Feasibility and Energy-Environmental Assessment of Solar-Powered Electric Vehicle Charging Stations in Commercial Buildings: A PVsyst-Based Case Study of Iran Mall, Tehran

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Finding suitable land for electric vehicle charging stations (EVCSs) is difficult in densely populated cities. Meanwhile, the growing adoption of electric vehicles (EVs) can substantially raise electricity consumption and put additional stress on the power grid. This paper suggests large shopping and commercial centers as suitable locations for solar-powered EVCSs to address these two challenges. The commercial complex will have photovoltaic (PV) power generation on the roof area and the parking capacity is also considered for fast EV charging. The case study is the commercial and recreation complex of Iran Mall in Tehran and the proposed PV system is simulated by PVsyst in three scenarios, fixed panels, single-axis tracking panels and dual-axis tracking panels. Simulation results show that the annual electricity generation of the fixed-panel scenario, single-axis tracking scenario, and dual-axis tracking scenario are 4,195,704 kWh, 5,490,709 kWh, and 5,688,468 kWh respectively for the available rooftop area of 11,000 m^2. The PV system is taken as a grid-connected system, which generates electricity during the available solar hours and the assumed EV charging operation window is from 8 a.m. to 2 p.m. In this charging period, the proposed EVCS can charge up to 180 EVs per day with 15 fast charging points, each EV with 50 kWh battery capacity and charging time of 30 min. The findings demonstrate that commercial and recreational complexes can be effectively utilized for solar electricity generation and EV charging, thereby reducing grid dependence and contributing to the reduction of urban air pollution.

Keywords: *Electric Vehicle Charging Stations (EVCS), Renewable Energy, Solar Energy, Hybrid Power Systems, Sustainability*

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Nomenclature

Parameters	Description
E_{hourly}	Energy consumed per hour (kWh/hour)
$N_{chargers}$	Number of chargers
$E_{Vehicle}$	Energy required to charge one EV (kWh)
T_{Charge}	Time to fully charge one EV (hours)
E_{dayly}	Total daily energy consumption (kWh/day)
$T_{operation}$	Total operation time per day (hours)
$N_{vehicle/hour}$	Number of EVs charged per hour
$N_{vehicle/day}$	Total number of EVs charged in one day
$V_{avoided}$	Value of avoided grid electricity
$E_{grid, avoided}$	Amount of grid electricity displaced by PV generation
$T_{purchase}$	Applicable electricity purchase tariff
R_{export}	Value or revenue associated with exported electricity
E_{export}	Surplus electricity exported to the grid
T_{export}	Applicable surplus-electricity compensation tariff

Abbreviation	Description
A2C	Advantage actor-critic
AHP	Analytical hierarchy process
CO_2	Carbon dioxide
DRL	Deep reinforcement learning
EVFCS	Electric vehicle fast charging Station
EVCS	Electric vehicle charging station
EV	Electric vehicle
GHG	Greenhouse gas
GP	Goal programming
ICEV	Internal combustion engine vehicle

LCOE	Levelized cost of energy
LCA	Life cycle assessment
MPP	Maximum power point
MPPT	Maximum power point tracker
PR	Performance ratio
PV	Photovoltaic
RES	Renewable energy source
SF	Solar fraction
STC	Standard test conditions

1. Introduction

With the growing number of electric vehicles (EVs) worldwide and increasing consumer interest in adopting them, the demand for electric vehicle charging stations (EVCSs) is higher than ever particularly in developing countries such as Iran [1-3]. The introduction of EVs has created a strong need for EVCS infrastructure [4]. Figure 1 illustrates the number of EVCSs and charging points in Iran based on a 2026 snapshot obtained from OpenChargeMap. Global electricity consumption is rising due to population growth and technological advancements [5, 6]. As EV adoption increases, electricity usage in countries will also increase [7]. One way to meet the energy demands of EVCSs is to utilize renewable energy sources (RESs) such as wind turbines and solar panels [8, 9]. These sources not only reduce greenhouse gas (GHG) emissions but also enhance electricity production capacity [10-12]. Additionally, RESs can be connected to the power grid, supplying energy during peak demand periods and alleviating pressure on the main grid [13-15]. They can also operate independently without being connected to the grid [16]. Solar panels have emerged as a particularly viable option due to their cost-effectiveness and environmental benefits [17]. Installing solar panels on the rooftops of homes or buildings [18] is regarded as a sustainable and economical solution, reducing dependence on the electrical grid and lowering operating costs [19]. Another challenge when establishing EVCSs in cities is the scarcity of suitable locations and space [20]. In densely populated urban areas, limited space and high land costs complicate the construction of EVCSs [21, 22]. To address this issue, public spaces such as gas stations, malls, large commercial centers, workplaces, and parking lots can be utilized [23, 24]. This approach not only saves time and money on construction but also provides greater convenience and comfort for customers [24]. By harnessing renewable energies, this plan partially achieves the goal of reducing reliance on fossil fuels and lowering GHG emissions while also paving the way for the attraction of both domestic and foreign investors [25]. In addition, the installation of PV panels on building rooftops supports the transition toward smart zero-energy buildings by supplying part of the building energy demand through on-site solar generation [26]. A practical solution involves utilizing the roof of the Iran Mall shopping center, one of the largest shopping complexes in the Middle East. Its expansive rooftop can accommodate a significant number of solar panels, while its large parking lot can be converted into an EVCS [27]. In this study, we examine an EV charging system at the Iran Mall parking lot, powered by both the electrical grid and a solar power plant installed on its roof [28]. Excess electricity will be fed into the power grid, and any additional energy required will be drawn from it. The PVsyst tool will be used to simulate various parameters, including production capacity, losses, efficiency, and the number of panels required. This study could serve as a model for the construction or expansion of EVCSs in other cities and commercial sectors.

1.1 Motivation

In many previous studies, limited land availability, the high cost of urban land, the development of EV charging infrastructure in urban environments, and the pressure imposed on the power grid by large-scale EVCSs have received limited integrated attention within real case-study frameworks. To overcome these limitations, the use of commercial and recreational complexes is suggested, since these large complexes usually have extensive rooftops suitable for the installation of solar power plants and parking areas suitable for the establishment of EVCSs. Therefore, using this multipurpose infrastructure can reduce the investment and operating costs of developing EVCSs in urban areas, while supporting the development of a sustainable urban charging network and reducing GHG emissions. In this study, the Iran Mall commercial and recreational complex in Tehran was selected as a practical case study due to its large rooftop area, extensive parking capacity, and location in a densely populated urban area.

1.2 Contributions

This paper presents an integrated, site-specific assessment framework for evaluating solar-powered EVCSs in large commercial and recreational complexes. The methodological contribution of this study is framework-level rather than algorithmic: the study does not claim to introduce a new mathematical optimization algorithm. Instead, it establishes a reproducible assessment procedure that links PV system configuration, EV charging demand, temporal PV–EVCS energy matching, grid interaction, and environmental performance within a single real-world urban case study.

The main contributions of this study are as follows:

- A practical and site-specific feasibility assessment of a rooftop PV-powered EVCS for a large commercial and recreational complex. The study evaluates the use of available rooftop space for PV electricity generation and existing parking capacity for fast EV charging, using the Iran Mall complex in Tehran as a representative case study of a large commercial facility in a dense urban environment.
- Development of a reproducible integrated assessment procedure that connects the available PV installation area, PV configuration, EV charging demand, direct PV supply to the EVCS, grid electricity import, surplus electricity export, and environmental performance. This integrated structure enables the technical consequences of alternative PV configurations to be assessed consistently within the same site and system boundary.
- Comparative PVsyst-based evaluation of three PV configurations under consistent site and equipment assumptions. Fixed PV panels, single-axis tracking PV panels, and dual-axis tracking PV panels are simulated and compared using annual electricity production, performance ratio (PR), solar fraction (SF), direct energy supply to the EVCS, grid import, and surplus electricity export.
- Integrated assessment of PV–EVCS–grid interaction. The proposed framework explicitly accounts for the temporal mismatch between PV generation and EV charging demand. Consequently, PV electricity is directly supplied to the EVCS when available, the grid supplies the residual charging demand when PV generation is insufficient, and surplus PV electricity is exported to the grid when PV generation exceeds the instantaneous EVCS demand.

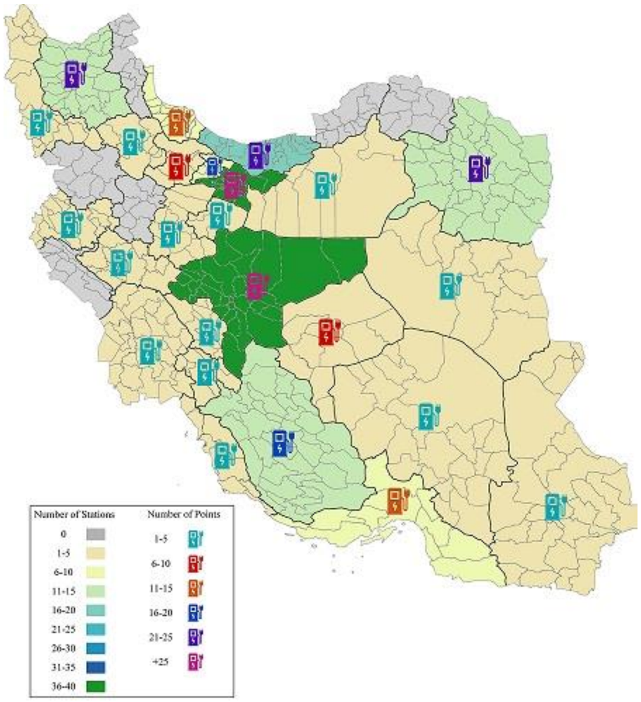

Fig. 1. Distribution of EVCSs and charging points in Iran based on the records available in OpenChargeMap at the time of access in 2026 [29] (licensed under CC BY 4.0)

- Identification of the principal design and operational parameters that should be examined in future techno-economic and sensitivity analyses, including PV capacity, EV charging demand, electricity purchase tariffs, surplus-electricity compensation mechanisms, and battery-storage capacity.
- The contribution of the study, therefore, lies in the integration and application of these components in a single location-specific framework for a large commercial complex. The framework is intended to support preliminary technical and environmental decision-making by building owners, urban planners, and policymakers, while detailed economic optimization and uncertainty-based sensitivity analysis remain important directions for future research.

1.3 Paper Structure

The remaining sections of this work are structured as follows. Section 2 examines the relevant literature on renewable energy-based EVCSs, PV systems, and urban charging infrastructure, highlighting the research gap addressed by this study. Section 3 describes the methods used to assess the proposed solar-powered EVCSs for the commercial complex. Section 4 describes the case study, which includes the Iran Mall commercial and recreational complex, the available rooftop areas, and the site's feasibility for PV power generation and EV charging infrastructure. Section 5 provides the PVsyst-based simulation setup, which includes solar panel orientation, system configuration, and assumptions about EV charging demands. Section 6 highlights and examines the simulation findings, which include yearly energy output, SF, PR, monthly energy distribution, and grid interaction. Section 7 examines the solar power plant losses under the different scenarios. Section 8 assesses the proposed system's environmental effect, including the decrease in CO_2 emissions. Section 9 discusses the limitations of this paper and future studies. Finally, Section 10 concludes the study by offering recommendations for the future development of solar-powered EVCSs in commercial and recreational buildings.

2. Literature Review

The increasing number of EVs and their widespread adoption have underscored the urgent need for EVCSs and infrastructure development [30]. One effective method to address this demand is the use of RESs, such as solar power [31]. Recent research highlights the importance of optimization techniques, hybrid systems [32], and environmental considerations in designing EVCS infrastructure, especially in urban and commercial areas [33]. Building on previous studies, this research proposes addressing existing challenges by integrating solar panels with EVCSs at the Iran Mall shopping center.

In [34], a study explores hybrid EVCS optimization scenarios using Monte Carlo simulations and the Erlang B queuing model. This hybrid approach enhances efficiency, reduces dependence on the electrical grid, and promotes sustainable infrastructure development, demonstrating significant economic potential across various configurations. Another study [35] examines the integration of solar energy into fast-charging station planning for EVs in urban settings, utilizing an advantage actor-critic (A2C) deep reinforcement learning (DRL) approach

Research [36] introduces an aggregated model that captures the flexibility potential of car parks with numerous charging stations. This model, applied through stochastic optimization techniques, calculates optimal flexibility margins to ensure appropriate EV charging levels. Its effectiveness is evaluated across various station configurations and daily forecasts. In another study [37], the location of EVCSs was optimized with a hybrid FUCOM-GIS approach. This approach decreases the number of pairwise comparisons, increases consistency and reduces the subjectivity in the determination of the criteria weights. In [38], a different decision-making framework was proposed in a smart city environment for the allocation of EVs to suitable charging stations. In this paper, the analytical hierarchy process (AHP) is integrated with multi-objective goal programming (GP) to optimize the requested energy, total response time, charging costs and battery degradation. In research [39], hybrid charging stations are proposed as a means to reduce the environmental impact of EVCSs. Using hybrid power sources significantly decreases the environmental footprint of these stations while potentially reducing battery charging costs. Another study [40] focuses on enhancing the energy grid for buildings in Southern Ontario, Canada, specifically addressing EV charging stations. The research demonstrates a 35% increase in charging station capacity, holding 353.4 GWh in summer and 480.1 GWh in winter. By incorporating hydrogen generation and fuel cell technologies, the capacity is increased by 28%. These strategies emphasize adaptive capacity solutions that consider both economic and environmental sustainability to create an efficient and sustainable transportation ecosystem and collectively highlight the critical role of renewable energy and optimization techniques in the design of EVCS infrastructure. Some studies address the importance of environmental motivation for providing EVCSs through RESs. For example, study [41] used a life cycle assessment (LCA) approach to examine the environmental impacts of EVs and internal combustion engine vehicles (ICEV), considering different scenarios and ambient temperatures. The results of this study showed that EVs, especially those powered by renewable energy, significantly reduce environmental impacts compared to conventional vehicles. For example, EVs powered by renewable energy at 30°C produce about 90% less CO_2 emissions than the corresponding ICEV scenario. Some studies also address the problems of land constraints for renewable energy farms. For example, study [42] examined floating solar power plants in wetlands and discussed their environmental challenges and economic benefits for local communities. This study concluded that PV systems can be considered an effective solution in areas with land use constraints, although environmental concerns should be carefully assessed at the planning stage. In study [43], a solar tracker with bifacial panels was modeled and simulated using the PVsyst program. The findings of this study showed that the use of solar trackers and bifacial PV panels can increase the energy extracted compared to fixed single-sided panels. This study has increased the motivation for current research to evaluate different PV configurations, including fixed systems, single-axis tracking, and dual-axis tracking, to meet the electric vehicle charging demand in a dense urban commercial complex. In this study, the proposed concept, through the application of previous research and the design and implementation of a solar energy-based hybrid charging system, can serve as a valuable model for the establishment of EVCSs in Tehran.

Table 1 illustrates that existing research focuses mainly on hybrid renewable charging-station optimization, Electric Vehicle Fast Charging Station (EVFCS) location planning, EV-to-CS allocation, flexibility modeling, microgrid optimization, building-level energy management, and environmental assessment. Nevertheless, there is limited focus on a comprehensive and location-specific assessment of a rooftop PV-based EVCS in a large commercial complex, encompassing PV configuration comparison, EVCS load supply, interaction with grid import/export, and reduction of CO2 emissions. This study fills in this gap by performing an evaluation of the case study of Iran Mall using PVsyst.

3. Methodology

This study employed a methodological approach to evaluate EVCSs in shopping malls, using Iran Mall as a case study. Figure 2 depicts the various stages of this process. First, previous research on charging EVs with solar energy was evaluated. The energy requirement for charging EVs and the projected number of EVs to be charged were then investigated, with solar panels being regarded as the primary charging source. Furthermore, solar panels were installed on shopping center rooftops, and EVCSs were established in parking lots. We tuned the tilt angle and position of the solar panels in three scenarios: fixed panels, single-axis tracker, and dual-axis tracker, to evaluate the energy performance of three alternative PV configurations . The annual solar energy production was computed to determine the system's efficiency. The study examined the number of EVs that can be charged every day based on the produced energy, and it assessed and computed the energy received from the grid and excess electricity injected back into it. The system's efficiency was also assessed to ensure long-term and continuous energy production. We calculated the environmental impact and the amount of CO_2 saved. Finally, the resulting PV–EVCS–grid configuration was evaluated as a grid-connected hybrid energy-supply system for reducing dependence on grid electricity. This approach helps make cities more energy sustainable. Since the present study is based on publicly available technical information and general assumptions rather than site-specific procurement, financing, operational, and tariff data, a detailed numerical techno-economic analysis is not included in the current assessment. However, the framework identifies the key parameters required for a subsequent LCOE, payback-period, NPV, and sensitivity analysis, including PV capacity, EV charging demand, electricity tariffs, surplus-electricity compensation, and battery-storage capacity. This sequence enables the technical and environmental consequences of different PV configurations to be evaluated within a common and reproducible system boundary. The resulting framework is therefore intended as a practical assessment methodology for preliminary planning and feasibility evaluation of PV-powered EVCSs in large commercial buildings and similar urban facilities.

4. Case Study

In this paper, we examine three different scenarios for arranging solar panels on the roof of this commercial recreational complex:

Scenario 1: Fixed panels

Scenario 2: Panels with single-axis tracker

Scenario 3: Panels with dual-axis tracker

Table 1. Comparison of recent studies on renewable-energy-based EV charging stations, EVCS planning, and the present study.

Ref	Focus	Method	Region	EVCS / Load	Indicators	Contribution	Limitation
[34]	Hybrid solar–wind EVCS	MC + optimization	Spain	EV arrival, PV, wind, ESS	NPV, IRR, cost	Hybrid EVCS model	No rooftop /PVsyst case
[35]	EVCS placement	DRL + GIS	USA	Traffic, PV potential	Reward, capacity	Smart placement model	No PV simulation
[36]	EV parking flexibility	Stochastic model	Generic	EV arrivals, V2G	Flexibility metrics	Flexibility estimation	No PV/EVCS design
[37]	EVCS site selection	FUCOM-GIS	Turkey	Spatial factors	Suitability maps	Improved GIS method	No load/PV modeling
[38]	EV allocation	AHP + optimization	Smart city	SOC, traffic	Cost, time	EV-CS assignment	No RES integration
[39]	Eco EVCS system	PV + diesel	India	EV load, PV	Footprint, cost	Reduced emissions	No PV scenarios
[40]	Building EVCS mgmt	Storage strategies	Canada	Building load	Capacity, peak	Peak reduction	No PV comparison
[41]	EV vs ICEV impact	LCA	Various	Vehicle energy	CO_2, health	EV benefits	No EVCS design
[42]	Floating PV	PVsyst	Iran	No EVCS	Capacity, env.	FPV concept	No EVCS link
[43]	PV tracker	PVsyst	Iran	No EVCS	Energy gain	Tracker benefit	No EVCS/grid
This study	Rooftop PV EVCS	PVsyst	Iran	EVCS demand	PV, grid, CO_2	Integrated case study	No storage

Table 2. Summary of the Iran Mall case study, PV scenario definitions, and EVCS load assumptions.

Case-study location	Selected complex	Iran Mall commercial and recreational complex
	City/region	Northwest Tehran, Iran
	Geographical coordinates	35.7538° N, 51.1919° E
	Application	Rooftop grid-connected PV system for supplying an EV charging station
Available installation area	Candidate area for PV installation	14,000 m²
	Total PV module area	11,000 m²
Scenario concept	Scenario 1	Fixed PV panels
	Scenario 2	PV panels with a single-axis tracker
	Scenario 3	PV panels with a dual-axis tracker
Orientation/movement	Scenario 1	Fixed tilt angle of 35.7° and azimuth angle of 0°
	Scenario 2	Axis angle of 35.7°, azimuth angle of 0°, and rotation range from −60° to +60°
	Scenario 3	Tilt rotation from 0° to 80° and azimuth rotation from −120° to +120°
Annual PV energy production	Scenario 1	4,195,704 kWh/year
	Scenario 2	5,490,709 kWh/year
	Scenario 3	5,688,468 kWh/year
EVCS load and energy-consumption assumptions	Number of charging points	15
	Rated power per charging point	100 kW
	Total rated EVCS charging power	1,500 kW
	Energy required per EV	50 kWh
	Charging time per EV	0.5 h
	Daily operating period	6 h/day
	Estimated daily EVCS energy demand	9,000 kWh/day
	Estimated annual EVCS energy demand	3,285,000 kWh/year
	Estimated number of EVs charged daily	180 EVs/day

4.1. Iran Mall

Located in northwest Tehran, the Iran Mall shopping center is set to become one of the largest malls in the Middle East by 2024, attracting a significant number of visitors daily. Given the expansive size of its roof, Iran Mall offers an ideal location for installing solar panels. Additionally, its large parking lot presents an excellent opportunity for setting up EVCSs [44]. It should be noted that this study uses publicly available information and general technical assumptions, rather than proprietary operational data directly obtained from Iran Mall.

4.2. Optimal Site for Solar Power Plant

To the west of the Iran Mall building, there is a 14,000 m² area suitable for constructing a solar power plant, of which 11,000 m² can be utilized, as shown in Fig. 3.

4.3. Simulating with PVsyst

To simulate the solar power plant, we use PVsyst, an advanced PV system simulation software that offers detailed panel modeling and technical analysis. Considering Tehran's geographical location and the equipment's technical specifications, PVsyst is an excellent tool for simulating the solar panels installed on the roof of Iran Mall. Table 2 reports the main characteristics of the Iran Mall complex and the available area for PV installation, the definition of the three PV scenarios and the EVCS load assumptions used in the PVsyst simulation.

5. Simulation

5.1. Orientation

5.1.1. Orientation for fixed panels

The simulation sets the solar panels at a tilt angle of 35.7 degrees, with the azimuth angle adjusted to zero degrees, ensuring the panels face south. This tilt angle approximately corresponds to the geographical latitude of the Iran Mall site in Tehran and was therefore selected as a latitude-based tilt angle suitable for annual PV energy production. The transposition factor, which measures the effect of converting horizontal radiation to radiation on a slanted surface, is 1.17, as shown in Fig. 4. Consequently, the conversion of horizontal radiation to inclined surface radiation results in a factor of 1.17. Each panel receives an annual radiation exposure of 2135 kWh/m2.

5.1.2. Orientation for Panels with Single-Axis Tracker

In this method, the solar panels are located around the axis with an angle of 35.7 degrees and the azimuth orientation is 0 degrees. The rotation range of the panels is set between -60 and 60 degrees, which can follow the sun during the day.

5.1.3. Orientation for Panels with Dual-Axis Tracker

In these types of systems, it is possible to adjust the panels in two directions, tilt and azimuth, where the tilt angle can be rotated between 0 and 80 degrees and the azimuth angle can be rotated between -120 and 120 degrees, and this advantage allows the panels to optimize their position during the day and in different seasons and have maximum solar radiation.

5.2. System

The proposed solar power plant is grid-connected and does not include storage. The primary reasons for omitting storage are to reduce initial investment costs and ensure that the generated electricity is consumed directly by the EVCSs, with any surplus electricity transferred to the grid. Based on a grid connection, the proposed system is considered a grid-connected PV–EVCS system oriented to self-consumption. In this configuration, the electricity produced by the PV system is mainly used to cover the EVCS demand. When the PV generation is lower than the charging demand, the grid provides the required deficit. On the other hand, when the PV generation exceeds the EVCS load, the surplus energy will be injected into the distribution grid. Thus, the grid acts as a backup source during periods of limited solar generation and as an energy receiver during periods of surplus solar generation. For such grid-connected PV systems, two common regulatory mechanisms can be considered, i.e., net metering and feed-in tariff or guaranteed power purchase agreements. In a net-metering scheme, exported electricity is offset against imported electricity, while in a feed-in tariff scheme, the surplus electricity is injected into the grid and is sold at a predetermined purchase tariff. In Iran, renewable electricity projects are generally supported by guaranteed power purchase or feed-in tariff mechanisms. Long-term power purchase agreements have been used to support renewable electricity producers [45]. Thus, in this work, the additional electricity supplied into the grid is considered under a feed-in tariff or guaranteed power purchase scheme rather than a pure net-metering scheme.

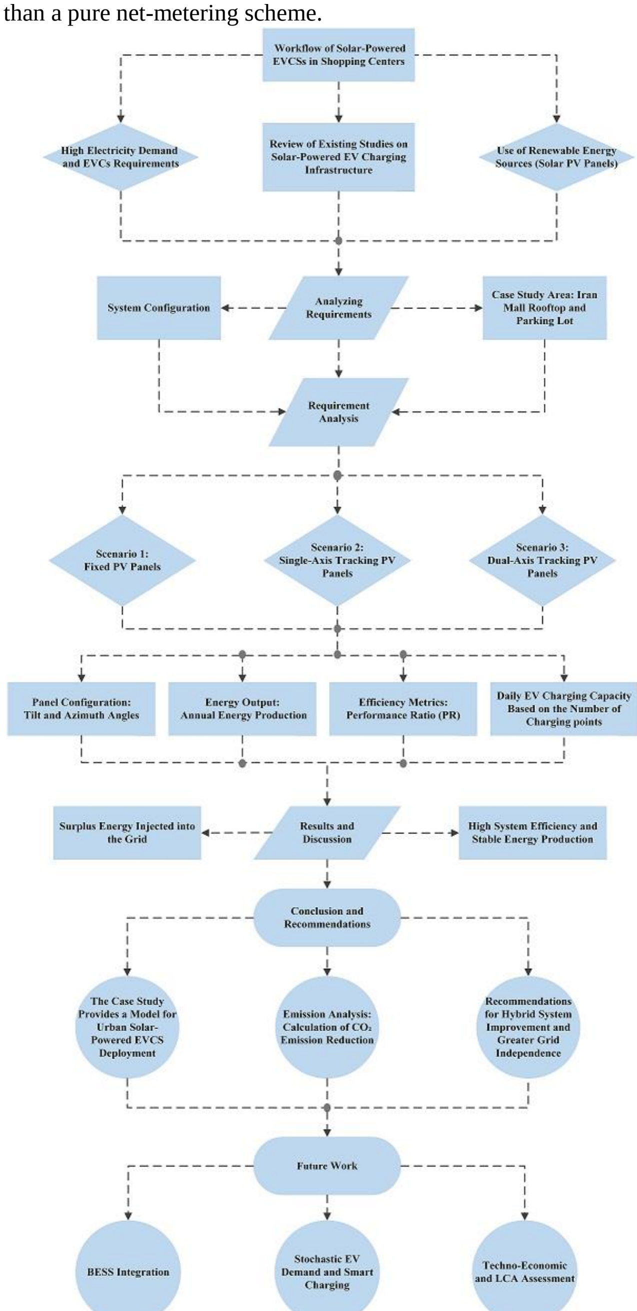

Fig. 2. Methodology for EVCSs in shopping centers with solar panels

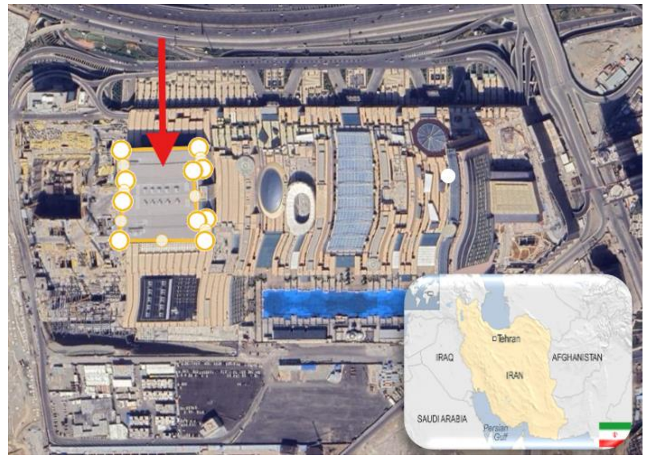

Fig. 3. The selected area for the installation of solar panels

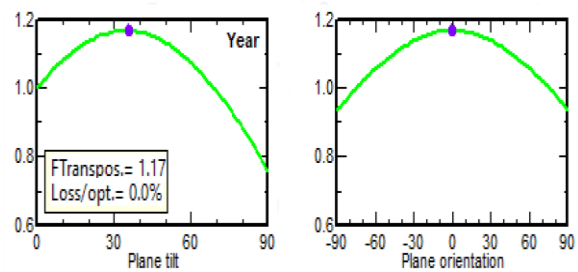

Fig. 4. The transposition factor

However, the practical implementation of grid-connected PV–EVCS systems in Iran may encounter some practical challenges. These include obtaining permits for grid connection, working with the distribution company, setting up suitable export or bidirectional meters, possible constraints on the capacity of local distribution feeders, uncertainty regarding electricity purchase tariffs, delays in payment, and changes in energy policy or economic conditions. Previous studies have also suggested that subsidy design, financing mechanisms, and conditions for policy implementation could affect the economic performance of feed-in tariff policies [46]. Thus, while the current study demonstrates the technical feasibility of the proposed system, a detailed regulatory and economic assessment of PV self-consumption, EV charging demand, surplus energy export, and grid connection requirements is needed for future implementation.

The solar power plant utilizes Longi Solar panels (LR5-72HPH-540M), which have a nominal power output of 540W and feature monocrystalline silicon technology. These panels are well-suited for large-scale commercial projects due to their high efficiency and reliable performance under intense sunlight conditions. Three scenarios have been considered for the design of the solar power plant on the roof of this complex, all of which have the same specifications and the only difference is in the placement of the panels. Fixed panels, Panels with single-axis tracker and panels with dual-axis tracker

The system employs Huawei Technologies SUN2000-330KTL-H2 inverters, which are well-suited for optimal coordination with the solar panels. These inverters support high voltages (800V AC, three-phase) and multiple Maximum Power Point Trackers (MPPTs). A total of seven inverters are used, increasing the AC system's capacity to 1925 kW. The solar arrays generate DC power equivalent to 2323 kW, resulting in a nominal power ratio of approximately 1.21. This ratio indicates a system with low energy loss, high efficiency, and an optimal design. Additionally, the system's maximum power output, under irradiation of 100 W/m² and at 50°C, is 2371 kW. This design, which leverages high-quality equipment and maximizes the use of available space, ensures strong performance and sufficient energy production for the EVCS at Iran Mall. Table 3 summarizes the solar panel and inverter specifications, while Table 4 details the characteristics of the simulated system.

Table 3. Technical Specifications of LONGi Solar Panels and Huawei Inverter

Specification	LONGi Solar LR5-72HPH-540M	Huawei Technologies SUN2000-330KTL-H2
Rated Power (Pmax)	540 W	330 kW
Efficiency	20.9%	99%
Nominal Voltage at MPP (Vmpp)	41.0 V	1100 V DC
Nominal Current at MPP (Impp)	13.17 A	300 A DC
Open-Circuit Voltage (Voc)	49.5 V	1500 V DC
Short-Circuit Current (Isc)	13.88 A	-
Dimensions	2256×1133×35mm	1075×757×361mm
Weight	27.2 kg	88 kg
Operating Temperature	-40 to 85 °C	-25 to 60 °C
Cell Type	Monocrystalline	-
Protection	IP68	IP66 and IP67 (for connectors)
Maximum System Voltage	1500 V DC	1500 V DC
Communication Capability	-	RS485, PLC, and Ethernet
Performance in Low Light	2% efficiency gain under low irradiation	-

Table 4. Global PV Summary

Specification	Value
Number of Modules	4301
Module Area	11,000 m²
Number of Inverters	7
Nominal PV Power	2323 kWp
Nominal AC Power	1925 kWAC
Pnom Ratio	1.207

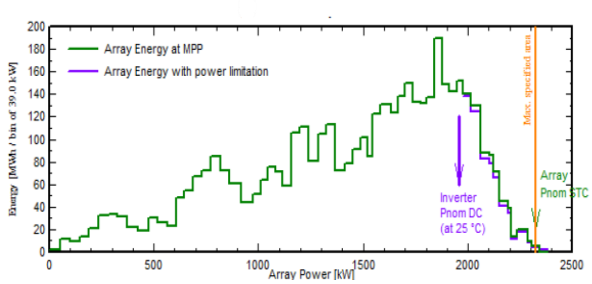

Fig. 5. Power sizing: Inverter output distribution

Figure 5 illustrates the inverter's output power distribution in the proposed PV system installed on the roof of the Iran Mall shopping center. This diagram compares the solar array's power output at the maximum power point (MPP) with the power limit set by the inverter. When the array's power output is below the inverter's nominal power (Pnom DC), the green and purple curves align. However, if the array's output exceeds the inverter's nominal power, the output is capped to prevent overload. The orange vertical line indicates the system's design limit, representing the nominal power of the solar array under standard test conditions (STC).

5.3. Load

In this study, it is assumed that the EVCS charging operation window is 8 a.m. to 2 p.m. On the other hand, a grid-connected PV system generates electricity during the available solar hours. The EVCS has 15 fast-charging points and each point can connect to one EV at a time. Figure 6 illustrates the load consumption profile considering a 50 kWh battery capacity for each EV. Assuming each charging point is a 100 kW fast charger to fully charge a 50 kWh battery in 0.5h. So each charging point can charge two EVs an hour. According to these, the total charging capacity is 30 EVs/hour and the total energy consumption is 1,500 kWh/hour. The charging operation window is 6 hours per day, so the proposed EVCS can charge up to 180 EVs per day and the total daily energy consumption is 9,000 kWh/day. The calculation procedure for estimating hourly energy consumption, total daily energy demand, number of EVs charged per hour and total number of EVs charged per day is given in Eqs. (1)–(4).

$$E_{hourly} = N_{chargers} \times E_{vehicle} \times \frac{1}{T_{charge}} \quad (1)$$

$$E_{daily} = E_{hourly} \times T_{operation} \quad (2)$$

$$N_{vehicles/hour} = N_{chargers} \times \frac{1}{T_{charge}} \quad (3)$$

$$N_{vehicles/day} = N_{vehicles/hour} \times T_{operation} \quad (4)$$

Where:

E_{hourly}: Energy consumed per hour (kWh/hour)
$N_{chargers}$: Number of chargers
$E_{Vehicle}$: Energy required to charge one EV (kWh)
T_{Charge}: Time to fully charge one EV (hours)
E_{dayly}: Total daily energy consumption (kWh/day)
$T_{operation}$: Total operation time per day (hours)
$N_{vehicle/hour}$: Number of EV charged per hour
$N_{vehicle/day}$: Total number of EV charged in one day

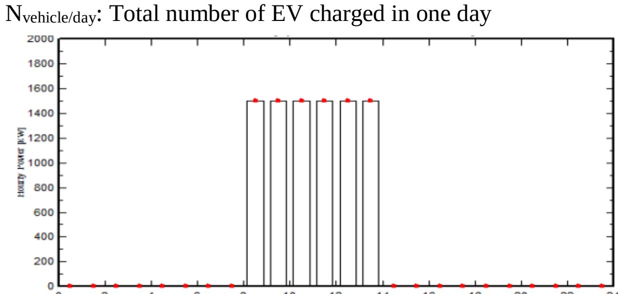

Fig. 6. EVs load in each hour

6. Simulation Result and Discussion

The simulation results of PVsyst software for the PV power plant on the roof of Iran Mall in each scenario are reviewed.

6.1. Annual energy production

In this study, the SF is defined as the share of the annual EVCS energy demand that is directly supplied by the PV system.

Therefore, SF is not calculated as the ratio of total annual PV generation to total annual EVCS demand. This is because part of the PV generation may not coincide with the EV charging demand and is therefore injected into the grid. Accordingly, SF is calculated as follows:

$$SF = \frac{PV_{energy\ directly\ supplied\ \ to\ EVCS}}{Total\ \ EVCS\ \ energy\ \ demand} \times 100 \qquad (5)$$

In Scenario 1, the total annual PV generation is 4,195,704 kWh, and the annual EVCS demand is 3,285,000 kWh. However, the EVCS directly consumes the PV generation of 2,669,335 kWh and the remaining surplus energy is injected into the grid, so the SF of Scenario 1 is 81.26%. For Scenario 2, the total annual PV generation is 5,490,709 kWh with the SF of 85.77%. Scenario 3 gives a total PV generation per year of 5,688,468 kWh and an SF of 86.06%. The results indicate that the annual PV generation is higher than the annual EVCS demand, however, the SF is still below 100% because of the temporal mismatch between the PV generation profile and the EV charging demand. The dual-axis tracking system provides higher annual energy production than the fixed and single-axis systems. However, the aim of this study is not to generally prove that dual-axis tracking is superior to other PV configurations. Rather, the objective is to evaluate how different PV configurations perform in a specific real-world case study, namely the Iran Mall, by considering the available rooftop area, selected system components, and EV charging demand. Therefore, this study investigates the PV energy generation, EVCS energy demand, grid import and export, solar fraction, surplus energy, system performance, and potential CO_2 emission reduction in a large commercial complex.

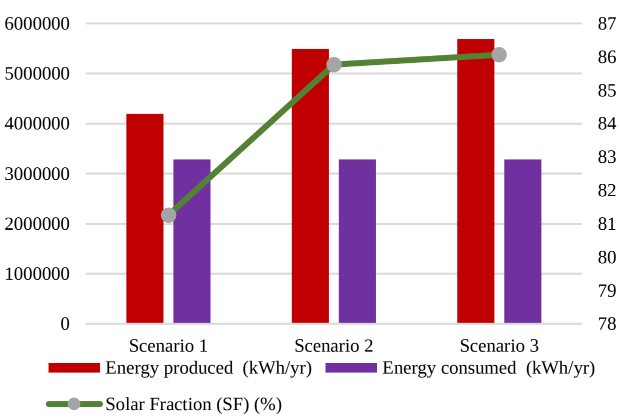

Fig. 7. Graphs of energy produced, consumed, and solar fraction (SF) in each scenario

6.2. System efficiency

Figure 8 shows that the PR has reached 86.2%, 85.9%, and 85.6% in each case, which means that the level of performance is effective and satisfactory and also Fig. 8 shows that the PV system has maintained a relatively stable performance in all months, and weather changes have had little effect on the system's efficiency due to careful selection of PV arrays and the appropriate angle for panel installation.

6.3. Monthly Energy Distribution

Figure 9 presents the energy supplied to EVCS, energy from the sun, energy injected into the grid, energy from the grid, and energy output from the inverter.

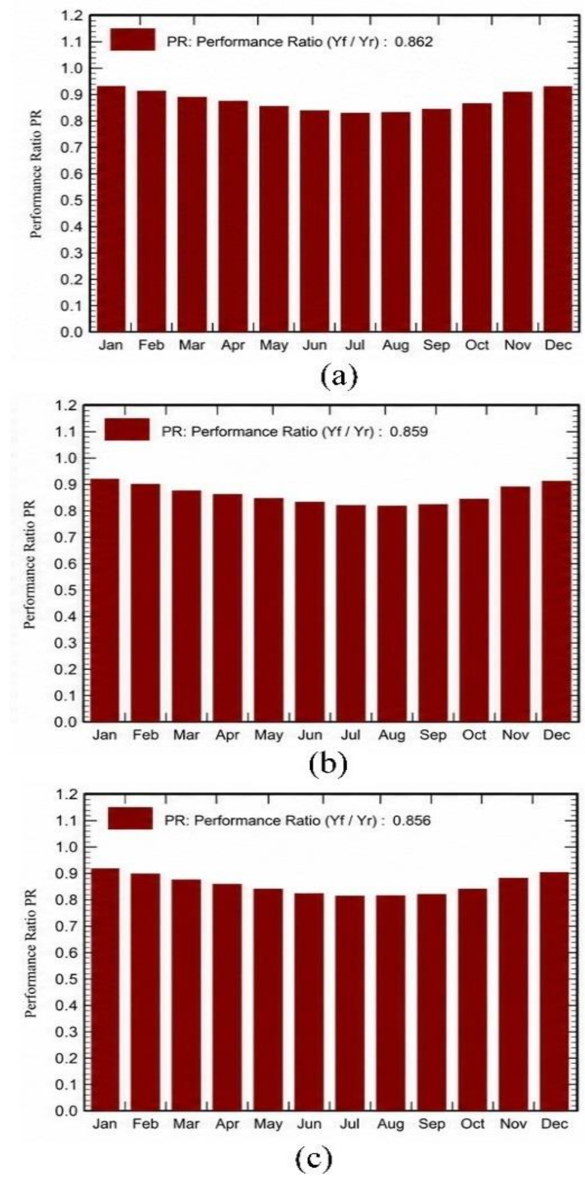

Fig. 8. Monthly Performance Ratio (PR) of the proposed PV system under the three investigated scenarios: (a) Scenario 1—fixed PV panels, (b) Scenario 2—single-axis tracking PV panels, and (c) Scenario 3—dual-axis tracking PV panels.

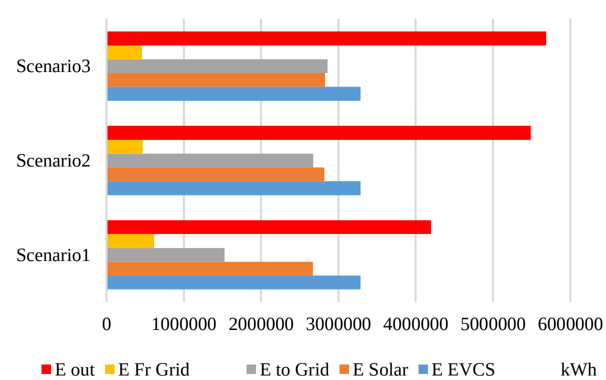

Fig. 9. Main results in each scenario

6.4. Energy Balance and Grid Interaction

In Scenario 1, the total PV electricity directly supplied to EVCS is 2,669,335 kWh, and the imported electricity from the grid to meet the residual charging demand is 615,665 kWh. Thus, the total annual demand of EVCS is 3,285,000 kWh. Moreover, the surplus PV electricity is 1,526,368 kWh injected into the grid and the total annual PV generation is 4,195,704 kWh. The reason for this simultaneous import and export to the grid is that the proposed PV–EVCS system does not have a battery energy storage system. Therefore, the PV generation profile and the EV charging demand profile do not completely coincide in time. If the PV generation is higher than the EVCS demand, the extra electricity is injected into the grid. However, if the PV generation is lower than the EVCS demand, the grid supplies the required deficit. Therefore the system can export electricity to the grid and import electricity from the grid at different time periods during the year. As shown in Fig. 9, the use of single-axis and dual-axis tracking systems increases the total PV generation and the amount of surplus energy injected into the grid. More PV generation decreases the amount of electricity imported from the grid and reduces grid dependency. The injected energy in the grid in the third scenario is 2,861,523 kWh, which is approximately 87.4% higher than that in the first scenario. In addition, the imported electricity from the grid decreases in relation to Scenario 1. The use of battery energy storage can increase the self-consumption of PV electricity by storing the surplus solar electricity and using it when solar generation is low or when there is high demand for EV charging. This could reduce the amount of electricity injected into the grid, as well as the amount of electricity imported from the grid. However, battery storage also adds to the initial investment cost, requires additional space, is affected by charging and discharging losses, and presents challenges related to battery replacement and end-of-life management. Therefore, the current work is concerned with a grid-connected PV–EVCS system without storage and presents a detailed techno-economic analysis of the integration of battery storage as a future research direction.

6.5. Single-line diagram

Figure 10 shows a single-line diagram of the solar energy production system designed for the Iran Mall recreational complex, which includes two sets of LR5-72HPH-540M solar panels. These panels are arranged in strings 26 and 27, with each string made up of 23 connected solar modules. This setup uses two types of inverters: one type contains two inverters with a capacity of 550 kVA, and the other contains five inverters with a capacity of 1375 kVA. The power generated by the panels is transferred to the energy injection point via inverters, where it is used to charge EVs or feed into the power grid.

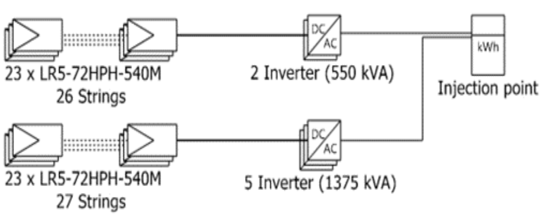

Fig. 10. Proposed system linear diagram

6.6. Parametric Sensitivity Analysis of Key PV–EVCS System Parameters

To further assess the robustness of the main technical conclusions, a parametric sensitivity analysis was conducted for the principal PV–EVCS system parameters. The analysis considered PV capacity, EVCS electricity demand, and electricity tariff because these parameters directly influence the relationship between solar generation, charging demand, grid interaction, and the potential economic value of the system. The reference case corresponds to the dual-axis PV configuration with a nominal installed capacity of 2,323 kWp, annual PV generation of 5,688,468 kWh, and annual EVCS electricity demand of 3,285,000 kWh. The reference EVCS demand corresponds to 9,000 kWh/day and an equivalent daily demand of 180 charging events based on the assumed 50-kWh energy requirement per vehicle. For the sensitivity analysis, low and high scenarios were defined as 80% and 120% of the corresponding reference value, respectively, while the reference case was maintained at 100%. The resulting sensitivity scenarios are summarized in Table 5.

Table 5. Parametric sensitivity scenarios for the principal PV–EVCS system parameters

Parameter	Low scenario (80%)	Reference scenario (100%)	High scenario (120%)
PV capacity	1,858.4 kWp	2,323 kWp	2,787.6 kWp
Annual EVCS electricity demand	2,628,000 kWh/year	3,285,000 kWh/year	3,942,000 kWh/year
Daily EVCS electricity demand	7,200 kWh/day	9,000 kWh/day	10,800 kWh/day
Equivalent daily 50-kWh charging events	144 EV/day	180 EV/day	216 EV/day
Electricity purchase tariff	80% of reference value	100% of reference value	120% of reference value
Surplus-electricity compensation tariff	80% of reference value	100% of reference value	120% of reference value

The effect of PV capacity was evaluated relative to the dual-axis reference configuration. Under a proportional first-order scaling assumption, reducing the PV capacity by 20% to 1,858.4 kWp corresponds to an estimated annual PV generation of approximately 4,550,774 kWh, whereas increasing the capacity by 20% to 2,787.6 kWp corresponds to approximately 6,826,162 kWh/year. These values are used to assess the directional effect of PV capacity variation around the reference case and should not be interpreted as replacements for independent PVsyst simulations of the modified system sizes. The sensitivity analysis indicates that increasing PV capacity increases the amount of solar electricity available to the EVCS and increases the potential for reducing grid electricity purchases when the additional PV generation coincides temporally with charging demand. However, because the EVCS demand is limited and PV generation is time-dependent, increasing PV capacity can also increase surplus electricity export during periods in which PV generation exceeds the instantaneous charging demand. Therefore, the effect of increasing PV capacity on the solar fraction is not necessarily linear. This observation is consistent with the reference results, in which annual PV generation exceeds annual EVCS electricity demand while the solar fraction remains below 100% because of the temporal mismatch between PV generation and charging demand. The EVCS-demand sensitivity was evaluated by varying the reference annual electricity demand by ±20%. The resulting demand levels are 2,628,000 kWh/year, 3,285,000 kWh/year, and 3,942,000 kWh/year, corresponding to approximately 144, 180, and 216 equivalent daily 50-kWh charging events, respectively. A lower

EVCS demand is expected to reduce the direct utilization of available PV electricity and increase the proportion of PV generation that may be available for export. In contrast, higher EVCS demand can improve the utilization of available PV generation but may increase grid electricity dependence during periods in which charging demand exceeds the temporally available solar generation. Accordingly, the influence of EVCS demand depends on its temporal coincidence with PV generation and cannot be fully represented using annual energy totals alone. Electricity tariffs do not alter the physical PV generation or EVCS energy demand; however, they directly affect the economic value of avoided grid purchases and exported surplus electricity. The value of avoided grid electricity can be expressed as:

$$V_{avoided} = E_{grid,avoided} \times T_{purchase} \quad (6)$$

where $V_{avoided}$ is the value of avoided grid electricity, $E_{grid,avoided}$ is the amount of grid electricity displaced by PV generation, and $T_{purchase}$ is the applicable electricity purchase tariff. Similarly, the economic value of surplus PV electricity exported to the grid can be expressed as:

$$R_{export} = E_{export} \times T_{export} \quad (7)$$

where R_{export} is the value or revenue associated with exported electricity, E_{export} is the surplus electricity exported to the grid, and T_{export} is the applicable surplus-electricity compensation tariff.

Because validated site-specific electricity tariffs, surplus-electricity compensation rates, financing conditions, and investment costs were not available for the present case study, the tariff analysis was conducted using relative changes of 80%, 100%, and 120% around the applicable reference values. This approach allows the directional influence of tariff variation to be examined without introducing unsupported absolute financial assumptions. Overall, the sensitivity analysis indicates that PV capacity and EVCS electricity demand are strongly coupled through the temporal PV–EVCS energy balance. Increasing PV capacity primarily increases solar-energy availability and the potential for surplus export, whereas increasing EVCS demand generally increases PV utilization but can also increase grid dependence when the charging demand exceeds the temporally available solar generation. Electricity tariffs mainly influence the economic value of avoided grid purchases and exported electricity rather than the physical energy balance. These findings demonstrate that the technical performance of a PV-powered EVCS should be evaluated by considering both annual energy quantities and the temporal interaction between PV generation and charging demand. A more detailed sensitivity analysis in future work should use repeated hourly PVsyst simulations for alternative PV capacities and validated hourly EV charging profiles. Such an approach would enable the quantitative variation of solar fraction, grid import, and surplus electricity export to be determined for each sensitivity scenario. The resulting hourly energy analysis could then be combined with validated local financial data to calculate LCOE, discounted payback period, and NPV under different PV-capacity, charging-demand, tariff, and surplus-electricity compensation scenarios.

7. Photovoltaic Power Plant Losses

According to the loss diagram in Fig. 11, the first scenario's total radiant energy loss is 1,832 kWh/m2, which is converted to effective energy on the collector surface by applying the angle of incidence factor and reaching 2,061 kWh/m2. With a module efficiency of 21.17%, the nominal output energy of the arrays is 4,796,103 kWh, including losses due to irradiation surface, temperature, module quality, module and string mismatch, and resistive losses. Due to the power reduction, the total energy output at the MPP stands at 4,266,684 kWh. The inverter loss is 1.66%, with an output energy of 4,195,551 kWh. Of this energy, 2,669,335 kWh are used to charge EVs, 1,526,368 kWh are injected into the grid, and 615,665 kWh are received from the grid. And the amount of losses in the two subsequent scenarios is specified in Fig. 11.

Figure 12 depicts the distribution of the simulated system's output power under three different scenarios. The graphs show the frequency of the system's output power throughout a year. Figure 12.A illustrates the distribution of the system's output power for the first scenario (fixed panels), which concentrates energy production in the mid-power range. Figure 12.B, which depicts the second scenario (single-axis tracker panels), shows enhanced output power and peak production as compared to scenario 1. The third scenario (dual-axis tracker panels) shown in Figure 12.C has the highest output power in higher ranges compared to the first two scenarios. This indicates that the dual-axis configuration produces a greater share of useful output at higher power levels under the simulated operating conditions.

8. Carbon Emission

The reduction of CO2 emissions was estimated based on the grid emission factor used in the PVsyst carbon balance calculation. In this study, the grid emission factor was assumed to be 575 g CO2/kWh or 0.575 kg CO2/kWh. This figure represents the quantity of CO_2 emitted in producing one kilowatt-hour of electricity from the grid. Thus, each kilowatt-hour of PV electricity used instead of grid electricity is considered as an avoided CO2 emission associated with the grid. The cumulative CO2 balance was calculated over the 30-year lifetime of the project, based on the simulated PV electricity generation, the grid emission factor and an annual degradation rate of 1%. As shown in Fig. 13, the CO2 balance is negative at the beginning of the project. This negative value represents embodied carbon emissions from manufacturing and production of the components of PV system, such as PV modules, support structures and inverters. For instance, the CO2 emissions of support structures and inverters are 189 tons and 3,053 tons, respectively. Therefore, the negative part of Fig. 13 should not be considered as a negative operational performance. It is the initial carbon burden of the system. During its operational lifetime the PV system gradually reduces these embodied emissions by avoiding CO^2 emissions related to the grid. After the initial embodied carbon is offset, the cumulative balance turns positive and increases over the project lifetime. Results show that the proposed solar power plant can reduce net CO2 emissions by 58,627.8 tons by the end of the 30-year project lifetime. The proposed solar-powered EV charging station has the potential to provide broader environmental and social benefits beyond the direct reduction of CO2 emissions. PV electricity can meet part of the EV charging demand that can decrease the dependence on fossil-fuel-based electricity generation and indirectly contribute to the reduction of urban air pollutants such as particulate matter, NOx and SOx. Furthermore, the use of PV-based EVCSs in commercial complexes may also generate sustainable jobs in different fields such as PV system installation, electrical equipment installation, charger installation, operation and maintenance, system monitoring, panel cleaning, and local technical services.

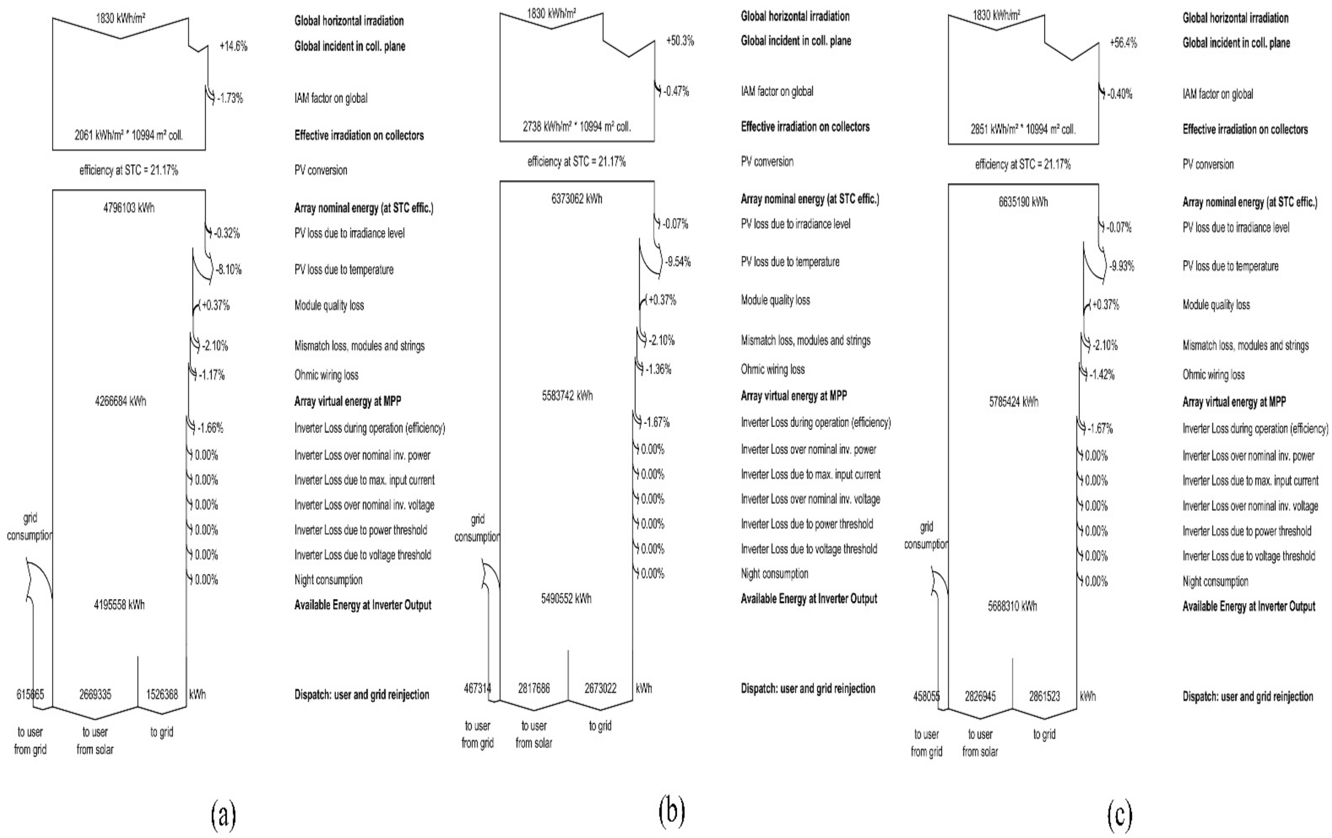

Fig. 11. PVsyst-generated loss and energy-balance diagrams of the proposed grid-connected PV system under the three investigated scenarios: (a) Scenario 1-fixed PV panels, (b) Scenario 2-single-axis tracking PV panels, and (c) Scenario 3-dual-axis tracking PV panels.

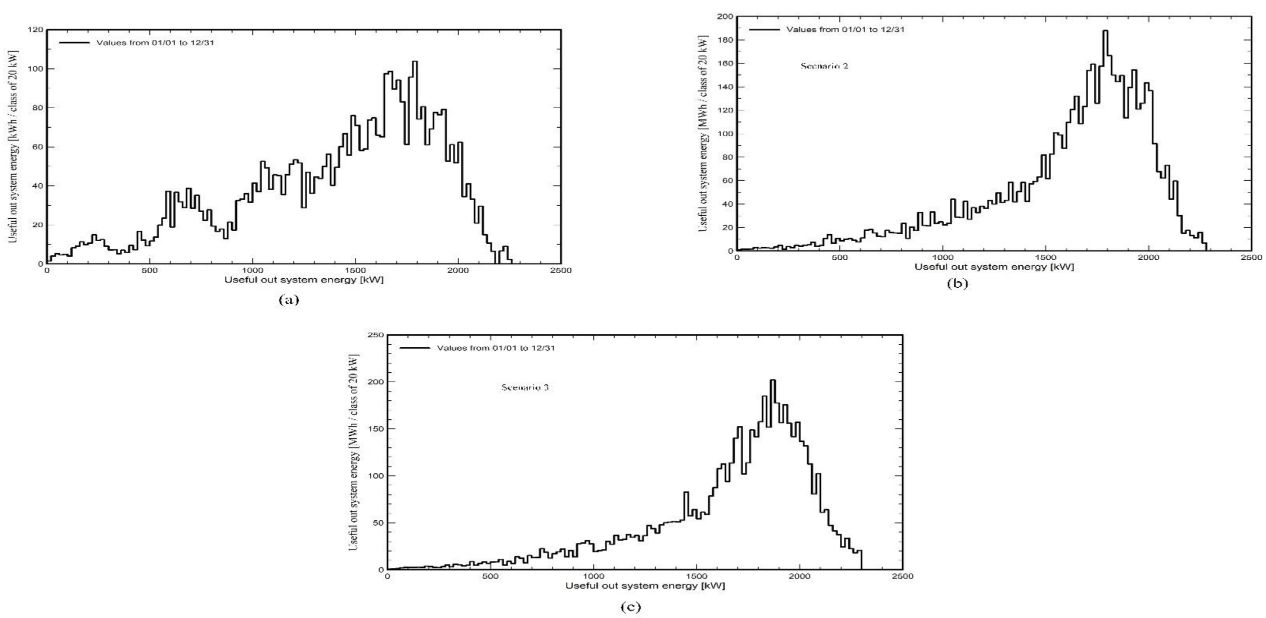

Fig. 12. Annual useful output power distribution of the proposed grid-connected PV system under the three investigated scenarios: (a) Scenario 1—fixed PV panels, (b) Scenario 2—single-axis tracking PV panels, and (c) Scenario 3—dual-axis tracking PV panels.

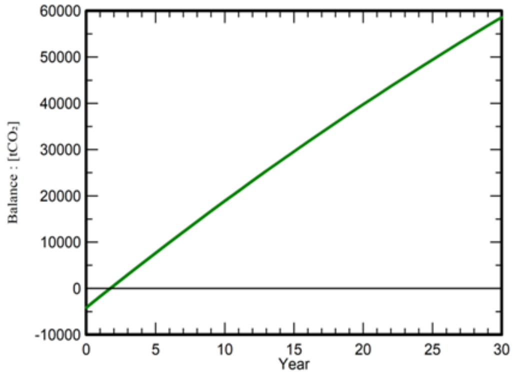

Fig. 13. Cumulative CO_2 balance over the 30-year project lifetime, including the initial embodied carbon emissions of PV system components and the avoided grid-related CO_2 emissions during operation.

It should be noted that the carbon emission analysis in this study is a project-level estimation based on the simulated PV electricity generation and the expected reduction in grid dependency. LCA can be utilised to carry out a more holistic environmental assessment. Recently, the research has shown that the accuracy of environment and carbon emission analysis can be improved by LCA considering the life cycle stages of the materials and equipment, such as production, transportation, installation, operation, maintenance, and end-of-life treatment [47]. Therefore, an expansion of the present analysis with a full LCA of PV modules, inverters, support structures, EV chargers, grid electricity mix and recycling processes can be addressed in future studies. This would give a more accurate assessment of the true environmental benefits of solar-powered EV charging infrastructure in dense urban areas.

9. Limitations and Future Studies

This paper presents a practical assessment of a solar-powered EV charging station in a commercial and recreational complex, however there are some limitations to be noted. The analysis is made based on a case study, the Iran Mall complex in Tehran. Therefore, the results are influenced by the geographical location, available rooftop area, solar radiation conditions, parking capacity and assumed EV charging demand of this site. To improve the generalizability of the proposed approach, future studies can apply the same framework to other commercial buildings, shopping centers, airports, universities and public parking areas in different cities and climates. Second, the proposed system is simulated without the battery energy storage. This assumption reduces the initial investment cost and simplifies the grid interaction but limits the system's ability to store excess solar energy and use it during non-sunny hours or peak charging periods. Further works can study the integration of the battery energy storage system and compare grid-connected, off-grid and hybrid operation strategies. Third, the EV charging demand in this study is based on the pre-defined operating hours, the charger capacity, and the assumed number of EVs. In general, EV arrival patterns, charging patterns, waiting time, seasonal variation in demand and user uncertainty can affect the required charging capacity and grid interaction. Further research can therefore employ real EV charging data, stochastic models or queuing-based approaches for a more detailed demand side analysis. In addition, future studies can improve the operational performance of the proposed PV-based EVCS by using smart control tools and artificial intelligence techniques. For example, neural networks can be applied to forecast solar power generation, EV charging demand, grid electricity price, and the optimal charging schedule under uncertain weather and user behavior conditions. Recent studies have shown successful applications of neural networks in energy systems. For instance, study [48] used an artificial neural network together with real power plant data to predict system performance and improve the operation of a heat recovery-based energy system. Therefore, similar data-driven approaches can be used in future research to develop an intelligent energy management system for solar-powered EV charging stations and to optimize the interaction between PV generation, EV charging demand, battery storage, and the power grid. Fourth, the environmental analysis in this study is mainly focused on the reduction of CO_2 emissions. A more comprehensive environmental assessment can be performed by applying LCA by taking into account the stages of manufacturing, transportation, installation, operation, maintenance and end-of-life of PV modules, inverters, support structures, EV chargers and batteries. This can lead to an enhancement of the accuracy of the environmental assessment and a more comprehensive comparison between different system configurations.

Finally, a detailed numerical techno-economic assessment is not included in the present study. The economic performance of a grid-connected PV–EVCS system depends on several site-specific and time-dependent parameters, including the capital cost of PV modules, inverters, tracking structures, EV chargers, installation, and grid-connection infrastructure; operation and maintenance costs; project lifetime; discount rate; electricity purchase tariffs; EV charging revenues; PV degradation; and the compensation mechanism for surplus electricity exported to the grid. A complete economic assessment should therefore include indicators such as the levelized cost of energy (LCOE), discounted payback period, and net present value (NPV). LCOE can be used to evaluate the discounted lifetime cost of the generated electricity, whereas the discounted payback period indicates the time required for the cumulative discounted project cash flow to recover the initial investment. NPV provides a complementary measure of the present value of the project's future net cash flows after accounting for the initial investment and the selected discount rate. These indicators should be calculated using validated local cost, tariff, financing, and revenue assumptions rather than generalized values. In addition, the parametric sensitivity analysis presented in this study examines the directional influence of the principal PV–EVCS design and operational parameters around the reference case. It is not intended to replace a complete uncertainty analysis based on repeated hourly PVsyst simulations. A more detailed assessment should rerun the PV system model for alternative PV capacities and use measured or stochastic EV arrival and charging profiles to capture the temporal interaction between PV generation and EVCS demand. Such an approach would provide more accurate estimates of solar fraction, grid import, and surplus electricity export under each sensitivity scenario. The effect of electricity tariffs is considered in relative terms because validated site-specific purchase tariffs, surplus-electricity compensation rates, financing conditions, and investment costs were not available. Therefore, the present study does not report numerical LCOE, discounted payback period, or NPV values. Future work should combine hourly PV–EVCS simulation with validated local economic data and calculate LCOE, discounted payback period, and NPV under multiple PV-capacity, charging-demand, tariff, and surplus-electricity compensation scenarios. Such an integrated analysis would provide a more robust basis for identifying economically resilient system configurations and supporting investment decisions by commercial-building owners, charging-station operators, and policymakers.

10. Conclusion

assessm This study developed and applied an integrated, site-specific ent framework for evaluating a grid-connected solar-powered electric vehicle charging station in a large commercial and recreational complex. The case study of Iran Mall in Tehran demonstrates how available rooftop space and existing parking infrastructure can be jointly considered for PV electricity generation and fast EV charging in a dense urban environment. The methodological contribution of the study is framework-level rather than algorithmic. The proposed procedure integrates PV configuration assessment, EV charging-demand estimation, PV–EVCS energy matching, grid import and surplus-electricity export, and project-level environmental assessment within a common and reproducible case-study framework. The approach therefore provides a structured basis for evaluating the technical feasibility of PV-powered EVCSs without claiming the development of a new mathematical optimization algorithm. Three PV configurations were evaluated under the same general site and equipment assumptions. The fixed-panel configuration produced 4,195,704 kWh/year, whereas the single-axis and dual-axis tracking configurations produced 5,490,709 kWh/year and 5,688,468 kWh/year, respectively. Relative to the fixed-panel configuration, the single-axis and dual-axis configurations increased annual PV generation by approximately 30.9% and 35.6%, respectively. The corresponding solar fractions were 81.26%, 85.77%, and 86.06%. The results further demonstrate that annual PV generation alone is not sufficient to evaluate the performance of a PV-powered EVCS. Because PV generation and EV charging demand do not perfectly coincide temporally, the grid remains important for supplying residual charging demand, while surplus PV electricity can be exported during periods of excess generation. The grid-connected configuration therefore provides a flexible energy pathway in which PV electricity supplies the EVCS when available, the grid supplies the remaining demand when required, and surplus PV electricity can be exported under the applicable grid-interconnection conditions. Under the assumed operating conditions, the proposed charging infrastructure corresponds to a daily demand equivalent to 180 50-kWh charging events using 15 fast-charging points during the defined operating period. The environmental assessment indicates a potential net reduction of approximately 58,627.8 tonnes of CO_2 over the 30-year project lifetime under the assumed emission factor and degradation conditions. This result should be interpreted as a project-level carbon assessment rather than a complete life-cycle assessment. The parametric sensitivity analysis further indicates that PV capacity and EVCS electricity demand are strongly coupled through the temporal interaction between solar generation and charging demand. Increasing PV capacity increases solar-energy availability and the potential for reducing grid electricity purchases when the additional PV generation coincides with charging demand; however, it can also increase surplus electricity export during periods of excess generation. Similarly, increasing EVCS demand can improve the utilization of available PV generation but may increase grid dependence when charging demand exceeds the temporally available solar generation. Electricity tariffs primarily affect the economic value of avoided grid purchases and exported surplus electricity rather than the physical energy balance.

The technically most productive PV configuration should therefore not automatically be interpreted as the economically optimal alternative. A complete investment assessment requires validated site-specific information on capital costs, operation and maintenance costs, electricity purchase tariffs, surplus-electricity compensation, EV charging revenues, financing conditions, project lifetime, and other financial assumptions. Accordingly, the present technical results should not be interpreted as evidence of economic feasibility in the absence of a site-specific techno-economic assessment based on validated economic data. The present study is subject to several limitations, including the use of general technical assumptions rather than proprietary operational data, the absence of battery storage, the use of a predefined EV charging demand profile, and the absence of a site-validated numerical techno-economic assessment. Future research should address these limitations by using measured or stochastic EV arrival and charging data, hourly PV–EVCS simulations, battery-storage integration, advanced energy-management strategies, comprehensive life-cycle assessment, and validated local economic data. A subsequent techno-economic assessment should calculate LCOE, discounted payback period, and NPV under multiple PV-capacity, charging-demand, electricity-tariff, surplus-electricity-compensation, and battery-storage scenarios. Overall, the results indicate that large commercial and recreational complexes can provide a technically promising platform for integrating rooftop PV generation with EV charging infrastructure. The proposed framework can be transferred to other commercial buildings, airports, universities, public parking facilities, and similar urban sites, provided that local solar resources, available space, EV demand, grid conditions, regulatory requirements, and economic parameters are appropriately considered.

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