

Article

Optimizing Solar Power Generation in Urban Industrial Blocks: The Impact of Block Typology and PV Material Performance

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Abstract: The block-scale application of photovoltaic technology in cities is becoming a viable solution for renewable energy utilization. The rapid urbanization process has provided urban buildings with a colossal development potential for solar energy in China, especially in industrial areas that provide more space for the integration of PV equipment. In developing solar energy resources, the block layout and the PV materials are two critical factors affecting the distribution of solar radiation and generation. However, few studies have analyzed how to select the most suitable PV materials for different layouts of industrial blocks to obtain the best generation. This study considered the layout of industrial blocks and PV materials simultaneously, and the generation yield was calculated when combined. A total of 40 real industrial block cases were constructed, and radiation distribution data on building surfaces of different block cases were calculated. Data on both were combined to calculate the generation of different PV materials for each block type. The findings indicated that single-story industrial blocks possessed the highest potential for solar radiation, primarily due to the higher percentage of roof area. The influence of PV materials on the installation rate of different building facades varied, with the installation rate of the west facade being the most impacted by PV performance and the roof being the least impacted. Using different PV materials in industrial blocks could lead to a 59.2% difference in solar generation capacity. For single-layer industrial blocks, mono crystalline and poly crystalline silicon were preferable to achieve higher power generation. In contrast, multi-story and high-rise industrial blocks were best suited for a-Si and CIGS to attain higher cost performance. The methods and results of this study guided the selection and installation of PV equipment in various block typologies, thereby improving the refinement of solar resource development, maximizing solar resource utilization, and promoting the development of energy conservation and carbon reduction in cities.

Keywords: block typology; photovoltaic materials; industrial blocks; optimization; impact and performance of solar power generation



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1. Introduction

Global warming represents the most significant threat to human societies and global ecosystems in the coming years [1]. Excessive energy consumption is a primary contributor to global warming [2]. Since cities account for approximately 78% of global energy use and 60% of global greenhouse gas (GHG) emissions, they represent the primary battleground for reducing energy consumption and carbon emissions [3]. The mitigation of excessive urban carbon emissions requires a sustained effort to develop renewable energy sources.

Solar energy is an efficient and renewable energy source that can be effectively integrated into buildings and widely adopted in urban areas [4,5]. The PVSITES initiative in Europe aims to promote the deployment of solar energy in urban areas by accurately quantifying the available solar energy potential in cities [6]. Similarly, China has committed to peak its carbon emissions by 2030 or earlier to achieve energy conservation and emission reduction, with plans to increase non-fossil energy usage to 20%, with photovoltaic energy being a key focus [7–10]. As such, enhancing the utilization of solar energy resources is crucial for Chinese urban areas to achieve low-carbon advancement [11].

The extensive adoption of solar energy in industrial buildings located within urban areas offers tremendous potential and numerous advantages [12–14]. Industrial buildings generally have substantial underutilized roofs and facades, providing ideal locations for solar energy development. The flat external surfaces of these structures are well-suited for installing PV panels. At the same time, as industrial buildings have a relatively high energy consumption level, they can maximize the consumption of PV generation, which helps to reduce the losses incurred by surplus electricity going online and mitigate the impact on the national grid [15]. Consequently, research aimed at harnessing solar energy resources within industrial blocks in urban areas represents a promising approach to achieving the objective of urban carbon reduction.

A crucial prerequisite for implementing solar energy in urban areas is a comprehensive and accurate assessment of its potential [16]. The continuous advancement of technology, specialized software such as geographic information systems (GISs), neural networks, and Grasshopper have been utilized to evaluate solar energy potential in various scenarios and scales with high calculation accuracy [17,18]. In a solar energy potential assessment conducted by Yaning An et al. [19] for the Shenzhen region of China, GIS and Grasshopper were employed to compute the solar radiation values of roofs and vertical facades in four representative areas of Shenzhen. The findings revealed that the buildings' total PV generation potential could exceed 88% of the local electricity demand. Furthermore, in a solar potential assessment study using the sun solar radiation model, the solar potential of the area was evaluated in conjunction with urban GIS data from the city of Baldejev in eastern Slovakia, and the study results confirmed that the PV potential of the region could cover two-thirds of the electricity consumption [20]. This demonstrates the impressive potential for solar energy development in cities, which can fulfill most energy requirements, and therefore warrants further in-depth research.

The urban form is crucial in determining the potential for solar energy development in urban areas [21]. Highly populated cities may suffer from mutual shading of buildings, reducing the capacity to harness solar energy. The typology of cities, including layout, height, orientation, and other indicators [22] of buildings within a block, can affect the potential for solar energy development. Ming Lu et al. [23] analyzed the impact of high-rise building layout forms on solar energy potential. They found that plot ratio, building density, and building height are the leading morphological indicators affecting solar energy potential. Research on solar potential in eight types of urban blocks showed that the U-shape has the highest average annual PV utilization potential of 143 kWh/m² and should be prioritized for PV panel placement [24]. A prediction study of solar radiation potential by K.H. Poon et al. [25] concluded that the average height of buildings within a block and height difference indicators could significantly impact solar potential. Furthermore, indicators describing the intensity of urban construction, such as building density and volume ratio, can reflect the degree of mutual shading and the relationship between buildings, and are closely associated with solar potential [26,27]. These indicators are widely used to assess solar potential in various urban blocks and show differences in different blocks and cities. For instance, a study of solar potential in residential blocks in Wuhan, China found that an increase in floor area ratio leads to an increase in solar potential [28]. In contrast, another study of solar potential in a mixed neighborhood in Adelaide revealed that floor area ratio decreases solar potential [29]. Overall, the urban form significantly influences solar potential, and further analytical studies are necessary to

examine the relationship between urban form indicators and solar potential in different types and regions of urban blocks.

Physical properties of PV materials directly affect solar power generation [30,31]. Silicon-based crystalline PV technology is the most prevalent technology currently available, mainly due to silicon materials' ready availability and environmental friendliness [32]. Other types of PV include thin-film technologies such as amorphous silicon, cadmium telluride (CdTe), and copper–indium–gallium–selenide (CIGS), as well as emerging technologies like organic photovoltaic (OPV) [33], perovskite photovoltaic (PPV), and dye-sensitized solar cells (DSSCs) [34]. In practical PV applications, environmental factors such as sunlight intensity [35,36], temperature [37], dust [38], and wind speed [39] can affect power generation efficiency [40]. Dust adhering to PV panels affected PV generation by hindering the interaction between the panels and the incident light [41,42]. Some studies [43] compared the effect of dust on the light transmittance of samples of PV panels with different placements under 120 days of uncleaned conditions. It was found that the light transmission decreased by 17.48%, 7.94%, and 14.13% for samples placed horizontally, vertically, and tilted, respectively. In addition, the operating temperature of the PV module was likewise a significant factor affecting the conversion of solar energy into electricity. Usually, manufacturers of PV devices stated the value of the power temperature coefficient for PV modules on the labels of PV products, which usually ranged from 0.3 to 0.5%/°C. This meant that for every 10 °C increase in temperature, the PV module temperature would be reduced to 0.5%/°C, which was the same as that of the PV module. That meant that for every 10 °C increase in temperature, the efficiency of PV modules decreased by 3 to 5% [44]. Moreover, the variability in materials among different PV panels leads to their varying responses to environmental factors [45,46]. A review study conducted by Martin A. Green et al. [47] on relevant articles up to 2020 summarized the performance of various PV materials under different environmental conditions. The distinct characteristics of each PV module type make them suitable for different scenarios of solar power generation, thereby emphasizing the importance of considering the kind of PV panels in researching the potential of solar energy resource exploitation.

Significant conversion efficiency and cost differences exist among various types of PV materials. Furthermore, different PV materials exhibit distinct power generation patterns under varying building configurations and solar radiation conditions. Consequently, when integrating PV panels with buildings, selecting appropriate PV panels is crucial to align with the distribution properties of solar radiation. This selection process is essential to maximize solar resource exploitation and increase user revenue.

However, previous studies have primarily focused on evaluating the potential for solar energy resource exploitation based on either block typology or PV material alone, whereas few studies have combined both block typology and PV material to determine the installation rate and power generation issues that arise when different PV materials are applied to different types of blocks or building surfaces. Therefore, to guide the design and planning of urban blocks for sustainable cities and the precise installation of PV equipment, it is crucial to summarize and explore the variations in power generation by different PV materials in various types of blocks.

This study, therefore, examines the impact of industrial block typology and PV material efficiency on the utilization of solar resources and provides recommendations for selecting appropriate PV materials based on different industrial block types. The ultimate objective is to offer guidance for designing industrial blocks and selecting PV materials to maximize solar resource utilization. To achieve this objective, the study would focus on the following aspects:

- (1) What are the differences between the distribution of solar radiation and the radiation potential of building facades in different layouts of industrial blocks?
- (2) What are the PV installation rates on the exterior surfaces of industrial blocks with different layouts when different materials are selected for PV equipment?

- (3) How will the PV equipment match different layouts of industrial blocks to obtain the best exploitation of solar resources?

2. Materials and Methods

This study was divided into three main parts. Firstly, the morphological characteristics of urban blocks and the performance parameters of PV materials were investigated by collecting information on urban industrial block cases and different PV products. (1) Block case selection is first, and is followed by (2) PV material selection. Secondly, the solar radiation simulation tool obtained the radiation data on the building surface in the block case according to the (3) solar radiation simulation. Finally, the radiation data and different PV materials were combined to analyze and conclude the installation rate and power generation of different types of PV in each block type. The findings are presented in (4) analysis, Figure 1.

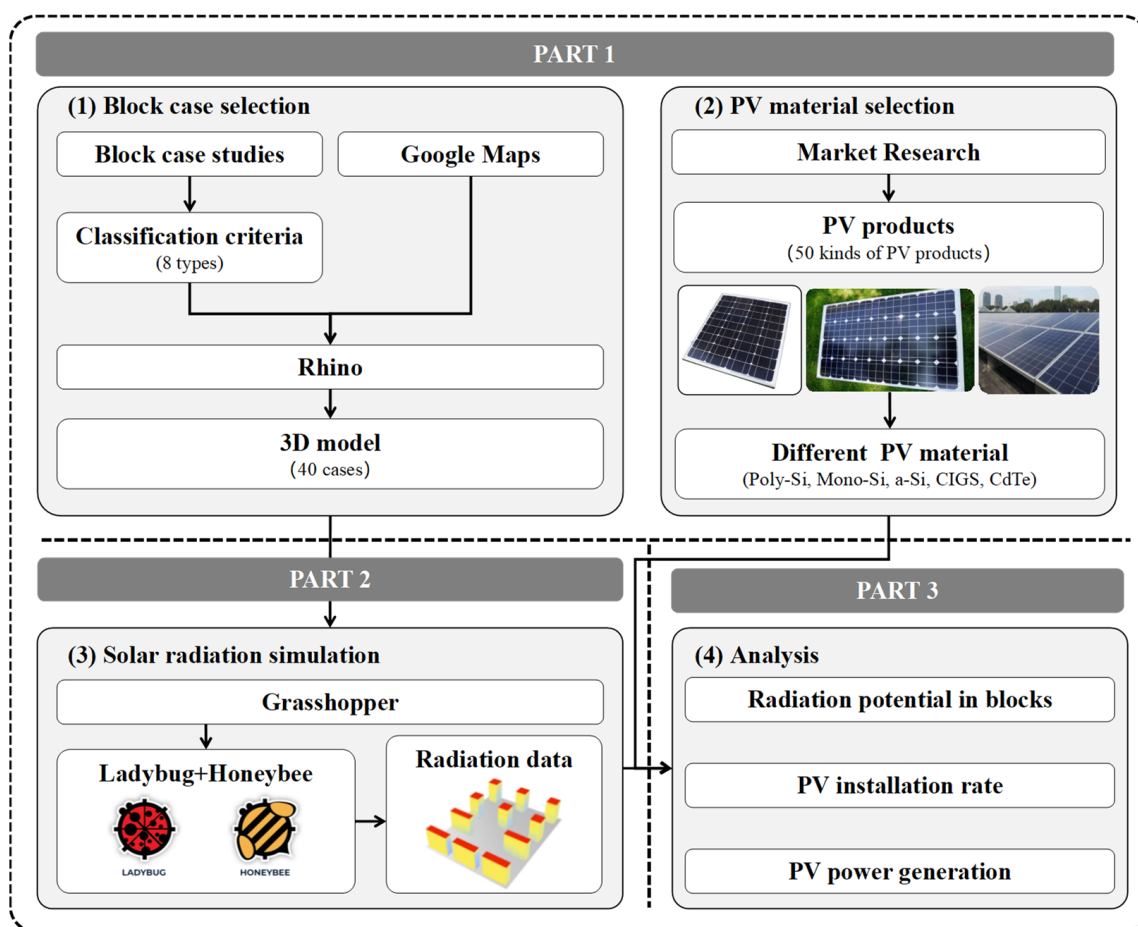


Figure 1. Workflow of the research.

2.1. Classification Criteria and Selection of Cases for Industrial Blocks

Wuhan, a densely populated city in China, was chosen as a case study. Digital information models were developed using field surveys and high-resolution satellite images of multiple industrial blocks in Wuhan. The study categorizes industrial blocks based on their morphological attributes, such as building height, layout, and other parameters.

The industrial block is a specialized urban block designed for industrial production, and its layout is primarily driven by production techniques. The height of the buildings in the block is a critical factor affecting the block's spatial configuration and shading relationships. According to national standards [48,49], industrial blocks are classified into single-story, multi-story, and high-rise blocks based on building height. In single-story

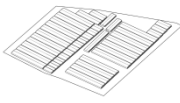
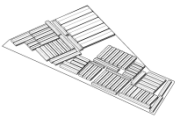
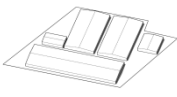
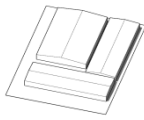
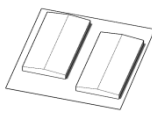
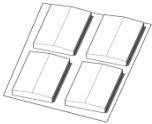
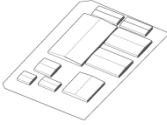
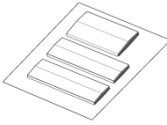
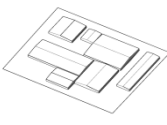
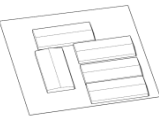
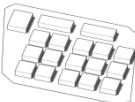
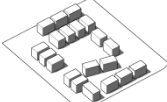
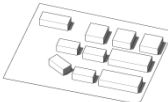
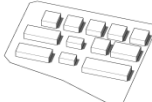
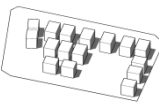
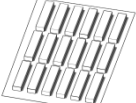
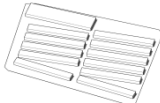
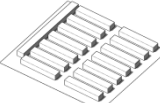
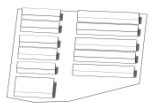
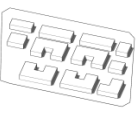
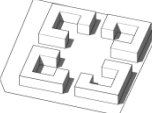
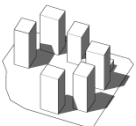
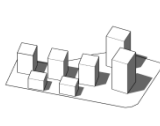
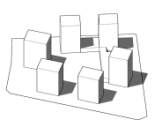
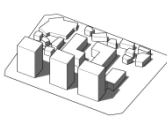
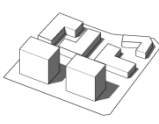
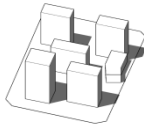
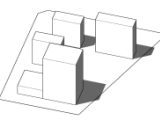
blocks, the buildings are all one-story primarily intended for heavy industries such as machinery and metallurgy. The main difference between multi-story and high-rise is whether the buildings in the block exceed 24 m [50]. The buildings in the multi-story blocks do not exceed 24 m in height and are predominantly used for light industries like food and textiles. The buildings in high-rise blocks are generally over 24 m in height and are mainly utilized for high-tech industries such as electronics and precision instruments. Then, the industrial blocks are further segmented according to their differences in form and layout. Single-story industrial blocks typically have flat-plan layouts with significant variations in building spans. Therefore, they can be classified based on their spans as small, medium, and large. Based on the weighted average width of buildings on the site, small-span industrial blocks do not exceed 36 m, medium-span blocks range between 36 m and 72 m, while large-span blocks exceed 72 m. Multi-story and high-rise industrial blocks are classified based on the weighted average of the height-to-width ratio of all buildings within the block. Multi-story blocks are classified into point, slab, and enclosed types based on the height-to-width ratio of their buildings, while high-rise blocks are classified into point and slab types. By these classification criteria, the industrial blocks in Wuhan were categorized into eight distinct types, as presented in Table 1.

Table 1. Classification criteria for industrial blocks.

Height	Typology	Classification Criteria
Single-story	Small span	• Single-story; • The weighted average of building widths < 36 m
	Medium span	• Single-story; • The weighted average of building widths 36 m–72 m
	Large span	• Single-story; • The weighted average of building widths > 72 m
Multi-story	Tower	• Multi-story and average building height < 24 m; • The weighted average of building aspect ratios < 2; • Point planes
	Slab	• Multi-story and average building height < 24 m; • The weighted average of building aspect ratios > 2; • Slab planes
	Enclosed	• Multi-story and average building height < 24 m; • The weighted average of building aspect ratios < 2; • Enclosed planes
High-rise	Tower	• High-rise and average building height of 24–100 m; • The weighted average of building aspect ratios < 2; • Point planes
	Slab	• High-rise and average building height of 24–100 m; • The weighted average of building aspect ratios > 2; • Slab planes

This study employed the classification of the above criteria to select 5 real cases for each of the eight industrial block types, thereby analyzing 40 different cases. The models of the above cases were constructed using Rhino tools. Table 2 shows the case models.

Table 2. Models of 40 industrial block cases.

Type		Models of Cases				
Single-story	Small span					
		A1	A2	A3	A4	A5
	Medium span					
		B1	B2	B3	B4	B5
	Large span					
		C1	C2	C3	C4	C5
Multi-story	Tower					
		D1	D2	D3	D4	D5
	Slab					
		E1	E2	E3	E4	E5
	Enclosed					
		F1	F2	F3	F4	F5
High-rise	Tower					
		G1	G2	G3	G4	G5
	Slab					
		H1	H2	H3	H4	H5

2.2. Selection of PV Materials and Performance Parameters

The photovoltaic effect is a phenomenon observed in certain semiconductor materials when exposed to solar radiation [51,52]. These materials include monocrystalline silicon, polycrystalline silicon, amorphous silicon, GaAs, GaAlAs, InP, CdS, and CdTe [53]. The photovoltaic effects of these materials can vary under different solar radiation conditions due to their unique characteristics, resulting in differences in PV conversion efficiency [46,54]. Monocrystalline PV panels, for instance, are more efficient at capturing and utilizing solar energy, resulting in a higher conversion efficiency [55,56]. However, the production of

monocrystalline PV panels involves higher costs and energy consumption than other types of panels.

This study carried out a thorough market research to investigate the characteristics of different solar panels that are commonly available in the Chinese market, given the country's wide usage of PV technologies. Monocrystalline silicon, polycrystalline silicon, amorphous silicon, CIGS, and CdTe [57] were chosen as the representative PV materials, and 50 products information were collected. Various parameters, such as photoelectric conversion efficiency, attenuation rate, and power density, were obtained from these PV products.

To facilitate the research, the arithmetic mean values of the performance parameters for each category of PV material were selected for subsequent calculations and analysis. The mean values for each material category were computed and displayed in Table 3.

Table 3. Average of performance parameters of different types of PV materials.

Types of PV Materials	Conversion Efficiency (%)	Attenuation Rate of PV System (%)	Power Density of PV Modules (W/m ²)
Poly-Si	17.92	1.40	174.30
Mono-Si	20.07	1.39	200.86
a-Si	8.08	1.40	71.593
CIGS	15.79	1.40	138.44
CdTe	16.14	1.40	172.63

2.3. Acquisition of Radiation Data

2.3.1. Acquisition of Solar Radiation Data from Building Facades in Blocks

In this study, the Ladybug and Honeybee plug-ins were utilized on the Rhino parametric platform Grasshopper for solar radiation simulation. Many scholars have recognized the use of Grasshopper for solar potential research [58], which is mainly due to the fact that solar radiation simulation using Grasshopper can fully take into account the effects of mutual shading, reflection, and diffuse reflection between buildings and can guarantee the accuracy of the simulation results. Previously, this research team had utilized this approach to validate measured and simulated solar radiation in Wuhan experimentally. This validation resulted in an error rate of less than 10%, which is considered to be within acceptable limits [59,60].

The simulation of solar radiation using the Ladybug and Honeybee plug-ins began by importing historical weather data from the Wuhan region into the Rhino 7. These data were used to create an accurate weather environment for the radiation simulation. To ensure the accuracy of the block solar simulation, the building surface was divided into a grid of 2 m * 2 m. The reflectance parameter of the building surface was established as 0.2 to account for the reflective properties of the building surface [61]. The simulation period was set for one year to derive the annual average radiation on the building surface. Figure 2 depicts the simulation framework of the calculation tool used for the simulation.

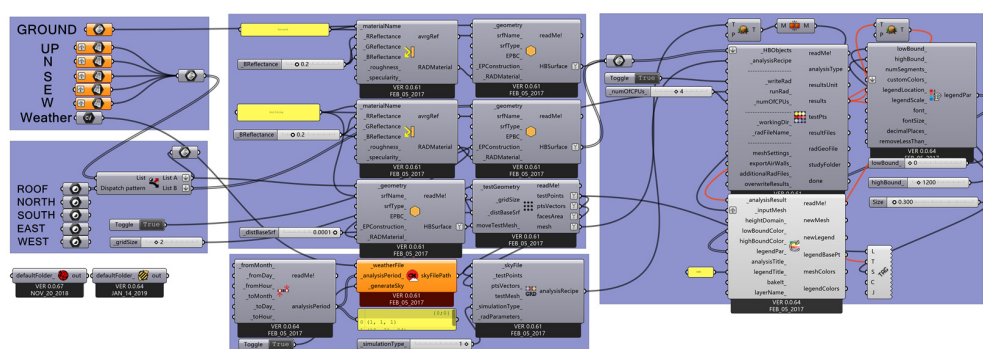


Figure 2. Solar radiation potential simulation workflow in the Rhinoceros Grasshopper platform.

2.3.2. Calculation of Radiation Thresholds

As for PV power generation, not all solar radiation can be efficiently converted into electricity. Therefore, it is necessary to consider both the technical and economic factors of a PV material to determine appropriate thresholds for radiation [62]. The threshold value refers to the minimum level of radiation required for a given PV material to operate efficiently. In this study, the life cycle balance of a PV system serves as a criterion to investigate the PV radiation thresholds. These thresholds are established based on the PV conversion performance, cost, and other parameters, which may vary significantly across different PV materials. In line with previous studies [63], the following equations (Equations (1) and (2)) can be utilized to calculate these thresholds.

$$C_{sys} = C_{pv} \times P_{pv} \times (1 + C_m \times N) \quad (1)$$

$$t = \frac{C_{sys}}{\eta \times K \times C_{ele} \times \sum_{i=1}^N (1 - R_d)^{N-1}} \quad (2)$$

In Equation (1), C_{sys} represents the PV system's overall cost, which considers the initial investment and annual maintenance costs. The unit power generation cost of the PV module is represented by C_{pv} , which is set to 5.5 RMB/W based on the IEA (International Energy Agency, 2018) standards [51]. P_{pv} denotes the power per unit area of the PV panels, which varies depending on the PV material utilized. C_m represents the annual maintenance cost factor, while N represents the life cycle of the PV module.

In Equation (2), the variable t represents the radiation threshold for the PV material under consideration. η denotes the photovoltaic conversion efficiency, which is dependent on its performance. R_d represents the PV system's attenuation efficiency, which considers the transmission loss caused by the PV module, the inverter, and other related components. The overall efficiency coefficient of the PV system, K , is set at 86% based on the findings of Kumar and Kumar [64]. C_{ele} refers to the revenue tariff for the generated electricity, which is comprised of the feed-in tariff and the government subsidies for PV power generation, set at 0.4 RMB/kWh and 0.08 RMB/kWh, respectively, resulting in a total of 0.48 RMB/kWh [65].

Using the equations and parameters above, the resulting thresholds were graphically displayed as a function of the PV module's life cycle. In accordance with the study's criteria, a 20-year life cycle was selected for the threshold calculations. The obtained radiation thresholds for the different PV materials are presented in Figures 3 and 4, as well as in Table 4.

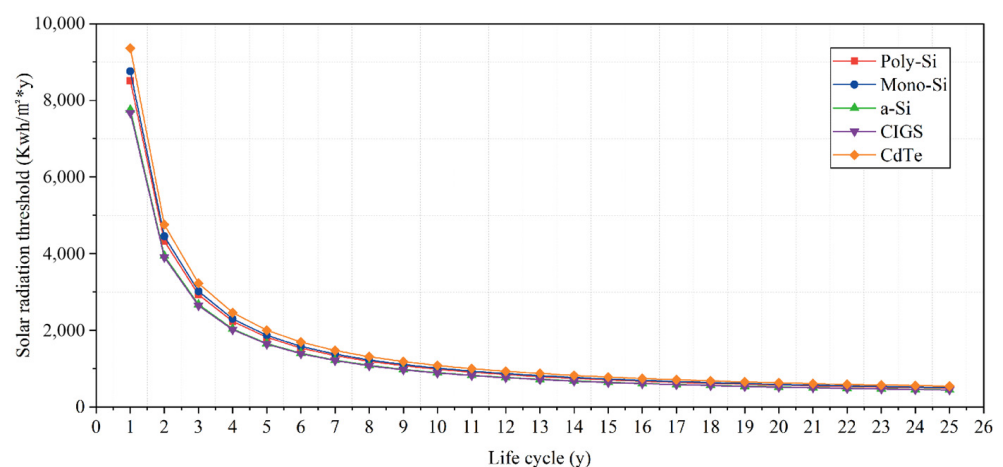


Figure 3. Relationship between solar radiation thresholds and life cycle (0–25 years) for different PV materials.

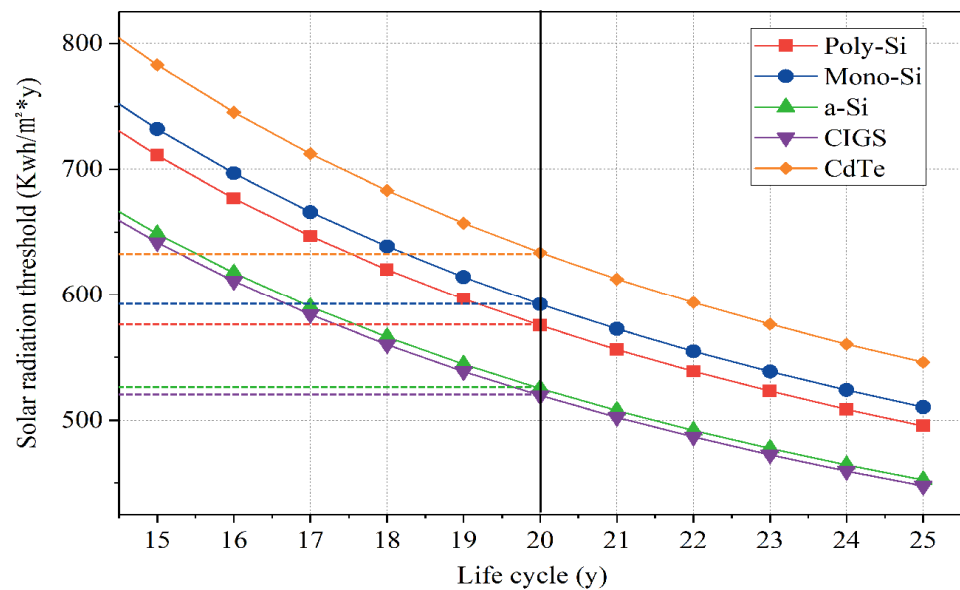


Figure 4. Relationship between solar radiation thresholds and life cycle (15–25 years) for different PV materials.

Table 4. Solar radiation thresholds for different PV materials.

Types of PV Materials	Solar Radiation Thresholds (kWh/m ² /y)
Poly-Si	575.28
Mono-Si	592.38
a-Si	525.12
CIGS	519.55
CdTe	633.73

2.4. Calculation of PV Power Generation

2.4.1. PV Power Generation

Annual PV generation assessments require consideration of parameters such as radiation distribution on building surfaces and threshold standards. In addition to this, the inclination and orientation of the PV panel installation are equally important influences on the amount of electricity generated by the PV system. However, since this study focused on the influence of block typology and PV materials on solar generation, the study assumed that the PV panels were installed in fixed forms and mounted parallel to the surface of the buildings in which they were located. The solar radiation distribution on the surface of the PV panels could be defaulted to be consistent with the solar radiation distribution on the building surface. With consideration of the above information, computation of PV equipment power generation could be accomplished by incorporating relevant national standards and utilizing Equation (3).

$$E_p = H_A \times A_{pv} \times \eta \times K \times (1 - R_d)^{N-1} \quad (3)$$

In Equation (3), the amount of electricity generated by the PV system denoted as E_p can be calculated by considering the amount of solar radiation received by the building surface, denoted as H_A . The installed area of the PV equipment on the building surface is denoted as A_{pv} .

The A_{pv} is influenced by the radiation threshold and the building surface installation factor. The radiation threshold is related to the material of the selected PV panel, as explained in Section 2.2. The installation factor is a discount on the building surface where the PV panels cannot be installed due to windows, dips, equipment, etc. The installation factors were obtained by collecting as well as processing images of the surfaces of the

buildings in the case block. Initially, accurate building surface information was gathered using satellite images from Google Maps and photos taken during the survey. Next, Adobe Photoshop Cs6 was used to identify areas on the roof or building facade suitable for PV module installation. Finally, the percentage of the building's external surface suitable for PV installations was calculated. The complete calculation process is illustrated in Figure 5. The installation factor data for the roof and facade of the buildings in each case block were shown in Figure 6.

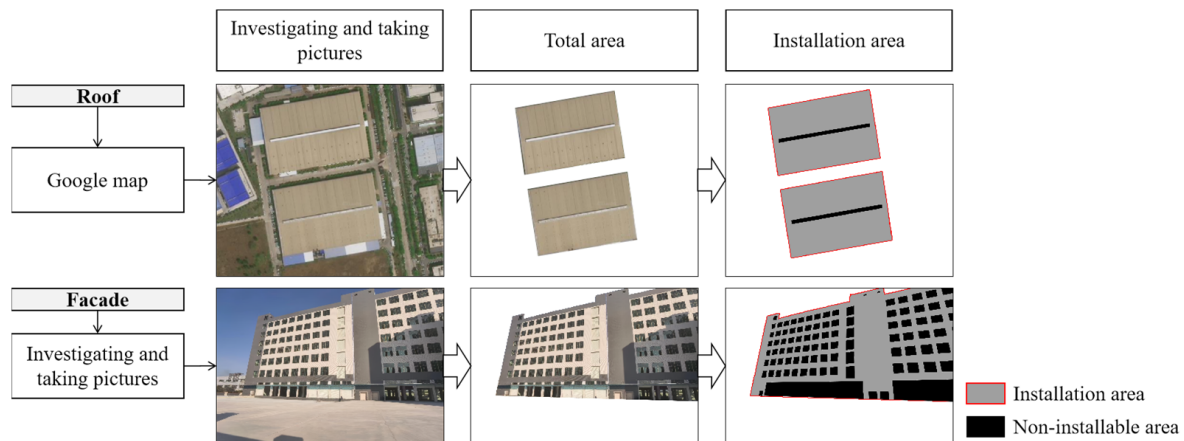


Figure 5. Method of obtaining the installation factor.

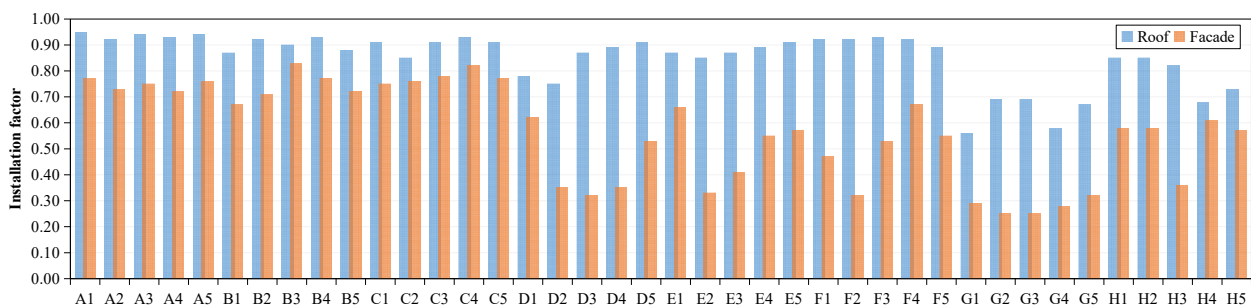


Figure 6. Installation factor statistics for roofs and facades.

As shown in Figure 5, the installation rate of building roofs is higher than that of facades in all cases; the average installation factor for roofs is 0.85, and for facades is 0.57, respectively.

2.4.2. PV System Cost of Power Generation

The economic viability of a PV system is paramount, and the cost of power generation is a critical factor in this regard. As a widely used and effective indicator to evaluate the economic performance of PV systems, the cost of power generation is defined as the ratio of each unit of electricity generated to the total cost of the PV system over its operating cycle, including both the initial investment and annual maintenance costs. To accurately assess the economic performance of the system, various factors, such as the total cost of the PV system (C_{sys}), the attenuation efficiency (R_d), and the annual energy production per unit area of the system (E_{ini}), were taken into consideration. The total cost of the PV system over its entire lifespan included both the initial investment cost and the later-stage maintenance cost. The initial investment cost was determined by the power generation per unit area of different PV panels and the investment cost per unit of power. Additionally, the annual maintenance cost for various types of PV systems was set at 2% of the upfront investment cost in this study. The total cost of various PV materials over a 20-year lifecycle was outlined in Table 5 below.

Table 5. Total cost of different PV materials.

Types of PV Materials	Total Cost of the PV System (RMB/m ²)
Poly-Si	1150.38
Mono-Si	1325.68
a-Si	472.51
CIGS	913.70
CdTe	1139.36

In this study, the cost of power generation was calculated by dividing the total investment in the PV system over its life cycle by the total electricity production according to Equation (4).

$$C_{cost} = \frac{C_{sys}}{E_{ini} \times \sum_1^N (1 - R_d)} \quad (4)$$

The cost of power generation is an important parameter that serves as a key factor in determining the economic feasibility of a PV system. This metric is used to quantify the financial investment needed for each unit of electricity produced by the PV system during its operational lifetime. The cost of power generation plays a crucial role in determining the overall efficiency and competitiveness of the PV system in the market. The lower the cost of power generation, the more economically viable and cost-effective the PV system is considered to be.

3. Result and Discussion

3.1. Solar Radiation Potential Results

Characteristics of the Distribution of Solar Radiation on Building Surfaces in Various Types of Industrial Blocks

Figure 7 presents the solar radiation potential for the surfaces of buildings in different industrial blocks. Single-story and high-rise industrial blocks exhibit higher radiation potential, with average radiation values of 942.93 kWh/m²/y and 963.73 kWh/m²/y, respectively. The radiation potential of multi-story blocks is relatively low, with an average value of 755.08 kWh/m²/y. This is primarily due to the larger roof area of single-story blocks and the larger facade area of high-rise blocks, allowing them to receive more solar radiation. Another study [66] on the potential of solar energy also came to similar conclusions. Analyzing the radiation potential of different exterior surfaces reveals that as the building height increases from single-story to high-rise blocks, the total radiation potential of building roofs decreases from 87.06 to 33.62%, while the radiation potential of building facades increases from 12.94 to 66.38%. Consequently, single-story and high-rise industrial blocks are the focus of solar resource development. In the development of solar energy, the building facade should also be given due consideration as an essential part of the installation of PV panels, and this issue is critical in high-rise buildings.

The investigation further delved into the percentage of the surface area meeting specific threshold criteria in each type of industrial block, as demonstrated in Figure 8. Two threshold criteria, 600 kWh/m²/y and 1000 kWh/m²/y, are employed to compare the intensity of solar radiation on building surfaces among single-story, multi-story, and high-rise industrial blocks. In single-story industrial blocks, 83.04% of the building surface area receives a radiation potential greater than 600 kWh/m²/y, whereas the figures in multi-story and high-rise industrial blocks are 67.07% and 53.72%, respectively. Additionally, when using the threshold criterion of 1000 kWh/m²/y, the percentage of building surface area exceeding this standard is 71.06% in single-story industrial blocks, compared to 47.71% and 22.23% in multi-story and high-rise industrial blocks, respectively. This shows a gradual reduction in the proportion of high-intensity solar radiation on building surfaces with an increase in the average height of buildings in the block. While there is only a slight difference between the total solar radiation potential of single-story and high-rise industrial blocks, the proportion of high-intensity solar radiation within single-story blocks

is considerably higher than that of high-rise industrial blocks. The increased total amount of radiation found in high-rise industrial blocks is primarily attributed to the extensive building exterior, particularly the building facade. However, the substantial mutual shading between high-rise buildings may have affected the potential of PV installations on the building facade. In contrast, the larger roof area, horizontal orientation, and minimal shading of single-story industrial blocks led to a higher proportion of high-quality solar radiation [13]. Consequently, the roofs of single-story industrial buildings appear to be the preferred location for developing solar resources. The development of solar energy resources on high-rise industrial block facades must carefully consider shading effects to enhance the power generation efficiency of the PV system.

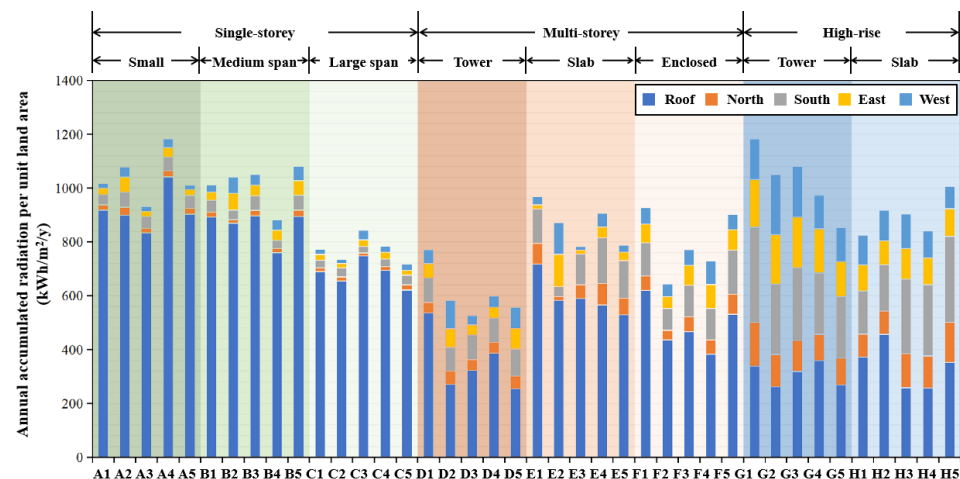


Figure 7. Solar radiation potential of building facades and roofs in various types of blocks.

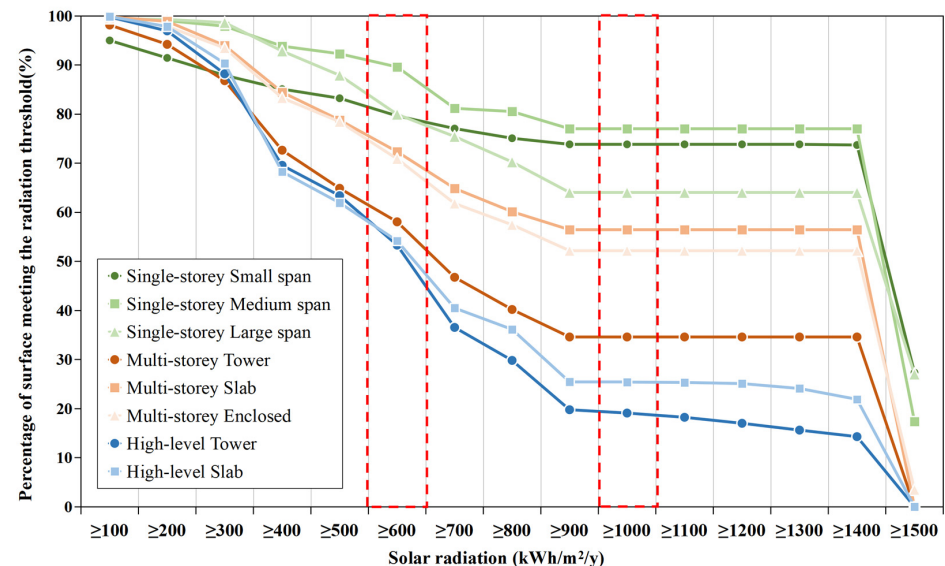


Figure 8. Average radiation intensity as a percentage of each type of block.

3.2. Analysis of PV Installation Rates

3.2.1. Percentage of the Area Meeting the Radiation Threshold

The study further calculated the percentage of the building surface area meeting the threshold criteria for various PV materials in each type of block.

Figure 9 illustrates the percentage of building surface area meeting the thresholds for different PV materials on the roof and on the south, east, and west facades. It should be noted that solar radiation data for the north facade are not included because the radiation potential on the north facade is not capable of meeting the thresholds for any of the different

PV materials. The roof is found to have the highest percentage of the area meeting the threshold on all surfaces, and in each type of block, where the percentage of the area meeting the different PV thresholds is above 98%. The south facade ranks second in terms of qualified area percentage, with a proportion of approximately 80%, except for the single-story small span block. The qualified area percentage in the east and west facades fluctuates significantly in different blocks. The average percentage of qualified areas in the east is higher than that in the west, at 53.96% and 50.43%, respectively. Moreover, the impact of different PV material thresholds on the installed area is equally significant on the west facade in each block type. The radiation threshold plays a crucial role in evaluating the installable area of PV. When screening the installable area on a building facade, the radiation threshold guarantees the PV's adequate generation capacity. The main reason is that the radiation intensity distribution on the building facade varied greatly, and the solar radiation intensity at some locations could not reach the radiation threshold. The difference in the radiation threshold for different PV materials gives the opportunity to make PV product choices. The combination of different types of PV materials could be carried out in the PV materials that satisfied the radiation threshold, with full consideration of economic efficiency, construction difficulty, aesthetics, and other factors [67–70]. This brought more possibilities for PV building integration design.

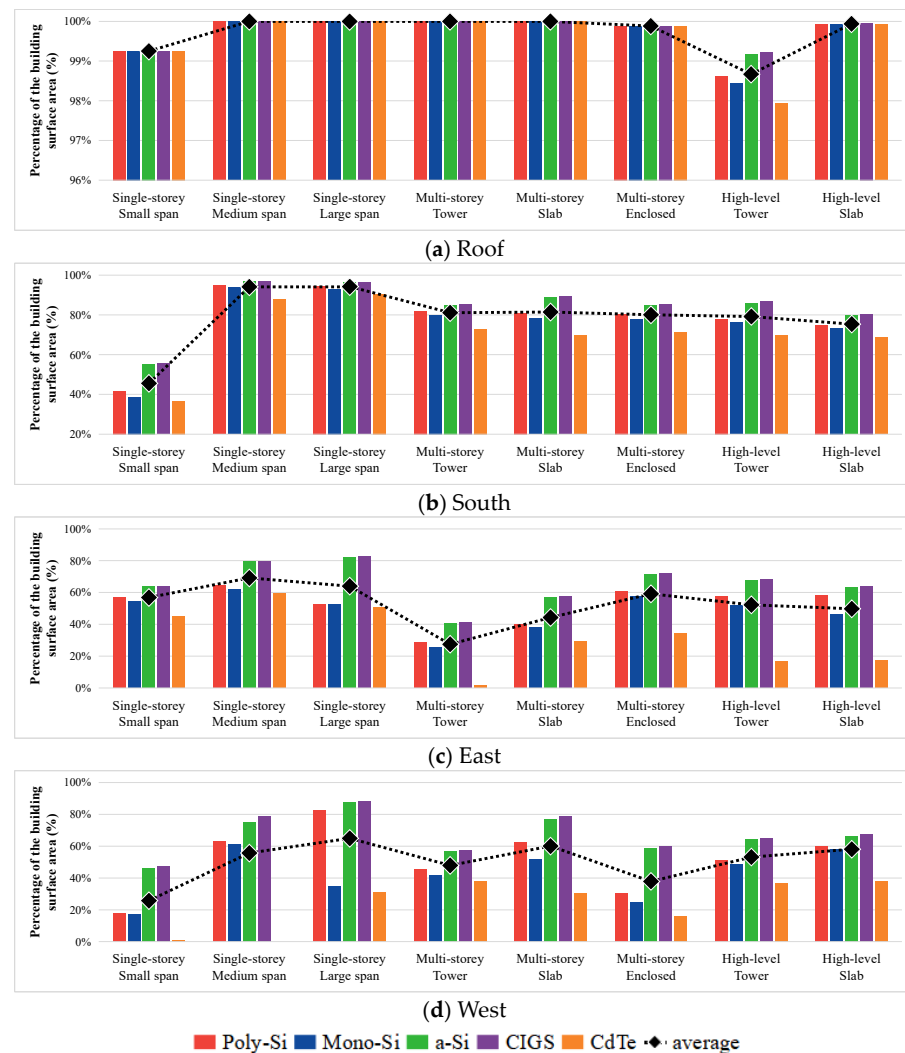


Figure 9. Percentage of the area meeting the threshold for various PV materials on different surfaces of each block type.

3.2.2. Installation Rates in Different Types of Blocks

Considering the effect of radiation thresholds and installation factors on the PV installation area of the building surface, the average installation rate data for each of the surfaces in different types of blocks with various PV materials applied were calculated, as shown in Table 6.

Table 6. The average installation rate data for each surface in different types of blocks with different PV materials applied.

		Single-Story			Multi-Story			High-Rise	
		Small Span	Medium Span	Large Span	Tower	Slab	Enclosed	Tower	Slab
Roof	Poly-Si	92.90%	90.00%	90.20%	84.00%	87.80%	91.49%	62.95%	78.54%
	Mono-Si	92.90%	90.00%	90.20%	84.00%	87.80%	91.49%	62.84%	78.54%
	a-Si	92.90%	90.00%	90.20%	84.00%	87.80%	91.49%	63.30%	78.56%
	CIGS	92.90%	90.00%	90.20%	84.00%	87.80%	91.49%	63.32%	78.57%
	CdTe	92.90%	90.00%	90.20%	84.00%	87.80%	91.49%	62.53%	78.54%
South	Poly-Si	30.76%	69.88%	73.41%	35.32%	39.78%	40.48%	21.79%	40.34%
	Mono-Si	28.63%	69.26%	72.34%	34.29%	38.41%	39.17%	21.27%	39.60%
	a-Si	41.10%	71.57%	74.86%	36.74%	44.06%	42.85%	23.91%	43.01%
	CIGS	41.15%	71.60%	74.90%	36.93%	44.21%	42.99%	24.22%	43.32%
	CdTe	27.07%	64.90%	70.38%	30.94%	34.46%	35.78%	19.43%	37.05%
East	Poly-Si	42.91%	48.04%	40.85%	12.63%	18.88%	31.25%	16.12%	31.44%
	Mono-Si	41.14%	46.10%	40.68%	11.23%	17.92%	29.92%	14.63%	24.51%
	a-Si	47.75%	58.91%	63.74%	18.05%	26.98%	36.06%	18.89%	34.25%
	CIGS	48.09%	58.98%	64.00%	18.29%	27.14%	36.46%	19.12%	34.75%
	CdTe	34.11%	44.31%	39.61%	0.85%	14.31%	17.51%	4.61%	10.06%
West	Poly-Si	13.32%	46.88%	64.14%	18.72%	33.18%	15.08%	14.12%	32.65%
	Mono-Si	12.76%	45.64%	27.28%	17.16%	27.34%	12.44%	13.45%	31.69%
	a-Si	34.83%	55.38%	67.97%	23.82%	40.09%	29.36%	17.85%	35.95%
	CIGS	35.60%	58.25%	68.80%	24.01%	41.03%	29.95%	18.06%	36.44%
	CdTe	0.02%	0.01%	24.00%	15.48%	17.32%	8.29%	10.16%	20.49%

The present study analyzed the variation in the average installation rate in response to the application of different PV materials to different types of blocks, as illustrated in Figure 10. The results reveal that the roof exhibits the highest average installation rate, with a mean of 84.74%, followed by the south facade, with an average installation rate of 44.30%. The east facade has an installation rate of 31.13%, while the west facade has the lowest installation rate, with an average of 28.48%.

It is observed that the installation rates on different building surfaces are influenced to varying degrees by the choice of PV material. The installation rate data for the west facade exhibit the most significant fluctuations across the different PV material conditions, with a squared variance of 1.98×10^{-2} for each data set. This is followed by the east and south facades, with squared variances of 6.67×10^{-3} and 1.26×10^{-3} for each data set, respectively. Conversely, the installation rate data for the roof exhibit the most minor fluctuations, with a squared variance of 1.38×10^{-7} for each data set.

These findings suggest that the installation rates of the various building surfaces are sensitive to the choice of PV materials, primarily attributed to the distinct radiation distribution characteristics of the different building surfaces.

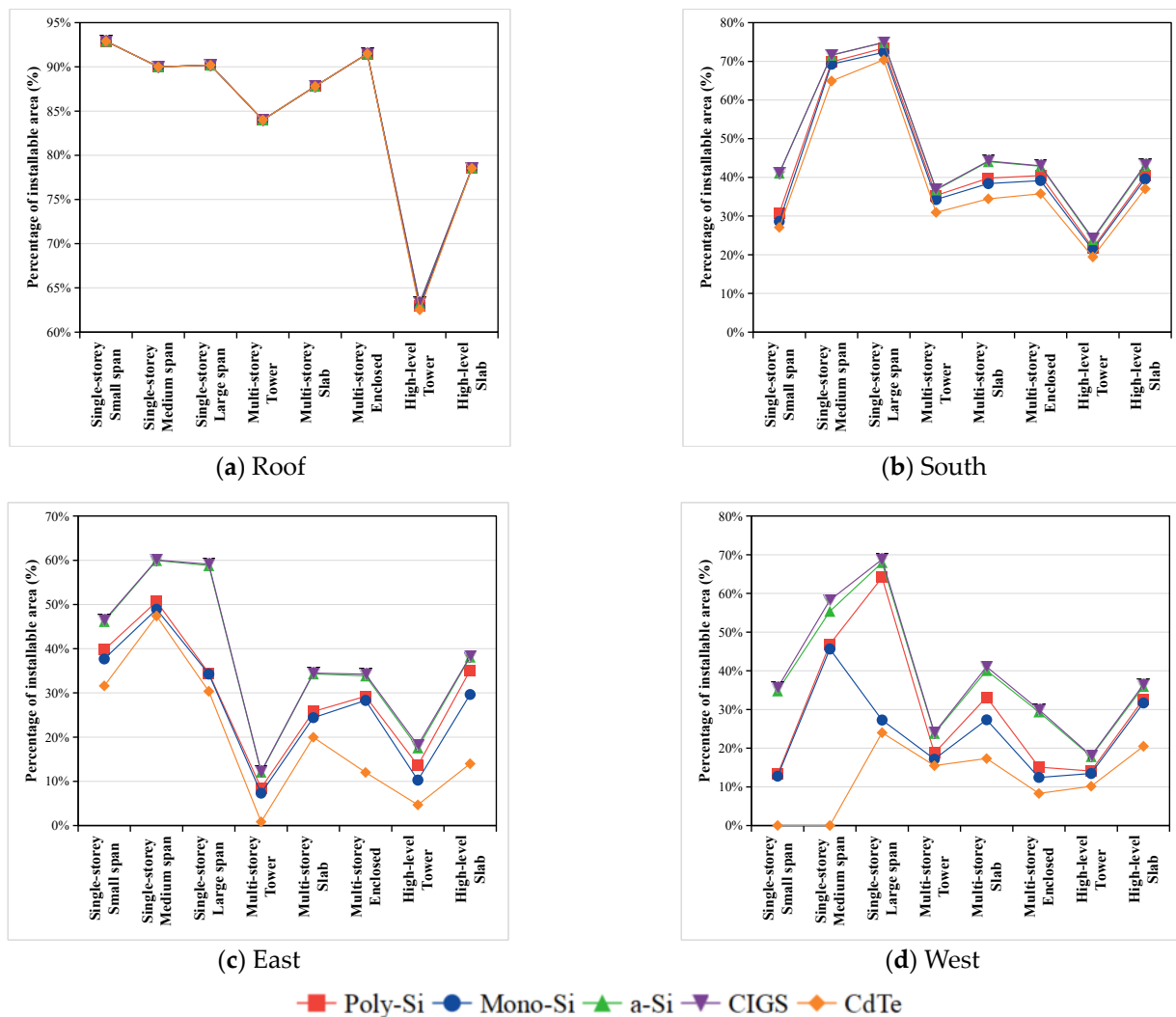


Figure 10. Installation rates of various PV materials for different surfaces of each block type.

3.3. Influence of the Different PV Materials on the Power Generation in Each Type of Block

3.3.1. Impact of PV Material Performance on Power Generation

The annual cumulative PV generation and the cost of power generation data on the unit site area when different PV materials were applied in each case block were obtained, as shown in Figures 11 and 12.

Figures 11 and 12 illustrate the changes in power generation potential and power generation cost for each case block when different PV materials are utilized. As the height of the buildings in the block increases, there is a gradual decrease in the level of PV generation and an increase in the cost of power generation. Among all block types, Mono-Si exhibits the highest average power generation, followed by Poly-Si, while a-Si demonstrates the lowest average power generation. As can be seen in Figure 11b, the maximum difference in power generation due to PV materials ranges from 57 to 80 kWh/m²/y for the three industrial blocks in the single-storey cases, with an average value of 71.06 kWh/m²/y. The corresponding average values for the multi-storey and high-rise cases are 44.56 kWh/m²/y and 29.22 kWh/m²/y, respectively. The variation in power generation from different PV materials within each block type ranges between 56.9 and 59.2%, indicating a significant impact of PV materials on power generation.

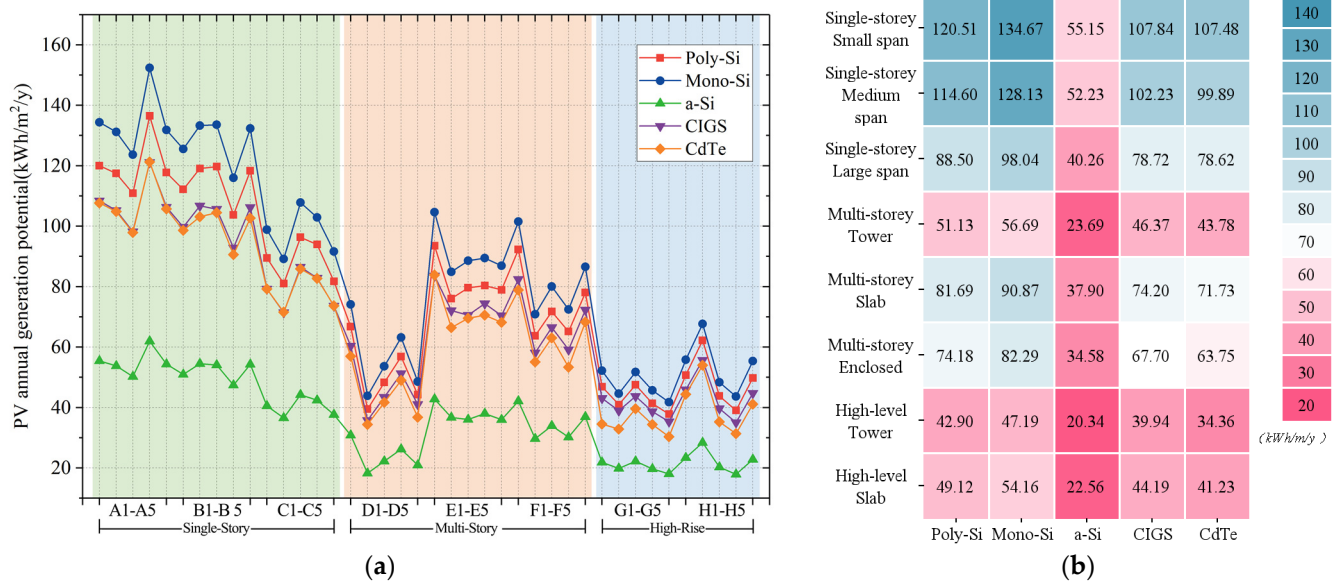


Figure 11. Changes in power generation potential. (a) Power generation potential of each block case. (b) Average power generation potential of different types of block.

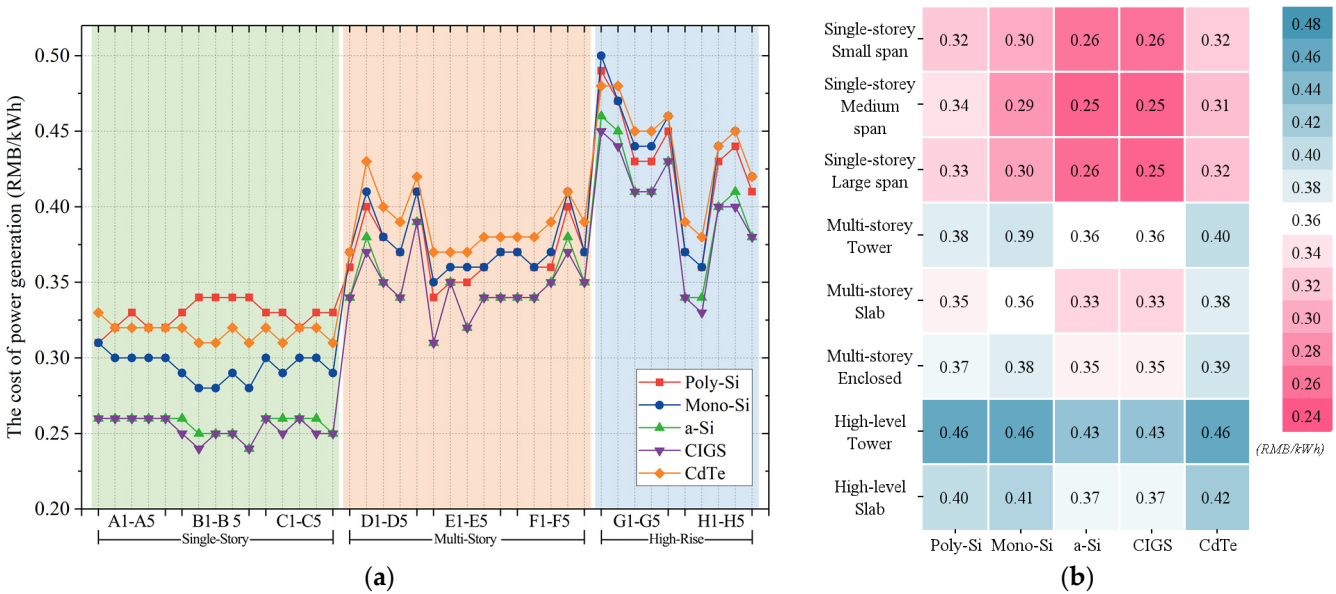


Figure 12. Changes in cost of power generation. (a) Cost of power generation of each block case. (b) Average cost of power generation of different types of block.

From the cost of power generation data in Figure 12, within each block type, a-Si and CIGS have the lowest generation costs. However, Poly-Si, Mono-Si, and CdTe show variations across block types (Figure 12a). In single-story industrial blocks, Mono-Si has the lowest generation cost with an average value of 0.29 RMB/kWh, followed by CdTe and Poly-Si with 0.32 RMB/kWh and 0.33 RMB/kWh, respectively. In both multi-story and high-rise blocks, the block case with Poly-Si has a lower generation cost, with an average value of 0.37 RMB/kWh and 0.43 RMB/kWh (Figure 12b). Careful consideration should be made according to the morphological characteristics of a block and the distribution of solar radiation in order to seek lower power generation costs and improve the cost performance of PV generation.

3.3.2. PV Generation of Different Building Exterior Surfaces

This study analyzed the PV generation and the cost for different building surfaces, as shown in Figures 13 and 14.

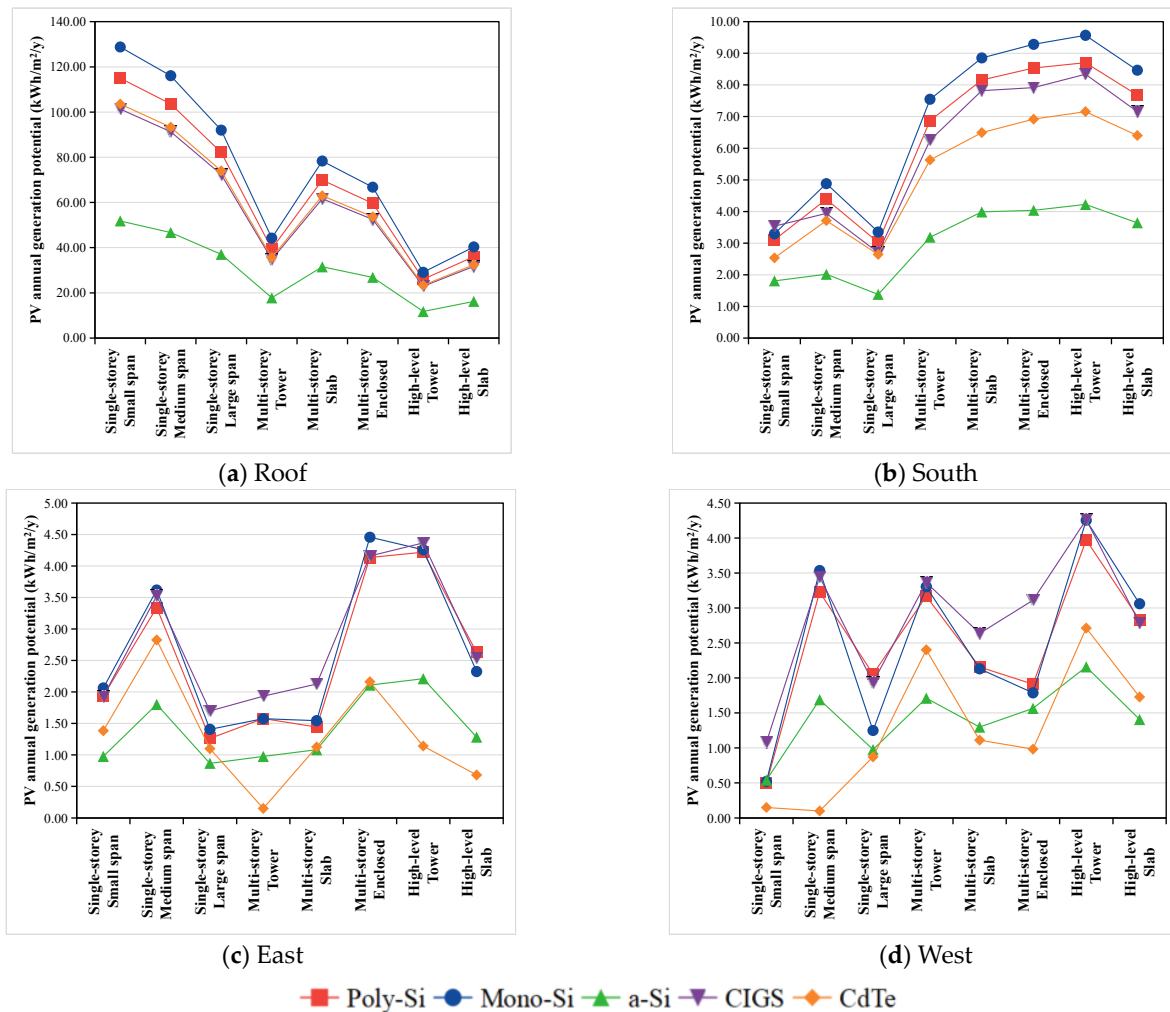


Figure 13. PV generation of different building surfaces.

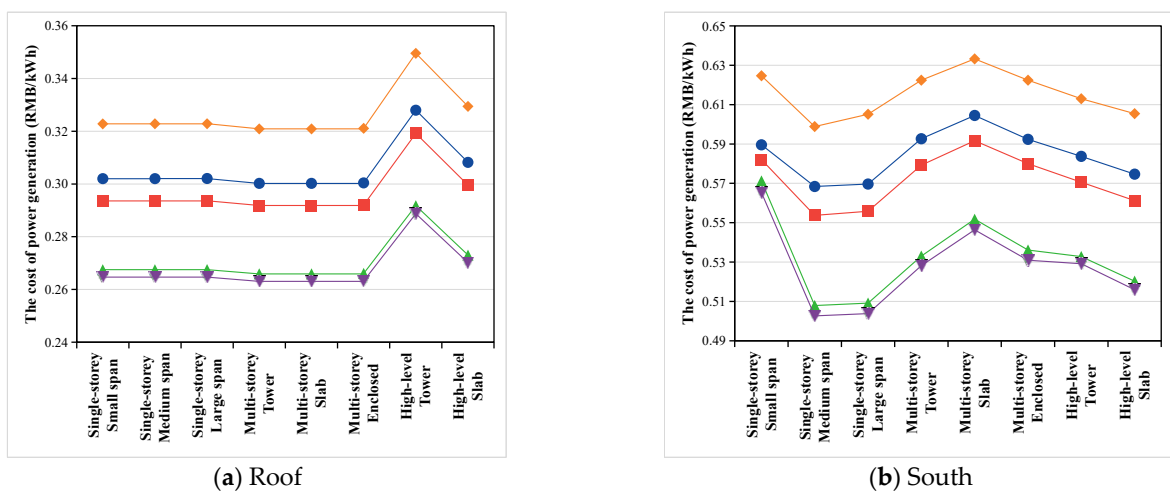


Figure 14. Cont.

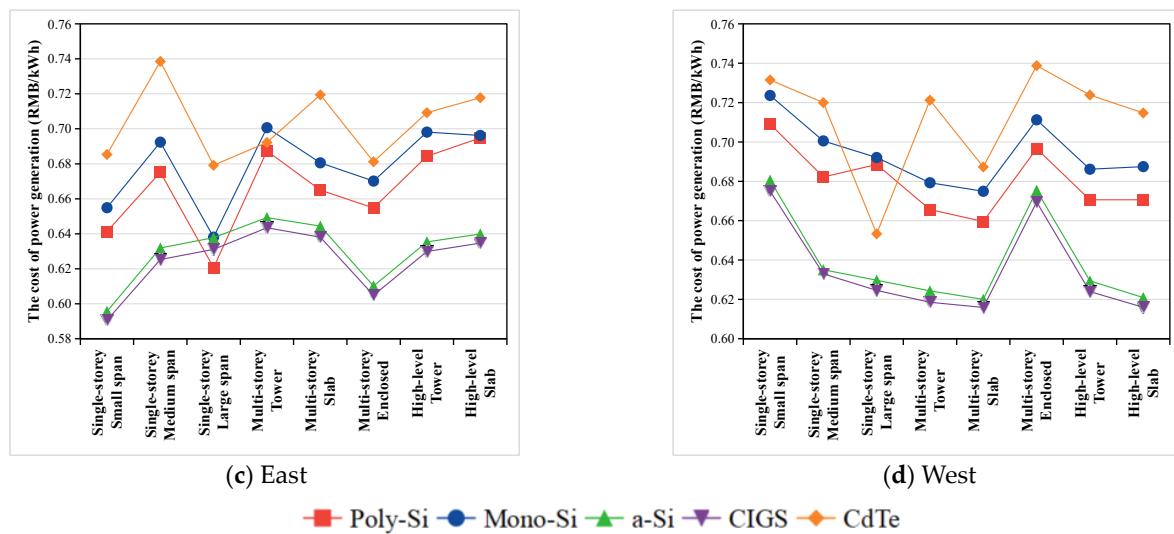


Figure 14. The cost of power generation of different building surfaces.

The PV generation and power generation cost for various building exterior surfaces are evaluated (Figure 12). The results reveal that roofs have a higher PV generation compared to other building surfaces, except for tower blocks. The PV generation on roofs decreases gradually with increasing building height, while the south facade exhibits an overall trend of increasing PV generation with height. The highest PV generation is observed for Mono-Si, followed by Poly-Si, for both roofs and south facades. In the east and west facades, CIGS exhibits higher power generation levels than other PV materials, with an average power generation of $2.79 \text{ kWh/m}^2/\text{y}$ and $2.83 \text{ kWh/m}^2/\text{y}$, respectively.

Furthermore, the analysis of power generation costs for building exterior surfaces showed that a-Si and CIGS have lower generation costs than Poly-Si and Mono-Si, while CdTe has the highest generation cost. The cost of power generation of different PV materials on the east and west facades varied across different types of blocks. For example, although a-Si and CIGS generally maintain lower generation costs, Poly-Si generation costs are lower than a-Si and CIGS in single-story large-span blocks. Therefore, the combination of the generation capacity of different PV materials should be carefully considered to determine the preferred PV installation for different block types (Figure 14).

In response to the analysis of the findings, it was found that different types of industrial blocks have a choice of PV materials based on the purpose of use. Since the intensity of solar radiation on the roofs of industrial buildings is higher than on the facades, the selection of Poly-Si and Mono-Si resulted in higher solar power generation. On the other hand, the intensity of solar radiation on the facade of the building is lower and unevenly distributed. The selection of a-Si and GICS could obtain higher cost-effectiveness of PV generation. Secondly, Poly-Si and Mono-Si are more suitable for single-story industrial blocks, which could bring higher PV generation. In contrast, multi-story and high-rise industrial blocks are more suitable for a-Si and Poly-Si, which could bring higher cost-effectiveness to PV generation. The reason for this difference is mainly due to the proportionality of building roofs and facades within the blocks. Larger roof areas bring high-quality solar radiation resources; when Poly-Si and Mono-Si are selected, high PV generation could be obtained. When the percentage of facade area is higher, the cost-effectiveness of the PV system for power generation had to be considered. Although the current Poly-Si and Mono-Si have a high power generation performance and market share, not all building surfaces are suitable for installation. The vast differences brought about by different PV materials make it necessary to consider the application and selection of PV materials in all kinds of scenarios. With the continuous progress of PV materials, traditional crystalline silicon material performance is constantly improving. In contrast, the performance of new PV materials continues to improve, which give more possibilities to choose from.

4. Conclusions

By analyzing the impact of urban block typology and PV material performance on solar energy utilization, this study provides important insights for planning and designing urban industrial blocks and installing PV panels in different types of blocks. The research findings of this study have significant implications for adopting sustainable energy practices and reducing carbon emissions in urban areas. Three main findings were established as follows:

- (1) Among all types of blocks, single-story industrial blocks have the highest radiation potential, and the roofs have a very high solar resource development value; the solar resource potential can be further improved by increasing the area share of roofs in the block.
- (2) Under the consideration of threshold conditions, there is a difference in the effect of PV material performance on the installation rate of different building surfaces, and the installation rate is affected by PV material from the largest to the smallest degree according to west > east > south > roof.
- (3) From the perspective of power generation, Mono-Si has a higher power generation level in all types of blocks, where different PV materials can lead to a maximum of 59.2% difference in power generation. Poly-Si and Mono-Si should be considered for higher power generation for single-story industrial blocks with a higher percentage of roof area, while for multi-story and high-rise industrial blocks with a higher percentage of facade areas, a-Si and CIGS can be considered for higher cost performance.

The quantitative analysis of the impact of urban block typology and PV material performance on solar energy utilization, as presented in this study, have produced the following findings: The design recommendations for the early stages of urban planning and building design, as well as for guidance for proprietors of industrial blocks on selecting and installing PV panels can aid in optimizing solar energy utilization and promote energy and carbon emissions reduction in urban areas. The research findings also offer a valuable contribution to the literature on solar energy resource utilization in industrial blocks and can inform future studies in this area.

It was important to note that the study had certain limitations. Firstly, the issue of the mounting inclination of the PV panels had yet to be considered in the study. The tilt angle of PV was a crucial factor that affected PV generation. Since the study focused on the impact of block morphology on solar energy utilization, the PV mounting tilt angle was treated as a fixed value in the study setup. Future studies would delve further into the effect of the tilt angle of PV panels on the power generation in different building parts. Secondly, the energy consumption of the industrial block was a critical factor that affected how PV power generation was utilized. As the study focused on the potential of PV generation, the matter of energy consumption in industrial blocks still requires attention. The allocation of power generated by PV should be examined in conjunction with building energy consumption to maximize the benefits of PV generation. Lastly, during the study, it was discovered that within industrial blocks, a large number of spaces were suitable for the installation of PV panels, showing high potential for solar energy utilization. This could further increase the solar power generation capacity of the industrial blocks. However, the study had yet to cover power generation from these spaces. The effective utilization of these spaces would be comprehensively discussed in subsequent studies.

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