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Energy and environment potential by urban building-integrated photovoltaic in China#

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ABSTRACT

As urban expansion drives escalating building energy consumption, responsible for a third of global energy-related CO_2 emissions, building-integrated photovoltaics (BIPV) present a multifunctional renewable energy solution. Addressing the limitations of previous single-city evaluations, this study establishes a spatial assessment framework integrating both rooftop photovoltaic (RPV) and facade photovoltaic (FPV) systems across prefecture-level 360 Chinese cities, encompassing 7.7×10^4 km² of installation areas. Our analysis demonstrates that the total BIPV generation potential reaches 10,023 TWh annually, equivalent to 126% of China's current electricity demand, in addition to a carbon mitigation potential of 8.32 Gt. Spatial cluster analysis reveals four distinct city typologies: high-density metropolises (Cluster 1), emerging industrial hubs (Cluster 2), developing inland cities (Cluster 3), and the cities in the western region (Cluster 4). Particularly, Cluster 1 cities exhibit 3.8 times greater photovoltaic potential per unit area than the national average, suggesting that these cities are strategic priorities for the energy transition. This spatially explicit evaluation methodology provides decision-support tools for optimizing photovoltaic urban planning and formulating regionalized renewable energy policies, offering practical insights for achieving carbon neutrality targets.

Keywords: Renewable energy, Building-integrated photovoltaics, Roof photovoltaic, Facade photovoltaic, Urban decarbonization

NONMENCLATURE

Abbreviations	
BIPV	Building-integrated photovoltaic
RPV	Rooftop photovoltaic
FPV	Façade photovoltaic
PV	Photovoltaic
ANOVA	Analysis of Variance

Symbols	
C_m	Carbon mitigation of the BIPV system
P_g	Power generation of the BIPV system
EF_{BIPV}	Average CO_2 emission factors

1. INTRODUCTION

Global urbanization is driving increased energy demand in buildings, which account for 37% of Global energy-related CO_2 emissions[1]. Building-integrated photovoltaic (BIPV) offers a dual-function solution by combining energy generation with architectural integration, supporting the renewable energy transition. With the development of GIS technology, existing research has advanced from assessing solar energy potential in individual cities to multi-city comparative evaluations, with analyses focusing on differences in solar energy potential across different urban areas[2].

A comprehensive energy and environment analysis is essential for assessing the systemic sustainability impacts of energy systems across their life cycle[3]. For China's renewable energy planning, evaluating the potential of BIPV at the city level is critical. Recent advancements in BIPV technology have expanded applications to building facades, prompting deeper analyses of photovoltaic (PV) potential based on building morphology. Yet, most studies remain limited to specific cities, leaving a gap in large-scale assessments.

To address this gap, this study develops a potential assessment framework for BIPV systems, incorporating rooftop photovoltaic (RPV) and facade photovoltaic (FPV). Utilizing urban building heights, solar radiation data, panel efficiencies, and module specifications, we quantify the BIPV power generation potential as well as the carbon mitigation potential of 360 prefectural-level cities in China. The methodology advances previous work through three key innovations: (1) nationwide coverage accounting for regional climatic and architectural variations; (2) coupled analysis of vertical and horizontal

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building surfaces; (3) development of city typologies to inform differentiated renewable energy policies. These outputs provide a decision-support platform for optimizing China's PV urban planning.

2. MATERIAL AND METHODS

2.1 Framework

To thoroughly evaluate the potential and influencing factors of BIPV at the urban level, this study constructs a multi-dimensional analytical framework (**Fig. 1**). Based on three-dimensional urban terrain data and incorporating architectural morphological analysis, this framework conducts precise spatiotemporal modeling of the developable capacity of RPV and FPV in urban buildings.

A quantitative evaluation system for BIPV resource potential is established by deconstructing the geometric characteristics of buildings in a systematic manner and combining this with a solar radiation model at the urban scale. Finally, by coupling architectural form parameters and solar resource distribution variables, this study proposes a BIPV potential assessment model tailored for Chinese cities. Considering the potential and spatiotemporal characteristics of BIPV, this model provides a decision-making support tool for photovoltaic (PV) urban planning.

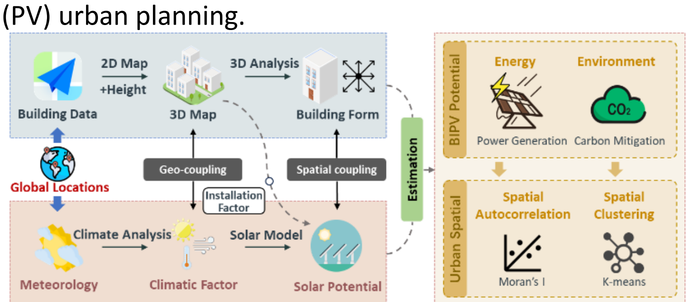

Fig. 1 Framework

2.2 Methods

2.2.1 Assumptions and system parameters

We made unified assumptions for the BIPV systems involved in this study. According to the current technical level of the PV industry the scale and performance parameters of PV applications were determined, including a RPV conversion efficiency of 20% and a FPV conversion efficiency of 15%. According recent literature review, the system efficiency correction parameters of PV module efficiency, solar radiation utilization, component surface contamination, etc. The average energy efficiency ratio of the PV system was calculated as 0.8[4].

The potential impacts of building rooftop appurtenances and the percentage of window openings and building shading on the building façade were considered. It was assumed that 70% of the building rooftop and 40% of the building façade could be used for the installation of BIPV systems.

2.2.2 Building Data

The building data comes from the GIS dataset provided by the Institute of Geographic Sciences and Nature Resources Research, Chinese Academy of Sciences. All building data is from May 2023.

2.2.3 BIPV power generation

The amount of electricity generated by a BIPV system is critical for subsequent potential assessments. For this purpose, we used a toolbox developed by Sandia National Laboratories called PV_LIB to calculate the power generation of BIPV systems. The toolbox covers modules for model selection, geographic location, and installation parameter settings, PV module and inverter configuration, temperature prediction, and power generation calculation. During the simulation, all the solar panels installed on the rooftop of the building face south and their tilt angle is set equal to the local latitude; all the solar panels installed on the building façade are kept close to the building façade and the tilt angle is set to 90°.

2.2.4 BIPV carbon mitigation

To assess the environmental potential of BIPV systems, the focus is on measuring their carbon emission reductions. Since the life cycle carbon emissions of the BIPV system are much smaller than the emissions prevented during the operation phase, any other life cycle phases are not considered.

The baseline emission factor for each city uses the average CO_2 emission factor for electricity at the provincial level to which it belongs. The carbon emission reduction factors of BIPV systems based on different power grids are calculated according to equation (1):

$$C_m = P_g \times EF_{BIPV} \tag{1}$$

where C_m is the carbon mitigation of the BIPV system, P_g is the power generation of the BIPV system, EF_{BIPV} is the average CO_2 emission factors.

2.2.4 Clustering analysis for location conditions

For the factors affecting the potential of BIPV: rooftop installation area, facade installation area, and solar radiation values. To analyze BIPV potential across different urban zones, the city is classified into distinct clusters using the K-means++ clustering algorithm, an improved version of the traditional K-means method that enhances initialization by spreading out initial centroids for more stable and meaningful groupings[6].

3. RESULTS

3.1 Study area

The research encompasses 360 cities across China, representing 96.77% of the nation's urban data, due to the unavailability of baseline emission factors for Hong Kong, Macau, Taiwan, and Tibet, as well as building data pertaining to Sansha, Hainan. **Fig. 2** provides solar radiation values and carbon emission factors for 360 cities. In this study, BIPV carbon mitigation potential is defined as the mitigation resulting from CO_2 replacement of grid electricity with electricity generated by the BIPV system.

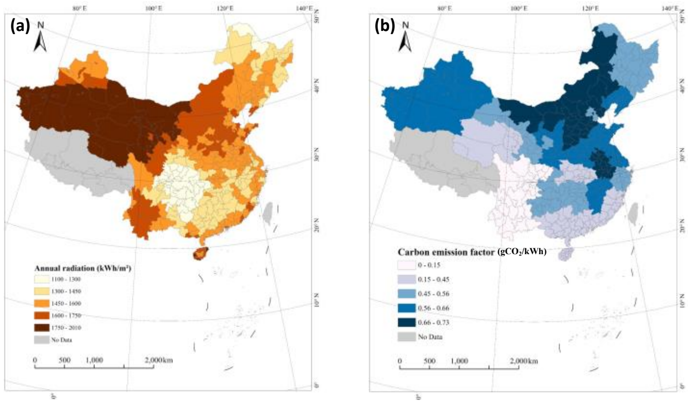

Fig.2 Study area parameters
(a)Annual radiation, (b)Carbon emission factor

3.2 Building Form

This study utilizes geospatial vector datasets to quantify rooftop and façade areas of urban buildings. **Fig. 3** presents the spatial distribution of building rooftop and façade areas.

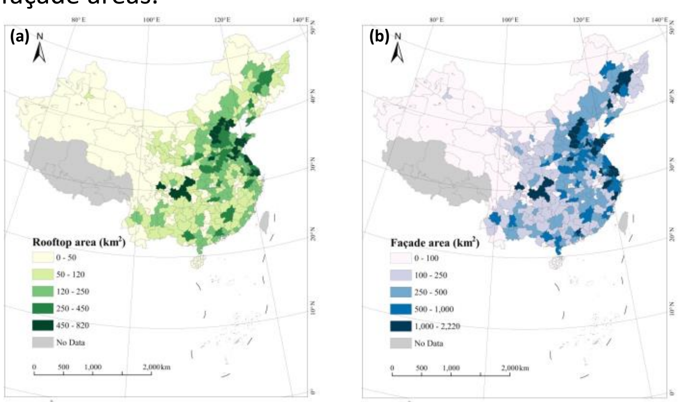

Fig. 3 Building rooftop and façade area by city
(a) Rooftop, (b) Façade

The buildings are mainly located in the southeastern part of the Hu Huanyong Line. The total areas of building rooftops and façades reached 4.49×10^4 km² and 1.14×10^5 km², respectively. RPV installation area and FPV installation area reached 3.14×10^4 km² and 4.56×10^4 km², respectively. Demonstrates a 145% increase in installation area by expanding the BIPV installation area to the façade.

Among them, only 5 cities had larger rooftop areas than façade areas. In 76% of the cities, the rooftop and façade areas were concentrated between 0.3 and 0.5. To analyze how building forms affect PV potential in future studies, this research examined building-form metrics such as building density and building aspect ratio. Building density was defined as the ratio of rooftop area to total urban area.

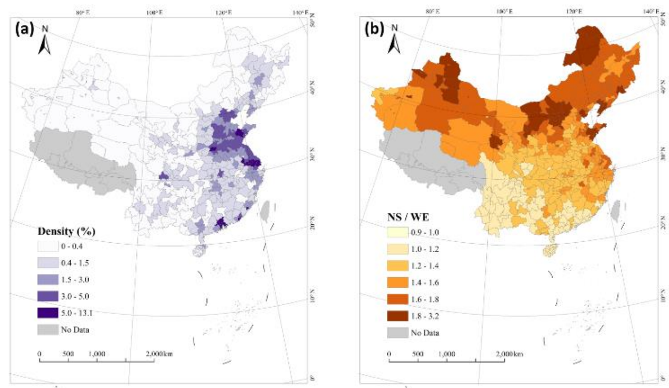

Fig. 4 Building density and aspect ratio
(a) Density, (b) Aspect ratio

High-density regions are predominantly found in Hebei, Shandong, Jiangsu, and Guangdong provinces, with Dongguan exhibiting the highest building density at 13.11%. Furthermore, the relative scarcity of land resources has driven the adoption of high-density construction practices to optimize spatial efficiency. Among these buildings, 99.7% are rectangular in shape, characterized by a "long north-south, wide east-west" orientation. The highest aspect ratio among them reaches 3.14. This particular layout offers a significant advantage for harnessing the maximum potential of south-facing façades.

3.3 Assessing current BIPV potential

To elucidate the differences in locational conditions determining the BIPV power generation potential, this study conducted intelligent zoning of 360 prefecture-level cities in China using an improved K-means++ clustering algorithm, with three key evaluation factors: rooftop installation area, facade installation area, and solar radiation values.

The optimal cluster number was determined as four groups through silhouette coefficient validation ($p<0.01$), effectively deconstructing the spatial hierarchical structure of BIPV resource endowment. Building upon the established geographic zoning model, the research further implemented one-way analysis of variance (ANOVA) with multiple comparison tests.

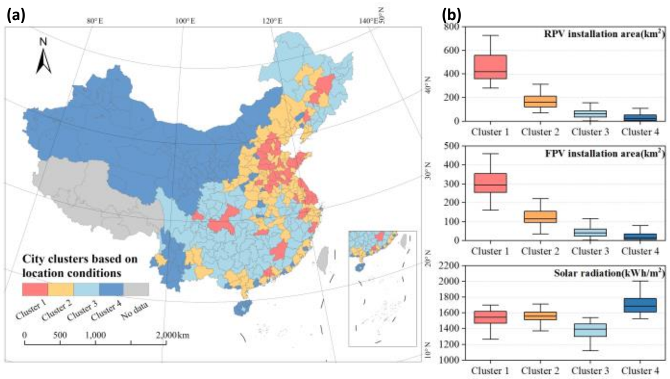

Fig. 5 Clustering analysis of cities, based on location conditions that determine the BIPV potential (a) Spatial distribution of cities in each cluster, (b) Location condition characteristics

As illustrated in **Fig. 5**, we observe distinct geographical clustering of cities within each cluster, indicating that adjacent urban agglomerations tend to share similar locational conditions for BIPV applications. Cluster 1 exhibits geographical dispersion while encompassing 37 cities, including several of China's most populous metropolises such as Beijing, Shanghai, and Chongqing, along with provincial capitals like Harbin, Suzhou, and Guangzhou. The substantial population size and economic stock in these cities correspond to significant building inventory, with Cluster 1 demonstrating exceptional BIPV deployment metrics: average RPV installations of 316.34 km² and FPV installations of 465.73 km², representing 3.62 and 3.67 times the national averages respectively. This cluster also maintains superior solar radiation levels at 1,527.30 kWh/m².

Cluster 2 predominantly occupies central and northeastern China, while Cluster 3 is distributed across eastern coastal regions. Collectively, these two clusters account for 55.11% and 54.47% of total rooftop installation areas nationwide. Notably, Cluster 2 achieves higher solar irradiance (1,552.52 kWh/m²) compared to Cluster 3's relatively lower radiation levels (1,376.38 kWh/m²). Cluster 4 cities are primarily located in China's sparsely populated and underdeveloped western regions, demonstrating the smallest average installation areas among all clusters, 22.55 km² for rooftops and 32.93 km² for façades, approximately half of the national averages. Paradoxically, this cluster records the highest solar radiation intensity at 1,698.25 kWh/m², suggesting significant untapped potential for PV applications in these regions.

3.3.1 BIPV power generation potential

The spatial distribution of RPV, FPV, and BIPV (Total) power generation potential from BIPV systems as shown in **Table 1**. Our analysis reveals that the aggregate BIPV generation potential across 360 Chinese cities in 2024 reaches 10,023 TWh, equivalent to 101.73% of the projected national electricity consumption. This demonstrates the technical feasibility of BIPV systems to fully satisfy China's electrical demand. The sectoral decomposition shows RPV and FPV contributing 5,389 TWh (53.77%) and 4,634 TWh (46.23%) respectively, indicating complementary spatial utilization patterns between roof and facade surfaces.

Table 1 Key indicators for the power generation potential of BIPV across 360 cities in China (Unit: Twh)

Power generation		Cluster 1	Cluster 2	Cluster 3	Cluster 4
	Minimum	27	6	0	0
	25% Percentile	43	15	4	1
RPV	Medium	51	20	7	3
	75% Percentile	60	26	10	6
	Maximum	98	68	17	23
	Minimum	26	7	0	0
	25% Percentile	38	13	3	1
FPV	Medium	44	17	6	2
	75% Percentile	56	22	8	6
	Maximum	89	32	22	15
	Minimum	65	19	0	0
	25% Percentile	81	30	7	2
BIPV	Medium	95	36	12	5
	75% Percentile	117	49	17	12
	Maximum	170	79	31	30

A hierarchical clustering analysis identifies four distinct city clusters with differential BIPV potential characteristics. Cluster 1, comprising the top decile of cities (10% of total cities), demonstrates superior generation capacity by contributing 3,777 TWh (37.69% of national total). Notably, the three highest-performing cities - Weifang (170.79 TWh), Zhengzhou (170.43 TWh), and Linyi (162.47 TWh) - exhibit generation capacities exceeding 11 times the annual output of the Three Gorges Hydropower Station (14.25 TWh). This exceptional performance correlates with their extensive PV installation areas (>1,000 km²), suggesting a strong positive relationship between available surface area and generation potential.

Cluster 2 accounts for 38.80% (3,889 TWh) of national generation, representing secondary high-potential urban centers. In contrast, Clusters 3 and 4, encompassing 62.78% of cities but contributing only 23.51% (2,357 TWh) of total generation, demonstrate constrained potential due to limited installable surface areas. These lower-performing clusters operate at 28.50% of the national average generation intensity, highlighting significant spatial disparities in BIPV implementation potential across Chinese cities.

3.3.2 BIPV carbon mitigation potential

The spatial distribution of power generation potential from RPV, FPV, and BIPV (Total) systems is illustrated in **Table 2**. The analysis reveals that by 2024, the total carbon mitigation potential of BIPV systems across 360 Chinese cities will reach 5.5 Gt, accounting for 43.65% of the nation's greenhouse gas emissions in 2023. Specifically, RPV and FPV contribute 54.17% (3.0 Gt) and 45.83% (2.5 Gt) of the total mitigation potential, respectively. The city-level mitigation potential exhibits substantial variation, ranging from 0.007 Mt to 109 Mt, with a mean value of 15.3 Mt. This study therefore provides critical insights into the significant spatial heterogeneity of mitigation potential at the urban scale.

Table 2 Key indicators for the carbon mitigation potential of BIPV across 360 cities in China (Unit: Mt)

PV type		Cluster 1	Cluster 2	Cluster 3	Cluster 4
RPV	Minimum	7	1	0	0
	25% Percentile	23	8	1	0
	Medium	32	11	3	1
	75% Percentile	40	16	5	3
	Maximum	64	49	9	9
FPV	Minimum	7	1	0	0
	25% Percentile	22	7	1	0
	Medium	25	10	2	1
	75% Percentile	35	13	4	3
	Maximum	52	22	11	9
BIPV	Minimum	14	3	0	0
	25% Percentile	46	16	3	1
	Medium	55	21	5	2
	75% Percentile	76	29	9	6
	Maximum	109	57	15	17

Advanced cluster analysis identifies that Cluster 1 cities demonstrate exceptional carbon mitigation capacity, contributing 2.23 Gt, 40.48% of national BIPV potential, with an average mitigation level 3.9 times the national mean. Notably, the Three Gorges Power Station achieved cumulative carbon mitigation of approximately 1.32 Gt over two decades, while leading cities in Cluster 1 - Weifang (109 Mt), Baoding (106 Mt), and Linyi (104 Mt) - are projected to surpass this historical benchmark within merely 13 years of BIPV implementation.

Cluster 2 shows a strong reduction potential of 2.2 Gt, forming a dual-core driving mode with Cluster 1, which together account for 80% of the national BIPV potential. In contrast, Cluster 3 and Cluster 4 show the paradoxical phenomenon of “high emissions-low mitigations”, with the average emission reduction of the cities with higher carbon intensity being only 4.76 Gt, 0.31 times the national average, which is mainly constrained by the limited BIPV deployment capacity. This discrepancy highlights the potential shortcomings of the current policy framework in terms of technology diffusion and industrial coordination.

4. DISCUSSION

4.1 Strategic prioritization framework for urban clusters

Our nationwide assessment reveals a hierarchical spatial pattern in BIPV implementation potential across Chinese cities, necessitating differentiated development strategies, and the BIPV potential of each cluster is shown in **Table 3**.

Table 3 BIPV potential for each cluster

Potential parameters	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Number of Cities	37	97	118	108
Power generation (Total)/TWh	3,777	3,889	1,500	857
Power generation (Ave.)/TWh	102	40	13	8
Carbon mitigation (Total)/Mt	2,230	2,203	679	397
Carbon mitigation (Ave.)/Mt	60	23	6	4

Firstly, Cluster 1 cities, including metropolises, should be given top priority. These cities not only have substantial rooftop and facade installation areas but also enjoy relatively high solar radiation levels. Their high building density and extensive building stock provide a solid foundation for large-scale BIPV deployment. The exceptional generation capacity and carbon mitigation potential of these cities make them key engines for driving China's BIPV development.

Cluster 2 cities also hold great potential and should be considered as secondary priority areas. These cities, mainly located in central and northeastern China, have large rooftop installation areas and relatively high solar irradiance. They can form a dual-core driving mode with Cluster 1 cities, contributing significantly to the national BIPV potential.

For Cluster 3 and Cluster 4 cities, which demonstrate constrained potential due to limited installable surface areas, a different strategy is needed. These cities, mostly situated in less developed regions, face challenges such as low building density or less favorable solar radiation conditions. It is suggested that cluster 3 focuses on the development of other renewable energy sources, while cluster 4 can concentrate on the development of PV power plants due to its “low building density-high solar radiation”.

In conclusion, by implementing a strategic prioritization framework that considers the varying BIPV potentials of different urban clusters, China can efficiently allocate resources, formulate targeted policies, and promote the widespread adoption of BIPV systems across the country. This will not only help meet China's growing electricity demand but also contribute significantly to its carbon reduction goals.

4.2 Regionalized Development Pathways

The spatial heterogeneity analysis underscores the necessity for geographically tailored implementation frameworks. East of the Hu Huanyong Line—housing 94% of China's population and 85% of built infrastructure—requires optimization of three-dimensional photovoltaic surfaces through parametric building design. High-density provinces (e.g., Hebei, Shandong, Jiangsu, Guangdong) must serve as pioneers in BIPV adoption, leveraging their dense urban agglomerations to:

(1) Maximize rooftop and façade PV integration through algorithmic solar potential mapping.

(2) Implement building energy-performance mandates that incentivize BIPV in new and retrofitted structures.

(3) Develop urban microgrids to enhance renewable energy absorption and grid resilience.

For western regions with dispersed urbanization patterns, decentralized BIPV deployment should prioritize. This spatial prioritization framework effectively addresses the "high-emission-low-mitigation" paradox in underdeveloped regions through three leverage points: technology leapfrogging, industrial symbiosis networks, and trans-regional carbon credit trading systems.

5. CONCLUSIONS

This study provides a comprehensive evaluation of BIPV systems across 360 Chinese cities, offering a detailed assessment of their power generation and carbon mitigation potential. By RPV and FPV systems, we have developed a robust spatial assessment framework that addresses the limitations of previous single-city evaluations. Our analysis reveals that the total BIPV generation potential is 10,023 TWh annually, significantly surpassing China's current electricity demand, and with a carbon mitigation potential of 8.32 Gt CO_2. Spatial cluster analysis has identified four distinct city typologies, highlighting the strategic importance of high-density metropolises (Cluster 1) in urban energy transitions.

The strategic prioritization framework proposed in this study highlights the differentiated development strategies for each city cluster. Cluster 1 and Cluster 2 together contribute 80% of the national carbon reduction potential, while Cluster 3 and Cluster 4 exhibit the paradox of “high emissions and low emission reductions” due to their limited surface area and decentralized infrastructure. Therefore, Cluster 1 cities and Cluster 2 cities have excellent BIPV potential and should focus on immediate large-scale deployment with targeted investments. For Clusters 3 and 4, the development of renewable energy technologies beyond BIPV is critical.

This research not only provides actionable insights for optimizing China's photovoltaic urban planning but also offers a decision-support platform for formulating regionalized renewable energy policies. The innovative assessment framework and findings contribute significantly to the advancement of BIPV technology and the achievement of carbon neutrality targets.

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