



Techno-Environmental Analysis of Small Scale Photovoltaic Assisted Electric Bike Charging Station at AKPRIND University Campus

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ABSTRACT

The expansion of electric vehicles and e-bikes necessitates a concurrent development of accessible, zero-emission charging infrastructure to facilitate a sustainable transition from fossil fuel-dependent transportation. To address this requirement, the present work aims to develop a small-scale photovoltaics-assisted electric bike charging station and evaluates its techno-environmental feasibility, specifically examining its thermal characteristics and capacity for greenhouse gas mitigation. The small-scale photovoltaics-assisted electric bike charging station is installed at AKPRIND university campus. Technical measurement and greenhouse gas analysis are performed at various tilt angles of 5°, 10°, and 15°. Data of solar irradiance, voltage, and current of the photovoltaic are collected from 10 a.m. to 2 p.m. For tilt angle observed (5°, 10°, and 15°), technical measurement demonstrate that the system operates optimally at a photovoltaic tilt angle of 15°, achieving a conversion efficiency of 6.79% while concurrently charging three electric bike units. Furthermore, environmental impact analyses indicate that the small-scale photovoltaics-assisted electric bike charging station yields a 93.9% reduction in carbon emissions relative to conventional grid-tied charging stations. These findings highlight the potential of solar-powered charging infrastructure to mitigate climate change, reduce reliance on fossil fuels, and support the broader evolution of green transportation systems.

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1. Introduction

Depletion and greenhouse effect of fossil fuel leads to optimize the use of renewable energy sources to fulfil world's energy demand, for example by harnessing solar solutions for a sustainable future renewable energy [1]. Recently, utilization of solar energy has got increasing attention in many sectors [2], [3], [4] including electric vehicle in green and sustainable transportation sector. Governments worldwide have undertaken major initiatives to decarbonize both the generation and demand sides of energy systems, positioning this as a key strategy for promoting an efficient energy transition and reducing carbon emissions [5], [6]. Electric vehicle is believed the most robust tool for achieving zero-carbon targets [7], [8]. In recent years, the use of electric vehicle increases significantly, including electric bike. This rapid expansion is largely attributed to key factors such as decreasing battery costs, government incentives, and environmental benefits [9]. The plummeted cost of lithium-ion batteries by over 89 % since 2010, making electric vehicle more affordable and accessible to a broader user [10]. In 2019, the worldwide market share reached 2.9% [11].

The transition of transportation sector from fossil fuel-based vehicle to electric vehicle (EV) has to be balanced with charging station availability. As a clean and renewable energy source, the application of solar energy in vehicle power systems is becoming an increasingly important direction for the development of green transportation [12]. Mostly, the EV charging stations available are on-grid system. Non-residential EV charging stations must be integrated into the local power grid, requiring substantial upgrades in some areas. Especially those EV charging stations with fast charging capabilities demand large amounts of electricity over short periods, putting strain on transformers and distribution networks [13]. Proper planning and strategic geographic distribution are crucial for providing seamless intercity travel for EV drivers [14]. The on-grid EV charging station depend on electric grid which comes from fossil fuel-based power plant, hence does not free carbon emission. The EV charging station should not only easily be accessed but also free carbon emission.

Developing renewable energy-supported EV charging stations could address the nexus of transportation electrification and green battery-charge operations. Photovoltaic (PV) powered EV charging can substantially reduce the carbon foot prints when compared to the conventional utility on-grid based EV charging [15], [16]. Several previous works in developing solar powered EV charging

station have been reported. Due to the temporal match between charging profiles and peak solar production, solar EV charging station studies tend to focus on workplaces [17],[18][19]. Deshmukh & Pearce [20] investigated the energy related aspects of developing EV charging stations powered with solar photovoltaic (PV) canopies built on the parking infrastructure of large-scale retailers. They obtained a promising results, but future work is needed to provide more granular quantification of the benefits of they approach. Wu *et al.* [21] studied techno-economic solar assists EV charging station placed at university campus. By using the proposed method they found that the campus's peak demand is reduced by around 12 % and net annual energy cost is reduced by up to 9.2 % while providing free EV charging. Hossain *et al.* [22] assessed economic viability and environmental impact of solar-powered EV charging station in Gazipur, Bangladesh. The results indicated the CO₂ emissions produced by solar-based EV charging systems are lower than those produced by coal-based chargers. Redwan *et al.* [23] predicted CO₂ emission of 300 kWp solar photovoltaic-powered electric vehicle charging station decreased about 6460.2 tons within 25 years.

Performance of solar energy system is affected by several parameters, such as location of the site, tilt angle and temperature [24]. Optimum tilt angle of the photovoltaic panel depends on location where the system installed. Different optimum tilt angle of the panel at different location have been reported. Optimum tilt angle at Surabaya city is 36°-39.4° [25], at Ankara city is 31.33° [26], at Jeddah city is 25° [27], and at Basra city is predicted 28° [28]. Temperature of photovoltaic panel can impact on conversion efficiency of solar irradiance into electric energy. Mostly, about 80% of solar irradiance is converted into heat and only 20% is converted into electrical energy [29]. High temperature of the panel can reduce degree of its conversion efficiency [30], [31]. To maintain panel temperature not exceed than maximum allowable value, it is important to perform cooling of a panel surface. Water cooling method has been proven method not only to keep panel temperature at design temperature, but also to enhance panel conversion efficiency. Water injection cooling resulted in an energy output growth [32]. Chanphavong *et al.* [33] found that conversion efficiency of cooled mono-crystalline PV module was higher than non-cooled mono-crystalline module. Mostakim *et al.* [34] observed PV panel efficiency enhancement up to 16.78 % at cooling water flow rate of 1.56 L/min. Meanwhile, Purwant & Badadhe [35] enhanced PV efficiency using direct cooling with

CuO nanofluid. They found that the CuO nanofluid reduced panel temperature by up to 9.25°C, increased electrical efficiency from 16.32% to 17.60% compared to conventional water cooling.

Various methods in developing solar energy system have been used to optimize performance of the system. Zhang *et al.* [36] used Computational Fluid Dynamics tool to optimize tilt angle of the photovoltaics. Ekren *et al.* [37] used HOMER software in sizing a solar-wind hybrid electric vehicle charging station. Meanwhile, Benayad *et al.* [38] combined an Analytic Hierarchy Process (AHP) based multicriteria decision analysis with geospatial tools and land cover classification using a deep learning model to identify optimal locations for solar powered charging stations. Other method used in location selection for solar based EV charging station is combination of GIS and MCDM methods [39]. A high efficiency of 97.42 % of PV-based EV charging system with SEPIC-Cuk converter was reported by Shyma *et al.* [40]. Khan *et al.* [41] optimized fuzzy-MPPT approach for superior solar power management in EV battery charging systems maximizing the utilization of available solar radiation. The implementation of MPPT techniques and sophisticated energy management systems further enhances energy extraction and utilization, ensuring that every watt of solar energy is captured and directed efficiently toward EV charging [42]. Several free access tools for designing photovoltaic system available online, i.e. PVWatts, and OpenSolar. The results show that PVWatts tends to produce higher energy estimates suitable for on-grid applications while OpenSolar better for its comprehensive feature set and financial assessment based on native tool capabilities [43].

Many works on solar energy utilization have been reported so far, especially in increasing performance of the system, such as by PV surface cooling, tilt angle optimization, and battery discharge characteristic. From many previous works have been studied and cited, it is found a research gap in solar powered electric vehicle charging station. None of those works reported in developing a small scale photovoltaic assisted electric bike charging station (PV-EBCS). Thus, the present work aims to build a small-scale PV-EBCS at AKPRIND university campus towards a greener and sustainable transportation and investigate its techno-environmental feasibility. The novelty of the work is the development of electric bike charging station powered by solar energy which has simple construction and a low fabrication cost, and also very suitable to be installed at campus.

2. Materials and Methods

Figure 1 shows workflow diagram of the present work. The work was started with component selection of the PV-EBCS, i.e. photovoltaic (PV), maximum power point tracker (MPPT), storage battery, inverter, and charging unit. The selection was based on charging power required for 3-unit electric bikes. Once the components have been selected, the PV-EBCS was then installed at the AKPRIND university campus located at the latitude 7°15'–49' of the South with an average solar radiation about 4 kWh/m²/day [44]. Once the data have been collected, techno-environmental analysis was performed to figure out feasibility of the PV-EBCS in terms of thermal performance and greenhouse gas reduction.

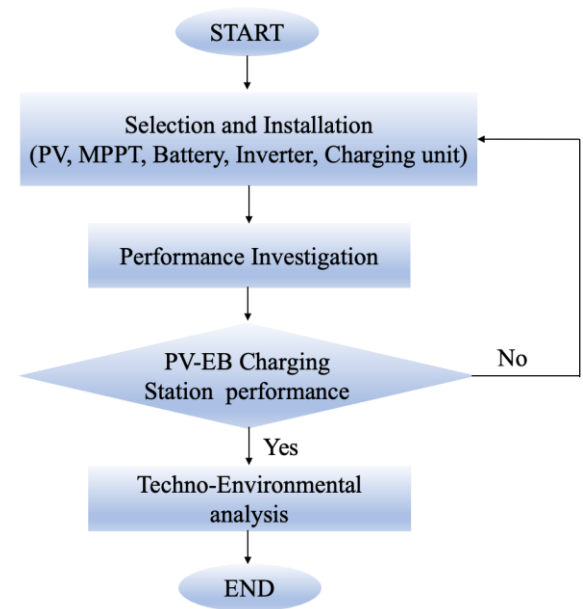


Figure 1. Flow diagram of the work

2.1. Component selection and installation

The charging station was aimed to be able for recharging 3-unit of electric bikes in the same time. Uwinfly bike used for the test has a battery with a specification of D7S/48V 12Ah. Selection of component of PV-EBCS was based on charging power needed.

2.1.1. Charging power required

Power required for charging Uwinfly electric bike is 300 Watt. For 48 V 12 Ah battery, total power required per charging time (t) is calculated using Eq. (1) where n is the number of electric bikes being charged.

$$P_{\text{charge}} = n \times 48V \times 12Ah \times t \quad (1)$$

2.1.2. Photovoltaics (PV) panels

Shortwave solar radiation from the sun is converted into DC electricity by PV panel. Total annual power output generated by the PV panel is calculated using Eq. (2) [9].

$$P_{\text{pv}} = PC_{\text{pv}} \times PSH \times DF_{\text{pv}} \times 365 \text{ days/year} \quad (2)$$

where P_{pv} is the annual power output, PC_{pv} refers to maximum power of the PV (PV Watt peak), PSH is the peak sun hours (the equivalent average daily solar energy received), DF_{pv} is the derating factor of the PV due to dust accumulation, energy losses, and temperature fluctuations that may decrease the panel's power output.

2.1.3. Battery system

DC electricity generated by the PV panel is stored in a battery. A battery ensures a reliable power supply during charging time. Its capacity depends on the depth of discharge (DOD), which must be assessed before installation. The DOD of the battery can be formulated as in Eq. (3) where SOC_{min} is the minimum state of charge. The overall cost of a solar system is largely influenced by the cost of the batteries, making the battery's lifespan a critical factor [9]. It is important to balance between charging efficiency and battery reliability for solar systems in order to longer lifespan of the battery [45].

$$DOD = 1 - \frac{SOC_{\text{min}}}{100} \quad (3)$$

Following Alsharif *et al.* [9], maximum duration of fully charged battery can charge 3-unit electric bikes without external source is estimated using days of autonomy (A_{batt}) term which is calculated using Eq. (4).

$$A_{\text{batt}} = \frac{N_{\text{batt}} \times V_{\text{nom}} \times Q_{\text{nom}} \times DOD \times (24h/d)}{I_{\text{avg}} \times (1000Wh/kWh)} \quad (4)$$

where N_{batt} represents the total number of batteries, V_{nom} is the nominal voltage of each individual battery (V), Q_{nom} is the nominal capacity of a single battery (Ah), and L_{avg} corresponds to the average daily load demand for charging

2.1.4. Inverter

The inverter converts DC current to AC current to supply the AC load of electric bike. The inverter capacity (C_{inv}) is calculated using Eq. (5) where L_{AC} is the maximum available AC load, η_{inv} is the

efficiency of the inverter, and SF represents safety factor [46]

$$C_{\text{inv}} = \left(\frac{L_{\text{AC}}}{\eta_{\text{inv}}} \right) \times SF \quad (5)$$

2.1.5. Charger unit

Charger type can be classified into 6 categories, i.e. Level 1 (slow charging), Level 2 (fast charging), DC fast charger, ultra-rapid charger, wireless charger, and portable charger [47], [48]. Considering daily charging need in campus which is in working time, i.e. 8 am to 4 pm (8 hours/day), Level 1 charger is proposed in the present work. With a charging time of approximately 8–20 hours for a full charge with power output 1.4-3 kW, the Level 1 charger perfectly match with the standard workday. Employees and student can connect their electric bike to the charger upon arrival in the morning, ensuring they are fully charged by the end of the day.

Once the specification of the components has been defined and selected, the work was followed by installing the PV-EBCS at AKPRIND university campus. Figure 2 presents a photograph of the PV-EBCS and Table 1 gives a detail specification of its components.



Figure 2. A photograph of the PV-EBCS

Table 1. Specification of the components

No	Component	Qty	Specification
1	PV panel	4 units	- Trina Solar TMS-665DE21, Monocrystalline, 665 Wp
			- $V_{\text{mp}} = 38.0 \text{ V}$
			- $I_{\text{mp}} = 17.51 \text{ A}$
			- $I_{\text{sc}} = 18.57 \text{ A}$

2	Battery	2 units	- Surface area (A) = 2 m ²
			- Lithium Iron Phosphate (LiFePO ₄)
			- Capacity = 100 Ah (1280 Wh)
			- V _{nom} = 12.8 V
			- I _{max charge} = 50 A
3	Inverter	1 unit	- V _{max charge} = 14.6 V
			- Model IHS3000
			- Capacity = 3000 VA
			- V _{input} = 90–280 VAC ±3V (Normal)
			- V _{out} = 220/230/240 VAC ±5%
4	Charger unit	1 unit with 3 plug in	- Frequency = 50/60 Hz ±5 (Adaptif)
			- Pure Sine Wave
			- Level 1 (slow charging)
			- V _{input} = 27 V
			- V _{output} = 229 V AC
			- I _{max@plug} = 220 V
			- P _{max} = 3000 W
			- Display monitor 8 inc

2.2. Performance test

Figure 3 shows the experimental setup of the performance test of the PV-EBCS in the present work. The PV-EBCS was tested by charging 3-unit Uwinfly bikes concurrently. The performance of the PV-EBCS was evaluated at PV tilt angle (α) of 5°, 10°, and 15°. Data of solar irradiance, voltage, and current were taken from 10:00 AM to 2:00 PM within 3 days for each α . The data curation was performed every 1 hour. Solar irradiance was measured using flux meter, voltage and current generated by the PV panel were measured using multi meter.

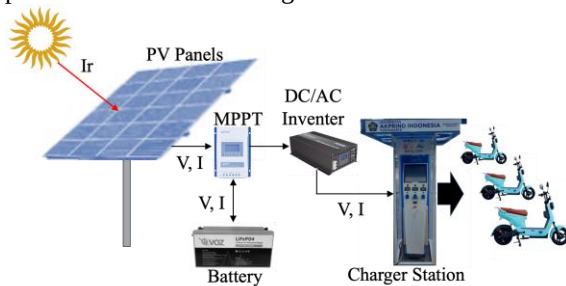


Figure 3. Experimental setup

2.3. Techno-Environmental Analysis

According to Aly *et al.* [29] it is only 20% of solar irradiance is converted into electric energy in the PV module. Power output of the photovoltaic and its conversion efficiency are calculated using Eq. (6) and Eq. (7).

$$P_{pv} = V_{pv} \times I_{pv} \quad (6)$$

$$\eta_{pv} = \frac{P_{pv}}{I_r \times A_{pv}} \quad (7)$$

where P_{pv} , V_{pv} , and I_{pv} are the PV power output, voltage, and current. η_{pv} is the PV conversion efficiency, I_r is the solar radiation, and A_{pv} is the PV surface area.

Annual reduction of greenhouse gas (GHG) emission CO₂ when using the PV-EBCS is calculated using Eq. (8) [9].

$$GHG_{reduction} = GHG_{grid} - GHG_{pv} \quad (8)$$

where GHG_{grid} is the annually CO₂ emission for charging 3-unit Uwinfly electric bikes with grid connection and GHG_{pv} is the annually CO₂ emission for charging 3-unit Uwinfly electric bikes with the PV-EBCS. GHG_{grid} and GHG_{pv} are calculated using Eq. (9) and Eq. (10) [9].

$$GHG_{grid} = EF_{grid} \times P_{charging} \times 365 \text{ days/year} \quad (9)$$

$$GHG_{pv} = EF_{pv} \times P_{charging} \times 365 \text{ days/year} \quad (10)$$

where emission factor EF_{grid} equals to 0.817 kg CO₂/kWh for Java-Bali electricity transmission network [49] and emission factor of photovoltaic EF_{pv} is 0.05 kg CO₂/kWh [9].

2.4. Uncertainty Analysis

Due to the devices accuracy and measurement data, uncertainty analysis of photovoltaic power output is performed using Eq. (11).

$$\frac{\Delta P}{P} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \quad (11)$$

3. Results and Discussion

Figure 4 presents solar irradiance from 10:00 AM to 2:00 PM during the test at varies PV's tilt angle (α) of 5°, 10°, and 15°. The result reveals highly

fluctuating profiles for each α , indicating localized atmospheric variations (such as intermittent cloud cover). The maximum solar irradiance recorded during the testing period reached approximately 900 W/m² at 12:00 PM at the $\alpha = 5^\circ$ configuration. This indicates that a lower tilt angle is highly effective at capturing peak overhead midday sun. Conversely, the $\alpha = 10^\circ$ configuration demonstrated superior performance earlier in the day, peaking at roughly 750 W/m² at 11:00 AM, before experiencing a sharp decline to 250 W/m² at noon. The $\alpha = 15^\circ$ configuration showed the most stable profile between 10:00 AM and 12:00 PM, maintaining irradiance levels between 310 W/m² and 500 W/m². However, it failed to match the higher peak outputs achieved by the $\alpha = 5^\circ$ and $\alpha = 10^\circ$ setups during their respective optimal hours. By 2:00 PM, the solar irradiance for all three angles converged to their lowest values, ranging tightly between 100 W/m² and 140 W/m². This simultaneous drop suggests a dominant external factor, such as heavy afternoon cloud cover or a late-day decline in solar altitude, which minimized the geometric advantage of any specific tilt angle.

Ultimately, these findings suggest that while $\alpha = 5^\circ$ delivers the absolute highest localized power spike at true solar noon, a dynamic tracking system or an intermediate fixed angle could be considered to balance out the severe midday drop observed in the $\alpha = 10^\circ$ profile and optimize overall daily energy yield.

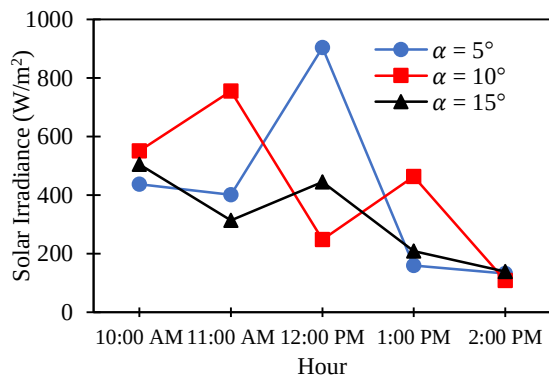


Figure 4. Solar irradiance at the test location

Figure 5 displays DC electricity generated by the PV. The hourly PV power output was monitored from 10:00 AM to 2:00 PM at three distinct tilt angles ($\alpha = 5^\circ$, $\alpha = 10^\circ$, $\alpha = 15^\circ$). This analysis bridges the relationship between the environmental solar irradiance data and the actual electrical energy converted by the system. In contrast to the fluctuating solar irradiance trends, the actual PV power output demonstrates a clear performance hierarchy. The

higher tilt angles configurations ($\alpha = 10^\circ$ and $\alpha = 15^\circ$) vastly outperformed the lower $\alpha = 5^\circ$ setting.

A significant observation occurs when comparing the systems at 12:00 PM and 1:00 PM. While the $\alpha = 15^\circ$, the PV achieved its maximum efficiency at 12:00 PM (reaching 201.4 W), the $\alpha = 10^\circ$ peaked later at 1:00 PM (reaching 203.3 W). Conversely, despite showing a high solar irradiance at midday (see Figure 4), the $\alpha = 5^\circ$ configuration generated the lowest overall electrical output. This suggests that the $\alpha = 10^\circ$ and $\alpha = 15^\circ$ provides a much more effective incidence angle for stable photovoltaic conversion across these hours. Regardless of the angle, all three configurations experience a drastic drop in power output at 2:00 PM, with all values plunging to 100 W or below as midday solar intensity fades.

The multi meter used for measuring voltage and current has an accuracy of ± 0.012 V and ± 0.035 A. Using Eq. (11), the uncertainty in power output becomes $\pm 3.7\%$.

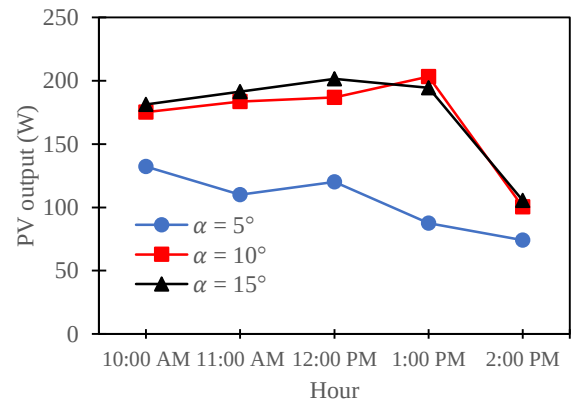


Figure 5. Power output of the PV

Figure 6 presents conversion efficiency of the PV at $\alpha = 5^\circ$, 10° , and 15° . The result shows the highest conversion efficiency is obtained at $\alpha = 15^\circ$ which is 6.79%. The $\alpha = 5^\circ$ orientation optimizes the perpendicular alignment of the PV cells relative to the incoming solar irradiance over the tested duration. The lower conversion efficiency of the PV when $\alpha = 5^\circ$ and $\alpha = 10^\circ$ were 3.23% and 5.0%, respectively. The lower efficiencies at $\alpha = 5^\circ$ and $\alpha = 10^\circ$ are due to higher optical reflection losses. As the α decreases, a larger portion of the solar radiation reflects off the PV surface rather than penetrating the PV for electrical conversion. The conversion efficiency obtained in the present work are comparable with that obtained by Chala *et al.* [32] i.e. 23.6% and by Mostakim *et al.* [34] i.e. 16.78%.

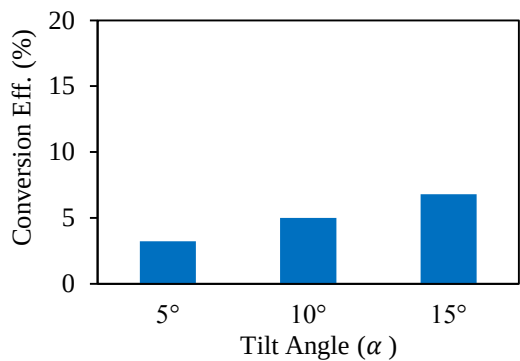


Figure 6. Conversion efficiency of the PV

Meanwhile, a comparison of GHG emission between PV-EBCS and relative to one powered by grid electricity is presented in Figure 7. GHG emission are 3091.79 kg CO₂/year and 189.22 kg CO₂/year for the charging station powered by solar energy and the one powered by grid electricity. The result shows the significant reduction in emissions achieved through solar energy adoption. Specifically, the PV-EB charging station demonstrates a carbon emission reduction of 2902.57 kg CO₂/year (93.9%). This reduction is comparable with a result obtained by Alsharif *et al.* [9], i.e. 87.5%. Beyond immediate emissions reduction, the use of PV powered charging station impacts to wider 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.

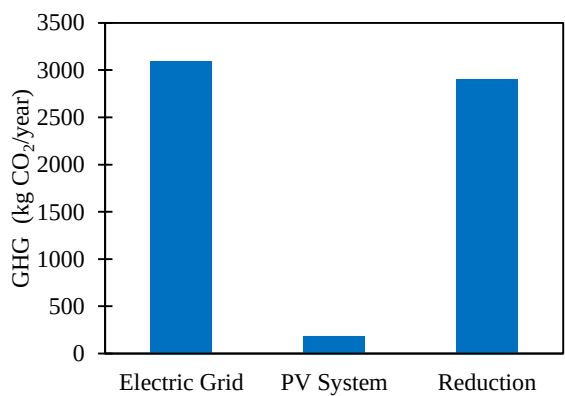


Figure 7. A comparison of GHG emissions.

4. Conclusions

The present work presents an innovative approach in reducing greenhouse gas emissions by integrating a 2.66 kW PV array, 2-unit batteries, and 3 kVA inverter into PV-EBCS. The system's viability was verified through technical and environmental analysis. For tilt angle investigated (5°, 10°, and 15°), technical analysis showed that the charging station work properly for charging 3-unit electric bikes in the same time with maximum conversion efficiency of 6.79% while PV tilt angle was set 15°. The environmental analysis showed the PV-EBCS charging station delivered a remarkable 93.9.% decrease in carbon emissions compared to conventional grid charging station, advancing worldwide initiatives to mitigate climate change and adopt clean energy alternatives. Beyond lowering greenhouse gases, shifting to solar power lessened dependence on fossil fuels and fostered the growth of a greener and more sustainable transportation. The present analysis was performed just limited on technical and environmental feasibility of the PV-EBCS. In order to figure out targeted customer satisfaction, it is essential to conduct PB- economic analysis of the PB-EBCS in the future work

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Nomenclature

A	Surface area of the PV (m ²)
C _{inv}	Inverter capacity
DOD	Deep of discharge
DF _{pv}	Derating factor
GHG _{grid}	Annually CO ₂ emission with grid connection
GHG _{pv}	Annually CO ₂ emission with the PV-EBCS
L _{avg}	Average daily load demand for charging
Imp	Current at maximum power (A)
I _{pv}	Actual PV output current (A)
I _{sc}	Short-circuit current (A)

N_{batt}	Total number of battery
PSH	Peak sun hours
PV	Photovoltaic
PV-EBCS	Photovoltaic assisted electric bike charging station
P_{pv}	Annual power output of photovoltaic
V_{pv}	Actual PV output voltage (V)
V_{mp}	Voltage at maximum power (V)
V_{oc}	Open-circuit voltage (V)
SOC_{min}	minimum state of charge
α	Tilt angle (°)
η_{pv}	PV conversion efficiency (%)
η_{inv}	Efficiency of the inverter

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