Decarbonization Pathways: Assessing Life Cycle GHG Emissions in Malaysia's Electricity Generation

Atiqah Hamizah Mohd Nordin
Electrical Engineering Studies, College of Engineering, Universiti Teknologi MARA Johor Branch, Malaysia
atiqah26@uitm.edu.my (corresponding author)

Shahril Irwan Sulaiman
School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia
shahril@uitm.edu.my

Rijalul Fahmi Mustapa
Electrical Engineering Studies, College of Engineering, Universiti Teknologi MARA Johor Branch, Malaysia
rijalulfahmi@uitm.edu.my

Received: 4 June 2024 | Revised: 17 July 2024 | Accepted: 3 August 2024

 DOI: https://doi.org/10.48084/etasr.8025

ABSTRACT

Electricity generation is a key contributor to global Greenhouse Gas (GHG) emissions. The urgent need to mitigate climate change demands a transition to more sustainable ways of electricity generation. However, focusing on operational emissions without assessing their life cycle may lead to less effective decisions on energy policy and technology advancements. This study examines the life cycle GHG emissions of major electricity generation systems in Malaysia, employing the life cycle assessment approach. The systems are based on energy resources of coal, natural gas, hydro, and solar photovoltaic (PV). Furthermore, five types of PV systems with different capacity range and module technologies were compared. Furthermore, the study also compares the scenarios of PV installation in major cities in the country. The results show that electricity produced by renewable energy yields substantially lower GHG emissions compared to fossil fuel energy. Throughout their lifetime, PV and hydro electricity systems release GHG emissions at least 5 and 7.4 times lower than coal respectively, and at least 3.5 and 5.2 times lower than natural gas, respectively, under the worst-case uncertainty scenario. Besides, the GHG emissions of PV system installed in major cities in Malaysia ranges from 61.4 to 72.5 g CO2-eq/kWh. The study highlights the potential of renewable energy in promoting sustainability within the energy sector, offering a viable pathway towards the decarbonization of the energy sector.

Keywords-GHG emissions; climate change; energy transition; life cycle assessment; renewable energy; decarbonization

I. INTRODUCTION

The electricity sector is one of the major contributors of carbon dioxide (CO_2) emissions. In 2022, the global power sector CO_2 emissions reached up to 14.8 GT CO_2, driven mainly by increasing coal-fired electricity generation [1]. With governments and industries around the world accelerating efforts to reduce Greenhouse Gas (GHG) emissions, Renewable Energy (RE) technologies have proven to be another tool in the battle against climate change.

As a developing nation, Malaysia's electricity demand has continuously grown in the past two decades. On average, the electricity consumption per capita is 4.963 MWh in 2021 [2]. It is reported that energy industry, particularly the electricity production, is the highest contributor to GHG emissions in the country [3]. The electricity mix in Malaysia has been predominantly relying on fossil fuel energy sources. The national energy policies have gradually shifted to focus more on resource security, reliability, and cost-effectiveness [4]. In 1995, natural gas was the main energy resource for electricity generation and its usage in the energy mix has remained relatively steady since 2010, as Malaysia was encouraging the diversification of fuel sources in electricity generation. Coal became significant in 2010 mainly driven by its attractive cost. As of 2020, the composition of electricity generation in the country remains heavily influenced by fossil fuels, with coal and natural gas contributing 37.9% and 37.3%, respectively [5]. In contrast, RE represents only 23.2% of the overall mix with hydro as the main RE resource with 17.7%. However, the current installed hydropower capacity in the country has not yet fully tapped into this abundant resource [6]. On the other hand, although solar energy currently constitutes 4% of the energy mix, it marks a notable advancement over the past decade. This progress can be attributed to a variety of factors and climate change mitigation actions, including RE initiatives such as Feed-in Tariffs (FiT), Large Scale Solar (LSS) projects, and Net Energy Metering (NEM) programs [7]. These measures have propelled the development of solar infrastructure and are expected to sustain its growth in the years to come.

Malaysia has been planning a strategic initiative to enhance its RE sector, setting clear targets for the country's energy mix. By 2025, through its National Determined Contribution (NCD), Malaysia intends to achieve an installed capacity of RE that constitutes 31% of its total energy production, with an ambition to further increase this percentage to 40% by 2035 [5]. In a significant move towards environmental sustainability and combating climate change, Malaysia is also aiming for a milestone of net zero emissions as early as 2050 [8]. In 2023, National Energy Transition Roadmap was established, setting out the pathway for the national energy mix, GHG emission reduction, and transition initiatives, showing its commitment to its net zero target [9]. This comprehensive strategy underscores Malaysia's dedication to transitioning towards more sustainable energy sources and reducing its carbon footprint on a global scale.

While RE is touted for its minimal environmental impact, it is important to note that emissions do occur at various stages of its life cycle, including the extraction of raw materials, manufacturing processes, operation and maintenance, and disposal or recycling at the end of its useful lifetime [10, 11]. In order to ensure a sustainable shift to renewable energy sources, conducting comprehensive analyses of the emissions associated with electricity generation is vital. Such studies are essential in providing policymakers with the data needed to make informed decisions that guide the transition to cleaner energy solutions.

Although there have been several studies addressing the environmental impacts of energy systems, only a few have employed the Life Cycle Assessment (LCA) approach. Furthermore, there is a notable absence of such studies concerning Malaysia. This lack of localized LCA limits the ability to fully understand the impacts of energy choices which is essential for effectively strategize the transition to sustainable energy sources. Besides energy and economic viability [12], environmental viability is also crucial to fully realize the potential of renewable energy for a more sustainable future.

In response to this gap, the current employs a comparative LCA approach to assess the GHG emissions of prominent energy systems in Malaysia, including coal, natural gas, hydro, and solar photovoltaic (PV). The GHG emissions of various PV system types under Malaysia's climate conditions are also evaluated. By providing a detailed comparison of these energy systems, this study aims to offer valuable insights to aid informed decision-making by the government and stakeholders, highlighting the unique environmental benefits and challenges of each energy pathway. In addition, by integrating region-specific data, this study provides a more representative and relevant analysis for Malaysia.

II. METHODOLOGY

The life cycle GHG emissions of electricity generation technologies were evaluated using the LCA methodology. As shown in Figure 1, the LCA was conducted based on four phases:

1. The goal and scope definition phase that defines the LCA scope and functional unit under study.
2. The inventory analysis phase that includes developing life cycle inventory models of each system under study.
3. The impact assessment phase where the life cycle inventory data are translated into their environmental significance.
4. The interpretation phase where the results are discussed, conclusions are drawn, and recommendations are provided based on the goal and scope definition.

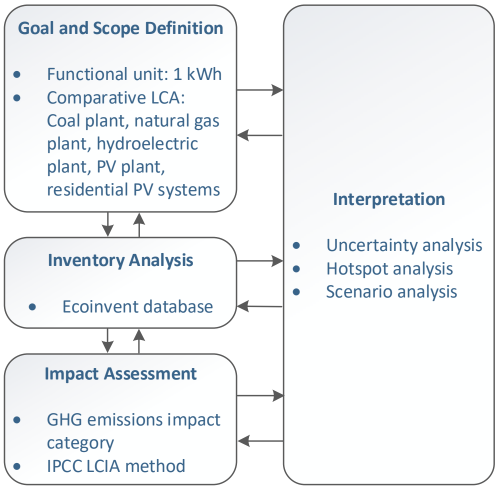

Fig. 1. LCA methodology.

The goal of this study is to compare the GHG emissions of electricity generation technologies from four main energy sources in the Malaysia capacity mix, i.e. coal, natural gas, hydroelectric, and solar PV. The functional unit which serves as a reference unit in this LCA study is 1 kWh of electricity generated by each system. Besides, five types of PV systems with different capacity ranges and PV module technologies were compared. Four types of PV systems, each with a similar system capacity of 3kWp and slanted-roof installation, vary in terms of their PV module technology i.e. multicrystalline silicon (multi-Si), monocrystalline silicon (mono-Si), amorphous silicon (a-Si), and cadmium telluride (CdTe), while another type is a larger scale PV system with capacity of 570 kWp, ground-mounted installation and utilizing multi-Si modules. Additionally, the study examines the scenario of PV installation in major cities across the country, specifically focusing on the use of multi-Si rooftop PV systems for this comparison. The Life Cycle Inventory (LCI) of the electricity generation systems under consideration is obtained from the Ecoinvent 3.9.1 database which contains default data quality scores. The datasets used are listed in Table I.

TABLE I. DATASET OF ELECTRICITY GENERATION SYSTEMS

Electricity generation technology	Ecoinvent dataset of product system
Multi-Si rooftop PV system	Electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted
Mono-Si rooftop PV system	Electricity production, photovoltaic, 3 kWp slanted-roof installation, single-Si, panel, mounted
a-Si rooftop PV System	Electricity production, photovoltaic, 3 kWp slanted-roof installation, a-Si, panel, mounted
CdTe rooftop PV system	Electricity production, photovoltaic, 3 kWp slanted-roof installation, CdTe, laminated, integrated
Multi-Si ground-mounted PV system	Electricity production, photovoltaic, 570kWp open ground installation, multi-Si
Hydro plant	Electricity production, hydro, reservoir, tropical region
Coal plant	Electricity production, hard coal
Natural gas plant	Electricity production, natural gas, conventional power plant

Then, GHG emissions of each system were obtained using the IPCC 2021 impact assessment method embedded in the Simapro software. Then, in the interpretation stage, several analyses and scenarios were performed. The LCIA results are then further interpreted using uncertainty analysis to obtain minimum and maximum limits of the impact when considering the uncertainty sourced from the data used. Providing uncertainty data in comparative LCA is essential to understand the variability and confidence of the results obtained, thus, providing insights into the reliability of the conclusions drawn. In this study, Monte Carlo simulation with 95% of confidence interval was utilized in performing the uncertainty analysis. Besides that, hotspot analysis was conducted for each generation system to identify processes or activities that have a large contribution the total impact [13]. The GHG emissions hotspot was analyzed in process tree diagram for a better visualization.

As PV technology gains increasing attention, evaluating installations across multiple locations enables the LCA to account for environmental variations that influence the overall impact of electricity production of PV systems. To examine the scenario of PV installations in cities across the country, the solar irradiation levels of these locations were identified to determine the electricity generation potential of the PV systems. The solar irradiations were obtained using the Meteonorm 8.1 data in the PVSYST software.

III. RESULTS AND DISCUSSION

The life cycle GHG emissions associated with electricity generation from different systems are illustrated in Figure 2. The results indicate that the electricity produced by RE yields substantially lower GHG emissions compared to fossil fuel energy. PV electricity exhibits GHG emissions ranging from 34.5 to 90.4 g CO_2-eq/kWh and varies with the types of PV module technology and installation type. Meanwhile, hydro electricity produces GHG emissions of 72.0 g CO_2-eq/kWh, falling within the range of the emissions from PV systems. On contrast, electricity generated from fossil fuel-based generation systems demonstrates significantly higher GHG emissions, with coal and natural gas producing 1207 and 821 g CO_2-eq/kWh, respectively. In other words, GHG emissions from PV and hydroelectricity are at least 13.3 and 16.7 times, respectively, lower than coal, and 9.0 and 11.4 times lower than natural gas. This result implies the potential for substantial GHG emissions avoidance through the utilization of PV and hydroelectricity. The uncertainty information of the GHG emissions and the results of hotspot analysis for each system are presented in the next subsections.

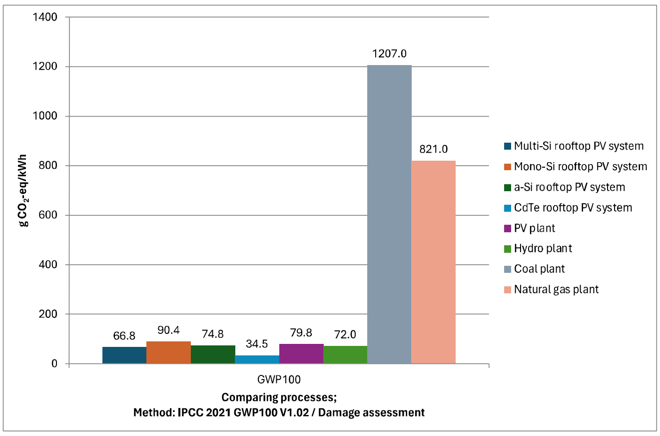

Fig. 2. Comparison of GHG emissions of electricity generation systems.

A. *Uncertainty Analysis*

The results of uncertainty analysis are presented in Table II. Besides the mean values of the GHG emissions, the uncertainty analysis yielded upper and lower limit values, representing the range within which the true value of GHG emissions is expected to lie with the level of confidence. Standard Deviation (SD) and Coefficient of Variation (CV) data are also provided. The calculated upper and lower limits indicate the potential variability in estimating the GHG emissons, considering the data uncertainty in terms of its reliability, completeness, temporal correlation, geographical correlation, and further technological correlation. It is shown that the GHG emissions of PV and hydro electricity are still much lower than the coal and natural gas even after considering the upper limit values of the former and the lower limits values of the latter. In the worst-case uncertainty scenario, PV and hydroelectricity emit GHG emissions at least 5 and 7.4 times lower than coal respectively, and at least 3.5 and 5.2 times lower than natural gas, respectively. It is important to note that these comparisons are based on the PV system with the highest emissions, i.e. mono-Si, in order to demonstrate the worst-case scenario. Meanwhile, the CV is a measure of dispersion that indicates the variability of the results in relation to the mean output. Hence, in terms of data quality, natural gas dataset exhibits the lowest uncertainty whereas the mono-Si PVsystem shows the highest uncertainty. The results highlight the importance of considering the data uncertainty when interpreting the comparative assessment. By doing so, a more comprehensive understanding of the range of possible outcomes is attained, enhancing the robustness of the analysis.

TABLE II. UNCERTAINTY ANALYSIS RESULTS OF GHG EMISSIONS OF DIFFERENT ELECTRICITY GENERATIONSYSTEMS

Electricity generation system	Mean	Lower limit (2.50%)	Upper limit (97.50%)	SD	CV
	(g CO_2-eq/kWh)				(%)
Multi-Si rooftop PV system	66.8	40.5	107.1	17.2	25.8
Mono-Si rooftop PV system	90.4	48.5	157.1	27.2	30.1
a-Si rooftop PV System	74.8	37.1	135.6	24.8	33.2
CdTe rooftop PV system	34.5	21.9	52.8	7.9	22.9
Multi-Si ground-mounted PV system	79.8	47.8	124.8	20.3	25.4
Hydroelectric plant	72.0	47.7	107.6	15.2	21.1
Coal plant	1207.0	792.6	1766.5	246.5	20.4
Natural gas plant	821.0	556.0	1198.5	160.6	19.6

B. Hotspot Analysis

The life cycle GHG emissions of electricity generated from the coal plant are significantly contributed by CO_2 emissions when burning hard coal during the operation. Besides that, other main processes contributing the GHG emissions are from hard coal mining and transportation of hard coal as illustrated in Figure 3.

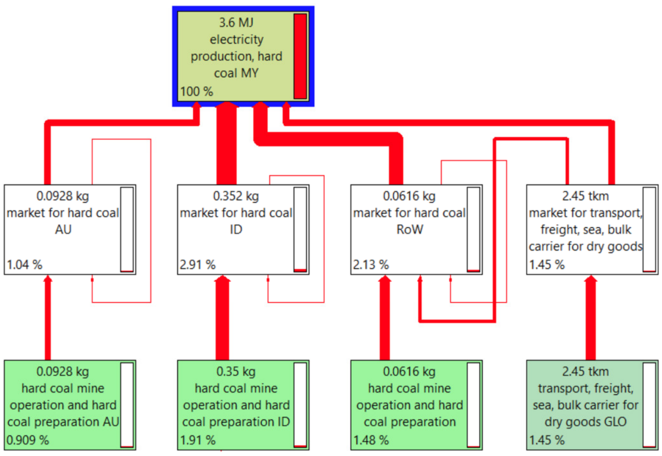

Fig. 3. Process tree of coal electricity generation.

On the other hand, the life cycle GHG emissions from electricity generated by natural gas plant are also primarily due to the combustion of natural gas during the operation. As shown in Figure 4, other main processes for contributing to the emissions are natural gas production, emissions occuring during the distribution, sweet gas and pipeline infrastructure for natural gas distribution. Meanwhile, the life cycle GHG emissions of hydroelectricity are significantly contributed by biogenic methane and CO_2 which are associated with bacterial processes in reservoirs [14]. Additionally, as illustrated in Figure 5, GHG emissions are also contributed by the construction of hydropower plant, particularly due to the cement used.

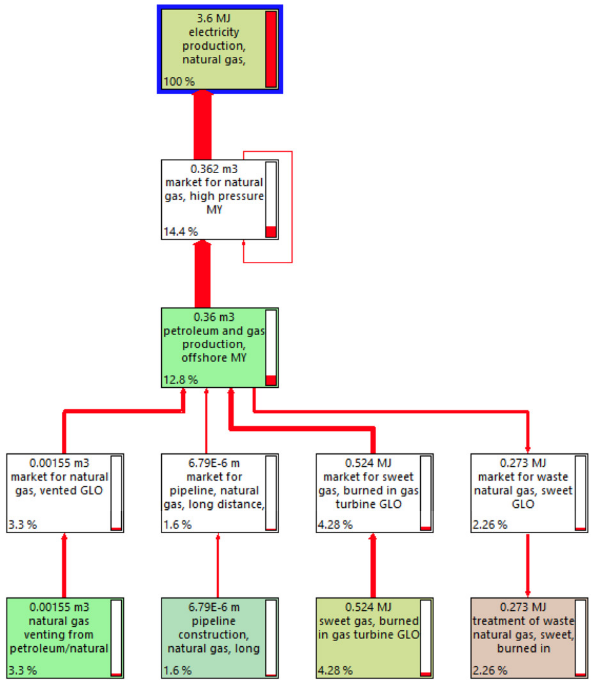

Fig. 4. Process tree of natural gas electricity generation.

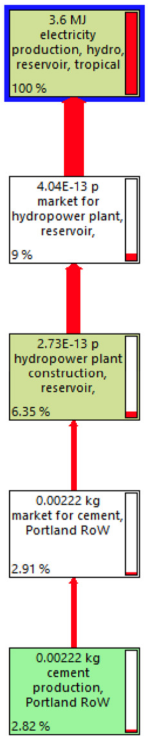

Fig. 5. Process tree of hydroelectricity generation.

Figures 6-10 show the tree diagrams of life cycle GHG emissions of PV electricity. As shown in Figure 6, the life cycle GHG emissions of electricity generated by the PV plant using multi-Si are primarily due to the PV module production with 69.9% share which entails from metallurgical silicon processing, silicon wafer production, and the manufacturing of the PV cells and the PV module. Besides that, the mounting structure also has a significant carbon footprint of 25.5% share.

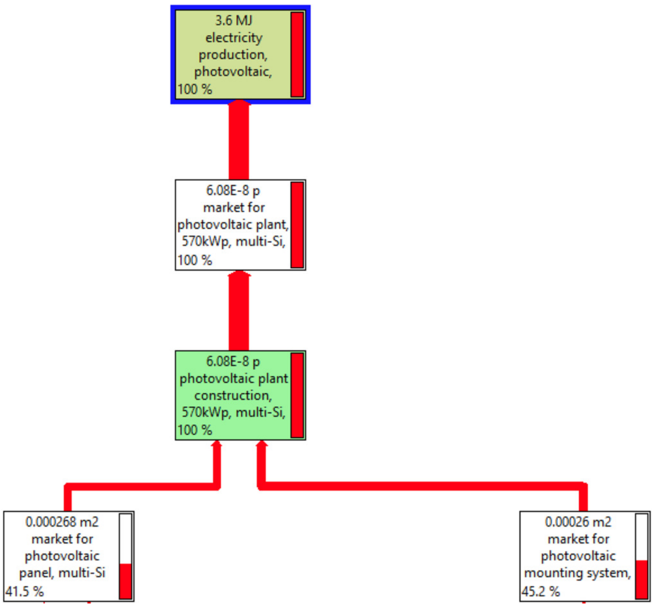

Fig. 6. Process tree of electricity generation from a PV plant.

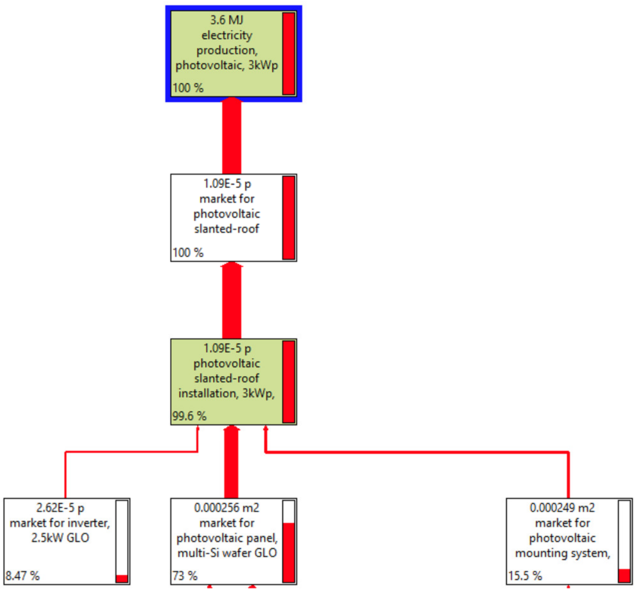

Fig. 7. Process tree of electricity generation from a residential multi-Si PV system.

Conversely, the operational phase of the PV plant contributes insignificantly to the overall life cycle GHG emissions. On the other hand, the GHG emissions of PV electricity from residential scale PV systems is also primary contributed by the PV module production. Among the four types of PV modules, mono-Si technology shows the highest share of GHG emissions with 77.4% of its total emissions as shown in Figure 8, which is due to intensive energy comsumption in the silicon manufacturing process [15].

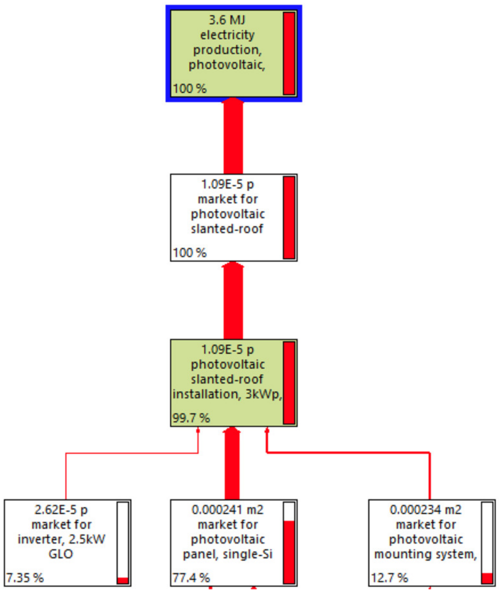

Fig. 8. Process tree of electricity generation from residential mono-Si PV system.

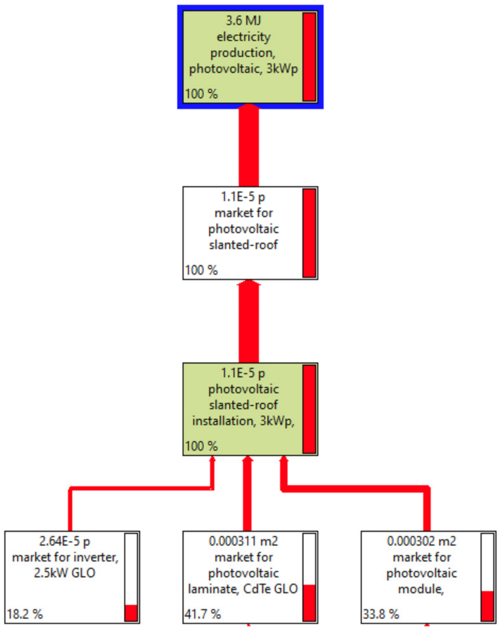

Fig. 9. Process tree of the electricity generation from a residential CdTe PV system.

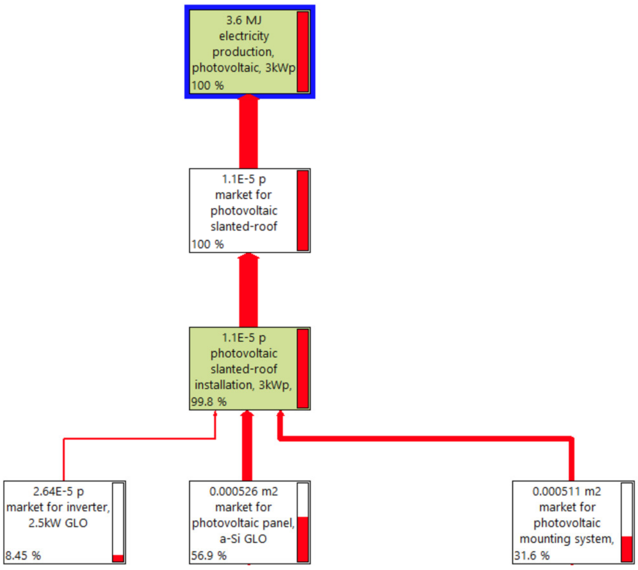

Fig. 10. Process tree of electricity generation from a residential a-Si PV system.

C. Scenario of PV Installed in Different States in Malaysia

Table III shows the GHG emissions of electricity generation from a multi-Si rooftop PV system installed in the capital cities for each state in Malaysia. The GHG emissions range from 61.4 to 72.5 g CO_2-eq/kWh, depending on the solar irradiation levels which range from 1645.0 to 1940.2 kWh/m^2/year. PV system performance is influenced by many factors including solar irradiation at the installed location; higher irradiation results in more electricity produced. Therefore, the life cycle GHG emissions of the electricity generated from PV system are also influenced by the solar irradiation received. Given this context, deploying PV systems in Malaysia is an effective strategy for the decarbonization of the country's energy sector.

TABLE III. GHG EMISSIONS OF MULTI-SI ROOFTOP PV SYSTEM INSTALLED AT SEVERAL CITIES IN MALAYSIA

City	**Solar irradiation (kWh/m^2/yr)**	**GHG emissions (g CO_2-eq/kWh)**
Johor Bahru	1645.0	72.5
Alor Setar	1816.6	65.6
Kota Bharu	1867.5	63.8
Malacca City	1732.5	68.8
Seremban	1768.9	67.4
Kuantan	1783.7	66.8
George Town	1807.6	65.9
Ipoh	1801.2	66.2
Kangar	1834.7	65.0
Kota Kinabalu	1940.2	61.4
Kuching	1751.6	68.0
Shah Alam	1790.1	66.6
Kuala Lumpur	1781.1	66.9
Kuala Terengganu	1811.9	65.8

IV. CONCLUSIONS

GHG emissions of prominent electricity generation systems in Malaysia are presented in this study. It shows that RE-based systems have much lower GHG emissions than coal and natural gas, or in other words, offer much cleaner electricity generation. The result indicates that RE deployment could lead to the attainment of GHG emission reduction substantially leading to minimizing effects on climate change. The findings further indicate that PV hold significant promise for generating clean electricity in Malaysia, thanks to the consistently high levels of received solar irradiation, particularly given its location within the sunbelt region. This also suggests that Malaysia has favorable conditions for harnessing solar energy through photovoltaic systems, which could contribute significantly to mitigating climate change. By leveraging the abundant solar irradiation in the country, Malaysia could reduce its dependence on fossil fuels for electricity generation, thereby lowering greenhouse gas emissions and advancing efforts to combat climate change.

Therefore, the current initiative to boost the RE share in the electricity mix should be intensified. For instance, incentives to encourage investment in PV and policies that promote PV in the country need to be continued and increased. Additionally, educating the public about the environmental benefits of RE such as solar energy could increase acceptance and adaptation of technology. This includes outreach campaigns, workshops, and educational programs targeting consumers, businesses, and policymakers. Further research and development efforts could focus on improving the efficiency and sustainability of PV technologies, as well as reducing their environmental impact across the entire life cycle. This could involve innovations in materials, manufacturing processes, and end-of-life recycling. This study offers valuable insights into life cycle GHG emissions of electricity generation systems in Malaysia which emphasizing the imperative of shifting towards renewable energy sources. These insights provide a critical evidence base for policymakers, demonstrating the environmental benefits of increasing the share of renewable energy in the electricity mix and guiding the development of supportive policies and incentives.

ACKNOWLEDGMENT

This work was supported in part by the Fundamental Research Grant Scheme, Ministry of Education Malaysia (Ref: FRGS/1/2022/TK08/UITM/02/67 and Ref: 600-RMC/FRGS 5/3 (096/2022)), and College of Engineering, Universiti Teknologi MARA Malaysia.

REFERENCES

[1] "Tracking Electricity: CO2 Emissions," *IEA*. https://www.iea.org/energy-system/electricity.

[2] "Sources of electricity generation," *IEA*. https://www.iea.org/regions/asia-pacific/electricity.

[3] *Malaysia's Fourth Biennial Update Report Under the United Nations Framework Convention on Climate Change*. Malaysia: Ministry of Natural Resources Environment and Climate Change Malaysia, 2022.

[4] S. N. Abdul Latif *et al.*, "The Trend and Status of Energy Resources and Greenhouse Gas Emissions in the Malaysia Power Generation Mix," *Energies*, vol. 14, no. 8, Jan. 2021, Art. no. 2200, https://doi.org/10.3390/en14082200.

[5] *National Energy Balance 2020*. SURUHANJAYA TENAGA, 2023.

[6] S. Tang, J. Chen, P. Sun, Y. Li, P. Yu, and E. Chen, "Current and future hydropower development in Southeast Asia countries (Malaysia, Indonesia, Thailand and Myanmar)," *Energy Policy*, vol. 129, pp. 239–249, Jun. 2019, https://doi.org/10.1016/j.enpol.2019.02.036.

[7] S. Sreenath, A. M. Azmi, N. Y. Dahlan, and K. Sudhakar, "A decade of solar PV deployment in ASEAN: Policy landscape and recommendations," *Energy Reports*, vol. 8, pp. 460–469, Nov. 2022, https://doi.org/10.1016/j.egyr.2022.05.219.

[8] *Twelfth Malaysia Plan 2021-2025*. Economic Planning Unit of Malaysia.

[9] *National Energy Transision Roadmap*. Putrajaya, Malaysia: Ministry of Economy.

[10] S. Guillén-Lambea, R. Abrahão, and M. Carvalho, "Life cycle assessment of power generation systems in Spain: Exploring a broader view from a consequential perspective," *Sustainable Production and Consumption*, vol. 38, pp. 28–40, Jun. 2023, https://doi.org/10.1016/j.spc.2023.03.018.

[11] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 555–565, Dec. 2013, https://doi.org/10.1016/j.rser.2013.08.013.

[12] Y. Kassem, H. Gokcekus, and F. A. R. Agila, "Techno-Economic Feasibility Assessment for the promotion of Grid-Connected Rooftop PV Systems in Botswana: A Case Study," *Engineering, Technology & Applied Science Research*, vol. 13, no. 2, pp. 10328–10337, Apr. 2023, https://doi.org/10.48084/etasr.5668.

[13] P. G. Jessop and A. R. MacDonald, "The need for hotspot-driven research," *Green Chemistry*, vol. 25, no. 23, pp. 9457–9462, Nov. 2023, https://doi.org/10.1039/D3GC03601D.

[14] E. G. Hertwich, "Addressing Biogenic Greenhouse Gas Emissions from Hydropower in LCA," *Environmental Science & Technology*, vol. 47, no. 17, pp. 9604–9611, Sep. 2013, https://doi.org/10.1021/es401820p.

[15] Y. Yu *et al.*, "Review of silicon recovery in the photovoltaic industry," *Current Opinion in Green and Sustainable Chemistry*, vol. 44, Dec. 2023, Art. no. 1100870, https://doi.org/10.1016/j.cogsc.2023.100870.