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Integrating photovoltaic noise barriers and electric vehicle charging stations for sustainable city transportation

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A R T I C L E I N F O

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A B S T R A C T

Photovoltaic noise barriers (PVNBs) offer a dual advantage of reducing traffic noise pollution and providing renewable electricity to cities. However, how the effective integration of PVNB-generated power into urban energy networks remains a critical area lacking research. To bridge this gap, this study proposes PVNBs-energy storage (ES)-charging station (CS; PVNBs-ES-CS) strategy. It can facilitate the actual consumption of PVNBs power and the mitigation the burden on the grid posed by electric vehicles (EVs) charging demands. The case study conducted in Guangzhou, China, reveals that PVNBs can support up to 5% of the total power demand for EVCSs. Under the PVNBs power maximization consumption scenario, PVNBs can meet up to 30% of the power demands from 60 EVCSs, with 58% of PVNBs generated power being consumed. In the PVNBs-ES-CS future utilization scenario, up to 30% of the power demand of 125 EVCSs can be met, and 36% of the power of PVNBs can be consumed. The combination of PVNBs and EVCSs offers a practical solution for incorporating renewable energy sources into urban energy networks. This application mode can be applied in various cities with EV demands and PVNB power generation data.

Variables			
i	The $i-th$ EVCS, $i \in [0,\ 647]$	P_{fi}	Rated power of fast-charging piles of the $i-th$ EVCS
R_i	The utilization rate of the $i-th$ EVCS	P_{si}	Rated power of slow-charging piles of the $i-th$ EVCS
F_i	Number of fast-charging piles of the $i-th$ EVCS	j	The $j-th$ PVNB
S_i	Number of slow-charging piles of the $i-th$ EVCS	$M_j(x_j, y_j)$	The longitude and latitude of the $j-th$ PVNB
t_{fi}	Usage counts of fast-charging piles of the $i-th$ EVCS	M_{jP}	Power generation of the $j-th$ PVNB
t_{si}	Usage counts of slow-charging piles of the $i-th$ EVCS	$N_i(x_i, y_i)$	The longitude and latitude of the $i-th$ EVCS
T	Total counts of should be uses of each charging piles	N_{iD}	Power demand of the $i-th$ EVCS
D	Total power demand of EVCSs	A, B	Threshold

1. Introduction

1.1. Background

Photovoltaic (PV) panels mounted on road noise barriers (RNBs) can

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help conserve limited urban land resources, increase the renewable energy supply, mitigate the urban heat island effect, and incentivize RNB construction due to the added benefits of power generation (Zhong et al., 2021). However, there has been limited research exploring how the effective integration of PV noise barriers (PVNBs) generated power into the urban energy network to achieve self-consumption. Concurrently, the growing popularity and fast development of electric vehicles (EVs) in urban environments are increasing EV charging needs (Leippi, Fleschutz & Murphy, 2022), presenting huge challenges to power grid stability (Patil, Kazemzadeh & Bansal, 2023; Zheng, Shao & Jian, 2021). Therefore, by integrating PVNBs with EV charging stations (CS; EVCSs) and directing PVNB-generated power to serve the EV charging demands, it becomes viable to optimize the utilization of PVNBs while simultaneously alleviating the load on the grid network (Liu, Kong, Liu, Peng & Wang, 2015). Embracing this approach enables PVNBs to actually apply to the city's energy needs while facilitating EV operations on purely renewable energy, resulting in zero emissions (Benyahia et al., 2021). However, an urgent challenge is how to formulate flexible strategies for matching PVNBs and EVCSs based on PVNBs power generation, EVCS power demand, geospatial location, and period to make PVNBs power can be delivered to appropriate EVCS and consumed.

1.2. Literature review

The main focus of PVNB research revolves around comparing the power generation capacities of different PV panel materials, RNB types, and PV panel mounting configurations (Jong, Van, Verkuilen & Folkerts, 2016; Soares & Wang, 2023) or predominantly assessing the PV potential of PVNBs at various scales (Gu et al., 2012; Hasmaden, Zorer & Yüğrük, 2022). While numerous studies have investigated the economic and environmental advantages of PVNBs, they have predominantly remained theoretical (Schepper, Passel, Manca & Thewys, 2012; Zdyb, Żelazna & Krawczak, 2019). A quantitative assessment of PVNB power utilization efficiency and the supply/demand of PVNBs in certain application scenarios is still absent, although several engineering examples suggest that PVNBs have the ability to power traffic lights and monitoring systems (Kesolar, 2015).

PV-energy storage (ES)-charging station (CS; PV-ES-CS), which combines PV, battery energy storage systems (BESSs), and CSs, is one of the most practicable strategies for enabling EV charging with PV (Sun, Zhao, Qi, Xiao & Zhang, 2022). Apart from minimizing wastage in PV generated power, PV-ES-CS strategies also alleviate the pressure on the primary grid due to the increasing need for EV charging (Li et al., 2021), lower grid operating and maintenance costs (McPhail, 2014), and facilitate the attainment of carbon peak and neutrality targets (Lei, Yu, Yu, Shao & Jian, 2023). Numerous researchers have delved into various aspects of PV-ES-CS systems in urban environments, including the optimization of location selection and evaluation processes (Li et al., 2022; Zhou et al., 2020), improving the operation patterns through simulations or modeling (Kouka, Masmoudi, Abdelkafi & Krichen, 2020; Lin et al., 2023), conducting economic feasibility and environmental benefits analysis based on case studies (Grande, Yahyaoui & Gómez, 2018; Karmaker, Ahmed, Hossain & Sikder, 2018), and utilizing the latest PV and BESS technologies to maximize the combined benefits of the PV-ES-CS strategy (Mohammad & Ali, 2022; Pathak, Yadav, Padmanaban & Alvi, 2022). PV-ES-CS strategy has proven to have significant economic and social benefits (Yang, Zhang, Zhao & Wang, 2021). However, the studies mentioned above either remain at a theoretical level, rely on a limited number of EVCS, or lack authentic consumption data from EVCSs. Quantitative analysis of the practical application of PV-ES-CS at the urban scale still lacks convincing cases.

1.3. Contributions

Considering the literature reviewed, certain research gaps are identified as follows:

(1) The incorporation of PVNB-generated power into urban energy consumption networks and consume through practical application scenarios lacks specific instances. Therefore, here are currently no relevant quantitative indicators to evaluate the true power consumption and utilization efficiency of PVNBs. The absence of substantial evidence complicates the evaluation of the economic sustainability of PVNB systems.
(2) There is a lack of quantitative assessment of actual application scenario for PV-ES-CS strategy using real EVCSs power consumption data at city-scale. Thus, need to further increase the accuracy of the PV-ES-CS strategy's practical application feasibility evaluation at the urban scale.

Therefore, the contributions of this paper can be outlined as follows:

(1) This study proposed PVNBs-ES-CS strategy for the first time. The PVNBs-ES-CS strategy ensures that the power generated by PVNBs is actual consumed by EVCSs, allowing for quantifiable power utilization rates. It serves as a reference for the practical application of PVNBs in urban environments, while also aiding in the evaluation of their economic feasibility.
(2) A matching strategy for PVNBs and EVCSs is developed based on two scenarios: PVNB power maximization consumption scenario and PVNBs-ES-CS future utilization. The power generated by PVNBs is delivered directly to nearby EVCSs based on EVCS's power demand, utilization rate, and locations. Any surplus power that is not needed by the EVCSs at that moment is temporarily stored in a BESS and then released later when needed during EV charging. It guarantees the delivery of PVNB-generated power to suitable EVCSs for optimal consumption.
(3) Quantify the operational performance of the PVNBs-ES-CS strategy using real city-scale power consumption data from EVCSs. The inclusion of all 647 EVCSs in Guangzhou within the supply-demand matching plan between PVNBs and EVCS holds significant reference value for quantitatively assessing the performance of the city-scale PV-ES-CS strategy.

1.4. Organization of this paper

The remainder of this study is organized as follows: Section 2 presents the basic information and related characteristics of the case study area, Section 3 outlines the proposed methodology, Section 4 presents the study results. Sections 5 and 6 offers discussion and conclusions, respectively.

2. Study area and materials

2.1. Study area

Guangzhou, located in the southeast coast of China, convers an extent between 112°57′ and 114°3′ E and 22°26′ and 23°56′ N. The city has an oceanic subtropical monsoon climate, with average annual temperatures ranging from 20 to 22 °C. Given its position in the south of the Tropic of Cancer, Guangzhou benefits from strong solar radiation and high solar altitude angles, even during the winter months, compared to other regions in China. This makes Guangzhou a region with relatively abundant solar energy resources throughout the year. Fig. 1 provides an overview of Guangzhou.

As of 2020, over 270,000 new EVs were registered in Guangzhou, accounting for 9% of the city's total automobile ownership—significantly higher than the national average of 1.75%. It is estimated that by 2025, Guangzhou will have 800,000 new EVs (Guangzhou Municipal Development & Reform Commission, 2021). This indicates a pressing need for convenient and efficient EV charging infrastructure in cities. Moreover, 85.6% of Guangzhou's power is generated from coal and gas, while a mere 3.2% comes from solar energy

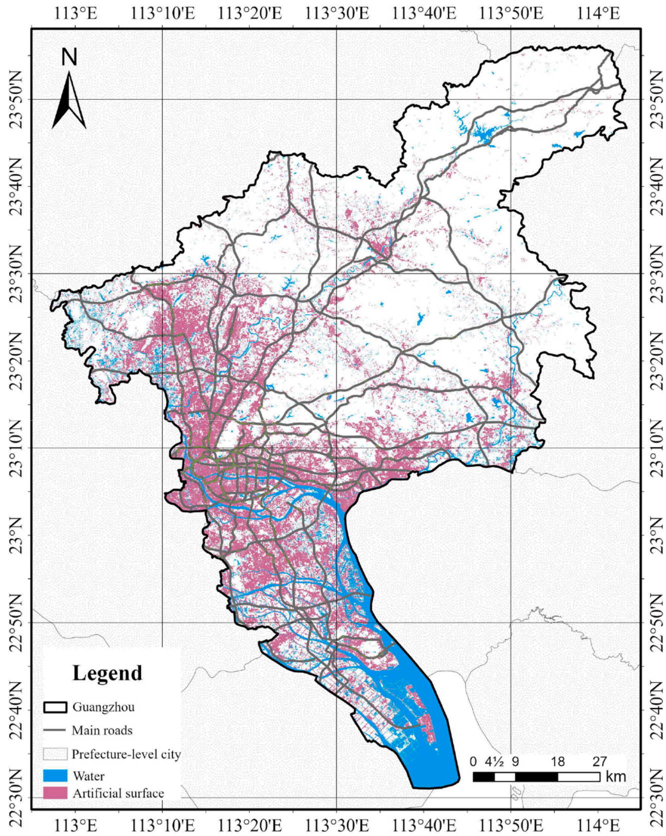

Fig. 1. Overview of the study area.

(Guangzhou Municipal Bureau of Statistics, 2022). Thus, constructing a PVNBs-ES-CS system in Guangzhou can be an effective solution to increase the city's supply of renewable energy, facilitate EV charging, and alleviate the burden placed on the main grid.

2.2. Data collection

Real-time energy consumption data for the EVCSs in Guangzhou were provided by our partners. The data contains specific information about the city's 647 EVCSs as well as the individual charging piles within each EVCS. Including the name, station ID, latitude, and longitude of each EVCS, and the rated power, charging status (whether charging or not), and charging mode (fast or slow charging) of each charging pile. The collected data spanned a period from 00:01 on June 19, 2022, to 23:56 on July 18, 2022. The EV charging records were updated at five-minute intervals. Therefore, a total of 7488 files containing more than 5 million data within the entire dataset. A Python script was employed to filter the data for better manageability and the script has been upload GitHub (https://github.com/zhangk2/EVCSs). Table 1 displays the cleaned EVCS data, illustrating the usage of charging piles at two CSs with identification ID 25,973 and 27,674 at 00:01 on June 19, 2022.

In this study, the PV potential was acquired based on our previous research involving bifacial PVNBs (currently under peer review). Initially, a deep learning approach was employed to detect RNBs in street view images, which were then vectorized using a geographic information system (GIS) method to crucial input parameters such as azimuth, latitude, and longitude, for assessing radiation potential (Qian et al., 2022). Subsequently, a model for calculating radiation on tilted surfaces was applied to evaluate the PV potential of the PVNBs. the power generation of PVNBs was calculated using prevailing market-standard PV panel power ratings and PV system conversion efficiency (Zhong et al., 2021).

3. Methodology

The methodology for this study consisted of three primary stages. Firstly, an evaluation of the utilization rate of each EVCS was conducted to identify malfunctioning or rarely used EVCSs. Based on this assessment, two scenarios were formulated: the PVNBs power maximization consumption and the PVNBs-ES-CS future utilization scenario. Secondly, the total power consumption of each selected EVCS was calculated by analyzing the power and duration of usage for each charging pile. Thirdly, for both scenarios, a corresponding matching scheme was established, considering factors such as PVNB power generation, EVCS power demand, and the distance between them. The technological flowchart for this study is depicted in Fig. 2.

3.1. Calculation of EVCS utilization and power demand

While data were analyzed for 647 EVCSs, it was observed that numerous charging piles within these EVCSs were either malfunctioning or never unused. Since transmission costs and losses must be taken into account when a PVNB supplies power to specific EVCS, this study excluded EVCSs that regularly malfunctioned or were not in use throughout the research period. As indicated in Table 1, the quantity of charging piles at each EVCS and their utilization status are available. Therefore, through calculate the actual charging count of each charging pile and maximized potential charging count during the study period, the utilization rate of each EVCS can be determined. The specific calculation formula is outlined as follows:

$$R_i = \left\{ \left(F_i \times P_{fi}\right) \times t_{fi} + \left(S_i \times P_{si}\right) \times t_{si} \right\} \div \left\{ \left(F_i \times P_{fi} + S_i \times P_{si}\right) \times T \right\} \quad (1)$$

where R_i, F_i, and S_i are the utilization rate, number of fast-charging piles, and number of slow-charging piles of the $i-th$ ($i \in [0,\ 647]$) EVCS, respectively. t_{fi} and t_{si} denote the usage counts of fast- and slow-charging piles of the $i-th$ EVCS during the research period, P_{fi} and P_{si} stand for the $i-th$ EVCS's rated power of fast-charging piles and slow-charging piles, and T stands for the total counts of should be uses recorded throughout the study period.

The total power demand of each EVCS was calculated according to Eq. (2):

Table 1
Explanation of EVCS data extraction results.

EVCS ID	Fast-charging pile count	Slow- charging pile count	Longitude	Latitude	Pile no.	Power (kW)	Status
25,973	1	4	113.41424	23.223452	1	20	Malfunction
					2	7	Charging
					…	…	…
					4	7	Charging
27,674	0	8	113.322765	23.141692	1	7	Off grid
					2	7	Charging
					…	…	…
					8	7	Charging

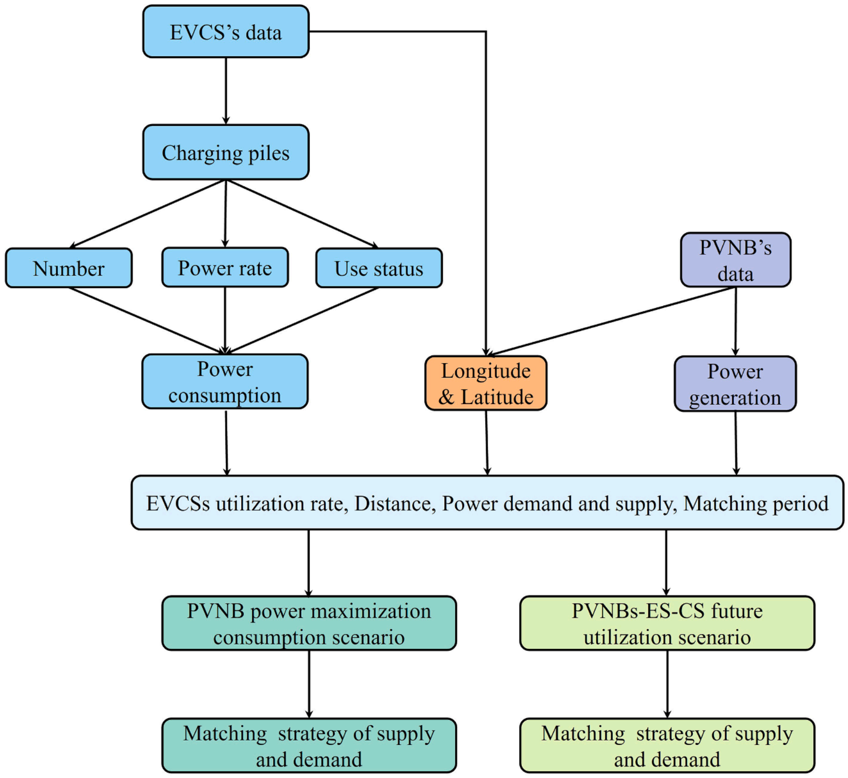

Fig. 2. Matching strategy of photovoltaic noise barriers (PVNBs) and electric vehicle charging stations (EVCSs).

$$D = \sum_{i}^{647} \left\{ \left[\left(F_i \times P_{fi} \right) \times t_{fi} + \left(S_i \times P_{si} \right) \times t_{si} \right] \times \frac{1}{12} \right\} \tag{2}$$

where D signifies the total power demand of EVCSs during the research period. Because the EVCS data is captured at 5-minute intervals, the time units must be changed to hours, hence the equation is multiplied by one-twelfth.

3.2. Matching of the supply and demand of PVNBs and EVCSs

In this study, the PVNB power supplied to EVCSs is assumed to be stored in BESSs, which charge the EVs before the main grid supply when needed. The calculation of PVNB power is based on the RNB with a length of 20 m (Zhang et al., 2022). Therefore, each PVNB segment with a length of 20 m is considered an individual PVNB unit to match the PVNB and EVCS power supply and demand. The conceptual diagram of the matching process is depicted in Fig. 3.

After calculating each EVCS's total power consumption and utilization rate using the method described in Section 3.1, the PVNBs power maximization and PVNBs-ES-CS future utilization scenarios were developed based on whether the EVCSs were filtered through their utilization rate. PVNBs power maximization consumption scenario: priority delivered the power of PVNB to those high utilize rate EVCSs, guaranteeing that the power generated by PVNBs can be maximize consumed by matched EVCSs; PVNBs-ES-CS future utilization scenario: focuses on matching PVNBs and EVCSs based on the shortest path of power delivered, the shortest delivery path minimizes power loss and transmission line building expenditures, lowering costs.

Thiessen Polygons are employed to assign each PVNBs unit to a specific EVCS, ensuring that the power generated by each PVNB is efficiently directed to corresponding EVCS through the shortest route. Thiessen Polygons, also known as Voronoi Diagrams, is a method of planar partitioning utilized to identify the region nearest to each point within a given set of points (Richter, Ng, Karimi, Wu & Kashani, 2019).

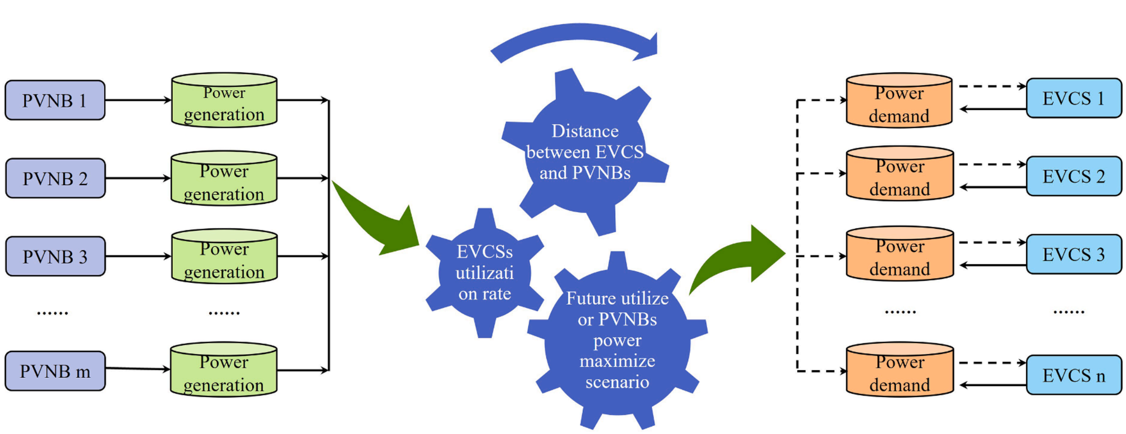

Fig. 3. Diagram of the photovoltaic noise barriers (PVNBs) and electric vehicle charging stations (EVCSs) matching process.

The detailed PVNB power distribution execution strategy is as follows:

a) Assume a set $M = \{1, 2, 3 \ldots m\}$, where each element represents a PVNB unit and $M_j(x_j, y_j)$ denotes the longitude and latitude of the $j-th$ PVNB with power production of M_{jP};
b) Assume a set $N = \{1, 2, 3 \ldots n\}$, where each element represents an EVCS and $N_i(x_i, y_i)$ represents the longitude and latitude of the $i-th$ EVCS with power demand N_{iD};
c) Select the EVCSs with utilization rates greater than threshold A;
d) Create Thiessen Polygons based on EVCSs that from step c), determine if there are any PVNBs scattered within each Voronoi Diagram, calculate the ratio of the total power of PVNBs falling into the Thiessen polygons to the EVCS demand;
e) If the calculated ratio is greater than a certain threshold B, retain the EVCS; otherwise, remove it;
f) Recreate the Thiessen Polygons based on the remaining EVCSs and recalculate the ratio of the total power of PVNBs falling within Thiessen polygons to the EVCS demand; and
g) Repeat steps e) and f) until all EVCSs and PVNBs satisfy the above requirements.

In addition, because EVCSs in various regions have varying utilization rates and levels of total power consumption, there may be a huge difference between PVNB power generation and the EVCS demand. If an EVCS is preselected based on its utilization rate, it will make the remained EVCS have a higher power demand, necessitating the delivery of power from a longer distance PVNB to that EVCS. However, if the EVCS is not filtered, the total power demand of the retained EVCS will be smaller. In this case, the Thiessen polygon created based on the EVCS will contain more PVNBs, and the PVNB power will not be fully consumed by the corresponding matched EVCS. Therefore, the PVNBs power maximization consumption scenario and PVNBs-ES-CS future utilization scenario are established to discuss the PVNB power allocation scheme under the above two scenarios, respectively, and the main difference between the two scenarios is whether to perform step c). That is, whether to filter EVCSs by utilization rates.

4. Results

4.1. Characteristics of EVCS utilization rates and the total power demand

A preliminary analysis of the obtained EVCS data reveals that a large proportion of CS charging piles were off grid or malfunctioning throughout the research period. Considering the cost of BESS and the construction of transmission lines for PVNBs to transmit power to EVCSs, there is no profit to transmitting power generated by PVNBs to these off-grid or malfunctioning EVCSs. In addition, two scenarios are established also need through EVCS utilization rates. Therefore, this study calculated the utilization rate and total power consumed by each EVCS. The statistical results on the power consumption of EVCSs are shown in Fig. 4. 76.34 GWh of power was used by EVCSs throughout the study period.

Based on Fig. 4, it can be observed that around 60% of the EVCSs have utilization rates below 10%. However, EVCSs with utilization rates above 30% constitute less than 12% of the total number of EVCSs, but they account for almost 60% of the total power consumed by EVCSs. In the same period as the EVCS data, the power generation statistics for PVNBs in Guangzhou were estimated using a related model (Zhong et al., 2021). There are approximately 133.71 km of RNBs in Guangzhou. Assuming that all RNBs are of the same type and 3 m in height, and PV panels are installed vertically on both facades of the RNBs. After calculation, the PVNBs can produce 3,936 MWh. Fig. 5 depicts the amount of energy generated by PVNBs and the spatial distribution of EVCSs in Guangzhou.

Fig. 5 depicts the spatial distribution characteristics of PVNBs in Guangzhou. It illustrates that PVNBs are erected in a linear manner along the city's circular motorways and important arterial routes. Although EVCSs are also generally distributed along major roads, the spatial distributions of PVNBs and EVCSs are not identical. Fig. 5 also depicts a heatmap of the total power consumed by EVCSs. It demonstrates that, except for area B, which has a higher concentration of PVNBs in its vicinity, other urban areas with high EVCS power consumption (such as areas A, C, and D) have either no PVNBs or only a few PVNBs with low power output in their vicinity. The PVNBs are distributed most densely in the E area of the ring road, but there are few EVCSs nearby, and their power consumption is relatively low compared to EVCSs in other areas.

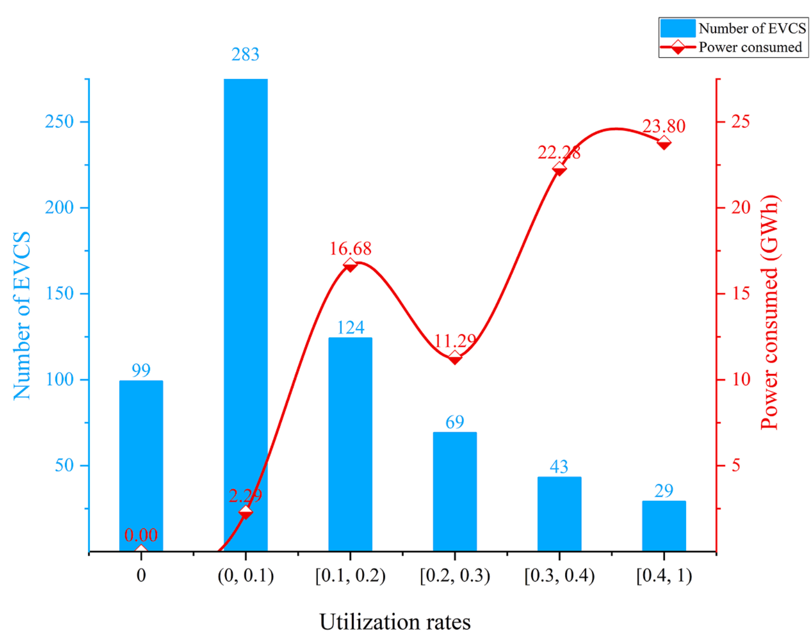

Fig. 4. Overall status of electric vehicle charging stations (EVCSs) power consumption in Guangzhou.

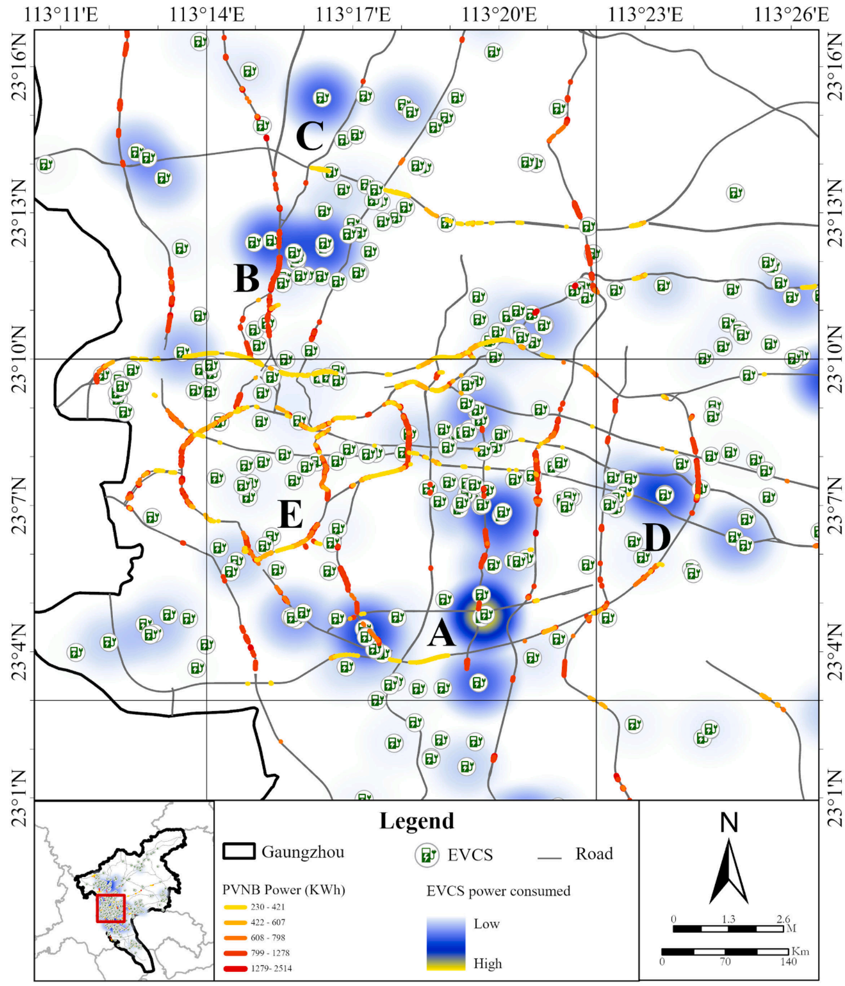

Fig. 5. Spatial distribution characteristics of electric vehicle charging stations (EVCSs) and photovoltaic noise barriers (PVNBs) in Guangzhou.

4.2. PVNB and EVCS matching strategy

As there are no advantages to transmitting PVNBs power to EVCSs with zero utilization rates, this study excluded such EVCSs. After preprocessing, a total of 548 EVCSs with a utilization rate greater than zero were identified for matching in accordance with the instructions detailed in Section 3.2.

4.2.1. PVNBs power maximization consumption scenario

In the scenario of PVNBs power maximization consumption, thresholds A and B were defined as 10% and 30%, respectively, as detailed in Section 3.2. After executing the above matching process, the matching result is obtained as shown in Fig. 6. When threshold A was set to 10%, there were 239 EVCSs remained that met the requirements, indicating that many EVCSs were not effectively utilized. Fig. 6 illustrates the matching results for PVNBs and EVCSs. Each closed polygon in Fig. 6 represents the radiation area of a single EVCS, and the PVNBs located within each polygon should transfer power to that EVCS. This scenario guarantees that the remaining EVCSs have a high utilization frequency and provide a high rate of PVNB power consumption.

An analysis and statistics of the matching results in Fig. 6 indicated that PVNBs can meet at least 30% of the EVCS charging demand of 60 EVCSs in Guangzhou city. The total power demand of these 60 EVCSs is 2,275 MWh, thus consuming 58% of the power that generated by PVNBs in Guangzhou. This is accomplished by first removing the EVCSs with a utilization rate lower than 10% and then allocating power to the remaining EVCSs. When threshold B is set to 50% and 80%, the number of supplied EVCSs decreases to 56 and 52, respectively (Supplementary Material, Fig. 1a). This tendency implies that the power produced by PVNBs may need to traverse longer distances to supply the corresponding EVCSs, leading to increased power transmission expenses.

Next, a weekly time interval is used to assess PVNBs power-matching strategy changes across a relatively condensed time span. The PVNB power supply was matched with the EVCS power demand for a four-week period beginning on June 20 and ending on July 17. In this scenario, however, when threshold A is set to 10%, it is remarkable that only week 3 meets the requirement with EVCS, while the remainder of the period has less than a 10% EVCS utilization rate. Table 2 displays the monthly and weekly supply and demand matching statistics for PVNBs and EVCSs.

4.2.2. PVNBS-ES-CS future utilization scenario

In the PVNBs-ES-CS future utilization scenario, by setting specified threshold B to 30% in Section 3.2, and matching PVNBs with EVCSs according to the PVNB power allocation procedure, Fig. 7 displays the matching results of PVNBs with EVCSs for Guangzhou in the research period. Similar to Fig. 6, each closed polygon in Fig. 7 represents the radiation area of a single EVCS, with the PVNBs located within each polygon transferring power to the corresponding EVCS. This assures that each PVNB unit has the shortest to the corresponding EVCS. Consequently, the cost of transmitting power to each EVCS is minimal.

After analyzing the matching results of PVNBs and EVCSs, PVNB power can be supplied to 125 EVCSs in Guangzhou if the total PVNBs power within each Thiessen polygon meets at least 30% of the EVCS

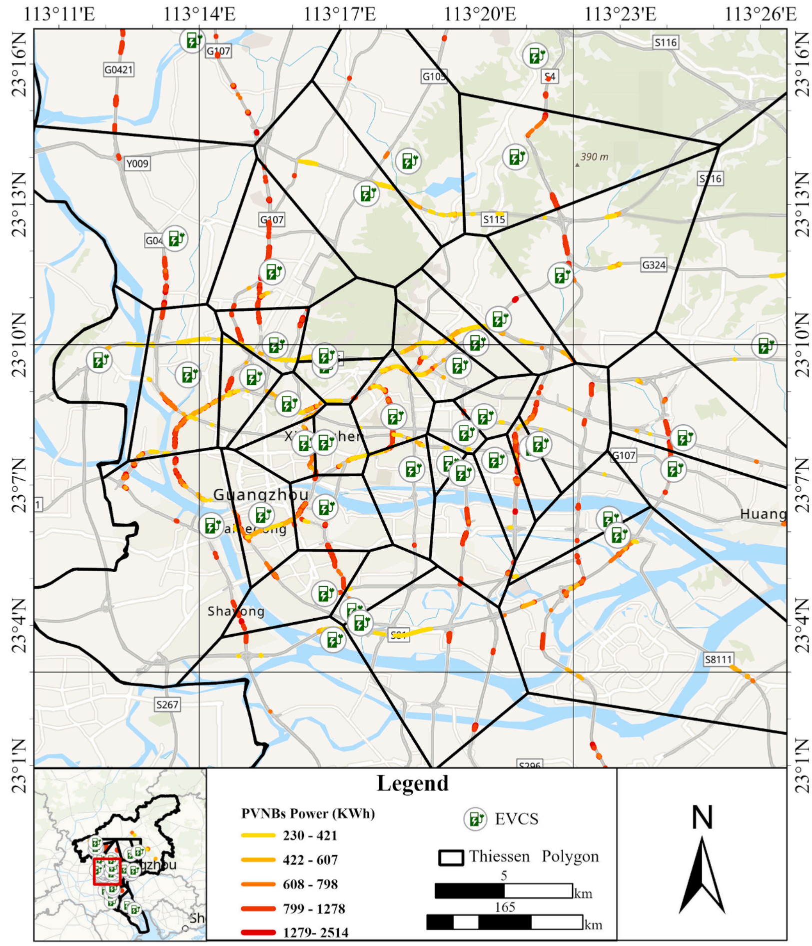

Fig. 6. Photovoltaic noise barriers (PVNBs) and electric vehicle charging stations (EVCSs) matching results for the PVNBs power maximization consumption scenario.

Table 2
Statistical results for the monthly and weekly power utilization of photovoltaic noise barriers (PVNBs) and electric vehicle charging stations (EVCSs) under matching strategy.

Scenario	Time	Threshold B	EVCSs (Number)	Demand (MWh)	Consumption Rate	Supply (MWh)
PVNB power maximization scenario	Monthly	30%	60	2,275	58%	3,938
		50%	56	1,832	47%	3,938
		80%	52	1,477	38%	3,938
	Week 1	30%	0	–	–	–
	Week 2		0	–	–	–
	Week 3		60	487	55%	873
	Week 4		0			

power consumption at each location. If threshold B reaches 50% and 80%, the number of EVCSs that can meet the requirements is 116 and 109, respectively (Supplementary Material, Fig. 2a). However, corresponding 125, 116, and 109 EVCSs consumed a total power of only 1,419 MWh, 869 MWh, and 381 MWh, respectively. This trend suggests that some EVCSs received more power than they needed in the current scenario, with EVCSs having a small power consumption and a large amount of supplied power. It was counted that even when the threshold B is set to 80%, some EVCSs still receive an excess of 50 to 300 times more power than they require. Although this strategy may result in a waste of power from PVNBs at the present time, it will allow for maximum benefit in the future as the number of EVs continues to increase or planning related incentive measures are established.

The study likewise attempts to refine the time scale of matching PVNBs with EVCSs to the weekly scale in this scenario. The matching results as illustrated in Fig. 8. In addition, this study calculated the monthly and weekly power utilization of PVNBs and EVCSs under the respective matching strategies was determined (Table 3). As observed in Fig. 8 and Table 3, except in week 3, when the matching scheme between PVNBs and EVCSs experienced notable changes, the matching between PVNBs and EVCSs remained relatively stable during the observation period. Because the majority of EVCSs had a utilization rate of 0 during week 3, these EVCSs were excluded during the matching process, resulting in only a small number of EVCSs receiving PVNBs' power. Compared to that in the PVNBs power maximization consumption scenario, the consumption rate of PVNB-generated power significantly decreases in the PVNBs-ES-CS future utilization scenario, and the number of EVCSs supplied by the PVNBs significantly increases.

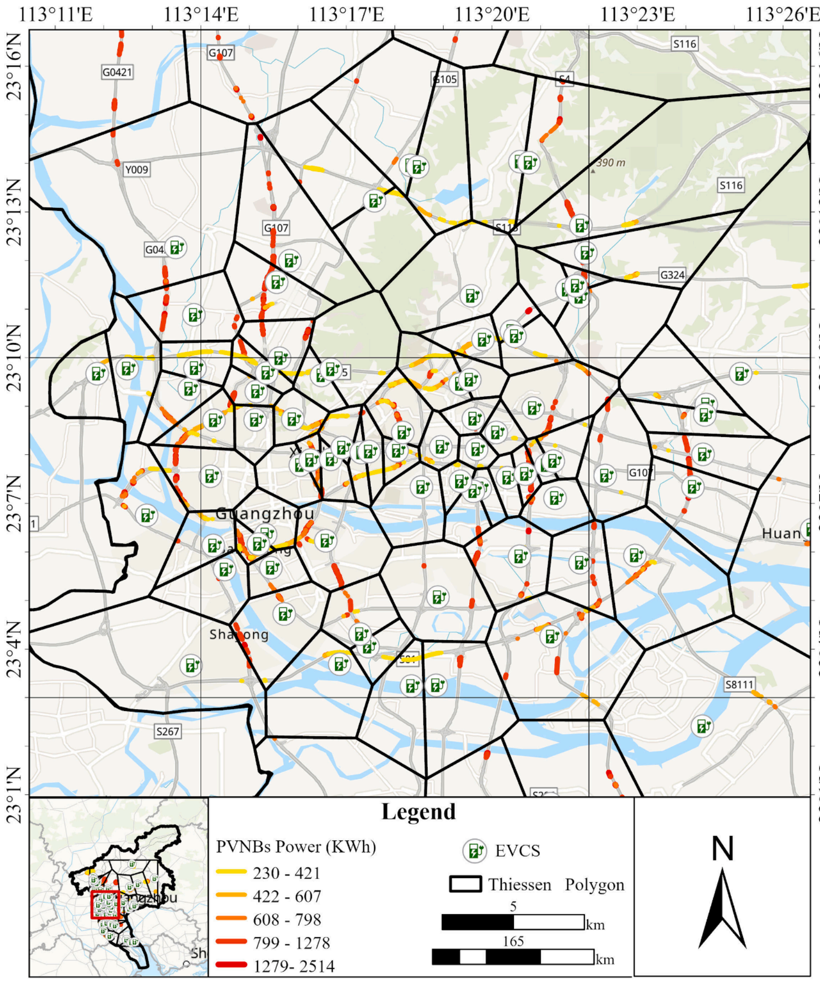

Fig. 7. Photovoltaic noise barriers (PVNBs) and electric vehicle charging stations (EVCSs) matching results under PVNBs-energy storage-charging station (PVNBs-ES-CS) future utilization scenario.

5. Discussion

This study utilizes real-time data from EVCSs to calculate the power demands of each EVCS, which are then coupled with the generated power of PVNBs to achieve a match between the power demand of EVCS and the power supply of PVNB at city-scale. Then, the PVNB electricity was effectively utilized, and the dependency on EVCSs on the main power network was minimized. The combination of PVNBs and EVCSs offers a practical solution to the problem of incorporating renewable energy sources into urban energy networks (Li et al., 2022). The research findings imply that PVNBs in urban environment have the potential to fulfill over 30% power demands for approximately 20% matched EVCSs and the approximately 5% total power demands of all EVCS.

However, several factors need to be considered when implementing the PVNBs-ES-CS strategy. 1) Due to the limitations associated with the availability of EVCS data, the supply and demand were only matched from June 19, 2022, to June 18, 2022. Moreover, matching could not be performed at the yearly scale. PVNBs generate more power during the summer than during the winter. Therefore, at the annual scale, the strategy to match the supply and demand of PVNBs and EVCSs may require more flexibility. 2) The economic feasibility of PVNBs and the costs of power transmission and BESSs were not considered. To promote and popularize the PVNBs-ES-CS approach in the actual cases, the benefit of charging income should cover the related costs of the whole system. 3) A flexible price strategy and related software and hardware that are easy to use should be implemented. Additionally, PVNB power management is needed to ensure that EV owners prioritize charging their vehicles with power from PVNBs. In addition, this research designed the power transfer lines solely based on the Euclidean Distance between PVNB and EVCS, while in practical scenarios, the planning of power transfer lines may need consider the existing power infrastructure and the scientific layout of the lines.

Fortunately, the pricing of PV and associated technologies is continuing to develop in a positive direction (Ding, Zhou, Liu & Zhou, 2020), which will accelerate the general application of PVNBs-ES-CS systems soon. The power generated by PVNBs is maximized consumed, and EVs achieved a decreased dependence on fossil fuel energy in the PVNBs-ES-CS strategy. In addition, PVNBs-ES-CS implementation has the potential to increase both people's participation and confidence in the transition to sustainable energy, further increasing the public's general knowledge about the current state of PV use and societal accountability for global climate control objectives (Yang et al., 2021). In urban environments, PV systems combined with other application forms are also advantageous for alleviating the urban heat-island effect and improving the urban microclimate (Berardi & Graham, 2020). Moreover, such systems are also essential for cities to reduce carbon emissions (Zhang, Chen, Zhong, Zhu & Qian, 2023), enhance the quality of life for residents, and promote sustainable urban development. Besides, GIS also can accelerate the development of PV systems (Zhu, Zhang, Yan, Ratti & Chen, 2023). The results of the PVNBs-ES-CS application model suggest that PV power utilization can be maximized by designing a scientific and practical scheme for distributed PV systems in urban environments.

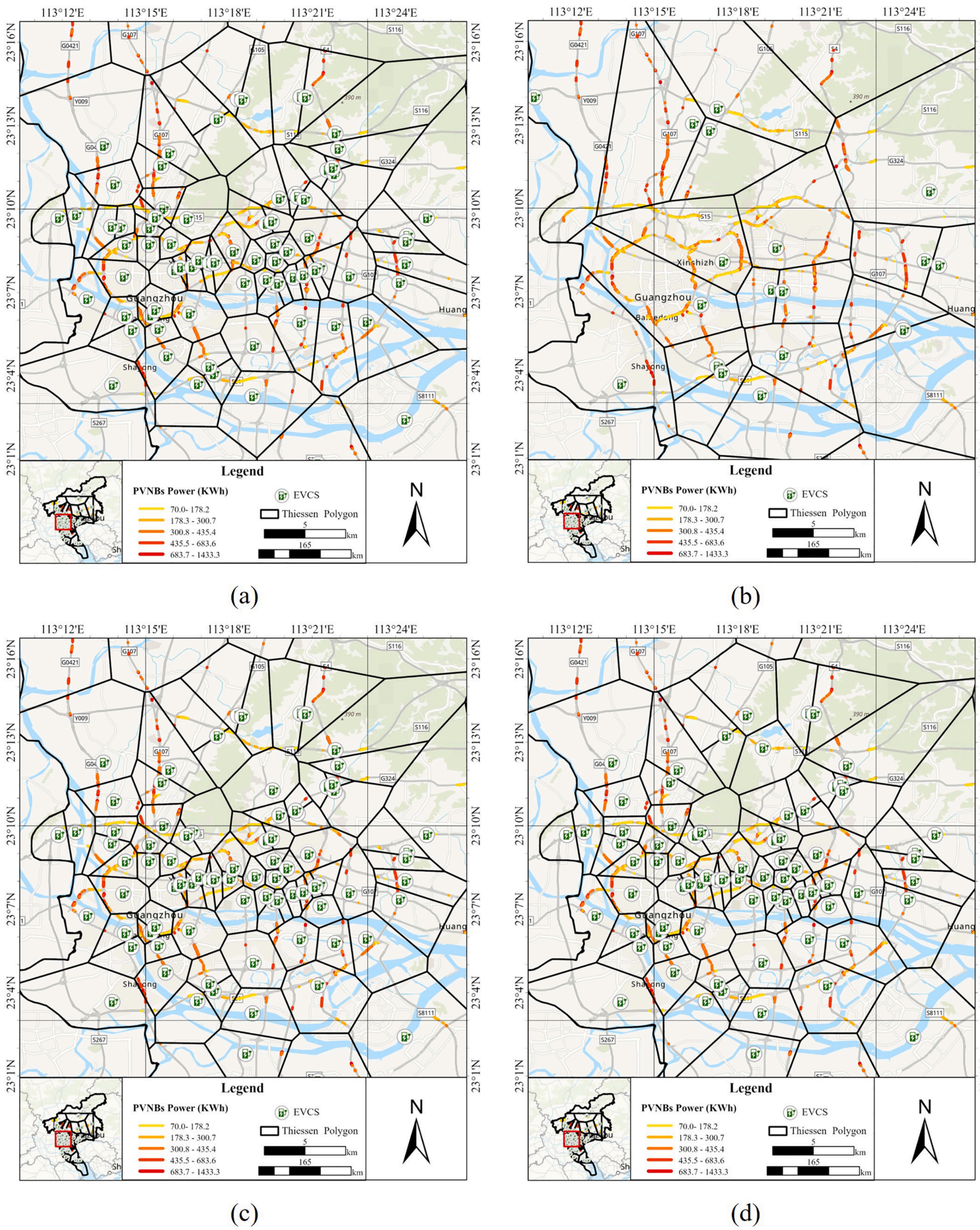

Fig. 8. Spatiotemporal characteristics of Photovoltaic noise barriers (PVNBs) and electric vehicle charging stations (EVCSs) power supply and demand matching strategies, where a, b, c, and d illustrate the results for week 1 (June 20 - June 26), week 2 (June 27 - July 3), week 3 (July 4 - July 10), and week 4 (July 11 - July 17), respectively.

6. Conclusions

This study proposed PVNBs-ES-CS strategy that combines PVNBs, BESS and EVCSs as an approach for utilizing the power generated by PVNBs and alleviating the conflict between the EV charging demand and the main grid capacity load. Guangzhou employed the strategy first as a case study to match the EVCS power demand with the PVNB power supply. The result indicates: 1) the total generated power of PVNBs in Guangzhou can support approximately 5% of the EV charging demand during the research period; 2) in the PVNB power maximization consumption scenario, the power generated by the PVNBs can satisfy over 30% of the individual power demands of the 60 matched EVCSs. The cumulative power demand of the 60 EVCSs is 2,275 MWh, accounting for 58% of the total power generated from the PVNBs. 3) in the PVNBs-ES-CS future utilization scenario, at least 30% of the individual power demands of 125 matched EVCSs can be met by PVNBs power. The cumulative power demand of the matched 125 EVCSs is 1,419 MWh, accounting for 36% of the total power generated from the PVNBs.

Table 3
Statistical results of the monthly and weekly power utilization of photovoltaic noise barriers (PVNBs) and electric vehicle charging stations (EVCSs) under matching strategies.

Scenario	Time	Threshold B	EVCSs (Number)	Demand (MWh)	Consumption rate	Supply (MWh)
PVNBs-ES-CS future utilization scenario	Monthly	30%	125	1,419	36%	3,938
		50%	116	869	22%	3,938
		80%	109	381	10%	3,938
	Week 1	30%	117	346	39%	881
	Week 2		31	199	23%	865
	Week 3		122	343	39%	873
	Week 4		119	330	37%	895

This study indicates that the PVNBs-ES-CS is a very flexible strategy to effectively link the PVNBs and EVCSs to realize multiple power supply and demand matching solutions. It represents a promising approach to achieving a more sustainable and resilient energy system, where EVs and renewable energy sources are interconnected and optimized in a decentralized and flexible manner. By embracing this strategy, we can accelerate the transition toward a carbon-free future and unlock the potential of clean energy and sustainable transportation. Furthermore, this study proposed the PVNBs-ES-CS approach can be applied to other cities with EV demand and PVNB power generation data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Power consumption statistics for EVCSs will be made available on request. PVNB geographical distribution and power generation are available on GitHub (https://github.com/zhangk2/EVCSs).

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104996.

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