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PV-Powered Shared Electric Micro-Mobility Hub with Shared Power Bank

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ABSTRACT

The rapid adoption of shared electric micro-mobility solutions, such as e-scooters and e-mopeds, has addressed the need for low-carbon transportation and efficient last-mile travel. However, challenges persist due to insufficient parking and charging infrastructure. This study introduces an innovative shared electric micro-mobility hub prototype, incorporating PV panels to provide energy and shared power bank stations for battery storage. Through a comprehensive case study, the economic and environmental benefits of different micro-mobility configurations and energy management strategies are evaluated. The results demonstrate that the micro-mobility with appropriately configured PV and shared power bank station can reduce carbon emissions by 99% and achieve a net income within one year. This research not only advances sustainable urban transportation but also provides a model for integrating various shared services, contributing to a more environmentally friendly and versatile urban lifestyle.

Keywords: shared electric micro-mobility hub, PV charging, shared power bank station, energy management

NONMENCLATURE

Abbreviations	
EF	Emission Factor
PV	Photovoltaics
SOC	State-of-charge
Symbols	
E	Energy consumption

1. INTRODUCTION

Addressing climate change stands as one of the most important challenges we currently face. The transport sector, as a pivotal role, contributes to over a third of the total carbon emissions from end-use sectors [1]. Urban transportation issues encompass concerns related to air pollution [2], traffic congestion [3], inadequacies in public transportation infrastructure [4], etc. The recent surge in the sharing economy has given rise to novel mobility solutions, exemplified by shared micro-mobility services [5].

Micro-mobility refers to a category of compact and lightweight modes of travel, characterized by a mass not exceeding 350 kg and a design speed not surpassing 45 km/h [6]. This encompasses a range of vehicles such as bicycles, electric bicycles, and electric scooters. It holds the potential to effectively curtail private vehicular usage, thereby alleviating urban congestion [7,8]. Furthermore, micro-mobility exhibits environmentally friendly attributes, contributing to reduced greenhouse gas emissions [9]. Many views micro-mobility as a pivotal solution for addressing last-mile urban transportation needs and facilitating eco-conscious travel.

Nevertheless, shared micro-mobility services remain contingent upon requisite infrastructure to ensure harmonious integration with existing road networks [10,11]. Various studies have introduced the notion of micro-mobility hubs, which entail comprehensive multimodal shared transportation services [12,13]. These hubs also accommodate the installation of charging infrastructure for shared micro-mobility, thus enabling recharging during parking intervals [14].

Presently, the majority of shared electric micro-mobility devices, such as electric bicycles and electric scooters, continue to rely on urban power grids as their primary source of energy [15], exerting a discernible strain upon the foundational power infrastructure of cities. The utilization of solar photovoltaic (PV) panels for recharging shared electric micro-mobility vehicles holds

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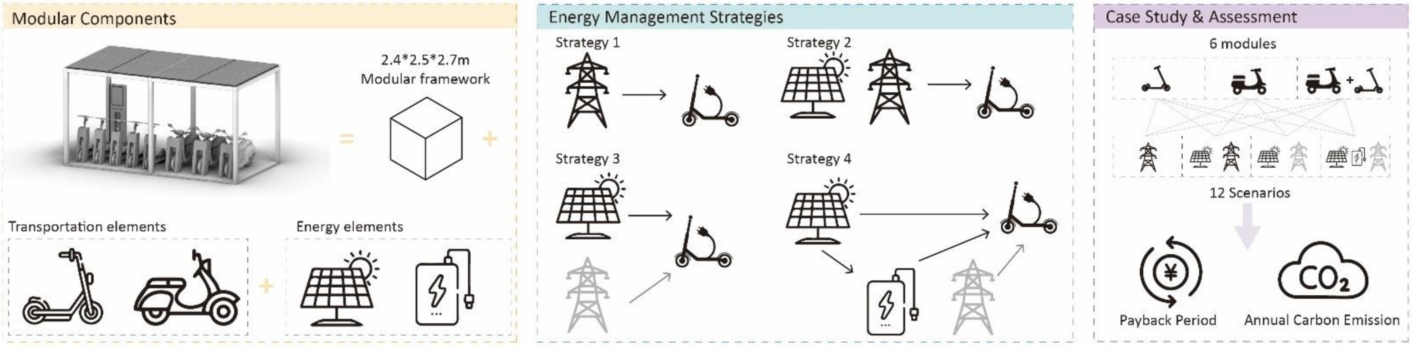

Fig. 1 Research framework.

substantial promise. For example, Zhu et al. developed a battery-level-aware real-time shareability network of solar-charged electric scooters, reducing charging costs with 1–3 m^2 PV module at each station [16]. Other researchers also proposed prototypes of off-grid solar charging stations tailored for shared electric micro-mobility, with several instances undergoing successful on-site evaluations [17–19]. However, current studies primarily focus on solar charging stations that exclusively address a single type of micro-mobility vehicle, with relatively scant attention devoted to the exploration of mixed-mobility hubs accommodating diverse micro-mobility modes for integrated travel solutions.

In addition, some researchers have highlighted that solar charging stations for electric shared micro-mobility must be equipped with adequate batteries to achieve completely off-grid, thereby realizing true zero-carbon operations [20,21]. However, batteries themselves entail a relatively higher cost and possess an elevated embodied carbon footprint [22]. An emerging trend in China, characterized by the proliferation of shared power banks, offers a distributed energy storage approach. These shared power banks, constituting a facet of the sharing economy, are strategically located at venues such as restaurants, transportation hubs, and malls. Users have the option to rent these power banks for mobile device charging, subsequently returning them to the same station or selecting an alternate one. Nevertheless, to our current knowledge, there exists no conclusive research demonstrating the practical implications of deploying shared power bank stations within solar-powered shared electric micro-mobility hubs as a substitute for conventional energy storage batteries.

To address the aforementioned challenges, this study introduces a prototype that combines a shared electric micro-mobility hub with shared power bank stations, presenting a novel approach to urban transportation and energy management. The main contributions of this research are: 1) developed a modular prototype for a novel shared electric micro-mobility hub, accommodating various types of micro-mobility vehicles and integrating PV panels and shared power bank stations; 2) proposed four transportation energy management strategies and analyzed the electricity consumption patterns of different micro-mobility types across varying scenarios; 3) assessed the environmental and economic performance of the micro-mobility hub by two essential metrics: the annual carbon emissions and the payback period. The findings in this study offer a comprehensive solution that not only enhances the energy efficiency and sustainability of shared micro-mobility but also provides suggestions on the transportation and energy configuration of the hub.

2. MATERIAL AND METHODS

Fig. 1 illustrates the research framework adopted in this study. First, a modular prototype for shared electric micro-mobility hubs is proposed based on the characteristics of micro-mobility, PV systems, and shared power bank stations. Subsequently, utilizing data of micro-mobility behaviors, PV generation, and shared power bank rental behaviors, four different energy management strategies are considered to simulate energy flows in the hub. Lastly, a case study of a micro-mobility hub in Guangzhou is conducted to evaluate the electricity consumption patterns across 12 different scenarios, as well as the environmental and economic performance.

2.1 Modular prototype for shared electric micro-mobility hubs

The proposed micro-mobility hub module with dimensions of 2.4 x 2.5 x 2.7 meters, is designed to harmonize with the size of PV panels and various micro-mobility products. It facilitates easy installation, disassembly, and recyclability and offers the flexibility to incorporate specific transportation and energy elements based on user requirements, thereby accommodating diverse urban settings, travel demands, and local conditions.

2.1.1 Transportation elements

Two prevalent forms of electric micro-mobility products were selected (Fig. 2). The scooter, a stand-up micro-mobility vehicle, offers a speed comparable to bicycles while requiring less parking space [23]. Shared scooters were initially introduced in Los Angeles in 2017 and have since gained popularity across global cities [24]. While shared scooters have yet to be widely adopted in China, private scooter usage remains significant in the market. Mopeds, motorbike-style vehicles without pedals, have gained widespread traction as a shared micro-mobility option in various Chinese cities [25]. By 2021, the number of shared electric mopeds in China had nearly reached 4 million, effectively assuming a role in certain contexts that previously belonged to cars, buses, and bicycles [26].

Fig. 2 Two types of micromobility products: scooter(left) and moped(right).

The product specifications for the selected scooter and moped are presented in Table 1. Notably, the moped exhibits a higher speed, a longer typical range, and consequently, a larger battery capacity. Conversely, the scooter features a shorter charging time and a smaller physical footprint.

Table 1

Specifications of scooter and moped.

Parameters	**Unit**	**Scooter**	**Moped**
Size	mm	108*43*114	160*72*102
Battery Capacity	Wh	259	672
Maximum Speed	km/h	25	25
Riding Range	km	30	50
Charging Time	h	5	6
No. in each module	-	6	3

Utilizing shared micro-mobility travel data from Austin[27] and the assessment outcomes from the Guangzhou Traffic Bureau[28], several key travel behavior patterns can be summarized (Fig. 4). Higher travel frequencies are observed on Fridays and weekends. A peak in daily travel activity is witnessed between 18:00 and 20:00. The average daily turnover rate stands at 3.5 trips per vehicle, with an average single-trip duration ranging from 8 to 12 minutes.

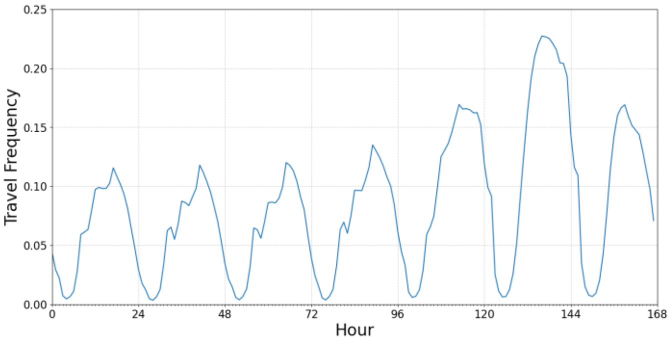

Fig. 3 Weekly travel frequency patterns of micromobility.

2.1.2 Energy elements

The micro-mobility hub will incorporate PV panels to harness renewable energy, while shared power bank stations will serve as energy storage solutions.

PV generation is currently regarded as one of the most widely accepted solutions in the field of construction for reducing energy consumption and carbon emissions [29]. The PV panels will be installed on the roof of the hub, with each module accommodating two panels, providing both energy generation and shading capabilities. Detailed specifications for the PV panels can be found in Table 2. The simulation calculations for PV energy generation will be conducted using the Ladybug Tools, a Rhino/Grasshopper plug-in [30].

Table 2

Specifications of PV panels.

Parameters	**PV panel**
Type	Mono-Si
Size	2465×1134×35mm
Temperature coefficient	-0.300%/℃
Module Efficiency	22%
Output Power	600W

The power bank station is featured with multiple charging slots, designed to hold and charge power banks until they are rented (Fig. 4 left). In the proposed micro-mobility hub, the power bank stations not only offer users the service of renting power banks, but also integrate with the hub's energy system, serving as energy storage for the hub. The daily rental behavior and the specifications of the shared power banks are illustrated in Fig. 4 right and Table 3.

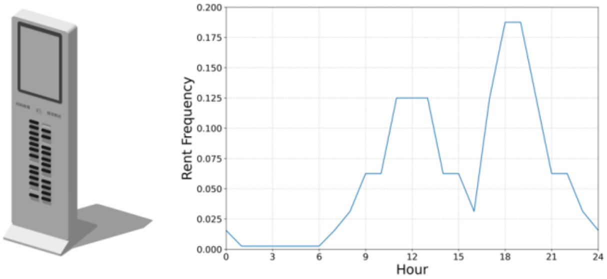

Fig. 4 Shared power bank station (left) and its daily rent frequency patterns (right).

Table 3

Specifications of shared power bank.

Parameters	Shared power bank
Size	5000 mAh
Battery Capacity	18.5 Wh
Input	5V2.1A
Output	5V2.4A
Charging Time	3 h
Leasing Price	CNY3/h

2.2 *Energy management strategies*

We simulated the energy system operations within the micro-mobility hub with Python using the micro-mobility travel behavior, PV generation, and power bank rental behavior from Section 2.1 as inputs and conducted a comparative study of four different energy management strategies (Fig. 5):

Strategy 1 serves as the baseline, directly charging micro-mobility vehicles from the grid—charging occurs immediately upon vehicle return, continuing until fully charged;

Strategy 2 integrates PV panels as an energy source. When PV generation is higher than the energy demand of micro-mobility vehicles, they are charged until full. If PV generation is insufficient, grid electricity is utilized;

Strategy 3 builds upon Strategy 2 by considering the potential for hub autonomy from the grid. Charging pauses when PV generation falls below the load, except when the battery state-of-charge (SOC) of the vehicles drops below a travel threshold (set at 30% in this study), prompting grid charging;

Strategy 4 extends Strategy 3 by integrating power bank station batteries for energy storage. PV energy charges both micro-mobility vehicles and power bank stations. If a vehicle's SOC falls below the travel threshold, power is initially sourced from the power bank station's batteries before resorting to grid electricity.

2.3 *Case study*

The case study focuses on a micro-mobility hub that consists of six modules and locates in Guangzhou, China. We employed twelve distinct scenarios to systematically assess the efficacy and efficiency of various vehicle configurations and energy management strategies.

In terms of vehicle configurations, the dimensions and battery specifications of both scooters and mopeds play a pivotal role in influencing factors such as parking capacity and charging behaviors within the hub. We intend to compare their individual performance as well as their combined effectiveness.

In the domain of energy element configurations, the manipulation of PV panel quantities, power bank station allocations, and the implementation of differing energy management measures are aimed at facilitating comparative analysis of their respective outcomes.

Consequently, three distinct vehicle configurations and four energy management strategies culminate in a total of twelve settings, as outlined in Table 4.

2.4 *Assessment metrics*

This study employs annual carbon emissions and payback period to assess the environmental and economic performance of various scenarios.

Annual carbon emissions are utilized to evaluate the environmental impact of the micro-mobility hub's operations, calculated as shown in Equation (1):

$$Annual\ Carbon\ Emissions = E_{grid} \times EF \tag{1}$$

where E_{grid} is the total grid energy consumption in a year, in kWh; EF is the emission factor of the China Southern Power Grid, which is 0.3748 kgCO$_2$/kWh.

The payback period represents the time required from the commencement of an investment until it generates returns [31]. It serves as a pivotal indicator for evaluating the attractiveness of investment projects. In this study, all S1 scenarios were used as baselines, treating energy elements as additional investments. The payback period is calculated as shown in Equation (2):

$$Payback\ Period = \frac{Initial\ Investment}{Annual\ Net\ Income} \tag{2}$$

where *Initial Investment* represents the total investment cost of the PV panels and shared power bank station; *Annual Net Income* refers to the annual gains achieved by saving on electricity costs, the remaining PV grid export revenue and the profits derived from the shared power bank station operations (with profit sharing set at 50% in this study).

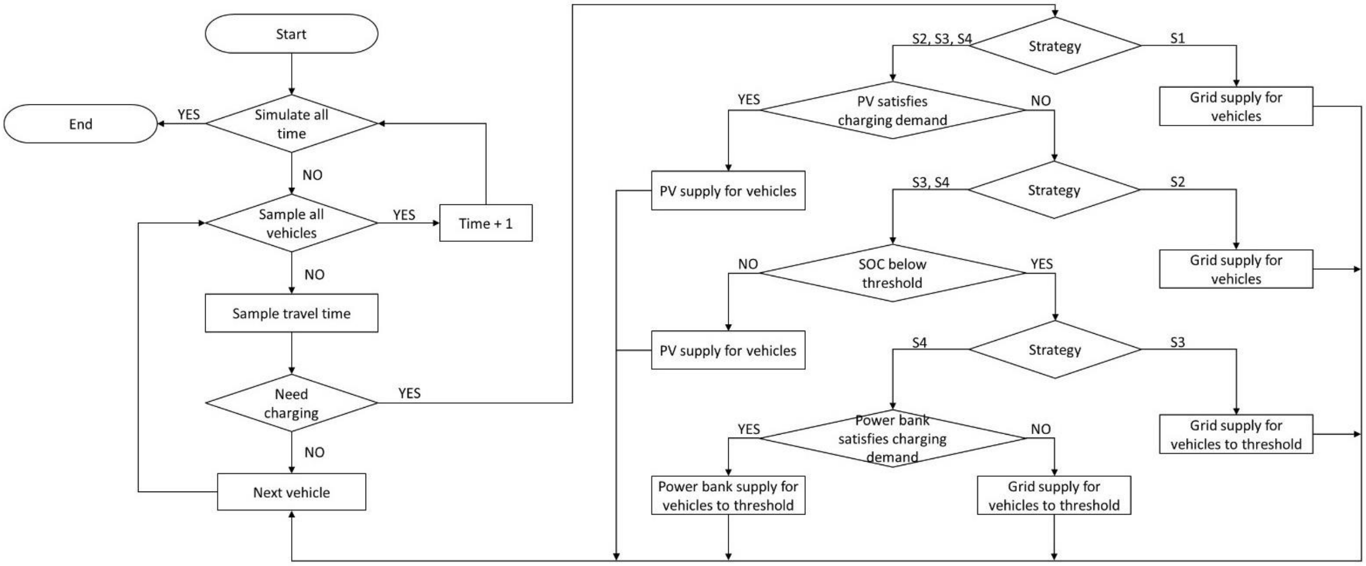

Fig. 5 Process diagram of four energy management strategies.

Table 4
Scenario Setting.

Scenario	Transportation		Energy		Energy Strategy
	Scooter	Moped	PV panels	Power bank Station	
V1_S1	36	/	/	/	1
V1_S2	36	/	12 sqm	/	2
V1_S3	36	/	12 sqm	/	3
V1_S4	36	/	12 sqm	24-port shared power bank station (1/3 as stationary energy storage)	4
V2_S1	/	18	/	/	1
V2_S2	/	18	12 sqm	/	2
V2_S3	/	18	12 sqm	/	3
V2_S4	/	18	12 sqm	24-port shared power bank station (1/3 as stationary energy storage)	4
V1+V2_S1	18	9	/	/	1
V1+V2_S2	18	9	12 sqm	/	2
V1+V2_S3	18	9	12 sqm	/	3
V1+V2_S4	18	9	12 sqm	24-port shared power bank station (1/3 as stationary energy storage)	4

3. RESULTS AND DISCUSSIONS

3.1 Charging patterns in a typical summer week

We selected a mid-July week (2022-7-11 to 2022-7-17) as a typical summer week to examine the charging power and mean SOC of the hub under four different scenarios of V1(Fig. 6).

V1_S1 and V1_S2, featuring immediate charging upon return, exhibit similar charging patterns but with different power sources. The charging profiles align with the trends in travel behavior, with higher energy consumption observed on weekends and charging peaks consistently occurring in the evening hours. Some days also display a noon peak. In V1_S3, the implementation of specific charging strategies concentrates the charging during daylight hours when PV generation is active. The peak shifts to the morning, addressing the overnight grid burden. A minor grid supply is necessary during the night to sustain operations. In V1_S4, where shared power bank

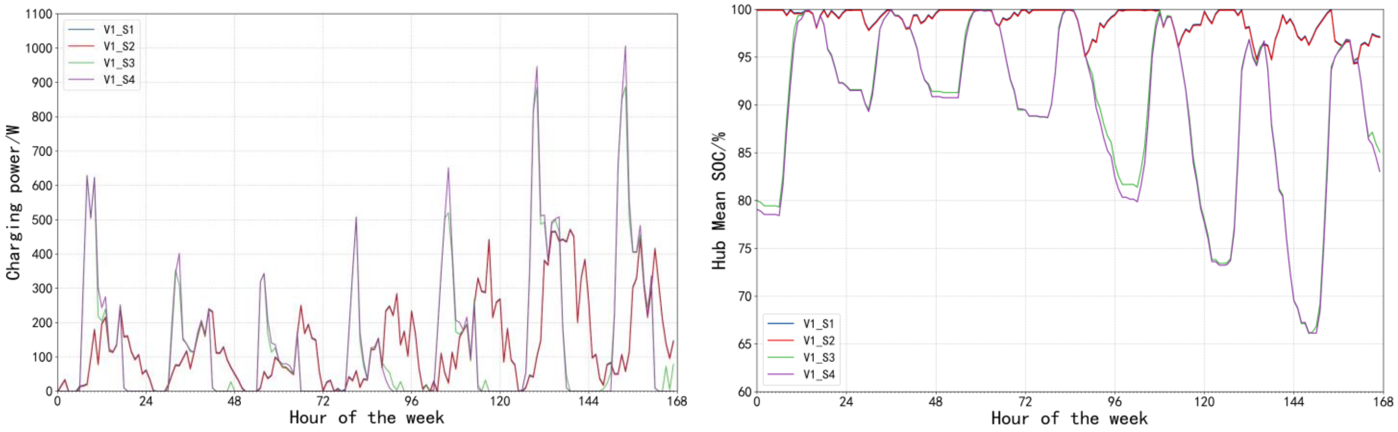

Fig. 6 Charging power(left) and Mean SOC (right) of the hub in a typical summer *week.*

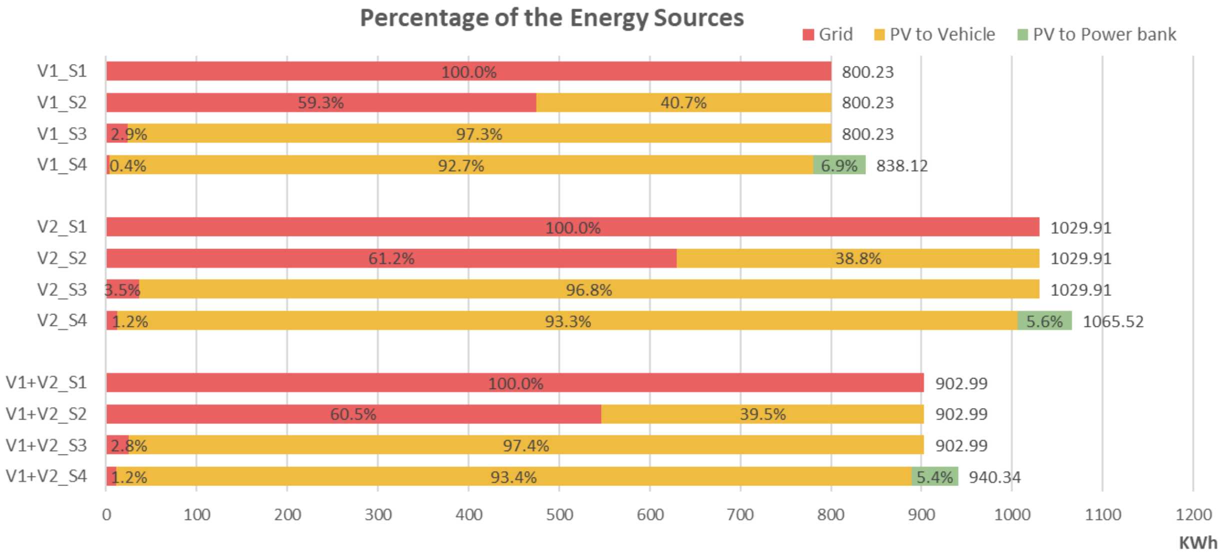

Fig. 7 The percentage of the energy sources of the hub under 12 scenarios.

stations serve as energy storage, the hub can be independent from the grid at night. However, due to the power demand of power bank stations, its charging profile is slightly higher than that of V1_S3.

In terms of the mean SOC within the hub, both V1_S1 and V1_S2 can consistently maintain levels above 95%, approaching close to 100% before the evening peak of travel demand. The high travel demand during the evening hours leads to reduced charging times at the stations, resulting in a slight decrease in SOC. For V1_S3 and V1_S4, due to limited grid charging, their SOC decreases to a range of 65% to 90% during the evening peak travel hours. The subsequent PV charging during the following day replenishes the SOC back to 100%. In V1_S4, where shared power banks supply energy at night, its SOC during the nighttime is slightly lower compared to S3.

Interestingly, even though some vehicles in S3 have SOC levels below the travel threshold and require grid charging, the mean SOC of the hub remains at a relatively high level. Further, considering the potential for vehicle-to-vehicle charging, the hub might be able to manage without grid supply.

3.2 *Energy sources distribution, annual carbon emissions and payback periods of different scenarios*

We further analyzed the annual energy sources of the micro-mobility hub under the 12 scenarios (Fig. 7). Despite the shared moped's parking capacity being half that of the scooter, due to its larger battery capacity and higher energy consumption rate, the annual total energy consumption of the shared moped is nearly 1.3 times that of the shared scooter. The combined V1+V2 scenario's energy consumption lies between that of V1 and V2. Under the same vehicle configuration, the annual total energy consumption remains consistent across S1-S3 scenarios, while the inclusion of shared power bank stations in S4 scenarios leads to an increase of approximately 40 kWh.

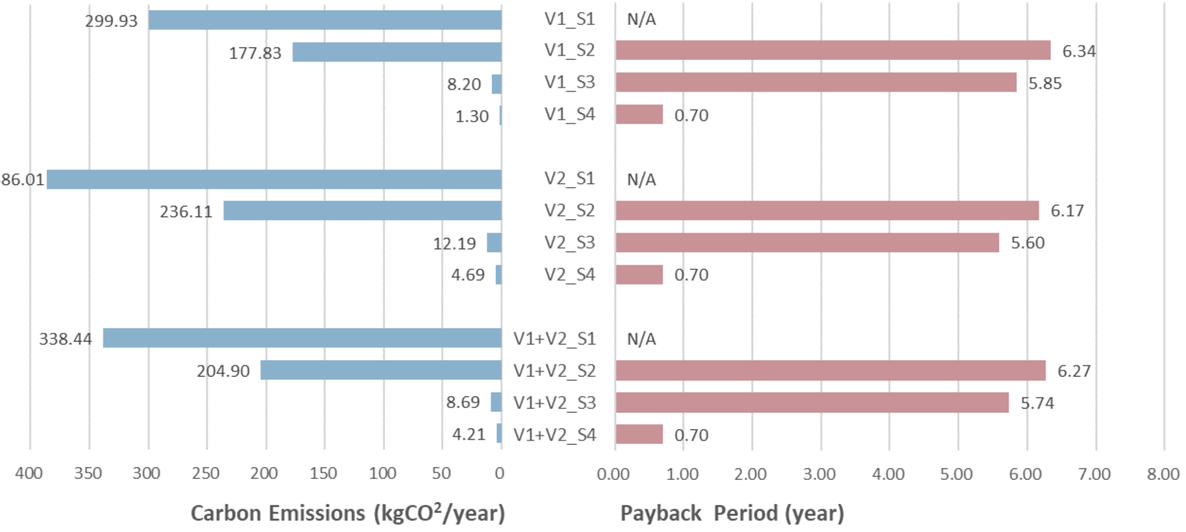

Fig. 8 Annual carbon emissions and payback periods of the hub under 12 scenarios.

In the S2 scenarios, PV supply contributes to around 40% of the total energy consumption. This distribution is due to the higher travel demand during the evening hours, resulting in approximately 60% of energy sourced from the grid during nighttime hours. In the S3 scenarios, where the constrained charging strategy 3 is implemented, the PV supply proportion dramatically rises to around 97%, with grid energy consumption primarily occurring during minimal nighttime usage. Notably, in the V1+V2_S3 scenario, the PV supply proportion slightly surpasses that of V1_S3 and V2_S3 scenarios, indicating that mixed vehicle configurations contribute to a higher level of self-sufficiency. Incorporating shared power bank stations in the S4 scenarios further reduces grid dependency to about 1%. In fact, the shared power banks largely cover the nighttime grid supply in S3, yet during continuous overcast days in the winter and spring seasons, a minor grid supply is still necessary due to insufficient PV output.

Subsequently, we calculated the annual carbon emissions and payback periods for each scenario (Fig. 8). The trends of annual carbon emissions closely resemble those of grid energy consumption. In S3 and S4 scenarios, annual carbon emissions significantly decrease, indicating that the micro-mobility hub achieves near-zero carbon operation. Regarding payback periods, due to the slightly lower PV grid export tariff compared to the grid electricity tariff in Guangzhou, the S3 scenarios result in a roughly half-year reduction in payback periods compared to S2 scenarios. In S4 scenarios, the high inherent profitability of the shared power bank stations leads to payback periods of less than one year. The differences in payback periods among various vehicle configurations are relatively small.

A comprehensive assessment of both environmental and economic performance across each scenario reveals that S2 scenarios can reduce annual carbon emissions by approximately 40% and achieve a payback period within 7 years. This is acceptable considering the 25-year lifespan of PV panels. Scenario 3, with a payback period of less than 6 years while nearly achieving zero carbon emissions, makes it a notably environmentally conscious option.

Scenario 4 not only achieves near-zero carbon operation but also achieves a payback period of less than one year. The integration of shared power bank stations with the micro-mobility hub proves to be a highly favorable option both in terms of economics and environmental performance.

3.3 Discussions

Although this study focused on a singular case study within China, the modular nature of the proposed micro-mobility hub prototype allows for its adaptability to diverse locations. Furthermore, its versatility extends to accommodating various types of micro-electric vehicles, such as e-bikes and Segways. This inherent flexibility implies that the findings and insights gained from this study have broader implications beyond the specific context examined.

Upon real-world implementation, numerous factors can influence the generation and consumption behavior of the micro-mobility hub. Factors such as building shading in actual urban environments could diminish PV generation [20], and variations in urban density and function might alter micro-mobility travel patterns and shared power bank rental behaviors. These dynamics could ultimately impact the hub's performance. However, the methodology and energy management strategies presented in this article remain adaptable and relevant. They can be employed for testing and application, albeit with necessary adjustments to align with specific real-world conditions.

On the other hand, this study considers the profitability of grid-connected PV. In the event of significant future reductions in grid-connected PV electricity prices, scenarios with lower self-consumption rates of PV might experience notable impacts on their economic performance. Further investigation could explore the effects of altering the configuration of PV panels and shared power bank stations on both economic and environmental performance.

In addition, this study has several limitations. It does not account for the effects of aging on PV panels, micro-mobility vehicle batteries, and power bank station batteries. Furthermore, the assessment of carbon emissions does not incorporate the embodied carbon of PV panels and power bank stations. These limitations suggest other potential areas for further research and refinement of the proposed micro-mobility hub concept to provide a more comprehensive understanding of its overall environmental and economic impact.

4. CONCLUSION

This study proposed a prototype of a micro-mobility hub that combines PV charging and shared power bank stations. Based on a case study in Guangzhou, we evaluated the performance of 12 scenarios involving different micro-mobility configurations and energy management strategies. The results indicate that installing PV panels alone, with immediate charging upon parking, can reduce carbon emissions by around 40%. With limited grid charging (strategy 3), the hub can achieve a remarkable reduction of approximately 97% in carbon emissions. Moreover, the integration of PV panels is able to achieve a net income gain within 6-7 years. When shared power bank stations serve as energy storage for the micro-mobility hub, carbon emissions can be reduced by 99%, and the stations lead to substantial profit enhancement, achieving payback within a year. These findings underscore the significant environmental and economic advantages of the micro-mobility hub integrating photovoltaic charging and shared power bank stations.

Another key finding is that when using different types of micro-mobility vehicles in the micro-mobility hub, the energy consumption of shared mopeds is approximately 30% higher than that of shared scooters. Mixing both types of vehicles can improve the photovoltaic self-consumption rate under strategy 3, highlighting the advantages of a hybrid micro-mobility hub configuration.

This study presents an innovative integration of China's popular shared power bank stations into a shared micro-mobility hub. Through energy operation simulations, we establish the potential for achieving zero carbon emissions and rapid returns. Furthermore, we offer recommendations for micro-mobility hub vehicle configurations and energy operation strategies. As shared services continue to gain popularity and diversity, there is an opportunity to establish an integrated shared micro-mobility hub that provides sustainable, low-carbon, and versatile travel and lifestyle services for people.

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DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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