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Article

Sustainability Assessment of Residential Grid-Connected Monocrystalline Module Solar PV Systems in Three Major Cities in Indonesia: A Life Cycle Assessment Perspective

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Abstract: This work presents a life cycle assessment (LCA) of grid-connected photovoltaic (PV) systems for households in three major cities in Indonesia, i.e., Jakarta, Surabaya, and Medan. The study emphasizes environmental sustainability and energy performance of monocrystalline-type modules. Adopting the previous similar work that employed the IMPACT2002+ and Cumulative Energy Demand (CED) methodologies, the study evaluates multiple environmental effects, such as greenhouse gas (GHG) emissions, energy payback period time (PBT), and energy return on investment (ROI) for PV systems with capacities of 2 to 15 kWp. It was found that GHG emissions decrease as system capacity increases. The emissions decrease is about 70.89 g CO_2-eq/kWh for smaller systems to 65.06 g CO_2-eq/kWh for larger systems. The primary source of emissions is from the energy-intensive manufacturing processes of PV modules. The PBT values were found to range from 6.88 to 8.10 years. The ROI values varied between 2.98 and 4.01. Extending the system lifespan from 20 to 30 years results in a 31% decrease in GHG emissions. The regions with higher solar irradiation, such as Surabaya, exhibited superior environmental performance and energy efficiency. This study emphasizes the potential of PV systems in Indonesia to advance sustainability objectives. Besides, the necessity for improved module manufacturing processes and system longevity should be considered.

Keywords: lifecycle assessment; photovoltaic systems; monocrystalline silicon; greenhouse gas emissions

1. Introduction

The worldwide energy industry is experiencing a significant change as nations work to lower greenhouse gas (GHG) emissions and address the impacts of climate change. Renewable energy technologies, particularly solar photovoltaic (PV) systems, have become essential to this transition. Solar PV systems harness energy from the sun to generate electricity with minimal emissions during their operational phase, making them an attractive option for both urban and rural electrification. This shift is critical for countries like Indonesia, where the need to reduce reliance on fossil fuels is becoming more urgent amid increasing energy demands and environmental concerns (IRENA, 2021)

Despite their environmental benefits, PV systems are not without their challenges. The entire lifecycle environmental impacts of PV systems must be considered to assess their sustainability accurately. These impacts begin with raw material extraction and continue to manufacturing, transportation, installation, operation & maintenance, and end-life disposal. The production of PV modules, particularly those based on monocrystalline silicon technology, is energy-intensive and involves the use of hazardous chemicals, which can contribute to global warming, resource depletion, and other environmental issues (fraunhofer.de, 2024). As such, a comprehensive lifecycle assessment (LCA) is needed to evaluate the true environmental footprint of PV systems. In Indonesia, solar energy is recognized as a key solution to meeting the country's ambitious renewable energy targets. The Indonesian government aims to increase the share of renewable energy (RE) of the energy mix to 23% by 2025, driven in large part by the deployment of solar PV systems (Hamdi, 2019; Kennedy, 2018). With abundant solar resources across its vast archipelago, Indonesia has significant potential for solar energy development. Residential-scale on-grid PV systems, in particular, are gaining attention as a means to reduce household energy costs while contributing to the country's renewable energy goals.

However, there has been limited research on the lifecycle impacts of residential solar PV systems in Indonesia (Saliman et al., 2019; Sianipar et al., 2022). While previous studies have been conducted in other regions, such as Malaysia (Mohd Nordin et al., 2020), they often focus on operational benefits like reducing electricity bills and GHG emissions during use, without fully addressing the environmental costs embedded in the production, installation, and disposal phases. Understanding these impacts within the Indonesian context is essential for developing policies and strategies that promote the sustainable deployment of PV systems.

The sustainability of photovoltaic (PV) systems has been the subject of various research during the last two decades, particularly concerning their environmental impact, energy efficiency, and role in mitigating greenhouse gas (GHG) emissions (Aleid et al., 2024; Lamnatou et al., 2024; Singh et al., 2023). The idea of life cycle assessment (LCA) has been crucial in assessing the of photovoltaic (PV) systems impact on the environment, as it offers a holistic view of their impacts, from raw material extraction to manufacturing, installation, operation, and eventual disposal or recycling. This literature review discusses key findings from studies on the LCA of PV systems, the role of PV systems in reducing GHG emissions, and the energy return on investment (ROI) for residential-scale solar energy systems. These insights provide a foundation for analyzing the sustainability of residential PV systems in Indonesia.

The life cycle assessment (LCA) approach has been extensively utilized to evaluate the environmental effects of photovoltaic systems (IRENA, 2021). Research has concentrated on different kinds of photovoltaic (PV) technologies, such as monocrystalline, polycrystalline, thin-film, and, more recently, innovative technologies like perovskite solar cells (Cocco et al., 2023; Singh et al., 2023). The LCA process typically involves quantifying environmental impacts across multiple categories, including global warming potential (GWP), human health impacts, resource depletion, and cumulative energy demand (CED). These metrics provide a comprehensive understanding of how PV systems perform over their lifespan (PVPS Task, 2020)

In addition to the Cumulative Energy Demand (CED), the energy Payback Period Time (PBT) is a significant metric that indicates the period required for the energy expended throughout the lifecycle of a solar energy system to be offset by the electricity produced by the installation (Mohd Nordin et al., 2020). This metric is crucial for assessing the sustainability of solar energy systems, as it elucidates the duration important for the system to produce an equivalent amount of energy to that initially invested in its production, installation, and maintenance. A reduced PBT signifies a more efficient system, enhancing its viability as a renewable energy solution. Furthermore, comprehending the PBT is essential for assessing the environmental implications of solar installations. It enables stakeholders, including policymakers, investors, and consumers, to evaluate the return on energy investment, facilitating informed decision-making regarding the adoption of solar technologies. By examining the PBP in conjunction with other metrics, a holistic understanding of the overall performance and sustainability of solar systems can be attained. Additionally, advancements in solar technology, including enhanced photovoltaic materials and manufacturing processes, have the potential to decrease the PBT, thereby improving the overall efficiency of solar energy systems. As the industry continues to innovate and pursue greater energy efficiency, the monitoring of PBT will remain a vital component in ensuring that solar energy solutions make a positive contribution to combating climate change and facilitating the energy transition.

Research has shown that monocrystalline silicon PV modules, which are widely used in residential installations, exhibit higher efficiency compared to polycrystalline and thin-film technologies, but their manufacturing process is more energy-intensive (Mohd Nordin et al., 2020). The impact of monocrystalline solar modules to the environment primarily comes from the energy-intensive production of silicon wafers and the use of hazardous chemicals during manufacturing (fraunhofer.de, 2024). For instance, the energy required for the extraction and purification of silicon contributes significantly to the lifecycle GHG emissions of these systems, even though their operational phase is emission-free (Cocco et al., 2023). Studies using LCA have found that although PV systems substantially reduce GHG emissions during their operational phase, their overall sustainability is influenced by the energy mix of the manufacturing process and the energy required for installation and maintenance.

In Southeast Asia, LCA studies have been conducted primarily in countries like Malaysia and Thailand, where solar energy adoption is increasing. In Malaysia, a study (Mohd Nordin et al., 2020) assessed the lifecycle impacts of monocrystalline silicon PV systems and found that while these systems contribute to significant reductions in operational GHG emissions, the environmental costs of manufacturing cannot be overlooked. The IMPACT2002+ and Cumulative Energy Demand (CED) techniques were employed to measure environmental impacts across various stages of the PV system's life cycle, providing a nuanced view of trade-offs between environmental costs and benefits.

However, LCA studies specific to Indonesia are sparse despite the country’s increasing interest in solar PV. Given Indonesia's reliance on fossil-fuel-based electricity generation and its unique geographic and climatic conditions, it is essential to conduct localized LCA studies to provide accurate assessments of PV system performance in this region. This study will fill this gap by focusing on the Indonesian context, using LCA tools such as OpenLCA (openLCA.org, n.d.)and the Ecoinvent database (Ecoinvent.org, n.d.), which have been extensively validated in previous studies.

PV systems are widely recognized for their potential to reduce GHG emissions by displacing electricity generated from fossil fuels. Globally, the carbon footprint of PV electricity generation is significantly lower than that of coal, natural gas, or oil (IRENA, 2021). A meta-analysis of GHG emissions from PV systems indicates that the global warming potential (GWP) of PV systems varies between 20 and 50 grams of CO_2 equivalent for each kilowatt-hour (kWh) electricity produced, depending on the PV technology and geographic location (Gerbinet et al., 2014; Roy and Pearce, 2024). This is a fraction of the GWP for coal-fired power, which ranges from 820 to 1050 grams of CO_2 equivalent per kWh (Paraschiv and Paraschiv, 2020)

The GHG emissions reduction potential of PV systems is especially significant in regions like Indonesia, where coal remains the dominant source of electricity. As Indonesia transitions to a more sustainable energy system, residential PV installations have the potential to play a crucial role in decarbonizing the electricity grid. Studies conducted in Southeast Asia, including Malaysia and Thailand, have demonstrated that the widespread adoption of residential PV systems could lead to substantial reductions in national GHG emissions (Do et al., 2021; Handayani et al., 2022; Qiu et al., 2024). This underscores the importance of promoting residential PV adoption in Indonesia, not only to reduce household energy costs but also to contribute to the country's climate mitigation efforts.

The energy return on investment (ROI) is another important metric for evaluating the sustainability of PV systems. ROI is defined as the ratio of the energy produced by a system over its lifetime to the energy required to manufacture, install, and maintain it (Torrubia et al., 2024; Zhou and Carbajales-Dale, 2018). A high ROI indicates that a system generates significantly more energy than it consumes over its life cycle, making it more energy-efficient and sustainable in the long term. However, the ROI of PV systems can vary significantly based on geographic location. In Indonesia, where solar irradiance levels are high, residential PV systems are expected to have relatively high ROI values. This makes them an attractive option for long-term energy savings. Nevertheless, understanding the specific ROI of PV systems in the Indonesian context is critical, as factors such as local manufacturing processes, installation practices, and grid connectivity can influence the overall energy performance of these systems.

The literature highlights the importance of conducting lifecycle assessments to accurately evaluate the environmental and energy performance of PV systems (Corcelli et al., 2018; Singh et al., 2023). Monocrystalline silicon PV modules, while efficient, have notable environmental impacts during the manufacturing phase. Studies in Southeast Asia have shown the potential for PV systems to reduce GHG emissions and improve energy efficiency (Mohd Nordin et al., 2020), but localized research is needed to assess their true sustainability in Indonesia. This study aims to address this gap by providing a comprehensive LCA of residential PV systems in Indonesia, with a focus on understanding their environmental impacts and energy return on investment.

Indonesia, as the largest economy and the most populous nation in Southeast Asia, faces a complex energy landscape. The country is heavily reliant on fossil fuels, particularly coal, which accounted for 86% of its electricity generation in 2024 (indonesiabusinesspost.com, n.d.). This dependence on coal not only exacerbates Indonesia's carbon emissions but also creates economic vulnerabilities due to fluctuating global fuel prices. In response, the Indonesian government has set out ambitious renewable energy targets to diversify its energy mix and reduce GHG emissions. Solar energy is seen as a key component of this strategy, with residential PV systems offering a decentralized solution to meeting energy demand in both urban and rural areas (IESR, 2018).

The deployment of residential-scale PV systems in Indonesia is still in its early stages, but interest is growing rapidly. Monocrystalline silicon modules are widely favored due to their high efficiency and long-term reliability (Mohd Nordin et al., 2020). However, like all energy technologies, the environmental performance of PV systems depends not only on their efficiency but also on the broader context of their life cycle. Lifecycle assessment (LCA) is a recognized method that enables a thorough analysis of the environmental effects linked to every phase of a product's life cycle, starting from the extraction of raw materials to its disposal at the end of its life. This approach is essential for quantifying the trade-offs between the environmental costs and long-term benefits of solar PV systems.

This study aims to address the knowledge gap by conducting a detailed LCA of residential-scale on-grid PV systems in Indonesia, with a focus on monocrystalline silicon modules. With OpenLCA 1.8 online software, the Ecoinvent 3.5 dataset, and the IMPACT2002+ and Cumulative Energy Demand (CED) assessment methods, this research will evaluate key environmental indicators, including global warming potential, human health impacts, and resource depletion. Additionally, the study will assess the return on investment (ROI) to understand the energy efficiency of these systems over their lifetime.

The results will enhance the overall knowledge of the environmental effectiveness of photovoltaic systems in Indonesia. By highlighting the potential for GHG emission reductions and energy savings, this research aims to inform policymakers, industry stakeholders, and consumers about the true sustainability of residential solar PV systems. Moreover, the study will offer insights into optimizing PV technology deployment in Indonesia, helping to achieve the country's renewable energy targets while minimizing negative environmental impacts. The worldwide energy industry is experiencing a significant change as nations work to lower greenhouse gas (GHG) emissions and address the impacts of climate change. Renewable energy technologies, particularly solar photovoltaic (PV) systems, have become essential to this transition. Solar PV systems harness energy from the sun to generate electricity with minimal emissions during their operational phase, making them an attractive option for both urban and rural electrification. This shift is critical for countries like Indonesia, where the need to reduce reliance on fossil fuels is becoming more urgent amid increasing energy demands and environmental concerns (IRENA, 2021).

2. Methods

This study employs a lifecycle assessment (LCA) approach to evaluate the sustainability of household scale of grid-connected PV systems in Indonesia, with a focus on monocrystalline silicon PV modules. The LCA approach is founded on internationally recognized standards such as ISO 14044 and ISO 14040 (Finkbeiner et al., 2006), which provides a system for evaluating the environmental effects throughout the entire life cycle of a product. The assessment follows four key phases LCA, including (i) Goal & Definition's Scipe; (ii) LCI (Life Cycle Inventory); (iii) LCIA (life cycle impact assessment), and; (iv) analyzing the findings or interpretation. The work adopts previous studies (Gandhi et al., 2022; Mohd Nordin et al., 2020; Shafie et al., 2023) with areas and climate conditions similar to those of the sites studied.

2.1. Goal and Definition Scope

The objective of the research is to quantify the emissions of greenhouse gas (GHG) and the main consumption of energy associated with household on-grid PV systems in Indonesia utilizing monocrystalline silicon photovoltaic modules. The study examined the Payback Time (PBT) of energy and the Return on Investment (ROI) of energy with anticipated system lifespans of 30, 25, and 20 years. Additionally, the influence of various installation locations on these metrics was evaluated. The operational unit used in this analysis was defined as 1 kWh or kilowatt-hour of electricity produced. A range of system capacities, specifically from 2 to 15 kilowatt-peak (kWp), was utilized to represent the typical capacities found in residential on-grid PV systems in Indonesia (Tarigan et al., 2015). The system boundaries encompassed the production of PV-cell modules and the components for BOS (balance of system), the system installation on the site location, and operation and maintenance activities (O&M), thereby encompassing the cradle-to-gate life cycle phase. In this study, the end-of-life phase of the PV system was excluded from the LCA due to the lack of sufficient and reliable data (Mohd Nordin et al., 2020). However, we have addressed this aspect from previous research (Daniela-Abigail et al., 2024). These are discussed in the results and discussion section.

2.2. Lifecycle Inventory (LCI)

Life Cycle Inventory (LCI) data were sourced from secondary databases, literature, and references. The manufacturing process of PV modules for monocrystalline silicon type encompasses some key stages, including (i) the refining and grading of silicon, (ii) the Czochralski process for crystallization, (iii) wafer cutting, (iv) PV-cell creation, and (v) assembly of the module. As by the reference adopted (Mohd Nordin et al., 2020) he Lifecycle Inventory for modules was derived mainly from the database of Ecoinvent 3.5. Some updated information was also obtained from the International Energy Agency Photovoltaic Power Systems (IEA PVPS) technical report (PVPS Task, 2020), especially for data of energy needed, material necessities, and emissions associated with each main process in the production of modules. The refining of silicon to obtain solar PV silicon cells is established using the 'modified Siemens' method. Furthermore, the thickness of the wafer is established at 180 micrometers, with an efficiency module of 20%. It was assumed that the PV module is manufactured in Germany, and therefore, the electricity mix and manufacturing supply chain were counted correspondingly.

Data for solar inverters were attained from updated data of LCI inverters as referenced in (L. Tschümperlin et al., 2016) is to supersede the existing Ecoinvent's inverters database. Additionally, it was assumed that the mass of the inverter per unit of power output decreases in a non-linear relationship as the nominal power of the inverter increases. This study, which focuses on residential-scale grid-connected PV systems, generated three distinct datasets for inverters rated respectively at 10 kW, 5 kW, and 2.5 kW. The inventory accounted for materials used in the casing, cables, plugs, inductors, integrated circuits, and components within the integrated circuit. The common type of module array installation used for household PV systems in Indonesia is a retrofitted construction designed for tilted roofs, similar to those in neighboring countries, as reported in (Anang et al., 2021; Mohd Nordin et al., 2020). The mounting structure primarily consists of aluminum and steel. The LCI was also applied to packaging materials, especially polystyrene and corrugated board.

The components for the balance of system (BOS) were accounted for as installation for the electricity process network, which covers cabling systems between PV and inverter, inverter and grid, lightning protection, and fuse devices. However, inverters and installation structures were not included in the BOS system. The modeling of mounting constructions and electrical installations was from extrapolations of the dataset of Ecoinvent 3.5 (Ecoinvent.org, n.d.). The PV system installation or array was modeled separately, with a capacity ranging from 4.5 to 10 kWp. These size of capacities are common for household or residential PV users in Indonesia. After the lifetime of the system, it is projected that certain components will require either maintenance or even restoration/replacement. Literature indicates that the annual degradation rate of solar modules typically ranges from 0.5% to 1.9% (Ishii et al., 2018; Rajput et al., 2024). Therefore, inventory at a rate of 30% is considered for the restoration/replacement of the bad PV modules throughout the lifetime of the system. This number also considered losses incurred during transportation and installation. For the inverter, a single replacement during the system's lifetime was anticipated, i.e., 15 years. This aligns with specifications provided by many manufacturers (igrowattinverter.com, 2024; solarquotes.com.au, 2024) and is supported by findings from previous research (Alavi et al., 2024). Throughout the operation, it is presumed that modules for PV system surfaces were cleaned annually by water to mitigate the accumulation of dirt and dust. In the inventory, 20 liters of water is used for cleaning one square meter of module array (Mohd Nordin et al., 2020).

2.3. Case Study

This work examines the lifecycle assessment (LCA) of household scale of PV systems with capacities spanning from 4.5 to 10 kilowatts peak (kWp), utilizing Monocristallyne cells modules installed on rooftops. Three case studies were developed to analyze the impact of various parameters, i.e., (i) the capacity of the PV system, (ii) the PV system lifetime, and (iii) the site irradiation. The specifications detailed for the case studies are shown in Table 1. A performance ratio (PR) of 0.75 was assumed for all rooftop installations in accordance with the guidelines established by the IEA PVPS (PVPS Task, 2020).

The first case study focuses on how a larger capacity of a PV system influences the impact to the environment and the consumption of energy. The site of installation is Surabaya, Indonesia, with solar energy/irradiation of 1,982.2 kWh/m²/yr. Surabaya is located in East Java at coordinates −7.25°S latitude and 112.74°E longitude. A system lifespan of 20 years was selected to reflect typical expectations for PV systems in Indonesia, although these systems can often exceed this lifespan based on the durability of their components. For example, while PV modules typically come with a power output warranty of 25 years, the mounting construction and wiring/cabling can last around 30 years. Inverters are generally expected to function for about 15 years; on the other hand, the LCI for inverters accounts for a single replacement during the entire lifespan of the system, effectively extending its entire expected lifespan to 30 years. Therefore, in the second case study, the system of PV was counted to find out the effects of the system with 20, 25, and 30 years of lifetime on the impact to the environment and the consumption of energy.

Table 1. Description of the Photovoltaic (PV) System in the case study.

Description	**Case study-1**	**Case study-2**	**Case study-3**
Photovoltaic technology	Monocrystalline Si	Monocrystalline Si	Monocrystalline Si
Efficiency	20%	20%	20%
Power capacity (kWp)	4.5–10	4.5–10	4.5–10
Location	Surabaya	Surabaya	Surabaya, Jakarta, and
Performance ratio	0.75	0.75	0.75
Lifetime	20 year	20, 25 and 30 year	20, 25 and 30 year
Mounting type	Rooftop	Rooftop	Rooftop
Annual solar irradiation	1,982.2 kWh/m²/yr	1,982.2 kWh/m²/yr	1,982.2, 1,806.8, & 1,724.1 kWh/m²/yr

The third case study investigates the impact of solar irradiation variation. Three major cities in Indonesia—Surabaya, Jakarta, and Medan—were selected for analysis, each exhibiting distinct annual solar irradiation profiles. Jakarta, the most populous city in Indonesia, is situated at −6.22°S and 106.85°E, receiving a solar irradiation of 1,806.8 kWh/m²/year. Medan, located in the northern part of Indonesia, has coordinates of −3.59°N and 98.66°E, with solar irradiation of 1,724.1 kWh/m²/yearr. For Surabaya and Jakarta cases, the irradiation values correspond to PV arrays facing north, with a tilt angle of 15°, while for Medan, they correspond to arrays facing south. This case study explores the impact of different levels of solar irradiation and varying system lifespans.

2.4. Lifecycle Impact Assessment (LCIA)

To evaluate the environmental effects linked to photovoltaic (PV) systems, this research adopted the previous work (Gandhi et al., 2022; Mohd Nordin et al., 2020), which used the IMPACT2002+ lifecycle impact assessment (LCIA) methodology, encompassing 15 mid-point impact categories. These categories cover a wide range of environmental concerns, such as water acidification, toxicity in aquatic environments, both cancer-causing and non-cancer-causing impacts, potential for global warming, exposure to ionizing radiation, land use, extraction of mineral resources, consumption of non-renewable energy, depletion of the ozone layer, respiratory issues caused by inorganic and organic substances, land acidification, nutrient enrichment, and toxicity in terrestrial ecosystems. Notwithstanding the extensive range of these categories, this study primarily concentrated on the potential of global warming, specifically focusing on GHG emissions.

The global warming potential (GWP) was quantified in grams of CO_2-equivalent (g CO_2-eq), which reflects the cumulative contribution of various greenhouse gases to global warming. To facilitate an accurate evaluation, other greenhouse gases, including methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs), were converted into their respective CO_2-equivalent values. This conversion utilized characterization factors based on data from the IPCC (Intergovernmental Panel on Climate Change). It considers a century-long perspective to reflect the differing impacts of various gases over time (S. Humbert et al., 2014). In addition to the assessment of GHG emissions, the Cumulative Energy Demand (CED) method was used to find the primary energy used associated with the life cycle of the PV system. The CED method quantifies the total energy input required throughout all phases of the product's life cycle, from raw material extraction to end-of-life disposal, encompassing both renewable and non-renewable energy sources.

Both the IMPACT2002+ and CED methodologies adhered to the classification and characterization phases as stipulated by ISO standards (ISO 14040/14044) (Finkbeiner et al., 2006). (Mohd Nordin et al., 2020) for life cycle assessment. The classification phase involves the categorization of environmental flows into designated impact categories, while the characterization phase quantifies the contribution of each flow to these categories using appropriate factors. However, this study did not incorporate the normalization and weighting phases of the LCIA, as these components are optional under ISO standards.

The ROI is calculated to determine the ratio of the total energy output from the PV system to the total energy input required throughout its life cycle. The ROI will be expressed as a ratio where a higher ratio indicates better energy performance and sustainability. The ROI calculation will be based on the total energy output of the system over its lifetime (in kWh) and the total cumulative energy demand (CED) over the same period. The ROI will provide a measure of the system's overall energy efficiency and will be compared with values from other regions to assess the performance of Indonesian PV systems relative to global benchmarks.

3. Results and Discussion

The life cycle assessment (LCA) results of the residential scale on-grid PV system in Indonesia are presented in this section, followed by a discussion of the findings about environmental impact categories, return on investment (ROI), and comparisons with international benchmarks. As mentioned, the results of this study are adopted from previously reported work (Gandhi et al., 2022; Mohd Nordin et al., 2020) which data were analyzed using the IMPACT2002+ and Cumulative Energy Demand (CED) methodologies. Whenever possible, the values were calculated and predicted from the adopted references. The discussion is focused on the system’s environmental performance and energy efficiency over its 20 – 30-year life span.

3.1. Effect of Different PV System Capacities

An analysis of greenhouse gas (GHG) emissions, measured per kilowatt-hour (kWh) of energy generated, reveals a significant reduction in emissions correlating with the increased capacity of photovoltaic (PV) systems. This research, conducted on an installation in Surabaya with an anticipated operational lifespan of 20 years, estimated GHG emissions at 70.89 g CO_2-eq/kWh for systems with capacities between 2 and 5 kWp, 68.01 g CO_2-eq/kWh for systems ranging from 5 to 10 kWp, and 65.06 g CO_2-eq/kWh for capacities from 10 to 15 kWp.

The distribution of GHG emissions, as illustrated in Figure 1, shows that PV modules are responsible for the majority of total emissions, contributing over fifty percent. In contrast, emissions associated with the installation and maintenance of PV systems are relatively minor, particularly when compared to those from the PV modules and other balance-of-system (BOS) components. The predominant contribution of PV modules to overall emissions is attributed to the energy-intensive nature of their production processes. Key manufacturing steps, such as the purification of silicon and the crystallization through the Czochralski process, necessitate high temperatures and substantial electricity consumption, resulting in significant emissions.

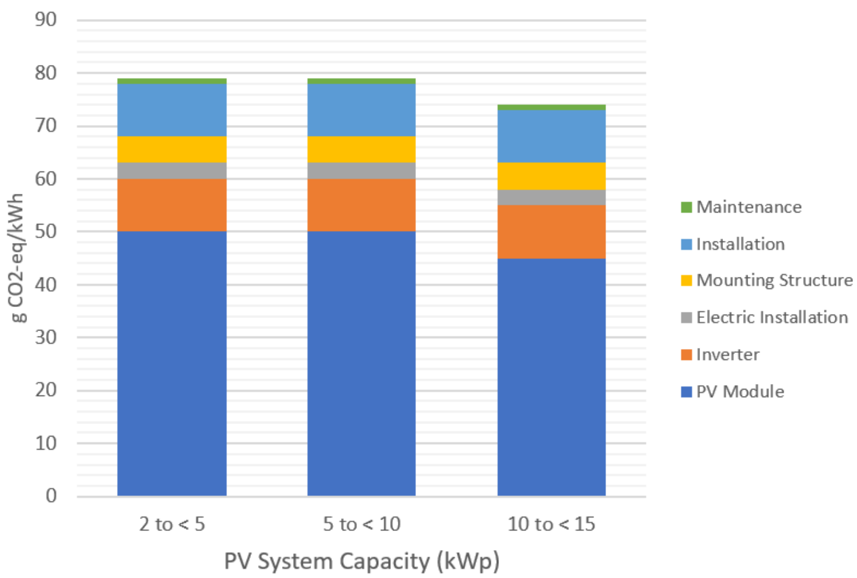

Figure 1. Distribution of GHG emission rates for on-grid PV system installed in Surabaya with a 20-year lifespan.

As the PV systems capacity increases, the GHG emissions per unit of electricity produced decrease, highlighting the benefits of environmental expansion of photovoltaic installations. Nevertheless, it is imperative to address the carbon footprint associated with module manufacturing to further mitigate the lifecycle emissions of solar energy systems. Future initiatives aimed at enhancing manufacturing efficiency and increasing the application of renewable energy resources in production processes could further diminish the GHG emissions linked to PV modules.

The analysis of GHG emissions rates indicated that the majority of unit processes exhibited comparable contributions across various capacities of photovoltaic (PV) systems, with the notable exception of the inverter. The influence of the inverter diminished as the system capacity increased, a phenomenon attributed to the correlation of nonlinearity between the mass of the inverter and its rated power. This relationship necessitates the application of distinct life cycle inventories (LCIs) when modeling inverters for different sizes of PV systems. Consequently, PV systems with greater capacities demonstrated reduced GHG emissions rates. Nevertheless, the proportion of total emissions attributed to the inverter in this study was found to be higher than that reported in prior research.

This variation can be explained by the utilization of a more contemporary inverter LCI, which more accurately represents current inverter technology. While modern inverters are typically lighter than their older counterparts documented in databases such as Ecoinvent, they nonetheless contribute to a greater environmental impact across multiple categories, including GHG emissions. A significant factor contributing to this increased impact is the substantial environmental burden associated with the printed circuit board assembly in newer inverters. In this investigation, the newer inverter was responsible for 59% of the total environmental impact, in contrast to older models, which accounted for only 16%. This discrepancy is primarily attributable to differences in manufacturing processes and the complexity of components.

As inverter technology continues to advance, it will be crucial to mitigate the environmental impact of components such as printed circuit board assemblies to decrease the overall carbon footprint of PV systems. The underscores the necessity of regularly updating LCIs to incorporate technological advancements, which can profoundly influence the lifecycle environmental performance of renewable energy systems.

The total Cumulative Energy Demand (CED) encompasses the aggregate of both renewable and non-renewable primary energy derived from natural sources. The CED values are presented per square meter of module area. The analysis indicates a slight decrease in CED as system capacity increases. Specifically, the CED values were recorded at 5,732.55 MJ/m² for systems with capacities ranging from 2 to 5 kWp, 5,414.40 MJ/m² for capacities between 5 to 10 kWp, and 5,253.06 MJ/m² for capacities from 10 to 15 kWp. This decline is primarily attributed to the utilization of distinct Life Cycle Inventories (LCIs) associated with inverters of varying rated power. Inverters with higher-rated power exhibit lower primary energy consumption, thereby contributing to the overall reduction in CED.

For systems installed in Surabaya, with a projected annual specific production of 1,525.6 kWh/kWp, the energy Payback Time (PBT) was found to range from 6.88 to 8.10 years. This finding suggests that the energy performance of the system is viable, as the Feed-in Tariff (FiT) period of 20 years significantly exceeds the estimated PBT, thereby ensuring a favorable long-term energy return.

Another significant parameter is the energy Return on Investment (ROI), which quantifies the ratio of energy gained to the energy expended in its production. For an energy system to be deemed advantageous for society, the ROI must surpass the value of 1. In this investigation, the ROI was determined to range from 2.98 to 4.01, signifying that the system generates more energy than is consumed during its production and installation, thus reinforcing its viability for sustainable energy generation.

3.2. Impact of Varying Lifespans of PV Systems

The following section examines the implications of prolonging the operational lifespan of photovoltaic (PV) systems from 20 years to 25 and 30 years on emissions of GHG and other critical metrics. The findings, shown in Figure 2, show a notable reduction in GHG emissions rates corresponding to an increase in the system's operational duration. Specifically, extending the lifespan to 25 years results in a decrease of approximately 16.5% in GHG emissions compared to a 20-year lifespan, while a 30-year lifespan yields a reduction of around 31%. This evidence underscores the significant environmental advantages associated with lengthening the operational duration of PV systems.

Furthermore, for PV installations in Surabaya, the GHG emissions rate was observed to vary between 38.38 and 75.01 g CO_2-eq/kWh, contingent upon the assumption of a 30-year versus a 20-year system lifetime, respectively. The extended operational period facilitates increased electricity generation throughout the system's lifespan, thereby diminishing the emissions per kilowatt-hour produced.

Notably, while the Payback Time (PBT) remained unchanged with the extension of the system's lifespan, the Return on Investment (ROI) exhibited a substantial enhancement. As illustrated in Table 2, the ROI escalated from 2.79 for a 20-year lifespan to 4.01 for a 30-year lifespan. This improvement signifies a greater overall energy efficiency and return associated with prolonged operation of PV systems.

It can be concluded that extending the operational lifespan of PV systems not only improves environmental performance by mitigating the carbon footprint but also enhances energy efficiency, rendering it a more sustainable and economically viable option in the long term. These findings emphasize the necessity of designing PV systems with an emphasis on durability and longevity to optimize their beneficial effects on both environmental sustainability and energy returns.

Table 2. Indicators of energy for PV system installation in Surabaya.

PV system Capacity (kWp)	**CED (MJ/m²)**	**PBT (Year)**	**ROI**		
			20 yr	**25 yr**	**30 yr**
2 to <5	5,732.55	8.10	2.98	3.31	3.76
5 to<10	5,414.40	7.82	3.09	3.45	3.89
10 to <15	5,253.06	6.88	3.20	3.52	4.01

For the end-of-life phase, the previous research (Daniela-Abigail et al., 2024)indicates that recycling processes can significantly reduce environmental impacts in various areas, reducing mineral resource scarcity by up to 89%. The cell processing phase is the most environmentally damaging stage, responsible for 37% of the overall impact, mainly due to silver and increased electricity consumption. A sensitivity analysis showed that different performance indicators reacted differently to uncertainties in the design variables, emphasizing the need for careful evaluation, especially regarding ecosystem impacts, when trying to minimize environmental effects throughout the life cycle of silicon solar panels.

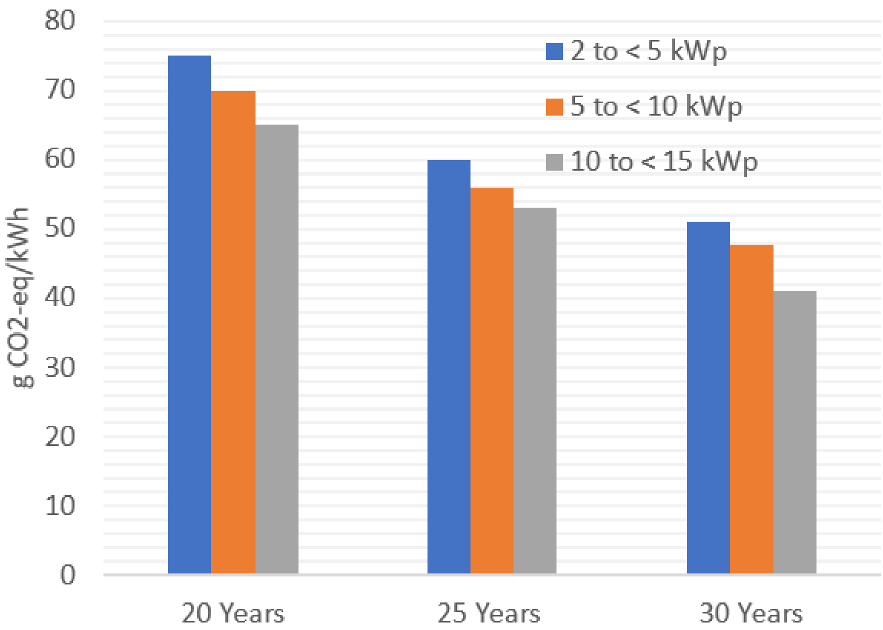

Figure 2. The PV system rate of GHG emissions in Surabaya with a variation of a lifetime.

3.3. Impact of Different Levels of Solar Irradiation

The preceding sections have concentrated on the installation of a photovoltaic (PV) system in Surabaya, which experiences an average solar irradiation of 1,982.2 kWh/m² annually. In this section, however, an analysis is conducted on the GHG emissions rate, energy Payback Time (PBT), and energy Return on Investment (ROI) across various geographical locations characterized by differing levels of annual solar irradiation. Table 3 provides a summary of the average outcomes for PV systems ranging from 2 to 15 kWp, mounted in three distinct sites within the country, each exhibiting unique solar radiation profiles and by operational lifetimes of 20, 25, and 30 years.

The analysis indicates that both the rate of GHG emissions and PBT exhibit a gradual decline as solar irradiation levels increase. This trend can be attributed to the fact that elevated solar irradiation facilitates greater electricity generation, which in turn diminishes the environmental impact per unit of energy produced and shortens the duration required to recuperate the energy expended throughout the system's lifecycle. Conversely, the ROI demonstrates improvement with higher solar irradiation levels, as increased energy production over the system's lifespan enhances the overall energy return.

Among the locations evaluated, Surabaya yielded the most advantageous results concerning environmental and energy performance. When considering a system period of 30 years, the GHG emissions rate in Surabaya was recorded at a minimal 47 g CO_2-eq/kWh, while the PBT was reduced to 7.65 years. These findings highlight the significance of optimizing PV system installations in accordance with regional solar potential, as areas with elevated solar irradiation provide superior environmental and energy returns, thereby rendering them more efficient and sustainable in the long term.

Table 3. A comparative analysis of diverse solar irradiation levels to varying system lifetimes for average system capacities ranging from 2 to 15 kWp.

Indicator	**Unit**	**Surabaya**			**Jakarta**			**Medan**		
		20 year	25 year	30 year	20 year	25 year	30 year	20 year	25 year	30 year
Solar irradiation	$kWh/m^2/yr$	1,982.2	1,982.2	1,982.2	1,806.8	1,806.8	1,806.8	1,724.1	1,724.1	1,724.1
GHG emissions	g CO_2-eq/kWh	70	56	47	76	61	51	80	64	54
PBT	year	7.65	7.65	7.65	7.92	7.92	7.92	8.00	8.00	8.00
ROI	dimensionless	3.09	3.42	3.89	2.79	3.25	3.75	2.52	3.10	3.43

3.4. Limitations and Uncertainties

This research presents a comprehensive life cycle assessment (LCA) of residential grid-connected monocrystalline photovoltaic (PV) systems in three main Indonesian cities: Jakarta, Surabaya, and Medan. However, it is important to consider the limits and uncertainties that may affect the analysis. These include the site electricity energy supply (fossil or renewable), development of PV technologies, and limited available data for analysis.

The regional electricity mix significantly influences the environmental impact of PV systems. In this study, however, the three main cities observed, Jakarta and Surabaya, are supplied by the National Grid (Perusahaan Listrik Negara, PLN) with similar network characteristics of the power generations. Medan, on the other hand, has a separate network. All three regions rely on coal-fired power plants, whereas other areas of Indonesia may integrate with renewable energy sources. Regional variability may present uncertainty in estimating the greenhouse gas (GHG) emission reductions and other environmental benefits of PV systems. This analysis used averaged grid emission parameters for each city; however, integrating more detailed, region-specific data may improve comprehension of the variation in environmental benefits.

Over the last ten years, the efficiencies of photovoltaic modules have significantly improved. The recent technologies such as bifacial modules, tandem cells, and inverters development will dominate PV system in the new future. These developments would affect the environmental performance of photovoltaic systems. The assumptions in this study are based on existing technologies and available data. Future research should include dynamic life cycle assessments to address possible advancements in photovoltaic technology and their effects.

The validity and reliability of the analyses results are highly depend on the data accuracy. The limitation availabel of PV system data, particularly for Indonesia, is one of limitation of this LCA study. In particular, the end-of-life phase of PV systems was excluded. This may effect the environmental impacts associated with waste generation and recycling processes of PV modules. Further work should be done in collaborations of local stakeholders and policymakers to provide appropriate data for these lifecycle phases.

The study was carried out with many assumptions based on literature and manufacturer specifications. However, in a real-world situation, nonconformities from the reported results may occur. Further studies ought to conduct sensitivity analyses to assess the influence of altering key factors on the results. Another limitation was the scope of the study. Tis study focused on monocrystalline PV systems installed in urban residential. On the other hand, there are various of PV cell technologies such as polycrystalline, thin-film technologies, etc. A different configurations, such as on-grid and stand-alone, also may result in different environmental impacts. Additionally, the findings may not fully represent conditions in other parts of Indonesia with different climatic, economic, or infrastructural situations.

Despite the limitations and uncertainty, this study provides insights to guide renewable energy strategies, particularly in adopting and promoting residential photovoltaic (PV) systems in Indonesia. The environmental benefits of photovoltaic (PV) systems highlight the necessity for specific policies to promote PV implementation. The regulatory frameworks should consider regional differences in solar potential by emphasizing investments and installations in regions with greater solar resource availability. This approach would optimize the environmental and energy advantages. This study aligns with Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR 2050) and the National Energy Policy (RUEN) targets. Residential PV system implementation is a fundamental element of the national renewable energy strategy. Indonesia can advance its commitment to enhancing the proportion of renewables in the national energy mix, mitigating greenhouse gas emissions, and attaining long-term sustainability objectives.

5. Conclusions

This study provided a life cycle assessment (LCA) of residential on-grid photovoltaic (PV) systems in Indonesia. It focuses on the PV system environmental impacts and energy performance metrics, including energy Payback Time (PBT) and Return on Investment (ROI). The findings highlight the substantial environmental and energy efficiency benefits of PV systems, particularly in the Indonesian context. A key observation is the inverse relationship between PV system capacity and greenhouse gas (GHG) emissions, with larger systems (15 kWp) producing lower emissions per kilowatt-hour (65.06 g CO_2-eq/kWh) compared to smaller systems (2 kWp) at 70.89 g CO_2-eq/kWh. Manufacturing processes, especially silicon purification and crystallization, account for the majority of emissions, emphasizing the need for advancements in module production technologies. Additionally, Cumulative Energy Demand (CED) decreases with increasing system capacity, indicating improved energy efficiency. The favorable PBT (6.88–8.10 years) and ROI values (2.98–4.01) further validate the feasibility of PV systems as a sustainable energy solution.

Extending the operational lifespan of PV systems from 20 to 30 years was shown to reduce GHG emissions by up to 31% while significantly improving ROI. Regions with higher solar irradiation, such as Surabaya, demonstrated superior energy and environmental performance, emphasizing the importance of location in optimizing PV system benefits. The study underlines the potential of residential PV systems to support Indonesia's renewable energy goals under the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR 2050) and National Energy Policy (RUEN). Policymakers are encouraged to promote PV adoption through targeted financial incentives, improved regulatory frameworks, and region-specific strategies. Additionally, enhancing manufacturing efficiency, reducing carbon footprints, and maximizing system longevity is critical to optimizing the long-term benefits of PV systems for Indonesia's sustainable energy future.

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