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Investigation of Cost-Effective Electric Vehicle Charging Station Assisted by Photovoltaic Solar Energy System

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Abstract

The impact of increased power demand on electricity grids due to the projected expansion of electric vehicles (EVs) could be lessened by integrating renewable energy-fed EV charging stations. The study aims to evaluate different combinations of electric vehicle chargers' technology for use in an EV charging station powered by a photovoltaic solar system. Then a technical, economic and environmental feasibility analysis of the EV charging station is presented in this paper.

Keywords: PV Solar Energy; Electric Vehicle (EV); EV Charging; EV charge station; Renewable energy sources (RES).

1. Introduction

Replacing current fossil-fueled modes of transport with electric vehicles represents the most robust tool for achieving zero-carbon targets. However, a smooth transition is crucial to reduce the electricity networks' carbon footprint and build more capacity to meet the expected extra demand for power. As the number of EVs is projected to increase rapidly, developing renewable energy-supported EV charging stations could address the nexus of transportation electrification and green battery-charge operations.

This paper aims to evaluate an EV charging station which combines five different types of charger technology supported by a PV solar energy system for application in a parking area at the University of Nottingham (UoN), UK. A stochastic approach is used to calculate EVs' charging demand. Also, the study provides six different charging station scenarios to determine the best combination of 3kW and 7kW capacity chargers. This study will provide a preliminary investigation of future charging stations to be established in the campus parking areas to evaluate the best combination of charge capacity and charger rate, solar energy potential, and economic viability of the installation. A schematic representation of the proposed system is shown in Fig.1.

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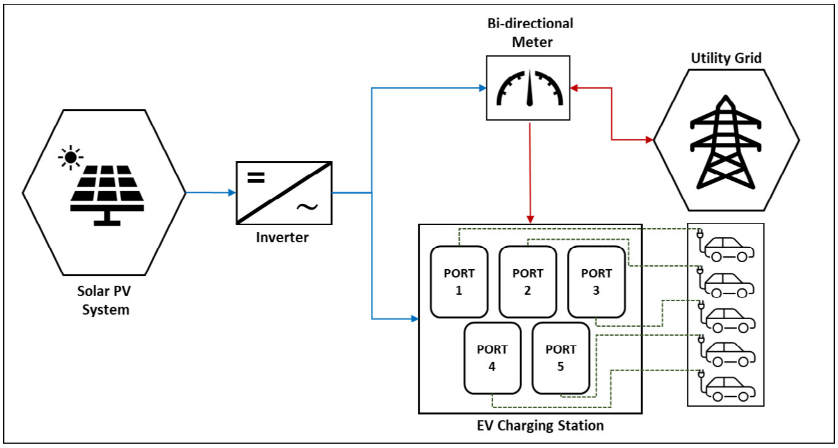

Fig. 1. Schematic diagram of the proposed PV-assisted EV-charging station

2. Methodology

This study uses computer modelling to estimate the solar energy potential of the location and presents a stochastic approach to selecting and sizing five separate charging ports for the individual EV charging station. Fig. 2 shows a flow chart of the steps used in developing the methodology of this study. The potential of solar energy resources and the effect of environmental parameters on the location are obtained from Photovoltaic Geographical Information System (PVGIS) (PVGIS, 2023). A mathematical tool was used in this study to determine the power generation capacity of the PV system to meet the total load of the EV charging station.

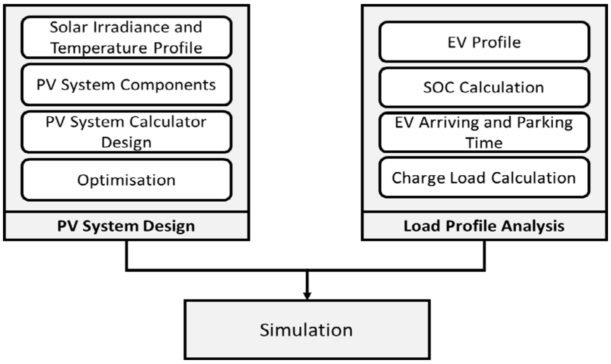

Fig. 2. The summary of the applied methodology

2.1. Solar Resources

The case study project is located at the University of Nottingham. The solar energy resources potential of the location (Nottingham: 52.95° N and 1.15° E) and the effect of environmental parameters on the location are obtained from Photovoltaic Geographical Information System (PVGIS) (PVGIS, 2023).

A mathematical tool is used to determine the power generation capacity of the PV system to meet the total load of the EV charging station. In this tool, the effect of weather conditions, including solar radiation and ambient temperature, is taken into consideration. Additionally, the energy generation from the PV array system (E_{PV}) is calculated using Eq. 1. Where A_{array} is the total needed solar array area, H_T is solar radiation on the plane of the module, and η_p refers to the panel efficiency.

$$E_{PV} = A_{array} \times H_T \times \eta_p \quad (1)$$

2.2. EV Charging Station Technology

To assess the charging station power load accurately, the computer model of the EV takes into account the number, type of EVs and state of charges (SOCs) (DfT, 2022). The total hourly load of the EV chargers was determined using a stochastic approach to provide randomness and uncertainty. Then, the average battery capacities were determined by considering the UK's current EV market trends. After then, the model generated an EV dataset with each EV randomly assigned a battery capacity. The Gaussian distribution is then used to generate the dataset's random SOCs of each vehicle. In this case, it is assumed that the SOCs of the EVs to be charged will be between 20% and 50%, and an EV battery is considered fully charged when it reaches 80% of its maximum charging capacity. Additionally, in this study, the efficiency of the chargers $(\mu_{charger})$ is taken as 90% (Jian et al., 2018). Moreover, the required charging demand (E_{EV}) and the charging duration ($t_{charging}$) of the EVs for a full charge can be estimated by using Eqs. 2 and 3.

$$E_{EV} = P_{battery} \times (0.8 - SOC_{current}) \quad (2)$$

$$t_{charging} = \frac{E_{EV}}{P_{charger} \times \mu_{charger}} \quad (3)$$

where $P_{battery}$ is the total battery capacity of the EVs, and $SOC_{current}$ and $P_{charger}$ refer to the charge status of the EVs when they reach the station and the charger power, respectively.

The EVs' arrival and parking time have also been considered in the paper. First, the research by Hovet et al. (2018) was used for modelling the plug-in and parking durations of the vehicles. Their study analysed many parameters such as charging power, charging, and parking times of vehicles using charge operation data collected from three charging stations at the University of Georgia, which was collected for approximately 3.5 years. The study claimed that vehicles usually complete the charging process within 1-3 hours, and more than three-quarters of the charging operations are in this range. In addition, the study showed that around 90% of the vehicles occupy the charging port for a maximum of 1 hour after completing the charge. Due to the short uncharged time, the distribution of charging times is modelled as the total parking (occupying the charging port) time in the current study. After that, the model determines the charging port with no vehicle for each scenario and randomly selects a new vehicle from the dataset for the free ports. This provides a multidimensional stochastic approach from the specification of vehicles to charging operations.

After completing the system sizing, a cost analysis can be performed using Eqs. 4 and 5 where $Cost_{system}$ is the total cost of the possible project, including the costs of equipment and installations. Also, the system cost per kWh charge is shown as $Cost_{charge}$. Addition to this, the annual total covered charge load and the system lifespan are referred to as P_{load} and $t_{project}$, respectively.

$$Cost_{system} = \sum Capital\ costs + \sum Installation\ costs \quad (4)$$

$$Cost_{charge} = \frac{Cost_{system} + \sum Cost_{replacement} + \left(t_{project} \times \sum Cost_{maintenance}\right)}{P_{load} \times t_{project}} \quad (5)$$

The research model flow chart is shown in Fig. 3. T and S, in Fig. 3, refer to time and the number of the combination scenarios, respectively.

A preliminary investigation revealed that EV chargers used at the University of Nottingham Campus are rated at 3-kW and 7-kW power output (ZAP-MAP, 2022). The present approach assumes that EVs with small and medium-sized battery capacities tend to use chargers with 3-kW and 7-kW charge rates. Also, in this study, the same type and power level of chargers' technology are considered to create a five-charging port station, as shown in Table 1.

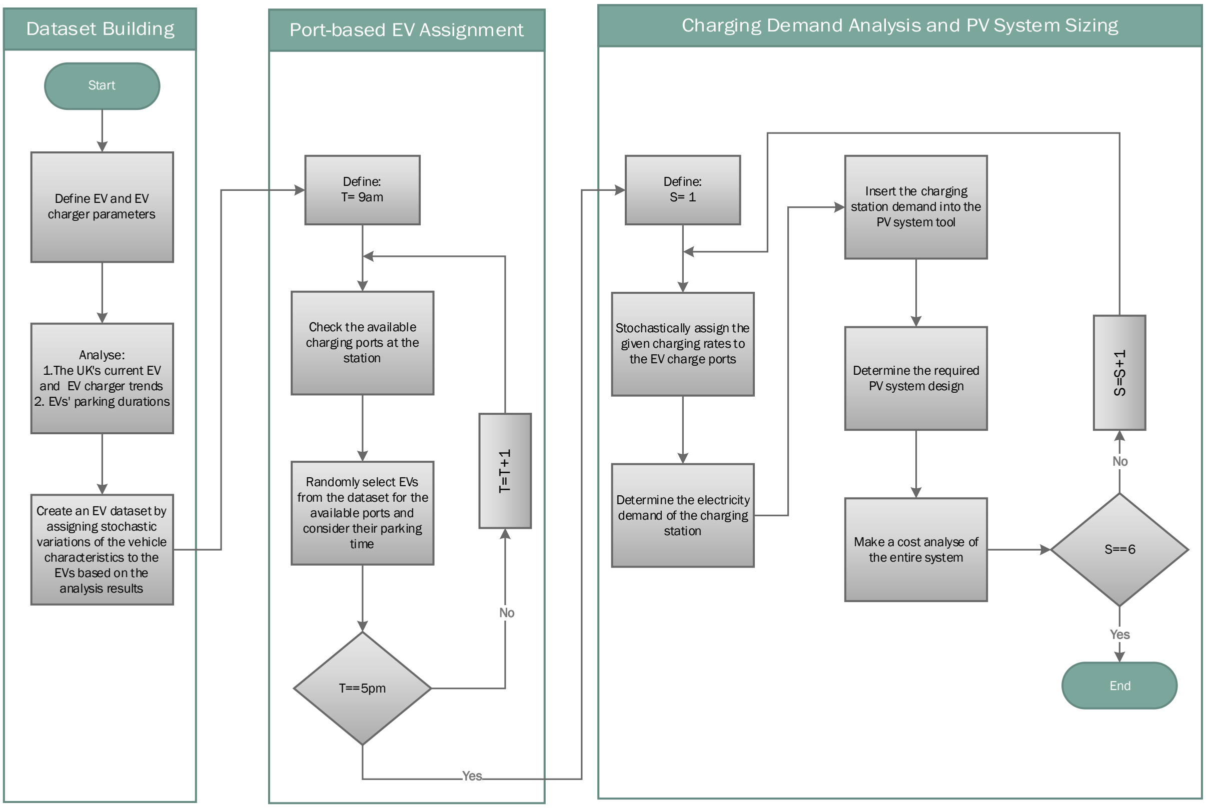

Fig. 3. The model algorithm flowchart

Table 1. The charger port combinations

Chargers Scenarios	S1	S2	S3	S4	S5	S6
	Number of Chargers	Number of Chargers	Number of Chargers	Number of Chargers	Number of Chargers	Number of Chargers
3-kW Chargers	5	0	3	2	1	4
7-kW Chargers	0	5	2	3	4	1

Here, the charge rate of each charging port is also determined randomly by the model for each scenario. For instance, in Scenario 3, the charging ports with a 3-kW charge rate are allocated stochastically rather than systematically throughout the simulation.

2.3. The Mechanics of Grid-Connected PV Systems

Solar PV-powered energy systems can be designed as standalone (independent of the grid) as found in remote areas or grid-connected which allows the export and import of electricity to and from the grid (Elthokaby et al., 2023).

This study focuses solely on the design of a grid-connected solar PV system that allows bi-directional power flow to ensure an uninterruptible electricity supply to the EV charging station. The electric power flow from and to the grid is measured through Net Metering which is then used for billing transactions between the electricity supplier and EV charging station owner (Marcelino et al., 2023). A grid-connected PV system consists of primary and secondary components such as an inverter, PV panels, electricity meters, fuses, and safety switches (Alternative-Energy-Tutorials, 2023).

Depending on the PV-field capacity, weather conditions, and operation mode, grid-connected PV systems have the advantage of providing direct electricity export revenues as well as meeting the site's electricity demand. The current UK government support program for low carbon energy generation called Smart Export Guarantee (SEG) allows licensed Microgeneration Certification Scheme (MCS) to purchase excess energy from private generators up to 5MW with tariff rates ranging between £0.02 and £0.15 per kWh ((Marcelino et al., 2023; MCS, 2019; OFGEM, 2023; Solar Energy UK, 2023).

In the UK, the connection of a PV system to the grid is related to the size of the system. The licensed system installer can only notify the Distribution System Operators (DNO) for small-size PV systems with up to 3.68kW installed capacity after connecting to the grid. However, the installer must obtain permission from the DNO before connecting to the grid for the PV systems exceeding the limits of the G83/2 engineering recommendation. In this case, the DNO can permit by considering the local grid capacities or perform the necessary actions to update the local network if the PV system owner agrees to pay the network modification cost (Energy Saving Trust, 2023).

The specifications of the PV panels used in this study are shown in Table 2 (Europe-SolarStore, 2023.).

Table 2. PV panel specifications

Physical and Electrical Parameters	
Module type	Mono-Si
Module area (m^2)	1.26
Peak power (W)	250
Open circuit voltage (V)	53.2
Short circuit current (A)	6.03
Max power voltage (V)	44.3
Max power current (A)	5.65
Operating temperature (°C)	-40 to 85
Panel efficiency (%)	19.8

3. Result and Discussion

The Global Solar Atlas (2023) shows that the global horizontal irradiation (GHI) and the direct normal irradiation (DNI) of Nottingham are 965.3 kWh/m^2 and 797.2 kWh/m^2, respectively. The solar resources simulation tool also shows a large fluctuation in available solar radiation ranging from 180 Wh/m^2 on average in winter to 277 Wh/m^2 in summer. The length of the region's sunshine is also observed to vary seasonally. The amount of sunshine rises to up to 17 hours in the summer and falls to 7 hours in January and December. Solar irradiation and sunshine duration change throughout the year in the UK. This fluctuation may also cause surplus energy production and unnecessary investment cost due to excessive energy potential in the summer months. Therefore, to evaluate the feasibility of the size and capacity of the required PV array computer modelling was used to calculate the required amount of power from the PV system on a monthly and annual basis and taking into account the estimated charging station's electrical load.

The computer model considers two different modes for sizing the solar arrays. In the first mode, the required PV array area is calculated by considering the annual balance between the exported and imported electricity from/to the grid (i.e., the electrical energy imported from and supplied to the grid is equal). Additionally, in this mode, in months with low solar radiation such as October, November, December, January and February, the charge needs of the EV charging station are met partly from the grid. However, in the remaining months of the year with the higher solar irradiance and longer daytime hours, the PV system generates excess power which is exported and sold back to the grid under the SEG scheme to generate financial revenue.

In the second mode, the size of the PV array was undertaken to meet the peak power demand of the EV-charging station throughout the year. This approach can make the system operate independently from the grid; however, the required PV area and capital outlay of the installation will be excessively high. For example, the computer model calculation shows that in the first mode of sizing the PV arrays 141 PV panels (177.57 m2 PV array area) are necessary for the EV-charging station of Scenario 1 with no net energy export. Whereas when sizing the PV panels in mode two, 337 PV panels will be required and generate a net excess of 53.98 MWh of energy per year. Therefore, in this work, the first mode of selecting and sizing the PV arrays was considered in the computer modelling and optimization of the EV-charging station design scenarios.

The daily amount of electrical energy required for the EV charging station made up of five charging ports, rated at 3-kW and 7-kW, was evaluated according to six different combination scenarios. When the availability of chargers and vehicle arrival time are stochastically taken into account, Port2 and Port5 provide charging services to five different vehicles between 9 am and 5 pm. These numbers are four units of vehicles in Port1, Port3, and Port4. This means that a charging station with five charging ports with a low charging capacity may serve 22 vehicles during working hours in the selected location.

In that case, it is anticipated that the first scenario, in which all ports are 3-kW, will have the lowest charge demand, and the second scenario, in which all ports are 7-kW, will have the highest charging load. Fig. 4 depicts the change of the hourly charging load delivered by the vehicles in max (S2) and min (S1) demand scenarios during operating hours, where it can be seen that the chargers with low charging rates create a smoother load curve than the high-rate chargers. This is crucial for charging stations that are powered by the grid because it prevents high peak demands that necessitate quick responses.

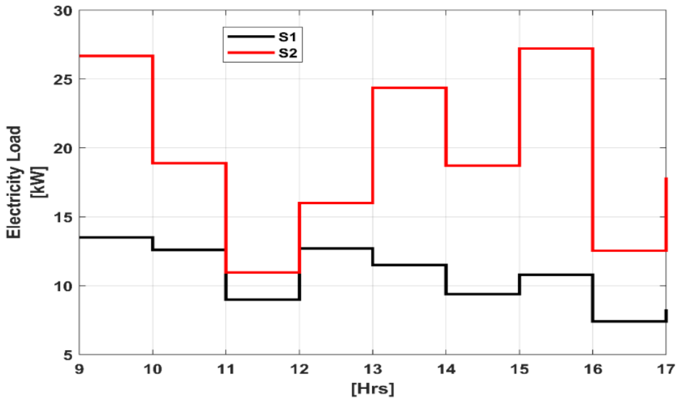

Fig. 4.The hourly electrical load of the charging station by minimum and maximum demand scenarios

The graph also demonstrates a typical challenge in EV workplace/public charging at this station. A peak charging load occurs at the beginning of the operation time due to the early charge trend at the public/workspace chargers. Assuming the same circumstances happen at all public or workplace charging stations, an additional charging demand can bring about a significant load by connecting with the high conventional electrical load in the early mornings. Smart charging (V1G) and Vehicle-to-Grid (V2G) technology could be potential solutions to such unmanaged EV charging loads (Dik et al, 2022).

To determine the performance level of the combination scenarios, a comparison between the electricity supplied for charging by the station and the total needed charge capacity of the EVs was made. The total electricity loads of the vehicle batteries for the full charge of 219.9 kWh and the charge needs of the vehicles that could be covered because of the parking time and personal preference were shown in column 2 and 3 of Table 3. Furthermore, the success rates of combination scenarios in meeting the total load of the EVs were shown in the fourth column of Table 3 which varies between 48% and 79%. Further analysis reveals that even if parking times are considered, 79% of the total energy needs of all EVs in the charging station can be covered by using five 7 kW chargers although this is at the detriment of creating high peak demands, which in turn will require a larger PV system to meet the load. Fig. 5 illustrates further the charge load of the station and the percentage of the total EV charge loads supplied by the PV system for the six-charging combination.

To assess the cost-effectiveness of the different combination scenarios of the solar PV-assisted EV charging station, a cost analysis was also undertaken, as summarised in Table 4. The listed cost of the components and engineering works of the charging station includes PV panels, EV chargers and inverters. In the analysis, the slow EV chargers' maintenance cost is ignored, whereas the PV system's annual maintenance cost is taken as $11.5/kW

(£9.21/kW) (Gioutsos et al., 2018). Additionally, the UK government's financial incentive in support of EV chargers installation was taken into account and amounts to £350 per charger port (OZEV, 2022) has been deducted from the EV chargers' payments in the table. Furthermore, the technical specification and details of the selected inverter and EV chargers used in the research can be found in (HWASS, 2023) and (Pod Point, 2023), respectively. In addition, the annual cost of electrical energy drawn from the grid and the annual income obtained from the excess energy production are detailed as grid payment and SEG revenue in the table. The excess energy sales tariff is also taken as £0.085/kWh as the average of the values available in the market (Solar Energy UK, 2023).

The results of the cost analysis show that the total cost of the installation under the selected EV-chargers scenarios total ranges from roughly £30,000 to £47,000. This cost estimate is conservative and could serve as an initial starting point for a more in-depth analysis.

Table 3.The optimisation results of PV system size by the charging station load

Combination Scenarios	EVs' Total Charge Needs [kWh]	Covered EV Charge [kWh]	Fulfilled Rate [%]	Needed PV Area [m^2]	Number of Panels [unit]	Inverter Capacity [kW]
S1	219.9	106.3	48	177.6	141	19.6
S2	219.9	173.3	79	289.4	230	32.0
S3	219.9	132.1	60	220.6	176	24.5
S4	219.9	142.3	65	237.5	189	26.3
S5	219.9	158.9	72	265.3	211	29.4
S6	219.9	120.7	55	201.6	161	22.4

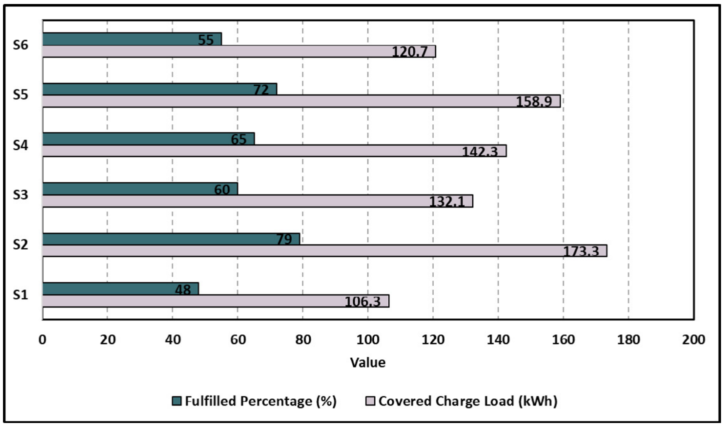

Fig. 5.The performance of the charging station design by the scenarios

Table 4. The cost analysis of the system components

Fees	S1 [£]	S2 [£]	S3 [£]	S4 [£]	S5 [£]	S6 [£]
PVs	23,677.57	38,622.98	29,554.98	31,738.01	35,432.39	27,036.09
Inverter	2,516.00	2,516.00	2,516.00	2,516.00	2,516.00	2,516.00
3-kW Charger	2,495.00	-	1,497.00	998.00	499.00	1,996.00
7-kW Charger	-	3,245.00	1,298.00	1,947.00	2,596.00	649.00
Grid Payment	2,332.40	3,801.20	2,896.80	3,121.20	3,485.00	2,648.60
SEG Revenue	-583.10	-950.30	-724.20	-780.30	-871.25	-662.15
Total	30,437.87	47,234.88	37,038.58	39,539.91	43,657.14	34,183.54

A further breakdown of the cost as depicted in Fig. 6, shows the cost could vary between 48.27 £/MWh and 50.79 £/MWh, assuming that the lifetimes of the PV system and EV charger are 20 years (Khezri, 2020) and 10 years (Tobin, T. 2020), respectively, and that the project lifetime for the charging station design mentioned in this study is 20 years. Therefore, the cost of charging an EV-vehicle from a PV-assisted charging station compares favourably to grid only charging station. For example, charging the most popular Tesla Model 3 in the UK, with a 60-kWh battery capacity, from a grid-only fed station would cost about £13.6 as a unit cost of £0.34/kWh (BEIS, 2023). Whereas, from this analysis, using the PV-assisted charging station, the cost will be roughly seven times cheaper (£1.83) even under the most expensive scenario.

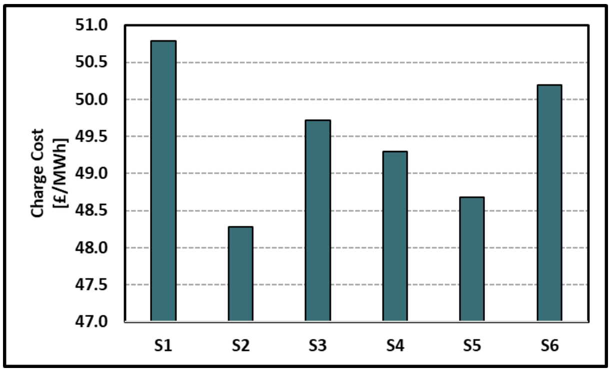

Fig. 6. The cost of the entire system per MWh charging by the combination scenarios

Furthermore, a PV-assisted EV-charging station provides additional environmental advantages in reducing the emission of greenhouse gases into the atmosphere. According to the BEIS, the carbon emission factor of the grid was 0.21233 $kgCO_2e/kWh$ in 2021 (Hill, 2020). This corresponds under computer modelling of Scenario 2 (173.3 kWh/day) to savings in CO_2 emission of up to 36.8 $kgCO_2e$ per day. Fig. 7 shows a plot of the total amount of renewable energy integration and saved CO_2 by the scenarios.

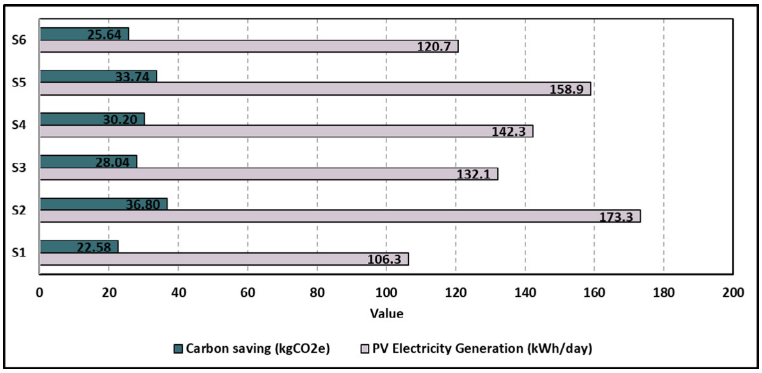

Fig. 7. The effectiveness of the design system on solar energy integration and carbon saving

4. Conclusions

This project aimed to assess a solar-powered EV charging station for a university campus case study and analyses the technical, financial, and environmental viability of six different EV charger combinations. The study has examined an approach to integrating solar PVs into the batteries of EVs. Based on the analysis, the conclusions are drawn as follows.

- The most prominent finding to emerge from this study is that before designing a charging station, the benefit to be obtained from the charging station (higher benefit or lower benefit to parkers) should be clearly determined. Because several factors, including the charging station's capital cost, the viability of a PV system, and even the stress on the grid, are directly impacted.

- Scenarios 2, 4 and 5, where 7 kW charging ports are dominant, can be preferred if the charging station is expected to meet the charge needs of parked vehicles at the maximum level. Although such a choice can meet the total needs of the cars by up to about 80%, it should not be forgotten that it might cause installation costs of up to approximately £47,000. Hence, selecting a combination with a majority of 3 kW charging ports, such as Scenarios 1, 3, and 6, can therefore minimise the installation cost by up to 55% under the condition that the users of the charging station receive a smaller benefit.
- The one of the most obvious findings to emerge from this study is that the design PV system may significantly reduce the charging cost. Even in the most expensive scenario, the charging cost can be reduced by about seven times.
- The research has also shown that the approach may reduce the stress on the grid and enhance large-scale renewable energy integration. The design system may use up to 173.3 kWh/day of renewable energy for EV charging. Also, this means the system can save up to 36.8 kgCO_2e per day, therefore paramount support to the zero-carbon targets.
- This study may also give an idea about pre-institutional cost and environmental analyses of possible solar-assisted charging station designs. This can help to increase the development of the charging station decreasing the concern about the charging station infrastructure, therefore supporting the adoption of EVs.

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