

ASSESSMENT OF EMBODIED CARBON EMISSIONS IN SRI LANKAN SOLAR PHOTOVOLTAIC SYSTEMS: IMPLICATIONS FOR CIRCULAR SUPPLY CHAINS

GOWSIGA, M^{1*}, SRIDARRAN P.² AND RAMACHANDRA, T.³

^{1,3}Department of Building Economics, University of Moratuwa, Sri Lanka

²Department of Facilities Management, University of Moratuwa, Sri Lanka

*Correspondence E-mail: gowsigam.22@uom.lk

Abstract. Despite the widespread recognition of solar photovoltaic (PV) systems for promoting energy efficiency, substantial embodied carbon emissions throughout their linear (take-make-use-dispose) supply chain significantly undermine their environmental sustainability. Understanding these emissions is essential for identifying opportunities to improve supply chain sustainability through circular economy (CE) practices. This study assesses the embodied carbon emissions of solar PV systems, providing insights to support CE practices in the supply chain. A case study was conducted on a hotel building with a polycrystalline solar PV system, selected as a representative commercial-scale installation. Data were collected through document reviews of installation and maintenance manuals and archival records, supplemented by three semi-structured interviews with professionals involved in the system supply chain. Descriptive statistical and qualitative content analyses were employed to evaluate emissions across supply chain stages. The upstream manufacturing accounts for 95% of the total emissions (148.06 g per kWh). 95.6% of midstream emissions are dominated by ocean transportation. The embodied carbon emission is sensitive to manufacturing-installation site distance, solar ratio, and the year of operation of the system. The study identifies emission-intensive components and lifecycle stages, providing evidence to guide targeted CE interventions for reducing embodied carbon in Sri Lankan solar PV supply chains.

Keywords. *Circular Economy (CE); Embodied Carbon Emissions; Solar Photovoltaic (PV) Systems; Sri Lanka; Supply Chain Sustainability.*

1. Introduction

Solar Photovoltaic (PV) systems are widely recognised as indispensable for achieving climate neutrality and mitigating global warming. They are reliable, energy-efficient, environmentally friendly, and have experienced rapidly falling costs (Heath et al., 2020; De Sousa et al., 2023). Solar PV systems do not use fossil fuels or release carbon during their operations, and thus the system seems to be completely clean and ecologically friendly (Baharwani et al., 2014). Further, PV systems have the potential to produce electricity with minimal operation and maintenance impacts, including minimal emissions, noise, and air pollution in the use stage (Farrell et al., 2020; De Sousa et al., 2023).

Despite these benefits, solar PV systems are not exempt from contributing to emissions during their life cycle. They consume considerable energy and emit embodied carbon in making solar cells, installing PV modules, making the balance of the system (BOS), transporting materials and components, installing and retrofitting PV systems, and recycling the system (Peng et al., 2013). Several studies argue that solar PV systems cannot be considered fully environmentally friendly when the entire supply chain is taken into account (Khemissi et al., 2021). For example, Constantino et al. (2018) indicated that approximately 67% of total lifecycle embodied carbon emissions originate from the

production of solar panels, and over 60% of these emissions are from the energy-demanding silicon purification stage. In addition, transportation and end-of-life processes (recycling and disposal) contribute further emissions (Peng et al., 2013).

Embodied carbon emissions vary depending on factors such as manufacturing location, installation conditions, system orientation, and transportation modes (Irvine & Rowlands-Jones, 2016). Moreover, concerns remain regarding waste generation and disposal at the end of the typical 25-30 years of lifespan of PV systems (Franco & Groesser, 2021).

Erol et al. (2021) highlighted that the conventional linear business model of take-make-use-dispose of the system serves as the foundation for the life cycle of most of the existing solar PVs worldwide, whereby natural resources are extracted, panels are manufactured, commercialised, used, and then mostly disposed of or recycled. To this end, Rahman and Chowdhury (2023) stress that a circular economic perspective throughout the solar PV value chain is required to address these challenges.

The circular economy (CE) represents a set of principles that collect a large variety of practices under the same objective of cutting the production of waste and emissions and consumption of resources by retaining the value of resources as long as possible while improving the efficiency of material and energy, using renewable energy and using environmentally low-impact and toxic-free materials (Askar et al., 2022; Joensuu et al., 2020; Minunno et al., 2018). In this context, Gallego-Schmid et al. (2020) found that there is a favourable relationship between CE solutions for climate mitigation and embodied carbon emission reductions. The latest international standards, which include Cradle-to-Cradle certification and the Sustainability Leadership Standard for solar PV towards circularity, were established to demonstrate the need for solar PV to move from a linear economy to a CE (Heath et al., 2020). Tawalbeh et al. (2021) highlighted the necessity for a paradigm shift towards a CE in the solar PV industry, which could reduce an estimated 42% of carbon emissions through enhanced recycling practices, design modifications for easier reuse, and stringent regulations. This shift, as advocated by Rahman and Chowdhury (2023), necessitates embedding CE principles across the solar PV value chain to enhance resource efficiency and reduce waste and energy consumption.

Despite extensive research on solar systems, most studies have focused on technological improvements rather than embodied carbon emissions. For example, Wikoff et al. (2022) analysed embodied energy and carbon emissions in cadmium telluride and silicon PV technologies during the manufacturing phase. Muteri et al. (2020) examined energy payback periods without addressing carbon emissions. Similarly, Prabhu et al. (2022) conducted a life cycle assessment (LCA) focusing on performance indicators, such as energy payback time, energy return on investment, and carbon emission rates, rather than detailed carbon emissions.

Franco and Groesser (2021) noted that, although case study research in this field has increased to approximately 16%, it remains limited to around 2% in developing countries. Similarly, Rabaia et al. (2024) identified a significant research gap in the adaptation of CE principles within the solar PV industry. Furthermore, existing studies indicate that comprehensive evaluation of lifecycle embodied carbon emissions remains limited.

Existing studies on embodied carbon emissions and LCA of solar PV systems are largely based on developed economies such as China, Europe, and the United States, where supply chains and recycling systems are relatively mature (Ludin et al., 2018; Muteri et al., 2020). However, these findings are not directly transferable to Sri Lanka due to its near-total reliance on imported PV components, long-distance maritime logistics, and limited recycling infrastructure. Moreover, most global LCA studies assume established CE systems and optimised reverse logistics, which remain limited in Sri Lanka (Franco & Groesser, 2021; Rabaia et al., 2024). Consequently, existing literature does not adequately reflect Sri Lanka-specific embodied carbon impacts in transport-intensive solar PV supply chains, highlighting the need for localised assessment to inform context-relevant carbon baselines and policy development.

Hence, this research aims to assess the embodied carbon emissions of solar PV systems and provide insights to support the implementation of CE practices within the supply chain. The paper starts with a literature review in Section 2, followed by a methodology in Section 3. Section 4 presents the analysis and findings, Section 5 discusses the results, and Section 6 concludes the study.

2. Literature review

The solar PV life cycle assumes a cradle-to-grave mechanism, starting from the extraction of raw materials until the disposal or recycling (grave) of solar PV components (Ludin et al., 2018). Zou et al. (2017) categorised the lifecycle of silicon-based PV panels into three main phases: upstream, midstream, and downstream.

Accordingly, Ali et al. (2022) and Chowdhury et al. (2020) stated that the upstream phase involves raw material extraction and processing of these materials into solar PV components. The midstream phase encompasses the transportation from manufacturing site to the installation site, installation process, and operational and maintenance activities associated with electricity generation. The downstream phase, which represents the end of the solar PV system's life, involves decommissioning, disposal, and recycling of PV components.

A comprehensive evaluation of the solar PV supply chain reveals that it is not entirely clean and ecologically friendly due to energy consumption and carbon emissions (Khemissi et al., 2021). Significant emissions occur during some phases of its life cycle stages, such as production and assembly of solar PV components, transportation of materials and PV components, installation and retrofitting of PV systems, and disposal or recycling of systems (Baharwani et al., 2014; Nugent & Sovacool, 2014). In particular, the manufacturing of solar PV cells leaves a significant carbon footprint. For example, monocrystalline silicon PV panels have been reported to require an embodied energy of approximately 2857 kWh/kWp for material and 2742 kWh/kWp for processing (Baharwani et al., 2014).

Irvine and Rowlands-Jones (2016) emphasised that the location of cells and modules, system orientation, transportation modes, and lifetime energy generation significantly influence the range of embodied carbon emissions. According to Constantino et al. (2018), the manufacturing of solar panels accounts for approximately 67% of carbon emissions across their whole lifecycle. Similarly, Tawalbeh et al. (2021) identified making glass, converting silica to silicon, and producing steel and aluminium for supports and frames are the main sources of manufacturing emissions. Although transportation emissions are relatively low, 0.1–1% of production emissions, they remain significant from a sustainability perspective.

Solar PV installation and operation phases typically produce minimal emissions (Ali et al., 2022). The dependability of operation and maintenance practices, including monitoring, preventive maintenance, corrective maintenance, and facility management, has a significant impact on the lifespan of a solar PV system (Tawalbeh et al., 2021). Table 1 summarises the components, types, and stages of solar PV systems.

Table 1, Components, types, and stages of a solar PV system

Solar PV System			References
Components	Panels		Lima et al., 2021; Gautam et al., 2020; Zou et al., 2017
	Balance of the system (BOS): inverter, controller, junction box, cable, array support, and battery		
Types	Silicon-based	polycrystalline, monocrystalline	Ali et al., 2022; Gautam et al., 2020; Lizin et al., 2013
	Thin-film-based		
	Others - organic PV/non-silicon-based panels	dye-sensitised cells, and perovskite	
Stages / phases	Upstream (manufacturing)	quartz mining, metallurgical-grade silicon, silicon purification, ingots and wafers, cell processing, and panel making.	Ali et al., 2022; Baharwani et al., 2014; Lamnatou et al., 2014; Lima et al., 2021; Zou et al., 2017
	Midstream (transportation, installation, use and maintenance)	– Transport to site – auxiliary electricity demand – cleaning of panels, repair, replacement	
	Downstream (End-of-life)	decommissioning, disposal, recycling, and reusing waste processing and transportation for these methods	

3. Research methodology

This research employs a case study research design to assess the embodied carbon emissions of solar PV systems and to generate insights for supporting CE practices within the supply chain. A single-case study approach was adopted, consistent with the methodological guidance of Yin (2018), who suggests that single cases are appropriate when the case is critical, unique, or revelatory and enables an in-depth investigation of a complex phenomenon.

The selected case, a solar PV system installed in an existing hotel building, represents a critical and information-rich case. Hotel buildings are among the highest energy consumers due to their continuous operational requirements and service-oriented functions (providing comfort and services to guests), contributing approximately 2% of the world's carbon emissions (Amanda & Sanjei, 2019). Additionally, the global hotel sector is under pressure to significantly reduce carbon emissions, with a target of 66% reduction by 2030 and 90% by 2050 relative to the 2010 level (Iorgulescu et al., 2019). This context makes the selected case particularly relevant for examining embodied carbon emission within a high-impact sector.

The case is also considered revelatory, as it provides rare access to detailed, whole-life data on solar PV systems, including information on design, installation, operation, and maintenance stages. Such comprehensive data are typically difficult to obtain due to fragmented supply chains, the involvement of multiple stakeholders, and restricted access to proprietary information. This aligns with Yin's (2018) argument that single-case designs are justified when they enable the investigation of phenomena that are otherwise inaccessible.

This study adopts a cradle-to-grave system boundary, covering all lifecycle stages of the solar PV system. This includes raw material extraction and manufacturing (upstream), transportation, installation, operation and maintenance (midstream), and end-of-life processes, including dismantling, recycling, and disposal (downstream). This boundary ensures a comprehensive assessment of embodied carbon emissions across the full lifecycle of the system.

Data collection was conducted using multiple sources of evidence to enhance the validity and reliability of the findings. Primary data were gathered through semi-structured interviews with three professionals directly involved in the design, operations, and maintenance of the solar PV system. According to Yin (2018), although the number of interviews is limited, this is consistent with qualitative case study research, which prioritises depth of understanding over breadth of coverage.

In addition, document analysis was undertaken to validate and supplement the collected data. The reviewed documents included system manuals, datasheets, summary sheets, and maintenance records that were examined to validate the data, including system components and their specifications, manufacturing countries, warranty, requirements of installation energy, maintenance activities and their frequencies, and manpower requirement details.

Where primary data were incomplete or unavailable, secondary data from established literature were used to support the estimation of embodied carbon emissions as presented in Table 2.

Table 2, Data gathered and assumptions formulated for the evaluation of embodied carbon emissions

Parameter / Data	Value / Description	Source
System capacity	300 kW	System documents
Panel specifications	Brand, efficiency, warranty, manufacturer location	System manuals
Number of components	Quantity, layout, and system configuration	System summary sheet
Maintenance activities	Frequency and type of maintenance	Maintenance records
System lifespan	25 years	Chowdhury et al. (2020); Kumar et al. (2020)
Average electricity generation per day	1200 kWh/day (300 kW × 4 peak hours)	System datasheet
Panel embodied carbon factor	210 kg CO ₂ -eq/m ² (as perecoinvent V2)	Kristjansdottir et al. (2016)
Mono- vs polycrystalline ratio	38.1: 27.2	Wild-Scholten (2013)
Inverter emission factor	3.36 g CO ₂ -eq/kWh (as perecoinvent V2)	Wild-Scholten (2013)
Mounting structure emission factor	8.97 kg CO ₂ -eq/m ² per panel	Wild-Scholten (2013)
Cables and connectors	0.511 kg CO ₂ -eq/m ² of panel	Wild-Scholten (2013)
Transport emission (road)	0.000624 kg CO ₂ /t·km	Ali et al. (2022)
Transport emission (ocean)	0.0529 kg CO ₂ /t·km	Ali et al. (2022)

Note. The study does not directly extract data from life cycle inventory databases such as Ecoinvent. Instead, emission factors are derived from peer-reviewed LCA studies that report values originally based on such databases.

Assumptions made during the calculation process were explicitly defined and listed below to ensure transparency and reproducibility:

- Alternative current (AC) cables, earth cables, and other miscellaneous components were sourced locally within a 4 km radius of the installation site (hotel).
- Transportation distances were estimated using standard logistics routes (e.g., port-to-port and road transport) based on Google Maps.
- Protective equipment (e.g., surge protectors, enclosures, MCBs, and RCCBs) was excluded from carbon calculations due to lack of reliable emission data; total estimated weight = 25 kg. OR Transportation emissions for minor components were considered negligible (<0.0001 kg CO₂) and excluded.

A combination of content analysis and descriptive statistical techniques was employed to interpret qualitative inputs and quantify carbon emissions. The detailed calculation procedures for embodied carbon calculations are presented in Section 4.2.

While the findings of this study are not intended for statistical generalisation, they contribute to analytical generalisation by providing context-specific insights into the carbon implications of solar PV systems and the role of CE practices within the supply chain.

4. Research Analysis and Findings

4.1. DESCRIPTION OF THE SOLAR SYSTEM USED IN THE HOTEL

The selected case study is a grid-connected (on-grid) monocrystalline solar PV system with a total installed capacity of 300kW. The system comprises rooftop installations, 100 kW (including parking roofs), and ground-mounted installations, 200 kW. Table 3 describes the components of the hotel’s solar PV system.

Table 3, Components of the Solar PV System of the Hotel

Component	Country of Manufacturer	Quantity	Total Weight / Area	Warranty (Year)
Panel	Singapore	990	21.6 kg x 990 = 21384 kg (21.384 tons) 1.665 m x 0.991 m x 990 = 1633.51 m ²	25
Inverter	Austria	1 6	34.8 kg x 6 = 208 kg (0.208 tons)	10
		4 8	43.4 kg x 08 = 347.2 kg (0.3472 tons)	
External DC disconnect		28	0.3 kg x 28 = 8.4 kg (0.0084 tons)	3
Protective equipment	Germany	5 sets	25 kg (0.025tons)	
AC and Earth Cables	Sri Lanka	5 sets		
Mounting Structure		5 sets	32,736 kg (32.736 tons)	

4.2. ASSESSMENT OF CARBON EMISSIONS OF THE SOLAR PV SYSTEM

The total carbon emission of the solar PV system of the hotel was estimated along the supply chain, which includes all the steps of electricity production via distributed solar PV, from the manufacturing of the PV system components to the end-of-life or decommissioning. The total system is divided into three main stages: upstream, midstream, and downstream. The solar PV system's supply chain highlights roles in selection, purchase, transportation, installation, and maintenance. Solar PV components are manufactured internationally and shipped to Sri Lanka, where local providers stock and transport them to installation sites. Some items are sourced locally for direct delivery to the hotel. Installation occurred during hotel construction and required minimal structural adjustments. Maintenance involves regular cleaning by trained hotel technicians and more thorough bi-annual checks by installers, focusing on panel cleanliness and system functionality. Components are replaced as needed, considering the 25-year panel warranty. Despite operating since 2017, only four panels are requiring replacement due to damage.

4.2.1 Upstream - Manufacturing Phase

This stage includes the calculation of the panel, inverter, mounting structures, cables and connectors. However, the lack of specific data on the carbon footprint of auxiliary electrical components like protective equipment necessitates their exclusion to ensure the analysis remains as accurate and reliable as possible with the available data. This decision prioritises precision in the calculation of carbon emissions by focusing on major components with well-documented emission profiles. In the absence of specific case data, authors referenced established studies and notably applied the Ecoinvent databases. The total carbon emission during the upstream phase is 507,596.46 kgCO₂; refer to Table 4 for detailed calculations.

Table 4, Estimated carbon emission from the solar PV system in the upstream stage

Component	Data from existing literature and Ecoinvent software		Carbon emission
Panel	Embodied carbon of polysilicon REC panels (Kristjansdottir et al., 2016)	210 kg CO ₂ eq/m ²	294.15 kgCO ₂ /m ²
	Ratio of mono- and polycrystalline silicon carbon footprints (Wild-Scholten, 2013)	38.1: 27.2	
	Panel area	1633.51 m ²	480,497 kg CO₂
Inverter	Carbon emission (Ecoinvent 2.2)	3.36 g CO ₂ per kWh	11,612.16 kg CO₂
	Electricity generation for 8 years	1200kWh/day x 30 days/month x 12 months/year x 8 years = 3,456,000kWh	
Mounting structures	Carbon emission for aluminium structures (Wild-Scholten, 2013)	8.97 kgCO ₂ -eq/m ²	14,652.58 kgCO₂
	Area of the panel (area of the mounting structure)	1633.51 m ²	
Cables and connectors	Carbon emission	0.511 kg CO ₂ per m ²	834.72 kgCO₂
	Panel area	1633.51 m ²	
<i>Total embodied carbon emission through the upstream phase</i>			507,596.46 kgCO₂

4.2.2. Midstream – Transportation, Installation, Operation, and Maintenance Phases

Transportation Phase

The distances between the manufacturing plant and the installation site, and the means of transport are used to calculate the emissions related to PV system transportation (Constantino et al., 2018). Specific transport distances for solar PV components are determined by common logistics routes and methods. This assumption allows for the incorporation of transportation emissions into the lifecycle analysis, acknowledging that while there is variability, a standard set of distances can provide a reasonable estimate of these emissions. According to Ali et al. (2022), carbon emissions from road transport are 0.000624 kg CO₂/t.km, and those from ocean transport are 0.0529 kg CO₂/t.km.

The panels are assumed to be transported by ocean freight from the place of manufacture to the Port of Colombo, and then delivered by containers to the warehouses and then delivered by trucks from the stores to the installation sites. The ocean transport from the port of Singapore to the port of Colombo in Sri Lanka was considered, and the road distance from the port of Colombo in Sri Lanka to the warehouse at Kandana and then from the warehouse to the hotel was considered. Other components, including the inverter and the external direct current (DC) disconnect, undergo a similar sequence of processes. However, trucks directly transport the locally manufactured mounting structures from the manufacturing company to the installation site.

Assume that local retailer shops within 4 km of the hotel are the source of the AC cables, earth cables, and other miscellaneous items, and assume that the total weight of these items is 25 kg. As a result, since the estimated value for these components' carbon emissions is 0.0001 kg of CO₂, it was not included in the computation. The total carbon emission through the transportation phase is 3774.1196 kg CO₂, (refer to Table 5 for detailed calculations).

Table 5, Carbon Emission During the Transportation Phase

Components	Country of manufacture (port)	Mode of Transport	Distance (km)	Carbon emission (kg CO ₂)	
Panel (21.384 t)	Singapore Port to Colombo Port	Ocean	3,040	3,438.8893	3441.0376
	Colombo Port to Kandana warehouse	Road	21	0.2802	
	Kandana warehouse to hotel (installation location)		140	1.8681	
Inverter (0.5552t)	Austria	Ocean	7,485	219.8350	219.8908
	Colombo port to installation site	Road	161	0.0558	
Mounting Structure (32.736 t)	Sri Lankan Company	Road	160	3.2684	3.2684
Protective equipment (0.025t)	Hamburg port of Germany to Colombo port of Sri Lanka	Ocean	8,060	106.5935	106.5960
	Colombo port to installation site	Road	161	0.0025	
External DC disconnect (0.0084 t)	Austria	Ocean	7,485	3.3260	3.3268
	Colombo port to installation site	Road	161	0.0008	
<i>Total embodied carbon emission through the transportation phase</i>				3774.1196	

Installation Phase

Installation-related carbon emissions, which might include site preparation and system assembly, are notably minimised for this solar PV project due to its integration in the design and construction phases of the hotel. The installation predominantly required electrical energy for minimal roof modifications, thereby allowing these emissions to be disregarded in our analysis.

Operation and Maintenance Phase

The solar PV system is emissions-free during operations, while maintenance is critical for its efficiency; it emits carbon emissions (Peng et al., 2013). Clemons et al. (2021) and Yudha et al. (2018) remark on the low maintenance needs of PV systems, primarily focusing on surface cleaning to remove debris, which typically uses water. Tawalbeh et al. (2021) also note that both manual and automated cleaning primarily employ water for this purpose. Despite the necessity of electricity for the hotel's water distribution system to facilitate this cleaning, the overall impact remains minimal. The need for maintenance varies with environmental conditions, with ground-mounted systems requiring more frequent cleaning due to their proximity to soil. Additionally, the lifecycle of system components, like the 25-year lifespan of PV panels compared to the shorter lifespan of inverters, dictates the schedule and nature of corrective maintenance activities.

According to the respondents' views, panel cleaning is done biennially and monthly for rooftop and ground-mounted solar PV systems, respectively. The sources of carbon emission from this maintenance activity are electricity used for the water distribution system and the upstream process of washing material. However, the upstream carbon emission of detergent is negligible, as mild detergent is used for solar panel cleaning and all-purpose detergent is used. According to the respondent and maintenance records, the estimated electricity required for the water distribution system to clean the hotel's solar panels is 3969 kWh. This estimate considers the pump's energy consumption (2 HP or 1.5 kW), the frequency of cleaning (monthly for ground-mounted panels and biennially for rooftop panels), the required water amount, and the cleaning time (approximately 4.5 hours for a 100-kW panel). Accordingly, for 8 years, the electricity used for cleaning the solar panels can be estimated as $1.5 \text{ kW} \times (3 \times 4.5 \text{ hours}) \times 196$ (rooftop 4 times in 8 years and 12 months \times 8 years \times 2) kWh. Assume that the solar PV system provides all the electricity for the water distribution system. According to the National Renewable Energy Laboratory (NREL, 2012), the carbon emissions per kWh of electricity generation by a solar PV system are approximately 40 g of CO₂. Therefore, the total carbon emissions from solar panel cleaning amount to 158.76 kg of CO₂ ($3969 \text{ kWh} \times 0.04 \text{ kg of CO}_2$). Further, in the case of panel replacement, since the installation within these 8 years, 4 panels (0.0864 tons) were replaced. Thus, the carbon emission for the replacement activity of the panel upstream is 13.9032 kg of CO₂. Further, other maintenance activities, including inspection of inverters, solar string testing, inverter terminal checking, panel board terminal block checking, cable insulation testing, and checking cable connectivity because the tendency to fail is high as all these are mostly under-soil wiring, once a year, can be excluded from the calculation as a minimal requirement of physical resources. Moreover, solar system installers or suppliers typically carry out all these maintenance tasks, which involve transporting carbon emissions from the solar provider's location to the site. But these can be excluded as less than 1 kg of CO₂. Thus, the total carbon emission from the maintenance phase of the solar PV system can be concluded as 172.66 kg of CO₂. Accordingly, the total carbon emission from the midstream solar PV is 3946.78 kg of CO₂.

4.2.3. Downstream - End-of-life or Decommissioning Phase

The carbon emission in the downstream phase was estimated based on assumptions and interviewees' perspectives, as the system is at one-third of its expected lifespan.

Respondents generally view panels, which contribute significantly to the solar PV system's waste volume, and recycling as the most effective method during the system's downstream process. A study by Prabhu et al. (2022) found that it takes 113.55 kWh/t of PV waste to treat silicon-based crystalline PV panels when they are no longer useful. Another study by Lima et al. (2021) found that recycling solar PV glass alone causes 25 MJ/m² of carbon emissions. As a result, recycling glass alone will generate 40,837.75 MJ ($25 \text{ MJ/m}^2 \times 1633.51 \text{ m}^2$) of carbon emissions. According to the respondent's perspective, the study assumes that the manufacturing company will handle the recycling; therefore, the transportation emissions, calculated in Table 5 for panel transportation, amount to 3,441.0376 kg of CO₂. Thus, the total carbon emission of panels at the downstream phase

will be 44,278.7876 kg of CO₂. Nonetheless, additional factors of the panel, primarily the emissions from silicon and stainless-steel recycling, must also be considered; transportation emissions, and emissions from other components also need to be included.

In the case of mounting structures, a local manufacturer was utilised, and generally, the manufacturer recycles aluminium at the factory level and uses that for making products. During recycling, the International Aluminium Institute (IAI, 2020) states that the aluminium recycling process consumes only 5% of the energy required for primary metal production, leading to carbon emissions of 0.5 metric tonnes of CO₂ equivalent per tonne of recovered aluminium (gate to gate). According to the respondents' perspective and the summary sheet document, each square meter of solar panels requires 2.5 kg of aluminium. This case requires the recycling of 4.08 tonnes of aluminium ($2.5 \text{ kg} \times 1633.51 \text{ m}^2 = 4083.775 \text{ kg} = 4.08 \text{ tonnes}$). The transportation costs are the same as those in Table 5, assuming a return to manufacturers, which amounts to 3.2684 kg of CO₂. Therefore, the expected carbon emission from the aluminium recycling is 2.04 tonnes, which is equal to 2,043.27 kg of CO₂.

In the Sri Lankan context, e-waste collectors receive various solar PV components, including inverters, cables, and protective equipment, due to the absence of a specific downstream management method for these components. Therefore, the downstream carbon emissions of the solar PV system only consider the panels and mounting structures. Total carbon emission from the downstream is 46,322.06 kg of CO₂.

Assessment is based on case study data, and with the estimated carbon emission value, the total embodied carbon emission of the case study with its 8-year lifetime is 511,543.24 kg of CO₂, equating to an estimated 148.06 g of carbon emission per kWh of electricity generation. There are chances to increase for the rest of the lifetime, as it has still reached one-third of its expected lifetime. Although the chosen case has not yet progressed to the downstream phase, the downstream carbon emission is 46,322.06 kg of CO₂, equating to an estimated 154.41 g of carbon emission per kWh of solar PV capacity. The manufacturing of the panel was responsible for over 95% of this total emission, while transportation was responsible for a significant emission (91%) in transportation in the midstream phase due to its heavy weight, even if it was a shorter distance via ocean. In the comparison of upstream and downstream carbon emissions of the solar PV system, upstream emissions are approximately eleven times greater than downstream emissions, highlighting the necessity for circularity in the solar PV supply chain. Thus, it is obvious that a considerable amount of carbon emissions is available for solar PV systems, even if they are stated as a sustainable solution. Thus, it is mandatory to take action to overcome this gap.

4.3. SENSITIVE ANALYSIS OF EMBODIED CARBON EMISSION

The embodied carbon estimation performed as mentioned above was repeated for the possible solar panel manufacturing countries of India, China, South Korea, the USA, and Canada. The embodied carbon of the solar PV system increases as the manufacturing countries are further away from the installation site. Similarly, an embodied carbon emission comparison of inverters at the upstream stage was performed for varying solar radiation times and years of operation of the solar PV system. Figure 1 presents a comparison

of the embodied carbon analysis for the selected solar PV system across these alternative solar manufacturing countries and the inverters' embodied carbon emissions against the solar ratio and the solar system's operation year.

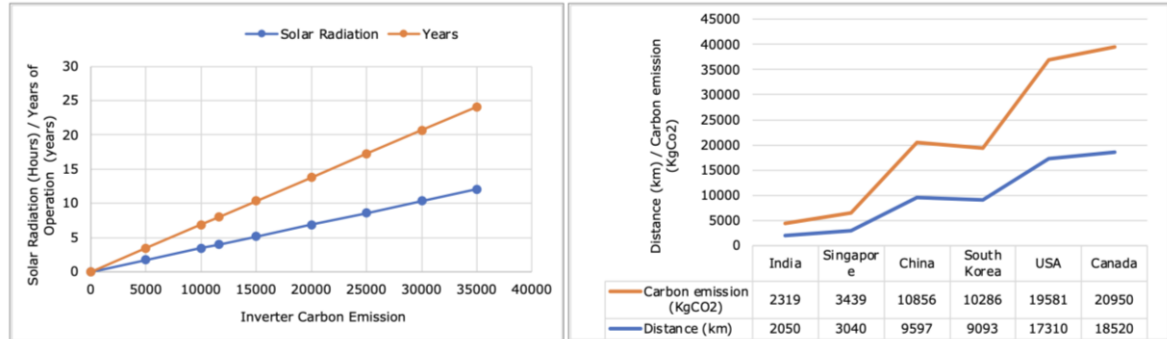


Figure 1, Embodied carbon emission comparison against solar panel manufacturers, solar ratio and operation year

5. Discussion

The findings of this study highlight a solar PV supply chain that is highly dependent on imported components, resulting in a disproportionate contribution from upstream manufacturing and international transportation. In the Sri Lankan context, this reflects a structural constraint arising from limited domestic manufacturing capacity, necessitating reliance on long-distance supply chains, particularly from Asian and European markets. Consequently, embodied carbon associated with maritime logistics becomes highly significant, despite being underemphasised in many global PV life cycle assessments. Furthermore, the dominance of upstream emissions highlights the limited development of localised CE mechanisms, particularly in relation to PV module reuse, refurbishment, and recycling infrastructure. From a policy perspective, the findings indicate a gap in Sri Lanka's renewable energy strategy, where emphasis has largely been placed on capacity expansion rather than lifecycle carbon optimisation. This underscores the need to integrate embodied carbon considerations into national solar energy policies, procurement frameworks, and end-of-life management systems.

The thorough examination of the solar PV system's lifecycle highlights the critical role of each phase in determining its overall carbon emission. The upstream manufacturing phase indicated that key components, such as solar panels, inverters, mounting structures, and cables, substantially contribute to lifecycle emissions, totalling 507,596.46 kg CO₂. The exclusion of auxiliary components, owing to data constraints, was a conscious decision that underscores the necessity for dependable emission profiles, especially from sources such as the Ecoinvent databases. This focused strategy elucidates the emissions linked to manufacturing while underscoring the imperative for continuous research aimed at mitigating these emissions. Future research should incorporate supplementary elements to provide a comprehensive evaluation of solar PV systems.

The transportation phase, contributing 3,774.1196 kg of CO₂, illustrates how logistical choices significantly impact emissions. The methodology, based on standard logistics routes, reveals that optimising transport strategies, especially given the notable difference in emissions between ocean transport (0.0529 kg CO₂/t.km) and road transport (0.000624 kg CO₂/t.km), could yield substantial reductions in transportation emissions. This highlights a critical area for stakeholders to focus on improving efficiency within supply chains.

The installation phase demonstrated the benefits of integrating solar PV systems into the building design from its inception. Minimal carbon emissions mostly stemmed from restricted roof alterations, demonstrating an efficient approach to mitigating installation-related emissions. This proactive strategy exemplifies sustainable construction techniques, indicating that future projects ought to implement comparable integrative strategies to improve efficiency and reduce environmental impacts.

The operation and maintenance phase reaffirmed the emissions-free nature of solar energy generation. Although maintenance tasks such as cleaning do incur some emissions (172.66 kg CO₂), the low frequency and energy-efficient practices mitigate their overall impact. The analysis highlights the potential to further optimise maintenance processes, suggesting that stakeholders should explore improved cleaning methods and logistics to enhance the sustainability of solar systems.

Finally, the downstream phase highlights the significance of efficient end-of-life management and recycling methodologies. The estimated carbon emissions of 46,322.06 kg CO₂ from waste management, predominantly from panel recycling, highlight the environmental consequences of inadequate waste management practices. The stark disparity between upstream emissions (exceeding 95% of total emissions) and downstream emissions underscores the imperative for circularity within the solar supply chain. This points to the importance of developing comprehensive e-waste management strategies and promoting recycling practices that could mitigate the carbon footprint of solar technologies.

The study reveals emissions of 148.06 g of CO₂ per kWh over an eight-year lifecycle. Tawalbeh et al. (2021) found that the carbon footprint emission from PV systems falls within the range of 14–73 g CO₂-eq/kWh, significantly lower than the emissions from oil burning. Thus, this investigation demonstrates significant emissions linked to the lifecycle of solar PV systems, despite their commonly held perception as sustainable energy options. Mitigating these emissions necessitates a comprehensive strategy that encompasses optimising manufacturing processes, refining logistics, augmenting maintenance practices, and formulating efficient end-of-life management plans. By concentrating on these domains, stakeholders may facilitate a more substantial contribution of solar energy to a sustainable energy future.

The present study supports the findings of Erol et al. (2021) and Kumar et al. (2020) that the market for solar PV systems currently operates under the linear economy model (take, make, use, and waste). This model perpetuates the inefficient use of natural resources and underutilises the potential of solar PV waste, which contains a variety of useful elements and provides low-cost material additions to the manufacturing sector.

Accordingly, Tawalbeh et al. (2021) emphasise the necessity for paradigm shifts towards a CE in the solar PV industry, which could reduce carbon emissions by an estimated 42% through enhanced recycling practices, design modifications for easier reuse, and stringent regulations. This shift, as advocated by Rahman and Chowdhury (2023), necessitates embedding CE principles throughout the solar PV value chain to ensure resource longevity, reduce waste, and reduce energy consumption. The principles of CE, detailed by Joensuu et al. (2020), propose a holistic approach to resource management that emphasises retaining value, improving efficiency, and minimising environmental impact.

The findings of this study corroborate those of Askar et al. (2022), Gallego-Schmid et al. (2020), and Minunno et al. (2018), highlighting the significant role that CE plays in enhancing resource efficiency, reducing energy consumption, and eventually contributing to climate mitigation efforts. In the realm of solar PV systems, the standard practice of recycling, as noted by Contreras-Lisperguer et al. (2021) and Radavicius et al. (2021), represents just the beginning of realising circularity. Van Opstal and Smeets (2023) put forth that extending the lifespan of PV panels through repair, reuse, and recycling is fundamental to achieving higher levels of circularity. Heath et al. (2020) and Tsanakas et al. (2020) further articulate the preference for repair and reuse over recycling, underscoring the potential of these practices in enhancing the CE for solar panels.

Furthermore, the findings resonate with Tsanakas et al. (2020) in recognising repair and reuse not just as viable but as preferred alternatives to recycling within the context of a CE for solar panels that are still far from the end of their technological life. Notably, approximately 80% of solar PV waste arises from panels compromised during manufacturing failures, shipping, or within the initial years of operation. On the other hand, these panels present an opportunity for repair or upgradeability, with 45% to 65% of them salvageable for further use. Van Opstal & Smeets (2023) and Curtis et al. (2021) have highlighted the significant potential for circular practices within the industry. However, due to challenges such as the lack of market development, standardised testing, and incentives for the repair, direct reuse, and recycling of solar PV components, this potential remains underexploited. Such insights underline the critical role of solar energy in fulfilling renewable energy needs while also highlighting the underlying link between the adoption of CE practices and the achievement of lower-embodied carbon objectives. Therefore, our findings advocate for a more concerted effort towards the integration of CE principles across the solar PV sector.

By 2050, leveraging the CE approach could markedly transform the solar PV industry, transitioning it from a linear to a regenerative model and positioning it as a cornerstone of sustainable development and climate change mitigation. This forward-looking perspective not only reinforces the environmental imperatives outlined by Tirelli and Besana (2023) but also sets a clear roadmap for future research and policymaking aimed at realising the full potential of solar PV systems within a CE framework.

6. Conclusions

The study concludes that the upstream, midstream, and downstream components of the selected monocrystalline solar PV system with the capacity of 300 kW are responsible for 511,543.24 kg CO₂ emissions (148.06 g of carbon emissions per kWh of electricity generation) for one-third of its expected lifespan. Of this, the upstream phase that contains the panel, inverter, mounting structures, and cables and connectors is responsible for 95% of the total, while the heavy weight of the components led to significant emissions (91%) during the midstream phase of transportation. As Sri Lanka is at an early stage of system use, it has yet to consider the downstream of the system, the disposal of components. However, it is expected that the downstream process will contribute another 46,322.06 kg of CO₂ from the panels and mounting structures alone. Further, returning panels and other components for recycling to e-waste collectors will be a prime challenge to the Sri Lankan solar PV system. These findings indicate that panel manufacturing and transportation have a greater potential for CE adaptation. The analysis revealed that the embodied carbon emission of the solar PV system is highly sensitive to the distance of the manufacturing countries from the installation site, while the embodied carbon emissions of the inverters are directly proportional to both the solar ratio and the solar system's operation year. The above conclusions are subject to consideration of eight years of the system's lifetime, assumptions about the exclusion of components due to data gaps, and speculative transportation impacts. The research provides an opportunity for the application of CE principles in the solar PV supply chain. This research will provide valuable insights for policymakers, manufacturers, and industry stakeholders to determine suitable spots for implementing circular economy concepts.

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8. References

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