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Performance Evaluation and Spatial Optimization of the "Photovoltaic + Carport" Model in Public Transportation Terminals

Junrui Mu[1*], Chunxiao Wu[2], Yuxuan Rong[3], Yunxi Zhang[3], Guang Li[4]

[1]*Institute of Mathematical Sciences, Chengdu University of Technology, Chengdu, China*
[2]*Institute of Environmental and Civil Engineering, Chengdu University of Technology, Chengdu, China*
[3]*Institute of Energy Engineering, Chengdu University of Technology, Chengdu, China*
[5]*Institute of Business, Chengdu University of Technology, Chengdu, China*
**Corresponding Author. Email: 3163480834@qq.com*

Abstract. To address the lag in charging infrastructure development during the promotion of new energy buses, this study proposes an integrated "photovoltaic + bus shelter" model targeting bus depots in Panzhihua City. Leveraging the city's abundant annual sunshine hours (2,700 hours), PVsyst software was used to simulate power generation efficiency at different installation angles, identifying the optimal tilt range (28°–31°) for each district. Field surveys of 20 representative bus depots identified a total of 26,518.75 square meters of convertible area, with an estimated total installed capacity of 5.46 MW and an annual power generation potential of 6.426 million kWh. In terms of environmental benefits, the project will reduce annual carbon dioxide emissions by 16,177 tons—equivalent to the carbon sequestration capacity of 884,000 trees—and save 2,570 tons of standard coal. Operationally, the PV shelters will alleviate 18.7% of peak grid loads and reduce bus charging queue times by 23 minutes. This paper innovatively proposes a three-pronged solution integrating "spatial restructuring, photovoltaic retrofitting, and smart charging." It provides a replicable and scalable model for overcoming infrastructure bottlenecks in promoting new energy buses, particularly in mountainous urban environments.

Keywords: photovoltaic bus shelters, bus depot retrofitting, PVsyst simulation, energy conservation and emission reduction, mountainous cities, charging infrastructure

1. Introduction

Against the backdrop of global energy transition and China's dual carbon goals, the photovoltaic industry has experienced rapid growth. Solar energy, a renewable resource with immense potential, is increasingly integrated into urban infrastructure. Panzhihua City possesses particularly abundant solar resources, with an average annual sunshine duration of 2,700 hours, classified as a Class II resource zone, offering natural advantages for developing photovoltaic applications [1]. By early 2024, new energy buses accounted for 59.33% (423 vehicles) of the city's fleet. However, the

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construction of supporting charging infrastructure has lagged behind, resulting in heavy reliance on the grid for vehicle charging and significant power supply pressure during peak hours [2].

Concurrently, the roof space of existing bus shelters within transit depots represents largely underutilized resources, offering ideal physical conditions for integrated photovoltaic construction. The "PV + Bus Shelter" model efficiently repurposes this space, enabling on-site generation and consumption of clean electricity to charge buses, thereby creating a synergistic cycle between green energy and green transportation. This approach holds particular value for mountainous cities like Panzhihua, characterized by limited land resources and complex topography.

Existing research has primarily focused on applications for building rooftops or large-scale photovoltaic power stations [3-6]. Systematic research on the integrated coupling of distributed photovoltaic power generation, spatial layout optimization, and charging scheduling specifically for bus depots in mountainous cities remains insufficient.

To address this gap, this study uses Panzhihua's bus depots as a case study, proposing an integrated "PV + Carport" solution. Employing a combined methodology of simulation (PVsyst, GIS) and field research, it systematically evaluates the technical feasibility, environmental benefits, and operational efficiency of this model. The aim is to provide a reference paradigm for green transportation transformation in cities with similar climatic and topographical conditions.

2. Project assumptions

To streamline analysis and enhance research efficiency, the team established the following key assumptions during the feasibility exploration of bus depot PV generation:

2.1. New energy bus dimensions

This study focuses on bus depots in Panzhihua City. Through systematic review of official documents from the Panzhihua Municipal Transportation Bureau and field survey measurements, the standard exterior dimensions for Panzhihua buses are uniformly defined as: 12 meters in length, 2.5 meters in width, and 3 meters in height. These dimensional parameters will serve as the foundational basis for subsequent depot planning, design, and capacity calculations.

2.2. Unit shelter measurement assumption model

To standardize photovoltaic coverage calculations, this study establishes a unit shelter measurement model. Each parking space is defined as 13m × 3.5m, with a 1m charging station installation zone reserved at the rear. The model comprises vertical and horizontal configurations (Figures 1 and 2), both featuring a roof inclination angle of α. The effective photovoltaic panel coverage area is determined by the following formula: - Vertical canopy: Roof width = 3.5m, length = $\frac{13}{\cos\alpha}$ m - Horizontal canopy: Roof length = 13m, width = $\frac{13}{\cos\alpha}$ m For equipment distribution and cost optimization, this study adopts a configuration where every two unit canopies share one charging station. When the total number of carports is odd, the charging station count is calculated as $N_{pile}=\lfloor N_{shed}/2 \rfloor$. The carport layout is shown below:

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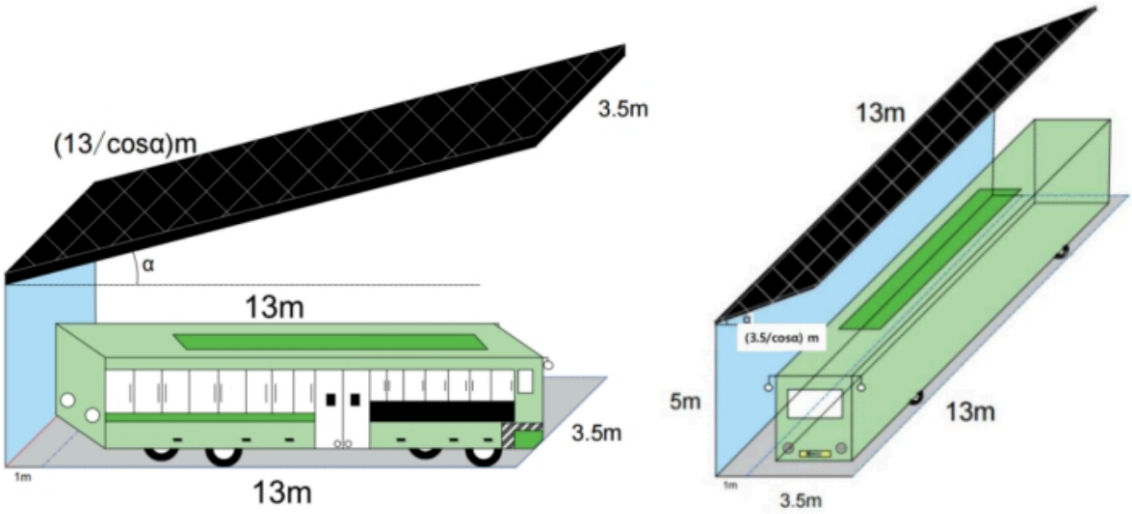

Figure 1. Horizontal unit carport measurement model

3. Bus depot distribution and preprocessing

To analyze the relationship between bus depot layout and urban functional zones, this study integrated multi-source data (bus routes, official depot records, AutoNavi Map API, and field surveys) to systematically preprocess and construct a Panzhihua City bus depot database. After data cleaning, GIS visualization revealed the spatial heterogeneity of depot distribution (Figures 3-8). Analysis indicates: - The Eastern District, as the core area, clusters 35 stations into a high-density cluster. - The Western District's 6 stations form a ribbon-like distribution along main thoroughfares. - Renhe District's 11 stations are arranged along Jinsha River Avenue. - Miyi and Yanbian counties primarily distribute stations along major transportation arteries. Station scales exhibit a three-tier differentiation, with their spatial functions deeply coupled to the urban structure.

Based on field investigations and multidimensional assessments, key selection criteria for photovoltaic application sites were established: sufficient canopy area, flat terrain, high average daily effective sunshine hours, low shading rates, existing or potential distribution needs, and good engineering feasibility. Through systematic screening, 20 typical sites were ultimately selected as research subjects for photovoltaic retrofitting.

The retrofit plan addressed existing infrastructure shortcomings: 25% of sites lacked designated parking spaces, 35% had ≤3 parking spaces, and 45% lacked charging facilities. Post-retrofit, 45 standard parking spaces were added, with a total of 225 charging stations installed. The total photovoltaic installation area reached 26,518.75 square meters (including 680 square meters on rooftops, 2,950 square meters in other areas, and the remainder under carports). Specific distributions are shown in Table 1. Results reveal significant regional differentiation potential. For instance, Panzhihua South Station in Renhe District offers an expansive 8,243.20 square meters for PV installation, while Taiping North Road Station in West District provides a smaller 157.61 square meter foundation for a compact system.

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Table 1. Installable area and charging pile modification status at bus terminals in Panzhihua City

Area	Station Name	Existing Number of Parking Spaces (Units)	Newly Added Parking Spaces (units)	Available Roof Area (m²)	Other available area (m²)	Total area available for solar panel installation (m²)	Total Number of Charging Stations (units)
MiyiCounty	Bus Station	18	10	120	0	1576.28	14
	Castle in the Sky	0	2	0	0	104.02	1
	Liu Xian	0	5	0	0	260.50	2
	Railway Station	3	0	0	0	156.03	1
	Yi'an Driving School	2	0	80	0	184.02	1
Yanbian County	Passenger Terminal	10	0	0	0	525.35	3
	Yanbian Terminal	28	0	0	0	1470.98	26
East District	Bajing	0	12	0	0	638.40	6
	Hulin Road	12	0	480	0	1118.40	6
	Xiao Panjiashan	6	0	0	0	255.36	6
	Xinmin Road	6	0	0	0	319.00	4
	Tianjin Road	34	2	0	0	1915.20	18
	Bingsan District Bus Stop	51	0	0	0	2713.20	21
	Jiangbian Street Charging Station	40	0	0	0	2128.00	20
West District	Taiping North Road	0	3	0	0	157.61	1
Renhe District	Panzhihua Railway Station	4	0	0	1750	August1956	2
	Panzhihua South Station	160	0	0	0	8243.20	80
	Lian Tong Street	0	2	0	1200	1303.04	1
	Luxie Bridge	16	0	0	0	824.32	8
	51st Square	4	9	0	0	669.76	4
Total		394	45	680	2950	26,518.75	225

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4. Solar radiation simulation analysis

This study employed PVsyst software to simulate the power generation of arc-free carport PV systems [7]. The software features comprehensive meteorological and module databases, supporting shading simulations and system loss parameter configuration. To validate input data accuracy, meteorological data from Panzhihua East District in the Metonorm 8.1 database was selected and compared with Solargis data, revealing a deviation of less than 5% [8].

Based on the PVsyst platform and incorporating local meteorological data, the optimal installation tilt angles for photovoltaic panels across each district/county were determined through simulation iterations, targeting maximum annual system power generation (Table 2). This method overcomes the limitations of traditional empirical formulas in complex mountainous terrain, with optimized tilt angles ranging between 28°–31° across districts. Taking the Eastern District as an example, the optimal tilt angle of 31° corresponds to a total solar radiation on the illuminated surface of 1937 kWh/m².

Table 2. Optimal tilt angle for each county

Region	East District	West District	Renhe District	Miyi County	Yanbian County
Inclination Angle (°)	31	30	28	29	30

To enhance simulation realism, the model comprehensively considers the following key losses:

Heat loss: A constant heat loss coefficient of Uc=29.0 W/m²K is applied.

Line Losses: DC line loss rate of 1.50%; AC line losses are negligible due to optimized cable cross-section and short-distance installation.

Module losses: Includes light-induced degradation (LID, 0.40% per year), power deviation, and mismatch losses (totaling approximately 2.0%).

Other losses: Annual system fouling loss set at 3.0%; annual module aging decay at 0.40%; and accounting for approximately 7.3 days of annual system downtime.

Based on the above model and the installable areas of stations across districts and counties, solar radiation levels for typical stations were simulated (Figures 16-20, Table 3-7). Results show that the annual average radiation density on inclined photovoltaic panels across Panzhihua's districts and counties is highly consistent, remaining stable within the range of 1622–1625 kWh/m², validating the simulation's stability and regional applicability [9].

Table 3. Summary of solar radiation simulations for bus terminals across districts and counties

Region	Photovoltaic Panel Area/m²	Annual Radiation/kWh	Annual Average Radiation Density/ (kWh·m⁻²)	Monthly Maximum Irradiance Density/ (kWh·m⁻²)	Monthly Minimum Radiation Density/ (kWh·m⁻²)
East District	9087.56	1.48×10^{7}	1623.8	174.0	96.7
West District	157.61	2.55×10^{5}	1622.8	173.9	96.6
Renhe District	12,996.40	2.11×10^{7}	1624.5	174.1	96.8
Miyi County	2280.85	$^{3}.70\times10^{6}$	1623.7	174.1	97.3

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Table 3. (continued)

Yanbian County	1996.33	$3.^{2}4\times10^{6}$	1622.3	174.0	96.3

5. Assessment of power generation benefits and application of models

5.1. Photovoltaic power generation capacity analysis

Power generation estimates were calculated using PVsyst simulations and the formula: $E=A\cdot G\cdot\eta$ (where A represents the photovoltaic area, G denotes the irradiation on the inclined surface, and η indicates the system efficiency). Taking the East District Lakeside Road site as an example, with an installed area of 1118.40 m², inclined surface irradiance of 1937 kWh/m², and system efficiency of 78.41%, the calculated annual power generation is 301,195 kWh. This aligns with simulation results, validating the model's reliability[10].

The power generation performance of representative stations in each district is shown in Table 8-12. Analysis indicates that annual power generation per unit ranges from 1301 to 1463 kWh/kWp, with system efficiencies between 74.34% and 78.58%. Among these, the Panzhihua South Station in Renhe District achieved the highest annual generation at 2,139,754 kWh. Stations in Miyi County demonstrated optimal power generation performance per unit, reaching 1454–1463 kWh/kWp.

5.2. Economic benefit assessment

Based on Panzhihua City's time-of-use electricity pricing policy (Table 14), with a calculated PV generation of 6,426,110 kWh:

Off-peak rate (0.30 yuan/kWh): Annual electricity cost savings of 1.9278 million yuan

Peak-period rate (0.75 RMB/kWh): Annual electricity cost savings of 4.8196 million RMB

In actual operation, PV generation aligns closely with bus charging schedules, yielding projected annual electricity savings between ¥1.9278 million and ¥4.8196 million, demonstrating significant economic benefits.

5.3. Environmental benefit assessment

Carbon reduction contributions comprise two components:

(1) Photovoltaic power generation reduction: 6,426,110 kWh × 0.785 kg/kWh = 5,044 tons CO_2/year

(2) Bus electrification emissions reduction: 13,842,721 km × 0.3 L/km × 2.68 kg/L = 11,133 tons CO_2/year

Total annual emissions reduction: 16,177 tons CO_2, equivalent to the carbon sequestration effect of planting 884,000 trees.

Resource Conservation:

Annual standard coal savings: 6,426,110 kWh × 0.4 kg/kWh = 2,570 tons

Synergistic reduction of pollutants including SO_2 and NOx: 6,426,110 kWh × 0.03 g/kWh = 9.7 tons

The environmental benefits overview shown in Figure 21 fully demonstrates the significant role of the "photovoltaic + public transport" model in promoting the green transformation of urban transportation.

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6. Conclusion

Based on the actual needs and resource endowments of Panzhihua City's bus depots, this study systematically explored the feasibility and application value of the integrated "photovoltaic + bus shelter" solution, drawing the following main conclusions:

6.1. The photovoltaic bus shelter model demonstrates significant comprehensive benefits

Technologically, it fully leverages Panzhihua's abundant solar resources. Simulation calculations validate the technical feasibility of generating approximately 6.426 million kWh annually across 26,518.75 square meters of convertible area with a 5.46 MW installed capacity. Environmentally, the project can help reduce carbon dioxide emissions by 16,177 tons annually and save 2,570 tons of standard coal, providing strong support for the region's "dual carbon" goals. Additionally, the system's innovative energy storage configuration enables "peak shaving and valley filling" for electricity loads, optimizing regional grid dispatch through grid-connected operation.

6.2. Innovative model effectively solves collaborative development challenges

Empirical research at Panzhihua's bus depot demonstrates that the "photovoltaic + bus shelter" model successfully addresses systemic challenges—such as infrastructure lag and insufficient energy supply—encountered during new energy bus deployment. This is achieved through a three-pronged solution: spatial reconfiguration, photovoltaic retrofitting, and smart charging. This model not only achieves deep integration of renewable energy and public transportation technologically but also establishes a multi-stakeholder win-win benefit mechanism in practice. It provides a replicable and scalable practical paradigm for cities with similar topographical features to achieve low-carbon transformation in the transportation sector.

In summary, photovoltaic retrofitting of bus depots serves as both a key technological pathway for advancing transportation electrification and a crucial entry point for building green, resilient urban infrastructure. Future research should further explore intelligent coordination strategies for optimizing photovoltaic power generation and charging scheduling, as well as the model's potential for broader application across urban spaces.

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