Solar World Congress 2025

QUANTIFYING THE IMPACT OF URBAN MORPHOLOGY ON SOLAR POTENTIAL: A CASE STUDY OF RESIDENTIAL AREAS IN XI’AN, CHINA

Summary

The utilization of solar energy in residential areas is pivotal for advancing urban low-carbon transitions. However, accurate evaluation of this potential remains a persistent challenge. This study proposes a hierarchical index system to quantify the solar potential of urban residential areas, employing Xi’an as a representative case study. Through web and field investigations, 100 residential models were derived, facilitating comprehensive solar potential simulations, benchmark development, and scoring equation formulation. The system's validity was empirically verified, followed by correlation analyses examining the relationship between morphological indices and SP across three hierarchical scales. The findings offer actionable design insights for optimizing solar energy capture in urban residential planning.

Keywords: Solar potential, Urban morphology, Residential areas, Evaluation

1. Introduction

Solar energy has emerged as a critical renewable resource for decarbonizing the built environment. With over half of the global population residing in urban areas and continued urbanization trends, optimizing solar energy utilization in urban settings has become an imperative research priority[1, 2].

Urban residential area (URA) morphology exerts a deterministic influence on solar irradiation accessibility and spatial distribution[2, 3]. Nevertheless, the quantitative relationship between settlement configuration and solar potential (SP) remains insufficiently characterized. This study employs Xi’an, China as a case study to establish a robust correlation between URA morphological parameters and SP, thereby providing evidence-based guidelines for solar-optimized urban residential planning and design.

2. Research methodology

The study follows a structured four-step methodology:

2.1 Data Collection and Modeling

Comprehensive data on 9,307 residential areas in Xi'an were collected through archival research and field surveys. A stratified sample of 100 representative cases was selected for detailed analysis (Fig. 1). Three-dimensional digital models of these areas were reconstructed to enable quantitative statistical analysis of their form and configuration patterns.

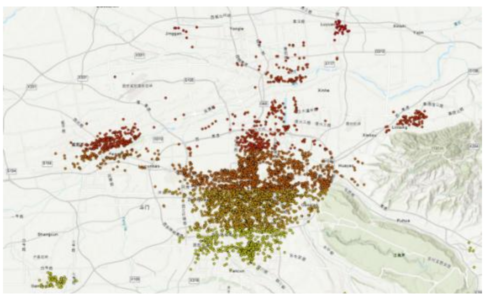

Fig. 1: Comprehensive data on 9,307 residential areas in Xi’an were collected

2.2 Solar Potential Evaluation

(1) Hierarchical Index System

A hierarchical index system were established to evaluation SP of the residential ares at four scales: plot, entire residential, building group and individual building, which were defined as access rate of solar irradiation on the plot, ratio of area that could potentially be used for PV or solar thermal system, ratio of area that could potentially be used for passive solar heating respectively. The threshold values for PV systems, solar thermal systems, and passive solar heating were established based on the methodology developed in R. Compagnon's seminal research[4].

(2) Simulation of SP values

The SP values of the 100 sample URA were simulated with Ladybug tool in Grasshopper software cross four hierarchical levels (plot, entire residential area, building group and individual building). For example, Tab.1 lists the simulated SP values at the Entire Residential level.

Tab. 1: Simulated SP values of URA at the Entire Residential level

Mo.	URA name	PV potential	Solar thermal potential	Passive solar heating potential
1	Weiyang-BL-LFGG	0.178	0.408	0.620
2	Weiyang-HR-HJHY	0.077	0.268	0.574
3	Weiyang-LH-FXT	0.204	0.39	0.582
...	...	...	...	...
99	Beilin-XLC	0.126	0.359	0.687
100	Beilin-RC	0.119	0.393	0.739

(3) Scoring and benchmarking

SPSS software was employed to develop score curves and equations for SP at each level. The mean index values served as benchmarks. For example, Fig. 2 illustrates the plot-level SP scoring curve for a sample URA.

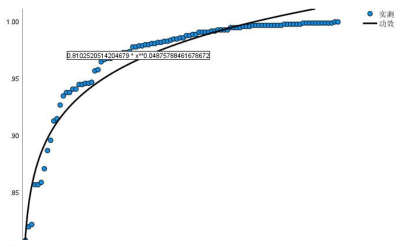

Fig. 2: Plot SP score curve

2.3 Correlation analysis

Correlations between SP and selected morphological indices (floor area ratio, building density, average building height, open space ratio, group layout, group shape coefficient) were analyzed at the Entire Residential Area, Building Group and Individual Building levels respectively.

3. Results and discussion

The score of SP evaluation for each of the 100 URAs across four hierarchical levels were achieved and visualized with a set of radar charts. For example, Fig.3 shows the SP of the JSCE residential area at the Plot and *Entire Residential* levels.

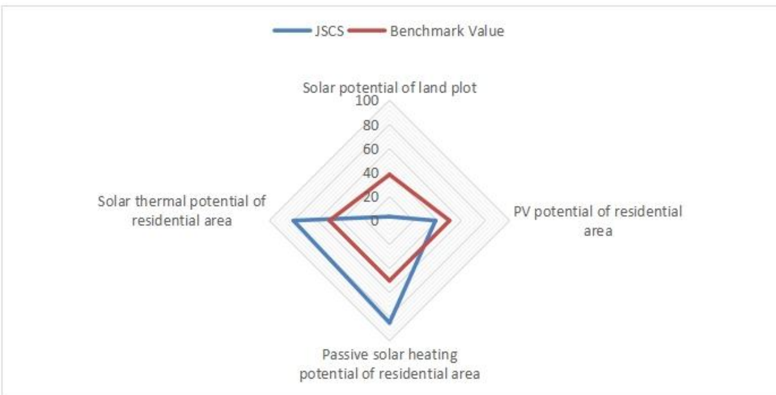

Fig. 3: SP of JSCS residential area at the Plot and Entire Residential levels

The study revealed significant correlations between solar potential (SP) and key urban morphological indices across different hierarchical levels. Key findings are summarized as follows::

3.1 Entire Residential Level

Both floor area ratio (FAR) and building density (BD) exhibited negative correlations with overall SP, as shown in Tab. 2. Open space ratio (OSR) demonstrated contrasting effects: while higher OSR values enhanced PV and solar thermal potential by increasing unshaded areas, they simultaneously reduced passive solar heating potential due to decreased building surface exposure.

Tab. 2: Correlation between SP and morphological indices

Morphological Index	PV Potential	Solar Thermal Potential	Passive Solar Heating Potential
FAR	-0.609	-0.653	-0.072
BD	-0.011	-0.058	-0.186
OSR	0.693	0.630	-0.079

3.2 Building Group Level

Shape coefficient (SC) showed a clear positive correlation with PV potential, as increased SC values enlarged roof surface area relative to building volume. However, this morphological characteristic negatively impacted passive solar heating potential by reducing facade-to-volume ratios. Although the statistical relationship between SC and passive heating potential was relatively weak, this trend aligned with theoretical expectations regarding building surface exposure.

3.3 Individual building Level

Morphological differences significantly influenced SP. Point-type residential buildings demonstrated superior PV and solar thermal potential, benefiting from their compact forms and greater roof availability. In contrast, plate-type buildings performed better in passive solar heating potential due to their extended facade exposure. Building height also played a crucial role, with taller structures exhibiting reduced PV potential (stemming from lower roof-to-volume ratios) but enhanced passive heating potential (resulting from increased vertical surface area).

4. Conclusions

This study develops a hierarchical evaluation framework for assessing SP in URAs, which was systematically applied to analyze 100 representative cases in Xi'an. The investigation elucidates quantitative relationships between SP and seven key morphological indices, while clarifying the multi-level impacts of urban form on solar energy utilization. These evidence-based findings offer actionable guidance for optimizing solar performance in urban design across spatial scales.

5. References

[1] Marja Lundgren, Johan Dahlberg. IEA SHC Task51/Report B2 Approaches, Methods and Tools for Solar Energy in Urban Planning[R], 2018.

[2] K. Simon. Implementation of solar energy in the urban planning and design process - an evaluation of methods, tools, instruments and stakeholder constellations as a study-related design aid[R], 2017.

[3] B. Liu, Y. Liu, S. G. Cho, D. H. C. Chow. Urban morphology indicators and solar radiation acquisition: 2011-2022 review [J]. Renewable & Sustainable Energy Reviews, 2024, 199

[4] R. Compagnon. Solar and daylight availability in the urban fabric [J]. Energy and Buildings, 2004, 36 (4): 321-328.