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Life-cycle assessment of residential-scale grid-connected photovoltaic system in Malaysia based on monocrystalline silicon modules

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ABSTRACT

Even though PV systems have been promoted as a green form of electrification, such systems are still contributing to environmental impacts after considering life-cycle impact during material extraction, manufacturing processes of its components, installation, operation, and maintenance. This paper presents a life-cycle assessment to quantify the environmental impact of residential-scale grid-connected PV systems in Malaysia using monocrystalline silicon PV module. LCA had been carried out by using OpenLCA 1.8 software, Ecoinvent 3.5 database, and impact assessment method of IMPACT2002+ and CED. The influence of varying system capacity from 3 to 12 kWp, system lifetime of 21, 25 and 30 years, and solar irradiation of 1560.8, 1651.8, & 1935.5 kWh/m^2/yr, were investigated. The results revealed that the greenhouse gas emissions rate, cumulative energy demand, and energy payback time of residential-scale grid-connected PV systems in Malaysia ranged from 37.97 to 67.26 g CO_2-eq/kWh, 4387.10 to 4699.99 MJ/m^2, and 6.37 to 7.90 years, respectively. This study also evaluated indicators of energy return on investment. The overall finding implies that the installation of residential-scale grid-connected PV systems in Malaysia offers significant potential for GHG emissions reduction in the country.

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1. INTRODUCTION

Grid-Connected Photovoltaic (GCPV) system is one of the popular modes of renewable-based electricity generation worldwide due to inexhaustible sunlight, ease of installation, and has strong government incentives and policy. In Malaysia, Feed-in-Tariff (FiT) is implemented to encourage the public to install renewable energy (RE) technology in order to improve the electricity mix. The generated electricity from RE resource is delivered to the national grid within the contract tenure known as renewable energy power purchase agreement (REPPA). Photovoltaic (PV) technology is one of the common RE technologies implemented under such scheme with total installed capacity already reaching 523.10 MW in 2017, through the FiT program alone [1]. PV system enables the conversion of solar energy from sunlight into electricity almost without environmental pollution during its operational phase. Therefore, PV system has been identified as an environmentally sustainable option of electricity generation when compared to fossil fuelbased power generation systems [2-4]. However, when taking into account its cradle-to-grave phases, some amount of pollution is expected during the raw material extraction, manufacturing processes, transportation, system installation, operation, maintenance, and end-of-life management [5, 6]. As a result, Life-Cycle Assessment (LCA) has been introduced to assess the environmental impact of PV system throughout its lifetime [7-12]. LCA is a methodology to quantify the environmental impact of a product, service, or system from a cradle-to-grave approach, which encompassing from the raw material extraction to waste management, e.g., landfill, incineration or recycling [13]. LCA approach also has been implemented widely to assess the environmental impact of other electricity generation technologies throughout its lifetime [14].

Several LCA studies based on monocrystalline silicon PV module have shown a variation in terms of the commonly reported indicators: greenhouse gases (GHG) emissions rate, cumulative energy demand (CED), and the energy payback time (EPBT). Earlier study in 1998 by Kato et al. [15] had reported GHG emissions rate, CED and EBPT of 83 g CO_2-eq/kWh, 15524 MJ/m^2 and 11.8 years based on rooftop installation in Japan under solar irradiation, performance ratio (PR), system lifetime, and module efficiency of 1427 kWh/m^2/yr, 0.81, 20 years and 12.2%, respectively. The study was based on PV module production scenario in Japan. In the same year, Alsema et al. [16] found that ground-mounted PV system installed in Italy with solar irradiation of 1700 kWh/m^2/yr, 0.82 PR, 12.7% module efficiency, 25 years of system lifetime, had the GHG emissions rate, CED and EPBT of 200 g CO_2-eq/kWh, 6000 to 13900 MJ/m^2, and 4 to 8 years, respectively. This range was caused by different silicon purification and crystallization step considered in the case study. Silicon feedstock preparation from semiconductor scrap was highlighted as the main uncertainty at that time.

In 2005, Alsema et al. collected a life cycle inventory (LCI) data on the crystalline silicon module, with a collaboration of eleven PV companies from Europe and the United States, to represent the current status of crystalline silicon module technology at that time. The research was conducted within the framework of the *CrystalClear* project [17]. Later in 2006, based on the collected data, Alsema et al. [18] found the GHG emissions rate, CED and EPBT of 45 g CO_2-eq/kWh, 5200 MJ/m^2 and 2.7 years, when considering Europe solar irradiation, module efficiency, PR and system lifetime of 1700 kWh/m^2/yr, 14%, 0.75, and 30 years, respectively. In 2008, using the updated Ecoinvent database based on data from the *CrystalClear* project, Jungbluth et al. [19] conducted an LCA for a 3kWp roof-top PV system in Switzerland with solar irradiation of 1117 kWh/m^2/yr, using monocrystalline silicon module with efficiency of 14%. With PR of 0.75 and system lifetime of 30 years, GHG emissions rate found to be 73 g CO_2-eq/kWh, and EPBT ranged from 3.2 to 3.5 years.

Apart from that, in 2010, L. Lu et al. [20] in their study reported results of 671 g CO_2-eq/kWh, 2397 MJ/m^2 and 7.3 years for PV system installed in Hong Kong with 1600 kWh/m^2/yr of solar irradiation,13.3% module efficiency and system lifetime from 20 to 30 years. A more recent study in China using average data of Chinese PV technology was conducted by Hou et al. [21]. With monocrystalline silicon module efficiency of 17%, installed in China with irradiation of 1600 kWh/m^2/yr, PR of 0.75 and system lifetime of 25 years, the GHG emissions, CED and EPBT were found to be 65.2 g CO_2-eq/kWh, 1186.47 MJ/m^2, and 1.7 years, respectively. The result variation indicates that LCA depends on several factors, including the geographical location of the PV system installation and LCI. A study to estimate the environmental impact of a monocrystalline silicon-based PV system in Malaysia was conducted by Seng et al. [22], which resulted in EPBT ranging from 3.2 to 4.3 years. However, it was based on older data from the literature [16], which may not be representative of current technology. Therefore, in this study, the environmental impacts and energy consumption indicators specifically for monocrystalline silicon-based residential-scale GCPV systems under the Malaysian climate were investigated using the LCA approach, based on presently available LCI data. The resulting LCA indicators are expected to provide baseline values for the PV industry in Malaysia.

2. RESEARCH METHOD

The GHG emissions rate and CED of the PV systems were evaluated based on the LCA framework established in ISO 14040 and ISO 14044 standards. The framework comprises four main phases; i) goal and scope definition, ii) life cycle inventory (LCI), iii) life cycle impact assessment (LCIA), and iv) interpretation [23, 24]. The LCA software OpenLCA 1.8 was utilized for system modeling, while the Ecoinvent 3.5 database was used for the background data.

2.1. Goal and scope of the study

The goal of this study was to estimate the GHG emissions and primary energy consumption of residential-scale GCPV systems in Malaysia with monocrystalline silicon PV modules. EPBT and Energy Return of Investment (EROI) were investigated based on the expected system lifetime of 21, 25, and 30 years. Besides, the impact of different installed location on these indicators was also assessed. The functional unit used in this study was 1 kWh of electricity generated from PV system. Different system capacities ranging from 3 to 12 kWp were adopted to mimic the typical range of system capacities used in residential-scale GCPV systems in Malaysia. The system boundaries covered PV modules and balance of system (BOS) components' production, system installation at site, and maintenance during the operational stage encompassing the cradle-to-gate stage. The end-of-life stage of the PV system, however, was not considered as part of the LCA in this study due to poor data availability.

2.2. Inventory data

LCI data were obtained from secondary sources that are available in the literature and database. The production of monocrystalline silicon module involves several main processes; purification of metallurgical silicon and solar-grade silicon, Czochralski crystallization, wafer sawing, cell production, and module assembly. Although LCI for PV module was performed using Ecoinvent 3.5 database, in this study, the data on the energy consumption, material requirements, and direct emissions for each main process in PV module production had been modified with the latest information from IEA PVPS technical report [25]. Metallurgical silicon purification to form solar-grade silicon is deemed to be based on the 'modified Siemens' method. In addition, the thickness of the wafer is set to be 180 µm whereas the module conversion efficiency is 14%. As the PV module is assumed to be made in Germany, the production supply chain and electricity mix had been modeled accordingly.

Inverter data was obtained from an updated LCI of low power solar inverter in [26] which was intended to replace the current Ecoinvent dataset for solar inverters. Moreover, the mass of inverter per power output was assumed to decrease with the increase of inverter's nominal power in a non-linear relationship. As this study focused on residential-scale GCPV systems, three different available datasets were generated for inverters with a rated power of 2.5 kW, 5 kW, and 10 kW, respectively. At this stage, materials for casing, cable, plug, inductors, integrated circuit, as well as components on the integrated circuit were accounted in the inventory.

The common type of array mounting structure used in residential-scale GCPV systems in Malaysia is a retrofitted structure for a sloped roof. This mounting structure is mainly made of aluminium and steel as the main materials. The inventory also included the packaging, which comprises of corrugated board and polystyrene materials. Apart from that, the balance of system components other than inverters and mounting structures are modeled as an electric installation unit process, which comprises the cabling from PV modules to the inverter, cabling from the inverter to the grid, fuse boxes, and lightning protection devices. The mounting structures and electric installation were modeled based on extrapolation from the Ecoinvent database.

The PV array was individually modeled based on rated power capacities ranging from 3 to 12 kWp to represent the typical residential-scale capacities in Malaysia. Over the lifetime, it was expected that some parts of the system will require maintenance and also replacement. Thus, the replacement of damaged PV modules during system lifetime, as well as handling losses during transportation and installation, accounted for 3% of the inventory. As for inverter, one-time replacement throughout system lifetime was expected considering its typical lifespan of approximately 15 years. During the system operational, it was assumed that the PV modules surface is cleaned with water once a year to reduce dirt and dust accumulated on the surface. An estimation of 20 liters of water per m^2 PV module area was assumed in the inventory [25].

2.3. Case study

This study assessed the LCA of residential-scale GCPV system with rated power capacity ranging from 3 to 12 kWp. Mono-Si PV modules with the rooftop-based installation were considered. Three cases were modeled to evaluate the effect of varying parameters according to i) system capacity, ii) system lifetime, and iii) solar irradiation. These cases are modeled based on the system description tabulated in Table 1. In all cases, PR of 0.75 has been assumed for rooftop installation as recommended by the IEA PVPS guideline [27]. Case 1 was intended to analyze the effect of increasing system capacity to the environmental impact and primary energy consumption. The installation site was in Kuala Lumpur, Malaysia, with an estimated annual solar irradiation of 1560.8 kWh/m^2/yr [28]. In addition, a system lifetime of 21 years was considered to reflect on the actual FiT contractual period implemented in Malaysia.

Nevertheless, PV systems can usually last more than the FiT period depending on their components' lifetime expectancy. For instance, the typical PV module output power warranty is 25 years. On the other hand, the life expectancy of the mounting structure and cabling is approximately 30 years. As for the inverter, it was expected that an inverter could last up to 15 years [27]. However, since the inverter LCI had already included a one-time replacement throughout the system lifetime, the prospective total life expectancy of the inverter is extended to 30 years. Hence, in Case 2, the PV system was modeled to investigate the impact of system lifetime of 21, 25, and 30 years on the environmental impact and primary energy consumption.

In case 3, the effect of varying solar irradiation on the environmental and energy indicators was investigated. Three different cities, i.e., Kuala Lumpur, Kota Bharu, and Johor Bharu having different annual solar irradiation profiles, were selected for evaluation. Kota Bharu is a city located on the east coast of peninsular with latitude and longitude of 5.28°N and 100.3°E, having annual solar irradiation of 1935.5 kWh/m^2/yr. Another city selected in this case study was Johor Bahru, which represents the southern region. The city is located at 1.46°N and 103.8°E, with annual solar irradiation of 1651.8 kWh/m^2/yr. All solar irradiation values are set for to South-facing PV array with a tilt angle of 10° [28]. The effect of varying solar irradiation along with different system lifetime was studied in this case.

Table 1. PV system description in the case study

Description	Case 1	Case 2	Case 3
PV module technology	Mono-Si	Mono-Si	Mono-Si
PV module efficiency	14%	14%	14%
Mounting structure	Retrofitted-rooftop	Retrofitted-rooftop	Retrofitted-rooftop
Performance ratio	0.75	0.75	0.75
System capacity	3 to 12 kWp	3 to 12 kWp	3 to 12 kWp
System lifetime	21 yr	21, 25 & 30 yr	21, 25 & 30 yr
Installation location	Kuala Lumpur	Kuala Lumpur	Kuala Lumpur, Johor Bahru, & Kota Bharu
Solar irradiation (PV module facing south with 10° tilt angle)	1560.8 kWh/m2/yr	1560.8 kWh/m2/yr	1560.8, 1651.8, & 1935.5 kWh/m2/yr

2.4. Life cycle impact assessment

The environmental impacts were calculated using IMPACT2002+ LCIA method that provides fifteen mid-point impact categories including aquatic acidification, aquatic ecotoxicity, carcinogens, global warming, ionizing radiation, land occupation, mineral extraction, non-carcinogens, non-renewable energy, ozone layer depletion, respiratory inorganics, respiratory organics, terrestrial acidification & nutrification and terrestrial ecotoxicity. However, this study only focused on the global warming impact, which is contributed by the emission of greenhouse gases (GHG). The amount of GHG emissions was presented in 'g CO_2-eq'. Therefore, other GHG compositions such as CH_4, N_2O, and CFCs were converted into their equivalent CO_2 impact based on the characterization factor from Intergovernmental Panel on Climate Change (IPCC) for 100-year time horizon [29]. On the other hand, the CED method was used to quantify primary energy consumption. Both IMPACT2002+ and CED methods covered the classification and characterization elements, which are made mandatory by the ISO standards. However, the normalization and weighting elements were not taken into account in this study.

3. RESULTS AND DISCUSSION

The environmental impacts and energy indicators for all the three cases described are presented in this section.

3.1. Case 1: effect of different PV system capacities

When analyzing the emission based on the functional unit of kWh, the amount of GHG emissions slightly decreased with the increase of PV system capacity. In this case, installation in Kuala Lumpur with a system lifetime of 21 years was considered. It was estimated that the GHG emissions rates were 70.04, 67.06, and 64.69 g CO_2-eq/kWh for PV system capacity range of 3 to 5 kWp, 5 to 10 kWp, and 10 to 12 kWp respectively. GHG emissions rate breakdown in Figure 1 shows that the PV module had contributed the most with more than half of total GHG emission while PV system installation, as well as maintenance, had a relatively smaller contribution compared to PV module and other BOS components. The larger share of the PV module in contributing to the emission is primarily due to the high electricity consumption during its energy-intensive manufacturing processes such as silicon purification and Czochralski crystallization that require high working temperature [30].

The GHG emissions rate breakdown also indicated that the contribution of all unit processes was similar for all system capacity except for inverter in which it decreased with higher system capacity. This is due to the non-linear relationship of the inverter mass to its rated power, which causes different inverter LCIs being used to model different capacity of PV systems. Thus, a lower GHG emissions rate was found for the PV system with larger system capacity. The share of GHG emissions rate for the inverter was, however, larger when compared to many previous studies. A more updated version of inverter LCI adopted from [26] had been used in this study to represent the current inverter technology. Even though the recent inverter is lighter in weight compared to the older inverter from Ecoinvent, the environmental impact in most impact categories, including climate change (GHG emissions), was somehow higher due to the impact from printed board assembly. Newer inverter carried 59% of the total impact, while the old inverter carried only 16% of the total impact due to the printed board assembly [26].

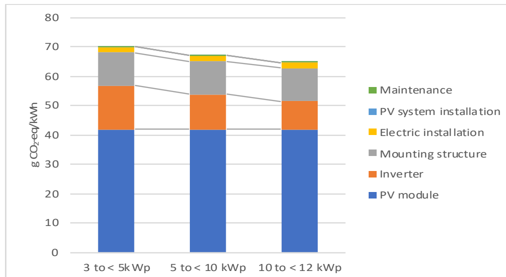

Figure 1. Breakdown of GHG emissions rate of PV module installed in Kuala Lumpur with lifetime of 21 years

CED is an indicator to assess the embodied energy of the system. Total CED comprises renewable and non-renewable primary energy harvested from nature. Table 2 presents the CED on the basis of per m^2 of the module area. When considering the per m^2 module area, the results indicated that CED marginally reduced with a larger system capacity range. The CEDs found to be 4669.99, 4512.46, and 4387.10 MJ/m^2 for system capacity range of 3 to 5kWp, 5 to 10kWp, and 10 to 12kWp respectively. The cause of the reduction is due to the usage of different LCI for different inverter rated power. Higher inverter rated power consumes a lower amount of primary energy.

Apart from CED, EPBT is also an important indicator of how fast the energy consumed throughout the project lifetime can be recovered using the solar electricity generation. With an estimated annual specific yield of 1170.6 kWh/kWp per year for installation in Kuala Lumpur, the estimated EPBT ranged from 7.66 to 8.15 years. Therefore, the feasibility of the system for electrification is acceptable since the FiT duration is 21 years, i.e., higher than the estimated EPBT. In addition, Energy Return on Investment (EROI) is the amount of energy that has to be expended in order to produce a certain amount of energy. EROI value has to be higher than 1 for energy to be returned to society. In this study, EROI was found to be from 2.58 to 2.74.

3.2. Case 2: effect of PV system lifetime

This section presents the results for extending the system lifetime from 21 years to 25 and 30 years. GHG emissions rate reduced considerably with the extension of system lifetime, as shown in Figure 2. When compared to 21 year system lifetime, a reduction of GHG emission of approximately 16% and 30% was found when the lifetime extended to 25 and 30 years, respectively. Besides that, the GHG emissions rate for installation in Kuala Lumpur was also found to be in the range from 45.28 to 70.04 g CO_2-eq/kWh if minimum and maximum system lifetime were considered to be 21 years and 30 years respectively. As the PV system can last longer, more electricity can be generated throughout its lifetime, consequently reducing the GHG emissions per kWh of the electricity generated. EPBT found to be unaffected by system lifetime, while EROI showed improvement with the extending system lifetime, which ranged from 2.58 to 3.92, as shown in Table 2.

Table 2. Energy indicators for installation in Kuala Lumpur

System capacity	CED (MJ/m^2)	EPBT (year)	EROI		
			21 yr	25 yr	30 yr
3 to <5 kWp	4669.99	8.15	2.58	3.07	3.68
5 to <10 kWp	4512.46	7.88	2.67	3.17	3.81
10 to <12 kWp	4387.10	7.66	2.74	3.26	3.92

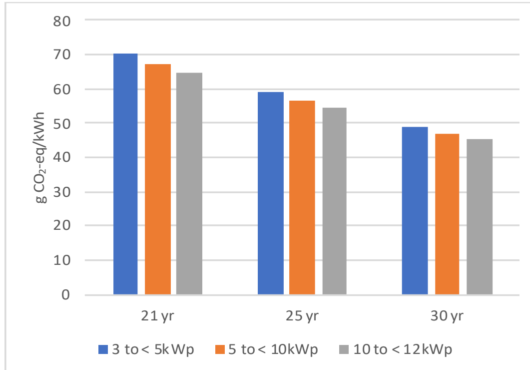

Figure 2. GHG emissions rate for PV system installation in Kuala Lumpur with varying system lifetime

3.3. Case 3: influence of varying solar irradiations

Results presented in previous sections are specifically for installation in Kuala Lumpur with solar irradiation of 1560.8 kWh/m^2 per year. However, this section presents the GHG emission rate, EPBT, and EROI at different locations with different annual solar irradiation. Table 3 summarises the average results of 3 to 12 kWp PV system installed in three different locations in the country distinguished by different solar irradiation levels, with a system lifetime of 21, 25, and 20 years. GHG emission rate and EPBT were found to decrease gradually with the increase of solar irradiation. In contrast, EROI increased when solar irradiation is higher due to increasing solar electricity generated, which helps to improve the EROI. The analysis showed that GHG emissions rate and EPBT obtained were lowest in Kota Bharu at 37.97 g CO_2-eq/kWh and 6.37 years, respectively, when 30 years of system lifetime being considered.

Table 3: Comparison of varying solar irradiation with different system lifetime for the average of 3 to 12 kWp system capacity

Indicator	Unit	Kuala lumpur (1560.8 kWh/m^2/yr)			Johor Bahru (1651.8 kWh/m^2/yr)			Kota Bharu (1935.5 kWh/m^2/yr)		
		21 yr	25 yr	30 yr	21 yr	25 yr	30 yr	21 yr	25 yr	30 yr
GHG emissions rate	g CO_2-eq/kWh	67.26	56.50	47.08	63.56	53.39	44.49	54.24	45.56	37.97
EPBT	year	7.90	7.90	7.90	7.46	7.46	7.46	6.37	6.37	6.37
EROI	dimensionless	2.66	3.17	3.80	2.82	3.35	4.02	3.30	3.93	4.71

4. CONCLUSION

A life-cycle assessment of the residential-scale GCPV systems in Malaysia was conducted using monocrystalline silicon module technology. The GHG emissions rate, EPBT, and EROI were determined to quantify the environmental impact of the system. The results showed that the PV module had contributed the most to the overall GHG emissions and CED, mainly dominated by the upstream processes during manufacturing. Also, using the updated inverter LCI to represent the latest inverter technology, it was found that inverter had also brought a significant impact on the GHG emission. Nevertheless, with the improvement of inverter technology, further reduction of energy consumption and GHG emissions is expected in the future.

The reduction of GHG emissions rate, EPBT, and EROI when the capacity increases are not significant within 3 to 12 kWp residential-scale PV systems, as most of the components are linearly upscaled to reach desired capacity except for the inverter which has less impact as its rated power increases. Given the scenario of extended system lifetime, these indicators reduce considerably. Thus it is worth highlighting that future effort by PV industries to ensure PV system components can endure in a more extended period could play a role in mitigating the global warming impact. Furthermore, the installation location also has a significant influence on its environmental performance since the PV system has intermittent nature where its electricity generation relies on its geographical location and weather. Hence, planning for a PV system installation on a larger scale when the location is not a constraint, should take into account the ideal location when addressing the global warming impact.

The average results of GHG emissions rate and EPBT ranging from 37.97 to 67.26 g CO_2-eq/kWh and 6.37 to 7.90 years, while for EROI from 2.66 to 4.71. Other factors that may increase the electricity generation of PV systems, such as improvement of PR and an increase of PV module conversion efficiency may improve the LCA results. Overall, in the context of residential-scale, PV technology offers a substantial potential for GHG emissions reduction in this country. However, continuous improvement effort in reducing its embodied energy and GHG emissions is crucial in the strive for a more sustainable future for PV technology.

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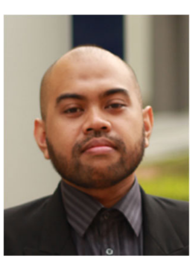

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