

Research Article

Sustainable Design: Building-Integrated Photovoltaic on Residential House Envelopes

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Article Info	Abstract
Article History	This research investigates the integration and optimization of Building Integrated Photovoltaic (BIPV) systems on residential rooftops in Amman, Jordan—an area experiencing rapid urbanization and high solar potential. The study aims to identify the most effective orientations and azimuth angles for maximizing solar energy generation during both summer and winter seasons. Solar radiation data was analyzed using a case study on Haneen Bin Isaac Street using PVGIS and Autodesk Ecotect Analysis tools. The methodology simulated insolation values on south-facing and south-eastern/south-western rooftop surfaces at different azimuth angles (120°, 135°, and 150°) and tilt configurations. The results demonstrate that south-eastern and south-western orientations yield higher solar gain during winter, especially at 135° and 150°. Southern orientations perform efficiently across all examined angles during summer, with only slight variation. These findings support the strategic application of BIPV in residential architecture, enhancing energy efficiency while maintaining design quality. The study concludes with practical design recommendations for architects and urban planners to incorporate BIPV as an active element in sustainable construction. The outcomes also provide a framework for broader regional application in similar climatic and urban contexts.
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1. Introduction

Rapid urbanization and population growth have intensified global energy demands, prompting an urgent need for sustainable solutions. While fossil fuels have historically powered urban development, they are also primary contributors to greenhouse gas (GHG) emissions and climate change [1, 2]. In contrast, renewable energy sources such as solar, wind, hydro, and geothermal offer clean alternatives that support urban expansion without environmental degradation [3]. Among these, solar energy presents a promising avenue for sustainable urban development, particularly when integrated into the built environment.

Building-integrated photovoltaic (BIPV) systems have emerged as a critical strategy in transitioning

toward low-carbon cities [4]. Unlike conventional Building-Applied Photovoltaics (BAPVs), which are mounted onto structures, BIPVs are embedded directly into the building envelope, allowing them to serve dual functions as construction materials and energy-generating systems [5]. In addition to reducing transmission losses, BIPVs enhance thermal insulation, soundproofing, and architectural aesthetics, aligning functional efficiency with design integrity [6].

The performance of BIPV systems is highly dependent on environmental and architectural variables, including solar radiation levels, local weather patterns, shading, building orientation, and material selection. Recent advancements in photovoltaic materials and optimization algorithms—such as Grey Wolf Optimization (GWO) and Whale Optimization Algorithm (WOA)—have further improved energy yields, particularly in urban environments where spatial and climatic constraints are significant [7, 8].

Jordan, a nation with high solar irradiance and increasing urban density, offers a compelling case for exploring BIPV applications in residential contexts. Amman, the capital city, faces rising energy consumption, significant temperature fluctuations, and urban heat island effects—challenges that underscore the need for integrated renewable energy strategies. Despite favorable climatic conditions and policy support for the adoption of renewable energy, BIPV implementation remains limited, often constrained by structural, regulatory, and aesthetic considerations [9].

This study examines the integration of BIPV systems into residential building envelopes in Amman, Jordan, with a focus on maximizing energy efficiency while preserving the architectural character. By evaluating factors such as building orientation, façade exposure, material performance, and climatic data, the research aims to develop a framework for the effective deployment of BIPV in hot and dry urban climates. The outcomes will support architects, urban planners, and policymakers in implementing sustainable, aesthetically integrated energy solutions that align with contemporary urban development goals.

2. Literature Review

2.1. BIPVs Building Design Considerations

A solar panel comprises several silicon-based semiconductor solar cells [10]. Solar energy is absorbed by these cells and converted into electrical energy. Figure 1 illustrates the classification of PV panel materials. The efficiency of the photovoltaic systems is between 5% and 20% [11]. When photovoltaic modules are exposed to solar energy, only 9% to 20% of the solar radiation that strikes the surfaces of the modules is transformed into electrical energy. Most solar radiation is absorbed or reflected from the photovoltaic module surfaces. The energy absorbed by the module surface increases the temperature of the photovoltaic modules [12]. Figure 2 shows a schematic representation of energy production using a solar panel.

By integrating photovoltaic components directly into the building envelope, BIPV systems provide a twofold solution that enables them to serve as energy-generating devices and building materials. BIPV

systems offer numerous benefits, including reduced transmission losses and decreased reliance on external power sources, as they generate electricity on-site. This local production enhances energy efficiency [11]. These systems enhance functionality and visual appeal, allowing seamless integration into windows, roofs, and façades while preserving architectural aesthetics.

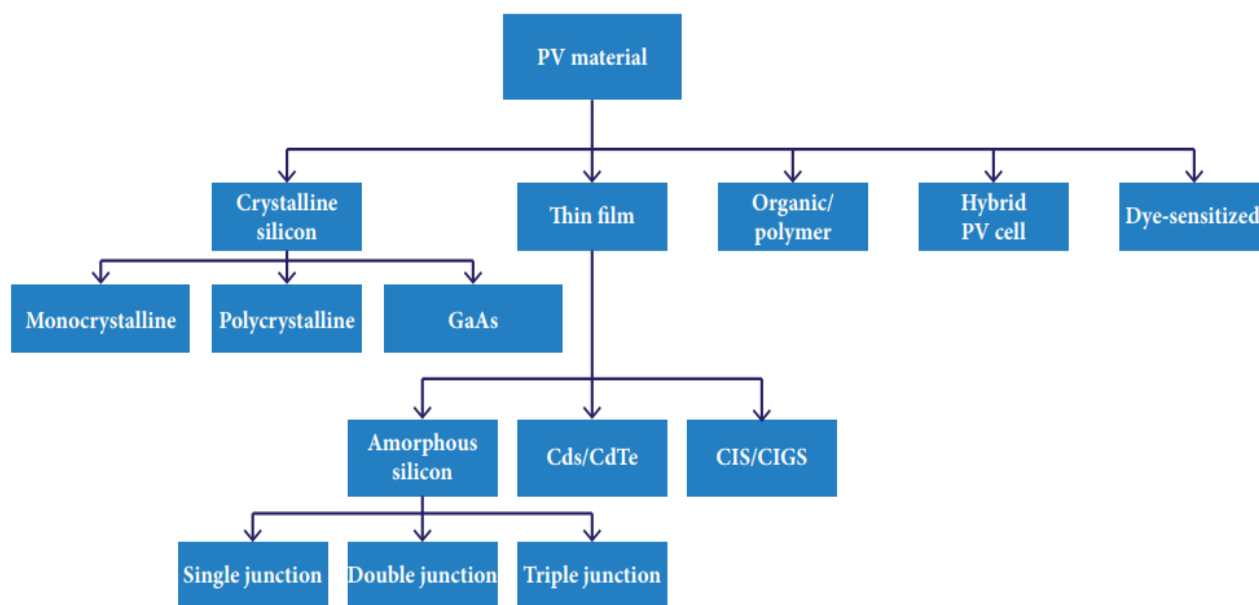


Figure 1. Classification of PV panel materials [11, 13]

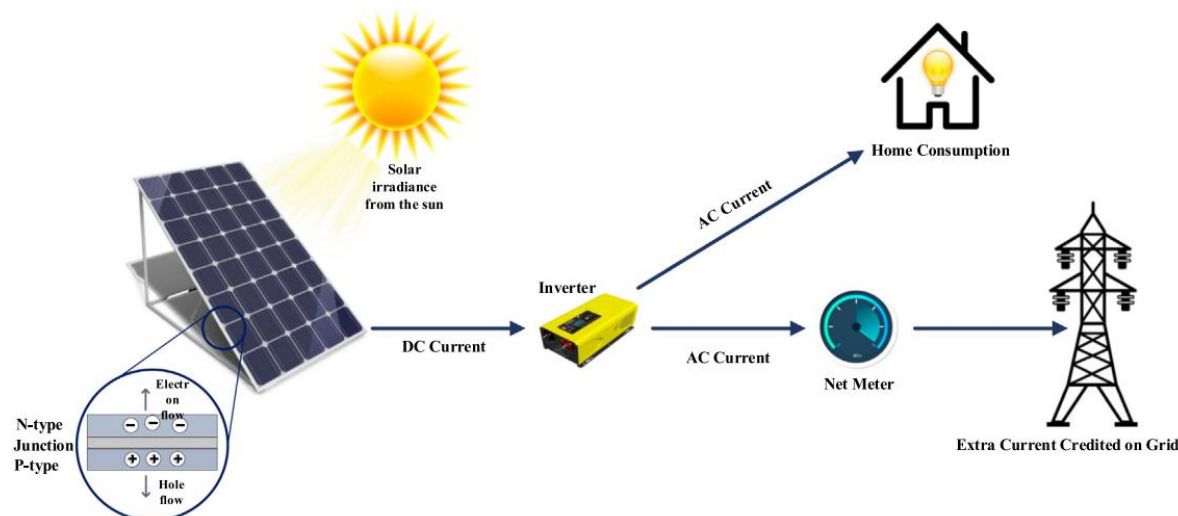


Figure 2. Schematic of solar panel performance [12]

Through access to renewable energy incentives and long-term energy savings, BIPV can economically offset the larger initial investment. These benefits are further supported when considering the wider advantages of solar energy. Solar energy offers a sustainable approach to meeting the world's energy needs, as it is an abundant and renewable resource [14]. It is an environmentally responsible option, as it drastically reduces greenhouse gas emissions and the carbon footprint of electricity generation. Furthermore, solar energy systems offer significant financial relief by reducing electricity bills; for instance, a recent study conducted in the UK found that solar panels could reduce energy expenses for low-income households by

as much as 24% [15]. Lastly, adopting solar energy enhances independence by enabling users to generate their own electricity and reduce their reliance on conventional utility providers [16]. When combined, solar and BIPV technologies make a compelling case for widespread adoption in contemporary sustainable architecture.

Environmental factors, structural considerations, and site-specific characteristics significantly limit the effectiveness of BIPVs. Energy production can be significantly reduced by environmental conditions, such as the amount of solar radiation and climatic factors like temperature, cloud cover, precipitation, and shade from surrounding buildings, trees, or architectural features [17, 18]. Similarly, the buildup of dust and airborne pollutants reduces energy output and necessitates regular maintenance. Integrating PV systems into the grid is essential for achieving energy independence for buildings, particularly during the supply phase, as it reduces reliance on storage solutions.

Architectural and aesthetic constraints, as well as the selection of materials such as crystalline silicon and thin film, significantly influence the efficiency, cost, and complexity of the installation process. Additionally, the orientation and shading of a building play a crucial role in the efficiency of PV systems. Conversely, the reduction in solar power generated by shading from nearby structures, vegetation, or other obstacles can be substantial. Installing BIPV to optimize exposure to sunlight is essential, ensuring maximum solar incidence between 9:00 A.M. and 2:00 P.M. throughout the year.

The angle of the sun's incidence and the height of the building contribute to the impact of surface area and the perimeter ratio of the building's massing. The stages of solar exposure may be linked to Sun path diagrams, facilitating the analysis of shading patterns before installation. Concurrently, slope, azimuth angle, and latitude will affect seasonal energy generation and consumption. Still, the incorporation of proper window openings has been proven to reduce the overall energy consumption of educational spaces [19]. Therefore, a comprehensive evaluation of these variables is essential to maximize the effectiveness of BIPV.

2.2. Building Integrated Photovoltaic

According to Basnet [20], BIPV products are currently divided into four categories: foil, tile, modules, and solar cell glazing.

2.2.1. Foil Module

The lightweight and flexible nature of BIPV foil modules (Figure 3) significantly increases their versatility throughout the construction process, reducing the potential risk of imposing excessive weight on the roof structure [21]. This solution is particularly well-suited for non-ventilated roofs due to their intrinsic properties and performance in elevated temperature conditions. The modules are composed of thin-film solar cells.



Figure 3. An Example of a BIPV foil product [21]

2.2.2. Tile Modules

Based on energy demands, this module allows the option to cover the entire roof or select targeted sections. An illustration of BIPV roof tiles covering specific areas of the roof is shown in Figure 4. A variety of options for tile shape and cell type are available. While some designs feature curved ceramic tiles for aesthetic appeal, it is essential to note that their curved configuration can negatively impact their area efficiency [22].

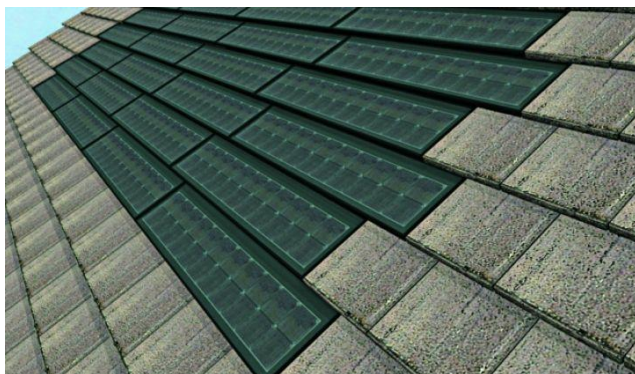


Figure 4. An example of BIPV roof tiles [22]

2.2.3. Module Products

While certain BIPV modules feature weather-resistant designs, typically resembling conventional PV modules, these products can replace a building's roofing element or be integrated with a manufacturer's exclusive roofing system. The installation process is streamlined due to the characteristics of the BIPV module. Depending on the mounting configuration, some of these products may qualify as BAPVs or BIPVs [23]. An illustration of a BIPV module affixed to the façade of an office building is presented in Figure 5.

2.2.4. Glazing Modules

Solar cell glazing modules are predominant products within the BIPV market (Figure 6). They uniquely ensure a positive return on investment [24]. These modules can be integrated into various

structures, including windows, curtain walls, glazed walls, tiled walls, façades, atriums, canopies, terrace floors, and roofs, offering a range of architectural possibilities. They offer a diverse range of options in terms of color, size, thickness, patterns, and levels of transparency, thereby enhancing aesthetic appeal and facilitating architects' creative expression. Furthermore, these solar cell glazing modules effectively filter 99% of harmful ultraviolet radiation, absorb 95% of infrared radiation, and transmit natural light, all while delivering thermal, water, solar, and acoustic insulation [25]. Additionally, they contribute to reducing operational expenses, cooling costs, and maintenance requirements while generating supplementary income through energy production.

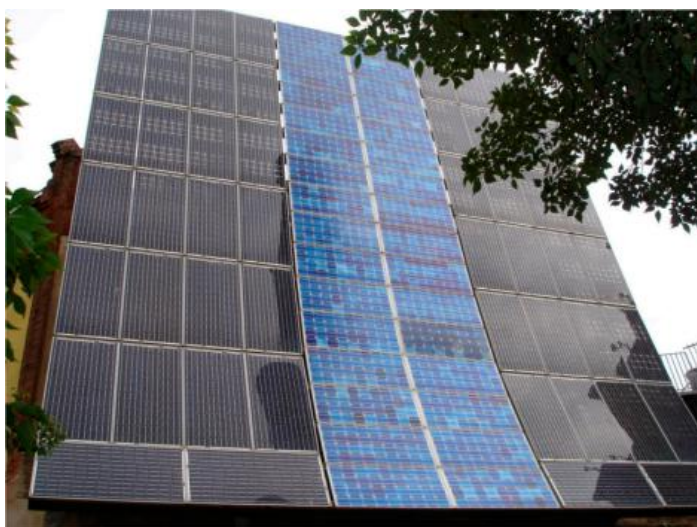


Figure 5. PV modules installed on a structure added to an office building. Photo by Celadyn and Filipek [21]



Figure 6. BIPV slide-like shape glass in the form of skylight OnyxSolar [26]

2.3. Applications of Building-Integrated Photovoltaic

2.3.1. Integrated PVs for Roofs

Integrated photovoltaic (BIPV) systems can be seamlessly mounted onto a building's structure to replace traditional roofing elements. The angle at which PV systems are positioned significantly influences their solar energy production capabilities [27]. For instance, monocrystalline and polycrystalline PVs exhibit reduced efficiency when installed on flat roofs, as their optimal performance is achieved at a specific angle [26]. In contrast, thin-film PVs demonstrate effectiveness even when installed on horizontally

oriented flat roofs. Consequently, the roof type plays a pivotal role in selecting an appropriate PV system; sometimes, the most efficient technology may not align with the architectural constraints or aesthetic considerations of the building's roof design. PV systems can be deployed on various roof types, including flat, inclined, and pitched roofs (Figure 7).



Figure 7. PVs integrated on a curved roof, BP solar showcase in Birmingham [26]

2.3.2. Integrated PVs for Façades

Skylight BIPV possesses an exceptional ability to filter harmful ultraviolet (UV) radiation while facilitating the indoor transmission of natural light, thereby promoting thermal comfort [27]. In addition to this primary function, it provides advantages such as ventilation, sound insulation, and thermal insulation. Consequently, the implementation of skylight BIPV leads to reduced operational, air conditioning, and maintenance expenses while enhancing energy generation returns.

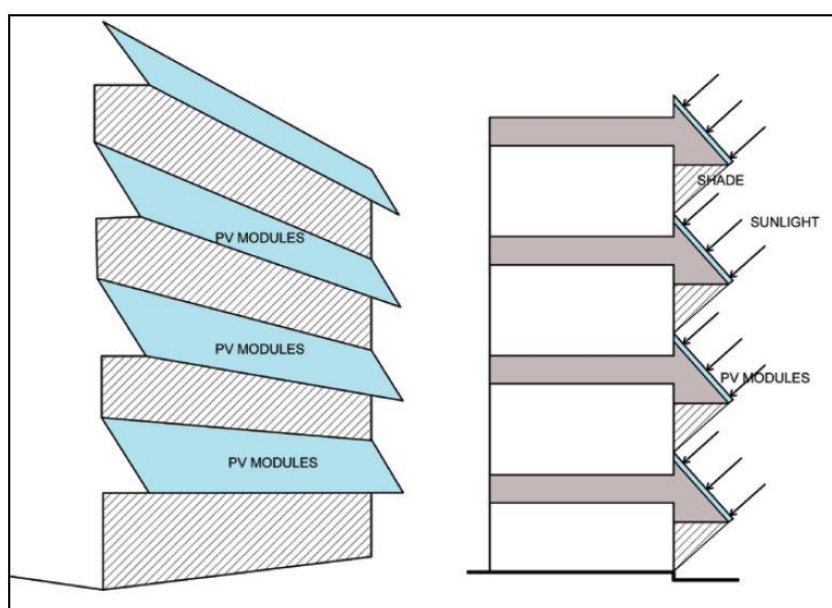


Figure 8. Saw-tooth PV design with an overhanging shading element [27]

Furthermore, this technology enhances the aesthetic appeal of buildings both externally and internally.

PV modules are adaptable in various dimensions, shapes, types, colors, transparencies, and patterns, allowing customization to meet client preferences as well as the architectural and structural requirements of the building. Additionally, it serves as a privacy solution for occupants who may have concerns regarding the visibility through façade windows. The operable integrated PV skylight structural system is illustrated in Figure 8.

3. Materials and Methods

This study employs an exploratory and quantitative research framework and is structured into two phases. The first phase focuses on literature reviews of Amman's PV systems and solar potentials, which align with the principles of the International Energy Conservation Code [28] and the Energy Conservation Building Code (ECBC). Similarly, this aligns with the earlier works of researchers studying the composite climate in India [29]. The second phase involves analyzing a specific case study area at an urban scale in Amman to assess the integration of PV systems. This area was selected due to its strategic location near the city's most social infrastructures, its densely populated nature, and vertical building densification. The climate behavior is a blend of Mediterranean and arid, with the latter being the dominant influence. That presents a crucial scenario for designers' and users' comfort, similar to the research that harnesses passive design resources, such as daylighting and shading [30]. The selected case is also a residential neighborhood and will be assessed from the perspectives of energy optimization, passive energy strategies, economic implications, climate purifiers, and façade beautification. Figure 9 simplifies the research framework conceptualized as BIPV on residential house envelopes.

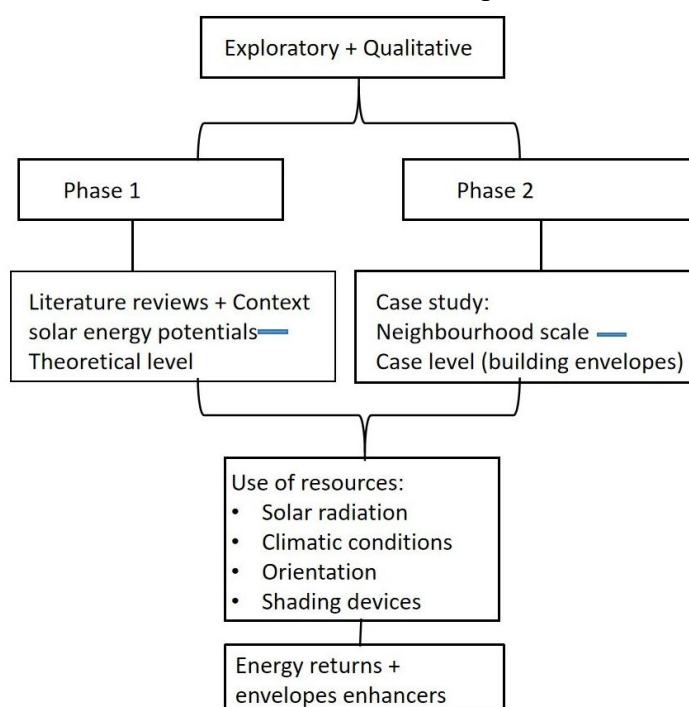


Figure 9. The research design of BIPV on residential house envelopes

3.1. Phase 1: Solar Energy Potential Assessment

In the first phase, solar potential was analyzed by determining optimal slope and azimuth angles for PV installations across Jordanian regions. This analysis section focuses on maximizing energy returns based on resources like regional solar radiation, weather patterns, orientation, and shading considerations. The study assesses the energy production capacity and CO₂ reduction potential of PV systems, offering a comprehensive examination of the feasibility of solar energy solutions in the country.

3.2. Phase 2: Case Study in Amman

The second phase involves a case study of PV system integration on the residential building envelopes of the Hannen Bin neighborhood of Amman. The residential blocks chosen for the study are located on Haneen Bin Isaac Street in the Jordanian metropolis of Amman, close to the Al Jazeera Hospital. The buildings have four stories and a total plot area of approximately 13,635 m². The buildings are characterized by white stone cladding, a common architectural feature in the region. Beyond adhering to traditional aesthetic tastes, this material enhances thermal efficiency by reducing heat gain, a vital consideration in hot and dry climates. The conceptual map and the current Geo Earth map are shown, with the case study area highlighted in both (Figures 10 and 11).

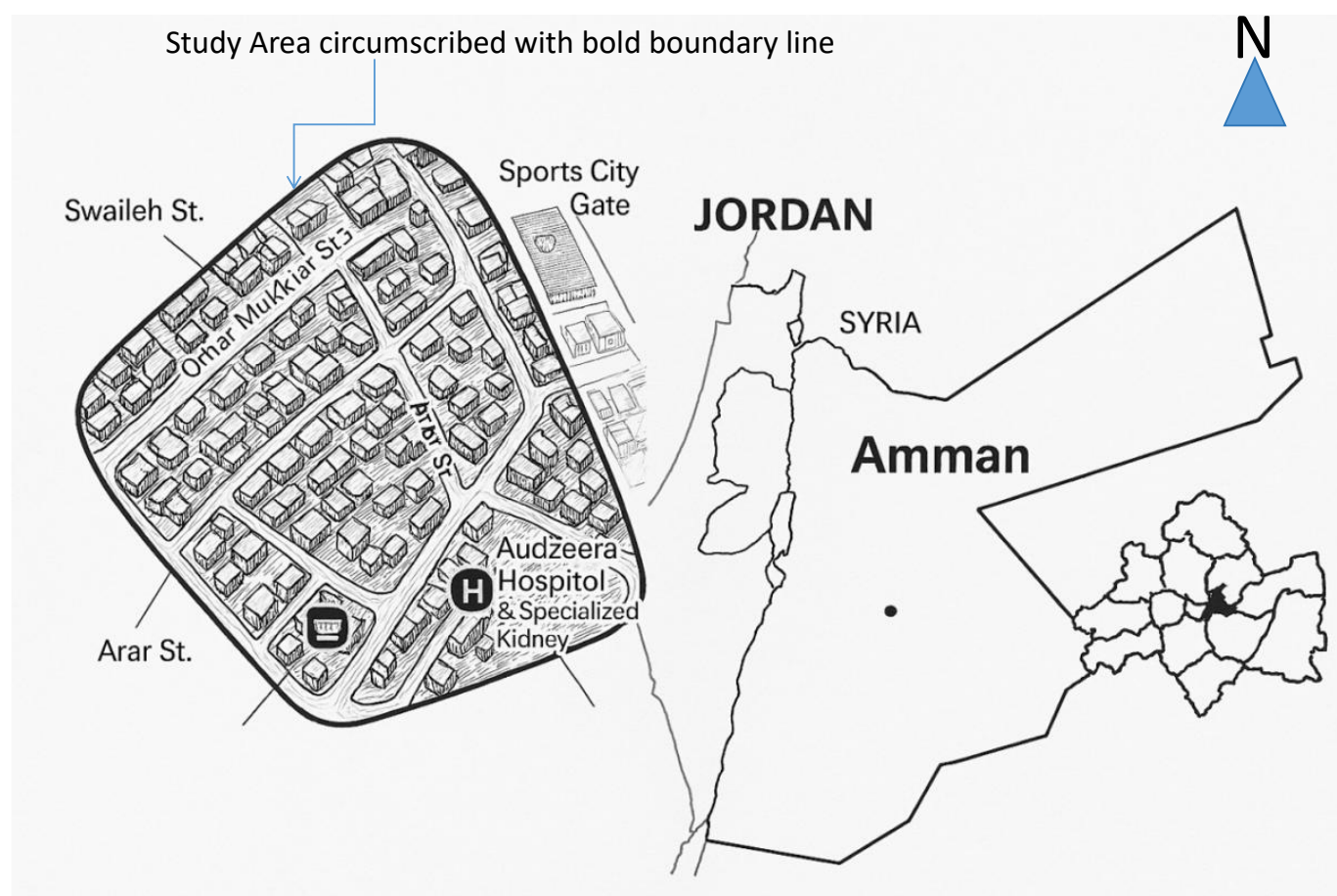


Figure 10. Conceptual map of the study area (by authors)



Figure 11. Geo map of Case Study area

The justification for selecting the study area, apart from the earlier remarks at the beginning of this theme, encompasses various city dynamics. As Amman experiences significant urban growth and a rising population, the development of more buildings increases the opportunity for large-scale PV system integration, thereby enhancing energy sustainability. The city's high solar irradiation levels make solar technology a promising energy solution, particularly in Jordan, where escalating electricity prices further bolster its viability. Nevertheless, challenges such as shading from nearby structures, limited rooftop availability, and the varied orientations of building façades in densely populated urban areas necessitate a comprehensive feasibility study before establishing optimal PV placement options.

Moreover, the variety of residential architecture typologies, including high-rise apartments, standalone villas, and traditional homes, offers a platform for examining various integration strategies. By promoting sustainability and aligning with renewable energy initiatives, this research will ultimately contribute to achieving national goals. Furthermore, installing PV systems in residential settings has the potential to reduce electricity costs and represents a significant advancement towards energy independence. Simultaneously raising public awareness of innovations in green energy. As a result, residential structures have been prioritized in this research. This phase investigates how building orientation, surface area, and geographical location influence energy returns to determine the most effective placement and types of PV

systems for urban environments. The study also tackles practical challenges, including shading, limited light exposure in densely populated areas, and temperature variations, which can impact system efficiency. Through this comprehensive analysis, the research seeks to establish best practices for integrating PV systems that promote enhanced energy efficiency, sustainability, and visual coherence of urban building envelopes.

3.3. Data Collection Tools and Analysis

Data for this study was collected and analyzed from multiple sources:

- **Energy, Environmental, and Economic Data:** The performance of solar tracking systems was assessed using both fixed and two-axis systems.
- The research also explored various PV technologies, including Cadmium Telluride (CdTe), Copper Indium Selenide (CIS), Amorphous Silicon (a-Si), Monocrystalline Silicon (mono-Si), and Polycrystalline Silicon (poly-Si).
- **RETScreen Analysis:** RETScreen software is a comprehensive tool that provides flexibility in conducting benchmarks, feasibility analyses, and performance evaluations. Its virtual analysis algorithm encompasses a wide range of archetypes suitable for both existing and proposed projects across various scales, including architectural and urban contexts. The software integrates climate data from NASA's database, enabling users to simulate and analyze the energy production and financial viability of PV systems and other urban infrastructure. The proposed system is designed with a capacity of 5 kWh, targeting small-scale, grid-connected renewable energy applications.
- **Mathematical Modeling:** The sourced data underwent further analysis utilizing a mathematical model developed in Microsoft Excel. This model enabled the evaluation of energy production capacities, cost efficiency, and environmental impacts associated with various photovoltaic systems and configurations.

The system characteristics utilized during the analytical process are detailed in Table 1. The analysis employed the Photovoltaic Geographical Information System (PVGIS) tool to ascertain the optimal slope and azimuth angle for fixed installations in various locations within Amman. Forty-four districts were analyzed to assess their PV system's potential and solar resources, as illustrated in Table 2. The study compared the performance of different angles to identify those that optimize the installation of photovoltaic systems in the specified areas. The findings also include environmental and financial data about these regions, presenting insights into their monthly and annual solar radiation capacities.

This study evaluated the effect of building façade placement and orientation on PV energy generation using the previously mentioned computational simulation. There were several important steps. To ensure accurate modeling of solar incidence throughout the year, we first inputted the location coordinates (latitude: 31.95°N, longitude: 35.91°E) of Amman, Jordan. With these coordinates, the software protocols were used to analyze geospatial and climatic data. The objective is to determine solar position parameters, such

as azimuth and altitude angles. A 3D conceptual digital model of the chosen residential blocks was created, incorporating architectural elements such as shading effects and façade placements. This process enables the analysis of solar irradiance distribution on various building surfaces. This allowed for identifying the best locations for PV integration while taking shading effects and seasonal variations for validation.

The most effective sites for PV installation were then identified using multi-criteria optimization, which balanced energy generation with architectural limitations and assessed surfaces with lower direct solar radiation. In order to confirm the efficacy of the optimization approach, a secondary validation and performance evaluation phase was included. Leading to ascertaining the determination of BIPV configurations evaluated from performance metrics, such as energy yield, efficiency, and shading losses. By combining these approaches, the study establishes a robust framework for optimizing PV placement in urban settings. The methodology is flexible and can be used in other cities with comparable urban and climatic features.

Table 1. Characteristics of the selected PV system during the analysis process (by authors)

PV system type	Mono-Si
Power capacity	5 kW
Efficiency	17.63%
Bifacial cell adjustment factor	2%
Miscellaneous losses	16%
Inverter efficiency	98.9%
Inverter capacity	6 kW
Inverter miscellaneous losses	1.5%
Initial costs	2800 \$/kW
Financial parameters	
Inflation rate	3%
Reinvestment rate	10%
Project life	20 years
Debt ratio	50%
Debt term	20 years

While the solar altitude angle shows the sun's height above the horizon, as shown in Table 2, the solar azimuth angle concerning true north indicates the sun's position along the horizontal plane. By utilizing precise geolocation data for the study location on Haneen Bin Isaac Street in Amman (latitude 31.95°N, longitude 35.91°E), the two parameters were calculated dynamically throughout the year. Integrating both perspectives into the simulation environment facilitated an accurate modeling of solar incidence on various building façades. This approach enhanced the reliability of the proposed BIPV optimization method, allowing for a comprehensive analysis of the performance of different surfaces and orientations in terms of solar energy capture.

Table 2. Slope and azimuth angles analysis for the case study areas (by authors)

First Table		Second Table	
Slope Angle	Azimuth angle	Slope Angle	Azimuth angle
-50 ⁰	0 ⁰	-50 ⁰	180 ⁰
-45 ⁰		-45 ⁰	
-40 ⁰		-40 ⁰	
-35 ⁰		-35 ⁰	
-30 ⁰		-30 ⁰	
-25 ⁰		-25 ⁰	
-20 ⁰		-20 ⁰	
-15 ⁰		-15 ⁰	
-10 ⁰		-10 ⁰	
-5 ⁰		-5 ⁰	
-0 ⁰		-0 ⁰	
5 ⁰		5 ⁰	
10 ⁰		10 ⁰	
15 ⁰		15 ⁰	
20 ⁰		20 ⁰	
25 ⁰		25 ⁰	
Region's slope angle		Region's slope angle	
30 ⁰		30 ⁰	
35 ⁰		35 ⁰	
40 ⁰		40 ⁰	
45 ⁰		45 ⁰	
50 ⁰		50 ⁰	

Meteorological data relevant to the study conducted in Amman were sourced from NASA's database, ensuring a precise analysis of the local climate's impact on PV system performance. This climate data facilitates the enhancement of building design aimed at optimizing energy generation and informs the selection of PV materials and systems to achieve optimal efficiency. This study contributes to advancing energy-generating surfaces within urban residential architecture by modifying building envelopes to integrate PV technologies effectively.

4. Results and Discussions

According to the Koppen climate classification, Jordan, located in the Northern Hemisphere, experiences its peak levels of direct sunlight during the summer solstice. The analysis shows that the roof surfaces of 44 districts achieved the highest average insolation in June, reaching a maximum of 215.90 kWh/m². This elevated insolation is linked to the summer equinox and remained significant in July at 211.05 kWh/m² before decreasing slightly in August to 186.22 kWh/m² and in May to 181.91 kWh/m². In contrast, the south-facing wall recorded its highest insolation of 106.22 kWh/m² in November, coinciding with the winter equinox, while other months displayed values ranging between 96 kWh/m² and 100.6 kWh/m².

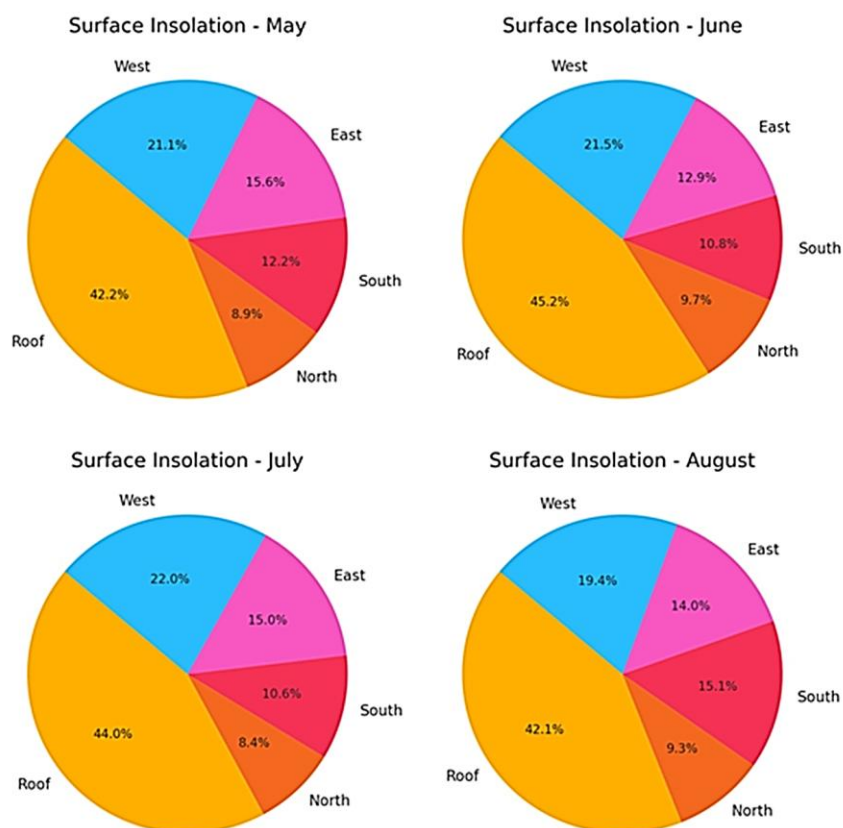


Figure 12. Average summertime surface insolation values per kWh/m² (by authors)

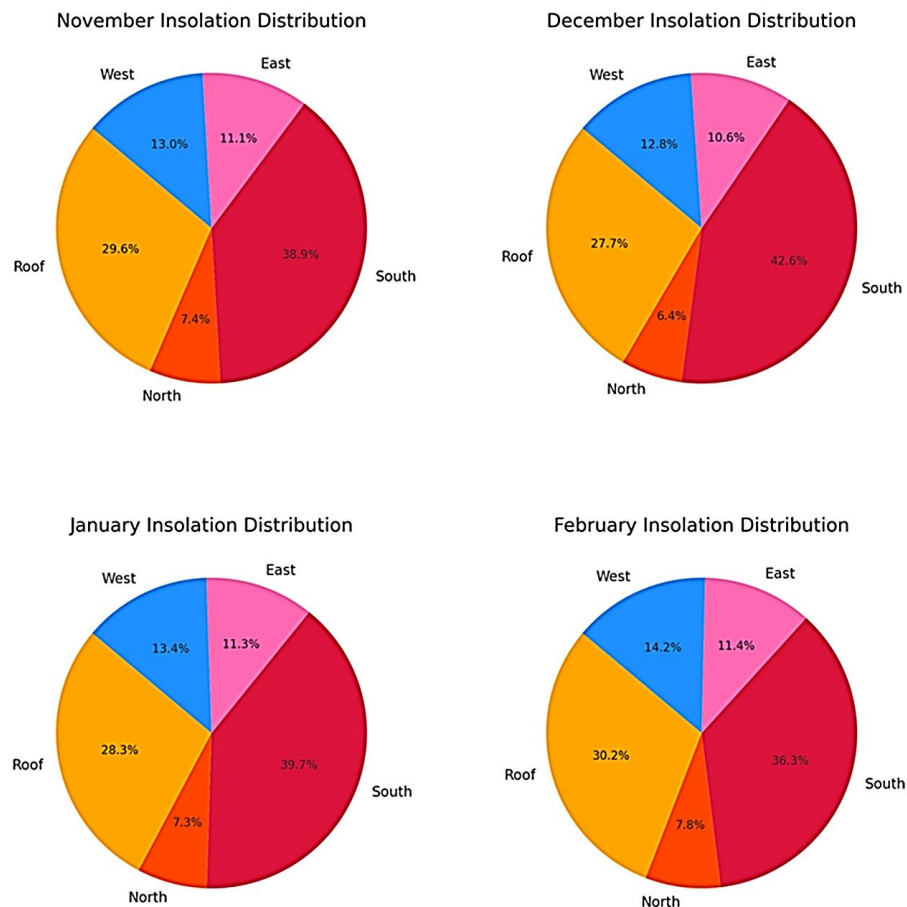


Figure 13. Average wintertime surface insolation values per kWh/m² (by authors)

During the summer, the roof surface consistently demonstrated the highest levels of solar energy insolation, reaching a minimum of 66 kWh/m² in winter and peaking at approximately 217 kWh/m² in summer. The west-facing wall is next to the roof results, which recorded the second-highest insolation levels during summer, with measurements ranging from 82 kWh/m² to 101 kWh/m². In winter, the roof's insolation varied from 66.6 kWh/m² to 89.5 kWh/m², making it second only to the south-facing wall in energy capture. Conversely, the north-facing wall consistently received the lowest insolation levels throughout the year, ranging from 13 kWh/m² to 46.6 kWh/m². Detailed results are presented in Figures 12 and 13.

Table 3. Surface insolation, study time, and range values, from Sunrise to Sunset, arranged in descending order [31]

July		May		December		November	
Surface Orientation	Average Surface Insolation Value- kWh/m ²	Surface Orientation	Average Surface Insolation Value- kWh/m ²	Surface Orientation	Average Surface Insolation Value- kWh/m ²	Surface Orientation	Average Surface Insolation Value- kWh/m ²
Roof	211.05	Roof	181.91	South	101.64	South	106.21
West	99.70	West	91.33	Roof	66.57	Roof	78.68
East	81.99	East	65.80	West	35.34	West	42.34
South	58.91	South	55.79	East	30.56	East	34.58
North	42.64	North	35.31	North	13.30	North	14.78
Sum	494.29		430.14		247.41		276.59
June		August		January		February	
Surface Orientation	Average Surface Insolation Value- kWh/m ²	Surface Orientation	Average Surface Insolation Value- kWh/m ²	Surface Orientation	Average Surface Insolation Value- kWh/m ²	Surface Orientation	Average Surface Insolation Value- kWh/m ²
Roof	215.90	Roof	186.21	South	96.10	South	100.59
West	100.99	West	90.78	Roof	66.75	Roof	89.55
South	53.97	South	77.69	West	36.51	West	47.22
East	53.97	East	70.20	East	30.10	East	36.93
North	46.60	North	32.05	North	13.00	North	15.81
Sum	471.43		456.93		242.46		290.1

Table 3 presents the monthly thermal gain for the building surfaces under investigation, while Figures 12 and 13 illustrate the conceptual orientation of the building concerning diurnal temperature variations and solar intensity in summer and winter. The figures illustrate a solar insolation study on a focus building using color gradients to represent solar radiation intensity, ranging from pink (low) to leaf green (moderate) to yellow (high). The vertical color bars beside each month serve as calibration scales, showing the variation in solar exposure levels throughout the year. The colorful overlays on the building represent conceptual forms generated through solar simulation tools, illustrating how sunlight affects different surfaces seasonally. The black-based surrounding blocks represent neighboring buildings, modeled to simulate real-world

shading effects on the target building and ensure accurate solar access and performance analysis. The findings indicate that the roofs and south-facing walls are exposed to greater insolation, positioning them as ideal surfaces for installing PV systems, thereby optimizing solar energy capture despite seasonal fluctuations.

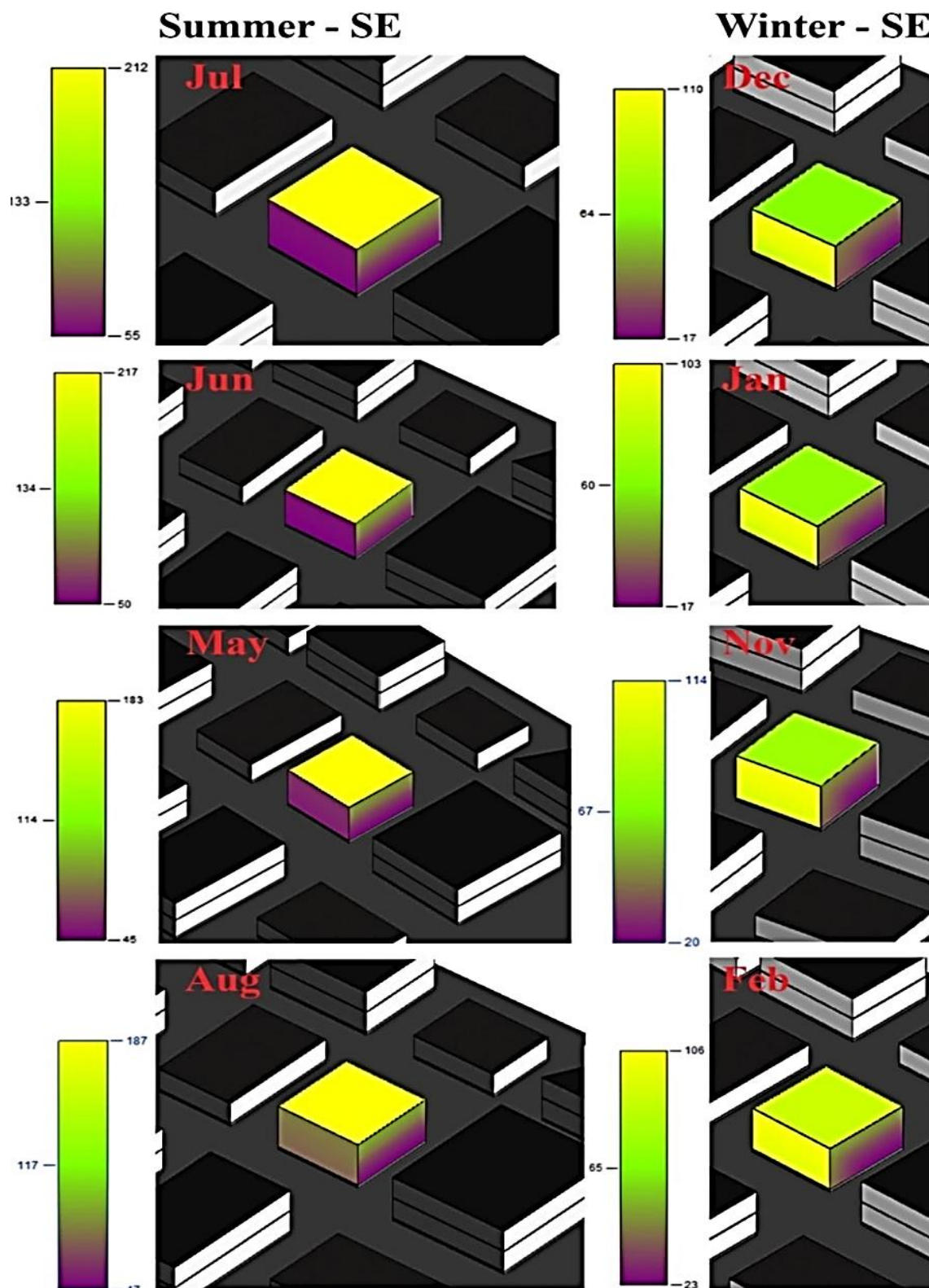


Figure 14. Average south-eastern insolation values for summer and winter (by authors)

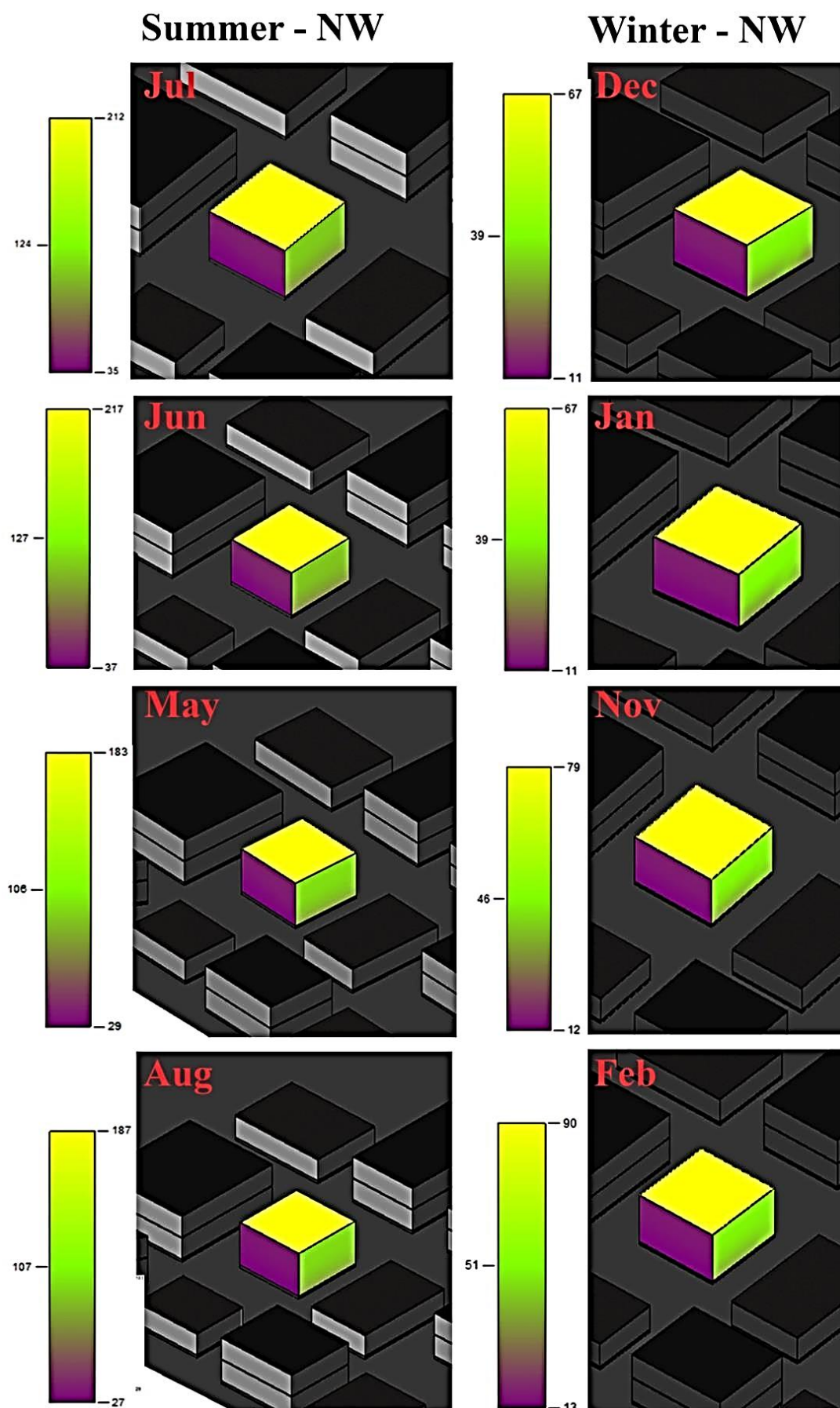


Figure 15. Average northern-western Insolation values for the summer and winter (by authors)

Table 3 and Figures 14 and 15 indicate that the roof surface captures the most solar energy during summer, accounting for 42.90%. The western-facing surface follows this at 20.66%, the eastern-facing at 14.68%, the southern-facing at 13.30%, and the northern-facing at 8.45%. In contrast, during the winter, the southern-facing surface receives the highest solar energy at 38.29%, followed by the roof at 28.54%, the western surface at 15.28%, the eastern surface at 12.51%, and the northern surface at 5.38%. These insights are vital for optimizing the placement of energy systems, such as heating and cooling units, to improve their efficiency throughout the year. By strategically installing these systems on surfaces that receive the most seasonal solar energy, operational efficiency can be maximized, resulting in lower energy costs, reduced maintenance, and enhanced returns on PV investments. These results enhance the energy returns anticipated in this study for regions characterized by arid climatic conditions.

The surfaces of the building in the case study exhibited varying responses to several factors, including roof design, orientation, and the extent of PV system utilization at that time. Their orientation primarily influenced the level of solar exposure on vertical surfaces; south-facing walls garnered the most sunlight, receiving 51.59% of insolation, making them ideal for PV integration, especially when lighter-colored PV materials were employed to mitigate overheating. Conversely, northern-facing walls, with lower insolation levels of 13.83%, were more suitable for PV materials optimized for low-light conditions, such as thin-film technology, allowing even shaded areas to contribute to energy production.

The design of rooftops significantly influenced the capture of solar energy, with flat horizontal roofs exhibiting the lowest sensitivity to orientation. However, the efficiency of PV systems was substantially affected by factors such as the tilt angle, surface area, and the potential for self-shading caused by the roof's structure. Expansive, unobstructed roof surfaces provided optimal conditions for PV installations, particularly when considering their overall insolation percentage, which averaged 71.47% across different seasons. Conversely, roofs with intricate geometries or those overshadowed by adjacent constructions required more strategic placement of PV systems to maximize energy output.

Based on observations of the buildings and policy documents in the study area, the current implementation of PV systems in residential buildings within the study context has been limited by policy constraints, structural requirements, and aesthetic considerations. Most installed PV systems were positioned on rooftops as a conventional approach rather than being integrated into building façades. That tendency reflects a preference for traditional PV applications over multifunctional integration into architectural elements such as windows, railings, or skylights. This trend suggests an underutilization of BIPV technologies, which could potentially enhance both architectural design and energy efficiency.

These results highlight the importance of matching the location of PV systems with the specific features of individual buildings to maximize solar energy production. PV adoption in urban residential buildings can be greatly increased by taking a strategic approach that considers orientation, roof design, shading

effects, and material selection. This will improve sustainability and energy efficiency.

Moreover, the color of PV materials significantly influences their energy absorption capabilities. Darker PV materials are more effective at absorbing heat, making them ideal for winter applications or installation on surfaces with minimal solar exposure, such as northern-facing walls in Amman, Jordan, which receive only 13.83% solar radiation during both the summer and winter months. In contrast, lighter-colored PV materials are better suited for summer applications or surfaces with high solar exposure, exemplified by southern-facing walls that capture 51.59% of solar radiation. Additionally, when examining roof surface insolation, totals reached 71.47% in the studied context during both summer and winter.

The results align with the ideas of other researchers on incorporating multifunctional PV systems into architectural designs [32-34]. PV panels contribute to both cooling and heating, thereby reducing the need for supplementary equipment while also optimizing interior space and enhancing the overall visual appeal of the building. Since these systems can be installed at different sections of the building's surfaces, this study has found that they offer designers and users the opportunity to transform open-air flat roofs into adaptable spaces suitable for social activities and domestic utilities.

Although, some indoor spaces are specifically designed for summer or winter activities or even for both. The results of this study provide insights into more effective design strategies for such spaces, ensuring a reduction in internal heat gains during summer and minimizing heat loss during winter. Moreover, these strategies offer natural lighting, thermal insulation, and weather protection, which can be optimized through the appropriate selection of PV materials and the careful integration of PV systems into various building components, such as external walls, windows, skylights, and railings.

The results indicate that surfaces with low solar insolation, including northern-facing walls or shaded regions, can still facilitate energy generation by employing PV materials that exhibit effective performance in low-light or shaded environments, such as thin-film glass. Furthermore, the strategic selection of PV materials based on color, darker shades for heat gain, and lighter shades for heat loss can significantly enhance the energy efficiency of the building. This approach supports heating and cooling functions throughout the year, optimizing overall energy performance.

Regarding the effect of building orientation, a large surface area facing north-south is practically viable; however, openings to the south will require shading elements to regulate summer sun insolation while admitting winter sunlight. However, the north-facing wall will be efficient by introducing an insulation layer to balance heat losses and gains. The results also show that orientation does not significantly impact flat roof surfaces. However, factors such as roof surface area, roof angle, self-shading, and the distance between the roof and surrounding buildings due to their shading effects play a critical role (see Figures 14 and 15). While building orientation is a key determinant in the amount of solar insolation received by vertical walls, external openings, or inclined roofs, it has minimal impact on flat roof surfaces. The flat

roof's neutrality can be leveraged to achieve energy efficiency.

The existing literature suggests that the sketch presented in Figure 16 is particularly suited for hot and dry climates, such as the one under investigation in this study. Conversely, based on the findings of this research, we have integrated the strategic placement and installation of PV systems to enhance energy returns, as depicted in Figure 17. These conceptual visual models are designed to optimize available resources, including shading, surface area, and insolation angle while integrating PV systems. This approach aims to ensure efficient performance and thermal comfort within the interior spaces of the residential buildings examined. Furthermore, these strategies can be applied in regions with similar climatic conditions.

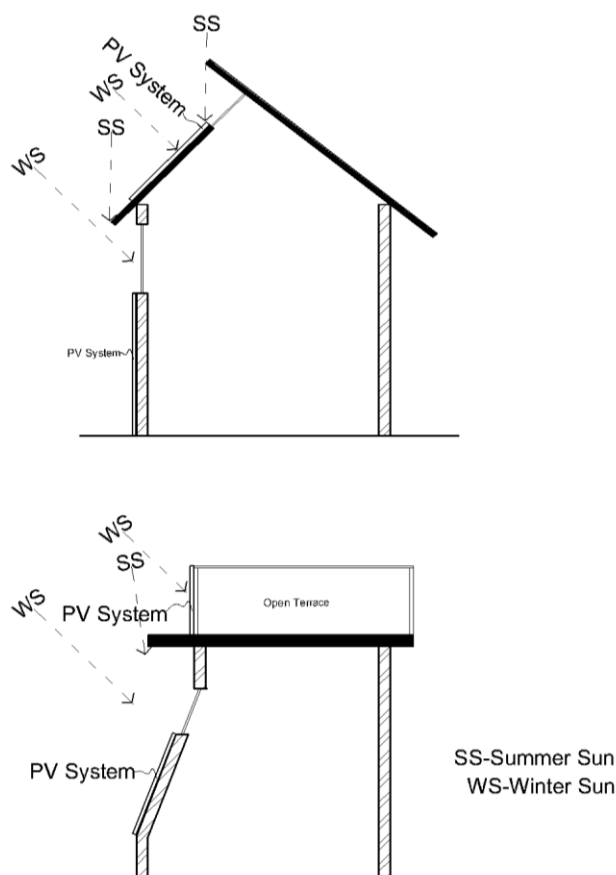


Figure 16. Conceptual integration of PV systems [35] adapted by authors

In multi-story residential buildings, installing PV systems is generally more effective when placed on surfaces oriented towards the south, assuming that these areas are free from shading caused by nearby structures and utilize the available surface area optimally [36-41]. The 'saw-tooth' roof design exemplifies a strategic approach to maximizing solar energy capture (see Figure 17). This architectural feature combines the benefits of both roofing and southern-facing slopes, thereby maximizing solar energy absorption from a single plane. Consequently, this design enhances energy production and serves as a viable solution for surfaces that experience lower insolation levels or are shaded, thereby improving the overall performance and efficiency of PV systems across various building configurations. This integration of PV systems into the design distinguishes our approach from previous saw-tooth applications, which did not explicitly

connect form-making with renewable energy harvesting. Thus, our design enhances passive solar gain for residential comfort and actively contributes to the building's energy production, aligning with modern sustainable design goals. This holistic strategy bridges passive solar design with active energy systems in a way that previous studies did not fully explore.

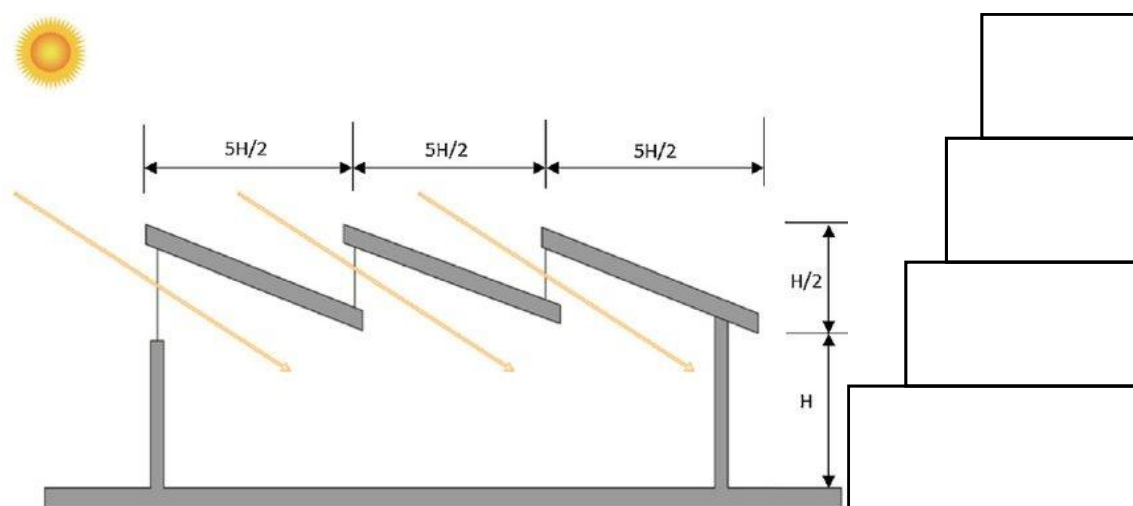


Figure 17. PV saw-tooth system provides directional distribution of daylight [42]

5. Conclusions

Integrating PV systems into building envelopes transforms structures into self-sustaining energy producers, a strategy crucial for mitigating the impacts of climate change. Tailoring these systems to regional climate conditions is particularly valuable for countries like Jordan, which face energy shortages, high population density, and temperature extremes. This research promotes the strategic use of BIPV in arid climates, optimizing local energy resources to enhance energy efficiency, environmental sustainability, urban aesthetics, and building thermal performance.

The study evaluated the feasibility of BIPV deployment in Amman using various PV technologies, monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si), cadmium telluride (CdTe), copper indium selenide (CIS), and amorphous silicon (a-Si), alongside fixed and dual-axis solar tracking systems. Findings indicate that mono-Si outperforms other technologies by 18–22%, while dual-axis tracking enhances output by 25–30% compared to fixed systems. However, fixed systems offer greater cost-effectiveness and ease of façade integration, making them more suitable for urban BIPV applications.

These results demonstrate the potential of PV integration to meet Jordan's growing electricity demands and reduce greenhouse gas emissions through the use of low-carbon technologies. Furthermore, the adaptability of BIPV systems to various climates, without compromising design or economic viability, underscores their role in shaping sustainable urban development.

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