Comparative Life Cycle Assessment of Monocrystalline and Multicrystalline-based Grid-Connected Photovoltaic Systems with Uncertainty Analysis

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ABSTRACT

A comparative Life Cycle Assessment (LCA) of Photovoltaic (PV) systems in Shah Alam, Malaysia using different PV module technologies, i.e. monocrystalline silicon and multicrystalline silicon installed was conducted in this paper to evaluate the energy consumption and global warming impacts using CED and IPCC methods. Several energy and global warming-related indicators were also determined and uncertainty, contribution, and sensitivity analyses were performed. The results show that multi-Si PV system outperforms the mono-Si PV system after taking into account the data uncertainty. The global warming impacts were found to be 47 and 54.7 g CO_2-eq/kwh for multi-Si and mono-Si systems, respectively. The contribution analysis shows that the PV module is the major contributor of each system. It is also highlighted that increased irradiation, extended system lifetime, and reduced module degradation rates could improve the overall performance. This study provides valuable insights into the environmental performance of different PV module technologies, offering guidance for optimizing PV system design and promoting sustainable energy development.

Keywords-solar PV; comparative LCA; uncertainty; global warming; energy payback time

I. INTRODUCTION

Nowadays, the global energy landscape is shifting toward renewable energy as nations strive to address pressing challenges such as environmental sustainability, energy reliability and climate change [1]. Among various renewable energy technologies, photovoltaic (PV) systems represent a leading solution for clean-energy generation [2, 3]. Globally, PV system integration into electrical grids is growing in popularity due to reduced expenses and cost, improvements in technology, and regulations supporting the switch to clean energy [4, 5].

Malaysia solar energy sector is experiencing a rapid growth as well, driven by supportive government policies. Malaysia has set a target of achieving 31% renewable energy in its power generation mix by 2025, demonstrating its commitment to mitigate climate change [6]. The National Energy Transition Roadmap (NETR) aims to increase the renewable energy capacity in electricity mix to 40% by 2035 and 70% by 2050, with solar energy playing a pivotal role [7]. Moreover, the country also aims to reach net zero emissions by 2050 as a long-term commitment to reduce emissions [8]. Therefore, various national programs and incentives related to renewable energy had been implemented including Feed-in-Tariff (FIT), Net Energy Metering (NEM), Large Scale Solar (LSS), and Self-Consumption (SELCO) [9].

Recently, there has been an increasing trend of PV Life Cycle Assessment (LCA) studies aiming to quantify the system's environmental performance [10]. For instance, authors in [11] conducted an LCA of a 33.7 MW ground-mounted multi-Si solar PV power plant installed in Zagtouli, Burkina Faso with solar irradiation of 2,140 kWh/m^2/year. It was reported that the GW impact is 40 g CO_2-eq/kWh while its Energy Payback Time (EPBT) is 1.63 years. In addition, the study also conducted analysis for six scenarios with different PV module technologies, installation locations, and material of mounting structure and foundation. The GW and EPBT results ranged from 37 to 48 g CO_2-eq/kWh and 1.47-1.9 years respectively [11]. Authors in [12] compared two scenarios of a 1 MW rooftop PV system using grid-connected and standalone multi-Si PV modules. The later showed higher impacts due to the inclusion of additional system components such as battery storage. The GW and EPBT for the standalone system were 101.41 g CO_2-eq/kWh and 6.74 years, respectively, and 58.52 g CO_2-eq/kWh and 3.71 years for the grid-connected system [12]. A comparative LCA of monocrystalline silicon (mono-Si) and multicrystalline silicon (multi-Si) PV systems installed in Korea was performed in [13]. A scenario of improved module efficiency was also performed for each system type. The results highlighted that the multi-Si PV system (efficiency of 14.91%) outperformed the mono-Si PV system (efficiency of 15.96%) with GW of 31.5 and 41.8 g CO_2-eq/kWh, and EPBT of 3.65 and 4.68 years, respectively. Furthermore, using the improved PV module efficiency (mono-Si: 27.60% and multi-Si: 20.30%) resulted in reduced GW of 27.4 and 25.25 g CO_2-eq/kWh and shorter EPBT of 3.11 and 2.97 respectively [13].

The variety of PV LCA results is contributed by many factors including different system boundaries, climatic conditions, scenarios considered, system and installation types, estimated lifetime, and functional units [11-18]. Furthermore, uncertainty analysis due to data variability has been rarely addressed in many comparative PV LCAs [11-13, 16, 17, 18, 20]. The absence of uncertainty information could decrease the reliability of conclusions, particularly in the context of decision-driven comparative LCA [20, 21]. Therefore, in this study, a comparative LCA of mono-Si and multi-Si PV systems in Malaysia was conducted with consideration of uncertainty analysis to increase the reliability of LCA results.

II. METHODOLGY

This study utilized LCA methodology under ISO 14040 [23], comprising of four stages, i.e. goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation as outlined below.

A. Goal and Scope

The goal of the study is to assess the energy and global warming impacts of two grid-connected PV systems with mono-Si and multi-Si PV module technologies using Cumulative Energy Demand (CED) and IPCC impact assessment methods. The systems were installed with flat-roof installation on the Green Energy Research Centre (GERC) building in UiTM Shah Alam with annual solar irradiation of 1,673.2 kWh/m^2/year. The system capacities are 9 kWp and 5.405 kWp for mono-Si and multi-Si, respectively. The functional unit had been set as 1 kWh of electricity generated from the PV system with system boundary encompassing raw material extraction, manufacturing, installation, operation & maintenance and transportation.

B. Life Cycle Inventory

The LCI models of the PV systems were developed based on compilation of data for the systems through foreground data collected at the site and supported with the background data from the Ecoinvent database [24, 25]. The PV system main components are the PV modules, mounting structures, inverter and Balance of System (BOS) components such as cabling, junction box, meters, Molded Cases Circuit Breaker (MCCB), and fuses. The LCIs of PV modules, mounting structure and inverter were adopted from Ecoinvent datasets while the LCI of the BOS components was developed based on data from site measurements, datasheets, schematic diagram and also inputs from an interview done with the system owner. The dataset for each component was modeled considering input flows such as material, energy consumption, direct emissions as well as output flows such as output product, emissions and produced waste. It was assumed that 2% of PV module replacement will be needed throughout 30 years of systems' lifetime. Besides, the operation of maintenance considered PV module cleaning with lifetime water consumption of 20 liter/m^2. The lifetime electricity generation of the systems was estimated considering the actual climatic condition at the site as well as the PV module degradation factor. During the LCI development, the data quality indicators for each input and output flow in each dataset were assigned based on the following five data quality indicators: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation.

C. Life Cycle Impact Assessment

The LCIA is the third phase of LCA where the LCI results are processed to generate the energy consumption and global warming impacts. In this study, Cumulative Energy Demand (CED) v1.11 method and Intergovernmental Panel on Climate Change (IPCC) 2021 were utilized to evaluate the energy consumption and global warming impacts respectively. Then, the LCIA results obtained are further interpreted into other related indicators.

D. Interpretation

Besides the primary energy consumption, i.e. CED, the EPBT and Energy Return On Investments (EROI) are the energy-related metrics determined. EPBT is the time it takes for the PV system to generate the same amount it took to generate the system, while EROI is the ratio of the total energy the PV system produces versus the energy used to get the system. On the other hand, regarding Global Warming (GW) metrics, the Global Warming Payback Time (GWPBT) and the Global Warming Impacts Mitigation Potential (GWIMP) were considered. GWPBT is the time it takes for the PV system's clean energy to offset the greenhouse gas emission produced in its lifecycle while GWIMP measures how much greenhouse gas emissions could potentially be reduced over its lifetime compared to its lifecycle emissions [26].

In addition, contribution, uncertainty and sensitivity analyses were performed to determine the hotspots of the impacts, the quality of the data used for reliability of the results, and effects of varying the key parameters of the system. The contribution analysis highlights the main contributors to the impacts considering all part of the PV system components and lifecycle phase, i.e. PV modules, mounting structure, inverter, BOS, and Operations and Maintenance (O&M). The uncertainty analysis utilized the Monte Carlo simulation in Simapro to determine the uncertainty indicators such as the coefficient of variation, the standard deviation, and the lower and upper limits of the impacts. In sensitivity analysis, three lifecycle input parameters, i.e. irradiation, degradation, and lifetime were varied and the effects were analyzed.

III. RESULTS AND DISCUSSION

This section presents the results of energy and GW-related metrics, contribution, uncertainty, and sensitivity analyses.

A. *Energy and GW-related Metrics of Mono-Si and Multi-Si PV Systems*

The results of energy and GW-related metrics of the PV systems are presented in Table I. It can be seen that multi-Si outperforms the mono-Si system in all evaluation metrics except for GWIMP. In comparison, the GW and CED for multi-Si system are 1.16 and 1.15 times lower than those of the mono-Si system, respectively. These results align with those of [13]. However, the variation in GW impacts observed in the reviewed studies highlights the influence of factors such as site-specific data, irradiation levels and data uncertainty on the LCA outcomes. Meanwhile, the multi-Si system is more effective at returning the energy due to its shorter EPBT and higher EROI than the mono-Si system. However, both systems offer positive values of EROI indicating that the energy generated from both systems over their lifetime exceeds the total consumed throughout their lifespan. Similar to EPBT, the multi-Si system has faster GWPBT than the mono-Si system with the difference being less than a year. In terms of GW impact avoidance, the mono-Si shows better GWIMP. However, the GWIMP is determined based on the cumulative impact avoidance where the mono-Si system provides higher GW avoidance due to its greater system capacity of 9 kWp compared to the 5.405 kWp of the multi-Si systems.

TABLE I. ENERGY AND GW-RELATED METRICS OF MONO-SI AND MULTI-SI PV SYSTEMS

	Mono-Si	Multi-Si
GW (g CO_2-eq/kwh)	54.7	47
CED (MJ/kWh)	0.858	0.744
EPBT (years)	7.1	6.2
EROI (dimensionless)	4.2	4.8
GWPBT (years)	2.2	1.8
GWIMP (tons CO_2 -eq)	257.5	158.9

B. *Contribution Analysis*

The contribution of system components for both PV systems on the CED and GW impacts are illustrated in Figure 1 and Figure 2, respectively. In terms of CED, the PV module is the main contributor with the 80.3% of the total CED in multi-Si system, followed by the mounting structure, inverter, BOS, O&M with 13.44%, 4.78%, 1.96%, and 0.02%, respectively. The mono-Si system follows the same trend, the PV module is the primary contributor with 83.22%, followed by the mounting structure, inverter, BOS, and O&M with 11.17%, 4.22%, 1.02%, and 0.02% respectively.

In terms of GW impact, the PV module is the main contributor with 77.3% of the total impact in the multi-Si system, followed by the mounting structure, inverter, BOS and O&M with 15.8%, 5.01%, 1.88%, and 0.027%, respectively. The mono-Si system shows the same trend with the multi-Si system. The PV module is the main contributor with 81.8% of the total GW impact, followed by the mounting structure, inverter, BOS and O&M with 12.9%, 4.35% 0.913%, and 0.022% respectively. While the contributions of mounting structure, inverter and BOS on the CED and GW impact are slightly different in mono-Si system compared to multi-Si system, the contribution of O&M is found to be similar in both systems.

Therefore, the PV module, mounting structure and inverter are the three top contributors for the CED and GW impact in these systems. The production of PV module involves energy-intensive processes during its manufacturing [27]. Meanwhile, the impact of O&M which involves PV module cleaning activity is found to be almost negligible in both systems which agree with several previous studies [10].

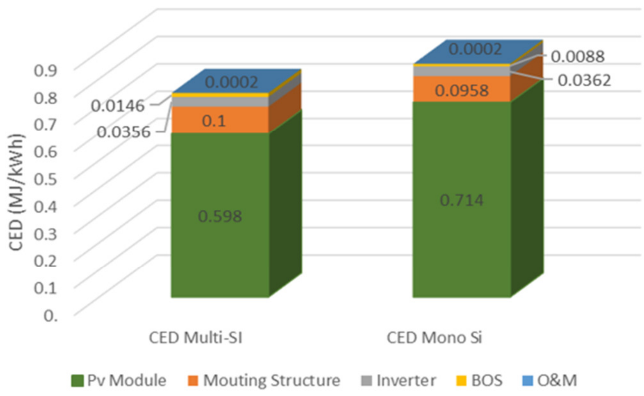

Fig. 1. CED contribution of PV systems.

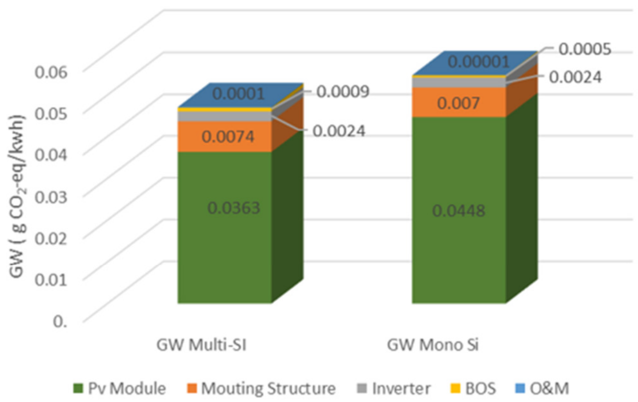

Fig. 2. GW contribution of PV systems.

C. Uncertainty Analysis

The results of uncertainty analysis on CED and GW impact are presented in error bars in Figure 3 and Figure 4, respectively. The error bar indicates the maximum and lower limits of the impact when taking into account the data uncertainty during the LCI modeling. The range of CED for the mono-Si system is from 0.55 to 1.38 MJ/kWh, while for the multi-Si system it is from 0.481 to 1.14 MJ/kWh. Furthermore, the standard deviation values for the mono-Si and the multi-Si systems are 0.219 and 0.174 MJ/kWh, respectively.

The uncertainty results for GW impacts exhibit similar trend to those of CED. The range of GW impacts for mono-Si system is from 36.4 to 84.4 g CO_2-eq/kWh, while for the multi-Si system it is from 32.9 to 69 g CO_2-eq/kWh. Furthermore, the standard deviation is 12.6 and 9.07 g CO_2-eq/kWh, respectively. This indicates that when accounting data uncertainty, the uncertainty range results demonstrate that the multi-Si system has overall lower CED and GW impact than the mono-Si system. Thus, presenting the uncertainty information alongside the LCA results is crucial to provide transparency and hence increase the reliability of the study.

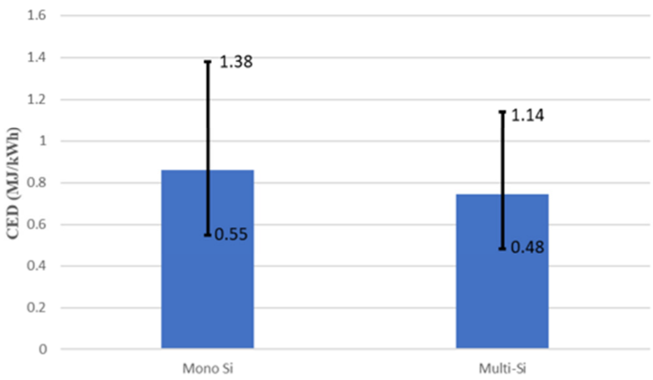

Fig. 3. Uncertainty range of CED.

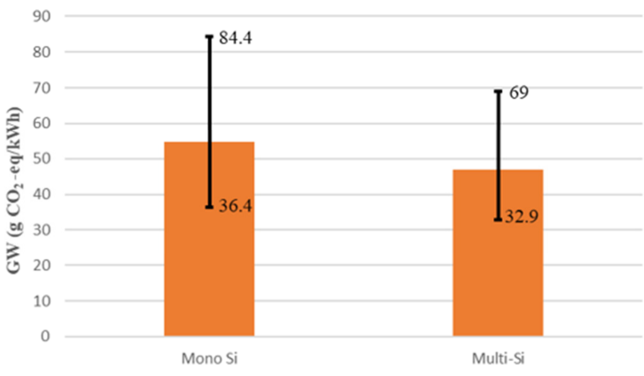

Fig. 4. Uncertainty range of GW impact.

D. Sensitivity Analysis

The results of sensitivity analyses of irradiation, system lifetime and degradation rate on energy and GW-related metrics are presented in this section.

Figures 5 and 6 show the results of energy and GW-related metrics for varying irradiation. It is observed that the EPBT of the system reduces for irradiation ranging from 1,500 to 1,900 kWh/m^2/year; from 6.9 to 5.5 years for the multi-Si system, and from 7.9 to 6.2 years for the mono-Si system. Meanwhile, it is observed that EROI increases with irradiation; from 4.31 to 5.46 for the multi-Si system and from 3.77 to 4.78 for the mono-Si system. On the other hand, it is observed that GWPBT decreases with irradiation increase from 2.05 to 1.62 years for the multi-Si system and from 2.41 to 1.90 years for the mono-Si system. However, GWIMP shows a different trend, since it increases with irradiation. The GWIMP range for multi-Si and mono-Si systems are 141.37 to 181.86 tons CO_2-eq and 228.78 to 295.11 tons CO_2-eq, respectively.

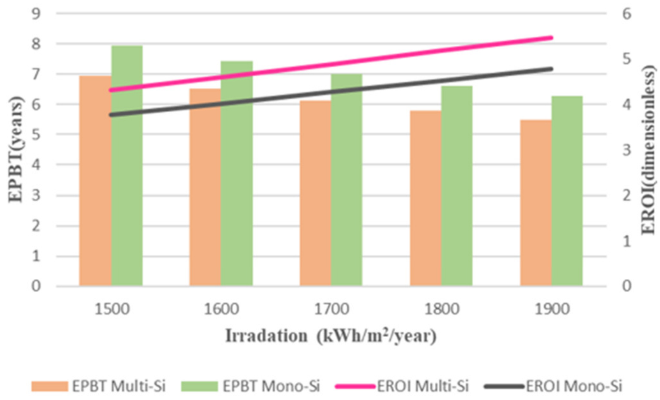

Fig. 5. Sensitivity of irradiation on energy-related metrics.

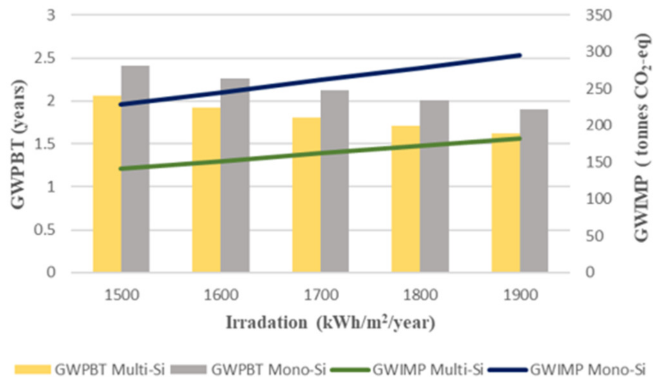

Fig. 6. Sensitivity of irradiation on GW-related metrics.

Figures 7 and 8 show the results of energy and GW-related metrics when varying system lifetime respectively. It is observed that the EPBT of the system slightly increases when extending the system lifetime from 20 until 40 years, from 6.03 to 6.44 years for the multi-Si system and from 6.89 to 7.35 years for the mono-Si system. Meanwhile, it is observed that EROI increases with the increase of system lifetime, from 3.31 to 6.20 for the multi-Si system and from 2.90 to 5.43 for the mono-Si system. Within the considered range, the EROI almost doubled. On the other hand, it is observed that GWPBT slightly increases with the increase of system lifetime, from 1.77 to

1.89 years for the multi-Si system and from 2.07 to 2.22 years for the mono-Si system. However, GWIMP increases significantly within the considered range. The GWIMP range values for multi-Si and mono-Si systems are 106.43 to 207.94 tons CO_2-eq and 171.29 to 338.33 tons CO_2-eq, respectively; with the GWIMP almost doubling its value.

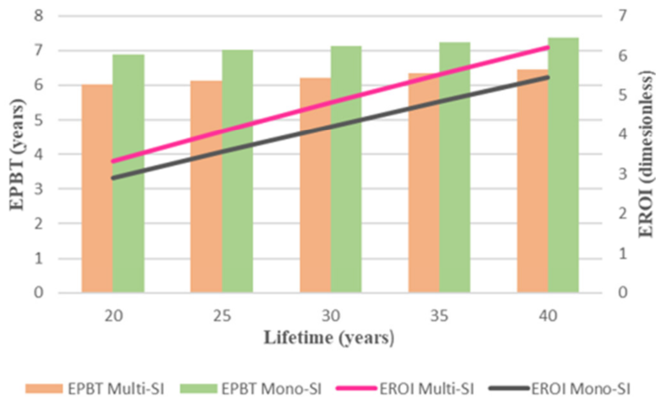

Fig. 7. Sensitivity of system lifetime on energy-related metrics.

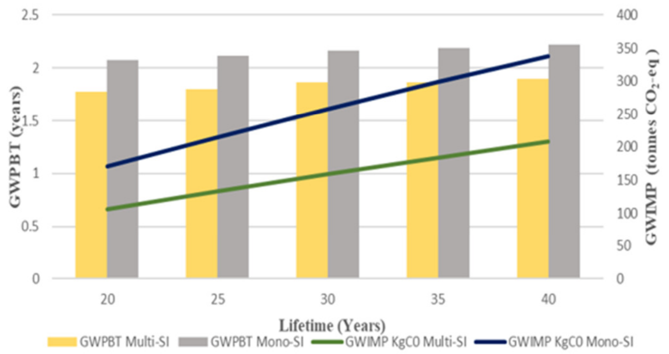

Fig. 8. Sensitivity of system lifetime on GW-related metrics.

The results of energy and GW-related metrics when different PV module degradation rates are considered are depicted in Figures 9 and 10. It is observed that higher PV module degradation rate leads to increased EPBT for degradation rate ranging from 0.4 to 1 %/year, from 5.97 to 6.49 years for the multi-Si system and from 6.85 to 7.46 years for the mono-Si system. Meanwhile, it is observed that EROI decreases with increasing degradation rate, from 5.02 to 4.61 and from 4.37 to 4.02 for the multi-Si system and mono-Si system, respectively. On the other hand, it observed that GWPBT slightly increases with the increase of degradation rates, from 1.76 to 1.92 years and from 2.07 to 2.26 years for the multi-Si system and the mono-Si system, respectively. Furthermore, GWIMP decreases significantly within the considered range, from 166.26 to 151.95 tons CO_2-eq and 268.35 to 244.98 tons CO_2-eq for multi-Si and mono-Si systems, respectively. The above analysis indicates that reducing the PV module degradation rate is beneficial for PV lifecycle performance.

Overall, the sensitivity analysis highlights that PV system installation at location with higher irradiation, extending system lifetime, and reducing PV module degradation rate could improve the overall lifecycle energy and GW-related metrics.

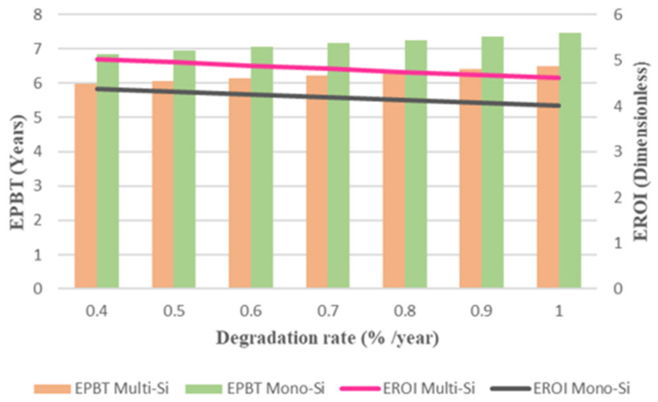

Fig. 9. Sensitivity of degradation rate on energy-related metrics.

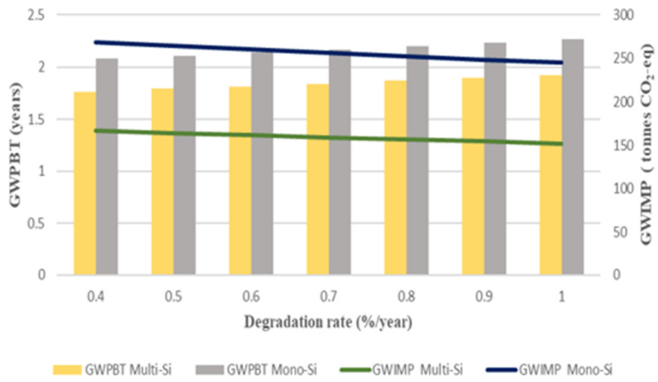

Fig. 10. Sensitivity of degradation rate on GW-related metrics.

IV. CONCLUSION

This study compares the life cycle energy and global warming impacts of 5.405 kWp multi-Si and 9 kWp mono-Si grid-connected PV systems using the Life Cycle Assessment (LCA) method. In overall, the multi-Si photovoltaic (PV) system demonstrates superiority in energy and environmental performance compared to the mono-Si PV system as the former offers better return on investment of energy, and shorter payback time of energy and GW impact. The findings also show that in both systems, the PV module, the mounting structure, and the inverter are the main contributors of the primary energy consumption and GW impacts. Meanwhile, the impact due to Operations and Maintenance (O&M) is found to be almost negligible in both systems. Furthermore, the sensitivity analyses show that greater irradiation, longer lifespan, and lower module degradation rate, all lead to reduced GW impact and primary energy consumption. These results provide PV stakeholders with useful direction for choosing and maximizing PV technologies.

The reliance on site-specific data in this study ensures that the results reflect local conditions including irradiation levels, climatic factors and operational parameters. Future work could benefit from incorporating scenario analysis such as technological advancement of PV modules with enhanced efficiency and reduced deterioration to investigate the impact of technological improvement to life cycle energy and environmental performance.

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