Available online at: https://journals.researchsynergypress.com/index.php/lomr
Logistic and Operation Management Research (LOMR)
e-ISSN 2830-2680/p-ISSN 2830-3334
Volume 1 Number 1 (2022): 77-88

Life Cycle Greenhouse Gas Emission Assessment of Photovoltaic System in Indonesia

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Abstract

Climate crisis is arguably the biggest challenge that the world is currently facing. Extreme weather events are becoming more frequent while the continuous rise in sea level is putting billions of lives will be at risk. Solving the climate crisis requires global carbon emission to peak by 2025, which means that carbon-intensive fossil fuels must be replaced by low-carbon renewable sources in fulfilling our energy needs. Solar energy, due to its abundance, rapidly decreasing cost, and low carbon emission, is one of the most promising energy sources. Many studies have calculated and compared the life cycle greenhouse gas (GHG) emissions of solar photovoltaic (PV) systems with conventional fuel generation. Nevertheless, the life cycle GHG emission values are affected by many location- and technology-dependent factors. This work provides an up-to-date and realistic assessment of the life cycle GHG emission for PV systems in Indonesia through thorough literature review and harmonization according to Indonesian parameters. The study shows that PV GHG emission of 37.3-64.3 gCO2eq/kWh are much lower than the current emission intensity of the Indonesian power sector. By fulfilling rising electricity demand using PV, up to 654 $MtCO_2eq$ can be avoided annually by 2050.

Keywords: *Greenhouse gas emission; Indonesia; life cycle assessment; photovoltaic system*

INTRODUCTION

Our generation is currently facing arguably the greatest and most important crisis of our lifetime: the climate crisis. The world has experienced a 1.0°C increase in temperature compared with the 20th century average (Lindsey & Dahlman, 2021). Should our "business-as-usual" approach continues, we are likely to see a temperature increase of up to 3.5°C by 2100 (United Nations Environment Programme (UNEP), 2019). Even with just a 2.0°C increase, extreme heat frequency will more than triple – worsening the severity and duration of droughts in many parts of the world, while the sea level is predicted to rise by 56 mm by 2100, putting tens of millions of people at risk of flooding ever year, on top of many other severe and irreversible consequences (Carbon Brief, 2018; CBC News, 2015). Global emissions have to peak by 2025 and be reduced by 43% by 2030 to keep our Earth temperature increase within 1.5°C (World Meteorological Organization, 2022).

Yet at the same time, the world energy demand has been increasing and will continue to do so as many developing countries experience increase in both their population and purchasing power. We are therefore facing a "dual challenge" of simultaneously meeting rising energy demand and reducing carbon emission (Gandhi & Srinivasan, 2020).

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https://doi.org/10.31098/lomr.v1i1.969

Solar energy, especially in the form of photovoltaic (PV) system, is one of the most promising solutions to the dual challenge; it is available worldwide, is environmentally friendly, and is now the cheapest sources of electricity (International Energy Agency (IEA), 2020). Because of its advantages, PV installation across the world has been increasing significantly over the past two decades, reaching 1 TW cumulative installed capacity earlier this year (Weaver, 2022).

Indonesia, although still heavily relying on fossil fuels – coal, oil, and gas comprise 37.62%, 33.40%, and 16.82% of the country's primary energy consumption[1] in 2021 (Ministry of Energy and Mineral Resources of Indonesia, 2022) – has also recognized the potential of solar PV for the country's electricity generation. Both the Ministry of Energy and Mineral Resources (MEMR) and the national electric company (PLN) revised the planned installed PV capacity to 4.68 GW by 2030 (Rahayu, 2021) in an effort to fulfill the renewable energy share commitment of 23% by 2025 and 31% by 2050.

Although PV does not require fuel and does not emit carbon directly, the manufacturing of its components is energy intensive. Proper life cycle assessments (LCA) of entire PV value chain needs to be conducted to determine if PV is indeed more environmentally friendly compared with existing conventional electricity generators.

Many studies, elaborated further in the literature review section, have conducted such assessments. Nevertheless, the life cycle emission values of PV vary widely and is often site-specific. To analyze the potential of PV to reduce greenhouse gas (GHG) emissions in Indonesia, these values have to be harmonized according to the prevalent conditions in the country. Therefore, the most relevant and up-to-date data are selected from works in the literature and employed to calculate the PV life cycle GHG emission values for Indonesia.

The results suggest that even a high estimate of the PV GHG emission is still lower by more than 10 times the current emission intensity of the Indonesian power sector. By integrating PV into the power sector, up to 654 $MtCO_2eq$ can be avoided annually in 2050. Regulators and policy makers therefore can use the results of this study to make informed decisions on how to reduce the country's emissions so as to fulfill its target of reducing GHG emissions "29% below business-as-usual" by 2030 and reach net zero by 2060 (Ministry of National Development Planning of the Republic of Indonesia, 2021).

LITERATURE REVIEW

The main components of PV system are PV modules (also known as solar panels), inverters, and balance of systems (BOS). BOS consists of mounting structure, cables, DC and AC combiner boxes, and other components. Unlike conventional generators, PV does not need any fuel to generate electricity, and requires very little operation and maintenance throughout its 25-to-30-year lifetime. Therefore, the largest emission for PV occurs in the upstream stage: the manufacturing of PV module and its components, comprising 60-70% of its total life cycle emissions (NREL, 2012). In comparison, the raw materials extraction and construction to build coal power plants make up only <1% of the total carbon emissions of the energy generation; more than 98% of the emissions

[1] When only considering the power sector, coal share goes much higher to 67.93%, a number which kept on increasing from 44.21% in 2011 (Ministry of Energy and Mineral Resources of Indonesia, 2022).

come from the coal mining, transport, combustion, as well as the plant operation and maintenance (NREL, 2012).

Silicon (Si)-based PV modules are the most established technology and account for approximately 95% of total production in 2020 (Fraunhofer ISE, 2022). Within Si-based PV module, there are three broad categories, in the order of descending energy conversion efficiency: monocrystalline Si (mono-Si), multi-crystalline (multi-Si) and amorphous Si (a-Si). Mono-Si was and is now again the most dominant technology in the market (its market share was 84% of total c-Si PV modules in 2020 compared with less than half in 2018, and more than 95% in 1980) (Fraunhofer ISE, 2022).

The manufacturing of crystalline Si-based PV module is very energy intensive, especially in the Silicon purification stage, with mono-Si consuming twice the amount of energy than multi-Si (Liu & van den Bergh, 2020), mainly because of the silicon ingot-growing process (Fthenakis et al., 2008).

Numerous studies have conducted life cycle assessment (LCA) of GHG emissions from PV. Luo et al. (Luo et al., 2018) compared different multi-crystalline silicon (multi-Si) PV technologies for the case of Singapore and obtained life cycle emission values of 20.9-30.2 gCO_2eq/kWh. The authors stated that replacing the standard PV module with double glass module without aluminium frame can reduce the emission further. Recycling the PV components, instead of sending them to landfill was also found to reduce the environmental impact of PV (Huang et al., 2017).

In (Kim et al., 2014), the life cycle emissions of mono-Si and multi-Si PV for the case of Korea were compared; the authors found them to be 41.8 and 31.5 gCO_2eq/kWh respectively. (Liu & van den Bergh, 2020) compared the CO_2 emissions for PV production in China, EU, and the US. The life cycle emissions were lowest in the EU, followed by the US, and China since the electricity production in the EU was the least carbon intensive.

(Jungbluth, 2005) estimated the GHG emission from PV in Switzerland to be 39-110 gCO_2eq/kWh. The higher emissions were for the case of façade installation (the PV modules are installed vertically, replacing windows or other building materials) where the energy production is not as high as standard roof installations.

Even more PV LCA studies with varying life cycle emission values have been reviewed in (Muteri et al., 2020) and (Hsu et al., 2012). For crystalline Si (c-Si) modules, the published life cycle emission range from 20 to 220 gCO_2eq/kWh with interquartile range of 44-73 gCO_2eq/kWh (Hsu et al., 2012). PV System with thin film modules like CdTe, CIGS, and amorphous silicon are found to have lower life cycle emissions (Fthenakis et al., 2008).

The variation in reported values is due to differing methods and assumptions among the works in the literature. Firstly, there are many different boundaries for LCA: cradle to gate (from raw material extraction up to components manufacturing), cradle to use (including the operations and maintenance), or cradle to grave (including end-of-life management, from decommissioning, to either recycling, landfill, or both). For example, (Luo et al., 2018) only analyzed the emissions from PV components manufacturing, without considering the operations and maintenance, or end-of-life management, whereas (Kim et al., 2014) conducted LCA from raw material extraction to disposal (cradle to grave).

Secondly, different irradiation values and different PV lifetime have also been employed to calculate the total PV energy generation in different works. When the PV generation is larger, the life cycle emission becomes lower.

To compare the different emission values reported in the literature, (Hsu et al., 2012) harmonized the reported life cycle emission from PV using irradiation of 1700 kWh/m^{2}year, typical of Southern Europe, PV system lifetime of 30 years and module efficiency of 14% for mono-Si and 13.2% for multi-Si. After the harmonization, the range for was reduced to 39-49 gCO_2eq/kWh, with median for multi-Si at 45 gCO_2eq/kWh, and at 40 gCO_2eq/kWh for mono-Si. To estimate the values for PV in Indonesia, local irradiation values have to be used.

To put the life cycle GHG emission values for PV into context, a brief review of LCA of coal power plant GHG emissions are also presented below. The authors of (Mittal, 2010) estimated that the emissions from burning coal to generate electricity emits 910-950 gCO_2/kWh (on top of 6.94-7.20 gSO_2/kWh, 4.22-4.38 gNO/kWh) for the case of India. However, the authors did not consider the mining of coal. The figure was 990 and 975.2 gCO_2eq/kWh for the case of Britain (Odeh & Cockerill, 2008) and Japan (Hondo, 2005), respectively. According to (Koornneef et al., 2008), the life cycle emission can be reduced from 1104 to 243 gCO_2eq/kWh through the carbon capture and storage (CCS). These emission values vary depending on the assumptions regarding mine emissions, thermal efficiency, and carbon emission factors (Whitaker et al., 2012).

The authors of (Arsyad & Setiadi, 2020) estimated that the LCA of Indonesian coal power plant in 2018 to be 800 gCO_2eq/kWh. Nevertheless, it only included the coal power plant operation, without including coal mining and other stages in the supply chain. Moreover, the study assumed the use of coal with net calorific value of 4,700 kcal/kg. However, this number is likely underestimated, since (Adiatma et al., 2018) reported that new coal power plants are designed to use coal of 4,000 kcal/kg. The decrease in coal calorific value was evident from the increase of coal consumption per unit electricity produced. In 2017, around 520 ton of coal is consumed per GWh electricity produced, up from 360 ton/GWh in 2002 (Adiatma et al., 2018).

When including the fugitive emissions which come from post-mining activities, the total life cycle emission of coal power plant is 10-13% greater than its direct emission (Wang et al., 2018), reaching 899.85 gCO_2eq/kWh for the case of China in 2016.

Meanwhile, natural gas-fired combustion turbine (NGCT) and natural gas-fired combine cycle (NGCC) life cycle emissions are in the rage of 570-750 gCO_2eq/kWh and 420-480 gCO_2eq/kWh, respectively (O'Donoughue et al., 2014).

METHODOLOGY

To calculate the PV life cycle emission value for the case of Indonesia, the median life cycle emission value from (Hsu et al., 2012) for mono-Si PV (40 gCO_2eq/kWh) are adopted to the Indonesian parameters listed below.

Global horizontal irradiation (GHI) is assumed to be 1698.5 kWh/m^{2}year, the value in Central Jakarta area (Global Solar Atlas, 2022), which is almost identical to the 1700 kWh/m^{2}year assumed in most studies elaborated earlier. Annual irradiation in Indonesia ranges from 1270 kWh/m^2 to 2190 kWh/m^2. The lifetime of the PV system is assumed to be 25 years (the length of the performance warranty of most PV modules) instead of 30 years as a conservative estimate.

The three Indonesian irradiation values shall be referred to as GHI^{lo}, GHI^{med}, and GHI^{hi} in ascending order.

As a sanity check, GHG emission data from the most updated PV technology are also obtained from (Müller et al., 2021). The module is 336 Wp (efficiency of 19.79%) 60-cell mono-Si passivated emitter and rear cell (PERC) module produced in China. The life cycle GHG emission (cradle to grave) for 1 kWp PV module (excluding inverter and BOS, installation and operation and maintenance) is 810 $kgCO_2eq$. The emission is lower for EU-produced module at 480 $kgCO_2eq$, but since Chinese-manufactured modules account for most of the PV installation in Indonesia and across the world, the emission figure for Chinese module is utilized.

To obtain the total life cycle GHG emission, LCE, in [gCO_2eq/kWh], LCE [gCO_2eq] has to be divided by the total energy produced by the PV system throughout its lifetime. Therefore, it is calculated as follows.

$$LCE\ [\text{gCO2eq/kWh}] = \frac{LCE\ [\text{gCO2eq}]}{\sum_{y=2}^{Y} GHI \times PR \times A \times \eta \times (1 - degrad^{\text{ini}}) \times (1 - degrad^{\text{an}})^{y-1}}$$

where PR is the system performance ratio, assumed to be 80%, while Y is the PV system lifetime, assumed to be 25 years. A and η are the surface area and efficiency of the PV module. The initial PV degradation, $degrad^{\text{ini}}$, is 2.0%, while the annual degradation, $degrad^{\text{an}}$, is 0.5% in the subsequent years, common for recent commercial mono-Si PV modules (Rodríguez-Gallegos et al., 2020).

FINDINGS AND DISCUSSION

Total 1 kWp PV energy generation with irradiation of 1700 kWh/m^2year throughout a 30-year lifetime assumed in (Hsu et al., 2012) (with annual 0.5% degradation) is 37464 kWh. With Indonesian irradiation values GHI^{lo}, GHI^{med}, and GHI^{hi} over 25-year lifetime and aforementioned higher degradation rates, the total energy generation for 1 kWp PV system is 23293 kWh, 31152 kWh, and 40166 kWh respectively. Therefore, the corresponding life cycle emission values are 64.3, 48.1, and 37.3 gCO_2eq/kWh.

As a comparison, when 810 $kgCO_2eq$ is divided by the energy generation at GHI^{med}, the life cycle emission of the PV module (excluding inverter, BOS, and use stage) is found to be 25.56 gCO_2eq/kWh, or 25.18 gCO_2eq/kWh when end-of-life management is excluded. This is very similar to the GHI^{med}-harmonized value of PERC life cycle emission from Luo et al. (Luo et al., 2018) of 25.43 gCO_2eq/kWh. (Luo et al., 2018) assumed module efficiency of 16.7% and have excluded end-of-life management. The nearly identical value despite efficiency improvement from 16.7% to 19.79% suggests that the efficiency improvement comes with increased carbon emission in the module manufacturing. Regardless, the similarity of calculated value in this work with those in the literature suggests that the range of life cycle emission values are estimated reasonably.

The PV life cycle emission values of 37.3-64.3 gCO_2eq/kWh are much lower than Indonesia's estimated power sector emission of 804 gCO_2eq/kWh in 2020 (Climate Transparency, 2020) (compared with the G20 average of 449 gCO_2eq/kWh). Indonesia electricity demand was 257

TWh in 2020 and is projected to increase 5% annually until 2050 (Enerdata, 2022), reaching 1110 TWh. Should this increase in electricity demand be fulfilled with current generation composition, this means there will be additional 686 MtCO_2eq emission per year in 2050 just from the power sector. In 2017, Indonesia already emitted 889 MtCO_2eq (Climate Transparency, 2020). Yet, to stay on the path of only 1.5°C temperature increase, the maximum annual emission by 2030 is only 622 MtCO_2eq.
Should the increase in electricity demand be 100% fulfilled by PV, then the increase in power sector emission will be much lower at 32-55 MtCO_2eq, potentially avoiding 631-654 MtCO_2eq annually by 2050. This number is undoubtedly optimistic, as it assumes 76.8% of the electricity demand is fulfilled by PV in 2020. Although the 628 GW of PV that needs to be installed to fulfill that electricity consumption is still within the Indonesian PV potential of 6749-7714 GW estimated in (IESR, 2021), before reaching such high PV penetration, many power system problems might arise (Gandhi et al., 2020). Moreover, energy storage will become a necessity, which will increase the total life cycle emissions. Nevertheless, as Indonesia is endowed with other renewable energy sources such as geothermal and hydropower, such magnitude of GHG emission reduction should be possible, even if not purely through PV alone.
As more and more sectors are being electrified, it is important to decarbonize the electricity sector. To accelerate the energy transition, government can boost the private sector efforts in implementing low-carbon solutions. Carbon tax, together with carbon capture and storage for existing fossil fuel generators are also required to expedite the emission reduction in Indonesia.

CONCLUSION

Thanks to its low cost, huge potential, and low carbon contribution, solar photovoltaic (PV) system is one of the most promising energy sources to combat the climate crisis. Through extensive literature review and harmonization according to Indonesian parameters, PV life cycle greenhouse gas (GHG) emission was found to be 37.3 to 64.3 gCO_2eq/kWh. This number is much lower than emission of 804 gCO_2eq/kWh from the current Indonesian electricity mix. As the electricity demand keeps on rising, PV has the potential to reduce the annual emission by 631-654 MtCO_2eq in 2050 and to help Indonesia reach net zero emission by 2060, in line with its commitment.

LIMITATION & FURTHER RESEARCH

Although this work only discusses the GHG emission, the detriments of relying on fossil fuels for our energy needs (and therefore the benefits of using renewable energy) are not only about carbon emission, but also about other pollutants like particulate matter, SO_x, and NO_x which contribute to air pollution. Hence, the benefits of PV and other renewable energy outlined here are still underestimated.
Beyond the environmental factors, there are also other factors to consider such as contribution of the technologies towards jobs, national and regional economy, amount of subsidies involved, and so on. Such investigation is left for future work.
While PV is one of the most promising renewable energy sources, it is not the only one. Indonesia also has abundant geothermal and hydro resources which will also be able to reduce the country emissions. Life cycle GHG emissions from these sources have not been investigated in this work.

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