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Electric Vehicle Charging Facility Configuration Method for Office Buildings

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Abstract: With the advent of advanced battery technology, EVs are gradually gaining momentum. An appropriate decision-making method for the number of charging piles is in need to meet charging needs, and concurrently, to avoid the waste of infrastructure investment. In this study, an optimal charging pile configuration method for office building parking lots is proposed. With the determination of the design period of charging facilities, a charging load prediction model is established under a collection of charging scenarios. Taking the average utilization rate of charging facilities and the average satisfaction rate of charging demand as the objective functions, the distribution of the optimal number of piles is obtained with the genetic algorithm. The benefits of the configuration method are also explored under the building demand response process. The results show that the optimal configuration of charging piles in office buildings with different volumes have similar characteristics. When the design period is 5 years and 10 years, the comprehensive indicator of the utilization rate of the charging facilities and the satisfaction rate of the charging demand can, respectively, be improved by 8.18% and 17.45%. Moreover, the reasonable scheduling strategy can realize the load regulation response with a maximum load transfer rate of 25.55%.

Keywords: electric vehicle; design period; optimal configuration; utilization rate of charging facilities; satisfaction rate of charging demand

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1. Introduction

The escalating demand for energy, fueled by the progress of society and the development of science and technology, has raised serious concerns about the overuse of primary energy sources such as natural gas and oil. Such overuse threatens the ecological environment, and environmental pollution and energy shortage have become global focal points [1]. Electric vehicles (EVs) have emerged as a promising solution to address energy and environmental problems. They are highly regarded for their ability to replace oil with electricity and mitigate harmful gas emissions. With the advent of advanced battery technology, EVs are gradually gaining momentum in various countries [2]. China, for example, has set a target for the adaptation rate of new energy vehicles to reach 20% by 2025, as stipulated in the New Energy Vehicle Industry Development Plan (2021–2035) [3,4]. Likewise, Poland has recently proposed an ambitious goal of developing one million EVs by 2025 [5].

As a result of the initiative to reduce carbon emissions, the adoption of EVs has increased significantly, spurring rapid progress in the establishment of essential charging infrastructure. To address the issue of mileage anxiety, various design standards have been issued to encourage the installation of charging facilities in buildings [6,7], particularly in office buildings [8]. Consequently, office buildings are poised to become the primary locations for EV charging in the future. To ensure sustainable development, it is essential to consider the life cycle of office buildings with EVs. This involves determining the number of charging stations to be installed in office buildings during the design period [9,10] and determining how to coordinate the office building energy system and charging stations during the operation stage when a significant number of EVs are connected. These pressing practical issues require urgent solutions [11,12].

In current practice, the determination of the number of EV charging piles in office building parking lots is generally based on an area-based empirical estimation method. This method utilizes the lower limit of the range of charging facilities prescribed in the relevant design standards. However, this design approach fails to satisfy the rapidly increasing demand for charging facilities that has arisen due to the significant growth in the number of EVs [13]. In January 2022, the National Development and Reform Commission issued the "Implementation Opinions on Further Improving the Service Guarantee Capability of Electric Vehicle Charging Infrastructure", which emphasized that the supply–demand conflict of charging facilities has become more serious than ever. Yet, blindly increasing the number of charging piles is not a viable solution, as it not only increases the initial investment unreasonably but also results in additional maintenance costs due to idle piles [14]. Therefore, relying solely on the standards to determine the number of charging piles may fail to satisfy the charging needs [15,16] and is insufficient to fulfill the building design and operation requirements.

To address this issue, an accurate EV charging load prediction model is required as a basis for the configuration of charging facilities in building parking lots [17]. The influencing factors and characteristics of the EV charging load need to be explored and analyzed [18,19]. In recent years, extensive research has been conducted on the analysis of the EV charging load, as presented in Table 1. The Monte Carlo algorithm has been utilized to construct a probability distribution model of travel and charging characteristics to predict the load demand when EVs are connected to the grid.

Table 1. Influencing factors of EV charging load.

	Vehicle Type	Charging Start Time	Charging Duration	Driving Distance	Initial SOC	Battery Capacity	Power Consumption per Kilometer	Charging Location
[20]		√	√		√			√
[21]		√	√	√	√	√	√	√
[22]		√	√	√	√			
[23]	√	√	√	√	√			
[24]				√		√	√	
[25]		√	√	√	√			

Based on this premise, it is possible to investigate the charging facility configuration method in building parking lots to accommodate the escalating demand for EV charging and improve the systematic operation and management of charging facilities within buildings [26,27]. The development of special EV charging stations has prompted scholars to research the optimal configuration method of charging facilities from multiple perspectives, such as investment cost, operation income and facility utilization [28]. The selection of suitable locations for charging stations, as well as the determination of the capacity and charging pile types and ratios, have been explored [29–31]. Several optimization models have been proposed to minimize the total cost associated with the establishment of charging facilities [32,33]. One such model focused on determining the optimal locations and capacities of EV charging facilities to minimize the comprehensive cost [32], while another model aimed to minimize the cost of EV charging while guaranteeing high service quality [33]. A two-stage model has also been proposed to optimize EV charging and the selection of charging piles by effectively grouping the distribution pattern of EV charging demand and various types of EVs, and by minimizing the annual investment and electricity purchasing costs of charging piles [34]. While prior studies have extensively examined the location and capacity of charging stations at the macro level of the entire city or urban area and the distribution network system [35–37], a systematic investigation of the configuration of charging facilities from the micro perspective of individual buildings is currently lacking in the literature.

With more and more EVs being connected to buildings, the planning of EV charging facilities should consider the participation of building energy system in grid demand response (DR) [38–40]. An EV coordinating algorithm has been proposed to control the charging/discharging power of each connected EV, and it is capable of responding to DR signals by adjusting the total parking lot load to the point that it can even supply power back to the grid if the charging plan of connected EVs allows it [41]. The proposed algorithm managed to significantly lower the total parking lot peak load in 300 simulated scenarios, with a 50–70% decrease in most cases, and increased the utilization of the much-lowered peak power. Moreover, a new energy management model has been proposed to determine the optimal scheduling of an office building that includes EV charging piles, batteries, and rooftop photovoltaic systems while minimizing the total operation cost by employing the flexibility of building batteries and EV charging [42]. Another two-stage optimization technique has been proposed to determine the charging and discharging schedule for EVs participating in a vehicle-to-grid (V2G) program in an office building [43]. Therefore, there is a need to study the optimal configuration and operation method of EV charging facilities from the perspective of buildings [44].

Based on an exhaustive study of the existing literature, it can be concluded that the previous research on EV charging facility configuration method for office buildings has the following deficiencies:

- The determination of the number of EV charging piles in office building parking lots is generally based on an area-based empirical estimation method. However, this design approach fails to satisfy the rapidly increasing demand for charging facilities that has arisen due to the significant growth in the number of EVs;
- Prior studies have extensively examined the location and capacity of charging stations at the macro level of the entire city or urban area and the distribution network system; a systematic investigation of the configuration of charging facilities from the micro perspective of individual buildings is currently lacking in the literature;
- Based on the optimal configuration of EV charging facilities, EV charging scheduling under the building demand response process is rarely further analyzed.

To bridge the research gaps listed above, this study has the following contributions to the field:

- An optimal configuration method for charging piles from the micro perspective of individual buildings is proposed to meet the rapidly growing charging demand in office building parking lots;
- The evaluation indicators of the utilization rate of charging facilities and the satisfaction rate of charging demand are established simultaneously;
- This approach takes into account both the investment cost and the long-term charging demand of EVs to maximize the overall benefits of the system;
- The proposed approach manages the integration of EVs in the building energy system, with the potential to improve the overall energy efficiency of the building.

The remainder of this study is organized as follows: Section 2 presents the methodologies regarding the EV charging load modeling based on the Monte Carlo simulation, the optimal configuration method for charging piles in office building parking lots and the demand response rehearsal. Section 3 provides a detailed case study, including the building description, optimal configuration, indicator comparison, and demand response rehearsal. Finally, the study concludes with a discussion on the conclusions and limitations of the current research study in Section 4.

2. Methodology

In this study, the research framework was mainly established according to the following four steps: (1) Initial determination of the design period and subsequent projection of the annual number of EVs anticipated to be accommodated in the building over the next Y years; (2) Development of a model for predicting the EV charging load and selection of a collection of charging scenarios in the next Y years; (3) Application of genetic algorithms to optimize calculations for each of the charging scenarios, followed by statistical analysis of all scenarios to derive the optimal pile distribution; (4) Verification of the effectiveness of EV charging facility configuration schemes participation in building grid demand response. A detailed framework of the methodology adopted in this study is graphically depicted as Figure 1.

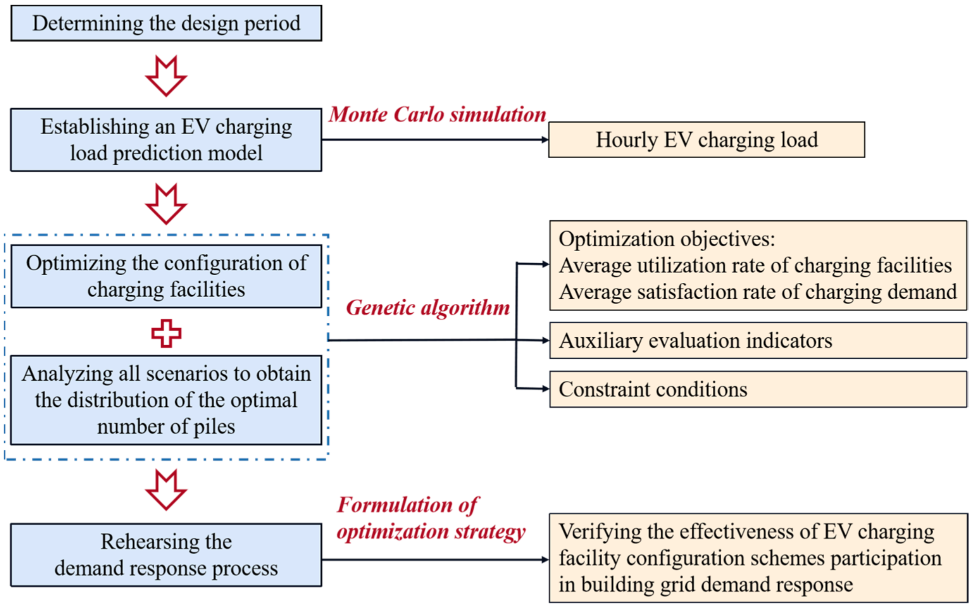


Figure 1. Research framework.

2.1. EV Charging Load Modeling Based on Monte Carlo Simulation

To reasonably configure the charging facilities in the parking lot of the office building, the commuting characteristics of EV users need to be obtained first to predict the charging load trend, so as to achieve a more accurate charging resource allocation. The factors affecting the EV charging load can be divided into two categories: the EV physical properties, including battery capacity and power consumption per kilometer and the commuting characteristics of EV users, including the charging start time, driving distance, and SOC at departure.

To gather data on these characteristics, both online and offline questionnaires were conducted across the country. Employees in scientific research office buildings and commercial office buildings were selected as research objects in the offline survey. The online mode was carried out through forwarding and forum channels. The results of the survey were used to fit the probability density distributions of the commuting characteristics of EV users in office buildings, which are presented in Table 2.

In this study, several assumptions have been made to facilitate the calculation of the charging load. Firstly, it is assumed that the electric vehicle initiates charging upon arrival and terminates once the battery is fully charged. If the battery cannot be fully charged by the end of the workday, the charging process will also cease. Secondly, it is assumed that the charging pile type is limited to full-slow charging piles. Lastly, the charging process is constant power, with a slow charging power of 7 kW in this investigation.

Table 2. Probability density distributions of commuting characteristics.

Commuting Characteristics	Distribution Characteristics	Probability Density Distribution
Arrival time (t_s)	Normal distribution	$f_s(x) = 0.487\ \exp\left[-\frac{(x-8.07)^2}{1.345}\right]$
Departure time (t_l)	Normal distribution	$f_l(x) = 0.387\ \exp\left[-\frac{(x-18.16)^2}{2.122}\right]$
Driving distance (D)	Weibull distribution	$f_D(x) = 0.106 \times \left(\frac{x}{13.17}\right)^{0.40} e^{-(x/13.17)^{1.40}}$
SOC at departure (SOC_l)	Bimodal normal distribution	$f_{SOC_l}(x) = 1.412 \exp\left[-\frac{(x-0.36)^2}{0.034}\right] + 1.958 \exp\left[-\frac{(x-0.77)^2}{0.024}\right]$
Battery capacities (R)	Weibull distribution	$f_R(x) = 0.050 \times \left(\frac{x}{75.27}\right)^{2.78} e^{-(x/75.27)^{3.78}}$
Power consumption per kilometer (K)	Uniform distribution	$f_K(x) = \begin{cases} 16.67, & 0.11 < x < 0.17 \\ 0, & else \end{cases}$

The charging duration of each vehicle is computed using Equation (1).

$$L_n = \frac{1 - SOC_{a,n}}{p_{c,n}} = \frac{1 - \left(SOC_{l,n} - \frac{K_n \times D_n}{R_n}\right)}{p_{c,n}} \tag{1}$$

where $SOC_{l,n}$ and $SOC_{a,n}$ are the state of charge of the n-th vehicle when it leaves home and arrives at the workplace, respectively; K_n is the power consumption per kilometer, kWh/km; D_n is the driving distance from home to the workplace, km; R_n is the battery capacity, kWh; L_n is the charging duration, hours; $p_{c,n}$ is the charging power, kW; the subscript n represents the n-th vehicle.

Additionally, then the hourly charging load of multiple vehicles can be calculated by Equations (2) and (3).

$$P_{EV}(t) = \sum_{n=1}^{N} P_{EV,n}(t) = \sum_{n=1}^{N} p_{c,n} \times \mathrm{I}_n(t) \tag{2}$$

$$\mathrm{I}_n(t) = \begin{cases} 0, & t_{s,n} > t \ or \ t_{s,n} + L_n < t \\ 1, & else \end{cases} \tag{3}$$

where $P_{EV,n}(t)$ is the charging load of the n-th vehicle at time t, kW; $P_{EV}(t)$ is the total charging load of N vehicles at time t, kW; $t_{s,n}$ is the charging start time of the n-th vehicle; $\mathrm{I}_n(t)$ is the variable of the charging state of the n-th vehicle at time t.

In the scenario of full-slow charging, the Monte Carlo random sampling method is employed to generate samples from the probability density distribution functions of the random variables for the purpose of computing the hourly charging load of each electric vehicle, starting from the first vehicle. This same process of sampling and calculation is then carried out for the remaining vehicles, and the hourly charging load of each vehicle is subsequently aggregated according to Equation (2). The simulation is repeated to gather multiple charging scenarios, and the charging load calculation process is illustrated in Figure 2.

2.2. Optimal Configuration Method of Charging Piles in Parking Lots

2.2.1. Optimization Objectives

An ideal charging facility configuration scheme should effectively fulfill the charging demands of electric vehicles throughout the design period, while simultaneously minimizing idle charging piles to reduce initial investment and maintenance costs. To evaluate the effectiveness of the charging configuration scheme, this study proposes two quantitative indicators: the average utilization rate of charging facilities and the satisfaction rate of charging demand.

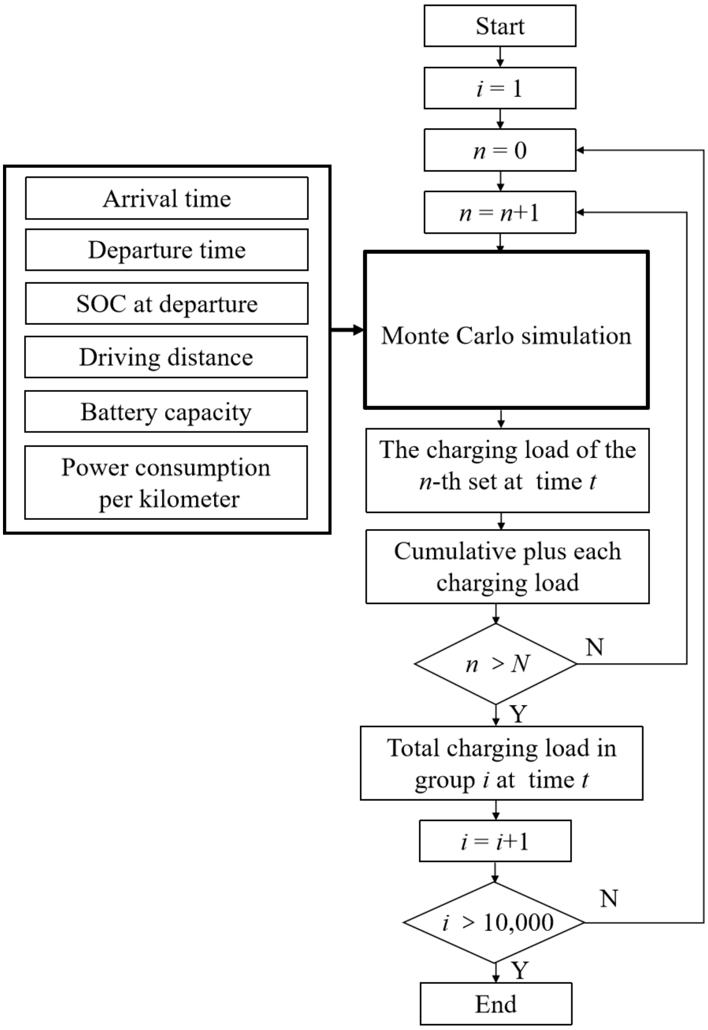


Figure 2. The charging load calculation process.

Indicator 1: Average utilization rate of charging facilities [45,46].

The intended purpose of this indicator is to measure the average hourly utilization rate of charging piles on a typical day during the design period. A higher value of this indicator suggests a greater number of piles charged concurrently, thereby leading to an increased overall utilization rate of the facilities. The calculation is presented in Equations (4) and (5).

$$\overline{\eta} = \frac{\sum_{i=1}^{Y}\sum_{t=t_0}^{t_N} \eta_i(t)}{Y \times (t_N - t_0)} \tag{4}$$

$$\eta_i(t) = \begin{cases} \frac{n_{i,ch}(t)}{M}, & n_{i,ch}(t) < M \\ 1, & n_{i,ch}(t) \geq M \end{cases} \tag{5}$$

where Y is the design period; $\overline{\eta}$ is the average hourly utilization rate of charging piles; $\eta_i(t)$ is the utilization rate of charging piles at time t on a typical day of the i-th year; $t_0 \sim t_N$ is the observation period within a day; M is the number of charging piles; $n_{i,ch}(t)$ is the predicted number of vehicles being charged at time t on a typical day of the i-th year.

Indicator 2: Average satisfaction rate of charging demand.

Since office building parking lots are considered, EV users seldom leave midway before the end of their shift. Whether EVs can be charged depends on the number of remaining available charging piles upon arrival. Therefore, the meaning of this indicator is to calculate the average percentage of vehicles that can be charged in the parking lot on a typical day of the year. A higher value of this indicator indicates a greater number of charging vehicles and a higher satisfaction rate. The calculation is expressed in Equations (6) and (7).

$$\overline{\lambda} = \frac{\sum_{i=1}^{Y} \sum_{t=t_0}^{t_N} \lambda_i(t)}{Y \times (t_N - t_0)} \tag{6}$$

$$\lambda_i(t) = \begin{cases} \frac{M}{n_{i,arr}(t)}, & n_{i,arr}(t) > M \\ 1, & n_{i,arr}(t) \leq M \end{cases} \tag{7}$$

where $\overline{\lambda}$ is the average satisfaction rate of charging demand; $\lambda_i(t)$ is the satisfaction rate of charging demand at time t on a typical day of the i-th year; $n_{i,arr}(t)$ is the predicted number of arrived vehicles at time t on a typical day of the i-th year.

In summary, an effective charging pile configuration scheme should consider both the average utilization rate of charging facilities and the average satisfaction rate of charging demand. Furthermore, the degree to which these two indicators are high in tandem reflects the quality of the configuration scheme. Thus, the comprehensive indicator can be mathematically expressed as in Equation (8).

$$Object = Max\left(\overline{\eta} + \overline{\lambda}\right) \tag{8}$$

2.2.2. Auxiliary Evaluation Indicators

The calculation of the total cost serves as an auxiliary evaluation indicator for comparing various potential alternatives, as represented by Equation (9).

$$C_{all} = C_b + C_r \tag{9}$$

where C_{all} is the total cost, USD; C_b is the construction cost of charging facilities, USD; C_r is the reconstruction cost of distribution network, USD.

$$C_b = \pi\left(M \times c_{ep} + M \times c_{in} + C_m\right) \tag{10}$$

$$\pi = \frac{\varepsilon(1+\varepsilon)^Y}{(1+\varepsilon)^Y - 1} \tag{11}$$

where c_{ep} is the acquisition cost of a single charging pile, USD/unit; c_{in} is the installation cost of a single charging pile, USD/unit; C_m is the maintenance cost, USD, which is set to be 6% of the acquisition cost in the first year and increases 2% annually thereafter; π is the annual conversion coefficient of funds; ε is the discount rate.

$$C_r = \pi \times \gamma \times R \tag{12}$$

$$R = \frac{P_c \times M \times 1.05}{\theta \times cos\varphi} \tag{13}$$

where R is transformer capacity, kVA; γ is the conversion factor between transformer capacity and price, USD/kVA; θ is the charging efficiency; $cos\varphi$ is the power factor; 5% capacity margin is reserved as the safety factor.

2.2.3. Constraint Conditions

The genetic algorithm is adopted to solve the above optimization problem in this study. The optimization variable in the configuration method is determined as the number of charging piles, with its search range constrained in accordance with Equations (14)–(17).

$$M_{min} \leq M \leq M_{max} \tag{14}$$

$$M_{min} = N_p \times 10\% \tag{15}$$

$$N_Y = M_{min} \times \omega^Y \tag{16}$$

$$M_{max} = N_Y \times 1.15 \tag{17}$$

where M_{min} is the minimum number of charging piles, which is determined as 10% of the parking spaces according to the lower limit based on the design standards [47–49]; N_p is the number of designed parking spaces; N_Y is the number of EVs in the building after Y years. ω is the average annual growth coefficient of EVs, and is predicted based on the public electric vehicle penetration statistics over the years. M_{max} is the maximum number of charging piles, with a margin of 15% based on N_Y.

2.3. Demand Response Rehearsal

After optimizing the configuration of EV charging facilities for office buildings, the demand response effect of the EV charging load participation in the building power grid is rehearsed, which will improve the orderly management of the building's energy system operation.

In this study, orderly charging scheduling is carried out for EVs. The minimum variance of the building's total load on the second day is taken as the optimization objective of the scheduling problem, which is described in Equation (18). The charging start time of each EV on the second day is set as the optimization variable, and the genetic algorithm is adopted to optimize the strategy.

$$\begin{gathered} Min\left\{Max\ \frac{\sum_{t=0}^{23}\left(P_{\text{total}}^{(i)}(t)-P_{average}^{(i)}\right)^2}{24}\right\} \\ \text{s.t. } min\left(t_{s,n}^{(i)}\right) \le t_{new,n} \le max\left(t_{l,n}^{(i)}-t_{\text{span},n}^{(i)}\right) \end{gathered} \tag{18}$$

where $P_{\text{total}}^{(i)}(t)$ is the building total electrical load at time t in the i-th group, kW; $P_{average}^{(i)}$ is the building average electrical load in the i-th group, kW; $t_{s,n}^{(i)}$ is the arrival time in the i-th group of the n-th vehicle; $t_{new,n}$ is the charging start time optimized for the n-th vehicle; $t_{l,n}^{(i)}$ is the leaving time in the i-th group of the n-th vehicle; $t_{span,n}^{(i)}$ is the charging span required for the n-th vehicle in the i-th group to reach a SOC of 0.8.

3. Discussion

3.1. Building Description

Taking the parking lots of a small-sized scientific research office building in Tianjin (Building 1) and a large-sized commercial office building in Beijing (Building 2) as examples, the optimal number of charging facilities in the office building parking lots with different volumes is calculated based on the proposed optimal configuration method.

The total area of Building 1 is 4953.4 m^2, with 50 parking spaces, and the total area of Building 2 is 96,983.0 m^2, with 406 parking spaces. The operational hours of both buildings are set to be 8:00–19:00. Figure 3 provides a realistic representation of the installation of EV charging piles in office buildings.

The minimum number of charging piles installed or reserved for the two buildings is, respectively, 5 and 40 based on the design standards. The optimal configurations of the charging piles in office building parking lots are carried out with design period of 5 and 10 years, respectively. According to the data published by the China Association of Automobile Manufacturers, the average annual EV growth coefficient ω_1 in the next 5 years is set as 1.278, and considering that the EV growth rate will slow down after the rapid promotion of vehicles, the average annual growth coefficient ω_2 in the next 6–10 years is assumed as 1.075, which results in the annual number of EVs in the building, as shown in Table 3.

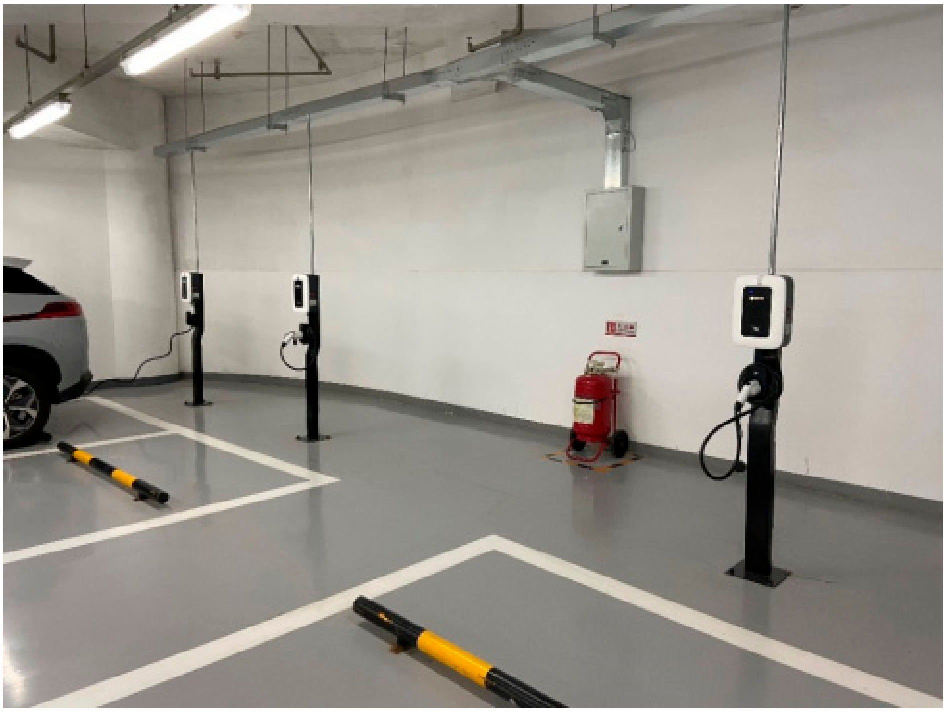


Figure 3. Realistic representation of the installation of EV charging piles.

Table 3. Predicted number of electric vehicles.

Time	Building 1 /Vehicles	Building 2 /Vehicles	Time	Building 1 /Vehicles	Building 2 /Vehicles
Year 1	5	40	Year 6	14	114
Year 2	6	51	Year 7	15	123
Year 3	8	65	Year 8	16	132
Year 4	10	83	Year 9	17	142
Year 5	13	106	Year 10	18	153

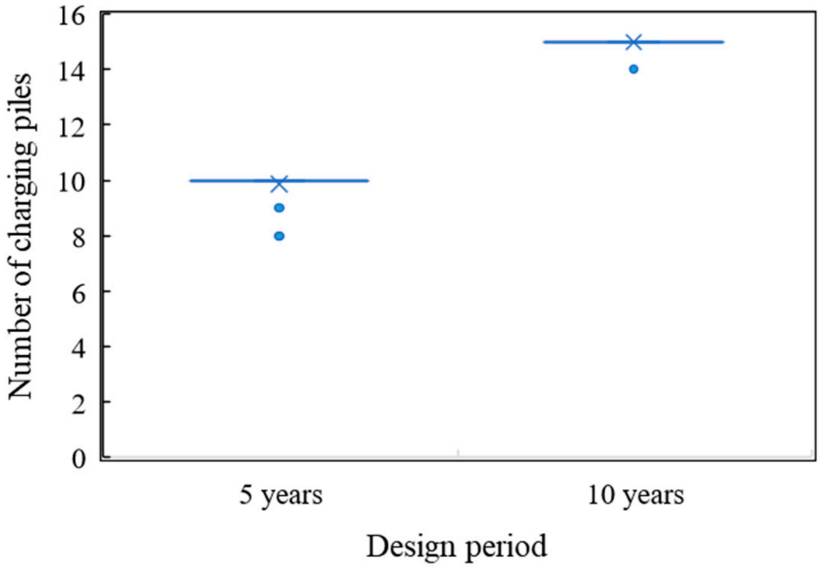
Assuming that the special charging piles with the largest market share are used, the unit price of the slow charging pile is USD 509.65, and the installation cost is USD 218.42. Other detailed parameters are shown in Table 4.

Table 4. Example parameters.

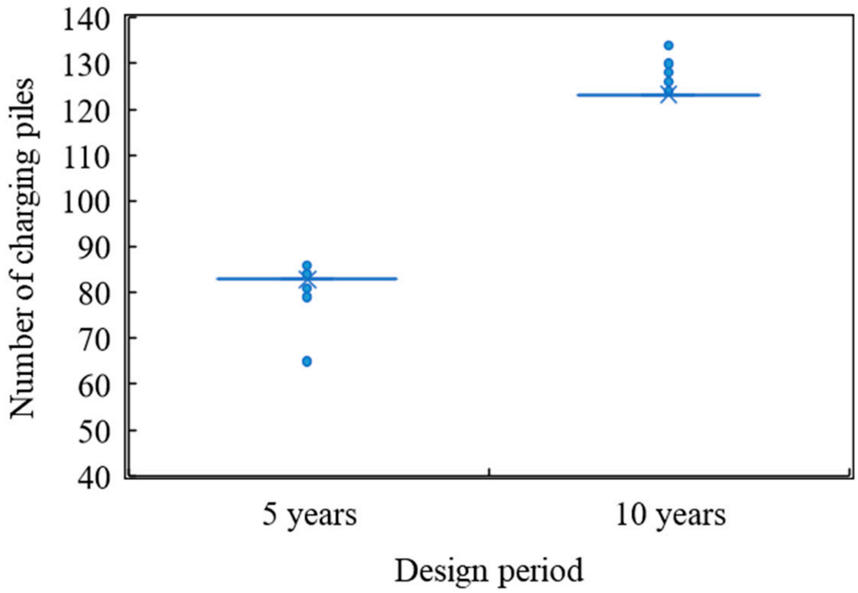
Parameters	Value	Parameters	Value	Parameters	Value
Y_1	5	c_{ep}	3500	ε	0.1
Y_2	10	c_{in}	1500	k	10,000
ω_1	1.278	θ	0.9		180 ($R < 100$)
ω_2	1.075	$cos\varphi$	0.95	γ	150 ($100 \leq R < 150$)
					120 ($R \geq 150$)

3.2. Optimal Configuration

The optimal configuration results of the two office buildings are shown in Figure 4.



(a)



(b)

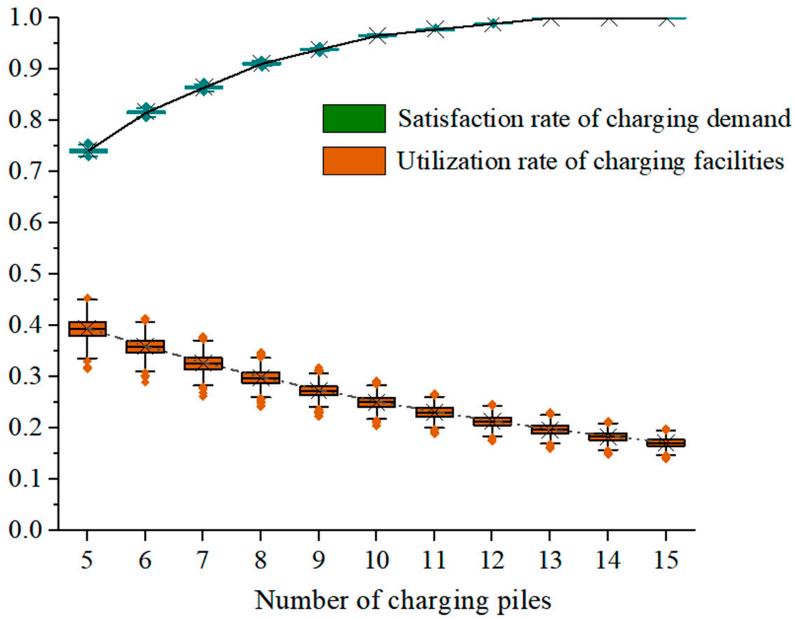
Figure 4. Optimal configuration results of charging piles for the two office buildings: (**a**) Scientific research office building; (**b**) Commercial office building.

As depicted in Figure 4, for the scientific research office building, the optimal number of charging piles is typically 10 and 15 when the design period is 5 years and 10 years, respectively. Conversely, the commercial office building requires a substantially greater number of charging piles, with 83 and 123 being optimal when the design period is 5 years and 10 years, respectively. However, according to the lower limit of the configuration number stipulated by design standards, only 5 and 40 piles are, respectively, installed in the two office buildings. This discrepancy underscores the inadequacy of area-based empirical estimation as a basis for determining charging pile requirements in building parking lots.

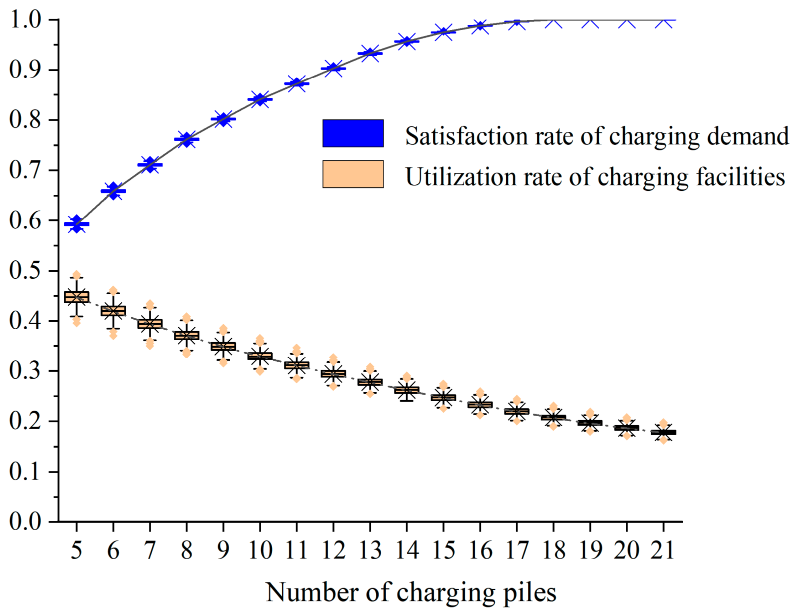
Moreover, the optimal configuration of charging piles in office buildings with different volumes have similar characteristics. Regardless of the large-sized commercial office buildings or small-sized scientific research office buildings, when the design period is 5 years, the optimal number of piles is about 2 times the minimum number of piles, and when the design period is 10 years, the optimal number of piles is about 3 times the minimum number of piles. Thus, a general reference range is provided for designers.

3.3. Indicator Comparison

An example is provided by the scientific research office building, wherein the average utilization rate of charging facilities and the average satisfaction rate of charging demand are calculated for 5 and 10 years. These indicators are shown in Figure 5.



(**a**)



(**b**)

Figure 5. Indicator comparison of configuration scheme: (**a**) Design period (Y = 5); (**b**) Design period (Y = 10).

Figure 5 demonstrates that the average satisfaction rate of charging demand exhibits an initial increase followed by a plateau as the number of charging piles rises, while the average utilization rate of the charging facilities displays a consistent decline. This can be attributed to the inadequate charging capacity in the later years of the design period when the number of charging piles is limited. As the number of charging piles increases gradually, the satisfaction rate of charging demand improves progressively, but the problem of idle charging piles is aggravated in the early years of the design period. Moreover, compared with the empirical estimation method, the average satisfaction rate of charging demand can reach 96.54% and 97.48% when the design period is set as 5 and 10 years based on the proposed optimal configuration method, which can be elevated by 34.93% and 68.80%, respectively, whereas the average utilization rate of charging facilities shows minimal variation. This suggests that the impact of this configuration method on the satisfaction rate of the charging demand becomes more evident as the design period increases.

Figure 6 presents the corresponding comprehensive indicator of various charging facility configurations in 5 and 10 years, which enables the comparison of different schemes' performance.

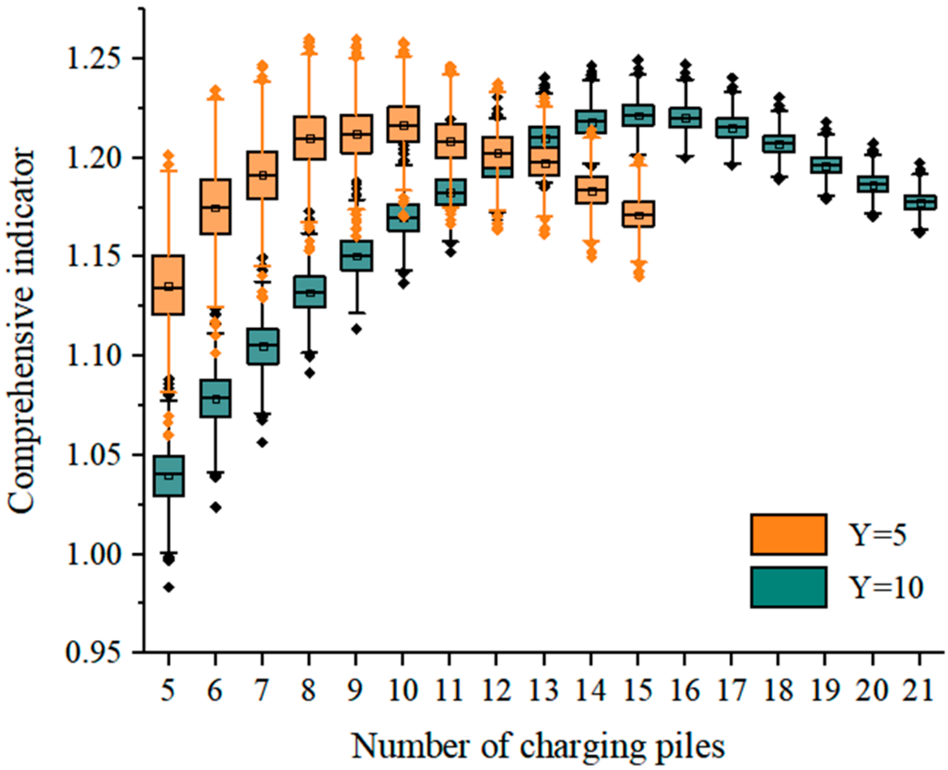


Figure 6. Comprehensive indicator of different configuration schemes.

Results show that when the design period is 5 and 10 years, the comprehensive indicator, respectively, exhibits an improvement of 8.18% and 17.45%, compared to the scheme of installing 5 charging piles determined by the area-based empirical estimation method. Additionally, an increase in the number of charging piles leads to a trend of initially increasing and subsequently decreasing values for the comprehensive indicator.

In addition, the annual commutation cost is calculated to facilitate comparisons, as depicted in Figure 7.

As the quantity of charging piles escalates, the annual commutation cost also increases, with the maximum cost between the 5-year and 10-year alternatives being USD 2986.46 and USD 3595.15, respectively.

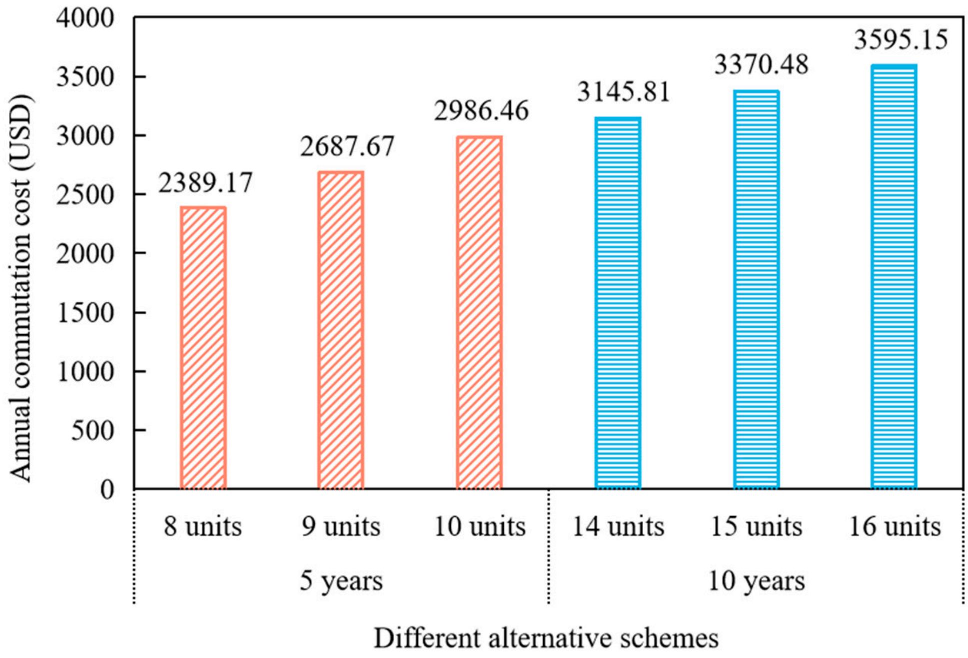


Figure 7. Comparison of annual commutation costs.

By comparing the existing literature on the charging facility configuration, the results of this study present certain advantages. This study comprehensively designs the configuration of charging facilities from the perspectives of charging cost, utilization rate of charging facilities and satisfaction rate of charging demand, so as to meet the charging demand of EV users, avoid idle charging piles as much as possible and reduce the waste of initial investment and later maintenance cost. Notably, the utilization rate of the charging facilities of the configuration scheme in this study can reach 28.94% when the design period is 10 years, surpassing that of previous research [45,46]. Additionally, the satisfaction rate of the charging demand of the configuration scheme in this study is 97.48%, which is also superior to previous research results [50,51], demonstrating its ability to effectively meet the growing charging demand of EV users.

3.4. Demand Response Rehearsal

After solving the configuration problem of charging facilities in the office building parking lots, an increase in electric vehicle usage will inevitably result in an additional charging load on the building. This may trigger peak demand for electricity and thereby impact the overall operation of the building energy system. Therefore, we further analyze the benefits of charging pile optimization under the building demand response process.

Taking the optimal number of 10 charging piles in the scientific research office building with a design period of 5 years as an example, the capacity configurations of 10 vehicles are selected as shown in Table 5.

Table 5. Electric vehicle battery capacity parameters.

No.	Battery Capacity (kWh)	No.	Battery Capacity (kWh)
EV1	87.85	EV6	69.50
EV2	61.19	EV7	59.58
EV3	81.17	EV8	81.08
EV4	66.88	EV9	87.71
EV5	71.80	EV10	98.45

No optimization strategy (Strategy 0: charging at any time for EVs) and charging load optimization strategy (Strategy 1: rescheduling the EV charging start time) are set for the case building. Detailed descriptions of these two strategies are as follows:

Strategy 0: The operation of building energy systems, such as EVs or air conditioners, are not constrained by scheduling. Each vehicle can be charged at any time when it arrives at the workplace, and the operation of building other energy systems remains unaffected.

Strategy 1: Orderly charging scheduling is carried out for EVs, and the charging start time of each EV on the second day is determined based on the day-ahead prediction results of the charging load. The optimization method is specifically described in Section 2.3.

Energy consumption research of the scientific research office building has been carried out. The summer conditions are set as the operation scenario. The building real-time load data can be obtained through the Internet of Things energy consumption information monitoring platform, which can monitor the real-time hourly cooling load of the building and the itemized power consumption of the equipment.

The total electrical load and EV charging load curves of the building under the two strategies are shown in Figure 8.

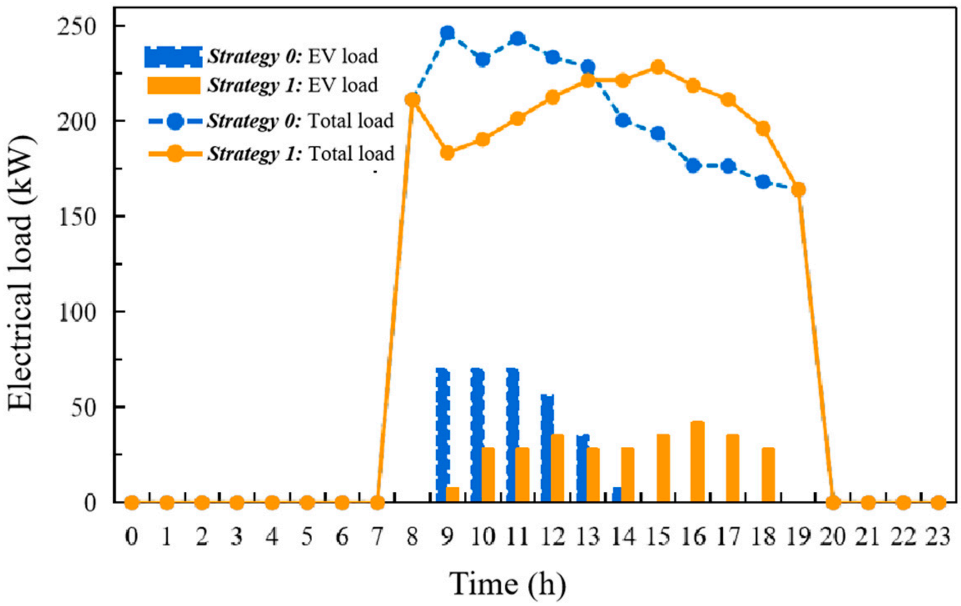


Figure 8. Load comparison between Strategy 0 and Strategy 1.

Compared to Strategy 0, the implementation of Strategy 1 yields a notable reduction in building load during peak hours at 9:00 and 10:00. The total electrical load of the building can achieve a maximum load transfer rate of 25.55% through the building energy demand response. Since the EV charging start time is redetermined, the transfer of charging load can be realized, making the load curve smoother and the operation stability of the system improved.

4. Conclusions

The increasing popularity of charging facilities in buildings has led to closer interaction between EVs and buildings. The research on the configuration method of charging facilities in office building parking lots can enable building grid to adapt to the rapidly growing demand for EV charging, and further balancing the investment cost and the long-term charging demand of electric vehicles to maximize the overall benefits of the configuration.

Therefore, aiming at exploring the optimal number of charging piles in the office building parking lots, the utilization rate of charging facilities and the satisfaction rate of charging demand are proposed as two indicators in this study. On this basis, the comprehensive indicator is established, and the optimal solution for the configuration of charging facilities in office buildings is obtained with the application of the genetic algorithm. Then, a demand response rehearsal is conducted for the building energy system to verify the effectiveness of the configuration scheme. By examining this method, as applied to a large-sized commercial office building and a small-sized scientific research office building, the specific analysis results are as follows:

(1) From the building cases with different volumes, the optimal number of piles is 2 times the minimum number of piles under the empirical estimation method when the design period is 5 years, while the optimal number of piles is about 3 times the minimum number of piles under the empirical estimation method when the design period is 10 years. According to the comparison results, designers can make a preliminary estimation of the charging facility configuration scheme for the office building parking lots based on the design period;
(2) Compared with the number of piles recommended in the design standards, the optimal configuration method proposed in this study can significantly improve the average utilization rate of charging facilities and the average satisfaction rate of charging demand. The longer the design period is, the more benefits the optimal configuration scheme will bring. Taking the scientific research office building as an example, when the design period is 5 years and 10 years, the comprehensive effect of the above two indicators can be increased by 8.18% and 17.45%, respectively;
(3) Making reasonable arrangements for the charging scheduling of EVs with the building energy system will help restrain the fluctuation of the power grid through demand response, reduce the peak load with a maximum load transfer rate of 25.55%, and ensure the stability of the building power grid operation.

However, this study only focuses on the optimal configuration of EV charging facilities in a single office building and the samples are limited. With the continuous promotion of EVs in the future, more and more buildings will be equipped with charging facilities. Considering the type and scale of the buildings participating in the demand response, the planning of charging facilities for multiple buildings should be further explored in future research.

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