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Research paper

Techno-economic optimization and environmental analysis of a solar-powered Electric Vehicles (EVs) charger system for a greener transportation ecosystem

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ABSTRACT

As the electric vehicle (EV) sector continues to grow, the environmental benefits of EVs increasingly depend on the energy sources powering charging stations, which are often supplied by the conventional electrical grid. Therefore, the adoption of sustainable charging solutions is becoming essential. This study investigates the integration of solar energy into EV charging infrastructure as a strategy to reduce greenhouse gas (GHG) emissions, aligning with Sustainable Development Goals (SDGs) 7 and 13. Focused on a 7 kW Level 2 charger, the analysis addresses optimal solar system sizing, energy output, economic feasibility, environmental impact, and sensitivity considerations. The proposed system including a 34 kW photovoltaic (PV) array, a 192-unit battery storage system, and an 8 kW inverter delivers consistent performance under real-world conditions, factoring in system losses, seasonal solar variations, and battery efficiency. The PV system generates 62,294 kWh annually, meeting an EV demand of 38,325 kWh/year and yielding a surplus of 31.54 %. The battery storage provides 66.4 hours of autonomy, ensuring energy availability during low solar generation periods. Economically, the system's net present cost (NPC) is $192,420, with an initial capital cost of $94,800, 60.76 % of which is attributed to battery investments. Battery replacements constitute 97.34 % of total replacement costs, while operation and maintenance (O&M) expenses total $38,567. A salvage value of $12,638 helps reduces overall lifecycle costs. Environmentally, the solar-powered system achieves an 87.5 % reduction in GHG emissions, emitting only 1917 kg CO_2/year compared to 15,330 kg CO_2/year for grid-based charging. These findings demonstrate that solar-powered EV charging offers both a cost-effective and environmentally sustainable solution, contributing meaningfully to global sustainability efforts.

1. Introduction

1.1. Background and motivations

The electric vehicle (EV) transportation sector has witnessed remarkable global growth, driven by advancements in battery technology, supportive government policies, and increasing awareness of environmental concerns. In 2023, global EV sales exceeded 14 million units, accounting for 18 % of total car sales, which translates to nearly one in every four cars sold, a significant leap from just 4 % in 2020 (Cui and Zhao, 2024). This rapid expansion is largely attributed to key factors such as decreasing battery costs, government incentives, and environmental benefits. The cost of lithium-ion batteries, a critical component of EVs, has plummeted by over 89 % since 2010, making EVs more affordable and accessible to a broader audience (Houache et al., 2022). Simultaneously, many countries have introduced subsidies, tax

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exemptions, and infrastructure investments, such as widespread installation of EV charging stations, to encourage adoption and accelerate the transition to cleaner transportation (Khaleel et al., 2024). Moreover, the environmental advantages of EVs are substantial, as they can reduce greenhouse gas emissions by up to 70 % compared to traditional internal combustion engine vehicles, particularly when powered by renewable energy sources (Liu et al., 2021). Given that the transportation sector is responsible for nearly 24 % of global CO_2 emissions, the shift toward EVs represents a pivotal step in mitigating climate change and promoting sustainability worldwide (Zhang and Hanaoka, 2021).

South Korea has emerged as a significant player in the EV industry, both as a consumer and manufacturer. Home to major companies like Hyundai, Kia, and LG Energy Solution, the nation is advancing EV production and battery technology, cementing its role as a key contributor to the global EV market. As of 2023, EVs accounted for 5.5 % of total vehicle sales in South Korea, and the government has set an ambitious target of reaching 30 % by 2030 (Kim et al., 2024). To support this growth, South Korea has developed a robust EV charging infrastructure, with over 140,000 public charging stations currently available and plans to expand this network to 500,000 by the end of the decade (BUI et al., 2024). On the international stage, South Korea is also demonstrating its strength as an EV exporter, shipping approximately 300,000 EVs in 2023, a 12 % increase compared to the previous year (Li et al., 2024). Several forward-thinking policies are driving this momentum. The green new deal has prioritized investments in EV infrastructure and offers subsidies to incentivize EV purchases. The country's dominance in battery manufacturing is another critical factor, with South Korea producing nearly 40 % of the world's EV batteries, positioning it as a global leader in this essential technology. Furthermore, the government has committed to achieving net-zero carbon emissions by 2050, with the transportation sector playing a pivotal role in this strategy (Lee et al., 2023). South Korea's transportation sector currently accounts for 15 % of the nation's total CO_2 emissions, amounting to approximately 92 million metric tons annually, with road transport particularly passenger cars and freight trucks being the largest contributor (Jeong and Park, 2024). The widespread adoption of EVs is viewed as a critical solution to mitigating these emissions, reducing the environmental impact of transportation, and aligning with the nation's broader sustainability goals. Together, these efforts underscore South Korea's commitment to fostering sustainable mobility and maintaining its leadership in the evolving EV landscape. Although the significant transformation with the adoption of EVs as a cleaner alternative to conventional vehicles, their environmental benefits remain closely tied to the energy sources used for charging. Many grid-powered EV chargers rely on electricity generated from fossil fuels, with coal still accounting for about 30 % of electricity generation, thereby limiting the potential emissions benefits of EVs (Yu et al., 2024). Additionally, infrastructure gaps persist, particularly in rural areas where the shortage of charging stations hinders widespread adoption. To overcome these challenges and maximize the environmental advantages of EVs, integrating renewable energy solutions, such as solar photovoltaics (PV), into EV charging systems has emerged as a promising strategy.

1.2. Scope and research questions

This paper investigates the techno-economic optimization and environmental benefits of a solar-powered Level 2 EV charger system with a capacity of 7 kW. Increasing the share of renewable energy, currently at 15 % of the grid mix, is essential to fully realize the potential of EVs in reducing GHG emissions (Ullah et al., 2023). The integration of solar energy into EV charging infrastructure represents a critical step toward decarbonizing transportation and advancing sustainability efforts. The proposed system aligns with the United Nations' SDG7 and SDG13, offering a scalable and impactful solution to address fossil fuel dependency, bridge infrastructure gaps, and leverage renewable energy for a sustainable future (Morte et al., 2023).

The generation of solar energy is influenced by various factors such as solar radiation, sunlight intensity, and the geolocation of solar panels. South Korea is selected as the case study due to its location between latitudes 34°N and 38°N and its strong solar energy potential, with daily radiation ranging from 2.474 kWh/m^2 in December to 5.622 kWh/m^2 in May (Alsharif et al., 2021). Additionally, the wind speed in the region is relatively low, as reported in references (Ryu et al., 2022), which led to the exclusion of wind turbines from the scope of this study. The primary research questions addressed in this study include:

- What is the optimal design for the solar system?
- Can the solar-powered system meet the EV's energy demands?
- When does the PV array reach maximum and minimum power?
- When does the battery achieve its maximum and minimum output?
- How many hours of autonomy can the battery provide if PV fails?
- Is there a significant risk of encountering load loss (LOL)?
- What are the projected costs of the solar-powered system?
- How does its feasibility compare with traditional energy sources?

Accordingly, this study utilizes the Hybrid Optimization Model for Electric Renewables (HOMER) to conduct a techno-economic feasibility analysis of a solar-powered EV charger. The HOMER is selected for this study due to its proven ability to perform comprehensive techno-economic analyses, particularly in off-grid and hybrid power applications. HOMER is specifically designed to model the performance of renewable energy systems, including solar, wind, and battery storage, under varying conditions, which is essential for assessing the feasibility of a solar-powered EV charger. Unlike other software tools, HOMER offers a robust optimization framework that can evaluate multiple system configurations, taking into account factors such as component sizing, energy production, storage, and economic costs (Thirunavukkarasu et al., 2023; Ansari et al., 2023). This allows for a detailed comparison of different design scenarios to determine the optimal solution for meeting the energy demand with the least net present cost (NPC). Furthermore, HOMER incorporates both technical and economic considerations, making it an ideal tool for this study, where both system performance and cost-effectiveness are crucial. Its flexibility and ability to model complex systems, along with its widely recognized validation in similar renewable energy projects, make HOMER the best choice for the analysis over other software options.

1.3. Contributions

The key contributions of this study are as follows:

- Optimizing a solar-powered Level 2 EV charger system to meet typical energy demand profiles, with a comprehensive evaluation of energy yields and system performance across seasonal fluctuations.
- Conducting an economic analysis that assesses the initial, replacement, and operational costs of the system over a 25-year lifespan, alongside quantifying the reduction in greenhouse gas (GHG) emissions.
- Performing sensitivity analyses to evaluate the impact of critical parameters, such as interest rates and solar irradiance, on system performance, and assessing battery autonomy and the risk of load loss in scenarios where the PV array fails.

The methodology of this study outlines the key steps undertaken to evaluate the feasibility and effectiveness of a solar-powered Electric Vehicle Charging Station (EVCS). Initially, the design and optimization of the EVCS were conducted, focusing on the integration of solar energy as the primary power source. The HOMER software was employed for system performance simulations, allowing for a detailed analysis of energy yield, storage requirements, and overall efficiency. The energy yield was carefully assessed to ensure that the solar system could meet the energy demands of the EV charger, while also considering variations

in solar radiation and other real-world factors. A comprehensive economic evaluation was then carried out, including the calculation of costs such as the NPC, initial capital investment, maintenance, and replacement costs. Finally, an environmental impact analysis was performed, comparing the greenhouse gas emissions from the proposed solar-powered system to those from conventional grid electricity. This methodology provides a holistic approach to evaluating the sustainability, economic viability, and environmental benefits of integrating solar power into EV charging infrastructure.

1.4. Paper organization

Section 2 reviews existing research on solar-powered EV charging, focusing on system design, energy performance, and economic feasibility, while highlighting gaps in reliability and scalability. Section 3 outlines the system and its mathematical framework. Section 4 presents the cost model optimization formula. Section 5 details the methodology and simulation setup. Section 6 presents the results from the optimization and simulations. Lastly, Section 7 provides a summary of the study's conclusions.

2. Related works

Table 1 presents a comprehensive summary of various research papers focused on solar-powered EV charging systems. Each study provides valuable insights into the integration of solar energy with EV charging infrastructure, contributing to the ongoing transition toward sustainable transportation solutions. The contributions of these papers range from optimizing energy efficiency through advanced technologies like Maximum Power Point Tracking (MPPT) and inductive power transfer (IPT), to reducing greenhouse gas emissions and enhancing the reliability of renewable energy sources in EV networks. The results indicate significant advancements in the field, such as improved charging efficiency, reduced carbon emissions, and the potential for sustainable, off-grid charging solutions.

This study makes several key contributions, particularly in the areas of energy reliability and economic feasibility, setting it apart from previous research. While earlier studies have explored the potential of solar-powered EV charging and highlighted its environmental benefits, such as emission reductions, this study goes further by evaluating the system's technical performance across four critical areas: optimal system design, energy yield assessment, technical performance, and economic evaluation. These areas together provide a comprehensive framework for assessing the feasibility and benefits of a solar-powered EV charging system. A notable innovation in this study is the incorporation of battery storage, which ensures continuous system reliability even during solar array failure. With the ability to provide backup power for up to 66.4 hours, the battery system addresses one of the major challenges associated with solar energy: intermittency. This reliability feature ensures that the system remains operational during maintenance or unforeseen downtime, making the solar-powered EV charger practical and dependable. On the economic front, the study offers an in-depth cost analysis, detailing initial capital investment, replacement costs, and operational expenses, while factoring in a salvage value at the end of the system's lifespan. This comprehensive economic evaluation presents a clear picture of the financial sustainability of the system and its long-term potential for cost savings, enhancing the practicality of solar-powered EV charging as a scalable solution. This study not only contributes to reducing GHG emissions but also plays a pivotal role in advancing discussions about energy independence and the future of EV infrastructure. By addressing both technical and economic challenges in a holistic manner, it provides a robust, actionable blueprint for the widespread adoption of solar-powered EV charging systems.

3. System and mathematical modeling

Fig. 1 illustrates the proposed system architecture, which is divided into two primary subsystems: (i) the EV charger and (ii) the solar power setup, including the PV array, battery bank, and inverter. The energy source for the system is a solar PV array, which is configured with both series and parallel connections to achieve the desired voltage and current specifications. A battery bank, made up of multiple smaller cells arranged in series and parallel, functions as the energy storage component. This bank, coupled with an intelligent energy management system, stores the surplus electricity generated by the PV array. The storage system plays a crucial role in enhancing the overall reliability and ensuring stable power quality. It also allows the system to provide energy during periods of low sunlight, such as at night or during power disruptions. The system is supported by a DC bus, which helps maintain a consistent voltage level (48 V in this case) to ensure smooth and

Table 1
Summary of related works on solar-powered EV charging systems.

Ref	Insight(s)	Contribution(s)	Result(s)	Limitation(s)
(Ullah et al., 2024)	Emphasized solar-powered storage for cost reduction and grid independence.	Proposed IoT-based SPBESS for real-time monitoring and optimized charging.	Cuts energy costs by 36 %, saving $1336–$4544 yearly, and reduces emissions by 5.5 tons annually.	Battery degradation and scalability not considered.
(Suh, 2024)	Assessed solar PV potential for EVs, noting shaded areas.	Developed GIS model to estimate solar generation for EVs.	Solar EVs cover 0.94–1.43 % of needs, reducing CO_2 by up to 34.5 kg/year.	Scalability limited by weather and shading, economic feasibility unstudied.
(Haces-Fernandez, 2024)	Identified colleges as prime sites for solar EV charging.	Used buffer analysis for optimal EVCS placement.	6500 + U.S. colleges as EV sites, with 0.97 correlation to vehicle ownership.	Economic feasibility and long-term costs not considered.
(Lakshmipriya et al., 2025)	Solar-powered EV charging infrastructure	Proposed solar/wind-powered charging, highlights benefits and challenges	Reduced emissions, supports sustainable transport	Challenges in renewable integration, intermittency
(Talawar and Aspalli, 2024)	Solar-powered EV charger system with DC power	Enhanced efficiency, reduces grid reliance	Sustainable transport, reduced emissions	Requires reliable solar conditions
(Raipure et al., 2024)	Solar-powered dynamic EV charging	Wireless charging via IPT, enhances convenience	Dynamic charging while in motion	High-speed IPT challenges, infrastructure cost
(Shiramagond and Lee, 2018)	Integrating solar energy in EV networks	Addressed variability, energy storage, and grid capacity	Success in renewable integration	Grid constraints and storage issues, scalability
(Balal et al., 2024)	Solar-powered EV charging station with storage	Integrated PV, bidirectional converters	Viable, cost-effective, sustainable solution	Storage capacity limits during high demand
(Shukla et al., 2024)	Solar-powered EV station	51.1 kW system, 98,313 kWh/year	Reduced grid stress, enhances energy security	68.90 % performance ratio, seasonal variations
(ALGHAMDI)	Solar PV EV charging with app monitoring	Monitored charging via smartphone	Sustainable design with monitoring app	Internet access dependency, privacy issues
(Priya and Brindha, 2026)	Solar-powered EVCS in Green Campus	Reduced emissions, enhances efficiency	Solar-powered, reduces carbon footprint	Seasonal energy availability, infrastructure cost

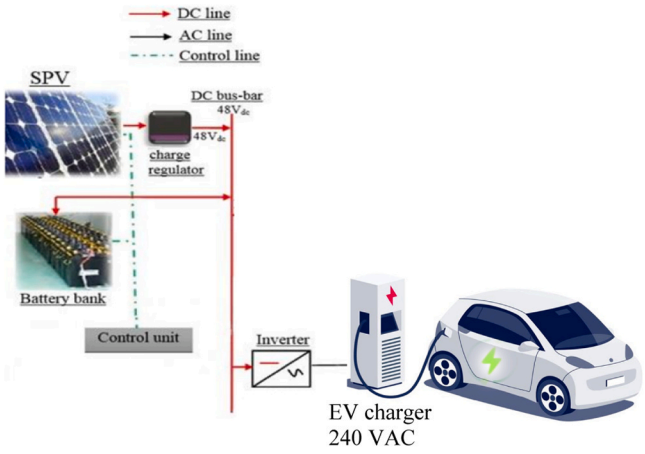


Fig. 1. Block diagram illustrating the proposed system.

efficient operation. Details in the following subsections.

3.1. Electric Vehicle (EV) charger

Approximately 80–85 % of EV owners rely on Level 2 chargers for their daily charging needs, typically during the morning or evening after work. These chargers are highly adaptable and can be installed at home or in workplaces, making them a convenient and efficient option for EV users. Level 2 chargers effectively balance practicality and performance, catering to the needs of most EV owners (BUI et al., 2024).

The proposed solar-powered EV charger is particularly suited for workplace applications, where it can charge 1–3 EVs per day. With a charging time of approximately 4–8 hours for a full charge, this setup aligns perfectly with the standard workday. Employees can connect their vehicles to the charger upon arrival in the morning, ensuring they are fully charged by the end of the day. This system not only utilizes renewable solar energy but also alleviates strain on the traditional power grid. By integrating workplace charging stations, organizations can encourage EV adoption, reduce carbon emissions, and provide employees with the convenience of reliable charging during working hours.

For the solar system design, a 7 kW Level 2 EV charger was selected as an ideal choice. Level 2 chargers, operating at 240 volts, typically provide power outputs between 3.3 kW and 19.2 kW, with most residential models delivering between 6 kW and 10 kW. A 7 kW charger falls within this range, offering a practical balance of charging speed and energy efficiency (Acharige et al., 2023). It is capable of fully charging most EVs within a few hours, depending on the battery capacity and state of charge, while remaining compatible with solar energy systems.

This 7 kW charger is particularly advantageous for optimizing solar energy use, as it can efficiently utilize power generated by a moderately sized solar array while meeting the energy needs of typical EVs. It strikes a balance between performance, cost, and scalability, making it well-suited for residential and small-scale workplace applications. Moreover, it provides a realistic and practical solution for users seeking faster charging than Level 1 systems without the need for excessively large solar setups. The selection of a 7 kW charger ensures that the system remains efficient, scalable, and practical, enabling detailed analysis of solar-powered EV charging performance in real-world scenarios.

3.2. Photovoltaics (PV) panels

The PV array converts shortwave solar radiation into DC electricity. The total annual energy output (E_{PV}) is calculated using the formula (Micropower):

$$E_{PV} = PC_{PV} \times PSH \times DF_{PV} \times 365 \text{ days/year} \quad (1)$$

Here, PC_{PV} (kW) refers to the maximum power output of the PV. *PSH* stands for peak sun hours, calculated as the equivalent average daily solar energy received. DF_{PV} represents the derating factor, which accounts for factors such as dust accumulation, energy losses, temperature fluctuations, and other issues that may decrease the panel's power output.

3.3. Battery system

A Battery system stores excess energy from the PV array for use at night or during poor weather, ensuring a reliable power supply. Its capacity depends on the depth of discharge (DOD), which must be assessed before installation. The DOD is defined as:

$$DOD = 1 - \frac{SOC_{\min}}{100} \quad (2)$$

Where SOC_{min} is the minimum state of charge. The Trojan L16P battery has a 70 % DOD, with 30 % reserved for emergencies.

Days of autonomy (A_{batt}) estimate how long fully charged batteries can power the load without external sources. In HOMER, A_{batt} is calculated as (Micropower):

$$A_{batt} = \frac{N_{batt} \times V_{nom} \times Q_{nom}\left(1 - \frac{SOC_{\min}}{100}\right)(24h/d)}{L_{prim-avg}(1000Wh/kWh)} \quad (3)$$

Here, N_{batt} represents the total number of battery units in the BESS, and V_{nom} is the nominal voltage of each individual battery (in volts). Q_{nom} denotes the nominal capacity of a single battery (in ampere-hours), while $L_{prim,\ ave}$ corresponds to the average daily load demand (EV).

The overall cost of a solar system is largely influenced by the cost of the batteries, making the battery's lifespan a critical factor. The battery's lifetime can be estimated based on its operating conditions, with the DOD during each daily charge-discharge cycle being a key factor in determining its longevity. The battery lifespan (R_{batt}) can be calculated using HOMER as follows (Micropower):

$$R_{batt} = \min\left(\frac{N_{batt} \times Q_{lifetime}}{Q_{thrpt}}, R_{batt.f}\right) \quad (4)$$

Here, $Q_{lifetime}$ refers to the total energy throughput of a single battery over its lifespan, measured in kWh. Q_{thrpt} represents the annual energy throughput of the battery in kWh per year, while R_{battf} indicates the battery's float life, expressed in years.

The number of batteries in series is calculated by dividing the DC busbar voltage ($V_{b\text{-}b}$) by the battery voltage rating (B_V), as shown:

$$N_{batt}^{series} = \frac{V_{b-b}}{B_V} \quad (5)$$

The total parallel paths are calculated by dividing the total number of batteries by those in series.

3.4. Inverter

The PV system generates DC power, which is converted to 240 V AC power by an inverter to supply the AC load, such as the BS cooling system. The inverter capacity (C_{inv}) is calculated as follows (Rehman and Al-Hadhrami, 2010):

$$C_{inv} = \left(\frac{L_{AC}}{\eta_{inv}}\right) \times \sigma_{sf} \quad (6)$$

Here, L_{AC} refers to the maximum available AC load, η_{inv} represents the efficiency of the inverter, and σ_{sf} is the safety factor.

4. Optimization formula of cost model

The design of a solar system involves selecting components,

determining their quantity, and defining their size. With many energy options available, HOMER software, developed by the U.S. National Renewable Energy Laboratory, simplifies this process by modeling solar systems and optimizing configurations. The HOMER tool helps identify the most cost-effective PV system design with the lowest NPC (Micropower). The NPC term includes all costs and revenues generated throughout the project's lifespan.

The total annualized cost (C_{TAC}) represents the yearly cost of the entire system in $/year, including the initial capital (IC) cost (C_{TAC}^{cap}), replacement cost (C_{TAC}^{rep}), and operation and maintenance (O&M) costs ($C_{TAC}^{o\&m}$). The full breakdown of the cost can be expressed as follows:

$$C_{TAC} = C_{TAC}^{cap} + C_{TAC}^{rep} + C_{TAC}^{o\&m} \tag{7}$$

The C_{NPC} can also be expressed as the annualized value:

$$C_{TAC} = C_{NPC} + CRF(i,N) \tag{8}$$

C_{NPC} represents the total costs over the system's lifetime, with future cash flows discounted to present value. It includes IC, replacement, and O&M costs, minus the salvage value. The capital recovery factor (C_{RF}) converts C_{NPC} into equal annual payments, calculated using the interest rate (i) and project duration (N) as follows:

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{9}$$

Where N represents 25 years and i is 3.5 %. The salvage value (S) is determined as follows:

$$S = C_{rep}\frac{R_{rem}}{R_{comp}} \tag{10}$$

Where R_{comp} denotes the component's total lifespan in years, R_{rem} indicates its remaining lifespan in years, and C_{rep} refers to the replacement cost of the component in US dollars ($).

This study minimizes the total NPC, considering constraints affecting standalone PV system design. The hypotheses for the proposed system assume that solar energy generation is relatively consistent, with seasonal variations considered but no sudden fluctuations in weather patterns. Additionally, the study assumes that the battery storage system operates with constant efficiency, and the EV load demand remains constant and predictable over time. The battery prioritizes charging from the PV system during surplus generation.

The conditions of the system focus on ensuring that the combined energy generated from the PV array and the battery meets the total energy demand of the EV load, accounting for energy losses. A key condition is that the battery storage system operates within its capacity, with no more than 70 % of the total battery capacity used, ensuring that reserve energy is maintained for critical situations. Another condition is that the PV system cannot generate energy during nighttime, which is considered a limitation in the modeling. The study also incorporates an economic evaluation of the system's NPC, including initial capital costs, operation and maintenance expenses, component replacements, and the salvage value at the end of the system's lifecycle.

The boundaries of the study focus on a geographical scope with typical annual solar radiation profiles, excluding areas with unpredictable weather that may impact solar generation. The system components analyzed include the solar array, battery storage, inverter, and EV charging station, all modeled based on standard specifications and efficiency metrics. The study considers a 25-year operational life for the system, corresponding to the typical lifespan of key components. Although the system is designed as standalone, potential grid integration is acknowledged, but grid power is not considered a primary energy source under normal operating conditions. These boundaries ensure that the study remains focused and provides realistic assumptions for the system's performance and evaluation.

The NPC objective function is:

$$(P): \underset{E_{PV},E_{Battery},E_{Losses},E_{EV}}{\arg\min} \frac{C_{TAC}}{CRF(i,N)} \tag{11}$$

Subject to ($S.t.$)

$$\mathrm{E_{Battery}} + \mathrm{E_{PV}} > 0 \tag{11.1}$$

$$E_{Battery} + E_{PV} \geq E_{EV} + E_{Losses} \tag{11.2}$$

$$E_{Battery_min} \leq E_{Battery} \leq E_{Battery_max}. \tag{11.3}$$

E_{EV} is the annual energy consumption of the EV load, while E_{PV} is the yearly energy produced by the PV array. This depends on (i) the number of panels, (ii) the derating factor, and (iii) the peak sun hours, as shown in Eq. (1).

$E_{Battery}$ refers to the energy supplied by the battery bank. This study utilizes the Trojan L16P battery model, known for its 70 % DOD. This means the battery can effectively provide up to 70 % of its energy, reserving the remaining 30 % for critical situations. If the energy generated by the PV system (E_{PV}) exceeds the EV load requirements, including losses, the surplus energy is stored in the battery bank. Conversely, if E_{PV} falls short of meeting the EV load, the battery bank compensates for the deficit, with a maximum energy usage limit of 70 % of the total capacity of the battery bank.

Note that the PV system's output power is not always greater than zero, particularly during nighttime when there is no generation. To address this, constraint (11.1) ensures that the combined energy produced by the PV system and the battery remains above zero. Furthermore, the second constraint Eq. (11.2) ensures that the total supply comprising the energy output from the PV system (E_{PV}) and the battery ($E_{Battery}$) is equal to or exceeds the total demand, which includes the load (E_{EV}) and energy losses (E_{losses}).

5. Methodology and simulation setup

The algorithm for the proposed system is shown in the flowchart in Fig. 2, aiming to minimize NPC while meeting design constraints. The process is summarized in the following steps:

i. If the green energy (E_{PV}) from the solar panels meets the EV demand and losses, no energy will be stored, and no deficit will occur.
ii. When E_{PV} exceeds the required EV load, the surplus solar energy is stored in the battery bank. However, the total losses, which include battery and converter losses, must be considered. These losses arise because devices are non-ideal, with DC-to-AC energy conversion causing converter losses, and the charging and discharging cycles of the battery leading to storage losses.
iii. If solar energy is insufficient, the storage device will supply backup power subject to ($E_{Battery_min} \leq E_{Battery} \leq E_{Battery_max}$).
iv. When the combined contribution of E_{PV} and the discharged energy from storage E_{disch} is less than the EV demand (including losses), the deficit energy is calculated. If energy production and consumption are balanced, the deficit is zero, as $E_{PV} + E_{disch}$ can fully meet the load demand under the given network conditions.

HOMER software evaluates, hour by hour, whether the EV load demand (including losses) is met by calculating the excess and deficit energy over a year. It determines the optimal combination of system components to satisfy the load demand without any energy shortages. Finally, the minimum NPC is derived by considering the total annualized cost and the capital recovery factor across multiple iterations.

HOMER generally consists of three key components: inputs, optimization, and outputs (Micropower). Monthly average solar irradiation (Fig. 3), economic parameters (Table 2), and PV system configurations, including component sizes, costs (IC, replacement, O&M), are detailed.

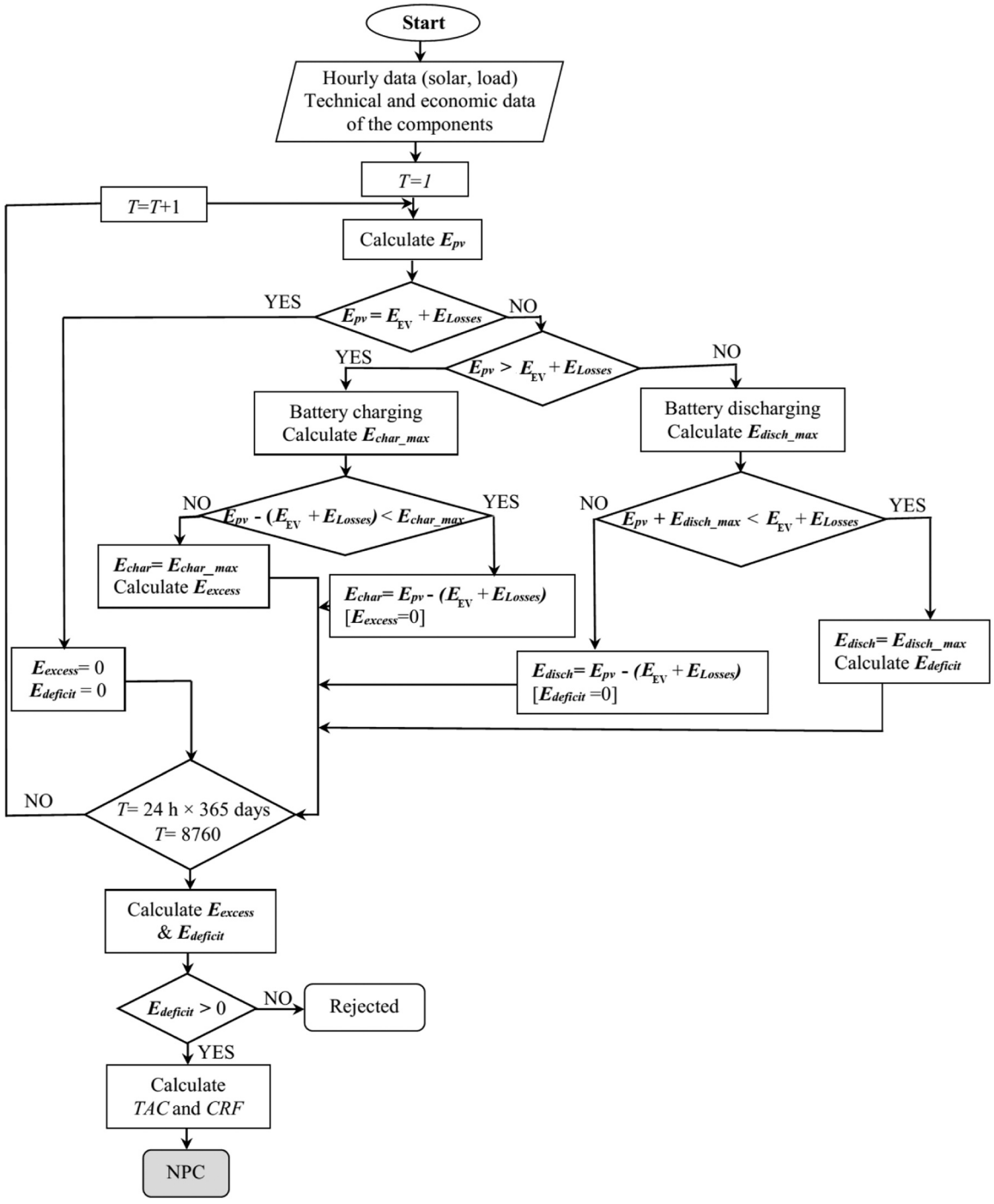


Fig. 2. Flowchart of the proposed system's algorithm.

Other technical constraints, like lifetime and efficiency, are also considered, as detailed in Table 1. During the optimization phase, HOMER performs an hourly simulation for all possible configurations. It calculates the available energy from the PV system (E_{PV}), compares it to the electric demand (E_{EV}) and losses (E_{losses}), and surplus PV power charges the battery, while deficits are managed by discharge. HOMER optimizes combinations to minimize NPC, factoring in investment, maintenance, replacement, and salvage costs. TAC is calculated to determine the total NPC.

6. Results and discussion

The proposed solar-powered Level 2 EV charger, comprising a 34 kW solar panel array and 192 batteries, has an optimal total NPC of $192,420, making it a highly cost-effective solution. The battery system is configured into eight parallel strings and is paired with an 8 kW inverter. The subsequent sections present a detailed analysis of the energy yield, economic viability, and sensitivity of the system. Although this study is based on a specific location, the results can be generalized to other regions at similar latitudes, provided there are only slight differences in daily peak sunlight hours (solar irradiation).

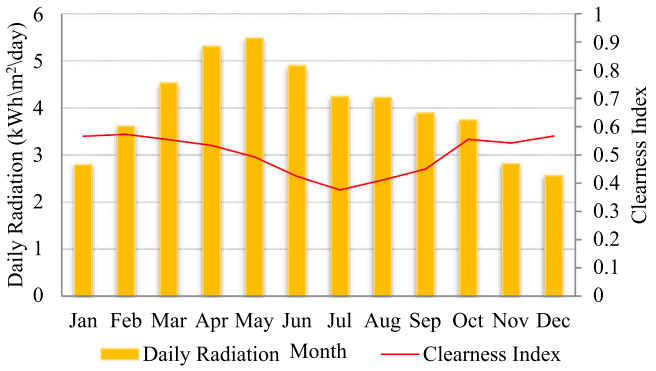


Fig. 3. Monthly average solar irradiance.

Table 2
Simulation setup.

Components	Parameters	Range
Control factors	Interest rate-Annual (Dec. 2024)	3.5 %
	Project lifespan (*N*)	25 years
	Dispatch scheme	cyclic charging
	Apply set point SOC	80 %
	Percentage of load and hourly load	10 %
PV	Sizes considered	30, 31, 32, 33, 34, 35, 35 kW
	Operational lifetime	25 years
	Efficiency	85 %
	System tracking	Two-axis
	IC	$1/Watt
	Replacement rate	$1/Watt
	O&M price/year	$0.01/Watt
Inverter	Sizes considered	6, 6.5, 7, 7.5, 8, 8.5 kW
	Efficiency	95 %
	Operational lifespan	15 years
	IC	$0.4/Watt
	Replacement rate	$0.4/Watt
	O&M price/year	$0.01/Watt
Trojan L16P Battery	Number of batteries	160, 168, 176, 184, 192, 200
	Round trip efficacy	85 %
	Minimum SOC	30 %
	Nominal voltage	6 Volt
	Nominal current	360 Ah at 20 h
	Nominal capacity	6 Volt × 360 Ah = 2.16 kWh
	Lifetime throughput	1075 kWh
	Maximum charge rate	1 A/Ah
	Maximum charge current	18 A
	Self-discharge ratio	0.1 % per hour
	Minimum operational lifespan	5 years
	IC	$300
	Replacement rate	$300
	O&M price/year	$10

6.1. Analysis of energy yield

The annual energy production of the PV array is estimated using Eq. (1) and amounts to 49,050 kWh, calculated as 34 kW × 4.65 h × 0.85 × 365days/year. With the inclusion of a dual-axis tracking system, the energy output could increase by up to 27 %, reaching a potential 62,294 kWh annually. This generated energy accommodates system losses, including approximately 2306 kWh from the battery and 2015 kWh from the inverter, while meeting the EV charger load demand of 38,325 kWh per year. Additionally, the system produces an annual excess energy of up to 19,648 kWh, accounting for 31.54 % of the total energy generation.

The battery performance is crucial for ensuring the reliability of the solar-powered system, particularly during periods when the PV array may not be generating sufficient energy, such as cloudy days or system malfunctions. The energy output of 13,319 kWh is a key factor in meeting the load demand during such times, while the input of 15,625 kWh accounts for the energy required to recharge the battery, considering its 85 % round-trip efficiency. The ability of the battery to supply power for 66.4 hours highlights the importance of having a sufficiently sized energy storage system to provide backup during unexpected downtimes.

The monthly energy generation patterns, shown in Fig. 4, indicate the highest output in February and the lowest in July. These variations are primarily influenced by seasonal changes in the sun's elevation angle. Furthermore, prolonged rainy periods during early summer, especially in late July and August, cause a significant decrease in global horizontal irradiance, resulting in a notable drop in energy production.

Fig. 5 shows the average hourly energy contributions of the PV system, battery, and excess electricity over a 12-month period. The system experiences its lowest energy contribution from the PV array during late July and early August, resulting in a minimal battery reserve and a state of charge (SOC) dropping to 42 %, as depicted in Fig. 6. Seasonal variations in SOC, including maximum and minimum values, are detailed in Fig. 7. Notably, the battery sees its highest utilization in August, compensating for the PV array's reduced energy contribution during this time.

The observed trends in battery SOC highlight the critical role of energy storage in ensuring consistent power supply. Optimizing the sizing and management of the battery system is essential to mitigate the effects of seasonal energy deficits and maximize the use of excess energy. By addressing these factors, solar-powered EV charging systems can achieve greater efficiency, reliability, and sustainability.

The inverter unit has a net capacity of 8 kW and operates with an efficiency of 95 %, calculated based on the difference between the annual input energy (40,307 kWh) and the output energy (38,292 kWh). This reflects the inverter's ability to convert DC energy from the solar panels into AC power for the EV charger. The total operating hours of the inverter are 5472 hours per year, which is equivalent to continuous operation for 15 hours a day over the course of a year (365 days). However, the 5 % energy loss is due to factors like internal resistance and heat generation, which are typical in all electrical systems. Fig. 8 shown the seasonal statistics inverter output power.

6.2. Economic analysis

Fig. 9 presents the cash flow summary over the lifespan of the project. Additionally, Fig. 10 offers a more detailed breakdown of the cash flow, categorized by component and cost type. This comprehensive analysis allows for a clear understanding of how the costs are distributed across different components of the system throughout its operational life. The detailed breakdown of this cash flow summary is provided as follows.

6.2.1. Initial Capital (IC) costs

The size of the system directly impacts the IC, with a larger system resulting in a higher investment. For the proposed solar-powered system, the total IC cost amounts to $94,800, which is distributed across various components of the system. Specifically, 35.86 % of the total cost is allocated to the photovoltaic (PV) array, which amounts to $34,000, calculated based on a 34 kW system size at a cost of $1000 per kW. The battery system, which makes up 60.76 % of the total IC cost, amounts to $57,600, derived from 192 battery units, each costing $300. Finally, the inverter contributes 3.38 % to the overall IC cost, totaling $3200, which corresponds to an 8 kW inverter at a rate of $400 per kW. The breakdown of the initial capital costs highlights the significant investment required for the battery storage system, which accounts for over half of the total IC cost. This is typical for solar energy systems, as batteries are crucial for storing excess energy produced during the day to power the EV charger during periods of low or no solar generation.

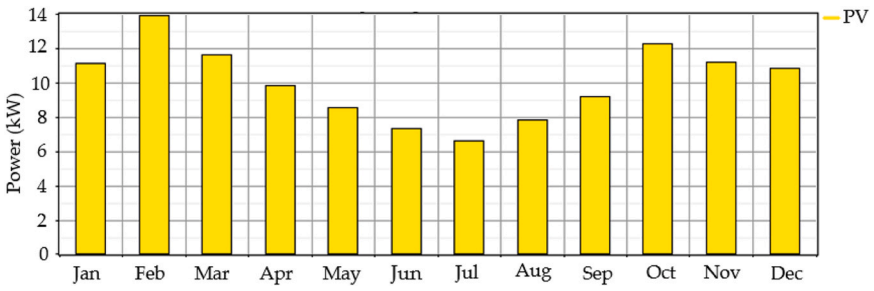


Fig. 4. Monthly Average Electric Production.

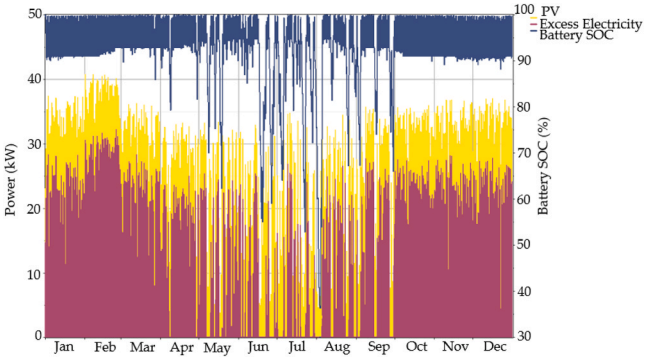


Fig. 5. Hourly average output of PV, Battery, and excess electricity.

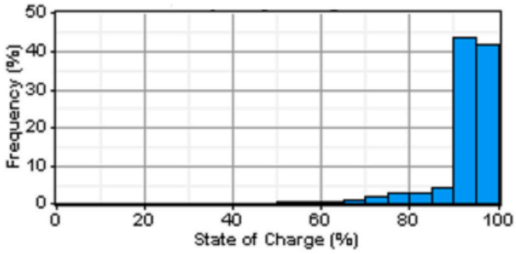


Fig. 6. Annual SOC frequency histogram.

6.2.2. Replacement costs

The replacement cost of the system amounts to $71,692 and is primarily composed of two components. A significant portion, $69,782 (97.34 %), is attributed to the battery bank. This value is calculated in two parts: $40,834, which is the result of applying a 10-year annual discount factor of 0.709 (as shown in Fig. 11) to the original cost of $57,600, and $28,948, derived from applying a 20-year annual discount factor of 0.503 (as shown in Fig. 11) to the same cost. The remaining $1910 (2.66 %) is allocated for the inverter replacement, calculated by applying a 15-year annual discount factor of 0.597 (as shown in Fig. 11) to the initial cost of $3200. Replacement costs for the PV system are not included, as the lifespan of the PV panels matches the 25-year duration of the project.

The replacement cost breakdown emphasizes the financial impact of battery replacements due to their shorter lifespan and higher cost compared to other system components. The reliance on annual discount factors demonstrates the importance of accounting for the time value of money in long-term projects, effectively reducing the nominal costs of future expenditures to their present values.

6.2.3. O&M costs

The O&M cost of the system totals $38,567 and is distributed across the three main components. The PV array accounts for $5604, representing 14.53 % of the total O&M costs. The battery system constitutes the majority of the expenses, amounting to $31,645 or 82.05 %. Lastly, the inverter contributes $1319, which makes up 3.42 % of the total O&M costs.

6.2.4. Salvage value

At the end of the project lifespan, the salvage value of each component plays a crucial role in offsetting the total cost of the system. Using Eq. (10), the salvage value of the battery bank is calculated to be $12,187, representing the highest contribution among all components due to its significant initial investment and partial remaining lifespan. Meanwhile, the salvage value of the inverter is estimated at $451, reflecting its smaller size and relatively lower cost. Together, these components yield a total salvage value of $12,638 at the conclusion of

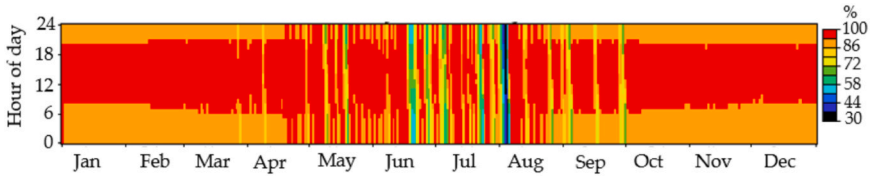


Fig. 7. Seasonal statistics of maximum and minimum SOC.

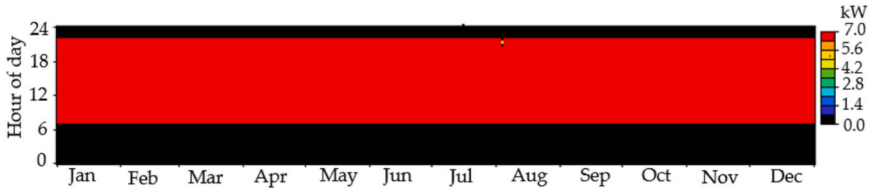


Fig. 8. Seasonal statistics inverter output power.

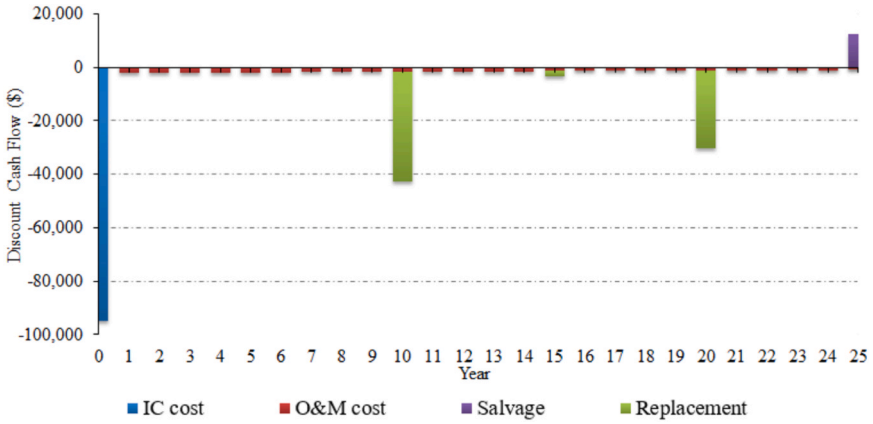
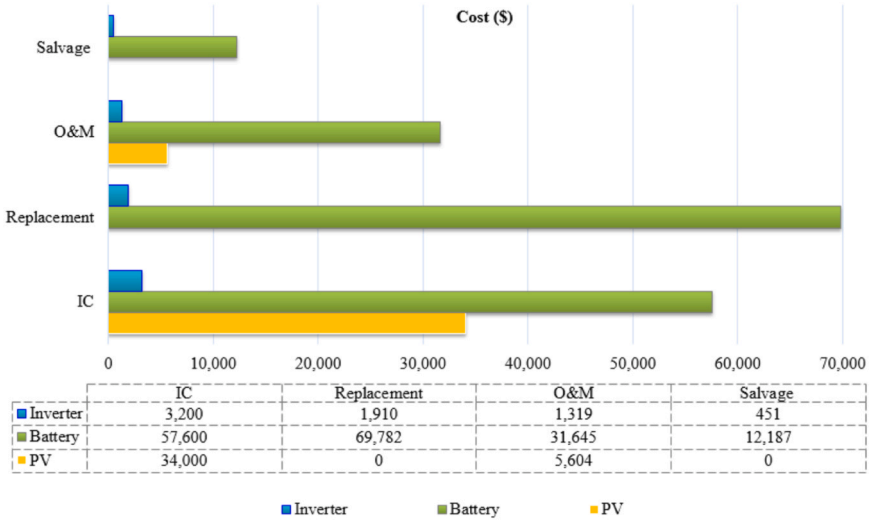


Fig. 9. Discount cash flow summary over the project lifespan.



	IC	Replacement	O&M	Salvage
Inverter	3,200	1,910	1,319	451
Battery	57,600	69,782	31,645	12,187
PV	34,000	0	5,604	0

Fig. 10. Cash flow categorized by component and cost type.

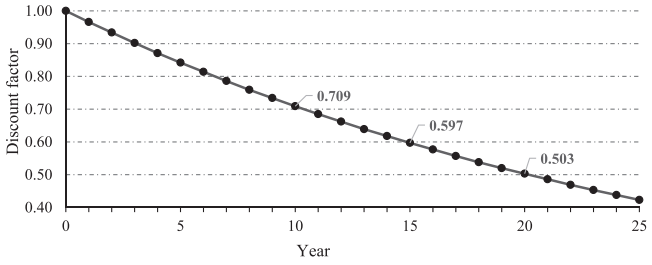


Fig. 11. Annual discount factor throughout the project lifespan.

the project's 25-year duration.

In the end, the NPC of the proposed solar-powered EV charging system is calculated to be $192,420. This value is derived from the sum of $94,800 for IC, $71,692 for replacement, and $38,567 for O&M, offset by a salvage value of $12,638 at the end of the project's lifespan. This analysis provides a clear financial picture of the system's lifecycle cost. Additionally, the methodology and findings can be adapted for other configurations, as system costs are directly influenced by the sizes and specifications of individual components.

The breakdown of the NPC highlights the relative contribution of each cost category, with the initial capital cost being the largest upfront investment, followed by substantial replacement costs over the project lifespan. The salvage value serves as a critical factor in reducing the overall financial burden, especially for components like batteries that retain significant residual worth. This analysis underscores the importance of careful sizing and selection of system components to achieve cost efficiency.

6.3. Environmental analysis

Greenhouse gas (GHG) emissions are determined by two primary factors:

1. The annual energy required (E_{load}): This represents the total energy consumption of the system over a year. For the 7 kW Level 2 EV charger, operating for an average of 15 hours per day, the annual energy requirement is calculated as: $E_{load} = 7\ \text{kW} \times 15\ \text{hours/day} \times 365\ \text{days/year} = 38{,}325\ \text{kWh/year}$.
2. Emission factor (EF): This parameter quantifies the amount of CO_2 emitted per unit of energy generated. The grid emission factor (EF_{grid}) for South Korea is 0.4 kg CO_2/kWh, while the emission factor for a PV system (EF_{PV}) is significantly lower, at 0.05 kg CO_2/kWh.

To assess the environmental benefits of a PV-powered EV charger compared to grid electricity, the following calculations were performed:

(i) The greenhouse gas (GHG) emissions resulting from using grid electricity to meet the annual energy demand of the Level 2 EV

charger amount to 15,330 kg CO_2 per year. This value is derived by multiplying the annual energy requirement (*Eload*) of 38,325 kWh by the grid emission factor (*EFgrid*) of 0.4 kg CO_2 per kWh.

(ii) By contrast of grid electricity, meeting the same energy demand with a PV-powered system results in emissions of 1917 kg CO_2/year. This value is derived by multiplying the annual energy requirement (E_{load}) of 38,325 kWh by the grid emission factor (EF_{PV}) of 0.05 kg CO_2/kWh.

(iii) The reduction in GHG emissions achieved by switching from grid electricity to the PV system can be computed as, GHG reduction = 15,330 kg CO_2/year (grid) −1917 kg CO_2/year (PV) = 13,413 kg CO_2/year.

Fig. 12 provides a comprehensive comparison of GHG emissions and the environmental benefits of a PV-powered EV charger relative to one powered by grid electricity, showcasing the significant reduction in emissions achieved through renewable energy adoption. Specifically, the PV-powered system demonstrates an 87.5 % reduction in carbon emissions, underscoring its critical role in addressing climate change and supporting global sustainability efforts. This substantial decrease highlights the environmental advantages of integrating PV technology into EV charging infrastructure, as it not only lowers the carbon footprint but also reduces dependence on fossil fuels and advances energy independence. In contrast, grid electricity—often reliant on non-renewable energy sources continues to contribute to higher GHG emissions, depending on the energy mix. Beyond immediate emissions savings, the adoption of PV systems contributes to broader sustainability goals, fostering a greener transportation ecosystem and driving the transition toward a low-carbon future. This analysis emphasizes the potential of solar-powered solutions to create a resilient and eco-friendly energy framework, positioning renewable energy as a cornerstone of sustainable development.

Table 3 provides a critical and quantitative comparison between conventional EV charging stations, international standards, emerging trends, industrial applications, and international policies, alongside the proposed solar-powered EV charging station (EVCS). The comparison covers key aspects such as energy source, efficiency, environmental impact, and technological innovation (Kumar and Mikkili, 2024; Karuppiah et al., 2024).

Integrating solar energy into EVCS provides a promising solution for both reducing greenhouse gas emissions and enhancing energy independence. As this integration becomes more widespread, however, several challenges related to power quality, energy supply reliability, and congestion during peak demand periods emerge. One significant issue arises during ultrafast charging, where ensuring a smooth and stable power supply becomes crucial. The intermittent nature of solar energy means that, on sunny days, the system might generate surplus power, but during cloudy or low-sunlight conditions, the energy supply may fall short of meeting the high demand. This can cause voltage fluctuations and instability, compromising the quality of service provided by the charging system. To mitigate such challenges, battery storage systems play a crucial role in providing backup power when solar generation is insufficient. However, correctly sizing these batteries is paramount to ensure that they provide sufficient backup during periods of low solar energy production without leading to excessive over-investment. In this study, the simulation tool HOMER was utilized to design and optimize the system, helped to determine the most efficient configuration for the solar panels, battery storage, and EV charger. Despite the advantages of simulation tools, real-world variables, such as fluctuations in seasonal solar radiation and the degradation of batteries over time necessitate continuous monitoring and fine-tuning of the system for long-term performance. Additionally, EV charging congestion poses a critical challenge. During periods of high demand, when many EVs are charging simultaneously, the system may face inefficiencies, such as extended charging times and potential overloading of the solar system or grid infrastructure. In these cases, grid support may become necessary, but this could reduce the environmental benefits of the solar-powered system, particularly if the grid electricity is sourced from fossil fuels. Grid electricity reliance could result in higher carbon emissions and compromise the sustainability of the system.

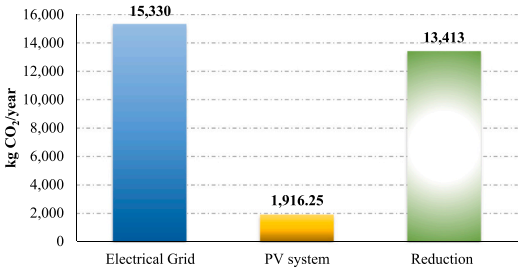


Fig. 12. A comprehensive comparison of GHG emissions.

Despite these challenges, solar-powered EVCS offers substantial environmental benefits. This study highlights a significant reduction in carbon emissions, aligning with global sustainability goals by moving away from fossil fuels and advancing the transition toward renewable energy sources. The findings from the simulation and real-world assessments demonstrate that while there are technical and operational challenges, the integration of solar energy into EV charging systems remains a crucial step toward building a more sustainable, low-carbon transportation infrastructure.

7. Conclusion

This study introduced a significant innovation in integrating solar power into electric vehicle (EV) charging systems, offering a sustainable solution for reducing greenhouse gas (GHG) emissions. To assess the feasibility of the proposed solar system, the discussion focused on four key areas: optimal system design, energy yield assessment, technical performance, and economic evaluation. The proposed solar system consisted of a 34 kW photovoltaic (PV) array, a 192-unit battery storage system, and an 8 kW inverter. Energy performance results showed that the solar array independently met the EV charger's energy demands, generating 62,294 kWh annually, which exceeded the charger's requirements by 19,648 kWh. In the event of a solar array failure, the battery bank provided backup power for up to 66.4 hours, ensuring system reliability during maintenance or downtime. From an economic perspective, the total NPC of the solar-powered EV charging system was estimated at $192,420, with a breakdown of $94,800 for initial capital (IC) costs, $71,692 for component replacements, and $38,567 for operation and maintenance (O&M), offset by a salvage value of $12,638 at the end of the system's life. These findings highlighted the cost efficiency and long-term viability of the proposed system. Environmentally, the solar PV system achieved an impressive 87.5 % reduction in carbon emissions compared to traditional grid electricity, supporting global efforts to combat climate change and transition to renewable energy sources. In addition to emission reductions, adopting solar energy decreased reliance on fossil fuels, promoted energy independence, and contributed to the development of a more sustainable energy infrastructure for the future.

List of abbreviations

EV	Electric Vehicle
GHG	GreenHouse Gas
SDGs	Sustainable Development Goals
PV	PhotoVoltaic
NPC	Net Present Cost
O&M	operation and maintenance
HOMER	Hybrid Optimisation Model for Electric Renewables
EVCS	Electric Vehicle Charging Station

Table 3
Comparative analysis of conventional EV charging stations, international standards, emerging trends, and the proposed solar-powered EVCS.

Aspect	Conventional EV Charging Stations	International Standards	Emerging Trends	Industrial Applications	International Policies	Proposed Solar-Powered EVCS
Energy Source	Grid electricity (primarily fossil fuels)	Varies by country; typically grid-based or renewable	Focus on renewable energy integration (solar, wind)	Growing demand for green energy solutions in commercial EV	Many countries have mandates for renewable energy integration	Solar energy (34 kW PV array) combined with battery storage (192 units)
Efficiency	Low, due to grid dependency and inefficiencies in power transmission	International Electrotechnical Commission (IEC), and Society of Automotive Engineers (SAE).	High-efficiency charging stations with fast charging and renewable energy	Industry using hybrid systems with solar, grid, and battery backup	EU and US regulations pushing for high efficiency	High efficiency, PV generating 62,294 kWh/ year, meeting EV demands with 19,648 kWh surplus
Environmental Impact (GHG Emissions)	High carbon footprint due to fossil fuel-based grid energy	Regulations aim for emission reductions, but effectiveness varies	Shift towards low-carbon solutions, including EVCS using renewable energy	Increased adoption of renewable-powered EVCS in green building projects	Countries like the EU and China push for zero-emissions vehicles and charging stations	87.5 % reduction in GHG emissions compared to grid-powered stations
Cost	Lower initial investment but higher operational costs due to energy purchase	Standards help ensure safe, reliable operations but do not focus on cost optimization	Focus on reducing operational costs, using renewables and energy storage	High initial costs for industrial installations with renewable integration, but lower OPEX	Financial incentives and subsidies available for green energy investments	Total NPC of $192,420, including $94,800 IC, $71,692 replacement costs, and $38,567 O&M, highlighting cost-effectiveness in the long term
Reliability	Dependent on grid stability; disruptions can impact service	Standards ensure minimum reliability but don't account for solar variability	Emerging technologies enhance system reliability with real-time adjustments	Hybrid systems increase reliability by providing multiple power sources	Policies focus on maintaining reliability while integrating renewable sources	High reliability with 66.4 hours of autonomy from battery backup and solar energy to ensure uninterrupted charging

PSH	Peak Sun Hours
CRF	Capital Recovery Factor
DOD	Depth of Discharge
IC	Initial Costs
SOC	State of Charge
TAC	Total Annualised Cost

List of symbols

E_{EV}	Annual energy consumption of the EV load
E_{losses}	Energy losses
E_{PV}	Energy output of the PV array
PC_{PV}	Rated capacity of the PV array
DF_{PV}	PV derating factor
$E_{Battery}$	Energy supplied by the battery bank
A_{batt}	Battery bank autonomy
N_{batt}	Number of batteries
V_{nom}	Nominal voltage of a single battery
Q_{nom}	Nominal capacity of a single battery
$L_{prim,ave}$	Average daily load
R_{batt}	Battery bank lifetime
$Q_{lifetime}$	Lifetime throughput of a single battery
Q_{thrpt}	Annual battery throughput
$R_{batt,f}$	Battery float life
C_{TAC}	Total annualized cost
R_{comp}	The component's total lifespan in years
R_{rem}	The component's remaining lifespan in years

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CRediT authorship contribution statement

Mohammed H. Alsharif: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Faisal Alsaif:** Software, Resources, Investigation. **Manish Kumar Singla:** Visualization, Supervision, Methodology. **Saibal Manna:** Visualization, Resources, Investigation. **Mun-Kyeom Kim:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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