World Electric Vehicle Journal

Review

Related Work and Motivation for Electric Vehicle Solar/Wind Charging Stations: A Review

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Abstract: The shift towards sustainable transportation is an urgent worldwide issue, leading to the investigation of creative methods to decrease the environmental effects of traditional vehicles. Electric vehicles (EVs) are a promising alternative, but the issue lies in establishing efficient and environmentally friendly charging infrastructure. This review explores the existing research on the subject of photovoltaic-powered electric vehicle charging stations (EVCSs). Our analysis highlights the potential for economic growth and the creation of robust and decentralized energy systems by increasing the number of EVCSs. This review summarizes the current knowledge in this field and highlights the key factors driving efforts to expand the use of PV-powered EVCSs. The findings indicate that MATLAB was predominantly used for theoretical studies, with projects focusing on shading parking lots. The energy usage varied from 0.139 to 0.295 kWh/km, while the cost of energy ranged from USD 0.0032 to 0.5645 per kWh for an on-grid system. The payback period (PBP) values are suitable for this application. The average PBP was demonstrated to range from 1 to 15 years. The findings from this assessment can guide policymakers, researchers, and industry stakeholders in shaping future advancements toward a cleaner and more sustainable transportation system.

Keywords: electric vehicle; solar charging station; transport; photovoltaic

Citation: Almasri, R.A.; Alharbi, T.; Alshitawi, M.S.; Alrumayh, O.; Ajib, S. Related Work and Motivation for Electric Vehicle Solar/Wind Charging Stations: A Review. *World Electr. Veh. J.* **2024**, *15*, 215. https://doi.org/10.3390/wevj15050215

Academic Editor: Aritra Ghosh

Received: 27 March 2024
Revised: 18 April 2024
Accepted: 23 April 2024
Published: 13 May 2024

1. Introduction

The combination of renewable energy (RE) and electric mobility has led to the development of a solar charging station network (SCSN) for electric vehicles (EVs) to create a cleaner and more sustainable future. Societies throughout the world are working to decrease their carbon footprint and shift away from fossil fuels. Integrating solar electricity into the charging infrastructure is a promising strategy to promote environmentally friendly transportation. This introduction explores the intersection between solar energy and EVs in the world of SCSNs. This paradigm shift combines advanced technology, environmental awareness, and the urgent need to reimagine our approach to urban mobility. The worldwide dedication to decreasing climate change and promoting sustainable practices is driving the shift to EVs. Solar charging stations utilize sunshine to generate clean energy, providing a scalable and environmentally friendly method for powering the future of transportation. This research will examine the complexities of solar charging infrastructure, including the installation of PV panels, energy storage systems (ESSs), and the incorporation of smart technology. These components work together to form a network that is ready to transform the way we fuel our EVs, offering not just decreased environmental harm but also enhanced energy self-sufficiency. We explore the promise, challenges, and revolutionary impact of a SCSN for EVs as we delve into the junction of solar energy and electric mobility. Let us work together to create a more environmentally friendly future where solar energy drives progress. EVs powered by traditional sources have a greater negative impact on the whole environment outside of their usage location compared to internal combustion cars. To accomplish the objectives of the Paris Agreement and the Sustainable Development Goals, it is imperative to decrease combustion emissions in energy generation and transportation. Table 1 visually depicts the share of new cars sold, which are electric in many countries, globally between 2010 and 2022. Meanwhile, Figure 1 presents the annual percentage share of EVs, buses, trucks, and vans sold internationally, indicating a consistent upward trend year after year. These figures show the growing significance of EVs and their impact on a global scale, which mean that research on EV usage is essential.

Table 1. Share of new cars sold that are electric (%), 2010 to 2022 [1].

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
China	0	0	0	0	0	1	2	2	5	5	6	16	29
Germany	0	0	0	0	0	1	1	2	2	3	13	26	31
Norway	0	1	3	6	15	22	29	39	49	56	75	86	88
Sweden	0	0	0	1	1	2	3	5	8	11	32	43	54
United Kingdom	0	0	0	0	1	1	1	2	3	3	11	19	23
United States	0	0	0	1	1	1	1	1	2	2	2	5	8
World	0	0	0	0	0	1	1	1	2	3	4	9	14

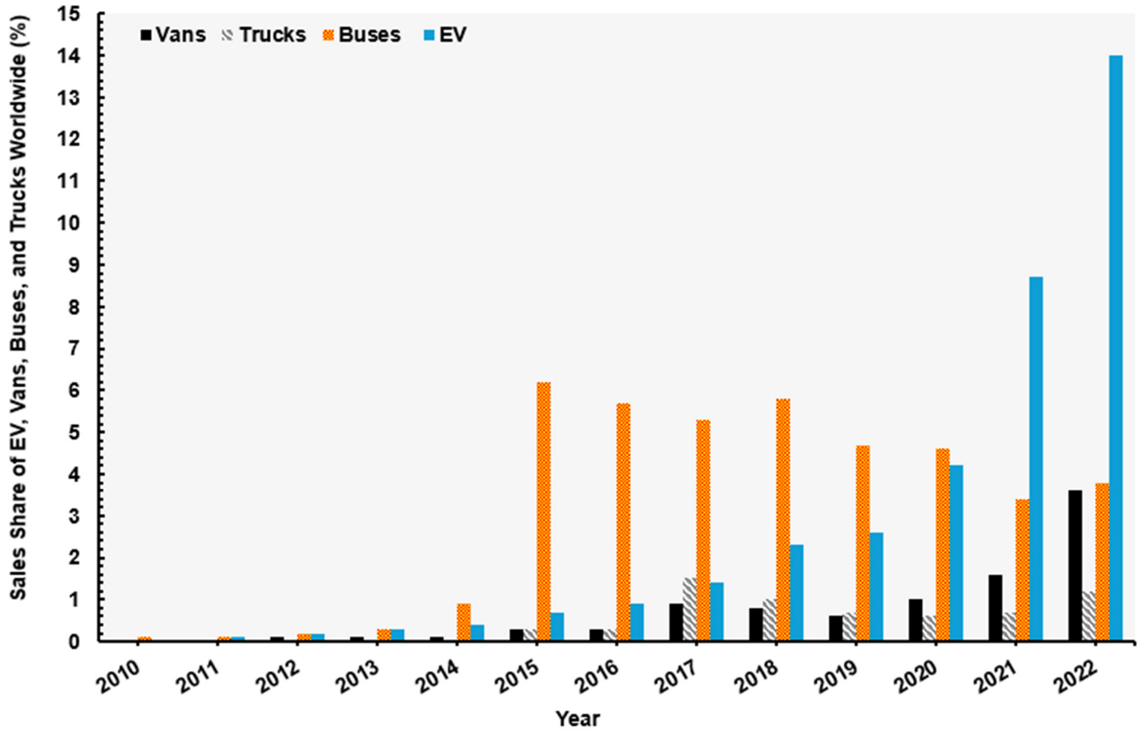

Figure 1. Global sales' share of different types of EVs between 2010 and 2022 [1].

Urban areas are shifting towards cleaner and more sustainable transportation options, with the integration of SCSNs for EVs playing a crucial role in combining RE with urban mobility. The need to decrease carbon emissions, improve energy efficiency, and deal with the environmental impacts of conventional transportation systems has led to a trend towards electrification. Solar charging stations are highlighted as innovative hubs that combine RE consumption with the increasing need for electric transportation. Urban regions with heavy traffic, increasing populations, and rising awareness of environmental responsibility, provide both obstacles and chances for the widespread use of EVs. Acknowledging this, strategically placing solar charging stations around urban areas has the potential to transform how we power and maintain our transportation infrastructure.

The National Renewable Energy Laboratory released the EVI-Pro Lite Tool to prepare for the expansion of infrastructure for charging EVs. The model uses detailed data on personal car travel patterns, EV specifications, and charging station features to calculate the necessary amount and type of charging infrastructure needed to promote the widespread use of EVs in a region. This tool helps local government agencies estimate the number of charging stations needed to support a certain quantity of plug-in devices in different scenarios [2]. The global adoption of EVs has been accompanied by a significant increase in the infrastructure required to support them, notably in the proliferation of EV charging points and stations. This growth is crucial for facilitating the widespread adoption of electric vehicles, as access to charging facilities directly influences consumer decisions and vehicle usability. As seen in Table 2, the number of both slow and fast charging points in China has been growing annually. Last year, there were around 2 million public charging points across China. This trend is also evident in many other countries around the world, including the United States and the United Kingdom, according to the Global EV Outlook by the International Energy Agency (IEA) [1].

Table 2. Number of slow and fast charging points from 2014 to 2022 in China [1].

	Fast Charging	**Slow Charging**
2014	21,000	9000
2015	47,000	12,000
2016	86,000	55,000
2017	83,000	130,000
2018	160,000	160,000
2019	300,000	210,000
2020	310,000	500,000
2021	470,000	680,000
2022	760,000	1,000,000

Our in-depth examination of charging infrastructure includes different charging levels, ranging from Level 2 chargers for regular use to direct current (DC) fast chargers for quick recharging. This examination also explores the interoperability of charging stations, guaranteeing their compatibility with various EV models and standards. This introduction gives a summary of the worldwide transition to electric mobility and the significance of solar charging stations in promoting eco-friendly transportation. This section emphasizes the technological components involved in incorporating solar EVCSs. Conversations cover improvements in solar panel efficiency and creative design factors. This section investigates the incorporation of batteries to store surplus solar energy, focusing on the function of energy storage systems. It also reviews scalable and sustainable storage options to tackle the difficulty of maintaining continuous and predictable power availability. This section examines the reliability of solar charging stations by investigating their connection to the traditional grid as an alternative power supply. Topics covered include grid connectivity, load control, and the function of backup systems in low sunlight conditions. Krim et al. [3] aimed to improve energy management in the growth of PV benefits by developing a technical-economic instrument for installing a PV-powered Charging Station (PVCS) using an algorithm. The suggested methodology helps the tool assist local authorities and stakeholders in making decisions about deploying PVCSs, as shown by the outcomes of the PVCS implementation. Xu et al. [4] studied the effects of highly electrified passenger automobiles in Regina, Canada. The city is dedicated to transforming itself into a sustainable city and is currently exploring methods to provide all of the city's energy requirements, including those for passenger transportation, from renewable sources, as stated by the authors. Seasonal considerations have a significant impact on the efficiency of utility-managed charging, with summertime EV fuel efficiency being the most favorable. The necessity to address climate change and reduce dependence on fossil fuels has led to a significant increase in interest and creativity in sustainable infrastructure. This literature review examines the growing subject of SCSNs for EVs, investigating the most recent breakthroughs, obstacles, and the significant impact of this integration. Buresh et al. [5] examined the potential impacts of large corporations utilizing PV solar carports in South Africa for their employees. The authors assessed how including the financial perspectives of service providers and car owners might reduce the potential strain on the national grid. The results showed that charging an EV is more cost-effective than refueling a gasoline-powered vehicle for car owners, and charging an EV at work is the most optimal option for owners.

This study analyzed 105 sources, among these sources, about 25% were published in this and the previous year. The second section offers a thorough summary of current research and progress in integrating solar or wind energy into transportation. The third segment examines case studies on PV wind-powered EVCSs, while the fourth section delves into customer behavior and acceptance of these technologies. Sections 5 and 6 cover the economic incentives, environmental factors, and growing need for cleaner RESs. Section 7 addressed challenges and opportunities in EV charging infrastructure, followed by our conclusions.

2. Integrating Solar Energy into Transportation

This paragraph will address the integration of RE into transportation. Note that the focus will be mainly on the use of solar energy and sometimes wind energy. The integration of RE with transportation infrastructure is becoming increasingly prominent in academic writings. Solar energy is acknowledged as a clean and plentiful source for powering EVCSs. Studies show that incorporating renewable energy sources (RESs) like solar PV into urban transportation systems can help decrease carbon footprints and improve the overall sustainability of urban mobility. It is also possible to rely on wind energy in charging stations if suitable conditions are available.

There are two types of PV systems: on-grid and off-grid. EVCSs are often intended for grid connections (Figure 2), although in certain situations, off-grid systems must be designed (Figure 3). Hybrid EVCSs with the possibility of an electricity storage device can be used (Figure 4). The systems with electricity storage devices are characterized by several capabilities, including that they can ensure charging operations in the absence of solar radiation and can also supply the network with electrical current in cases of need.

The integration of RE with transportation infrastructure is becoming increasingly prominent in academic writings. Given the importance of the topic, there have recently been several review studies on the integration of PV systems with their transportation, such as [7–12]. In these works, the integration process was discussed from technical, economic, environmental, and social aspects. Barman et al. [7] state that integrating efficient EV charging with RESs is crucial for maximizing the environmental benefits of EVs. Advancements in this field have enabled the use of eco-friendly and sustainable EV charging technology, resulting in reduced charging costs. Government policymakers need to implement strategies such as employment creation, subsidies, research grants, financial aid, and other initiatives to support sustainable mobility. Promoting public awareness about the advantages of adopting RE, both in terms of the environment and the economy, should be given top priority. Despite the abundance of RESs, current EV charging technology only relies on solar, wind, and hydropower. Future research should explore the potential of utilizing a wider range of RESs. Taghizad-Tavana et al. [8] examined EV charging controllers that enhance the design and deployment of charging station infrastructure.

The document also includes information on worldwide charging protocols, structures, and types of EVs. Research was conducted on the relationship between the electrical energy system and its integration with RESs. Sinha et al. [13] provided academics with the latest developments in integrating EVs and RESs into the grid, along with highlighting unresolved research issues. Bhatti et al. [9] presented a comprehensive summary of the key aspects of PV–EV charging, including power converter structures, charging procedures, and control mechanisms for different types of PV systems. Hutchinson and Bird [10] concentrated on methods that provide a more direct link between the timing and location of EV demand and the accessibility of RE. The authors examined the pricing, the correlation between consumer charging and the availability of power generation from renewable sources, customer reaction, and the configuration of these goods based on their initial experience with these programs. Khan et al. [11] conducted thorough research on many aspects and strategies of solar PV–EV charging technologies. The topics covered were solar charging methodologies and modes, economic analysis, barriers and problems, sustainability, and more related subjects. An explanation is provided on the functioning of the commercial business model, along with control and safety protocols at solar charging stations. Mwasilu et al. [12] provided an overview of the interaction between RESs, smart grid infrastructure, and EV technology. The authors stated that EVs can provide additional services to the grid.

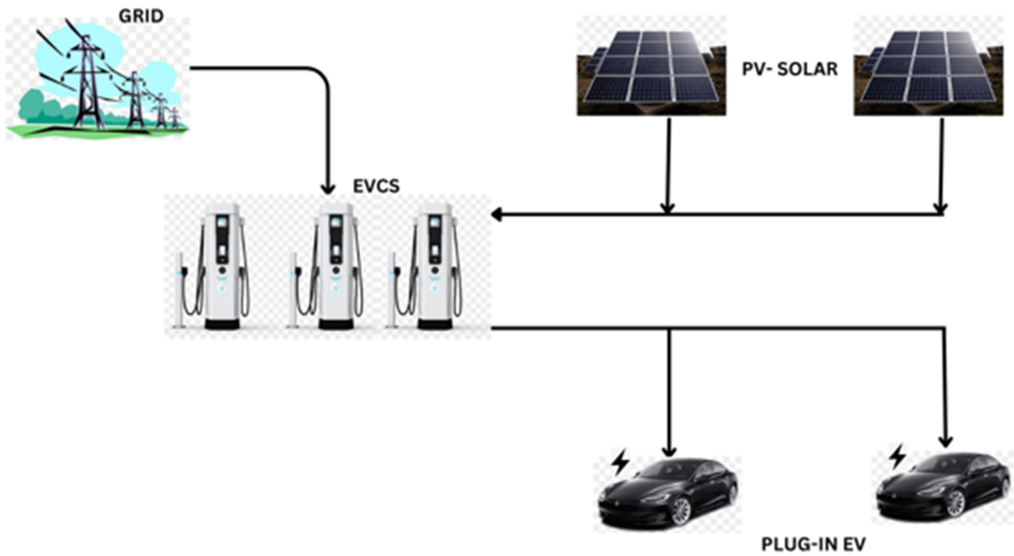

Figure 2. On-grid PV-EVCS's architecture.

There are several studies on the integration of PV systems using MATLAB. Atawi et al. [14] developed and evaluated a standalone charging station driven by PV energy using MATLAB. Furthermore, a physical verification setup for the system is created. The strong correspondence between simulation and experimental results validates the efficacy of the proposed system. The results show that the EV battery is charging consistently and continuously under different amounts of sunlight exposure. The ESS battery effectively charges and discharges to store and balance variations in PV energy. The voltage and current controllers of the converters exhibit a rapid response and accurately maintain their set references. Moreover, the maximum power point tracking (MPPT) controller accurately monitors the peak conditions of the PV system. Shariff et al. [15] illustrated the process of constructing and executing a modern solar-assisted level-2 EVCS using MATLAB. A comprehensive hardware setup has been developed to showcase the efficacy of power factor correction in a stable situation with fluctuating loads and a 3 kW, 230 Vrms, single-phase, 50 Hz input. The setup also seeks to generate a 48 V buck converter DC output. The Center of Advanced Research in Electrified Transportation parking lot at Aligarh Muslim University in India was selected as the site for the 6.4 kW PV charging station.

A lab test has been conducted on a prototype model. The solar panel is tested under standard settings in the study using a 10 kWh lithium-ion battery pack. The MATLAB model can efficiently size and operate a whole PV–EV charging system more quickly than empirical methods, which depend on assumed data or the direct and applied approach with specified data. Fachrizal and Munkhammar [16] utilized MATLAB to evaluate PV smart EV charging system strategies for decentralized and centralized residential buildings in Sweden. The proposed systems aim to reduce fluctuations in net load. A charging efficiency of 90% and a maximum charging power rate of 3.7 kW were determined. The authors suggest that smart charging networks could lead to a substantial decrease in residential peak loads. EV experts analyzed fast charging facilities to determine their compatibility with long-distance highway travel for EVs. Determining the optimal number of these stations throughout major road networks is the primary focus of the study. Nair et al. [17] proposed a combined control strategy for the EVCS that integrates the advantages of droop and master control methods. MATLAB is utilized for formulating and validating the EVCS's design. The scientists explained that EVCSs utilizing DC supply technology is more suitable due to less conversion loss. The energy storage unit at the charging station ensures that EVs may charge without interruption while also enabling the cost-effective utilization of photovoltaic systems. Enhanced battery charging and discharging speeds, together with better DC bus voltage regulation, can be attained by implementing droop, master–slave, and snubber circuits in combination with EVCS control. Enescu et al. [18] utilized RETScreen to present a detailed design for a fuel cell and electrolyzer system, or a fuel cell-free PV energy-based EVCS, in a residential property located in Pitesti City, Romania. The power-following strategy-based EVCS design has a battery capacity approximately 20 times smaller than the reference design. Additionally, an EVCS design that utilizes a power-following approach is almost 50% cheaper than the reference design. Three distinct EVCS operation scenarios were analyzed utilizing the power-following approach.

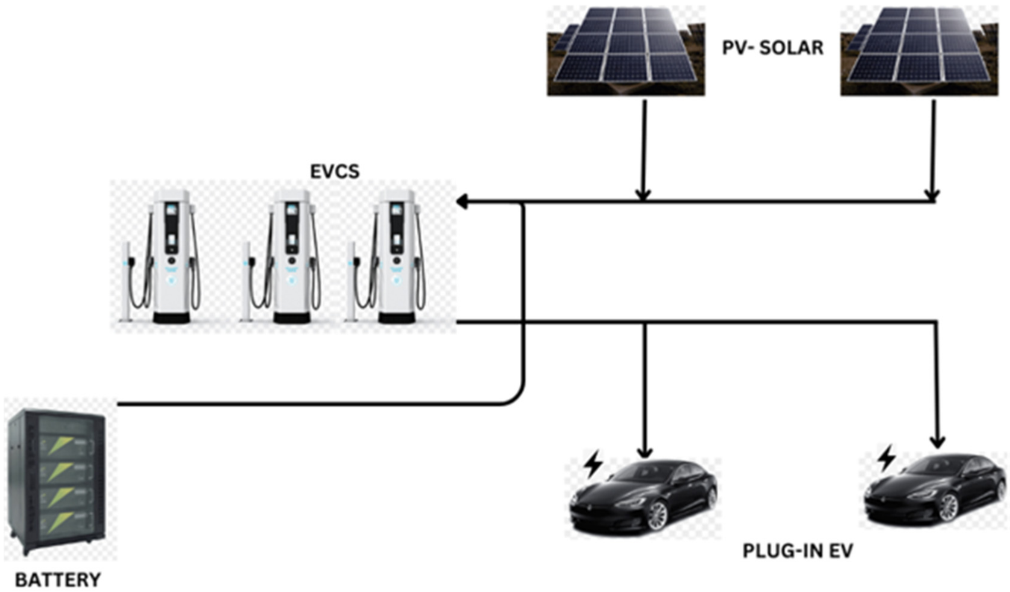

Figure 3. Off-grid PV-EVCSs with electricity storage device architecture.

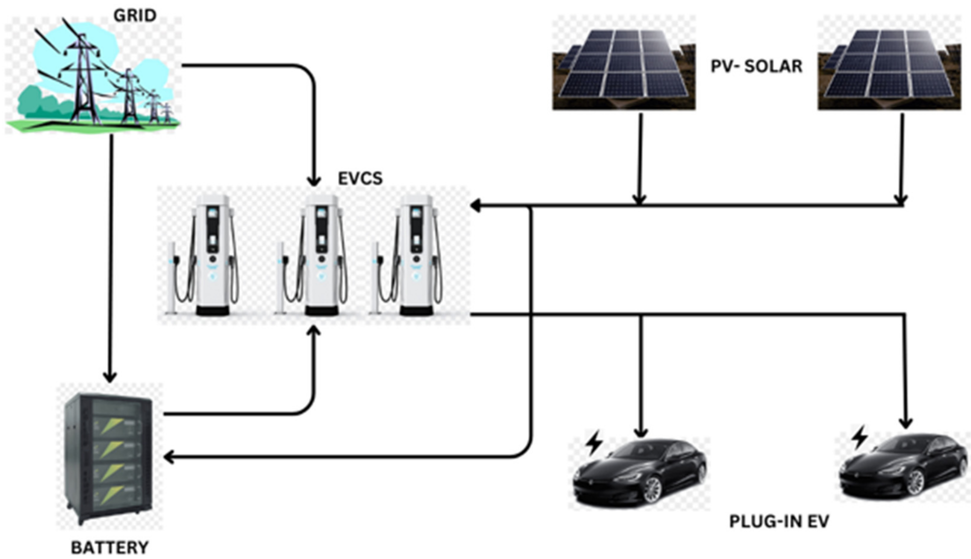

Figure 4. Hybrid EVCSs with electricity storage device architecture [6].

Seddig et al. [19] compared a stochastic optimization model to plan the charging of several EV fleets in a parking lot with a PV system and a transformer limit for charging. This model utilizes load flexibilities. Moreover, this PV system provides three unique forecasting options for electricity output. The results show that it is feasible to charge different fleets of EVs in a parking lot while considering technical constraints and uncertainties associated with different signals. Every group of EVs needs an operator to manage charging and provide load flexibility. Osório et al. [20] found that 26% of global EV charging outlets are situated in parking lots. Various tactics and advanced program designs are currently being used in the United States (US) to align EV loads with RESs. Tran et al. [21] proposed an efficient energy management technique to operate PV electric systems that charge EV batteries. The system's operational strategy is designed to allow the distribution grid or PV cells to efficiently charge the EV's battery. The proposed energy management plan can help with the implementation of vehicle-to-grid (V2G) technology and reduce unexpected peak power usage. The simulation and experiment results show that the proposed strategy can reduce the impact of high EV penetration. Chaudhari et al. [22] proposed a hybrid algorithm to lower the expenses of EV charging at PV-integrated charging stations by utilizing an ESS. The authors tested the algorithm's effectiveness by implementing a statistical EV charging model in Singapore. Three test cases were analyzed: EVCS without ESS and PV, EV charging stations with ESS but without PV, and EVCS with both ESS and PV. The study investigates the subsidies needed to profitably deploy PV systems near EVCSs due to their current high cost. Thus, employing the recommended algorithm, ESS on the distribution side can facilitate the economical installation of PV systems near EVCSs. Wu et al. [23] developed a finite-horizon Markov decision process (MDP) model to optimize the control of a PV-assisted EVCS. The model considers the dynamic energy pricing in France and utilizes V2G technology to provide auxiliary services. The energy management system can guarantee the satisfaction rate of EV charging demand, as indicated by simulation results. The proposed MDP technique can guarantee higher state of charge levels and significantly reduce overall operating costs compared to the randomly delayed charging strategy. In summer, total expense reductions can reach 71.38 percent, while in winter, they can be as high as 24.91 percent. The MDP strategy reduces expenses by 29.69% in winter and 55.05% in summer compared to the first come, first served method, according to Wu et al. [23] and Mbuwir et al. [24] introduced a control system that merges rule-based management and reinforcement learning to oversee the charging of EVs in an office building. The objective was to lower the electricity charging costs for EVs by leveraging real data from EnergyVille, Belgium. The simulation findings indicate that the proposed strategy decreases electricity costs by 62.5% compared to the current standard practices. Additionally, there is only a 5 percent performance gap compared to an almost perfect strategy that assumes a perfect understanding of the energy needs and user behavior of each EV. Charging EVs from solar PV systems offers two primary advantages: cost-effectiveness and sustainability. In Belgium, solar-powered EV charging is more energy-efficient, produces less net emissions, and has a smaller environmental impact compared to traditional ways [25,26]. Moreover, in several regions worldwide, solar PV electricity is now cheaper than conventional electricity because of the declining costs of PV systems. An EV's operational expenses are currently less than those of a similar internal combustion engine car [26]. The significant role of solar PV systems in EV charging is emphasized by the untapped opportunity of installing solar panels on parking lots and office building rooftops [27]. Ji et al. [28] introduced an optimization model to plan the sizes and locations of solar-assisted EV charging stations in a metropolitan area. Historical data from 297 users of an EV rental company in Beijing, China, are utilized for the tests. The results show that the proposed technique is capable of producing high-quality decisions within a practical computational timeframe. With the increasing number of EVs, future studies should prioritize the development of effective methods for handling charging. Xu et al. [4] studied the impact of EVs on Regina, Canada. The survey found that most inhabitants of Regina support wind farms, and 25% of respondents said they would install solar panels on their rooftops without any compensation. PV panels are a great fit for EVCSs because they can be easily installed on the roof of the CSs. Given their potential for both EV charging and RE integration, PVCSs offer promising solutions. Furthermore, multiple PV-CSs pose greater challenges in both modeling and energy management aspects, making them a target application within the scope of CSs. Therefore, Zhang et al. [29] proposed a way to manage energy for charging stations with PV panels for multiple EVs. The system considers both the stations' goals (stable battery levels) and the EV owners' goals (fast charging). They claimed that the proposed approach achieves this through a two-level method with a learning algorithm, resulting in efficient energy distribution. The results show the proposed approach works well for multiple CSs compared to stations without this proposed management system. Shin et al. [30] introduced a multiagent deep reinforcement learning methodology for managing energy in distributed EV charging stations equipped with PV systems and ESSs. Unlike traditional centralized approaches, the proposed approach computes optimal charging schedules in a distributed manner, accommodating dynamic data fluctuations across multiple charging stations. Through extensive performance evaluation, the proposed approach demonstrates cost reductions in operating EVCSs. The proposed approach is claimed to be tailored for PV/ESS-enabled EVCSs, effectively handling real-time variations in charging-related data and achieving desirable performance outcomes. Feizi et al. [31] introduced a framework for determining the PV generation dispatch limits in distribution networks with EVCS interconnection, accounting for the associated PV generation and EV uncertainties. The proposed framework establishes dispatch boundaries for PV generation considering various factors, such as the storage capacity and power dispatch of different EV clusters, and departure and arrival times. Results indicate that integrating EVs with charging capability can affect PV generation dispatch limits while increasing the uncertainty budget.

3. Case Studies on Solar-Powered EV Charging Networks

This paragraph will address case studies on solar-powered EVCSs. Csiszár et al. [32] proposed using a geographic information system and a greedy algorithm to optimize the placement of rapid charging stations across Europe. The approach was applied in Hungary as a case study, and real origin-destination data were utilized for validation. The operation's cost-effectiveness and results customized for each nation were determined.

Ilieva and Bremdal [33] discussed potential capacity-related grid problems that may occur and how to mitigate the challenges produced by the high demand for charging at the INSPIRIA charging station in Norway. The charging station has approximately 200 parking spaces and offers a variety of charging deals. The INSPIRIA charging station should be more capable of meeting future demand due to its variety of flexible local resources.

Charging stations facing similar challenges and objectives might effectively replicate the INSPIRIA charging station as a model pilot case to enhance both the electrification of transportation and the exploitation of RESs. Turan and Gökalp [34] examined the ideal sizes for solar power facilities and parking areas for EVs connected to the Yildiz Technical University's campus grid in Istanbul, Turkey. The comparison between the recommended protection system and the conventional protection approach reveals that in specific substations with fluctuating loading and voltage management, the protection system's duration is reduced by 20%. The increasing utilization of EVs and solar power plants is expected to have a notable effect on distribution networks and protection systems, as per reports. The recommended system design should consider reducing line losses, carbon emissions, improving voltage regulation, and ensuring a reliable protective system to meet the system's requirements.

Chowdary and Rao [35] suggested a grid-connected PV-based microgrid for EV charging stations in Visakhapatnam City, India. The proposed model showed a high solar component with minimal reliance on imports and exports to the grid. This showed that EV charging stations can operate without relying on the grid; however, it is recommended to have grid connectivity because of the variability of RESs. Chowdary and Rao [35] state that the PV plant supplies electricity to the computer system; the required peak capacity of the solar power plant changes based on the scaled session. The overall energy production varied between 946,235 and 1,734,764 kWh per year under varying conditions. About 97% of the observed power came from solar sources. Bilal et al. [36] developed three hybrid energy system topologies to provide electricity for the EVCS in northwest Delhi, India. The configurations are as follows: (a) grid and PV-based EV charging system; (b) PV/battery-based system; and (c) PV/diesel generator/battery-based system. The authors emphasized that to gain advantages from these systems, financial support must be provided by governmental and non-governmental organizations. They also stressed the necessity for more research to investigate the impact of charging and discharging cycles on battery longevity and energy expenses. Prakobkaew and Sirisumrannukul [37] described a grid-based spatial estimate technique for public fast chargers in Thailand. The authors estimate the total daily energy use to be around 79.4 GWh. In total, 12,565 public fast chargers are necessary to support local EV usage, with almost half of these chargers needed in the metropolitan area. The authors strongly recommend minimizing any impacts on the electric power system when establishing an electric truck depot. Shah et al. [38] examined the rooftops of active petrol stations in three Pakistani cities to set up the grid-connected PV system for EVCSs. The utility grid design and the techno-economic performance indicator comparison have both been finished. The architecture utilizes buses that carry both alternating current (AC) and DC to distribute electrical power. Pakistan will meet the minimal greenhouse gas emissions (GHE) reduction target set by the Paris Agreement through the implementation of this strategy.

Various case studies worldwide have investigated the incorporation of solar electricity into EV charging infrastructure. The studies offer insights into the technological characteristics, economic viability, and user reception of these systems. Sokolovskij et al. [39] examined the economic and energy benefits of a 1 kW PV carport at the WSEI University parking lot in Lublin, Poland, designed for charging an electric Renault Twizy car, see Figure 5. The car is equipped with 6.1 kWh batteries, providing a range of 60 to 100 km. The carport generated 2.75 kWh, which accounts for 46% of the total electricity use. Iringová and Kovačic [40] researched designing PV systems on the roof of a parking garage for passenger cars in Žilina, Slovakia. The authors stated that installing a PV system in a parking garage has social, environmental, and financial benefits. The analysis found that the PV panel with the highest performance in the area being assessed is positioned facing south at an angle of 37°. Crystalline silicon monocrystals in PV panels offer the highest economic return and power production efficiency in the assessed area. Kulik et al. [41] showed how a PV system with 4.89 kW of installed capacity was created as a carport covering two parking places at the Federal University of Technology—Paraná, Brazil. If 15% of the fleet is replaced with EVs, 17,151.8 MWh of electricity would need to be generated, requiring the construction of 36,856 carports, totaling around 1,105,685 square meters. Kulik et al. [42] showed that a solar carport system may effectively fulfill the energy needs for EV usage. The carport may generate an average of 483 kWh per month. It is estimated that a distance of 3525.5 km can be covered in a month, assuming an average energy consumption rate of 0.137 kWh/km. Seasonal fluctuations impact consumption significantly as regions with colder climates tend to utilize more electricity. While utilization can drop to 0.15 kWh in ideal weather conditions, the average consumption for most countries throughout the year is around 0.20 kWh [43]. The energy efficiency of EVs on the global market varies from 0.139 to 0.295 kWh/km, with an average of 0.195 kWh/km. [44]. Schücking et al. [45] analyzed empirical data from seven EVs over 2.75 years. Each vehicle had a monthly mileage of over 3000 km. They utilized a specialized model for energy consumption. Muneer et al. [46] assessed an EV through experiments. An electric Renault Zoe automobile has been used for this project. The car was driven on the main roads of Celje, Slovenia, and the city of Edinburgh, Scotland, to observe its speed and energy usage. The environmental and energetic performance of the vehicle in motion is measured by presenting the data. The study reported that the actual fuel consumption of the automobile exceeded the theoretical estimate by 12%. The specific energy usage varied from 0.139 to 0.295 kWh/km as shown in Table 3. The variation in specific consumption may be influenced by factors such as automobile size, weather conditions, driving speed, driver behavior, and the character of the place. It was also noted that in most of the cases studied in practice, car parking shades were used as solar PV fields to provide the energy needed to charge EVs.

Figure 5. A 1 kW PV carport at the WSEI University parking lot, Poland [39].

Table 3. Global PV system capacity and energy usage of EVs.

Locations	PV System Capacity kW	Specific Energy Consumption Wh/km	References
Lublin, Poland	1.00	-	[39]
Žilina, Slovakia	56.70 to 78.40	-	[40]
Paraná, Brazil	4.89	0.158	[41]
Celje in Slovenia and Edinburgh in Scotland	-	0.146–0.164	[46]
EU	-	0.150–0.200	[43]
Global market	-	0.139–0.295	[44]
Germany	-	0.150–0.280	[45]
Thailand	-	0.148	[47]

4. User Behavior and Adoption of Solar-Powered EV Charging

This paragraph will address the effects of user behavior on solar or wind-powered EV charging. Comprehending user behavior and acceptability is crucial for the success of any EV charging infrastructure. The literature examines aspects that affect user preferences, including the location of charging stations, payment structures, and consumers' environmental awareness. Within the EU, the majority of EV users utilize home chargers, with 61% of charging taking place at home and 15% at work. Existing research in EVCSs often assumes operators possess complete information about users' behaviors, but reality presents an asymmetry, with EV users holding more accurate information. This puts operators of EVCSs at a disadvantage, as users may intentionally misrepresent their behavior. This challenge affects centralized and bidirectional scheduling modes, particularly in fast-charging stations. To tackle this, the authors calibrated a proposed retail package design approach based on contract theory for PV-battery CSs (PV-BCSs). This promotes the adoption of the proposed energy package mode, where the operator utilizes signal game and contract theory to develop energy packages with a fixed price and charging power by expanding services to include both charging and discharging. By offering a wider range of packages, CS operators can better aggregate EVs and mitigate uncertainty. The proposed work by Li et al. [48] included an EV aggregation method based on retail packages and a charging and discharging allocation strategy using Lyapunov optimization. The results show an improvement in the income of CS operators and EV aggregation stability, while improving operator income compared to existing strategies. Also, this work achieves EV separation equilibrium, which involves redistributing a portion of the operator's profits to enhance user charging utility and discharging costs, thereby adding value to the overall system. In summary, a design approach for PV-BCSs, integrating contract theory and Lyapunov optimization, offers a promising solution to EV charging challenges, enhancing the stability and profitability of charging station operations. According to Todts and Mathieu's research, [49] public chargers were utilized to power over 25% of EVs. The proportion of home charging is projected to decrease from 61% in 2020 to 45% in 2030. Despite the apparent decrease in the price of EVs compared to traditional cars, there are still obstacles hindering their widespread acceptance. Henriksen et al. [50] conducted a qualitative survey to investigate householders' experiences following the smart charging of EVs in Norway. The results indicate that the factors influencing people's decision to use smart charging, such as safety, user experience, practical and financial benefits, and enhanced comfort, may be equally important as the financial reasons. The results indicated that future adaptability and grid enhancement opportunities will be impacted by the way different motivations for adopting smart home technologies are articulated. Van Heuveln et al. [51] studied how Dutch EV drivers see V2G technology and provided insights into the factors influencing their decision to use this technology. The authors identified compensation, system operational transparency, and dependable user control as the most significant criteria for fostering acceptance among users. Most participants expressed a preference for being able to control battery depletion sometimes, ideally using a smartphone application, even if some were not interested in additional effort. The main barriers to the implementation of V2G include consumers' range concerns, anticipated discomfort, battery degradation, uncertainty about standards, and the scarcity of V2G infrastructure. The majority of users expressed satisfaction with the system and stated their willingness to participate. Knez and Obrecht [52] identified that the cost and restricted driving range of EVs are the main factors influencing individuals' car purchasing choices. The authors suggest that while EVs are highly environmentally benign, they may not be appropriate for every driver. Sendek-Matysiak and Łosiewicz [53] suggest that increased funding for EV purchases, tax incentives, partial purchase price refunds, home wall charger installation options, and highway access without restrictions can help boost the popularity of EVs. Verma et al. [54] proposed utilizing a solar PV array-powered EV charger to inject surplus electricity back into the grid once the EV battery is fully charged. The charger can transfer battery energy to the grid to earn money when energy costs are high. The grid current maintains harmonic distortion levels within the IEEE 519 standard in all operational modes. The recommended charger has been confirmed by experimentation. Xu et al. [4] studied the impact of electrified passenger automobiles in Regina, Canada. The majority of Regina residents support wind farms, and 25% would install solar panels on their rooftops without any reward, as per a recent survey. Ji et al. [28] found that most short-term parking behavior is inconsistent and erratic, which hinders its ability to effectively reflect the actual charging demands. Users are unwilling to charge EVs if the parking duration is less than twenty minutes, as indicated by user behavior. The authors focused on parking behavior starting at 5 a.m. until 8 p.m. in commercial areas exceeding 20 min in Beijing, China. Wang et al. [55] studied customers' acceptance of EVCSs in Hangzhou, China, to understand acceptance mechanisms and improve user uptake. An analysis was performed on the parameters affecting acceptance willingness and the differences in EVCSs' acceptance among social groups. Based on the results, 81.2% of the participants were willing to participate in EVCSs. User acceptability was significantly influenced by perceived threat in a negative way, and by early trust and social influence in a favorable way. There were no statistically significant differences in the acceptance of EVCSs among males and females, as well as groups with different levels of education and wealth. However, married individuals and those aged 31–40 were more receptive compared to other groups. Shrestha et al. [56] categorized research on EV users' range anxiety into three groups: user perceptions, variables influencing range, and strategies to alleviate concern. Although current EVs may fulfill daily requirements, customers harbor doubts about them. Several factors determine the range of an EV. Additional methods to alleviate consumer concern involve optimizing energy usage, ensuring an even and efficient distribution of charging stations, utilizing range extenders, implementing car-sharing programs, creating modular batteries, and widening lanes. Installing a solar roof maximizes daily insolation as an alternative to constructing additional infrastructure. Fett et al. [57] presented the results of a study on user acceptance of wireless EV charging. The main factors influencing the survey's participants' willingness to adopt wireless EV charging include emotional evaluations of wireless charging, personal beliefs, perceived practicality of wireless charging, and environmental consciousness, as indicated by the research. Fett et al. [57] claimed that wireless charging is commonly acceptable, according to the findings. By comparing residential vs. other charging modes and examining data from Canadian charging stations, Jonas et al. [58] analyzed data from Canadian charging stations to find patterns in user behavior by comparing residential charging with other modes. The authors introduced an "EV Duck Curve" that highlights future grid stability concerns by magnifying the power production baseline. In Canada, Bailey et al. [59] and in Saudi Arabia, Almutairi [60] found that over 60% of participants selected their residences as the preferred location for EV charging. Sheldon and Dua [61] found that over 70% of respondents reported traveling 10 to 60 km each day. Al-fouzan and Almasri [62] completed a survey to shed light on the possible uptake and effects of EVs in

Hail City, Saudi Arabia, and the shift away from conventional cars. The findings indicate a strong preference for EVs, with 37.9% of participants saying they would be happy to convert to an EV and 78.6% of participants knowing where EV charging stations are. The results point to a rising interest in EVs and emphasize the necessity of building strategic infrastructure to handle the expected spike in EV adoption.

Schelte et al. [63] conducted an exploratory study in 2021 to assess the acceptability of battery switching and solar charging stations among German users. Authors assert that 50 to 80 percent of potential users of the sharing system are interested in utilizing battery swapping and solar charging facilities. Between 71% and 77% of respondents find battery swapping and solar charging facilities easy to use. In total, 96% of participants found inductive charging for solar charging stations easy to use. The authors report that most participants believed that a discount ranging from ten to twenty percent on the next shared excursion would be an adequate incentive. Men are more inclined to use battery swapping stations, whilst women are more interested in using solar charging stations. Aguilera-García et al. [64] aimed to conduct an early analysis of the demand for moped sharing in Spain. The research offers a deeper understanding of the collaborative moped industry and its potential effects on city transportation. The findings suggest that age, occupation, income, and environmental awareness are the primary factors affecting the potential future utilization of these services. Sixty-one percent of EV owners in the EU charge their vehicles at home, while fifteen percent charge them at work. Henriksen et al. [50] conducted a qualitative analysis to gain a deeper knowledge of the experiences of Norwegian householders following the intelligent charging of EVs. The results indicate that individuals' choices to utilize smart charging may be equally significant as their economic justifications. Moreover, the findings suggested that the potential for flexibility and grid optimization in the future hinges on the articulation of different motivations for adopting smart home technologies.

Alotaibi et al. [65] analyzed data from 698 surveys to identify and rank the challenges related to EV adoption in a major oil-producing country with a hot climate like Saudi Arabia, focusing on infrastructure, performance, financial, social, and policy barriers. The authors identify the lack of charging infrastructure, increased pressure on the national grid, and worries about battery safety, cost, and performance at high temperatures as the main challenges in this scenario. Almutairi et al. [66] confirmed the general and electricity profiles for dwellings and businesses in five different regions and cities in KSA using survey data. The profiles provided are significant for policymakers and grid operators since they offer essential information for projecting EV loads in various scenarios. The authors stressed the importance of considering appropriate charger layouts tailored to specific charging conditions to facilitate seamless EV integration and enhance grid performance. Ottesen et al. [67] studied the opinions of 472 EV drivers in Kuwait, regarding the important characteristics, advantages, and obstacles of EVs for potential purchasers. Based on the study, more than 50% of participants would buy an EV within the next three years if specific conditions were met. This involves a reduced purchase cost, together with access to express lanes, complimentary parking, and suitable infrastructure. Furthermore, nearly 40% of respondents indicated that a 50–199% increase in petrol and fuel prices would lead them to contemplate buying an EV. Participants expressed a preference for driving EVs in the future because of their technological, economic, and environmental benefits. The impacts of user behavior on solar or wind-powered EV charging were discussed in this paragraph. The results point to a rising interest in EVs and emphasize the necessity of building strategic infrastructure to handle the expected spike in EV adoption.

5. Environmental Impacts of Solar or Wind-Powered EV Charging

In this paragraph, the environmental impacts resulting from utilizing solar or wind-powered EV charging will be discussed. Solar vehicle charging stations (SVCSs) have become a crucial nexus between RE in the fast-changing sustainable transportation sector. SVCSs offer a forward-thinking solution that coincides with economic, environmental, and social goals as the global community works to address climate change and decrease reliance on fossil fuels. EVs must be charged using renewable electricity. Due to its advantages in promoting environmental sustainability, numerous countries are transitioning to RESs. Fossil fuels pose a significant threat to the Earth's biosphere due to their substantial role in CO_2 emissions. Table 4 displays the International Energy Agency's categorization of the percentage distribution of CO_2 emissions from different sectors. The table indicates that the transportation industry is the second source.

Table 4. The percentage of CO_2 emissions attributed to each sector [68].

Sector	Electricity and Heat	Transportation	Industry	Residential	Other
Percentage contribution of CO_2	42	22	21	6	9

In order to identify and create demand management alternatives to maximize power production and distribution using wind and solar energy [69], Carvalho et al. [70] analyzed various scenarios that compared the RE capacity of the system to the EV market share, specifically focusing on the CO_2 emissions associated with EVs when charged at night in the Portuguese power grid. Results indicate that with high wind capacity and low EV penetration, EV-specific CO_2 emissions range from 57 g CO_2/km to 129 g CO_2/km. The results show that increasing installed wind capacity along with EV penetration rates can benefit the environment. Muneer et al. [46] reported that the CO_2 intensity of the United Kingdom grid's power is 542 g/kWh. The amount lowers to 11 and 44 g/kWh for wind and solar PV electricity produced locally. Hence, preparing for RESs to charge EVs is environmentally beneficial. Cavalcante et al. [71] introduced a novel structure that enables external EV charging utilizing surplus solar-generated energy, leading to the emergence of new commercial prospects. EVs charged exclusively using PV energy have the potential to emit twenty percent fewer greenhouse gases than EVs charged with a mixed electrical source.

Elshurafa and Peerbocus [72] calculated the total carbon emissions resulting from the implementation of EVs in Saudi Arabia by considering the energy sources and incorporating a significant proportion of RE. Implementing policies that promote the concurrent adoption of EVs and RE sources can result in increased social and economic benefits. The authors stated that time-of-use pricing is not an effective method for reducing emissions, but it can still be utilized to encourage charging during off-peak hours and reduce strain on the power system. Filote et al. [73] assessed the environmental impacts of green independent energy systems in the EVCS's power supply, and compared them to the conventional grid for electricity distribution. The authors suggest that the selected technologies provide feasible solutions for supplying EVCSs with autonomous energy support. For 1 kWh of power, the CO_2 emissions are typically 11.40% for energy from the European grid and 7.10% for electricity from the world grid. dos Santos et al. [74] utilized the optimal pricing method according to Brazilian regulatory guidelines to develop a model for determining charging station tariffs, creating a tariff system that utilizes available natural resources to charge EVs at public charging stations. The results suggest that the approach enables cost reductions related to battery charging, hence promoting the use of this technology in the nation's transportation sector. When replacing gasoline with RESs, the cost per kWh/km increases by almost three times, and nearly doubles when diesel and gas are used as fuel. Buresh et al. [5] examined the potential impacts of large corporations utilizing PV solar carports in South Africa for their employees. The study showed the significant benefits of office EV charging with PV-augmented carports, either used independently or in combination with home-based charging, leading to a decrease in the total carbon footprint. Erickson and Ma [75] discussed the utilization of PV parking lots and grid-connected charging stations to offer EV consumers cost-effective demand management rates. The authors suggest that the best locations for solar-powered charging networks are where users' EVs are parked for most of the day, such as at work. Sizable parking areas are present in educational institutions, hospitals, retail malls, museums, and other enterprises. These locations offer parking spaces that can be utilized for solar-powered charging networks by both employees and visitors. Kulik et al. [42] analyzed the electricity generation of a PV carport at Brazil's Federal Technological University of Paraná. It is estimated that a distance of 3525.5 km can be covered in a month, assuming an average energy consumption rate of 0.137 kWh/km. An EV might potentially avoid emitting 4.23 tons of CO_2 each year. Sadeghi et al. [76] studied the most efficient way to determine the size of a microgrid's resources in two modes while considering the presence of EV, using the multi-objective particle swarm optimization technique. The optimal number of components and associated costs at different reliability levels are determined in the initial scenario involving PV, wind, and battery systems. The second system consisted of PV panels, wind turbines, batteries, and an EV. The results show that the EV enhances system reliability. The initial system demonstrated greater efficiency compared to the second system; however, the results indicated that the designs of both systems were feasible. Elkadeem and Abido [77] investigated a hybrid grid-connected energy system comprising gas boilers, batteries, PV, and combined heat and power (CHP). Based on the data, the optimal system consists of an inverter power of 53 kW, CHP power of 105 kW, and PV power of 73.9 kW. It outperforms the standard setup of CHP/gas boiler/grid, leading to a 16% reduction in CO_2 emissions. Khan et al. [78] examined the feasibility and design of a building-integrated PV-powered EV charging system in a standard Malaysian household to meet the need for residential and EV charging. Three systems were assessed: grid integrated without a battery, with 75% battery storage, and with 100% battery storage. The proposed system has a plant capacity of 5.6 kW. The annual energy output ranged from 7.19 to 8.05 MWh for all three scenarios. The battery-free system showed the most significant decrease in GHE, totaling 137,321,924 kg of CO_2. In October 6 City, Egypt, as described by Ibrahim [79], used PV-SOL to give a tech-economic study of a 5.9 kW grid-connected PV system for an electric charging station at a workplace. Electricity fueled the appliances in the office buildings and charging stations. The annual PV energy production was determined to be 10,463 kWh. The method prevents 4912 kg of CO_2 emissions annually. The environmental effects of using solar or wind-powered EV charging were covered in this paragraph. Research has indicated that the implementation of these technologies yields positive environmental outcomes, particularly in urban areas and traffic-heavy areas.

6. Economic Metrics for EVCSs Powered by Solar or Wind Energy

The economic effects of using solar or wind electricity for EV charging will be covered in this paragraph. This analysis of the economic indicators of SVCSs examines the various factors that support their financial sustainability and wider economic consequences. This analysis aims to explore the economic factors influencing the success and expansion of solar-powered charging infrastructures, including initial investment costs, operating efficiency, job creation, and economic growth. This research will examine important economic metrics that impact the development, implementation, and sustainability of SVCSs. Awad et al. [80] utilized MATLAB software to construct and evaluate a PV system designed to utilize DC fast charging for charging five distinct types of EVs. Charging time is calculated between 20% and 80% in the state of charge zone. Models are tested with temperatures ranging from 20 °C to 30 °C and irradiance levels between 600 W/m^2 and 1000 W/m^2. The results showed that the PV system can efficiently and inexpensively charge EVs on its own. Soares et al. [81] investigated the potential for decreasing grid running expenses by coordinated EV charging. The charging schedule of each EV can be modified to charge the battery during periods of lower energy costs. This will help reduce grid congestion and save money for both the distribution system operator and EV owners. Ilieva and Iliev [82] evaluated the financial feasibility of investing in solar-powered EVCSs in the north central region of Bulgaria. The solar system configuration assessed is 10 kW, with PV modules placed at the optimal tilt angle on a 70 m^2 shed roof in an administrative parking lot. Even without considering all the environmental and social impacts of using PV modules, the investment is still beneficial. Filote et al. [73] assessed the economic impacts of green independent energy systems on the EVCS's power provision. The authors state that the average cost of generating 1 kWh of electricity from the systems is 4.3 times greater than the average cost of a unit of grid energy in the EU. According to the authors, operating costs are lower when compared to the use of all fossil fuels.

Obrecht et al. [83] asserted that different nations have introduced legislation to stimulate the usage of EVs, such as tax breaks or other incentives designed to induce customers to acquire EVs. Nations with effective promotion policies have the highest percentage of EVs and invest the most in their marketing, as shown by studies. Elkadeem and Abido [77] studied a hybrid grid-connected energy system comprising gas boilers, batteries, PV, and CHP for EVCSs to save lifespan costs. The optimal system outperforms the standard case, leading to a 9% decrease in the system's net present cost, a 10% reduction in energy costs, and a 45% lower annual utility bill. Kulik et al. [42] analyzed the electricity production of a PV carport at Brazil's Federal Technological University of Paraná. The PBP for a PV system is around 5 years when simply taking into account the power aspect. When factoring in fuel savings and comparing it to a car with combustion engines, the PBP decreases to around one year. Kulik et al. [41] showed the construction of a carport with a PV system that had an installed capacity of 4.89 kW across two parking places. An economic analysis comparing an internal combustion engine to an EV shows that the costs of charging the batteries with electric energy are 3.3 times lower than the costs of purchasing gasoline, assuming the same driving habits. Diahovchenko et al. [84] evaluated the use of PV panels to enhance the efficiency of EVs in Kyiv, Ukraine. The authors state that the EV can travel a range of 7.98 km to 12.64 km during the summer and 1.55 km to 2.32 km in the winter. The authors state that the PBP for flat PV panels on the roof is 5.32 years, but it decreases to 5.07 years when a moving roof is utilized. The results confirm that employing PV arrays for EV off-board charging is feasible. Cavalcante et al. [71] proposed an innovative framework for utilizing solar-generated energy surpluses to charge external EVs, creating new economic opportunities. The authors obtained data using a PV system with a capacity of 724 kW. The firm could utilize the surplus energy to completely charge 3213 EVs within a year, as shown by the data study. The project's economic feasibility is confirmed by the economic assessment, revealing a PBP of about two years, an internal rate of return of 61%, and a net present value of EUR 33,485.

The PBP for the lot in the UK would be four years and three years in Germany in 2025 if a small EV with a 35 kWh capacity was paired with a 4 kW residential PV rooftop system and a battery storage unit of a comparable size. Due to the UK's low electricity costs and existing EV incentives, the combination of EVs and PV installations can increase the expected PBP to nine years. According to Willuhn [85], that would equate to seven years in Germany. Shabbir et al. [86] did an economic analysis to assess the feasibility of house PV and battery ESS for residential EV users. The PBP ranges from 12 to 46 years, depending on the specific scenario and the established system. The average PBP for the recommended systems ranges from 13 to 15 years, depending on the variation in system size. The PBP of a PV-powered EV charging system depends on various aspects including:

- Technical specifications about power output and energy consumption of the system;
- The state of the economy concerning the cost of a traditional energy unit, taxes, and the methods of funding the installation and maintenance of the system;
- Different regulations in different countries, state of the electricity grid, wealth level, climate, and social factors;
- Ecological productivity.

Table 5 displays the PBP for several projects utilizing PV-powered EV charging systems. In the identical scenario, this resulted in a different PBP solely because of the alteration in the price of the energy unit (electricity or fossil fuel) as documented by Kulik et al. [41,42]. The typical PBP ranged from 1 to 15 years. In one case analyzed, the recovery duration was reported to be 46 years by Shabbir et al. [86]. All PBP values in the table are economically suitable for this application.

Table 5. PV system capacity and payback period for different EVCSs' studies.

Locations	PV System Capacity (kW)	Payback Period (Year)	References
Paraná, Brazil	4.89	6.75	Kulik et al. [41]
		1.0 and 5.0	Kulik et al. [42]
Lisbon, Portugal	724.00	2.0	Cavalcante et al. [71]
October 6 City, Egypt	5.90	5.0	Ibrahim [79]
Kyiv, Ukraine	0.234	5.07–5.32	Diahovchenko et al. [84]
UK and Germany	4.00	3.0 to 4.0 *	Willuhn [85]
Estonia	5, 10, 20	13.0–15.0	Shabbir et al. [86]

* See text.

Nishanthy et al. [87] studied the techno-economic and environmental elements of on-grid hybrid solar wind car charging stations on a highway in southern Tamil Nadu, India. The gadget is expected to charge 17 EVs as scheduled over the day. The authors found that by reducing emissions by 50%, the Levelized Cost of Energy (LCOE) was 0.072 USD/kWh and the net current cost was USD 303,291.26. Schetinger et al. [88] conducted a simulation at the Federal Fluminense University's School of Engineering in Rio de Janeiro, Brazil, which combined the charging of EVs with the generation of RESs. Solar energy had a higher penetration index than wind energy. The researchers discovered that the lowest LCOE values of USD 0.12 per kWh were generated by PV systems accounting for 39% of the total electricity produced. Hasan et al. [89] proposed the installation of an EVCS at Shah Amanat International Airport in Chattogram, Bangladesh, with a daily average consumption of 10.54 MWh. Four unique scenarios with different combinations of resources were analyzed. The grid-connected PV and wind turbine setup proved the most optimal. The LCOE was 0.041 USD/kWh, calculated from the 84.3% renewable share. The data led to the calculation of an annual profit of USD 0.22 million using a billing rate of 0.141 USD/kWh. LCOE and emissions can be decreased by 63% and 75%, respectively, compared to the grid-only situation. Khan et al. [78] studied the feasibility and design of a building-integrated PV-powered EV charging system in a typical Malaysian home to meet the need for residential and EV charging. Ye et al. [90] studied the feasibility of solar-powered EVCSs in Shenzhen, China, including both technological and financial aspects. The modeling results indicate that a system meeting a daily power consumption of 4500 kWh has a total net present value of USD 3,579,236. Compared to a traditional gasoline-powered car, the PV-powered EV model may reduce pollution by around 100%. The LCOE increases from 0.027 USD/kWh to 0.097 USD/kWh when the interest rate climbs from 0% to 6%. Shafiq et al. [91] performed a techno-economic and environmental assessment of RE-based grid-tied EVCSs in the State of Muzaffarabad, Pakistan. The HOMER grid program evaluates the system's feasibility, and the Helioscope then verifies it. The suggested remedy decreases grid use by 215,945 to 254,030 kWh/year, at a LCOE of 0.016 USD/kWh. Furthermore, the system consumes 13% of the generated electricity. In total, 87% of the power is resold to the grid. In October 6 City, Egypt, Ibrahim [79] considered a tech-economic study of a 5.9 kW grid-connected PV system for an electric charging station at a workplace. The annual PV energy production was determined to be 10,463 kWh, with an annual efficiency of 1786.69 kWh/kW. Al-Buraiki and Al-Sharafi [92] assessed the performance of a standalone hybrid PV/wind/battery system in Saudi Arabia in meeting the electricity needs of a residential home in different weather conditions. The hybrid system was interfaced with an EV using MATLAB. Various scenarios of the EV's daily journey distance, ranging from 25 to 100 km, were considered. The results showed considerable variances in the best system configurations at the locations due to different RE potentials. The authors said that the LCOE for the most efficient setups was 0.4381 and 0.5645 USD/kWh when considering an average daily travel distance of 50 km. Ekren et al. [93] utilized the HOMER software to optimize a wind–solar hybrid energy charging station in Izmir, Turkey. As per the authors' instructions, the optimal setup for this system consists of a single 200 kW wind turbine and 250 kW of PV panels. The hybrid charging station costs USD 697,704 in total. The system would generate 843,150 kWh of power per year, with 55.6% sourced from solar energy and 44.4% from wind energy. The hybrid charging station charges five EVs per hour and operates for 14 h daily.

The LCOE ranges from 0.0032 to 0.5645 USD per kWh, as indicated in Table 6. There is a significant difference in prices, with the highest price being for an off-grid system due to the inclusion of a storage system. The LCOE for the solar system installed on the car roof ranges from USD 0.6654 to 1.1013 per kWh as shown in Table 6. There is a significant variation in the LCOE for the 5.6 kW and 5.9 kW capacities, with the latter being many times more, possibly due to the environmental and economic conditions in this research. The LCOE of a PV- or wind-powered EV charging system depends on various parameters such as technical specifications, economy concerning, different regulations in different countries climates, and social factors.

Table 6. Data and LCOE from several studies on EVCSs.

Locations	Applications	Power (kW) or Daily Energy Production (kWh)	LCOE USD/kWh	References
Malaysian	Building-integrated PV	5.6	0.0340 and 0.1400	Khan et al. [78]
October 6 City, Egypt	On-grid PV	5.9	0.0032	Ibrahim [79]
Kyiv, Ukraine	PV panels affixed to EVs' roofs	234 W	0.6654 to 1.1013	Diahovchenko et al. [84]
Tamil Nadu, India	On-grid hybrid solar wind	-	0.0720	Nishanthy et al. [87]
Rio de Janeiro, Brazil	Solar and wind sources	-	Lowest value 0.1200	Schetinger et al. [88]
Chattogram, Bangladesh	Shah Amanat International Airport connected PV and wind turbine	10,540	0.0410	Hasan et al. [89]
Shenzhen, China	Solar-powered EVCSs	4500	0.0270 to 0.0970	Ye et al. [90]
State of Muzaffarabad, Pakistan	RE-based grid-tied	150	0.0160	Shafiq et al. [91]
Kingdom of Saudi Arabia	Standalone hybrid PV/wind/battery	Residential home's electrical load connected with an EV	0.4381 and 0.5645	Al-Buraiki and Al-Sharafi [92]
Izmir, Turkey	Solar and wind sources	*	0.0640	Ekren et al. [93]

* See text.

7. Challenges and Opportunities in EV Charging Infrastructure

This paragraph will discuss the potential problems associated with EV charging infrastructure. The global shift to EVs is driving the need for a strong charging infrastructure to support the increasing usage of EVs. Global research has investigated several structures of EV charging systems, highlighting the importance of sustainable and expandable solutions. Solar power integration in charging stations is a viable technique to mitigate the environmental impact of EVs and improve energy resilience. Previous studies have identified the challenges and opportunities associated with establishing EV charging infrastructure in metropolitan areas. Portugal's distribution infrastructure is facing a big challenge due to the upcoming mass adoption of EVs in the next decade. Nogueira et al. [94] highlighted that the distribution network's capacity to handle the increased energy demand from the expanding number of EVs is a significant worry. Comparable situations are present in numerous other local networks, and in some areas, they can escalate dramatically. This analysis has shown the pressing necessity for strengthening the distribution network due to the imminent arrival of EVs' development, which will have an instant effect. Directive

European Union (EU) 2018/844 [95] outlines the technical specifications and legal rules for EV charging stations in the EU. Member states should promote the deployment of recharging infrastructure by implementing laws that eliminate administrative barriers faced by individual owners when installing recharging stations in their parking spaces. Gnann et al. [96] studied the fast-charging infrastructure requirements in Norway and Sweden. They determined that a key challenge is connecting the charging station to the local power grid. The authors state that at power rates of 150 kW, there can be one fast-charging station for every 1000 battery EVs. The results indicate that these stations can be profitable if they are located near business and service establishments. By 2030, 6.8 million public charging outlets will be required to promote consumer-driven EV uptake in the passenger automobile sector in the EU. An investment of EUR 144 billion is required for the infrastructure to support charging EVs, with a substantial focus on slow alternating current charging [97]. Szumska [98] investigated which countries in the EU had rapid charging stations for EVs in their existing infrastructure. The fast-charging infrastructure for EVs is lacking in many areas, as indicated by an evaluation of the current state of the infrastructure and future expansion plans in alignment with the EU Green Deal for European law. The progress of charging infrastructure construction varies because of the diverse economic conditions throughout the EU member states. Central European states, like Western European countries, also want to develop infrastructure for charging EVs. In the Netherlands, the latest data show an average of 1.18 semi-public charging stations per square km. The Netherlands is among five countries globally where the proportion of electric passenger cars in total exceeds 1%, together with Norway, Iceland, Sweden, and China. The Netherlands boasts the largest density of charging points compared to any other nation in terms of infrastructure [99]. Poland's reported figures indicate growth in the nation's EV charging infrastructure. Poland has 5139 charging points distributed across 2622 public charging stations by the end of January 2023, showing a growth of almost 33% compared to the previous year [100]. Respondents from Eastern Poland indicated that Stoma and Dudziak [101] discussed the challenges hindering the overall market introduction of EVs. The main challenges identified by the authors include inadequate infrastructure, high costs, and limited battery capacity for each charge. Halbey et al. [102] suggest that including fast charging stations in the infrastructure could be a beneficial solution. Enhanced battery capacity, strategic assessment of charging station locations, and grid density are crucial elements that could enhance acceptance and alleviate range anxiety. Stańczyk and Hyb [103] identified three primary challenges to electromobility: limited EV range caused by battery capacity, extended charging durations, and a lack of rapid charging station infrastructure. Extensive national networks are essential for enhancing travel comfort.

Funke et al. [104] assert that home charging is the predominant way for charging devices in many countries, especially where there are numerous options available beyond early adopters, and this trend is expected to continue in other nations. Countries vary in the composition of their pricing systems. Thus, there is no ideal percentage of plug-in electric vehicles (PEVs) per charging station for any certain country or charging type. The author's study indicates that national laws on charging infrastructure may have limited general applicability. Alrubaie et al. [105] extensively discussed the EV market, including its technological needs, charging infrastructure, and power management techniques. The writers also examine research on several EVs and solar system configurations. They presented an overview of the current status of EVs and conducted a thorough analysis of key global grid connectivity and EV charging standards. Finally, proposals and concerns about the future development of EV charging and grid connectivity infrastructure were evaluated. PV-grid charging has been proven to be financially viable. The power system may not be cost-effective due to the low capacity of the photovoltaic panels and batteries. The possible issues with EV charging infrastructure were covered in this paragraph. Research indicates that for the use of EVs to increase, there has to be a system in place that incentivizes investment in RE-powered charging stations. Promoting the use of EVs is also beneficial.

8. Conclusions

This review thoroughly analyzed the existing research and reasons behind the advancement of PV-powered EVCSs. It discussed the progress in charging station technologies, energy storage options, and the incorporation of smart grid technologies, emphasizing the ever-changing landscape of the industry and the ongoing initiatives to improve the effectiveness and eco-friendliness of EVCSs. The information gathered from this review is a valuable resource for policymakers, researchers, and industry stakeholders, aiding in the advancement of a more sustainable transportation ecosystem. Collaborative efforts in this field are crucial, and the literature analysis establishes a strong basis for future study and deployment of PV-powered EVCSs worldwide. The study demonstrates various RES-based methods available for installing EVCSs, each with advantages and disadvantages. One immediate and efficient alternative is to use PV systems on parking lots or rooftops of residential buildings as a reliable source for EVCSs. This study examined 105 sources, among these sources, about 25% were published in this and the previous year. The results can be summarized as follows:

- The majority of the theoretical research was conducted using MATLAB;
- The majority of PV-powered EVCS initiatives focused on shading parking lots;
- The energy consumption varied from 0.139 to 0.295 kWh/km. The variation in specific consumption is influenced by factors such as automobile size, weather conditions, driving speed, driver behavior, road quality, and geographical characteristics;
- The LCOE ranges from USD 0.0032 to 0.5645 per kWh. This is a large discrepancy, noting that the price is for an off-grid system more than this range, and this is normal as a result of the presence of a storage system;
- The majority of PBP values are economically suitable for this application. The average PBP ranged from 1 to 15 years, with one example showing a PBP of 46 years.

For maximum utilization of PVCSs, further research should consider optimization variables such as increasing the number of EVCSs, reducing charging times, and implementing EV rotation. Furthermore, a PV production forecast is necessary to optimize the sizing and administration of PV systems. The goal of PV forecasting is to reduce the overall LCOE by following production schedules.

Author Contributions: Conceptualization, R.A.A. and T.A.; methodology, O.A.; validation, R.A.A., S.A. and M.S.A.; investigation, R.A.A.; resources, O.A.; writing—original draft preparation, T.A.; writing—review and editing, M.S.A.; visualization, T.A. and S.A.; supervision, R.A.A.; project administration, R.A.A.; funding acquisition, O.A. All authors have read and agreed to the published version of the manuscript.

Funding: The Researchers would like to thank the Deanship of Graduate Studies and Scientific Research at Qassim University for financial support (QU-APC-2024-9/1).

Data Availability Statement: Not application.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AC	alternative current
CHP	combined heat and power
CS	charging station
DC	direct current
EU	European Union
EV	electric vehicle
EVCS	electric vehicle charging station
GHE	greenhouse gas emissions
LCOE	levelized cost of energy

MDP	Markov decision process
PBP	payback period
PV	photovoltaic
PV-BCSs	PV-battery CSs
PVCS	PV-powered Charging Station
RE	renewable energy
RES	renewable energy source
SCSN	solar charging station network
SVCS	solar vehicle charging station
UK	United Kingdom
V2G	vehicle to grid

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