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Life-Cycle Environmental Impacts of Charger Mix in a Photovoltaic – Battery Energy Storage System Electric Vehicle Charging Station: A Case Study of a Highway Rest Stop in Vietnam

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Abstract

Vietnam's rapid transport electrification and its carbon-intensive power sector necessitate decentralized renewable energy solutions. While solar photovoltaic (PV) systems are expanding, comprehensive life cycle assessments (LCA) of PV integrated with battery energy storage systems (BESS) for electric vehicles (EVs) charging stations under local tropical conditions remain scarce. The study assesses the cradle-to-grave environmental impacts of a grid-connected PV-BESS EV charging facility in South-Central Vietnam over a 25-year lifespan. Adhering to ISO 14040/14044, an attributional LCA was conducted using OpenLCA and Ecoinvent 3.11, applying the ReCiPe 2016 Midpoint (H) method. The functional unit is defined as the direct current electricity delivered to the EV battery. The system exhibits a total global warming potential (GWP) of 5.58×10^5 kg CO_2-eq, translating to an emission intensity of 0.0611 kg CO_2-eq/kWh. Upstream manufacturing dictates the environmental burden, with the PV subsystem and BESS accounting for 70.09% and 6.09% of total climate impacts, respectively. The system also induces mineral resource scarcity evaluated at 2.87×10^4 kg Cu-eq. The sensitivity analysis indicates that different EV charger deployment scenarios lead to significant variations in the environmental indicators. By stratifying supply-chain electricity grids to separate manufacturing and operational phases, this study provides a geographically precise carbon footprint for hybrid infrastructure.

Keywords: Battery energy storage system, charging infrastructure, cradle-to-grave, life cycle assessment, photovoltaic systems.

1. Introduction

The environmental impacts of road transport emissions have driven the global transition toward low-carbon mobility, with electric vehicles (EVs) recognized as a key solution for reducing greenhouse gas (GHG) emissions [1, 2].

In Vietnam, this transition is accelerating under the commitment to achieve net-zero emissions by 2050 through national policies such as the Power Development Plan VIII (PDP8) [3]. However, since the power sector remains strongly dependent on fossil fuels, large-scale transport electrification may still be associated with substantial indirect emissions while simultaneously increasing electricity demand and peak-load pressure on the grid [4].

To reduce the carbon intensity of EV charging, renewable energy sources, particularly solar photovoltaic (PV) systems, have been rapidly deployed, reaching over 18.677 GW by 2024 [5]. Nevertheless, the output of solar PV is inherently intermittent and may not coincide with EV charging demand, which often varies over time and may concentrate during specific operating periods. In this context, battery energy storage systems (BESS) can play an important role by storing surplus solar electricity and supplying it when PV generation is insufficient, thereby improving the reliability and environmental performance of EV charging stations (EVCs).

The rapid expansion of EV charging infrastructure also creates additional electricity demand and local grid stress [6]. Previous studies have shown that electricity use during operation can be a dominant contributor to global warming potential (GWP) in charging-related systems [7, 8]. For this reason, integrating PV–BESS systems into EVCs has attracted increasing attention as a strategy to reduce indirect emissions and improve the environmental performance of charging services [9].

Despite this growing interest, the existing literature still presents three important gaps. First, although EV charging infrastructure and renewable-powered charging systems have been studied in various contexts, there remains limited life cycle assessment (LCA) evidence for grid-connected PV-BESS EV charging systems under Vietnamese conditions, where the electricity mix, climatic conditions, and infrastructure context differ from those of more frequently studied

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regions. Second, many existing studies implicitly treat EV charging stations as single-function systems, even though real facilities may simultaneously serve EV charging demand and auxiliary loads such as lighting, cooling, retail, and other service-house functions. This multifunctional nature complicates the attribution of environmental burdens and requires a more explicit allocation framework. Third, while recent studies on EV charging infrastructure have primarily focused on charging technology development [10, 11], the interaction between infrastructure provision and EV use [12, 13], deployment strategies and optimal site selection, as well as the economic and technical performance of installation and operation [14, 15], there is still insufficient evidence on how charger deployment strategy itself influences life-cycle environmental burdens, especially across impact categories beyond climate change.

This study addresses this research gap by conducting an LCA of a grid-connected PV-BESS system for an EVC located in Cam Lam, Khanh Hoa province, Vietnam. The system configuration comprising a PV capacity of 1,238 kW, a BESS capacity of 899 kWh, and a converter capacity of 247 kW was optimized based on prior techno-economic simulations using HOME Grid, as illustrated in Fig. 1 [16]. Environmental impacts are evaluated following ISO 14040/14044 using OpenLCA with the Ecoinvent 3.11 database (cutoff system) and the ReCiPe 2016 Midpoint (H) method over lifetime.

Beyond quantifying life-cycle impacts, this study is intended to support system design and management of PV-BESS EV charging infrastructure. Specifically, it aims to: (i) identify the dominant environmental hotspots across life-cycle stages and system components; (ii) evaluate the implications of treating the charging station as a multifunctional system with both EV load and service-house load; and (iii) examine how alternative charger deployment strategies affect environmental burdens. By doing so, the study provides practical insights for designing lower-impact EV charging infrastructure in Vietnam and similar emerging-market contexts.

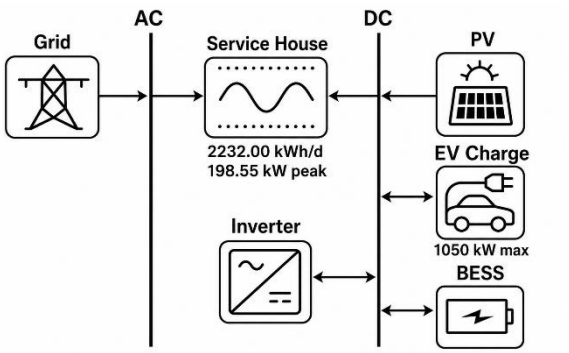


Fig. 1. Simulated components of the system

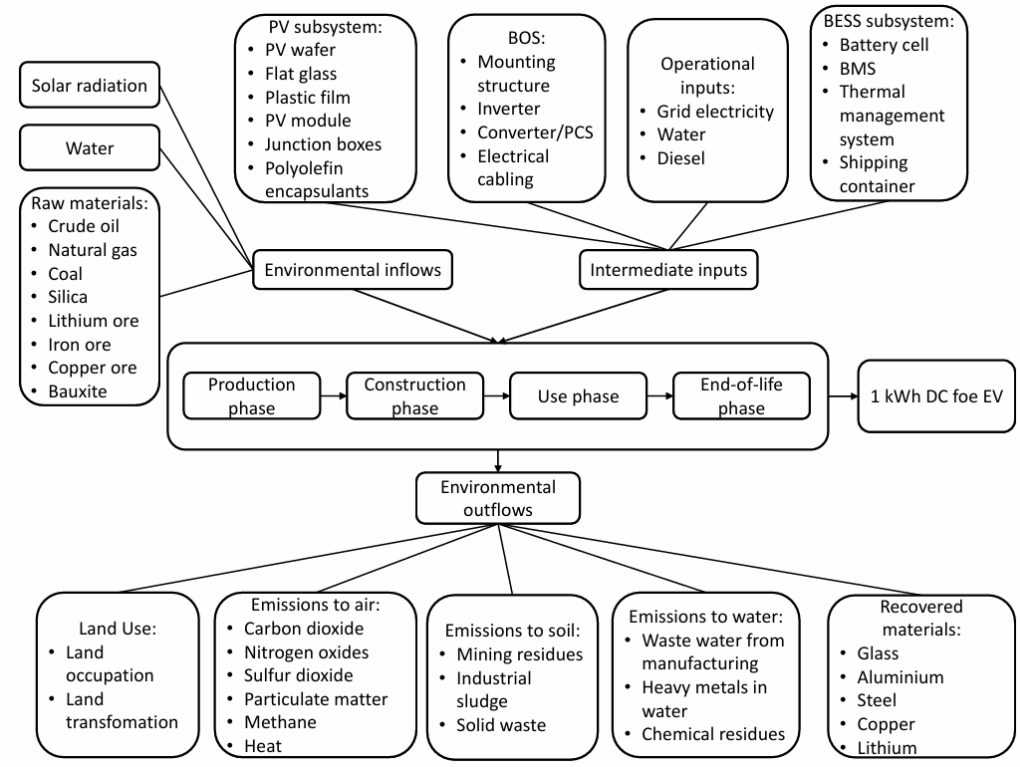


Fig. 2. System boundary, material flows, and life-cycle stages considered in the system

2. Materials and Methods

2.1. Research Objective and Intended Application

Accordingly, this study aims to quantify the life-cycle environmental impacts of the proposed system over a 25-year lifespan, as shown in Fig. 2, identify environmental hotspots across specific life-cycle stages, components, and elementary flows (e.g., silver paste production, aluminum framing, or international logistics), and report impact intensity results normalized to the functional unit (e.g., kg CO_2e per kWh delivered). These results can support policymakers, infrastructure developers, and the scientific community in benchmarking future green mobility projects in the ASEAN region.

2.2. Goal and Scope Definition

The system consists of a PV array, a lithium-ion BESS, and a bidirectional power converter connected to the low voltage grid. In this grid connected PV-BESS-EVC system, the BESS is not intended to replace grid supply, but functions as an energy buffering and renewable integration component. It stores surplus PV electricity and supplies electricity when PV generation is insufficient for EV charging and service house loads, thereby improving temporal balancing, increasing local PV self consumption, and reducing instantaneous dependence on grid electricity.

In accordance with ISO 14044 and International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task 12 guidelines, the functional unit serves as the quantitative reference for the study, normalizing all material flows and environmental impacts to a common measure of service delivered [17]. Although the system is grid-connected, all electricity whether originating from PV or battery discharge, or grid import is converted and delivered as DC electricity at the EV charger output (Fig. 1); therefore, DC electricity delivered to the EV battery is selected as the functional unit. The calculated impacts reflect the useful energy that provides the mobility service, offering a more accurate and conservative metric for "green mobility" than generation-based functional units. This functional unit is adopted in previous studies. For instance, Rosmeika *et al* (2026) assessed one kWh of electricity, representing the total electricity delivered during operation as the functional unit [18].

Based on simulations at the Cam Lam site, the EV charging station is considered to serve 20 charging sessions per day and the load demand of the service house over 25 years is 20.4 GWh [16]. This assumption was used as the basis for a representative design of the demand derived from the prior HOMER Pro techno-economic simulation. The PV capacity, BESS capacity, and converter capacity were optimized according to this demand level. Incorporating time-varying demand growth would require re-optimizing the PV-BESS-converter sizing and re-simulating system dispatch, which is beyond the scope of the present study. This study assumes an average charging demand of 50 kWh per session, resulting in a lifetime throughput of approximately 9.125 GWh. The PV-BESS energy supply system provides electricity to the entire rest stop and serves two main types of demand: service house load and the EV charging load, which contain a system of EV chargers. The total lifetime electricity demand of the system, expressed in kWh over the 25-year lifetime, can be written as:

$$E_{total} = E_{EV} + E_{service} \tag{1}$$

where E_{total} (kWh) is the total lifetime electricity demand of the system, E_{EV} (kWh) is the lifetime electricity delivered to EV batteries, and $E_{service}$ (kWh) is the lifetime electricity demand of the service-area facilities. Based on the functional unit, the environmental impact intensity of EV charging is calculated by dividing the total life-cycle impact attributed to EV ($Impact_{EV,total}$) by the lifetime electricity delivered to EV batteries (E_{EV}):

$$\mathrm{IE} = \frac{\mathrm{Impact}_{\mathrm{EV,total}}}{\mathrm{E}_{\mathrm{EV}}} \tag{2}$$

where *IE* represents the impact intensity per unit of electricity delivered to EV, expressed in kg CO_2-eq/kWh and $Impact_{EV,total}$ is the total life-cycle impact attributed to EV charging, expressed in the unit of the selected impact category (kg CO_2-eq for climate change).

The PV-BESS infrastructure supplies electricity to both EV charging and service-area loads. Therefore, the environmental impacts of the power supply system cannot be fully attributed solely to EV charging. In accordance with the allocation principles of ISO 14044, these impacts should be distributed among the system functions based on their underlying physical relationships. In this study, an energy-based allocation method is applied because it reflects the physical relationship between electricity generation and electricity use within the system. The ISO 14040 framework allocates environmental burdens based on physical causes rather than market-based mechanisms [19]. Under the energy-based allocation method, the study estimates the emissions of the PV-BESS system allocated to the EV charging system. The allocation factor assigned to EV charging (AF_{EV}) is calculated as:

$$\mathrm{AF}_{\mathrm{EV}} = \frac{\mathrm{E}_{\mathrm{EV}}}{\mathrm{E}_{\mathrm{total}}} \tag{3}$$

The environmental impacts of the PV-BESS system attributed to EV charging ($Impact_{PV\text{-}BESS,EV}$) are then determined as:

$$\mathrm{Impact}_{\mathrm{PV\text{-}BESS,EV}} = \mathrm{Impact}_{\mathrm{PV\text{-}BESS}} \times \mathrm{AF}_{\mathrm{EV}} \tag{4}$$

where $Impact_{PV\text{-}BESS,EV}$ is the portion of the total life-cycle impact of the PV-BESS system allocated to

EV charging (kg CO_2-eq for climate change) and $Impact_{PV\text{-}BESS}$ is the total life-cycle impact of the PV-BESS system (kg CO_2-eq for climate change).

Finally, the total environmental impacts attributed to EV charging ($Impact_{EV,total}$) includes the amount of environmental impact of the PV-BESS system serving the chargers ($Impact_{PV\text{-}BESS,EV}$) and the environmental impact of the manufacturing process of those chargers ($Impact_{chargers}$). This parameter is expressed as:

$$\text{Impact}_{\text{EV,total}} = \text{Impact}_{\text{PV-BESS,EV}} + \text{Impact}_{\text{chargers}} \quad (5)$$

where $Impact_{EV,total}$ is the total environmental impacts attributed to EV charging (kg CO_2-eq for climate change), and $Impact_{chargers}$ is the environmental impact of the chargers (kg CO_2-eq for climate change).

Following the system-boundary principles of ISO 14040/14044, the cradle-to-grave life cycle of the studied system is grouped into four analytical phases: production, construction, use, and end-of-life. The production phase captures upstream raw material extraction and component manufacturing, including PV modules, BESS, power conversion systems, EV chargers, and balance-of-system (BOS) components. The construction phase includes transportation and installation of all system components. The use phase covers operation, maintenance, component replacement, and operational energy losses over the 25-year lifetime. The end-of-life phase includes dismantling, transportation, recycling, and final disposal. This phase also covers hydrometallurgical recycling of battery materials after thermal treatment for electrolyte removal, enabling metal recovery; non-recoverable polymers and LiPON are treated by incineration [20].

2.3. Life Cycle Inventory Analysis

The data and sources are shown in Table 1 and Table 2. When Vietnam-specific datasets (VN) are unavailable in Ecoinvent, "Rest of World" (RoW) or" Global" (GLO) datasets are utilized. For manufacturing processes, datasets reflecting the Chinese (CN) electricity mix are prioritized, as the PV and battery supply chains are heavily concentrated in China.

An attributional LCA approach is applied using the "allocation, cut-off by classification" system model from Ecoinvent, in which the product system accounts for primary material extraction and manufacturing burdens. To ensure geographical representativeness as required by ISO 14044, the electricity mix modeling was stratified by life cycle stage. For the upstream production phase, the Chinese power mix (CN grid, 0.354 kg CO_2-eq/kWh) is used to manufacture PV modules, BESS, and EV chargers. Conversely, the Vietnamese power mix (VN grid, 0.641 kg CO_2-eq/kWh) is used to manufacture the remaining components and for the operational phase (downstream) to accurately assess grid interactions and displacement effects at the installation site in Cam Lam [21]. Emission factors for both power grids are consistently taken from the Ecoinvent database. These grid emission factors are applied as a static baseline value, consistent with the attributional LCA framework and representative electricity-mix datasets in Ecoinvent. A time-dependent grid decarbonization pathway is not included because it would require additional assumptions on future power-sector transitions and was not considered in the prior HOMER Pro simulation.

Table 1. Inventory of major PV-BESS system components used in the production-phase life cycle inventory

Component	Quantity	Unit Mass (tonne)	Total Mass (tonne)	Description
PV Modules	1,782 items	0.0375	66.825	Risen RSM132-8-695BHDG (HJT, Bifacial). Modeled as 'photovoltaic module production, single-Si' modified for HJT material intensity (Ag paste, thinner wafers).
Mounting Structure	1 system	N/A	27.7	Aluminum/Galvanized steel rail system. Modeled using 'aluminum, extrusion' and 'steel, zinc coated'.
BESS	899 kWh	~0.018 t/kWh	16.182	LiFePO4 Containerized System. Includes cells, racks, battery management system (BMS), HVAC, and steel container. Modeled as 'battery production, Li-ion, LFP'.
Converter	247 kW	0.204	0.408	Bidirectional PCS, including replacement. Modeled as 'inverter production, 500kW'.
Inverter	150 kW	0.096	1.536	Huawei SUN2000-150K-MG0 inverter, including replacement
Cabling	1 system	N/A	4.5	DC solar cable (copper/cross-linked PE) and AC grid cable. Modeled as 'cable production, copper'.

Table 2. Transportation assumptions for major system components

Device	Origin-Destination	Transport mode	Length (km)
PV modules (RisenEnergy)	Zhejiang (CN) – Port (CN)	HD truck (>32t)	327
	Port (CN) - Hai Phong (VN)	Container Ship	1,873
	Hai Phong (VN) - Khanh Hoa (VN)	HD truck (>32t)	1,384
BESS (LFP, containerized)	Shanghai (CN) – Port (CN)	HD truck (>32t)	300
	Port (CN) - Hai Phong (VN)	Container Ship	785
	Hai Phong (VN) - Khanh Hoa (VN)	HD truck (>32t)	1,384
Bidirectional PCS	Hai Phong (VN) - Khanh Hoa (VN)	HD truck (>32t)	1,200
Inverter	Hai Phong (VN) - Khanh Hoa (VN)	HD truck (>32t)	1,200
EV Charger	Shenzhen (CN) – Port (CN)	HD truck (>32t)	300
	Port (CN) - Hai Phong (VN)	Container Ship	785
	Hai Phong (VN) - Khanh Hoa (VN)	HD truck (>32t)	1,384
Mounting structure (Al/steel)	Binh Duong (VN) - Khanh Hoa (VN)	HD truck (>32t)	451
Power cabling (Cu)	Dong Nai (VN) - Khanh Hoa (VN)	HD truck (>32t)	350

The *LCI* of PV generator subsystem models high-efficiency *HJT* technology. The total mass of 116.071 tonnes encompasses the core technical equipment, while civil works are modelled separately in the installation phase. The inventory of PV modules reflects glass-glass bifacial modules, comprising tempered flat glass, solar-grade polysilicon, silver metallization, copper interconnects, and polyolefin encapsulants. Manufacturing energy is modelled using the Chinese high-voltage electricity mix to match the specific supply chain. The mounting structure is modelled using aluminum based on IEA PVPS Task 12 benchmarks, assuming a material intensity of 5 to 10 kg per m^2 of module area [22]. A PV lifetime performance factor of 0.88 over the 25-year project lifetime was included in the prior HOMER Pro simulation, and the optimized PV-BESS-converter configuration used in this LCA was derived based on this PV output degradation assumption.

The BESS is modeled as a lithium iron phosphate ($LiFePO_4$) battery system. The ecoinvent dataset is adapted for containerized stationary storage by adding the mass of the steel shipping container, steel racking, and copper busbars. The energy density is adjusted to the system level (approx. 55 Wh/kg) rather than the cell level (approx. 160 Wh/kg) to capture the impacts of housing and cooling equipment. The baseline battery lifetime was assumed to be 6,000 cycles, equivalent to an expected lifespan of 15 years [16]. A depth of discharge (DoD) of 80% is applied to represent practical operating conditions. This lifetime is treated as a baseline assumption for a containerized stationary $LiFePO_4$ BESS equipped with battery management and thermal-control systems. Under tropical operating conditions in Vietnam, elevated ambient temperatures may accelerate temperature-dependent battery degradation, including both calendar aging and cycle aging, and may shorten the actual service life if thermal management is insufficient. In the present LCI model, this effect is not modeled as a separate temperature-dependent degradation function. Instead, the 15-year lifetime is retained as the baseline replacement assumption under controlled operating conditions.

The bidirectional Power Conversion System (PCS) is rated at 247 kW and is modelled using a proxy dataset representative of a large-scale central inverter. Material inputs are dominated by copper, steel, and aluminum. The PCS is assumed to undergo one replacement during the project lifetime.

The EVC system is designed according to the maximum charging demand of 1050 kW. Four charger power levels that according to VinFast charging network are considered: 30 kW, 60 kW, 150 kW, and 300 kW. The EV chargers are assumed to have corresponding masses of 60 kg, 170 kg, 395 kg, and 1500 kg, respectively. Since detailed mass data for VinFast chargers is not public, these values are approximated based on reference data from DC chargers of ABB. The chargers are assumed to be manufactured by suppliers in China then transported to Vietnam for installation. In OpenLCA, charger production is modeled as the process "charger production, for electric passenger car". The charger lifetime is assumed to be 15 years, while the charging efficiency ranges from 90% to 98.5% [23]. Four 150 kW chargers, five 60 kW chargers, and five 30 kW chargers are installed for the EV charging system.

The assumed manufacturing locations, transport modes, and representative overland transport distances for the major system components, which are used to quantify transport-related impacts in the life cycle inventory, are shown in Table 2. The analysis evaluates impacts at the Midpoint level. Midpoint indicators characterize environmental problems at an intermediate point in the cause-effect chain, providing a detailed and scientifically robust environmental profile. The study reports on the full suite of 18 ReCiPe Midpoint (H) indicators.

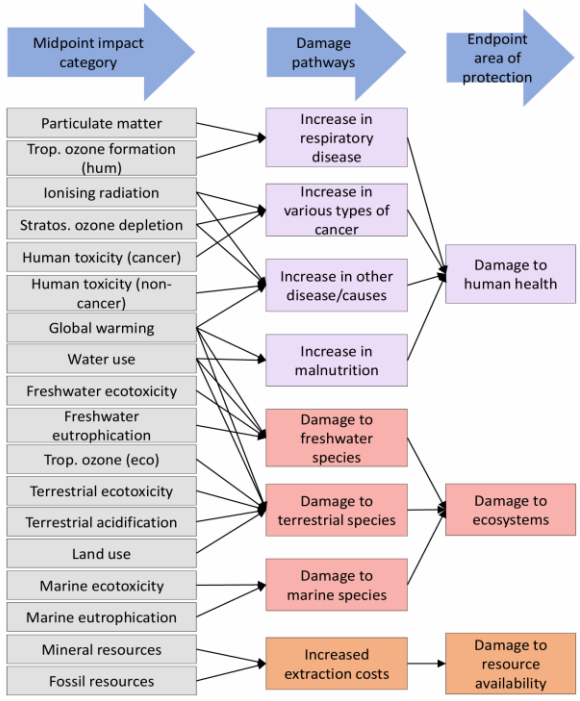


Fig. 3. Overview of the impact categories in the ReCiPe 2016 method

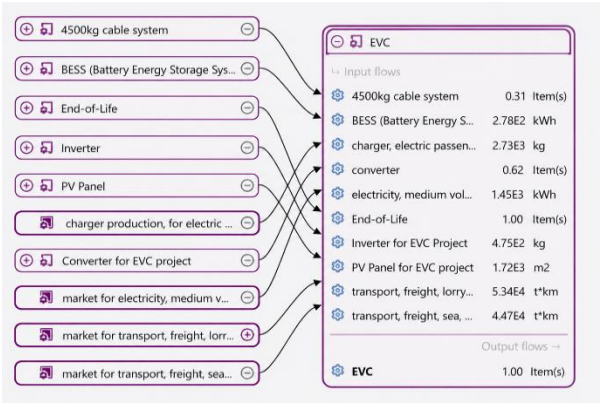


Fig. 4. Structure of the product system model 'Cam Lam EVCs' implemented in OpenLCA

2.4. Charger Deployment Scenarios

Three charger deployment scenarios were defined to examine how charger mix affects the life cycle environmental performance of the PV-BESS-EVC system. The number of chargers in each scenario is treated as a fixed deployment configuration rather than a time dependent expansion plan. These scenarios represent charger deployment strategies rather than dynamic charging operation strategies. Therefore, the PV-BESS configuration, electricity demand, functional unit, allocation procedure, and cradle to grave system boundary are kept unchanged. The BESS capacity, DoD, lifetime, and operating role are also kept identical across scenarios. Only the charger composition is varied, while the total installed charger capacity remains 1,050 kW in all scenarios.

The same lifetime EV charging demand is applied to all scenarios, with the functional unit remaining DC electricity delivered to the EV battery. Therefore, total charging time, vehicle arrival rate, queueing behavior, charger occupancy, vehicle specific charging duration, peak demand stress, and accelerated BESS degradation under ultra fast charging are not explicitly modeled. Ultra fast charging is represented through charger power ratings and material intensity rather than dynamic grid impact or C rate based BESS degradation modeling.

Scenario 1 represents a balanced configuration for a standard highway rest stop, combining different charger ratings to serve diverse charging needs and dwell times. Scenario 2 represents an ultra fast priority configuration for long distance users and EVs with larger battery capacities. Scenario 3 represents a flexible hybrid configuration, combining high power and lower power chargers to balance fast charging availability and operational flexibility. The detailed charger composition is summarized in Table 3.

Table 3. EV charger deployment scenarios considered in the sensitivity analysis

Scenario	Charger power rating (kW)	Number of chargers	Total mass (kg)
1	150	4	2,730
	60	5	
	30	5	
2	300	3	4,895
	150	1	
3	300	1	3,485
	150	3	
	60	4	
	30	2	

3. Results

3.1. Global Warming Potential

The complete environmental profile of the PV-BESS charging station over its 25-year lifespan was evaluated. The total results for key impact categories are summarized in Table 5. A detailed analysis of the GWP breakdown by system component in Table 4 reveals that the upstream equipment manufacturing phase constitutes the primary environmental hotspot. The total GHG emissions of the entire infrastructure amount to 5.58×10^5 kg CO_2-eq, corresponding to an emission intensity of 0.0611 kg CO_2-eq/kWh, with a standard deviation of 1.00×10^{-10}. The 5th and 95th percentiles were both approximately 5.58×10^5. The extremely small standard deviation proves that the overall GWP of the system is not sensitive to the uncertain the input data.

Table 4. Contribution of life-cycle stages to selected environmental impact categories

Impact category	Unit	Production / manufacturing	Construction / transportation / installation	Use / operation / maintenance / replacement	End-of-life
Climate change	kgCO2-eq	5.50×10^5	6.17×10^3	9.29×10^2	8.52×10^2
Material resources	kg Cu-eq	2.85×10^4	1.80×10^2	3.674	25.118
Human toxicity	kg 1,4-DCB-eq	2.95×10^6	5.80×10^3	1.11×10^3	8.31×10^2

Table 5. Life cycle impact assessment results (ReCiPe 2016 Midpoint H) for the entire system

Impact Category	Unit	Total Result
Climate change	kgCO_2-eq	5.58×10^5
Human toxicity: non-carcinogenic	kg 1,4-DCB-eq	2.95×10^6
Human toxicity: carcinogenic	kg 1,4-DCB-eq	2.49×10^5
Ecotoxicity: freshwater	kg 1,4-DCB-eq	1.75×10^5
Ecotoxicity: marine	kg 1,4-DCB-eq	2.29×10^5
Ecotoxicity: terrestrial	kg 1,4-DCB-eq	1.04×10^7
Material resources: metals/minerals	kg Cu-eq	2.87×10^4
Fossil resources	kg oil-eq	1.47×10^5
Eutrophication: freshwater	kg P-eq	3.91×10^2
Eutrophication: marine	kg N-eq	41.793
Ionising radiation	kBq Co-60-eq	4.01×10^4
Land use	m^2*a crop-eq	1.54×10^4
Ozone depletion	kg CFC-11-eq	0.234
Particulate matter formation	kg PM2.5-eq	1.44×10^3
Photochemical oxidant formation: human health	kg NOx-eq	1.62×10^3
Photochemical oxidant formation: terrestrial ecosystems	kg NOx-eq	1.70×10^3
Water use	m^3	1.19×10^4
Terrestrial acidification	kg SO_2-eq	3.28×10^3

According to Table 6, the PV module subsystem is the predominant contributor, overwhelmingly accounting for 70.09% of the total GWP. This dominance is primarily driven by the substantial electricity consumption required for polysilicon purification and wafer slicing processes within a carbon-intensive supply chain. Following this, the EV chargers and BESS contribute 13.90% and 6.09%, respectively. The environmental impacts associated with transportation (1.26%) and medium-voltage grid electricity consumption (0.17%) are negligible. Ultimately, these findings corroborate a fundamental characteristic of renewable energy systems: environmental burden shifting, whereby emissions are effectively mitigated during the operational phase but densely accumulate throughout the raw material extraction and manufacturing stages.

Table 6. Breakdown of global warming potential (GWP) contribution by process

Contribute	Process	Emission Intensity
100.00%	EVC (Total System)	0.0611
70.09 %	PV Panel	0.0429
13.90 %	EV Charger	0.0085
6.09 %	BESS for EVC	0.0042
4.04 %	Inverter	0.0025
2.06 %	Converter for EVC project	0.0013
1.55 %	4500kg cable system	0.0009
1.26 %	Market for transport, freight	0.0008
0.17 %	Market for electricity, medium voltage	0.0001

3.2. Sensitivity Analysis

The Life Cycle Impact Assessment (LCIA) results in Table 7 show a consistent environmental hierarchy among the three deployment strategies defined in Section 2.4. Scenario 2 (Ultra fast priority) has the highest impacts, followed by Scenario 3 (Hybrid mix), while Scenario 1 (Balanced configuration) shows the lowest burdens. This indicates that increasing the share of high power chargers intensifies life cycle environmental impacts.

For climate change, measured in GWP, increases from 5.58×10^5 $kgCO_2$-eq in Scenario 1 to 6.20×10^5 kg $kgCO_2$-eq in Scenario 2. Although the total system impact is dominated by the PV panel subsystem (70.09%), the variance between scenarios is exclusively driven by the chargers-only component. The causal mechanism for this increase is the nonlinear relationship between charging power and material intensity.

The Mineral Resource Scarcity results in Table 7 follow a similar trajectory, with Scenario 2 requiring 3.14×10^4 kg Cu-eq. This represents an increase in resource depletion compared to Scenario 1 (2.87×10^4 kg Cu-eq).

Table 7 also presents the results for human non-carcinogenic toxicity, one of the midpoint impact categories in the ReCiPe 2016 Midpoint (H) method, which is used to assess the potential human-health burden associated with non-carcinogenic emissions across the life cycle. Scenario 2 exhibits a total impact of 3.47×10^6 kg 1,4-DCB-eq. At the component level, the toxicity contribution from the chargers alone in Scenario 2 is greater than that of Scenario 1 (2.59×10^6 kg 1,4-DCB-eq).

Table 7. Summary of sensitivity analysis results across charger deployment scenarios

Impact category	**Scenario 1**	**Scenario 2**	**Scenario 3**
Climate change (kgCO2-eq)	5.58×10^5	6.20×10^5	5.78×10^5
Material resources (kg Cu-eq)	2.87×10^4	3.14×10^4	2.96×10^4
Human toxicity (kg 1,4-DCB-eq)	2.95×10^6	3.47×10^6	3.13×10^6

3.3. Discussion

The results show that the production stage dominates the overall environmental profile of the studied PV-BESS EV charging system, with PV module manufacturing identified as the principal hotspot. The use stage is the second most important contributor because it includes electricity use, maintenance, and component replacement over the 25-year lifetime, whereas the construction and end-of-life stages contribute comparatively less.

The scenario analysis also indicates that charger deployment strategy materially affects environmental performance. In particular, the ultra fast priority configuration (Scenario 2) produces higher burdens than the balanced configuration in several impact categories, including climate change, material resources, and human toxicity. For toxicity related categories, the difference between scenarios is mainly associated with the charger subsystem rather than the shared PV-BESS infrastructure, suggesting that charger mix is an important environmental design variable. The analysis does not model network scale charging station expansion, future market growth, or technology learning effects that may reduce the material intensity of high power chargers. Future studies could extend the framework by considering station rollout, charger utilization, market growth, and technology learning over time.

These findings imply that the environmental performance of PV-BESS charging infrastructure depends not only on the generation and storage backbone, but also on how charging demand is configured and served. For rest-stop EV charging in Vietnam, lower-impact design should therefore focus on reducing upstream burdens from major components, especially PV modules, and carefully selecting charger deployment strategies.

4. Conclusion

This study evaluates the lifecycle environmental performance of a grid-connected PV-BESS-EVC system at a highway rest stop in Vietnam, with emphasis on the effects of different charger configurations. The results show that the environmental burden is mainly associated with upstream production rather than operation. At the component level, PV modules are the main concern, highlighting the need to reduce impacts from PV supply chains and component manufacturing.

The scenario comparison indicates that charger deployment strategy is a critical design variable. Configurations prioritizing ultra-fast charging may improve charging service availability but can increase lifecycle burdens due to the higher material intensity of high-power chargers. In contrast, balanced or hybrid configurations can better align charging service quality, infrastructure flexibility, and environmental performance.

Future EV charging infrastructure in Vietnam should prioritize low-impact PV and charger supply chains, avoid unnecessary over-deployment of ultra-fast chargers, and select charger combinations suited to local charging needs. Future studies should consider time-varying charging demand, charger utilization, PV and BESS degradation, grid decarbonization, and technology learning to support long-term infrastructure planning.

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