.0                 |
| February  | 164.7                 |
| March     | 169.9                 |
| April     | 159.7                 |
| May       | 147.0                 |
| June      | 137.1                 |
| July      | 140.8                 |
| August    | 140.5                 |
| September | 139.7                 |
| October   | 138.6                 |
| November  | 129.4                 |
| December  | 131.9                 |

Life-cycle of energy
In LCA of energy, the final yield, $G_y$ was first computed to indicate the kilowatt-hour of electricity generated from the GCPV system [6]. It is calculated using

$$G_y = P_{stc} H_{PSH} f_{temp} f_{mm} f_d f_{aivcab}$$

(1)

where $G_y$ is the final yield from the complete system in kWh, $H_{PSH}$ is the expected annual number of peak sun hours, $P_{stc}$ is the rated power output of PV array in kWp, $f_{temp}$ is the reduction factor due to cell temperature, $f_{mm}$ is the reduction factor due to mismatch in PV modules, $f_d$ is the reduction factor due to dirt covered at surface of PV modules, $f_a$ is the reduction factor due to ageing of PV module, $\eta_{iv}$ is the maximum efficiency of inverter and $\eta_{cab}$ is the efficiency of DC cables running from PV array to inverter. The $P_{stc}$, $f_{mm}$, $\eta_{iv}$ were set to be 5.184 MW, 1.0 and 0.983 respectively based on the system and component specifications. On the other hand, the $f_d$, $f_a$ and $\eta_{cab}$ were assumed to be approximately 0.98, 0.99 and 0.95 respectively based on the site conditions. Besides that, $H_{PSH}$ was obtained from the accumulative irradiation in Table 2 in peak sun hours. In computing $f_{temp}$, the average maximum cell temperature was found to be approximately 54.14 °C. The $f_{temp}$ was then calculated using

$$f_{temp} = 1 + \left[ \frac{\delta}{100\%} \times (T_{cell} - 25) \right]$$

(2)

where $\delta$ is temperature coefficient of voltage (% per °C) and $T_{cell}$ is average cell temperature, in °C. The $f_{temp}$ was found to be approximately 0.874712. After considering all these factors, the final yield was estimated to be 7,284,249.9 kWh yearly.

After determining the final yield, the Energy Payback Time (EPBT) in years was calculated. EPBT provides an indication of the duration required for the system to generate the same amount of input energy that has been used to develop such system [7]. It was determined using

$$EPBT = \frac{E_{input}}{E_{output}}$$

(3)

Where $E_{input}$ is the total energy consumed during manufacturing, transportation, installation, and annual service life of system components while $E_{output}$ is the expected annual output energy from the GCPV system.

The estimated energy consumed to fabricate poly-crystalline PV modules was approximately 4,200 MJ/m² with efficiency of 13 % and performance ratio of 75 % [8]. In this study, this embodied energy was translated into 1,145 kWhm². Thus, for 17,280 modules, the total embodied energy was approximately 34,624,800 kWh. In addition, the input energy consumed by plant operation and
maintenance during service life was estimated to be 35,712.38 kWh per year. Therefore, the total input energy was 34,660,512.38 kWh.

Apart from that, Energy Return on Investment (EROI) was computed to indicate the number of times over its lifetime, the system generates the cumulative energy used in the production of PV system [9]. EROI was calculated using

\[
EROI = \frac{T}{EPBT}
\]  

(4)

Where, \( T \) is the lifetime of the PV system / project.

Life-cycle of economics

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Apart from life-cycle analysis of energy, the life-cycle of economics was also conducted to quantify the economic performance indicator of the system throughout its service life. In this study, the system was subscribed to the Malaysian Feed in Tariff (FiT) scheme. The FiT was given to the system owner at RM0.804 per kWh throughout 21 years of contract period. Several economic performance indicators were calculated based on this information, as explained in the following sub-sections.

Net Present Value

Net Present Value (NPV) is an indicator that is frequently used by an investor before deciding to continue or stop an investment. A positive value of NPV indicates that a project is profitable and vice versa [6]. NPV of the system was determined using

\[
NPV = PVR - PVC
\]  

(5)

\[
PVR = \sum_{n=1}^{T} \left( E_n \times \frac{(1+i)^n}{(1+d)^n} \right) \times C_{FIT} \times (1-f_d)^n
\]  

(6)

\[
PVC = E_{int} + \sum_{n=1}^{T} (E_{OM} \times E_{rep} \times E_{etc}) \times \frac{(1+i)^n}{(1+d)^n}
\]  

(7)

where PVR is present worth revenue, PVC is present worth cost, \( T \) is lifetime of the system, \( n \) is \( n \)-th year of system operation, \( E_n \) is estimated energy in kWh generated in the \( n \)-th year of system operation, \( i \) is inflation rate, \( d \) is discounted rate, \( C_{FIT} \) is feed in tariff for the system in RM per kWh, \( f_d \) is degradation rate of the system annually, \( E_{int} \) is capital cost, \( E_{OM} \) is cost for operation and maintenance for \( n \)-th year of operation, \( E_{rep} \) is cost of replacement of system component, and \( E_{etc} \) is miscellaneous cost in \( n \)-th year of operation.

According to the warranty given by PV module manufacturer, the degradation rate of the PV module for the first year is 3% and for the subsequent year is 0.7 %. The lifetime of the project is 21 years. In addition, a nominal discounted rate of 7.4 % and nominal inflation rate of 3.2 % [10] were assumed for 21 years period. The initial cost of solar PV system was approximately RM36,000,000.00 while the annual operation and maintenance cost was estimated to be RM 731,000.00. The operation and maintenance cost includes maintenance staff salary, land lease, utilities, security, and insurance. In
addition, the operation and maintenance cost was also assumed to be increased by 1% every year. The cost of total replacement of inverters was assumed to be minimal while the number of spare modules was assumed to be sufficient for replacement during the project lifetime. A summary of the economic parameters used in the life-cycle analysis are shown in table 3.

Table 3. Economic parameters used in analysis.

| Parameter                                      | Value                        |
|------------------------------------------------|------------------------------|
| Lifetime of system / project, $T$              | 21 years                     |
| Annual energy generated, $E_n$                | 7,284,249.9 kWh              |
| Discounted rate, $d$                          | 7.4%                         |
| Inflation rate, $i$                           | 3.2%                         |
| Feed in Tariff, $C_{FiT}$                     | RM0.804 per kWh              |
| Degradation rate, $f_d$                        | First year, 3 %              |
|                                               | Each subsequent year, 0.7%   |
| Capital cost, $E_{int}$                       | RM36,000,000.00             |
| Operation and maintenance cost, $E_{OM}$      | RM731,000.00                 |

**Internal rate of return**

Internal Rate of Return (IRR) is the interest rate at which the present value of revenue is equal to present value of cost, i.e. when NPV becomes zero [6]. It is calculated using

$$E_{int} = \frac{\sum_{t=1}^{T} \left( E_n^{-C_{FiT}} \cdot (1-f_d)^{t} \right) - (E_{OM}^{-E_{deg}} \cdot E_{int})}{(1+IRR)^n} = 0$$

(8)

**Return of investment**

Return on Investment (ROI) indicates the percentage of profit or loss with respect to the amount that has be invested. It is calculated using

$$ROI (\%) = \frac{PVR - PVC}{PVC} \times 100 \quad (9)$$

**Simple payback period**

Simple payback period (SPP) is the number of years required to pay off the capital cost. It is calculated using

$$SPP = \frac{E_{int}}{R_{sty}} \quad (10)$$

where $E_{int}$ is initial cost and $R_{sty}$ is the revenue for the first year.

3. Results and discussion

The life-cycle of energy was performed to determine the EPBT and EROI. A summary of the LCA of energy is presented in table 4. The EPBT was found to be 4.76 years while the EROI was found to be 4.41. These results were obtained based on estimated final yield of approximately 7,284,2499 MWh per year. However, the results did not include energy consumed during transportation and installation activities. Besides that, the energy consumed during decommissioning phase of the system was not included in the EPBT calculation. On the other hand, since EROI is greater than 1, the system is justified to be sustainable.

Table 4. Performance indicators for life-cycle of energy.

| Parameter          | Value                                      |
|--------------------|--------------------------------------------|
| Final yield        | 7,284,2499 MWh per year                   |
| EPBT               | 4.76 years                                 |
| EROI               | 4.41                                       |
Apart from that, the life-cycle analysis of economic performance had provided several economic indicators as shown in table 5. The NPV is RM 29,213,323.31 based on estimated total PVR of RM 76,274,709.14 and total PVC of RM 47,061,385.83 throughout project lifetime.

| Parameter | Value          |
|-----------|----------------|
| NPV       | RM 29,213,323.31 |
| PVC       | RM 76,274,709.14 |
| PVR       | RM 47,061,385.83 |

Besides that, the economic performance of the project throughout project lifetime is summarized in figure 1. The estimated payback of the project was approximately 9 years while the SPP was calculated to be approximately 6.33 years. These figures vary due to the inclusion or exclusion of discounted rate and inflation rate as well as the inclusion or exclusion of other costs besides the capital costs. In addition, the IRR was found to be approximately at 12.06%. Since the IRR is greater than the discounted rate, the overall investment is deemed to be financially feasible. On the other hand, the ROI was found to be approximately 115.2% for the 21 year period.

![Figure 1. Cumulative present value of the project throughout the project lifetime.](image)

4. Conclusion

The LCA was performed to evaluate the energy and economic performance of a large-scale GCPV system in the East Coast of Malaysia. The EBPT and EROI were evaluated to assess the energy performance of the project whereas the NPV, IRR and ROI were used as the indicators for economic performance. The results showed that the EPBT and EROI were 4.76 years and 4.41 respectively. On the other hand, the NPV, IRR and ROI were found to be RM 29,213,323.31, 12.06 % and 115.2 % respectively. These results could be used as guidelines in developing large-scale GCPV power plants in Malaysia.

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