Life Cycle Assessment of Stand-Alone Photovoltaic (SAPV) System

Mickley Bin Yahya
Faculty of Electrical Engineering
Universiti Teknologi MARA,
40450, Shah Alam, Malaysia
Email: mickleyyahya@gmail.com

***Abstract*—This paper presents a study on Life Cycle Assessment (LCA) of Stand-alone Photovoltaic (SAPV) system. The SAPV power station was selected locating at Sekolah Kebangsaan (SK) Kalabakan Tawau in Sabah, Malaysia. The LCA has been carried out to evaluate overall performance of the photovoltaic (PV) system. The performances are in terms of economic, carbon dioxide (CO_2) emission, energy pay-back time (EPBT) and levelized cost of energy (LCOE). For economic and LCOE analysis purposes HOMER simulation software has been applied. The HOMER software compute the economics of the SAPV system by mean net present cost (NPC) technique. The data of solar resource and load demand of the site have been taken from actual data provided by PV system at SK Kalabakan. The EPBT and CO_2 emission of the system are calculated manually through the mathematical formulation. In this project, it was found that the total NPC of the PV system is $384517. The PV modules contribute most in total NPC around 45%, follow by battery 25%, power conditioning including controller 14%, O&M of the system 11% and diesel generator contribute only 5%. The estimated LCOE, annual CO_2 emission and EPBT of the PV system are 1.594 $/kWh, 2898 kg-$CO_2$/year and 10.47 years respectively.**

Keywords- photovoltaic hybrid system; homer software; life cycle assessment; energy payback time, carbon dioxide emission; economic; levelized cost of energy

I. INTRODUCTION

Energy is very important component for economic and social development in any country. Every year as the population and economic growth the energy demand also increases. Nowadays, most of power energy in the world is use non-renewable sources such as fossil fuel, crude oil, natural gas and nuclear. However, high prices, limited resources, health risks and the issues of global warming create a big question mark on electricity generation by the non-renewable energy sources [3]. Due to these factors, stronger emphasis is required on electricity generation through renewable energy sources like wind, biomass, solar and hydro power in order to counter of those problems. Solar energy is considered to be the most promising alternative source of energy and become the most popular of renewable sources being exploited. The most significant factors that cause the SAPV system become the dominant renewable source among the others renewable source are it is simple and flexible to build in any place [1]. Another benefit of SAPV system is require less maintenance compared to the electricity generation by the non-renewable source and hence reduce the operational cost. Moreover, SAPV system also reduces the Green House Gas (GHG) emission especially of carbon dioxide (CO_2) and makes them environment friendly [2]. Because of these advantages, the SAPV system becomes more important especially in developing countries

As the initial cost to build the SAPV system is high, thus at first sight the fossil fuel or crude oil powered generators may better options compare to the SAPV system. However, the true performance comparison is not only calculated based on the different cost of construction. Therefore, the purpose of this project was to evaluate the LCA of the SAPV in effort to analyze the comprehensive performance of SAPV system.

A. Description of the SAPV System

The SAPV system at the SK Kalabakan was located at 4.413506^0 North and 117.493057^0 East. This project funded through the Akaun Amanah Industri Bekalan Elektrik (AAIBE) Malaysia as a contribution to Malaysia's 8th plan. Government had taken initiative to encourage the utilizations of renewable energy such as solar photovoltaic (PV), biomass, biogas and small hydro power through the "Sustainable Energy Development Authority Malaysia (SEDA)". The objective of SEDA was to improve the utilization of renewable energy resource to contribute toward national electricity supply security and maintainable socioeconomic development [4]. The purpose for the project is to provide electricity supply for primary school of Kalabakan Tawau, Sabah as the grid system cannot reach for supplying on that remote area. This SAPV system categorized as PV hybrid system. The system consists of PV array, battery bank, generator and the power conditioning including controller. The schematic diagram of system is shown in figure 1. The tropical climate in Malaysia with sunshine

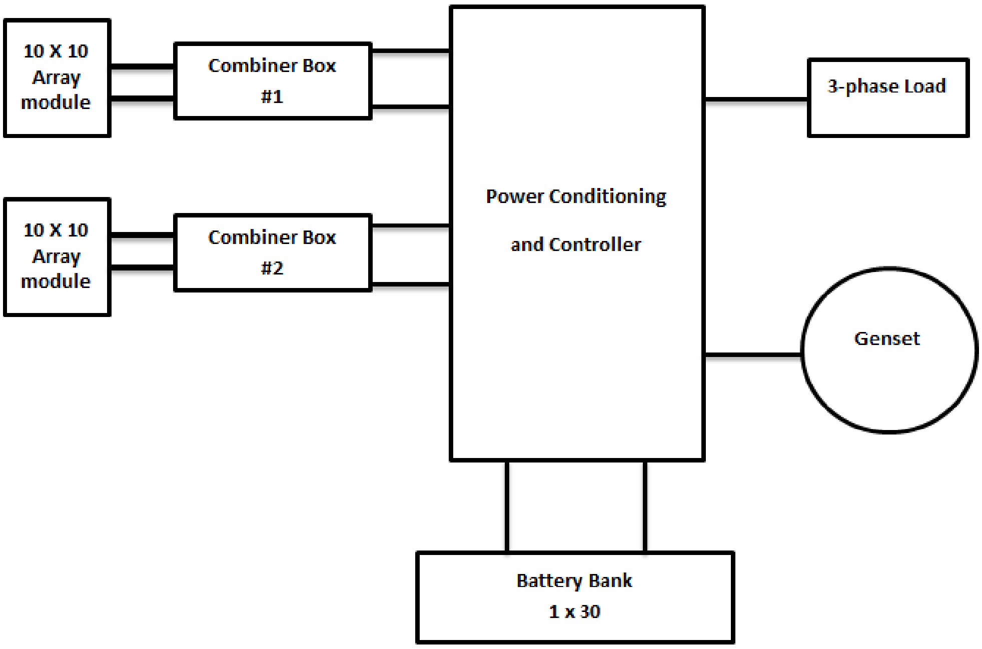

Fig. 1. Schematic diagram of SK Kalabakan PV hybrid system

throughout the year will increase the potential of solar energy generation. Malaysia has an average annual solar irradiation from 4.21kWh/m^2 to 5.56kWh/m^2 with the highest and lowest solar irradiation occurs in August at 6.8kWh/m^2 and November 0.61kWh/m^2 [4]. In Malaysia, a Solar PV panel is expected to absorb more than 30% of the total energy radiated from the Sun. Sabah and East Malaysia measured has highest solar irradiance [4].

The capacity of the PV hybrid at SK Kalabakan is 30 kW_p with consists of 200 poly-crystalline silicon modules mounted on a ground. Tilt angle of the PV module was taken as 20^0 due south. The modules have been arranging into two arrays separately which is each of array consist of 10 number of module in parallel and also 10 number of module in series as well as the second array arrangement as shown in figure 1. The PV module has been applied is manufactured by Sharp Company. The module brand is NE-POE3Z. The characteristics of module can be shown in table 1. The PV generator is connected to power conditioning unit which control the charge of a bank of batteries from the PV generator. The bank of batteries is consist of 30 tubular positive flooded batteries connected in series and only one number of parallel strings offering 4 V of nominal voltage of each battery. The battery bank is connected to the power conditioning unit as an inverter which feed the AC loads. The battery brand is Enersun (SSR1320-4 Century Yuasa). The capacity of each battery is 1320 Ah charges at 100 hours rate. As the nominal voltage of each battery is 4 V and it are connected in series with 30 batteries thus the system voltage is 120 V. The table 2 below shown the number of unit for each component applied in the system.

TABLE 1. PV module characteristics

Module Characteristics	
Maximum power, P_{mp_stc}	150 W_p
Maximum power voltage, V_{mp_stc}	33.7 V
Maximum power current, I_{mp_stc}	4.45 A
Open circuit voltage, V_{oc_stc}	43.1 V
Short circuit current, I_{sc_stc}	4.85 A
Efficiency	11.5 %
Lifetime	25 years

TABLE 2. Number of unit for each component

Component	No. of Unit
PV module	200
Battery	30
Diesel generator	1
Power conditioning unit	1

B. Life Cycle Assessment

Life cycle assessment (LCA) is a technique to evaluate the comprehensive performance of the solar system. As has been explained in the previous, LCA for PV system at SK Kalabakan has been divided into four parts which are economic, energy payback time (EPBT), carbon dioxide (CO_2) emission and the levelized cost of energy (LCOE).

1) Economic and LCOE

In this project, HOMER simulation software was applied as an easier way to calculate the economic and LCOE of the SAPV system. The HOMER software calculates the economics of the SAPV system by mean net present cost (NPC) technique. The expected costs were discounted to their present value by considering the real interest rate. The total NPC of a system is the present value of all the costs that it incurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. The costs may include are capital costs, replacement costs, operation and maintenance costs, and fuel costs [13]. Revenues include salvage value. According to HOMER calculation formula the NPC can be calculated as follow:

$$NPC = \frac{Cann,tot}{CRF(i,Rproj)} \quad (1)$$

Where $Cann,tot$ is total annualized cost, CRF is the capital recovery factor, i is real interest rate, and $Rproj$ is project lifetime. The $Cann,tot$ and CRF can calculated through the equation 2 and 3 respectively.

$$Cann,tot = Cacap + Car + Cao\&m + Caf \quad (2)$$

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N-1} \quad (3)$$

The $Cacap$ is annual capital cost, Car is annual replacement cost, $Cao\&m$ is annual operation and maintenance cost, Caf in annual fuel cost and N is number of year. Annual capital and replacement cost could be obtained as equation below:

$$Cacap = Ccap\ x\ CRF\ (i,Rproj) \quad (4)$$

$$Car = Cr.fr.SFF\ (i,Rcomp) - Sv.SFF(i,Rproj) \quad (5)$$

Where $Ccap$ is capital cost, Cr is replacement cost, $Rcomp$ is lifetime of component, fr is factor arising, SFF is sinking fund factor and Sv is salvage value. The fr can be defined as follow:

$$fr = \frac{CRF(i,Rproj)}{CRF(i,Rrep)} \quad (6)$$

and the SFF formula is as follow:

$$SFF(i,N) = \frac{i}{(1+i)^N-1} \quad (7)$$

Salvage value (Sv) is the value remaining in a component of the power system at the end of the project lifetime. HOMER assumes linear depreciation of components, meaning that the salvage value of a component is directly proportional to its remaining life. It also assumes that the salvage value is based on the replacement cost rather than the initial capital cost [13]. This is expressed mathematically as:

$$Sv = Cr(\frac{Rrem}{Rcomp}) \quad (8)$$

$$Rrem = Rcomp - (Rproj - Rrep) \quad (9)$$

$$Rrep = Rcomp\ x\ INT\left[\frac{Rproj}{Rcomp}\right] \quad (10)$$

Where Cr is replacement cost of component, $Rrem$ is remaining life of the components at the end of the project lifetime $Rcomp$ is lifetime of the component and $Rrep$ is the replacement cost duration. The $INT[\,]$ is integer function to round down the integer portion into real value.

The total annualized cost is important value in order HOMER to calculate the NPC and the LCOE. HOMER defines the LCOE as the average cost per kWh of useful electrical energy produced by the system [13]. In other word, LCOE in $/kWh represent the minimum electricity price that need to be sold to the customer. Thus, the PV suppliers encouraged to sell the electricity of their PV system at a price higher than LCOE of the system to earn a profit. The LCOE can be evaluated follow the equation below:

$$LCOE = \frac{Cann,tot}{Econs} \quad (11)$$

The $Econs$is total energy consumption by the load per year.

2) CO_2 emission

In SAPV system life cycle, the CO_2 emission basically occurs from the energy used in manufacturing for individual components of the SAPV system [9]. The energy consumed in producing for each component in SAPV also referred as embodied energy. Thus, the CO_2 emission of the SAPV system is depend on the total embodied energy of the system. The CO_2 emission of the SAPV system over its lifetime can be obtained by multiplying the total embodied energy of the system to the corresponding emission factors. The expressed mathematically as follow:

$$CO2\ emission = Ein\ x\ fe \quad (12)$$

Where Ein is total embodied energy of PV system and the fe is emission factor

TABLE 3. Initial and replacement cost of component

Component	Initial Cost ($)	Replacement Cost ($)
PV module[a, b]	175000	0
Battery[c]	40500	38000
Power Conditioning[d]	38700	36000
Diesel Generator[c]	19500	18000

[a] Mohd. Arif and M. Erman Khan (2010)
[b] J. Abdulateef, K. Sopian, W. Kader, B. Bias, R. Sirwan, B. Bakhtyar and O. Saadatian
[c] Data collection of diesel generator in South Australia (2013)
[d] Solar-diesel Hybrid Options for the Peruvian Amazon (2007)

3) Energy payback time

EPBT is the time needed of the PV system to generate the equivalent amount of energy that has been consumed to produce the system [3]. In other words, the EPBT is defined as the ratio of energy consumed to produce the photovoltaic (PV) system to the annual energy generated by the PV system [6].

$$EPBT\ (years) = \frac{Ein}{Eaout} \qquad (13)$$

$Eaout$ is define as annual energy generated by PV system.

II. METHODOLOGY

In HOMER simulation software, it is require some input in order to calculate the economics of the PV system. The inputs required such as hourly load profile, monthly solar radiation and ambient temperature value for a PV system, the initial and replacement cost of each component (PV module, diesel generators, battery and power conditioning unit including controller), maintenance and operation (O&M) cost of system, cost of diesel fuel, annual real interest, and rate project lifetime. The monthly solar irradiation and ambient temperature and hourly load profile data was taken from the actual data getting from the PV hybrid system at SK Kalabakan. Capital and replacement cost for PV module, diesel generator, battery and power conditioning including controller have been shown in table 3. The capital costs of PV module are including cost for mounting hardware, wiring and installation of the system.

The lifetime of the PV system is expected follow the lifetime of the PV module which is 25 years. Battery and the power conditioning including controller lifetime are expected 7 and 15 years respectively. This means that the battery requires 3 times replacement and the power conditioning including controller replaced once in the lifetime of project. Diesel generator lifetime expected 15000 hours operation. However this project has been assumed that there is no replacement of the diesel generator occurs. The annual real interest rate assumed as 5% [2]. Diesel price was taken according to the current diesel price in Malaysia 0.62 $/litre. Operation and maintenance cost from table 4 is total O&M of the system except for the diesel generator O&M cost. Then, the O&M of diesel generator was assumed as 2.80 $/hour [10].

A. Embodied Energy Assumption

Embodied energy is the energy consumed by all of the processes related with the production, from the mining and processing of natural resources to manufacturing, transport and product delivery [6]. This energy need to be calculated in order to evaluate the CO_2 emission and EPBT of the PV system. Since the embodied energy data for PV system in Malaysia is not available, thus this project was taken the embodied energy data from the PV system at IIT Delhi, India with assumption the embodied energy of PV system in Malaysia is approximately equal to the PV system at IIT Delhi, India. Table 5 show the embodied energy of 2.32 kWp SAPV system at IIT Delhi, India. Based on the table 5 data, the PV module in this project requires 266560 kWh of embodied energy due to PV area is 272 m^2. As 22.4 m^2 PV area requires 153.5 kg of support structure and for 272 m^2 of PV area requires 1864 kg. Thus, the embodied energy for 1864 kg of support structure of the PV system is 16570 kWh. Total energy of battery at IIT Delhi PV system is 17.28 kWh and requires 2172 kWh of embodied energy. Then for 158.4 kWh total energy of battery they require embodied energy approximately to 19910 kWh. The power conditioning and controller assumed to be 500 kWh and for the overall O&M assume as 10% of the total embodied energy which is equal to 30354 kWh. Therefore the total embodied energy of PV system calculated is 333894 kWh.

TABLE 4. Cost data of the PV system [1 & 12]

Item	Cost ($)
PV module	5/Wp
Installation	10% of PV cost
O&M per year	2% of PV cost

TABLE 5. Embodied energy of different component in PV system [6]

Process/items	Embodied energy (kWh)
1. PV module (Glass to Tedlar) Energy density: (980kWh/m^2) (Existing PV area: 22.4 m^2)	21952
2. M.S support structure a. Steel angle 150 kg b. Screw 2 kg c. Nut and bolt 1.5 kg Energy density: (8.89 kWh/kg of each)	1360
3. Lead acid battery Energy for production:(331kWh_{th}/kWh) Existing 16 battery of 17.28 kWh	2172
4. Inverter Energy for production: (331kWh_{th}/kWh)	284
5. Charge regulator Energy for production: (331kWh_{th}/kWh)	182
6. Overall operation and maintenance, electronic component, cables and miscellaneous etc. taken into account 10% extra	2595
Total embodied energy (kWh)	**27911**

III. RESULT AND DISCUSSIONS

In this chapter, the load profile, solar source and ambient temperature of the PV system site has been explained. Result economic of HOMER simulation, CO_2 emission and the EPBT of the PV system also discussed.

A. Load Profile of Site

Based on the actual load data of the site, the daily and monthly load profile of the PV system at SK Kalabakan is shown in figure 2 and 3. As shown in figure 2 there is significant load demand at midnight to early morning. This load demand comes from the teacher hostel and also from the lights that was switched on for security purpose. This school have two sessions of learning which is in the morning and afternoon. This cause the load demand in the morning is approximately equal to the load demand in afternoon. The average load estimated is 1.95 kW. Therefore average energy required by the load in a day is 46.8 kWh/day.

Based on the monthly load profile, it was found that the highest load demand occurs on April and July and the lowest occur on December. By referring to the school calendar in Malaysia, normally on April and July there is less school break occurs. However on December is a school break for whole of the month.

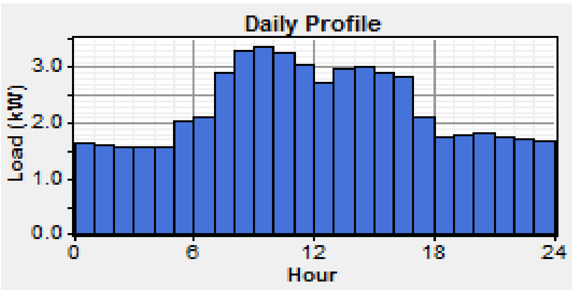

Fig. 2. Daily load profile

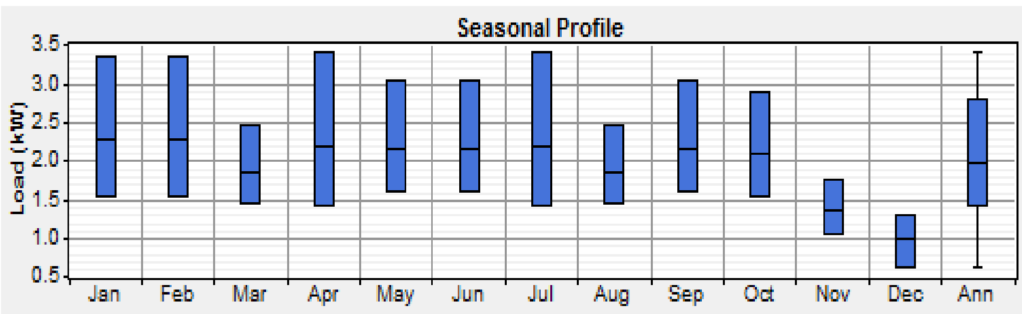

Fig. 3. Monthly load profile

B. *Solar Source and Ambient Temperature*

The PV system design is depend on the geographical location where the system is installed. This is because the amount of the electricity generated by the PV system is varies with the irradiance and temperature. Figure 4 and 5 represent the average monthly for solar irradiation and the ambient temperature of the PV system site.

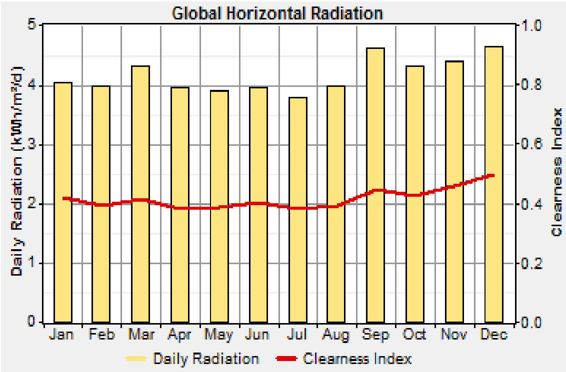

Fig. 4. Average monthly solar irradiation

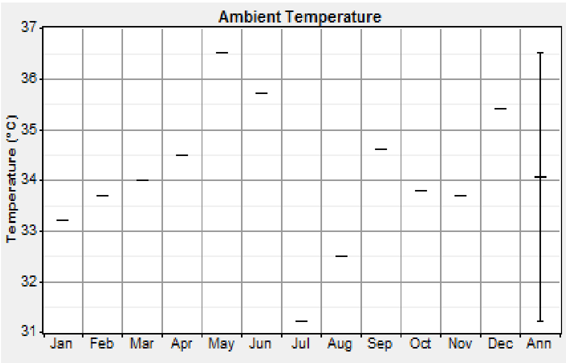

Fig. 5. Average monthly ambient temperature

Annual average of solar irradiation and the ambient temperature estimated to be 4.15 kWh/m^2/day and 34.1^{0}C respectively.

C. *Economical and LCOE*

Net present cost (NPC) is the HOMER's economic main output. From the HOMER simulation output, the estimated total NPC of the system is $384517. The contribution cost of each component of PV system in total NPC of the system can be shown in figure 6.

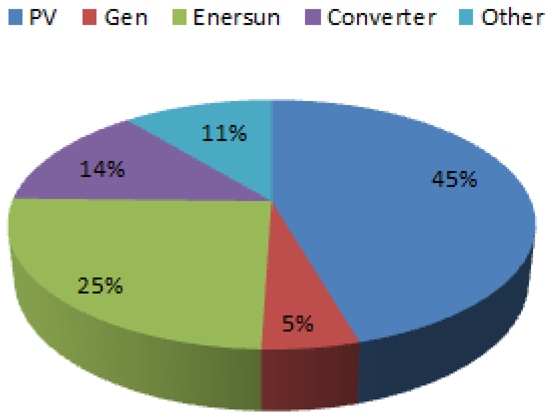

Fig. 7. NPC for each component in percentage

Based on the figure 7, PV modules contribute most in the total NPC of the PV system which is 45% ($175000). Second highest possessed by battery with 25% ($95529). Power conditioning and controller contribute 14% ($52473) follow by other (O&M of system) 11% which is equal to $42282. Finally, the diesel generator contributes only 5% ($19233) of the total NPC of the PV system. The total NPC of system in terms of cost type can be referred in figure 8. From that figure, the salvage is in negative value represent the revenue that earns over the lifetime of system. The estimated total annualized cost $(Cann, tot)$ of the system is $27282. Total annual energy consumed by the AC load is 17119 kWh/year. By applying the equation 11, thus the LCOE of system calculated to be 1.594 $/kWh.

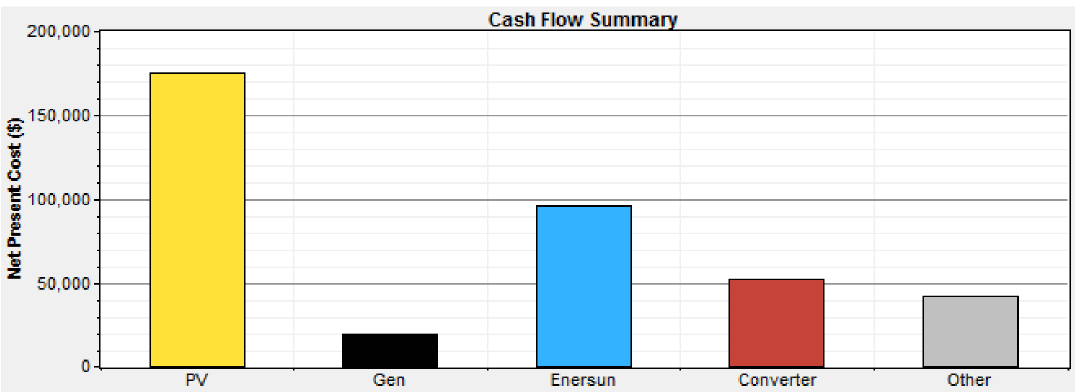

Fig. 6. NPC of each component

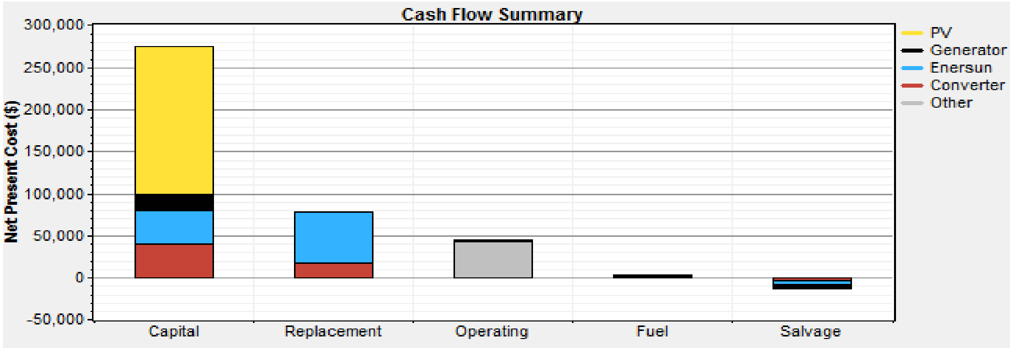

Fig. 8. NPC in term of cost type

The LCOE of PV system at lower Mediterranean countries is US$ 1.039/kWh and in northern European countries around US$ 8.177/kWh [2]. Since the obtained LCOE in this project was found within the ranges for both countries, thus the LCOE of this project acceptable. The LCOE result in HOMER simulation shown in figure below.

Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)
$ 273,700	7,863	$ 384,517	1.594

Fig. 9. HOMER simulation result

D. CO_2 Emission

From the previous chapter, the total embodied energy of the PV system at SK Kalabakan is 333894 kWh. As have been explain in the introduction, the CO_2 emission of the PV system can be obtained by multiplying the embodied energy to the emission factor. The emission factor has been assumed as about 217 g-CO_2/kWh from the electricity generation of the PV system [9]. The CO_2 emission of the system can be calculated through equation 12. Therefore the calculated total CO_2 emission of the PV system over its lifetime is 72455 kg-CO_2. For annual CO_2 emission of system, it can be evaluated by dividing the total CO_2 emission to the system lifetime. Thus the annual CO_2 emission evaluated to be 2898 kg-CO_2/year.

The oil-fired steam turbine emission factor is 937 g-CO_2/kWh [9]. Based on the emission factor of the steam turbine and PV system, it is show that the CO_2 emission from the steam turbine higher four times compared to PV system.

E. Energy Payback Time

The HOMER simulation output of the annual energy generated by the PV system is 31882 kWh/year. The embodied energy is 333894 kWh. Therefore by applying the equation 13, the EPBT of the PV system evaluated to be 10.47 years. Meaning that the system requires at least 10.47 years in order to cover back the energy consumed for producing the PV system.

IV. CONCLUSION

Life cycle assessment (LCA) has been performed for PV system in Malaysia. From the economic perspective, by using HOMER simulation software the estimated total NPC of the PV system is $384517. The PV modules contribute most in total NPC around 45%, follow by battery 25%, power conditioning including controller 14%, O&M of the system 11% and diesel generator contribute only 5%. The annual electricity consumed by the load and generated by PV system are 17119 and 31882 kWh/year respectively. Embodied energy consumed to produce the PV system calculated is 333894 kWh and the estimated of the total annualized cost is $27282. Therefore, the calculated of LCOE, annual CO_2 emission and EPBT of the PV system are 1.594 $/kWh, 2898 kg-$CO_2$/year and 10.47 years respectively.

The LCOE estimated for PV system much higher than the average electricity tariff in Malaysia. However, due to the issue of high price, limited resource and the health risk of the non-renewable source also the PV system price continuously declining over the year. Therefore, SAPV system could be a preferred alternative for providing electricity in remote area as the grid system cannot reach for supplying electricity on that area.

ACKNOWLEDGMENT

The author gratefully acknowledgment to the project supervisor Mr. Zulkifli Othman and Dr. Shahril irwan Bin Sulaiman for giving an idea, support and comment on this paper.

REFERENCES

[1] J. Abdulateef, K. Sopian, W. Kader, B. Bais, R. Sirwan, B. Bakhtyar and O. Saadatian, “Economic analysis of a stand-alone PV system to electrify a residential home in Malaysia”.

[2] Abdul Qayoom Jakhrani, Al-Khalid Othman, Andrew Ragai Henry Rigit, Saleem Raza Samo and Shakeel Ahmed Kamboh, “Life Cycle Cost Analysis of a Standalone PV System” 2011.

[3] A. F Sherwani, J. A Usmani, Varun and Siddhartha, “Life cycle assessment of 50 kWp grid connected solar photovoltaic (SPV) system in India”, *Energy and Environment*, vol. 2, pp. 49-56, 2011.

[4] Prayun Wirun, Chee Wei Tan, Cheng Siong Lim, Chin Kim Gan, Goh Joon Sern and Syahrul Hisham Mohamad, "Solar Technology and Implementations in Malaysia: A Review", *Advances in Natural and Applied Sciences*, pp. 542-555, 2013.

[5] R. Garcia Valverde, C. Miguel, R Martinez Bejar and A. Urbina, "Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system", *Solar Energy*, vol. 83, pp. 1434-1445, 2009.

[6] Rakhi Sharma and G. N Tiwari, " Life cycle assessment of stand-alone photovoltaic (SAPV) system under on-field conditions on New Delhi, India", *Energy Policy*, vol. 63, pp. 272-282, 2013.

[7] C. O. C. Oko, E. O Diemuodeke, N. F. Omunakwe and E. Nnamdi, "Design and Economic Analysis of a Photovoltaic System: A Case Study", *Renewable Energy Development 1*, vol. 3, pp. 65-73, 2012.

[8] Md. Ashfanoor Kabir and Apratim Roy, "Life Cycle Assessment of Solar PV Systems in Bangledesh with Respect to Conventional Sources".

[9] R. Kannan, K.C. Leong, R. Osman, H.K. Ho and C.P. Tso, "Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore", *Solar Energy*, pp. 555–563, 2006.

[10] Nic Jacobson, Joe Wyder, Simon Franklinn and Philippe McCracken, "Data Collection of Diesel Generators in South Australia", 2013.

[11] "Solar-diesel Hybrid Options for the Peruvian Amazon" 2007.

[12] Mohd. Arif and M. Emran Khan, "Design and life cycle cost analysis of a SAPV system to electrify a rural area household in India ", *Current World Environment*, vol. 5, pp. 101-106, 2010.

[13] HOMER legacy simulation software, 2012.

[14] Andreas Sumpera, Mercedes Robledo-García, Roberto Villafáfila-Robles, Joan Bergas-Jané, and Juan Andrés-Peiró, "Life-cycle assessment of a photovoltaic system in Catalonia (Spain)", *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 3888-3896, 2011.