buildings

MDPI

Article

Enhancing Electric Vehicle Charging Infrastructure: A Techno-Economic Analysis of Distributed Energy Resources and Local Grid Integration

Tacklim Lee [1,2], Guwon Yoon [2], Byeongkwan Kang [1], Myeong-in Choi [1,2], Sangmin Park [1], Junhyun Park [1] and Sehyun Park [1,2,*]

[1] Department of Intelligent Energy and Industry, Chung-Ang University, Seoul 06974, Republic of Korea; tacklim34@cau.ac.kr (T.L.); byeongkwan@cau.ac.kr (B.K.); auddlscjswo@cau.ac.kr (M.-i.C.); motlover@cau.ac.kr (S.P.); wnsgus7522@cau.ac.kr (J.P.)

[2] School of Electrical and Electronics Engineering, Chung-Ang University, Seoul 06974, Republic of Korea; gw1206@cau.ac.kr

* Correspondence: shpark@cau.ac.kr; Tel.: +82-2-822-5338

Abstract: The electric vehicle (EV) industry has emerged in response to the necessity of reducing greenhouse gas emissions and combating climate change. However, as the number of EVs increases, EV charging networks are confronted with considerable obstacles pertaining to accessibility, charging time, and the equilibrium between electricity demand and supply. In this paper, we present a techno-economic analysis of EV charging stations (EVCSs) by building type. This analysis is based on public EVCS data and considers both standalone local grid operation and integrated operation of distributed energy resources (DERs) and the local grid. The analysis has significant implications for the management of the electricity grid and the utilization of sustainable energy, and can result in economic benefits for both residential, commercial, and public buildings. The analysis indicates that integrating DERs with the local grid at EV charging stations can reduce local grid usage relative to EV demand. Nevertheless, there are also complexities, such as initial investment and maintenance costs, especially the weather-dependent performance variability of solar, which require financial support mechanisms, such as subsidies or tax incentives. Future research should focus on different DER integrations, regional and seasonal variability, user behavior, installation location, policy and regulatory impacts, and detailed capital expenditure analysis. Such research will advance DER and EVCS integration and contribute to increasing the efficiency and sustainability of urban energy systems.

Keywords: techno-economic analysis; electric vehicle charging station; electric vehicle fast charger; distributed energy resource; electricity tariff; distributed energy resource simulation

Citation: Lee, T.; Yoon, G.; Kang, B.; Choi, M.-i.; Park, S.; Park, J.; Park, S. Enhancing Electric Vehicle Charging Infrastructure: A Techno-Economic Analysis of Distributed Energy Resources and Local Grid Integration. *Buildings* **2024**, *14*, 2546. https://doi.org/10.3390/buildings14082546

Academic Editor: Yan Ding

Received: 8 July 2024
Revised: 5 August 2024
Accepted: 16 August 2024
Published: 19 August 2024

1. Introduction

Information and communication technology (ICT) continues to advance through increased data collection, faster network speeds, and the advent of artificial intelligence. These technologies are transforming industrial paradigms beyond traditional vertical industries encompassing fields such as the environment, energy, construction, and transportation [1]. Among these, the mobility industry is particularly notable. Historically, the mobility industry has been a critical mode of transportation for people worldwide. Nevertheless, the majority of its energy sources remain dependent on fossil fuels, particularly gasoline and diesel. The increase in fossil fuel-based internal combustion engines has led to higher carbon emissions, which result in adverse environmental impacts, such as air pollution, greenhouse gas emissions, and climate change [2].

In order to reduce carbon emissions worldwide, the mobility industry is investing in and researching low-carbon energy technologies and infrastructures [3]. This effort is rapidly shifting the industry sector from internal combustion engines to low-carbon energy-based EVs. This transformation drives the restructuring of the automotive industry towards a low-carbon framework, which creates new value chains in battery materials, charging technology, equipment, and energy trading. A representative example is the EVCS. The EVCS facilities are designed to charge EV batteries and provide drivers with fast and slow charging devices and spaces. However, several factors, such as limited accessibility, insufficient charging speeds, and the quality of the equipment used, are currently suboptimal for drivers of EVs [4].

First, there is a shortage of EVCSs relative to the number of EVs on the road. According to the 2022 IEA report, South Korea's EV sales accounted for nearly 12% of all vehicles sold globally (approximately 28,000 units). Concurrently, the global penetration rate of EV charging stations is considerable. However, out of the 205,000 operational EVCSs, only 21,000 are fast chargers. This indicates a shortage of EVCSs equipped with fast charging facilities relative to the EVs in use [5].

Second, it is challenging to minimize the waiting times for fast chargers. Fast chargers are typically located in public facilities, commercial areas, and other locations with high EV driver traffic. However, charging typically takes 30 to 60 min, which can cause delays and problems when vehicles suddenly queue up. For instance, during the Arctic cold wave in the winter of 2023 in the United States, the efficiency of EV batteries dropped sharply, which led to long queues at charging stations and multiple EVs being discharged completely. Seasonal variations can also cause charging times to double in winter and summer compared to spring and autumn, which can lead to a 20% reduction in the average driving range [6]. These are some reasons why faster charging is highly desirable.

Third, the increase in the number of EVCSs can lead to significant energy supply problems, especially in urban areas [7]. In order to address this challenge, it is essential to utilize sustainable distributed energy resources (DERs). Continuing to use fossil fuel-based energy would not contribute to carbon reduction. Using sustainable DERs, such as photo voltaic (PV) energy, can also mitigate energy supply problems in urban areas [8]. However, integrating DERs into the EV industry and achieving carbon neutrality requires careful consideration of the economic feasibility of construction and operation.

Equipping more EVCSs with fast chargers requires a distributed energy management plan that leverages both local grids and renewable energy. Installing EVCSs in buildings involves the consideration of factors such as power supply, charging patterns, and overload [9]. Thus, a thorough economic analysis of EVCSs according to building type is desirable. Currently, the installation of most EVCSs prioritizes the convenience of setup over user convenience, which results in the availability of mainly slow chargers and a notable shortage of fast chargers. Furthermore, to alleviate overload due to limited energy supply, a careful analysis of the DERs is needed that takes into account both accessibility and real-life demand [10]. This paper investigates the operation of fast chargers by building type to facilitate the expansion of EVCSs equipped with fast chargers. Additionally, it introduces a method for economic analysis that compares the operational status of EVCSs through the integration of local grids and DERs.

The remainder of this thesis is organized as follows: Section 2 presents a review of the literature on the design of the EVCS infrastructure, optimized charging methods, the calculation of charging service tariffs, and the combined operation of DERs and EVCSs. Section 3 provides an overview of the research approach taken in this thesis and presents an analysis of the testbed selection and operational characteristics of different building types (residential, commercial, and public) using public EVCS data, disaggregated by month, week, and hour. Section 4 presents a techno-economic analysis of district grid-based EVCSs, based on the selected testbed data for each building type. This section begins by examining the revenues generated by EVCS charging services. It then derives the electricity costs used for fast charging services and discusses the return on investment (ROI) process based on EVCS revenues. Subsequently, a techno-economic analysis of the regional grid operation of the EVCS testbed is presented. Section 5 outlines the methodology employed in the techno-economic analysis of EVCSs with integrated DERs and district grid operation. To this end, a DER simulation utilizing PV is conducted, with the resulting data integrated into the EVCS operation algorithm for a techno-economic analysis of the integrated EVCS testbed and regional grid operation. Furthermore, a comparison of two operational scenarios is conducted through an ROI analysis.

(1) Utilizing solely the local grid infrastructure.
(2) Employing an integrated DER and local grid configuration.

Finally, Section 6 presents the findings of the study and outlines potential avenues for future research, taking into account the limitations encountered during the course of the investigation.

2. Related Work

This paper presents a comprehensive analysis of existing studies that address the design of the EVCS infrastructure, optimization strategies for EV charging, the pricing of EVCSs, and the interconnection between DERs and EVCSs. In order to conduct this economic analysis, data pertaining to the operation of fast chargers within various building types, as recorded by the EVCS, were employed.

2.1. Studies on Infrastructure Design of EVCS

The specific design of the EVCS infrastructure is crucial for the widespread adoption of EVs. Key elements include the selection of the optimal EVCS locations, addressing technical problems, and ensuring economic feasibility. When selecting locations for EVCSs, the design approach takes into account traffic patterns, grid impact, and user convenience [11]. In order to alleviate the challenges associated with long and inconvenient charging times, a multi-charging system was reported to mitigate grid problems caused by EV charging [12]. EVCSs were also shown to be more energy efficient through the use of grid availability/unavailability modes that enable fast charging at higher voltage levels. Additionally, optimizing the routing EVCS involves installing charging equipment at facilities, e.g., multiple depots, which allows sustainable logistics development and operational cost efficiency [13]. Another research group reported considerations and measures for implementing residential EVCSs, which are accessible to the public in future smart cities [14].

Several economic and operational strategies address the impact of EVCSs on the local grid and the challenges in constructing EVCSs. These strategies include suggestions for maximizing revenue by applying specific economic scenarios to meet operational requirements [15]. It has been proposed that the use of residential PV may serve to enhance the equity of EV capacity and fast charging stations in medium- and low-voltage distribution networks. This could prove to be an effective means of significantly improving the equity and capacity of EVCSs [16].

Furthermore, the use of a particle swarm optimization algorithm to build EVCSs based on uniform distribution was proposed [17]. In order to address the capacity problems of EVCSs in commercial buildings, a modeling of the EVCS system using the Markovian queues algorithm was described, which could reduce the waiting time by 60% and the queue length by 42% compared to existing systems [18].

A network-based, low-carbon distributed energy charging station construction plan focusing on the characteristics of EVs was also reported. This plan aimed to minimize the annual total cost of the regional EVCS network through a carbon trading mechanism. This was performed by establishing a collaborative planning strategy for charging station networks that allocate low-carbon DER capacity through the network [19]. Moreover, optimal construction plans for EVCSs with controllable charging and RE resources within multiple microgrids were reported, which helps improve power quality and reduce the overall system cost [20]. Assuming the widespread adoption of EVs and EVCSs in the future, a scenario for energy sharing was proposed that could stabilize the energy supply. Scenario-based simulations showed that it is possible to reduce electricity costs [21].

2.2. Studies Focusing on Optimization Strategies for EV Charging

To determine the optimal charging strategy for different equipment types, a distributed collaborative framework based on multi-agent deep reinforcement learning was reported, which demonstrated the framework's ability to resolve many different EVCS problems [22]. Comprehensive research on integrating EVs into existing distribution systems, considering both slow and fast charging options, suggests that EVs could mitigate adverse impacts on the node voltage in the distribution system [23]. In addition, a methodology to optimize the layout of EVCSs was proposed that takes into account EV charging methods, sequential charging demand, and additional impacts on the power system [24].

Another proposal included an optimization framework for low-carbon integrated energy system management in response to EV demand, featuring a low-carbon district energy system model. This framework significantly reduced carbon emissions and decreased the previously elevated economic costs associated with charging demand response [25]. Researchers also suggested a scheduling technique to maximize solar energy utilization to optimize EV charging [26]. Furthermore, the proposal included a mixed-integer linear programming model that addresses distribution system expansion planning problems, considering distributed generation units, energy storage systems (ESSs), and EVCSs. This model combined demand and renewable generation-related environmental impacts and uncertainties, and it suggested the simultaneous optimization of investments in substations, circuits, and DERs from an environmental perspective [27].

In proposing sensitive intervention points (SIPs) to achieve climate neutrality by 2050, they underscore the significance of expanding infrastructure related to the pervasive adoption of EVs. They regard EVs as the principal conduit for supplanting conventional internal combustion engine vehicles and assess the favorable impact of augmenting the EV charging infrastructure on climate change mitigation. Their work represents a pivotal contribution to optimizing and expanding the EV charging infrastructure to attain both economic and environmental benefits [28].

In addition, when designing EVCSs for the parking lot of an office building, a load-prediction model based on various charging scenarios can be established. This model allows for load control that adapts to specific charging demands [29].

2.3. Studies Focusing on Service Fee Calculations for EV Charging

Charging fees for electric vehicles is crucial as they directly affect the costs of charging, the efficiency of the grid, and the overall adoption of EVs. Time-of-use (TOU) pricing has been proposed to lower charging costs and shift consumption to off-peak periods, which can help avoid system congestion during peak times [30]. To address the demand charge challenge, a significant barrier to EV industry growth in commercial and industrial sectors, an analysis of TOU pricing for EVs from both customer and grid perspectives was suggested [31]. In addition, another research group developed a pricing model for public EVCSs based on prospect theory. Their model takes into account price factors and the charge state of the battery and proposes that user behavior adjustments can benefit the charging station operators and the power system [32]. The JoAP algorithm, which jointly optimizes EV charging control, pricing, and scheduling, was used to maximize the profit of EVCSs. In this way, higher revenues than traditional methods were achieved [33]. The objective of this study was to evaluate the impact of EV charging on the power distribution system and to discuss the opportunities and challenges of integrating it with DERs. The study addresses the impact of the integration of electric vehicles and DERs on the power system [34].

Unfortunately, regulatory bodies and power companies have relatively little experience with EV-related rate design because the EV industry is so new. One study suggested methods for developing EV-specific rate designs and policies using a database that includes pilot rates and proposed rates from investor-owned utilities in the United States [35]. Another study evaluated the economic viability of implementing time-of-use (TOU) electricity rates, renewable energy, and battery storage systems within distribution systems to support the expansion of EVCSs with fast chargers [36].

Furthermore, to improve profits for EVCSs and reduce carbon emissions, a carbon revenue model for the participation of EVCSs in the carbon trading market was proposed. This approach involved sharing carbon revenues with EV users to reduce their charging costs, increase EVCS income, and decrease carbon emissions. This method can reduce EV charging costs by 16.25%, increase the profit of charging stations by 30.09%, and decrease carbon emissions by 74.68% [37].

2.4. Studies Focusing on the Integration of DERs and EVCSs

A new energy management approach for residential EVCSs was proposed that utilizes ESSs and PV-based DERs. This approach was tailored to residential parking patterns, and simulations for both summer and winter demonstrated its efficiency [38]. Moreover, an electric hydrogen charging station (combining PV and hydrogen energy storage (HES) systems) was suggested. Such a station minimizes operational costs through a model predictive control (MPC) system that optimizes energy dispatch [39]. An energy management system (EMS) for solar grid-connected EVCSs equipped with battery energy storage systems (BESSs) was also reported. This approach yielded a 32% decrease in emissions and a 29% cost reduction by considering the price and carbon emissions associated with the energy transferred from the EVs to the grid [40]. In order to address the uncertainty related to charging demand, a multi-purpose sizing method that integrates solar energy with retired batteries for EVCSs was proposed. This study incorporated a battery life calculation method based on a calendar life degradation model to predict the remaining life of retired batteries. Demonstrations showed a 29.4% cost reduction in the long-term operation of EVCSs that utilize these retired batteries [41].

The objective of this study was to evaluate the impact of EV charging on the power distribution system and to discuss the opportunities and challenges of integrating it with DERs. The study addresses the impact of the integration of electric vehicles and DERs on the power system [42]. Another study investigated a multi-year planning framework for integrating DER systems with EV charging in nearby business centers. This paper considers two types of EVs with different probabilistic behaviors and proposes a new data-driven method using actual weather data to generate different charging scenarios. The findings included a reduction in economic costs and carbon emissions by 67.8% and 31.6%, respectively [43]. To address energy supply issues and enable carbon reduction, another research group suggested building a specific LSTM prediction model for a PV-based power supply. Their model simulates the integration of EV charging platforms and offers solutions for carbon emission reduction [44].

In another study, researchers configured a DC microgrid-based EMS to ensure power balance and system stability via distributed control. The DC microgrid, which operated on both PV and ESSs, employed a novel two-stage energy management strategy, which was detailed with regard to its energy-saving measures [45]. Other researchers suggested an improved EMS for microgrids that was designed to reduce energy costs and manage power peaks. This approach achieved a 78% reduction in energy costs and a 70% reduction in peak power using ESSs [46]. To address risk challenges stemming from long-term uncertainties in DER demand, EV demand, RE production, and pricing, another group proposed a modeling approach linking DERs and the distribution system [47]. In addition, a microgrid approach was suggested that combines energy generated from DERs, storage capabilities through ESSs, load entities in the form of EVCSs, and energy trading with the main grid [48]. One study described an energy management optimization method for renewable energy-integrated buildings utilizing PV and ESSs. Their approach improved important sustainability indicators such as RE efficiency, economic resilience, and environmental friendliness [49].

This thesis distinguishes itself by complementing the shortcomings of existing studies and proposing a new approach to EVCS infrastructure design and optimization.

(1) A comprehensive analysis of different building types and a real data-based economic evaluation are presented. Previous studies have focused on specific building types or limited data, whereas this paper analyzes EVCS operation data from building types, including residential, commercial/business, and public facilities. The characteristics and challenges of each environment are identified, and real data provided by KEPCO are used to evaluate the economics, ROI, and payback period, thereby obtaining reliable results;
(2) Integration of DERs and the local grid: While existing studies mainly focus on either DERs or the power grid, this paper proposes to maximize the efficiency and cost-effectiveness of EVCSs through the integration of DERs and the local power grid. In doing so, we explore ways to increase energy reliability, address grid congestion, and generate additional revenue by selling excess energy from DERs.
(3) Optimization strategy through seasonal and hourly demand pattern analysis: While existing studies mainly consider the overall demand pattern, this paper analyzes the EVCS operation data in detail by monthly, weekly, and hourly data to understand the variability in charging demand. Based on this, an efficient charging infrastructure operation strategy is proposed, and policy and regulatory factors are considered to provide effective support.

Through this approach, this thesis aims to contribute to the development and optimization of the EVCS infrastructure by improving the efficiency and economy of EVCS operation and suggesting policy support measures.

3. Process for EVCS Techno-Economic Analysis

It is imperative that the EV industry be revitalized in order to effectively address the ongoing energy challenges that are being faced by urban centers. This will require the proliferation of EVCSs. Nevertheless, the current ratio of EVCSs to EVs is insufficient. As a result, drivers who wish to utilize fast charging facilities must often endure lengthy wait times. An increase in the number of EVCSs, particularly in urban areas, could potentially give rise to significant challenges in terms of energy supply. To address these issues, a techno-economic analysis of local grid-based EVCS operation by building type and integrated operation of the local grid and DERs is required. Such an analysis can help mitigate energy supply challenges, ensure efficient charging infrastructure operations, and ultimately provide a better service experience for EV users. Furthermore, the analysis can identify SIPs in energy management, providing important insights for policymakers, energy management organizations, and utilities to formulate and implement effective strategies.

Figure 1 depicts a descriptive architectural representation of EVCS operations. This architectural framework is designed to facilitate discourse on the techno-economic analysis of two operational scenarios: a regional grid-based operation of EVCSs by building type and a regional grid and DER integration operation scenario. In this chapter, we present a discussion on the characteristics of EVCS data and the process for selecting EVCS testbeds by building type, with the objective of describing the techno-economic aspects of the aforementioned operational scenarios.

3.1. Selection of EVCS Testbeds and Analysis of Building Types Using Public Data

To conduct an economic analysis of EVCSs, obtaining operational information on fast charging is essential. In South Korea, both public and private institutions operate EVCSs. However, to avoid information leakage, most institutions limit access to charger operation data to specific personnel only. Therefore, data from EVCS operated by public institutions were collected. Table 1 represents public data from EVCSs in Seoul, operated by KEPCO.

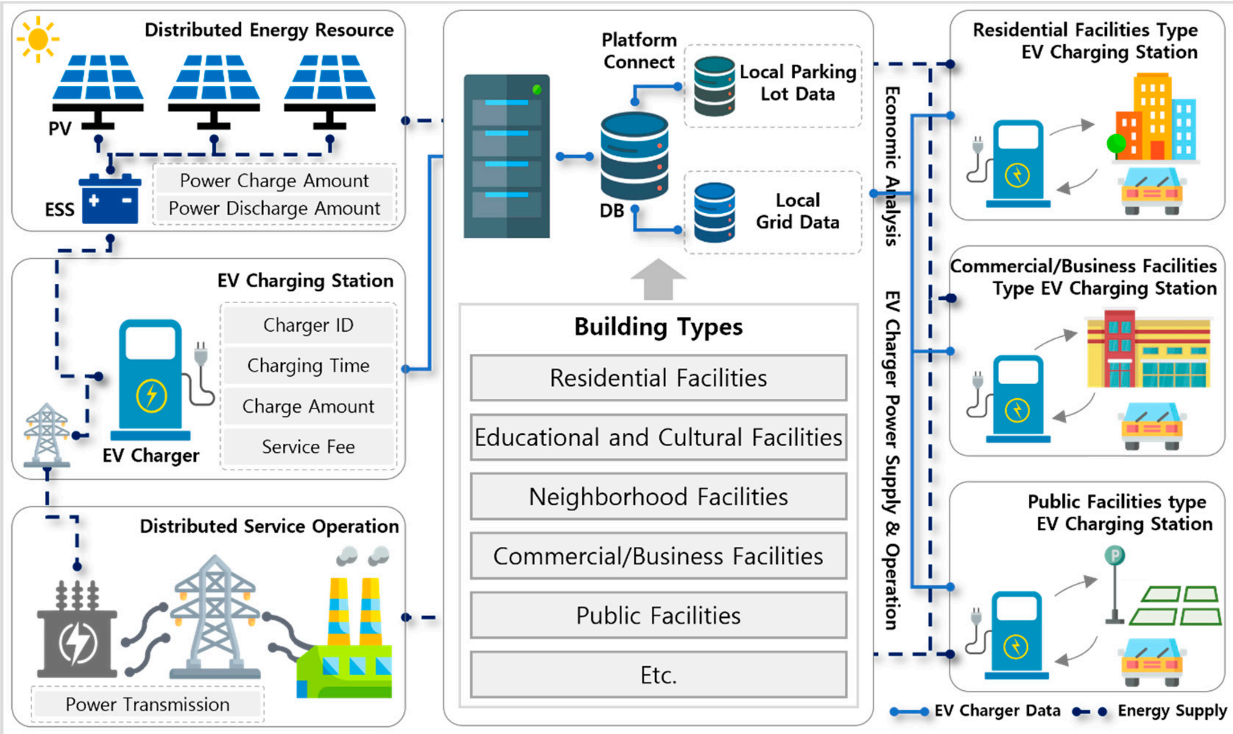

Figure 1. Schematic of the techno-economic analysis for EVCSs with different building types.

Table 1. Annual public data of EVCSs in Seoul.

Type	2020	2021	2022
Data Collection Period	January 2020~ December 2020	January 2021~ December 2021	January 2022~ December 2022
Number of EVCSs (EA)	391	409	443
Amount of Collected Data (Sessions)	278,071	138,999	252,149

The consequences of the global pandemic rendered the collection of data in 2021 and 2022 more challenging than it had been in the preceding year. The outbreak of COVID-19 in early 2020 led to movement restrictions and lockdowns around the world. However, South Korea did not implement a national lockdown and adopted a strategy of responding with short-term measures. As a result, the number of infections increased in the second half of 2020, and on 8 December 2020, South Korea maintained a tightened lockdown until 2022 [50]. This also affected EVCS usage patterns. In addition, data collection in 2021 and 2022 was incomplete due to poor management of fast chargers due to corona restrictions. Therefore, data for these years may be less quantitative and less qualitatively complete than in 2020. These factors may limit the techno-economic analysis based on real data. In this paper, we conduct a techno-economic analysis based on EVCS data collected in 2020.

Table 2 presents a categorization of the 50 kW fast chargers in operation in Seoul, based on data collected in 2020. The categorization is organized according to the type of building where the chargers are installed, including public facilities, residential facilities, commercial/business facilities, educational/cultural facilities, neighborhoods, and other facilities. While it is important to categorize EVCS usage characteristics in a manner that reflects traffic volume and demographic characteristics, the objective of this study is to analyze actual EVCS data by building type.

Table 2. Classification by building type in 2020.

Type	Residential Facilities	Educational/ Cultural Facilities	Neighborhood Facilities	Commercial/ Business Facilities	Public Facilities	Other Facilities
Number of EVCSs (EA)	281	10	6	18	70	6
Number of Fast Chargers (EA)	301	21	13	35	101	8
EVCS Charging Session (times)	31,194	5936	9321	18,725	67,041	3939
EVCS Charging Amount (kWh)	780,323	152,814	221,760	437,545	1,609,891	98,662
Charging Time (min)	2,314,955	322,653	447,157	947,566	3,487,964	223,283
Average Charge Time per Session (min)	74	54	48	51	52	57
Average Charging Session (Times)	85	16	25	51	138	11

The objective is to conduct a techno-economic analysis of EVCSs in three building types, applying two scenarios: utilizing the local grid and integrating DERs and the local grid. This necessitates the selection of an appropriate testbed, and a heatmap analysis was conducted to identify EVCSs with high EV charging demand within the three building types, as illustrated in Figure 2.

The installation of EVCSs in residential facilities is typically undertaken for the benefit of the local community or to enhance the quality of life for residents. In order to qualify for the installation of an EVCS and the provision of charging services, the facility in question must have a minimum of 100 parking spaces. As illustrated in Figure 2, the heatmap analysis reveals that J apartment exhibits the highest charging demand among the 281 residential EVCSs. The site has the capacity to accommodate 567 vehicles and is equipped with a single 50 kW fast charger. This fast charger is employed for the provision of fast charging services to residents, neighbors, and visitors.

The objective of operating EVCSs at commercial and business facilities is to facilitate commercial activities. A total of 18 commercial and business facility EVCSs are currently in operation within the Seoul region. The heatmap analysis presented in Figure 2 indicates that T-Mart has the highest demand for EV charging services. This site has the capacity to accommodate 2184 large vehicles and features a single 50 kW EV fast charger. This fast charger provides fast charging services to tenants of the commercial and business facility as well as to visitors from the surrounding area.

The objective of public facilities' EVCSs is to address parking issues at the national or regional level. In the Seoul region, there are 70 public facility-type EVCSs currently in operation. As illustrated in Figure 2, the G Administration agency has a high demand for charging services. This site has an outdoor parking facility for 120 vehicles and one 50 kW EV fast charger. This fast charger provides fast charging services to government employees, visitors to the facility, and nearby residents.

The objective is to employ the selected testbed data to conduct a more detailed analysis of the operational characteristics of EVCSs, with a focus on the building type.

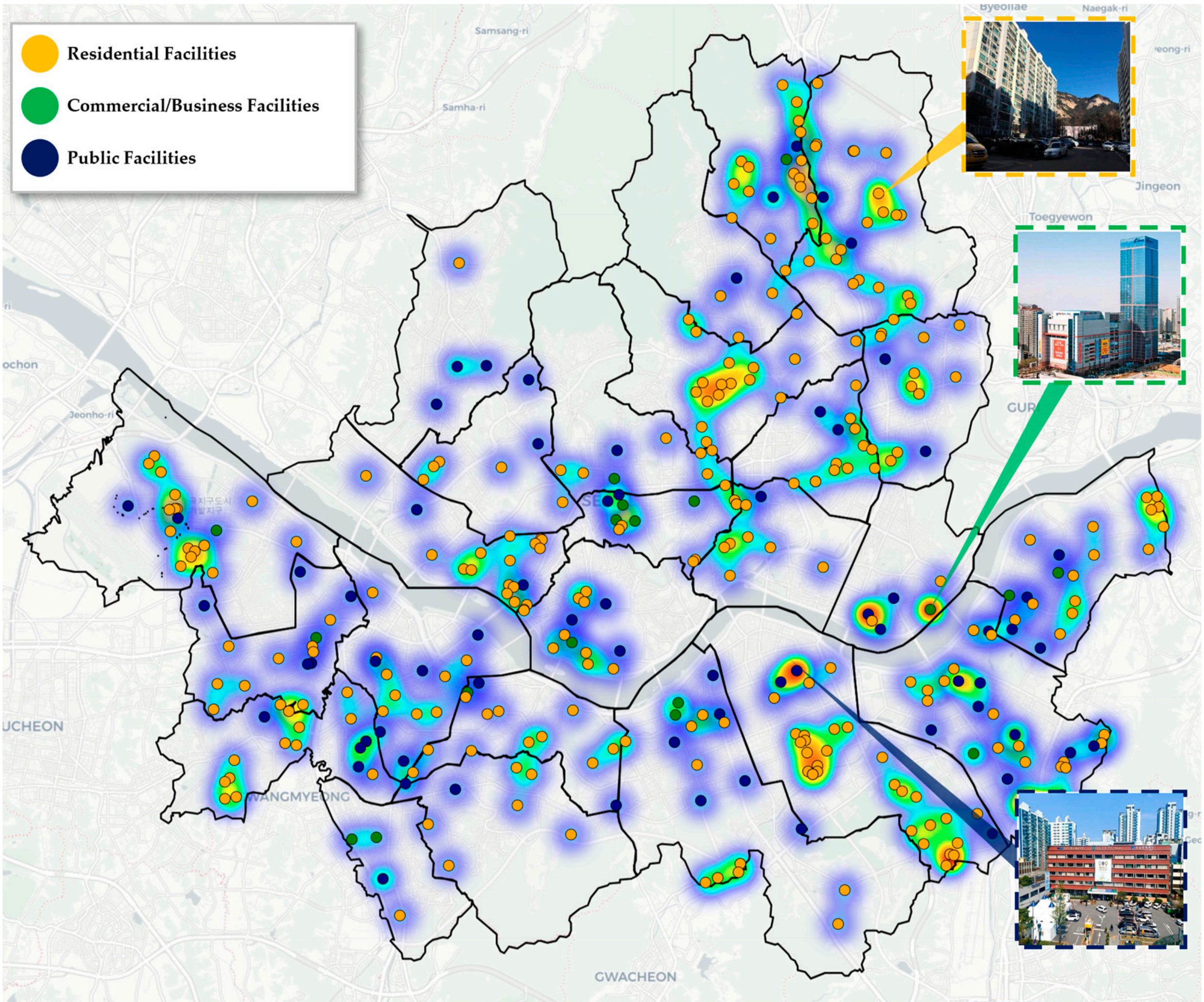

Figure 2. Heat map analysis of EVCSs' operational status.

3.2. Examination of the Operational Characteristics of EVCS Testbeds by Building Type

A comprehensive examination of the operational characteristics of fast chargers can be conducted based on the data collected from the EVCS testbeds for the selected building types. This analysis is based on the operational data collected from the EVCS testbeds for each building type, which has been broken down into monthly, weekly, and daily time-series data based on charge volume and number of charges. This approach provides important information regarding the operational characteristics and patterns of fast chargers for each building type, which can contribute to the efficient operation and management of EVCSs in the future.

3.2.1. Monthly Operation Characteristics Analysis

Seasonal changes in temperature and ambient environment affect the energy consumption of EVs [51]. To identify the seasonal demand for EV charging services, we conducted a monthly characterization of EVCS targets by building type. Figures 3–5 depict the monthly charging characteristics (using operational data from 2020) collected from EV fast chargers in selected building facilities. The bar graph depicts the cumulative electric vehicle charging data for each month, aggregated from the EVCS database. Monthly data shows that of the selected building types, the public facility testbed has the highest charging, followed by the commercial/business and residential.

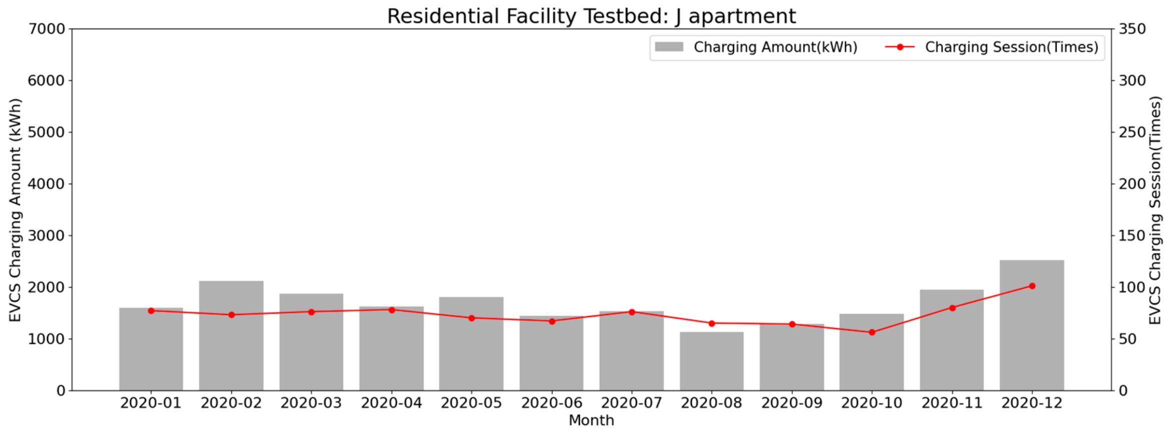

Figure 3. Monthly EV charging characteristics of residential facility testbed.

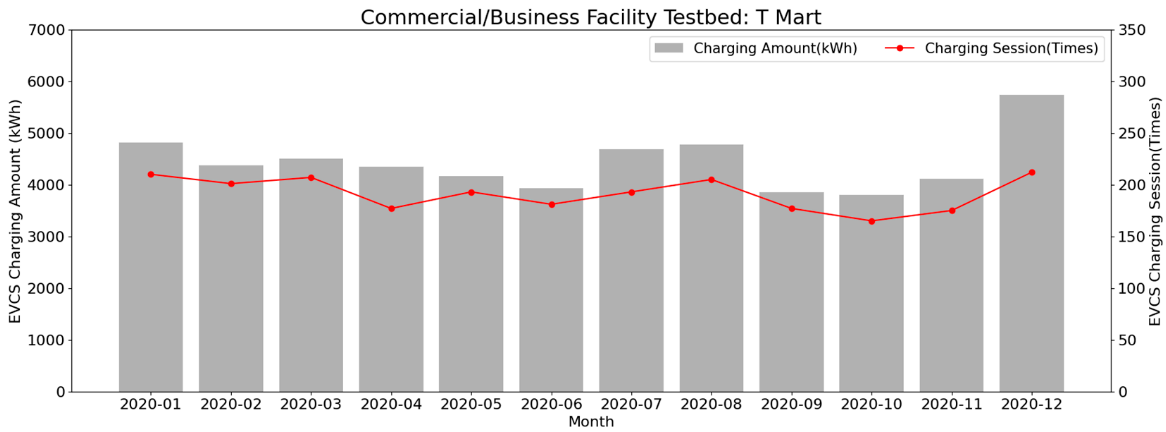

Figure 4. Monthly EV charging characteristics of commercial/business facility testbed.

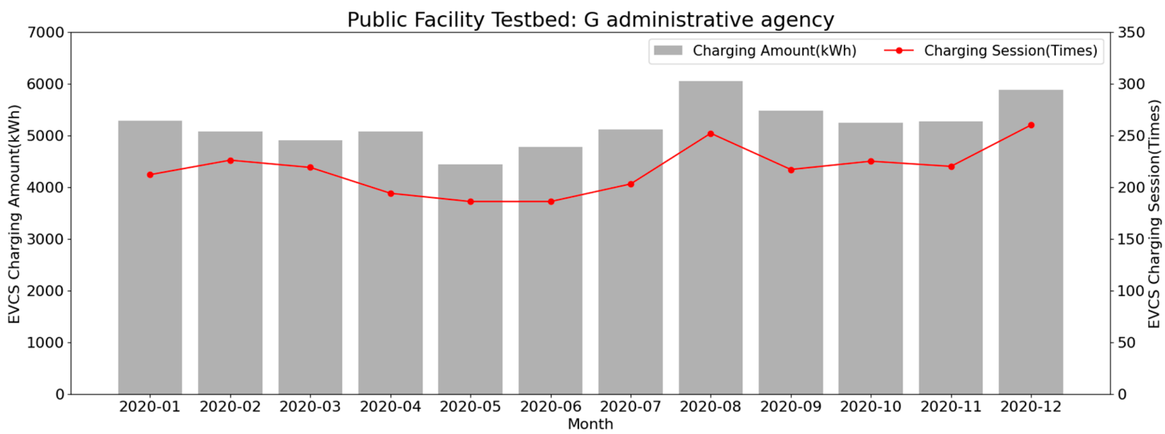

Figure 5. Monthly EV charging characteristics of public facility testbed.

Figure 3 shows the monthly charging characteristics of the residential facility testbed. The graph shows that the highest usage was in December, while the lowest usage was in August. Figure 4 shows the data for the commercial/business facility testbed. In this case, December featured the highest usage, whereas September and October had the lowest. Figure 5 depicts the charge characteristics of the public facility testbed. The utilization rate was highest in August and December, with the lowest being in May.

The analysis of monthly operational data for the EV fast charger across the three building types revealed that the usage rate of charging services was highest during the summer (July to August) and winter (November to February). This can be attributed to decreased EV battery efficiency.

Conversely, the usage rate was relatively low during spring (March to May) and fall (September to October). Hence, strategies for providing EV charging services during off-peak times (such as spring and fall) should be considered, based on the monthly characteristics above.

3.2.2. Weekly Operation Characterization

In order to derive the greatest benefit from EV charging services at EVCSs by building type, it is essential to analyze not only the monthly and hourly characteristics but also the weekly characteristics [52]. To analyze usage patterns, the total of charging recorded for each day of the week is calculated based on the weekly usage characteristics of the fast charger for the three building types. We found that the public facility testbed utilized EV charging services the most, followed by the commercial/business facility testbed and the residential facility testbed. According to Figure 6, the residential facility testbed shows high usage on Fridays and Saturdays and significantly lower usage on Sundays and Mondays. Figure 7 indicates that the commercial/business facility testbed exhibits high usage on Mondays and low usage on Saturdays and Sundays. Figure 8 indicates that the public facility testbed shows high usage on Fridays and low usage on Saturdays and Sundays.

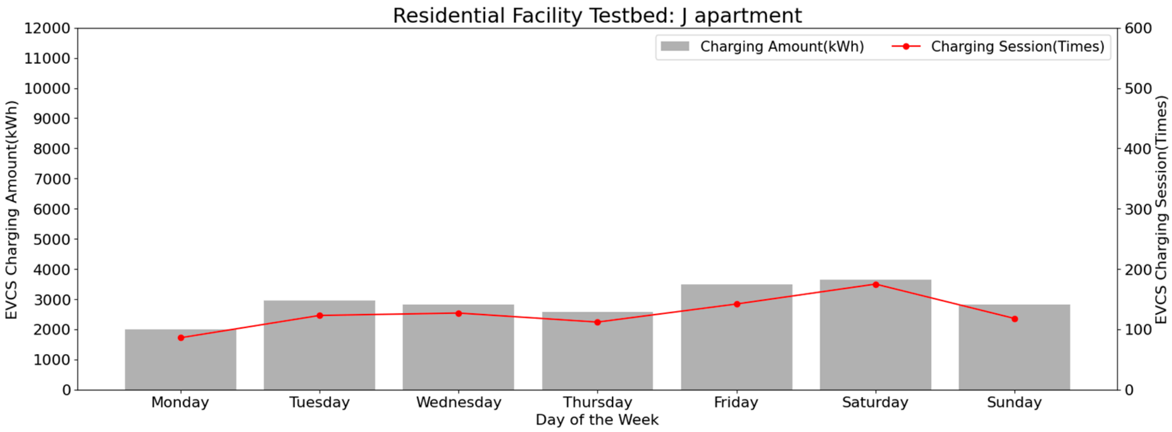

Figure 6. Weekly EV charging characteristics of residential facility testbed.

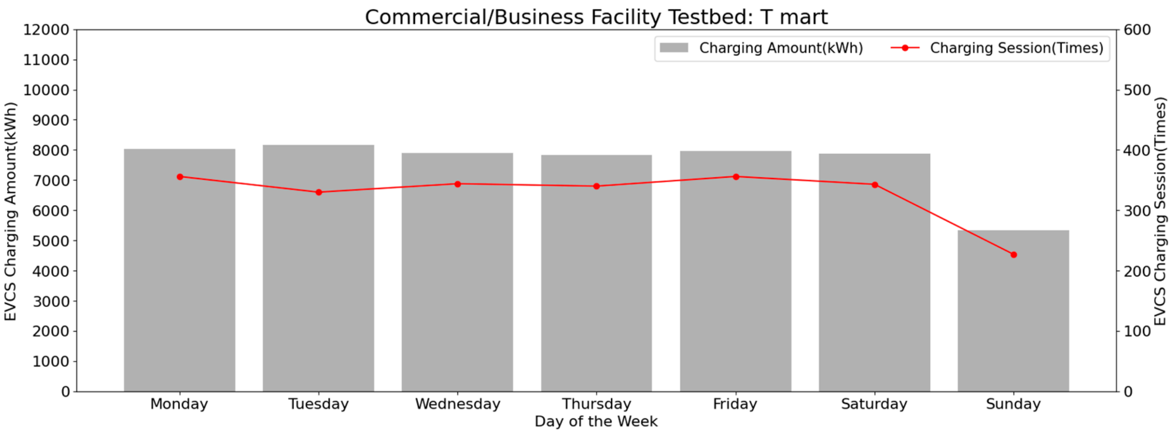

Figure 7. Weekly EV charging characteristics of commercial/business facility testbed.

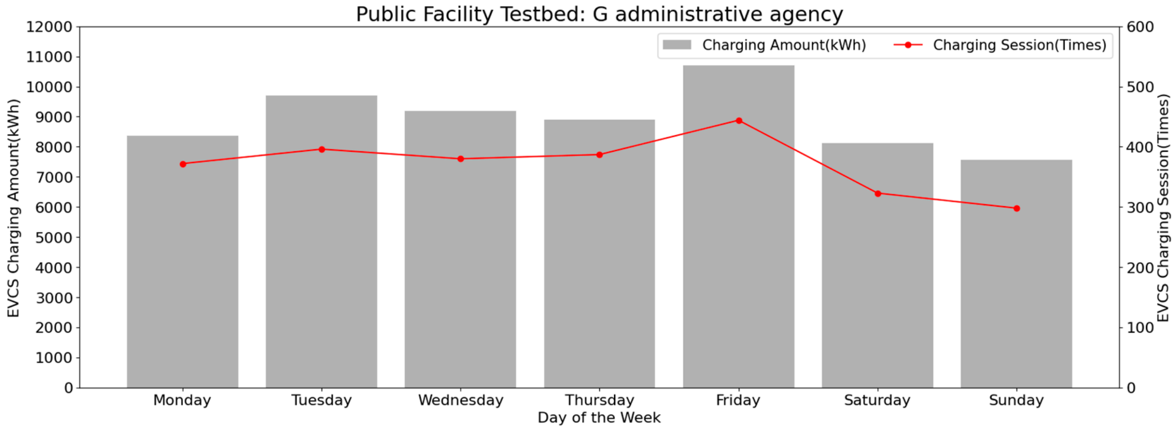

Figure 8. Weekly EV charging characteristics of public facility testbed.

The weekly analysis of fast charger usage for the building types reveals that EV charging service usage is higher on Fridays and lower on Thursdays and Sundays. Considering these weekly characteristics, energy supply methods, such as DERs, should be considered to provide EV charging services during off-peak days, like Thursdays and Sundays, to improve both service efficiency and cost-effectiveness. Given these weekly characteristics, strategies should be developed to supply energy from DERs to provide economic EV charging services on low-usage days, like Thursdays and Sundays, thereby improving service efficiency and cost-effectiveness.

3.2.3. Hourly Operational Characterization

To gain insight into the usage patterns of the fast chargers by the three building types, we calculated the total number of hourly charges on the fast chargers for the three building types by time of day (0:00 to 23:00). The analysis revealed that the public facility testbed had the highest usage rate of EV charging services, followed by the commercial/business facility testbed and the residential facility testbed. As shown in Figure 9, for the residential facility testbed, the utilization rate of charging services is high during night and early morning hours but low during daytime hours on weekdays. In Figure 10, for the commercial/business facility testbed, charging service usage is highest between 9 a.m. and 8 p.m., with low usage rates after 8 p.m. and during early morning hours. In Figure 11, for the public facility testbed, the utilization rate of charging services increases from 7 a.m. to 12 p.m. and decreases from 8 p.m. to 6 a.m.

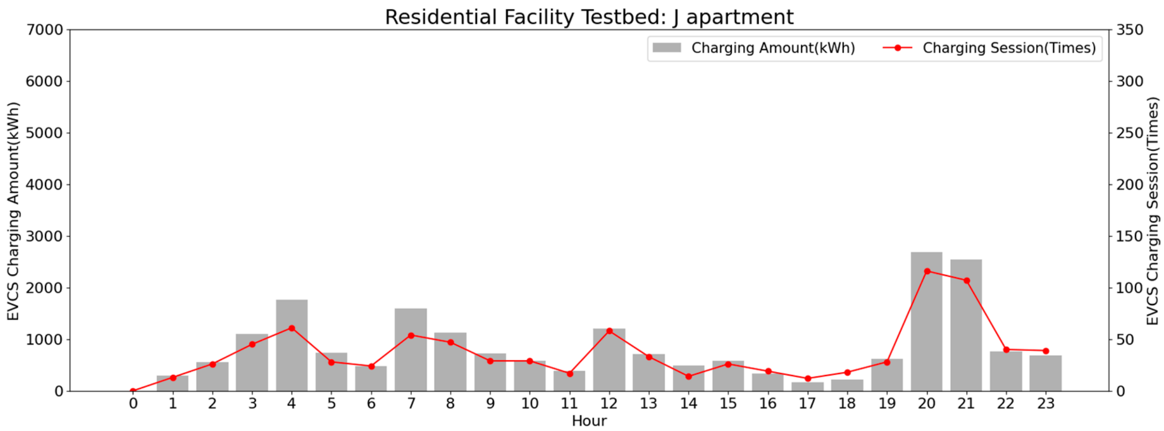

Figure 9. Hourly EV charging characteristics of residential facility testbed.

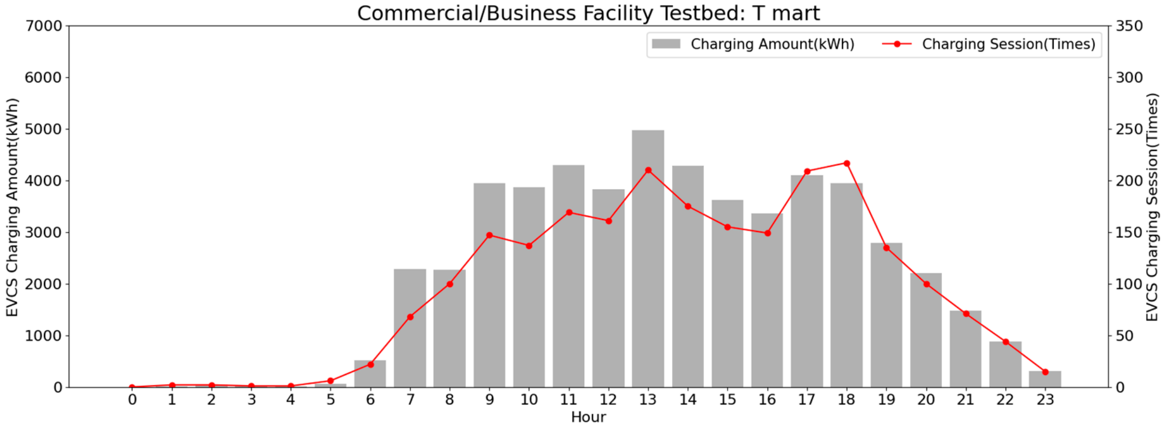

Figure 10. Hourly EV charging characteristics of commercial/business facility testbed.

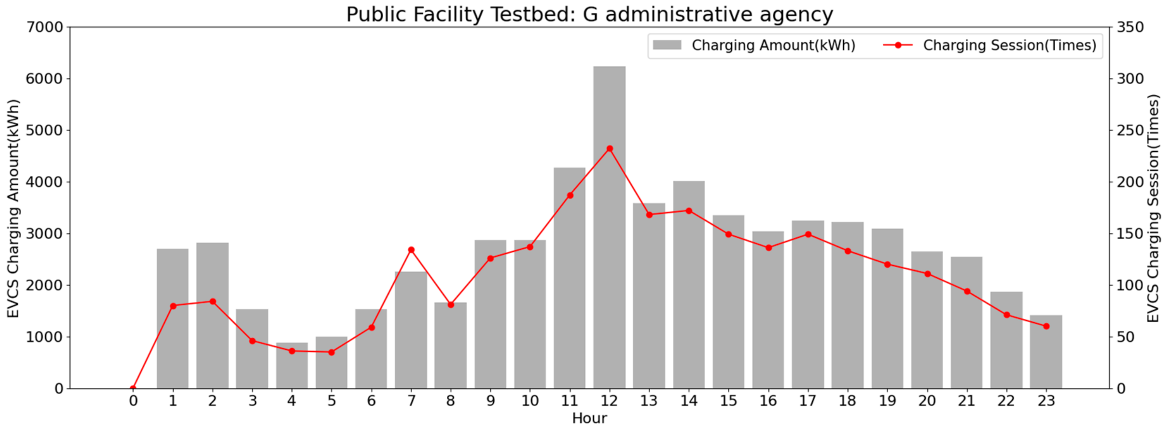

Figure 11. Hourly EV charging characteristics of public facility testbed.

As a result of analyzing the usage patterns of the EV fast charger by time across the building types, it was found that the utilization rate was high at noon and low between 9 p.m. to 11 p.m. and 4 a.m. to 5 a.m. Considering these time-specific characteristics, it is necessary to explore ways to manage energy during off-peak hours (from 9 p.m. to 11 p.m. and 4 a.m. to 5 a.m.) to improve service efficiency and cost-effectiveness.

The preceding monthly, weekly, and hourly analyses of the testbed permitted the elucidation of the characteristics of EVCSs by building type. Consequently, a particular analysis is required to disseminate the EVCS industry, reflecting a multitude of factors, including policy, EV industry investment, and facility management. The following chapter presents a comprehensive examination of the techno-economic aspects of EVCSs with a focus on their integration with the local power grid.

4. Techno-Economic Analysis for EVCS Based on Local Grid

A comprehensive examination is necessary to assess the economic viability of employing the local power grid in an EVCS testbed for each of the three selected building types. This is to inform policymakers, investors, facility managers, and others to consider a variety of factors, including cost-effectiveness, power demand management, stability and reliability, environmental impact, and policy and regulatory compliance, in order to stimulate the EV industry. In order to conduct a techno-economic analysis, data pertaining to EVCSs are analyzed using fast charger data collected from three selected building type testbeds. The data are provided in order to identify charging times and charge volumes, while electricity rates are derived from the 2020 KEPCO rate schedule in order to reflect the EVCS target rate. This allows for a discussion of the techno-economic analysis to be conducted by aligning the amount of electricity used to charge EVs from the local grid at the selected testbeds with the local utility's rates.

4.1. Examination of Revenue Generated by the EVCS Charging Services

In order to conduct a techno-economic analysis of EVCSs using the local electricity grid, it is essential to have access to information regarding profit margins. This necessitates the gathering of data concerning the revenue generated by the EVCS providing charging services for each selected building type, in addition to the electricity tariff paid to the utility.

The initial step is to delineate the methodology employed for the calculation of revenue. A single quick charger, situated within the testbed, is capable of providing charging services to multiple EVs. To calculate the energy demand for a single quick charge service provided by a quick charger in the EVCS testbed, one may utilize Equation (1). This equation allows for the calculation of the power consumption and charging time per unit time of the fast charger, thus providing the total energy demand. As this quick charger provides service continuously, one may utilize Equation (2) to calculate the total energy demand for each use of the charging service. Here, the variable "i" represents the number of times the service is utilized:

$$EV\ Charging\ Energy\ Demand = Load\ Demand \times t \quad (1)$$

$$Total\ EV\ Charging\ Energy = \sum_{i=1}^{n} EV\ Charging\ Energy\ Demand\ _i \quad (2)$$

To calculate the cost of using the EV fast charging service based on total energy demand, use Equation (3) to calculate the total service cost based on total energy demand. The service fee reflects the 2020 rate, which is USD 0.19 per kWh:

$$EVCS\ Revenue = Total\ EV\ Charging\ Energy \times Service\ Fee \quad (3)$$

In this way, Equations (1)–(3) allow you to systematically calculate your total energy demand and the resulting total cost of service. In the next lesson, we shall discuss how much you should pay your utility based on your total energy demand information.

4.2. Examination of the Cost of Electricity Used for EVCS Fast Charging Service

The preceding section addressed the monetization of charging services. This chapter presents the methodology for calculating the cost of electricity consumed through EV fast charging services at an EVCS. Table 3 presents a summary of the time-of-use (TOU) electricity rates for EVCSs, provided by KEPCO in 2020. It is important to note that the applicable rate schedule is dependent upon both the season and the load time. Consequently, EVCS operators are able to calculate the electricity usage charge paid to the utility by reflecting the aforementioned variables.

Table 3. 2020 TOU electricity tariff for EVCSs in South Korea.

Type (Unit: USD/kWh)	**Demand Price**	**Energy Charge**			
		TOU Electricity	**Summer**	**Spring, Autumn**	**Winter**
Tariff (EVCS)	1.87	Low load	0.045	0.039	0.052
		Medium load	0.074	0.046	0.066
		Peak load	0.09	0.049	0.076

Equations (4) and (5) delineate the methodology for calculating the contracted electricity rate and the usage rate when utilizing a 50 kW EV fast charger in an EVCS, in accordance with the electricity rate schedule delineated in Table 3. Equation (4) provides a means of calculating the contracted power price for a 50 kW fast charger at an EVCS. In this context, "*EV Fast Charger Capacity*" refers to a 50 kW fast charger:

$$Demand\ Charge = Demand\ Price \times EV\ Fast\ Charger\ Capacity \tag{4}$$

Equation (5) provides a detailed methodology for calculating the usage power charge for the EVCS, based on power consumption and the TOU electricity rate. In this formula, i represents time-of-use (TOU) electricity, and j represents the season:

$$Total\ Energy\ Charge = \sum_{i=1}^{3}\sum_{j=1}^{3} Energy\ Charge_{\ i,j} \times Total\ EV\ Charging\ Energy \tag{5}$$

4.3. Examination of ROI Investment Process Based on EVCS Profit

This chapter builds on the preceding discussion of revenue generation from charging services and the calculation of electricity costs. It elucidates the methodology for determining the profitability of an EVCS and demonstrates how this can be employed to ascertain a return on investment. Equation (6) delineates the methodology for calculating the EVCS profit margin:

$$EVCS\ Profit = EVCS\ Revenue - Demand\ charge - Total\ Energy\ Charge \tag{6}$$

Equation (7) elucidates the methodology for leveraging the EVCS profit margin from Equation (6) to ascertain the ROI for an EVCS. ROI analysis assesses the efficacy of an investment by quantifying the return on investment. A higher ROI signifies a greater return on investment, which is a pivotal consideration in determining whether to augment the number of fast chargers or enhance existing infrastructure:

$$ROI = \frac{EVCS\ Profit}{Total\ Investment} \times 100 \tag{7}$$

4.4. Technical and Economic Analysis of Local Grid Operation to EVCS Testbeds

Figure 12 presents a graphical representation of the revenue generated by the EVCS fast charger for each building type, based on the local electricity grid. The graph illustrates the monthly sum of EVCS revenue, demand charge, total energy charge, and EVCS profit for the operation of a single fast charger within the EVCS testbed for each building type.

The EV fast charger installed in the residential facility testbed paid a total energy charge of USD 1131.17 and a demand charge of USD 1121.1 to the electric company out of the USD 3760.27 in EVCS service revenue earned from charging services, resulting in a final profit of USD 1508. The highest profit during the operating period was observed in December when the USD 465.89 EVCS revenue was remitted to the electricity company for a USD 161.09 total energy charge and a USD 93.42 demand charge, resulting in a final EVCS profit of USD 211.37. The lowest profit came in August, when a USD 208.22 in EVCS revenue resulted in a USD 43.3 profit after paying USD 71.5 in total energy charges and USD 93.42 in demand charges to the electric company. In August, the usage of charging services was lower compared to other periods, and because of the seasonal and time-of-use power load rates, profits were minimal. Upon analyzing the service usage times in August, there were 65 total service uses, averaging 2.3 uses per day, with most of the usage occurring during the nighttime and early morning hours.

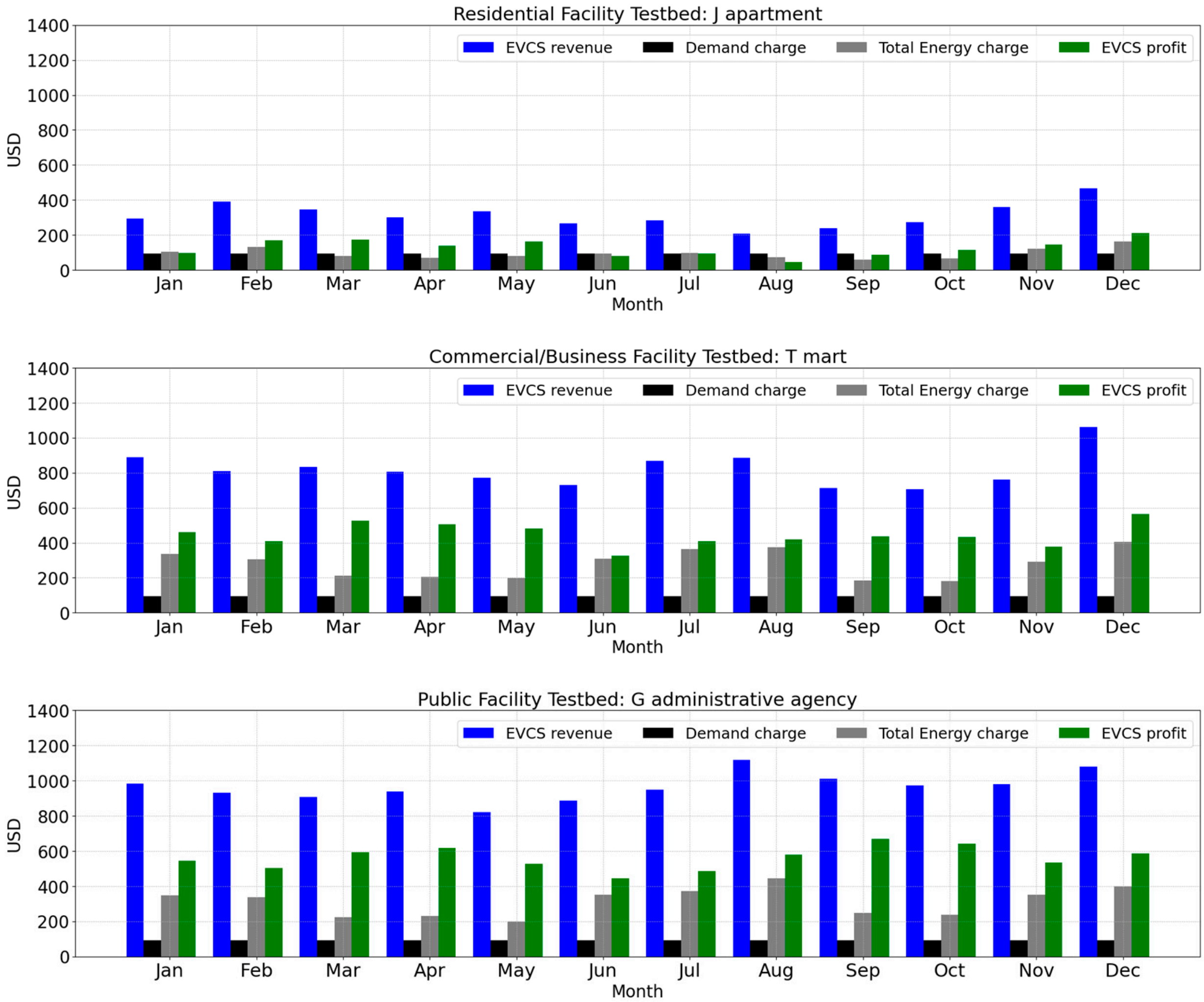

Figure 12. Techno-economic analysis of EVCSs based on the local grid.

The EV fast charger installed in the commercial/business facility testbed paid USD 3365.24 in energy charges and USD 1121.1 in demand charges to the utility from the USD 9832.47 in EVCS service revenue earned from charging services, resulting in a final profit of USD 5346.13. The highest profit during the operating period occurred in December, when we paid the electricity company an energy charge of USD 406.43 and a demand charge of USD 93.42 from our EVCS profit of USD 1063.3, resulting in a final profit of USD 563.45. Although January, July, and August showed high usage of fast charging services, profits were lower due to the seasonal and time-of-use power load rates. The lowest profit was recorded in June, with the electric company being paid USD 309.42 in energy charges and USD 93.42 in demand charges out of USD 729.14 in EVCS revenue. This resulted in a profit of USD 326.30. In June, despite higher usage of EV charging services compared to September and October, profits were not realized due to seasonal and time-of-use power load rates. In analyzing the service usage times in June, out of 181 uses, 166 occurred during peak and intermediate load rates in the daytime.

The EV fast charger installed in the public facility testbed paid USD 3741.29 in energy charges and USD 1121.1 in demand charges to the utility from the USD 11,587.52 in EVCS service revenue earned from charging services, resulting in a final profit of USD 6725.14. The highest profit during the operating period occurred in December, when we paid the electricity company USD 399.5 in energy charges and USD 93.42 in demand charges from our USD 1080.26 EVCS profit, resulting in a final profit of USD 587.33. Although August had higher usage of fast charging services compared to December, the high seasonal and time-of-use power load rates resulted in lower profits compared to December. The lowest profit was recorded in June, with the electricity company receiving USD 350.49 in energy charges and USD 93.42 in demand charges out of USD 888.32 in EVCS revenue. This resulted in a profit of USD 444.41. In June, despite higher usage of EV charging services compared to May, profits were not realized because of the seasonal and time-of-use power load rates. Upon analyzing the service usage times in June, out of 187 uses, 141 occurred during peak and intermediate rates in the daytime and nighttime.

Table 4 presents a summary of the operational results of a single quick charger in the EVCS testbed, organized by building type, as illustrated in Figure 12. The data include the total investment (fast charger, 1EA), EVCS revenue, demand charge, total energy charge, EVCS revenue, ROI, and EVCS payback period. Equation (8) represents the payback period, calculated based on the cost of the equipment and the total revenue generated:

$$EVCS\ payback\ period = \frac{50\ \text{kW}\ EV\ fast\ charger\ price\ (1\ \text{unit})}{EVCS\ profit} \tag{8}$$

Table 4. Summary of economic analysis of EVCSs based on the local power grid.

Type (Unit: USD)	Residential Facility Testbed	Commercial/ Business Facility Testbed	Public Facility Testbed
Total Investment (Fast charger, 1EA)	14,484.5	14,484.5	14,484.5
EVCS Revenue	3760.3	9832.5	11,587.5
Demand Charge	1121.1	1121.1	1121.1
Total Energy Charge	1131.2	3365.2	3741.3
EVCS Profit	1508	5346.1	6725.1
ROI (%)	10.4%	36.9%	46.4%
EVCS Payback Period (years)	9.61	2.71	2.15

The ROI analysis reveals that the public facility yielded the highest return on investment, followed by the commercial/business facility and residential facility. The fast EV charger in the public facility testbed exhibited the shortest payback period, at 2.15 years, while the commercial/business facility demonstrated a payback period of 2.71 years, indicating a relatively rapid return on investment. In contrast, the residential facility testbed required a considerably longer period, 9.61 years, to achieve a positive net present value.

In contrast to commercial, business, and public facility testbeds, a residential facility testbed is not an appropriate setting for the implementation of rapid charging stations for EVs. Usage is limited due to user constraints, which leads to lower utilization compared to the other two building types. Also, charging service times are concentrated around 8 p.m. and 9 p.m. Furthermore, according to South Korean eco-friendly vehicle regulations, both installation and operation must be completed within three years. Variable costs such as labor and maintenance per charger, as well as electricity costs exceeding 10% per fast charger, contribute to a longer payback period than initially predicted. In order to shorten the payback period for the residential facility testbed, increasing profitability would be necessary.

The following chapter presents a comprehensive examination of the potential for DERs to enhance the economic viability of existing local grid operations. This is achieved through a techno-economic analysis of DER integration with local grids in a building-specific EVCS testbed.

5. Technical and Economic Analysis of EVCSs Based on Integration of DERs and Local Grid Operations

In the preceding chapter, we discussed the techno-economic analysis of EVCS operation with regard to the local grid. As the number of EVs gradually increases with the development of the EV industry, the operation of EVCSs via the local grid may cause a number of problems related to grid overload. This may pose a serious threat to the stability of the urban power supply. Therefore, energy and EV industry players need to comprehensively consider a variety of factors, including cost-effectiveness, power demand management, stability and reliability, environmental impact, and policy and regulatory compliance. DERs are critical to addressing these issues. This is because DERs can improve grid flexibility, prevent congestion, maximize energy efficiency, and facilitate the integration of renewable energy.

To maximize the sustainability and efficiency of EVCS operations, this chapter constructs a DER simulation with PV and correlates it with EVCS testbed data by building type to perform a techno-economic analysis. It also compares the techno-economic analysis between operation on the local grid alone and operation with the local grid and DERs to evaluate the advantages and disadvantages of each approach.

5.1. Simulation of DERs Utilizing PV

A techno-economic analysis of DERs and the local grid for building-type EVCSs necessitates the consideration of a variety of DER approaches. While there are numerous types of DERs, this study concentrates on building-type EVCSs in urban areas, which constrains the utilization of DERs such as wind and hydropower. This is due to the fact that wind turbines and hydropower facilities necessitate a considerable amount of space for installation, and the tall and expansive buildings in urban cores present challenges in identifying suitable locations for installation and operation. Consequently, our objective is to construct a simulation that integrates DERs in urban settings with the local grid.

In order to construct a simulation that integrates a DER in a city with the local grid, it is imperative to meticulously calculate the precise amount of PV power required for each space. In consideration of the geographical characteristics of the Seoul region, solar panels have an efficiency of up to 20% and are capable of generating a capacity of 0.2 kWp per 1 m^2 [53]. In accordance with the aforementioned considerations, the available area for solar installation in the testbed, as detailed in Table 5, was duly measured. In accordance with the aforementioned spatial data, a methodology was devised for the design of PV power generation facilities within the confines of the testbed, employing Equation (9).

Table 5. Spatial measurement data for the DER simulation.

Type (Unit: m^2)	Residential Facility	Commercial/ Business Facility	Public Facility
Area	640	570	608

In order to calculate the PV-generating capacity per 1 m^2, it is necessary to apply each of the spatial information items from Table 5 to Equation (9). The value of 0.2 kWp per area has been used. The results of this calculation show that within the three testbeds, it is possible to design PVs with a minimum capacity of 114 kW, a maximum capacity of 128 kW, and an average capacity of 121 kW:

$$PV\ Energy = Area_{Avg} \times 0.2\ \text{kWp} \quad (9)$$

The implementation of PV installations is constrained by legal regulations and spatial limitations inherent to each testbed, thereby limiting the scope of data collection. Nevertheless, our analysis was based on PV power generation data from other regions. The PV power generation data utilized in this analysis was obtained from an operational PV power plant in Dangjin, Chungcheongnam-do, South Korea. The plant consists of a 100 kW

PV-generating facility and an ESS capable of storing the generated energy. The data were collected from January to December 2020. As illustrated in Figure 13, PV generation occurs between the hours of 6 a.m. and 6 p.m., while ESS charging occurs between the hours of 10 a.m. and 3 p.m. The stored energy is discharged from 4 p.m. to 11 p.m., after which it is sold to the local utility. The average energy sale from a PV is approximately 15 kWh. The maximum PV generation is 94.4 kWh, which generates the highest PV generation revenue, while the minimum PV generation is 0.01 kWh.

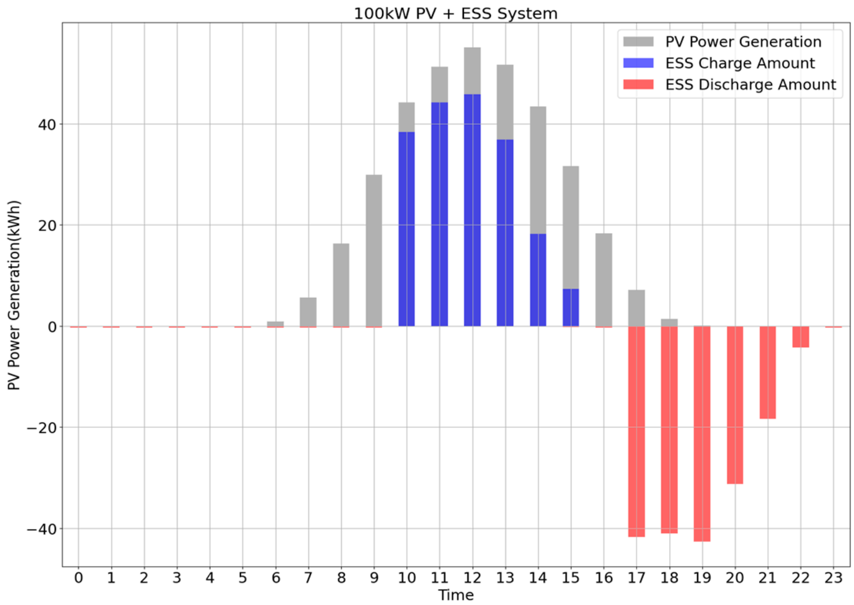

Figure 13. Daily average generation and discharge characteristics of PV generation data.

The data collected from the solar power sources were integrated with the DERs and local grid, which were then applied to the EVCS for each building type. The simulation conditional expression for the integration of DERs and the local grid within the EVCS is provided by Equation (10). This equation will now be elaborated upon:

$$Energy_{\ DER}\begin{cases} IF\ 6 \le t < 16,\ \ Energy_{ESS}(t+1) = Energy_{ESS}(t) + Power_{PV}(t) \\ EV_{Charger}(t) = Power_{Grid}(t) \\ IF\ 16 \le t < 24,\ \ Energy_{ESS}(t+1) = Energy_{ESS}(t) - Power_{Charge}(t) \\ EV_{Charger}(t) = Energy_{ESS}(t) \\ IF\ Energy_{\ ESS}(t) = 0,\ \ EV_{Charger}(t) = Power_{Grid}(t) \\ IF\ 16 \le t < 24\ and\ EV_{Session}(t) = 0,\ \ Power_{Sell}(t) = Energy_{ESS}(t) \\ IF\ Energy_{ESS}(t) = 0,\ \ EV_{Charger}(t) = Power_{Grid}(t) \end{cases} \tag{10}$$

The EVCS is integrated with the DERs and the local grid, facilitating the charging of the ESS via PV from 6 a.m. to 4 p.m. During these hours, the local grid is utilized to power EV fast chargers, thereby enabling the provision of EV fast charging services. From 4 p.m. to midnight, the ESS provides fast charging for EVs. EVs are charged by drawing energy from the ESS, and when the stored ESS energy is depleted, the EV fast charger draws power from the local grid to continue charging. In the event that no EV fast charger sessions are utilized between the hours of 4 p.m. and midnight, the remaining energy within the ESS is sold to the local utility company. Following the sale, the fast charger provides EV fast charging services through the local power grid.

The condition was applied to the EVCS for each building type, and the revenue generated by the residual energy was derived for each period through the use of a conditional expression. To derive the revenue, the unit price of PV generation was applied using Equations (11) and (12), based on the renewable energy certificate (REC) and system margin price (SMP) from the Korea Power Exchange (KPX). Equation (11) employs the residual energy and REC unit price to ascertain the REC revenue, whereas Equation (12) utilizes the residual energy and SMP unit price to determine the SMP revenue. Equation (13) derives the DER revenue associated with the EVCS from the REC and SMP revenue:

$$REC\ Profit = Energy_{\ DER} \times REC_{\ Price} \tag{11}$$

$$SMP\ Profit = Energy_{\ DER} \times SMP_{\ Price} \tag{12}$$

$$Residual\ Energy\ Sales\ Revenue = \sum_{i=1}^{n} REC\ Profit\ + \sum_{i=1}^{n} SMP\ Profit \tag{13}$$

Table 6 presents a summary of the outcomes of residual energy sales of DER and local grid integration in the EVCS testbed for each building type over time.

Table 6. Residual energy sales revenue by building type from integrated DER and local grid operations for EVCSs.

Operational Period	Residential Facility (Unit: USD)	Commercial/ Business Facility (Unit: USD)	Public Facility (Unit: USD)
Jan 2020	481.7	284.5	336.3
Feb 2020	475.5	326.8	313.3
Mar 2020	671.1	495.8	566.8
Apr 2020	817.6	697.3	676.9
May 2020	774.8	657.8	665.8
Jun 2020	674.4	522.5	515.5
Jul 2020	570.2	405.7	369.5
Aug 2020	554.8	352.4	304.0
Sep 2020	633.3	519.8	445.4
Oct 2020	734.5	568.8	550.2
Nov 2020	544.7	403.1	340.5
Dec 2020	572.3	397.1	361.6
total	7504.8	5631.6	5445.7

5.2. Technical and Economic Analysis of EVCS Testbeds Integrated with DERs and Local Power Grid Operations

Simulations of DER and local grid connections in urban contexts were applied to EVCS testbeds for each building type to derive returns. This approach was employed to analyze the technical and economic aspects of EVCSs with DERs and the local grid. Equation (14) was used to derive the profit margins for DER and grid-connected EVCSs.

$$\begin{aligned} EVCS\ Profit = EVCS_{\ revenue} + Residual\ Energy\ Sales\ Revenue \\ -Demand\ Charge - Total\ Energy\ Charge \end{aligned} \tag{14}$$

Figure 14 presents a graphical representation of the monthly integration of EVCSs with DERs and the local grid, based on data on EVCS power usage, EV fast charging service charges, and DERs.

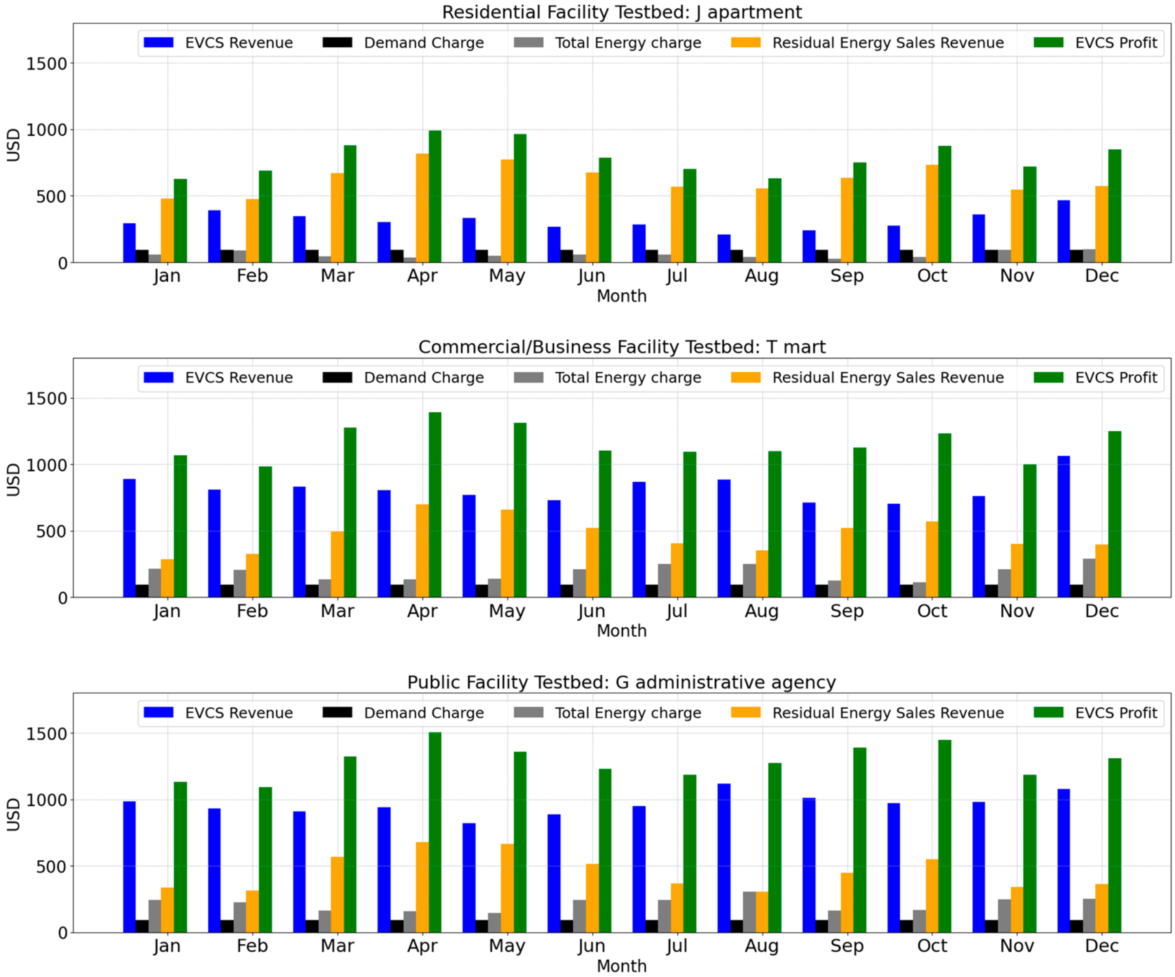

Figure 14. Techno-economic analysis of EVCSs integrated with DERs and local grid.

The EV fast charger installed in the residential facility EVCS testbed generated USD 3760.30 in revenue from charging services, as recorded in the EVCS service revenue ledger. Of this amount, USD 688 was paid in total energy charges, and USD 1121.10 was paid in demand charges to the electricity company. The residual energy sales revenue generated by the DERs was USD 7504.8, resulting in a final profit of USD 9456.0 for the residential EVCS testbed. The highest profit of the operational period is observed in April, with an EVCS revenue of USD 465.89. The electric company remits a total energy charge of USD 33.8 and a demand charge of USD 93.4, while the DERs generate USD 817.6 in residual energy sales revenue, resulting in an April EVCS profit of USD 991.2. The lowest profit is observed in August, with an EVCS profit of USD 208.2. The total energy charge paid to the electricity company is USD 40.2, while the demand charge is USD 93.4. The residual energy sales revenue generated by the DERs is USD 554.8, while the EVCS profit for August is USD 629.4. The diminished EVCS profit in August can be attributed to a reduction in the utilization of the charging service in comparison to other months. Furthermore, a comparative analysis of meteorological data with a simulation of the DERs' integration with the local grid revealed that August was characterized by a total of 20 days of precipitation, which coincides with the rainy season. This weather pattern led to a decline in PV power generation, consequently reducing the revenue generated from energy sales.

The EV fast charger installed in the commercial/business facility EVCS testbed yielded a total of USD 9832.50 in revenue generated from charging services. A total of USD 2285 in energy charges and USD 1121.10 in demand charges were remitted to the electric company. The remaining energy sales revenue generated by the DERs was USD 5631.6, resulting in a final profit of USD 12,057.9 for the residential EVCS testbed. The highest profit during the operating period is in April, with an EVCS revenue of USD 805. The electric company pays a total energy charge of USD 135.9 and a demand charge of USD 93.4. The residual energy sales revenue from utilizing the DERs is USD 697.3, resulting in an EVCS profit of USD 1273 in April. The lowest profit is observed in November, with an EVCS profit of USD 761.4. The total energy charge paid to the electricity company is USD 210.4, while the demand charge is USD 93.4. The residual energy sales revenue from the DERs is USD 403.1, and the EVCS profit in August is USD 860.7. The utilization of the EV charging service was comparable to that observed in April, yet the residual energy sales revenue was diminished. A comparison of the weather data to the simulation with the DERs and the local grid indicates that precipitation occurred on 12 out of 30 days in November, which demonstrates that PV generation reduces the energy sales revenue.

The EV fast charger installed in the public facility EVCS testbed generated USD 11,587.50 in revenue from charging services, as recorded in the EVCS account. A total of USD 2555.60 in the energy charge and USD 1121.10 in the demand charge were remitted to the electricity company. The remaining energy sales revenue generated by the DERs was USD 5445.7, resulting in a final profit of USD 13,356.5 for the residential EVCS testbed. The highest profit of the operating period is observed in April, with an EVCS revenue of USD 938.8. The electric company remits a total energy charge of USD 158.7 and a demand charge of USD 93.4, while the residual energy sales revenue from utilizing the DERs is USD 676.9. This results in an EVCS profit of USD 1363.6 for April. The lowest profit is observed in November, with an EVCS profit of USD 933.2. The electric company remits a total energy charge of USD 224.6 and a demand charge of USD 93.4. The residual energy sales revenue from the DERs is USD 313.3, and the EVCS profit for August is USD 928.5. A comparison of the weather data with the simulation of connecting the DERs to the local grid indicates that the utilization of the EV charging service was similar to that observed in April, but the residual energy sales revenue was lower. The weather data for February indicates that 17 out of 29 days had fog, rain, or snow, which suggests that the reduction in PV generation contributed to the decline in energy sales revenue.

Table 7 shows the payback periods according to the techno-economic analysis of the EVCSs integrating DERs and the local grid by building type. The payback periods were calculated using the cost of an EV fast charger and the revenue generated during operation, as shown in Equation (8). Among the EVCS testbeds integrating DERs and the local grid, the public facility has the shortest payback period at 1.13 years, followed by the commercial/business at 1.23 years and residential at 1.57 years. To analyze the short payback period, Figure 15 compares the ROI for the local grid operation scenario and the DERs and local grid integration operation scenario.

Table 7. Summary of the techno-economic analysis of EVCSs integrated with DERs and local grid.

Type (Unit: USD)	Residential Facility Testbed	Commercial/ Business Facility Testbed	Public Facility Testbed
Total Investment (Fast charger, 1EA)	14,484.5	14,484.5	14,484.5
EVCS Revenue	3760.3	9832.5	11,587.5
Demand Charge	1121.1	1121.1	1121.1
Total Energy Charge	688	2285	2555.6
Residual Energy Sales Revenue	7504.8	5631.6	5445.7
EVCS Profit	9456	12,058	13,356.5
ROI (%)	65.3	83.2	92.2
EVCS Payback Period (years)	1.53	1.20	1.08

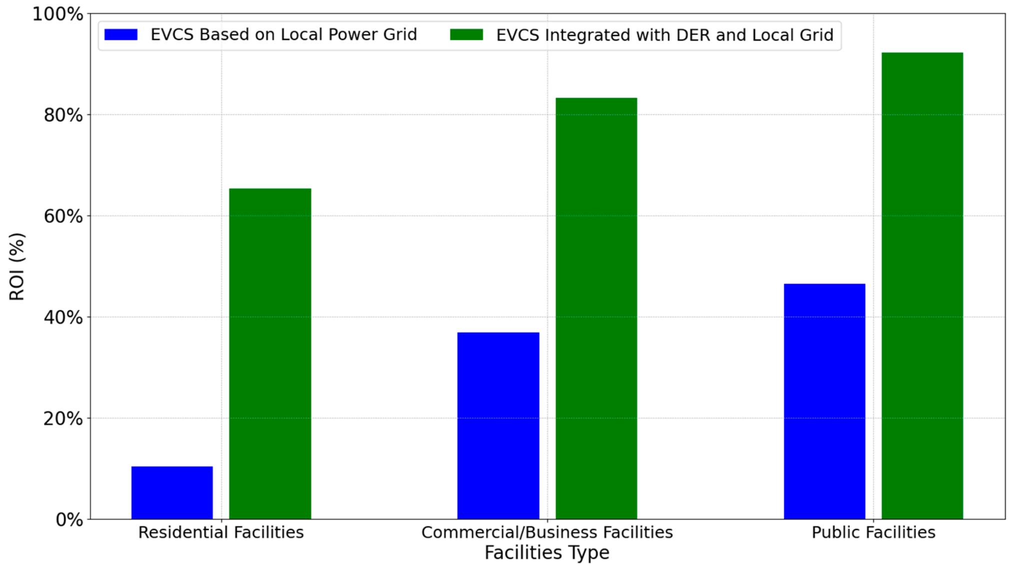

Figure 15. Comparison of the ROI vs. local grid integrated with DERs.

Figure 15 provides a comparative and analytical overview of the ROI derived from Tables 4 and 7. A comparison of the two scenarios reveals that the EVCS with DERs and local grid integration can achieve notable benefits. In particular, the EVCS with the local grid and DERs can save on average 1.53 times the amount of electricity charges compared to the local grid alone. Moreover, the sale of residual energy has the potential to generate an average of USD 6194.02 in operating revenue. The residential facility testbed can expect to earn an average of USD 7504.80, the commercial facility testbed an average of USD 5631.60, and the public facility testbed an average of USD 5445.70.

The ROI analysis further illustrates that operating an EVCS integrated with a DER and local grid in a residential facility testbed results in total energy charge savings of USD 443.18 and residual energy sales of USD 7504.78 in comparison to traditional operations. This results in an increase in the ROI from 10.4% to 65.3%, as well as a more rapid attainment of profitability than in other building types.

In the case of a commercial/business facility testbed, the integration of DERs and the local grid resulted in a reduction in the total electricity charge by a total of USD 1080.19, in addition to a gain of USD 5631.58 in revenue from the sale of residual energy. This resulted in a notable increase in the ROI, from 36.9% to 83.2%. Moreover, the ROI for the public facility testbed increased from 46.4% to 92.2%. The total energy charge for the integrated operation with the DERs and local grid was determined to be USD 1185.71 less than that of the previous operation. Moreover, residual energy sales yielded a revenue of USD 6725.14. This indicates that operating an EVCS with an integrated DER and local grid can facilitate the storage and sale of greater quantities of energy, thereby generating higher revenue than would be possible with a local grid in isolation.

The techno-economic analysis of EVCSs by building type showed that connecting DERs to the local grid can reduce the use of the local grid relative to EV demand. Due to the nature of urban buildings, PV was the predominant type of DER used, and revenue from excess energy sales was affected by weather. Policy implications and recommendations to address this issue are as follows:

First, governments and municipalities should mandate the installation of DER infrastructure in new buildings above a certain size and provide economic incentives to subsidize a portion of the installation costs or provide tax credits;

Second, utilities should apply rate incentives during times of high DER use (e.g., 4 p.m. to midnight) to lower electricity rates and encourage DER use, thereby reducing local grid use and lowering overall costs;

Third, utilities should prioritize the adoption of integrated DER and EVCS operating systems and create successful operating examples in public parking lots and government buildings to encourage private sector participation.

Implementing these policies will promote the integration of DERs and EVCSs and improve the efficiency and sustainability of urban energy systems. These policies will help the energy and EV industries improve the operation of EVCSs to reflect the characteristics of urban buildings. This can be achieved, for example, through the expansion of the fast charging and DER infrastructures, price incentives, and subsidies.

6. Conclusions and Discussion

This study conducted a technical and economic analysis of local grid operation scenarios and the integration of DERs with the local grid for EVCSs, with a particular focus on different building types from the perspective of urban energy supply. The analysis based on both scenarios demonstrated that the integration of DERs with the local grid can contribute to electricity cost savings and improve the efficiency of the EV charging infrastructure. While the findings confirm the economic and technical benefits of integrating DERs and the local grid with the EV fast charging infrastructure, especially the reduction in electricity costs, which can bring economic benefits to both households and commercial buildings, there are also some limitations.

First, the global pandemic posed significant challenges to ensuring the integrity of data collection. The lack of data from 2021 and 2022 constrained the scope of the analysis period. Furthermore, the investigation of technology economics was primarily focused on urban centers, which may have yielded different results in rural areas. These limitations highlight the need for a more comprehensive data-driven analysis in future research.

Secondly, the influence of variables beyond the classification of buildings on the utilization of EVCSs was not sufficiently addressed in this study, indicating the necessity for a comprehensive investigation of additional factors that may impact EVCS usage patterns.

Thirdly, the financial impacts of ESSs have not been sufficiently explored. The absence of detailed capital expenditure (CAPEX) costs, including installation and maintenance costs of ESSs, precludes a comprehensive economic analysis.

Finally, a lack of feasibility and sensitivity analysis was observed with regard to additional data variables. This was particularly evident in the assumption that average electricity bill savings are 1.53 times greater when DERs are integrated with the local grid. It is therefore recommended that additional sensitivity analyses be conducted, considering different variables and conditions, in order to increase the accuracy of the average electricity bill savings.

In consideration of the aforementioned factors, we propose that future research focus on the following areas:

(1) Integration of different DERs: Future research should investigate the integration of various DERs, including wind and hydropower, in suburban and rural areas, with the aim of enhancing energy efficiency and cost savings;
(2) Regional and seasonal variations: It is recommended that future research investigate how geographic region and seasonal variations affect the integration and efficiency of different DERs, not just solar power;
(3) User behavior and installation location: It is essential to analyze the impact of user behavior, EVCS installation location, electricity supply reliability, price volatility, and policy factors on EVCS usage patterns in order to improve deployment and operational strategies;
(4) Policy and regulatory compliance: The impact of policies, regulations, economic incentives, and subsidies on the integration and efficiency of DERs and EVCSs in different regions must be investigated.
(5) CAPEX analysis: A comprehensive CAPEX analysis, including the costs associated with ESSs, is essential to evaluate the economic viability of integrating DERs and

EVCSs and to inform the development of effective financial support mechanisms by policymakers.

In view of the preceding research, it is recommended that the introduction of integrated DER and EVCS operating systems be given priority. This can be achieved by the establishment of successful operational exemplars in public parking facilities and government buildings, with the objective of attracting private sector involvement. The implementation of these recommendations will facilitate the integration of DERs and EVCSs, thereby enhancing the efficiency and sustainability of urban energy systems.

Author Contributions: Conceptualization, S.P. (Sehyun Park), T.L. and B.K.; data curation, T.L., G.Y., B.K. and J.P.; methodology, S.P. (Sehyun Park), T.L., G.Y., M.-i.C., B.K. and S.P. (Sangmin Park); software, T.L., G.Y. and B.K.; project administration, S.P. (Sehyun Park); visualization, T.L.; supervision, S.P. (Sehyun Park); validation, T.L., M.-i.C. and S.P. (Sangmin Park); writing—original draft, T.L., G.Y., M.-i.C. and S.P. (Sangmin Park); writing—review and editing, T.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant, funded by the Korean government (MOTIE) (RS-2024-00398346, ESS Big Data-Based O&M and Asset Management Technical Manpower Training). This work was also supported by the International Energy Joint R&D Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), with a granted financial resource from the Ministry of Trade, Industry, and Energy, Republic of Korea (No. 20218510010130). Furthermore, this research was supported by the Chung-Ang University Research Scholarship Grants in 2022.

Data Availability Statement: Data are contained within the article.

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

References

1. Jagani, S.; Marsillac, E.; Hong, P. The Electric Vehicle Supply Chain Ecosystem: Changing Roles of Automotive Suppliers. *Sustainability* **2024**, *16*, 1570. [CrossRef]
2. He, L.Y.; Liu, L.; Ouyang, Y.; Li, L.L. Consumer Demand, Pollutant Emissions and Public Health under Increasing Block Tariffs and Time-of-Use Pricing Policies for Household Electricity in China. *Emerg. Mark. Financ. Trade* **2020**, *56*, 2993–3014. [CrossRef]
3. Shahzad, K.; Cheema, I.I. Low-carbon technologies in automotive industry and decarbonizing transport. *J. Power Sources* **2024**, *591*, 233888. [CrossRef]
4. Zhang, Y.L.; Liu, X.Y.; Wei, W.S.; Peng, T.J.; Hong, G.; Meng, C. Mobile charging: A novel charging system for electric vehicles in urban areas? *Appl. Energy* **2020**, *278*, 115648. [CrossRef]
5. Asna, M.; Shareef, H.; Prasanthi, A. Planning of fast charging stations with consideration of EV user, distribution network and station operation. *Energy Rep.* **2023**, *9*, 455–462. [CrossRef]
6. Fiori, C.; Ahn, K.; Rakha, H.A. Power-based electric vehicle energy consumption model: Model development and validation. *Appl. Energy* **2016**, *168*, 257–268. [CrossRef]
7. Ahmad, F.; Iqbal, A.; Asharf, I.; Marzband, M.; Khan, I. Placement and Capacity of EV Charging Stations by Considering Uncertainties With Energy Management Strategies. *IEEE Trans. Ind. Appl.* **2023**, *59*, 3865–3874. [CrossRef]
8. Elkadeem, M.R.; Abido, M.A. Optimal planning and operation of grid-connected PV/CHP/battery energy system considering demand response and electric vehicles for a multi-residential complex building. *J. Energy Storage* **2023**, *72*, 108198. [CrossRef]
9. Yousuf, A.K.M.; Wang, Z.L.; Paranjape, R.; Tang, Y.L. An In-Depth Exploration of Electric Vehicle Charging Station Infrastructure: A Comprehensive Review of Challenges, Mitigation Approaches, and Optimization Strategies. *IEEE Access* **2024**, *12*, 51570–51589. [CrossRef]
10. Woo, H.; Son, Y.; Cho, J.T.; Kim, S.Y.; Choi, S. Optimal expansion planning of electric vehicle fast charging stations. *Appl. Energy* **2023**, *342*, 121116. [CrossRef]
11. Loni, A.; Asadi, S. Data-driven equitable placement for electric vehicle charging stations: Case study San Francisco. *Energy* **2023**, *282*, 128796. [CrossRef]
12. Afshar, S.; Pecenak, Z.K.; Barati, M.; Disfani, V. Mobile charging stations for EV charging management in urban areas: A case study in Chattanooga. *Appl. Energy* **2022**, *325*, 119901. [CrossRef]
13. Enescu, F.M.; Birleanu, F.G.; Raboaca, M.S.; Raceanu, M.; Bizon, N.; Thounthong, P. Electric Vehicle Charging Station Based on Photovoltaic Energy with or without the Support of a Fuel Cell-Electrolyzer Unit. *Energies* **2023**, *16*, 762. [CrossRef]
14. Marinescu, C. Design Consideration Regarding a Residential Renewable-Based Microgrid with EV Charging Station Capabilities. *Energies* **2021**, *14*, 5085. [CrossRef]

15. Huang, K.; Zhao, J.T.; Sun, X.H.; Li, W.; Zheng, S. Analysis of Optimal Operation of Charging Stations Based on Dynamic Target Tracking of Electric Vehicles. *Electronics* **2022**, *11*, 3175. [CrossRef]
16. Sugihara, H.; Funaki, T. Increasing electric vehicle hosting capacity and equality for fast charging stations using residential photovoltaics in medium- and low-voltage distribution networks. *IEEJ Trans. Electr. Electron. Eng.* **2020**, *15*, 364–371. [CrossRef]
17. Li, W.Z.; Yang, L.L.; Wen, Z.; Chen, J.L.; Wu, X. On the Optimization Strategy of EV Charging Station Localization and Charging Piles Density. *Wirel. Commun. Mob. Comput.* **2021**, *2021*, 6675841. [CrossRef]
18. Bayram, I.S.; Devetsikiotis, M.; Jovanovic, R. Optimal design of electric vehicle charging stations for commercial premises. *Int. J. Energy Res.* **2022**, *46*, 10040–10051. [CrossRef]
19. Gong, C.Y.; Yao, Z.L.; Chen, H.; Huang, D.M.; Wang, X.L.; Wang, Z.X.; Shi, S. An optimal coordinated planning strategy for distributed energy station based on characteristics of electric vehicle charging behavior under carbon trading mechanism. *Int. J. Electr. Power Energy Syst.* **2023**, *147*, 108884. [CrossRef]
20. Asaad, A.; Ali, A.; Mahmoud, K.; Shaaban, M.F.; Lehtonen, M.; Kassem, A.M.; Ebeed, M. Multi-objective optimal planning of EV charging stations and renewable energy resources for smart microgrids. *Energy Sci. Eng.* **2023**, *11*, 1202–1218. [CrossRef]
21. Park, S.; Yun, S.P.; Lee, K.G.; Kang, B.K.; Choi, M.I.; Jang, H. Design and Implementation of a Futuristic EV Energy Trading System (FEETS) Connected with Buildings, PV, and ESS for a Carbon-Neutral Society. *Buildings* **2023**, *13*, 829. [CrossRef]
22. Li, H.; Han, B.; Li, G.J.; Wang, K.Y.; Xu, J.; Khan, M.W. Decentralized collaborative optimal scheduling for EV charging stations based on multi-agent reinforcement learning. *IET Gener. Transm. Distrib.* **2024**, *18*, 1172–1183. [CrossRef]
23. Mazumder, M.; Debbarma, S. EV Charging Stations With a Provision of V2G and Voltage Support in a Distribution Network. *IEEE Syst. J.* **2021**, *15*, 662–671. [CrossRef]
24. Jiang, Z.Y.; Han, J.Z.; Li, Y.T.; Chen, X.Y.; Peng, T.D.; Xiong, J.L.; Shu, Z. Charging station layout planning for electric vehicles based on power system flexibility requirements. *Energy* **2023**, *283*, 128983. [CrossRef]
25. Wang, Z.S.; Li, X.; Li, Y.; Zhao, T.Q.; Xia, X.; Zhang, H.Z. An Optimization Framework for Low-Carbon Oriented Integrated Energy System Management in Commercial Building under Electric Vehicle Demand Response. *Processes* **2021**, *9*, 1737. [CrossRef]
26. Ullah, Z.; Wang, S.R.; Wu, G.; Hasanien, H.M.; Rehman, A.U.; Turky, R.A.; Elkadeem, M.R. Optimal scheduling and techno-economic analysis of electric vehicles by implementing solar-based grid-tied charging station. *Energy* **2023**, *267*, 126560. [CrossRef]
27. De Lima, T.D.; Franco, J.F.; Lezama, F.; Soares, J. A Specialized Long-Term Distribution System Expansion Planning Method With the Integration of Distributed Energy Resources. *IEEE Access* **2022**, *10*, 19133–19148. [CrossRef]
28. Castle, J.; Hendry, D. Five sensitive intervention points to achieve climate neutrality by 2050, illustrated by the UK. *Renew. Energy* **2024**, *226*, 120445. [CrossRef]
29. Zhu, Y.; Ding, Y.; Wei, S.; Zafar, H.M.Y.; Yan, R. Electric Vehicle Charging Facility Configuration Method for Office Buildings. *Buildings* **2023**, *13*, 906. [CrossRef]
30. Griffiths, B. Harnessing TOU Rate Complexity to Reduce Residential EV Charging Costs. 2021. Available online: https://ssrn.com/abstract=3812640 (accessed on 15 August 2024).
31. Kucuksari, S.; Erdogan, N. EV Specific Time-of-use Rates Analysis for Workplace Charging. In Proceedings of the IEEE Transportation Electrification Conference and Expo (ITEC), Electr Network, Chicago, IL, USA, 21–25 June 2021; pp. 783–788.
32. Bao, Y.; Chang, F.Y.; Shi, J.K.; Yin, P.C.; Zhang, W.G.; Gao, D.W. An Approach for Pricing of Charging Service Fees in an Electric Vehicle Public Charging Station Based on Prospect Theory. *Energies* **2022**, *15*, 5308. [CrossRef]
33. Wang, S.Y.; Bi, S.Z.; Zhang, Y.J.A.; Huang, J.W. Electrical Vehicle Charging Station Profit Maximization: Admission, Pricing, and Online Scheduling. *IEEE Trans. Sustain. Energy* **2018**, *9*, 1722–1731. [CrossRef]
34. Panossian, N.; Muratori, M.; Palmintier, B.; Meintz, A.; Lipman, T.; Moffat, K. Challenges and opportunities of integrating electric vehicles in electricity distribution systems. *Curr. Sustain. Renew. Energy Rep.* **2022**, *9*, 27–40. [CrossRef]
35. Cappers, P.; Satchwell, A.; Brooks, C.; Kozel, S. A Snapshot of EV-Specific Rate Designs among US Investor-Owned Electric Utilities. 2023. Available online: https://emp.lbl.gov/publications/snapshot-ev-specific-rate-designs (accessed on 15 August 2024).
36. Cancian, B.P.; Andrade, J.C.G.; Freitas, W. Technical-Economic Evaluation of EV Fast Charging Station with Distributed Energy Resources. *J. Control. Autom. Electr. Syst.* **2022**, *33*, 1724–1738. [CrossRef]
37. Qiang, H.; Tang, W.Q.; Hu, Y.C.; Sun, X.P.; Zheng, J.F. Profit improvement strategy of electric vehicle charging stations sharing carbon trading revenue. *J. Renew. Sustain. Energy* **2023**, *15*, 025903. [CrossRef]
38. Kouka, K.; Masmoudi, A.; Abdelkafi, A.; Krichen, L. Dynamic energy management of an electric vehicle charging station using photovoltaic power. *Sustain. Energy Grids Netw.* **2020**, *24*, 100402. [CrossRef]
39. Fang, X.L.; Wang, Y.B.; Dong, W.; Yang, Q.; Sun, S.Y. Optimal energy management of multiple electricity-hydrogen integrated charging stations. *Energy* **2023**, *262*, 125624. [CrossRef]
40. Cabrera-Tobar, A.; Blasuttigh, N.; Pavan, A.M.; Lughi, V.; Petrone, G.; Spagnuolo, G. Energy Scheduling and Performance Evaluation of an e-Vehicle Charging Station. *Electronics* **2022**, *11*, 3948. [CrossRef]
41. Li, J.W.; He, S.C.; Yang, Q.Q.; Ma, T.Y.; Wei, Z.B. Optimal Design of the EV Charging Station With Retired Battery Systems Against Charging Demand Uncertainty. *IEEE Trans. Ind. Inform.* **2023**, *19*, 3262–3273. [CrossRef]
42. Kintner-Meyer, M.; Davis, S.; Sridhar, S.; Bhatnagar, D.; Mahserejian, S.; Ghosal, M. Electric Vehicles at Scale–Phase I Analysis: High EV Adoption Impacts on the Western US Power Grid. 2020. Available online: https://www.pnnl.gov/sites/default/files/media/file/EV-AT-SCALE_1_IMPACTS_final.pdf (accessed on 15 August 2024).

43. Li, X.; He, Y.C.; Guo, L.D.; Yang, G.T. Multi-year planning for the integration combining distributed energy system and electric vehicle in neighborhood based on data-driven model. *Int. J. Electr. Power Energy Syst.* **2022**, *140*, 108079. [CrossRef]
44. Yoon, G.; Kim, S.; Shin, H.; Cho, K.; Jang, H.; Lee, T.; Choi, M.I.; Kang, B.; Park, S.; Lee, S.; et al. Carbon-Neutral ESG Method Based on PV Energy Generation Prediction Model in Buildings for EV Charging Platform. *Buildings* **2023**, *13*, 2098. [CrossRef]
45. Han, Y.; Chen, W.R.; Li, Q.; Yang, H.Q.; Zare, F.; Zheng, Y.K. Two-level energy management strategy for PV-Fuel cell-battery-based DC microgrid. *Int. J. Hydrogen Energy* **2019**, *44*, 19395–19404. [CrossRef]
46. Bekiroglu, E.; Esmer, S. Improved Energy Management System for Wind Power-Based Microgrid with EV Charge Station. *Electr. Power Compon. Syst.* **2024**, *52*, 1808–1820. [CrossRef]
47. de Lima, T.D.; Soares, J.; Lezama, F.; Franco, J.F.; Vale, Z. A Risk-Based Planning Approach for Sustainable Distribution Systems Considering EV Charging Stations and Carbon Taxes. *IEEE Trans. Sustain. Energy* **2023**, *14*, 2294–2307. [CrossRef]
48. Preusser, K.; Schmeink, A. Energy Scheduling for a DER and EV Charging Station Connected Microgrid With Energy Storage. *IEEE Access* **2023**, *11*, 73435–73447. [CrossRef]
49. Choi, M.I.; Kang, B.; Lee, S.; Park, S.; Beck, J.S.; Lee, S.H. Empirical study on optimization methods of building energy operation for the sustainability of buildings with integrated renewable energy. *Energy Build.* **2024**, *305*, 113908. [CrossRef]
50. Ha, J.; Lee, J.; Choi, S.; Park, S. COVID-19 waves and their characteristics in the Seoul metropolitan area (20 January 2020–31 August 2022). *Public Health Wkly. Rep.* **2023**, *16*, 111–136.
51. Al-Wreikat, Y.; Serrano, C.; Sodre, J. Effects of ambient temperature and trip characteristics on the energy consumption of an electric vehicle. *Energy* **2022**, *238*, 122028. [CrossRef]
52. Mahlberg, J.; Desai, J.; Bullock, D. Evaluation of Electric Vehicle Charging Usage and Driver Activity. *World Electr. Veh. J.* **2023**, *14*, 308. [CrossRef]
53. Byrne, J.; Taminiau, J.; Kurdgelashvili, L.; Kim, K. A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. *Renew. Sustain. Energy Rev.* **2015**, *41*, 830–844. [CrossRef]