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Effect of Photovoltaic (PV) Module Degradation Rate on The Greenhouse Gas Emissions: A Life-Cycle Assessment

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***Abstract*—In this paper, a life-cycle assessment (LCA) is carried out to evaluate the greenhouse gas emissions of the photovoltaic (PV) system, focusing on the effect of the PV module degradation rate throughout the system's lifetime. The LCA is done on monocrystalline silicon PV module technology using actual data from manufacturers' datasheets. In this study, three different manufacturers under three scenarios are done, which involves the inclusion and exclusion of the degradation factor: i) Scenario A – PV module degradation is considered with a PR of 0.75, ii) Scenario B – PV module degradation is considered and the PR is calculated based on each PV module's temperature coefficient and other de-rating factors, iii) Scenario C – PV module degradation is ignored. Using the Intergovernmental Panel of Climate Change (IPCC 2013) impact assessment method, the results show that the greenhouse gas (GHG) emissions rate ranges from 66.05 to 79.25 g CO_2-eq/kWh depending on the scenarios presented. The results also suggest that a lower degradation rate reduces the environmental burden of the PV system.**

***Index Terms*—GHG emissions, global warming, degradation rate, life cycle assessment, LCA, photovoltaic, mono-Si.**

I. Introduction

THERE is no doubt that photovoltaic (PV) is a popular renewable energy (RE) technology that generates electricity from cleaner resources compared to fossil-fuel based resources, e.g., coal or oil. However, an increasing number of life-cycle assessment (LCA) studies reveal that PV still produces greenhouse gas (GHG) emissions when considering the life-cycle stages of the system, i.e., raw material extraction, manufacturing, transportation, installation, operation, maintenance, and end-of-life (EoL) activities. However, an increasing number of life-cycle assessment (LCA) studies reveal that PV still produces greenhouse gas (GHG) emissions when considering the life-cycle stages of the system, i.e., raw material extraction, manufacturing, transportation, installation, operation, maintenance, and end-of-life (EoL) activities.

Kato et al. [1] conducted an LCA of a rooftop grid-connected (GC) PV system in Japan with irradiation of 1,427 kWh/m^2/y, using monocrystalline silicon (mono-Si) PV module made of off-grade silicon. Assuming a performance ratio (PR) of 0.81, system lifetime of 20 years, and a cradle-to-gate system boundary, the GHG emissions ranged from 21 to 91 g CO_2-eq/kWh, depending on different processing considerations. Alsema [2] compared the GHG emissions of rooftop PV systems using two different PV module technologies: multicrystalline silicon (multi-Si) and amorphous silicon (a-Si). According to the authors, the study boundary only covered the production of PV modules and BOS components, due to negligible energy consumption during operational phase and lack of PV EoL data. It was found that the PV system with a-Si module had lower emissions of 50 g CO_2-eq/kWh than the former with 60 g CO_2-eq/kWh, under irradiation of 1,700 kWh/m^2/y, and PR of 0.75.

Meanwhile, an LCA of a large-scale PV system in Marsciano, Italy, with an installed capacity of 1.778 MWp, was investigated by Desideri et al. [3]. The installation was different from the rooftop or small-scale PV system, including additional infrastructure such as fence, and electrical substation. The GHG emissions of 88.74 g CO_2-eq/kWh was obtained using multi-Si PV module with module efficiency of 14.4% and system lifetime of 25 years, taking into account a recycling scenario at its EoL phase. Beylot et al. [4] compared four different scenarios of PV system installation type: i) fix mounting structure with primary aluminium support, ii) fix mounting structure with wood support, iii) mobile structure with single-axis tracker, and iv) mobile structure with dual-axis tracker. The finding showed that the first scenario had the highest GHG emissions due to the high carbon footprint of the primary aluminium, even considering the environmental credits from the recovery of aluminium through recycling at EoL. The results ranged from 37.5 to 53.5 g CO_2-eq/kWh, under

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irradiation, module type, system capacity, system lifetime, and PR of 1,700 kWh/m^2/y, multi-Si, 5 MWp, 30 years, and 0.855, respectively.

The reported GHG emissions showed a wide range of results, and several factors had been highlighted as the main influence on the results, such as solar irradiation, PR, system lifetime, type of installation, and system boundary considered [5]–[10]. The system's lifetime of 25 to 30 years was mostly considered in previous studies. During this period, the performance of the PV module will eventually degrade over time. Nevertheless, many of previous studies had not mentioned whether the PV module degradation was taken into account or not in their studies. There were also studies that clearly stated the value of degradation rate considered [3], [11]–[14]. In the International Energy Agency Photovoltaic Power Systems (IEA-PVPS) guideline, the recommended degradation rate is 0.7%/year or 10.5% in the entire lifetime [15]. Nevertheless, nowadays, a lower degradation rate can be found in new PV module datasheets. In this paper, we demonstrate the impact of the PV module degradation over the system's lifetime on GHG emissions in order to highlight the importance of the factor from the environmental point of view.

II. METHODOLOGY

A case study of 3.45 kWp slanted-roof GCPV system installed in Kuala Lumpur, Malaysia with annual solar irradiation of 1,695.72 kWh/m^2/y was considered. Mono-Si PV modules from three different manufacturers with similar nominal power rating were selected for comparison, with the technical specification listed in Table I. The system was assumed to consist of ten units of 345 W modules. The system was assumed to be in operation for 30 years, based on the IEA-PVPS guideline [15]. Within this period, the annual electricity generation will reduce as the operating year increases. Equation 1 is used to estimate the annual electricity generation of the PV system. For a cumulative electricity generation throughout the lifetime, $E_{sys\_lifetime}$, the parameter of lifetime module degradation factor, $f_{mod\_degrade\_lifetime}$ is multiplied to the Equation 1.

TABLE I
SPECIFICATIONS OF MONOCRYSTALLINE SILICON PV MODULES

Parameter	Unit	SunPower	Longi	Jinko Solar
Model	--	SPR-X21-345-COM	LR4-60HPB-345M	JKM345M-72
P_{mod_stc}	W	345	345	345
η_{mod}	%	21.2	18.9	17.78
γ_{Pmp}	%/ºC	-0.298	-0.35	-0.40
f_o	%	98	98.5	97
x	%	0.25	0.55	0.7

The PR of a PV system is influenced by several design factors, namely temperature, dirt, module mismatch, cable losses, and inverter efficiency, as expressed in Equation 2. For a rooftop installation, depending on situation, a PR of 0.75 is common, as recommended in the IEA-PVPS guideline. However, a more accurate value can be estimated according to the module's temperature coefficient declared by the manufacturer and expert judgement for other de-rating factors. In this study, assumptions of f_{dirt}, f_{mm}, f_{cable}, and η_{inv} were 0.95, 0.95, 0.98, and 0.96, respectively were made [16]. The temperature de-rating factor, f_{temp_ave} was estimated using Equation 3 and 4, where the cell temperature, T_{cell_ave} was 58.56ºC, assuming the ambient temperature $T_{amb\_ave\_max}$, nominal operating cell temperature (NOCT), and irradiance, $G_{amb\_ave\_max}$ were 32ºC, 45ºC, and 850 W/m^2, respectively [16].

$$E_{sys\_annual} = P_{array\_stc} \times H_{annual} \times f_{design} \quad (1)$$

$$f_{design} = f_{temp\_ave} \times f_{dirt} \times f_{mm} \times f_{cable} \times \eta_{inv} \quad (2)$$

$$f_{temp\_ave} = 1 + \left[\left(\frac{\gamma_{Pmp}}{100}\right) \times \left(T_{cell\_ave} - T_{stc}\right)\right] \quad (3)$$

$$T_{cell\_ave} = T_{amb\_ave\_max} + \left[\left(\frac{NOCT-20}{800}\right) \times G_{amb\_ave\_max}\right] \quad (4)$$

PV module degradation is a gradual deterioration that affects its output power generation over time. In general, the degradation is caused by several factors: temperature, humidity, irradiation, corrosion, discoloration, delamination, and breakage or cracking cells [17]. In the first year, the PV module usually degrades at a certain percentage of the warranted output power (f_o). In the following years ahead, the output power usually degrades linearly with a degradation rate (x) [18], as commonly described in PV module datasheets. Based on the manufacturers' warranty, the degradation is linear from the first year until 25 years, as illustrated in Figure 1. In this study, we assume that it is extended to 30 years. Thus, the module degradation factor for the lifetime was derived and presented in Equation 5, which is further utilized in Equation 6 to determine the total generated electricity throughout the lifetime, $E_{sys\_lifetime}$. In Figure 1, it is observed that the SunPower module has the slowest annual degradation rate, while Jinko Solar has the fastest.

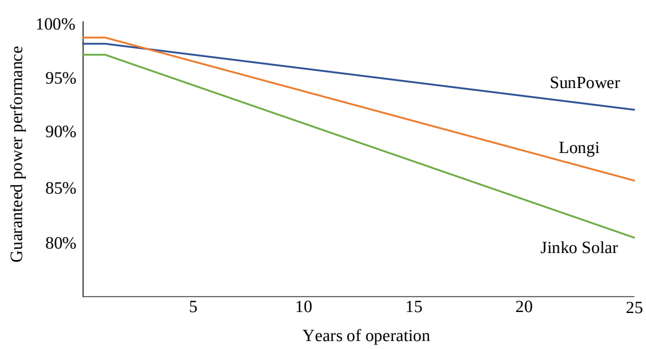

Fig. 1. Power performance over years of operation.

$$f_{mod\_degrade\_lifetime} = f_o t - x\frac{t(t-1)}{2} \quad (5)$$

Where,
f_o is initial degradation factor (absolute value)
x is annual degradation rate (absolute value)
t is operating year

$$E_{sys\_lifetime} = P_{array\_stc} \times H_{annual} \times f_{design} \times f_{mod\_degrade\_lifetime} \quad (6)$$

In this study, three scenarios are considered: i) Scenario A – PV module degradation is considered with a PR of 0.75, ii) Scenario B – PV module degradation is considered and the PR is calculated based on each PV module's temperature coefficient, and the above-mentioned de-rating factors, iii) Scenario C – PV module degradation is ignored. The flowchart of the study is illustrated in Figure 2. After the $E_{sys\_lifetime}$ is determined, the input flows in the unit process are related according to the functional unit of 1 kWh electricity generation. In the LCA framework outlined in the ISO 14040 and 14044, there are four stages involved in conducting an LCA study: i) goal and scope definition, ii) life cycle inventory (LCI), iii) life cycle impact assessment (LCIA), and iv) interpretation. The goal of this study is to investigate the influence of mono-Si PV module degradation factor on the GHG emissions. The system boundary encompasses the cradle-to-gate approach which covers most of the system's lifecycle stages including the raw material extraction, PV module, and balance of system (BOS) component production, installation, and operational and maintenance. Nevertheless, the EoL stage which may involve activities such as system decommissioning, reuse, and recycling of some parts of the system is excluded due to a lack of data considering the amount of EoL PV waste in the country as in the case study is relatively low.

The LCI is a set of data consisting information on material, energy consumption, and direct emissions of a process or system, interrelated with the functional unit. In this study, the LCI is adopted from the Ecoinvent 3.5 database, where the default 3 kWp PV system dataset in the database is up-scaled to 3.45 kWp. The LCI covers complete mono-Si PV module production chains including metallurgical silicon production, mono-Si ingot production using the Czochralski process, wafer production, PV cell production, and PV module assembly. The production and installation of BOS components such as mounting structure, inverter, and cabling are also included. Moreover, the operation and maintenance such as PV module cleaning is also taken into account [19]. Subsequently, the GHG emissions results are generated using the IPCC 2013 LCIA method, embedded in the Simapro 9 software. In this stage, the emission substances are classified and characterized based on the characterization factor of the global warming potential (GWP 100) provided by the IPCC. The GHG emissions rate is reported in 'g CO_2-eq/kWh', where all types of involving greenhouse gases (CH_4, N_2O, etc.) are converted into their equivalent impact magnitude of CO_2 based on the characterization factors, which can be written as in Equation 7. Finally, the GHG emissions obtained for each scenario are compared.

$$GHG\ emissions = \sum_s GWP_s \times m_s \quad (7)$$

Where,
s is the substance
GWP_s is the characterization factor of substance s
m_s is the emitted amount of substance s in kg

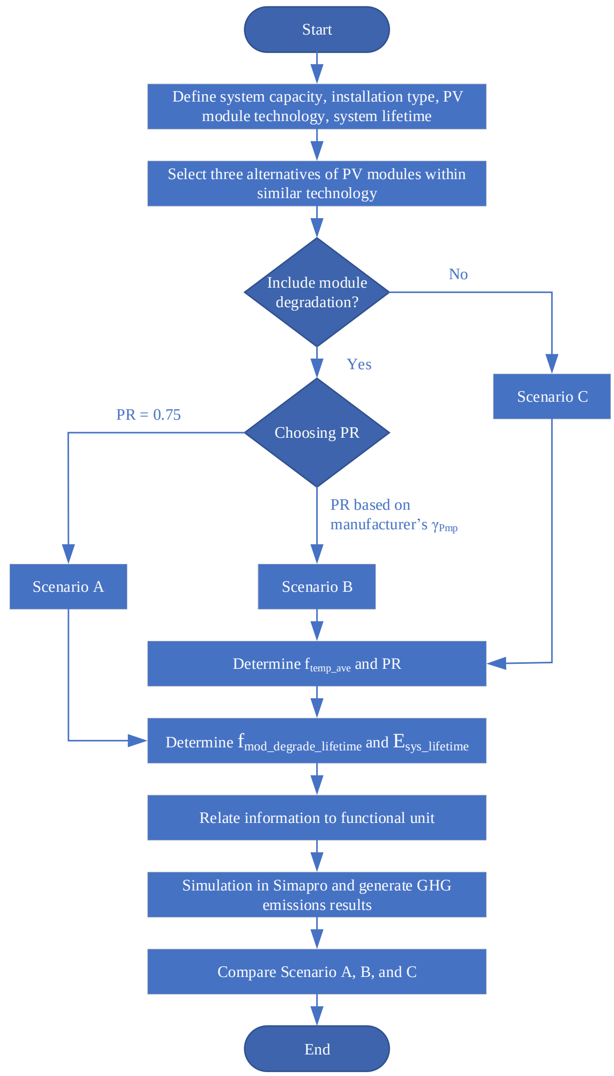

Fig. 2. Flowchart of the study.

III. Result and Discussion

Table II outlines the GHG emissions rate obtained under different values of parameters ($f_{mod\_degrade\_lifetime}$ and PR), for all scenarios. The correlation coefficients between variables in Scenario A, B, and C are all 1, which indicates a strong correlation. The GHG emissions rate obtained in this study ranges from 66.05 to 79.25 g CO_2-eq/kWh, which in percentage-wise is illustrated in Figure 3. It is observed that in all scenarios, the SunPower module has the lowest GHG emissions, which is mainly due to the lowest annual degradation rate compared to the other two modules; subsequently, the $E_{sys\_lifetime}$ is greater. Meanwhile, when comparing between Scenario A and B, it can be seen that for the Jinko Solar module, considering PR calculated from the datasheet's power temperature coefficient has resulted in higher GHG emissions. On the contrary, the SunPower module produces lower emissions when the factor is taken into account. In other words, a lower power temperature coefficient will result in higher PR and subsequently lower GHG emissions. Note that the $f_{mod\_degrade\_lifetime}$ in Scenario C is equal to the system lifetime (30) due to no degradation considered over the lifetime.

In Scenario C, it is observed that when neglecting the PV module degradation, the emission is considerably lower compared to both Scenario A and B. Comparing to the most realistic case (Scenario B), 8.62% to 13.15% lower GHG emissions is obtained in Scenario C. Having similar conditions of solar irradiation, system lifetime, PV module types, and installation types for each scenario, the range of variation is considered high. This implies that considering the PV module degradation in estimating the environmental impact is crucial and should not have left out, which otherwise would cause an underestimation.

TABLE II
RESULTS FOR DIFFERENT SCENARIOS

Parameter	$f_{mod\_degrade\_lifetime}$	PR	$E_{sys\_lifetime}$	GHG emissions
	-	-	[kWh]	[g CO_2-eq/kWh]
Scenario A				
SunPower	27.4125	0.750	120277.15	73.82
Longi	27.1575	0.750	119158.30	74.52
Jinko Solar	26.0550	0.750	114320.89	77.67
Scenario B				
SunPower	27.4125	0.766	122843.07	72.28
Longi	27.1575	0.749	118999.42	74.61
Jinko Solar	26.0550	0.735	112034.47	79.25
Scenario C				
SunPower	30	0.766	134438.38	66.05
Longi	30	0.749	131454.76	67.55
Jinko Solar	30	0.735	128997.66	68.83

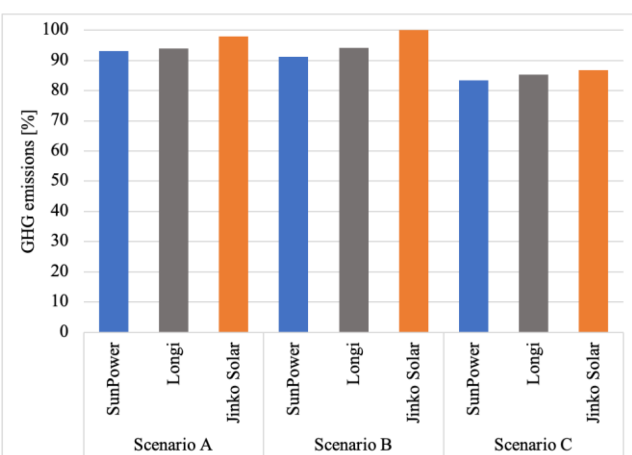

Fig. 3. Comparison of GHG emissions rates in percentage.

IV. CONCLUSION

In this study, the effect of PV module degradation on the life-cycle GHG emissions is demonstrated. The results suggest that the PR value of 0.75, as recommended by the IEA-PVPS, is acceptable for GHG emissions estimation of a rooftop PV system. Nevertheless, determining the PR considering the PV module's actual power temperature coefficient resulted in a more accurate result. It can also be concluded that considering the PV module degradation factor when evaluating an LCA of PV system is crucial. It has a significant influence on the results, as the effect of degradation will increase with longer system's operational year. The study also concludes that a lower PV module degradation rate is favorable, and research and development efforts focusing on lowering the module degradation rate in the future will indirectly benefit in mitigating the impact of global warming caused by GHG emissions.

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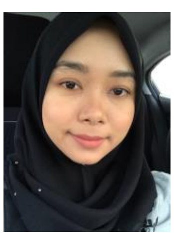

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