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Estimating the efficacy of solar photovoltaic panels in Lebanon using a digital surface model: A geospatial approach

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Abstract

With the escalating need for alternative energy sources due to economic crises and fossil fuel shortages in Lebanon, solar photovoltaic (PV) panels have emerged as an attractive solution. This study examines the capacity and efficacy of rooftop-installed PV solar panels. Using geospatial technologies, including Digital Surface Models drone-based photogrammetry, the study assesses geometric and solar characteristics, seasonal solar radiation, solar duration, and power for 40 PV units installed in the study area. This research presents specific quantitative values for optimal orientations that result in high solar radiation across various seasons and identifies varying slopes influencing the performance of PV solar panels. Employing the Agglomerative Hierarchical Clustering (AHC) technique, PV units are systematically classified into clusters labeled as Moderate, High, Low, and Very Low solar power, offering quantitative metrics regarding the effectiveness of distinct panels. The high-efficiency Cluster exhibits an average solar power of 1868.114 kWh/m^2 during the summer season, whereas the Very Low Cluster, comprising panels with minimal solar power output, averages 150.578 kWh/m^2 in the same season. In conclusion, the most effective PV solar panels within the study area are those oriented between 195 and 225 degrees, with shallow inclination angles and larger surface areas contributing to enhanced performance in capturing solar radiation and generating power. These precise quantitative insights contribute to informed decision-making for optimizing the placement of PV panels to enhance energy generation. The study's recommendations are substantiated by specific numerical data, guiding future solar installations to maximize solar energy generation.

1. Introduction

Due to the economic crisis that struck Lebanon in late 2019, coupled with power outages caused by fossil fuel shortages and high prices, the depletion of global fossil fuel resources has prompted a critical search for alternative energy sources to meet contemporary demands. Once considered an expensive and inefficient method of generating electricity, solar PV panels have become increasingly affordable and appealing when compared to rising energy prices from non-renewable sources. Solar power has also grown more accessible to homeowners.

Individuals have installed solar panels on building roofs to generate electricity for their household needs. Certain residents have achieved energy independence and reduced reliance on the public electricity grid. PV technology directly converts solar energy into electricity based solely on the availability and quality of renewable resources, technical system performance, topographic limitations, and environmental and land-use constraints [1].

PV technology stands as one of the fastest-growing technologies worldwide. It boasts independence and adaptability to various scenarios, making it versatile. It can seamlessly integrate with smart grid networks and can also be tailored for small-scale applications like stand-alone PV power systems on rooftops [2,3].

Numerous solar radiation estimation models, such as remote sensing, geo-statistics, and Geographic Information Systems (GIS), have been developed to provide a more cost-effective and convenient way of measuring radiation, as opposed to deploying multiple sensors to the area for direct measurement.

Using GIS has gained momentum in renewable energy across various regions of the world. It has proven invaluable in developing spatial decision support systems, aiding decision-makers in resolving spatially related issues by leveraging geographical controlling factors [4].

On a global scale, the primary controlling factors include latitude, distance from the sun, and the time of the year. On a local scale, significant sources of spatial variation encompass elevation above sea level, surface inclination, surface orientation, and the shadowing effects of nearby terrain features [5].

In this study, weather conditions were excluded due to their instability, unpredictability, and the challenges associated with modeling cloud patterns. Atmospheric conditions can span from overcast skies and clear skies to partly cloudy skies, direct sunlight, and uniform skies. The solar radiation for the study area was calculated under clear-sky conditions.

As interest in solar power generation continues to rise, the number of published studies evaluating the photovoltaic (PV) potential of different regions has steadily increased for more than a decade.

The Energy Sector Management Assistance Program (ESMAP) has identified the theoretical, practical, and economic potential of PV in each country, presented through maps and summary tables. This resource could serve as a foundation for global study [6].

One area of research is dedicated to precisely estimating the power production of photovoltaic (PV) systems installed on building roofs and identifying potential locations for solar energy harvesting [6].

The research conducted by [7] assessed the solar energy potential across Europe. On a more localized level, individual country and regional studies strive to pinpoint and suggest viable solar energy project opportunities. These studies utilize methodologies such as multiple-criteria decision-making (MCDM), the analytic hierarchy process (AHP), and fuzzy logic, to establish recommendations for solar energy development.

Choi et al. [8] reviewed geographic information system (GIS)-based methods and their applications in the planning and design of solar power systems. They categorized GIS-based studies into three main groups: 1) solar radiation mapping, 2) site evaluation, and 3) potential assessment. The review involved classifying previous GIS-based studies into subtopics based on factors such as the complexity of the GIS methods employed, the solar power conversion technology, or the scale of the study area.

The majority of GIS research and its applications in solar power have focused on identifying the potential for solar panels [9-11], suitability for PV farms [12], and feasibility of PV implementation [13,14]. There has been a lack of research examining the capacity of PV solar panels after installation using geospatial technologies.

Our study introduces a fourth category to the three groups identified by [8]. This category will delve into the efficacy of rooftop-installed PV solar panels, specifically focusing on their capacity to generate electricity. However, to our knowledge, no such assessment has been published at the micro level. This research gap underscores the significance of our study within the local solar industry, we analyze the capacity of rooftop PV solar panels within a small area of the El Meten region in Lebanon.

There are three primary causes of spatial variability in radiation at the land surface: (1) the orientation of the Earth relative to the sun, (2) clouds and other atmospheric inhomogeneities, and (3) topography. The first cause influences latitudinal gradients and seasons. The second cause is linked to local weather and climate, but it will not be addressed in this study. The third cause, including spatial variability in elevation, slope, aspect, and shadowing, can give rise to pronounced local gradients in solar radiation. These gradients support our study [15].

Topographic effects on direct radiation were calculated for each grid node in a Digital Surface Model (DSM) using the spatial analysis tool within ArcGIS Pro, over Fall, Winter, Spring, and Summer. Sun elevation and azimuth were factored in.

Digital Surface Models (DSM) and Ortho mosaics, generated through drone photogrammetry and Geographic Information System (GIS) technology, were utilized for analyzing the capacity and efficacity of the pre-installed rooftop PV solar panels.

The utilization of drones was preferred over previously available digital elevation data due to their higher precision and ability to identify rooftop solar panels accurately.

The surface model was also employed to calculate panel slopes and aspects, aiding in identifying the optimal locations and orientations for the installed photovoltaic solar cells. Solar radiation duration and power were computed for each of the four seasons: Fall, Winter, Spring, and Summer

This study serves as an initial step toward developing a plan by assessing the solar potential and power generation capacity of rooftop solar panels. Leveraging geospatial data enables the calculation of a more precise estimation of solar capacity for structures across the entire region. Traditional methods have often relied on less accurate datasets like bare earth Digital Elevation Models or time-consuming individual property assessments. Through the utilization of drone photogrammetry to generate high-resolution elevation data, the Digital Surface Model (DSM) can influence solar energy specifically on the Earth's surface [16].

It's important to note that not all rooftop PV systems are installed uniformly. Evaluating the efficacy of these solar panels can be achieved through manual surveys conducted by experts in the field. However, this approach is highly impractical for estimating PV efficacity over a larger region with numerous rooftops.

This study aims to address these questions:

1. What are the geometrical and solar characteristics of the installed PV units that exhibit high solar radiation and power?

2. How can PV solar panels be categorized based on their efficacity?

2. Materials and method

In Lebanon, a Middle Eastern country, there is an urbanized area of 5 hectares in the El Meten region. According to the Global Solar Atlas 2.0, the long-term yearly average of potential photovoltaic electricity production, covering the period between 1999 and 2018, was 1583 kWh. This value is promising for conducting solar energy experiments [17].

The experiment area is relatively small due to restrictions on drone flights in urban areas and the limited endurance of drone batteries.

The study area in Figure 1 is characterized by its urban structure, which includes a variety of small private homes and large residential buildings suitable for the installation of PV solar panels.

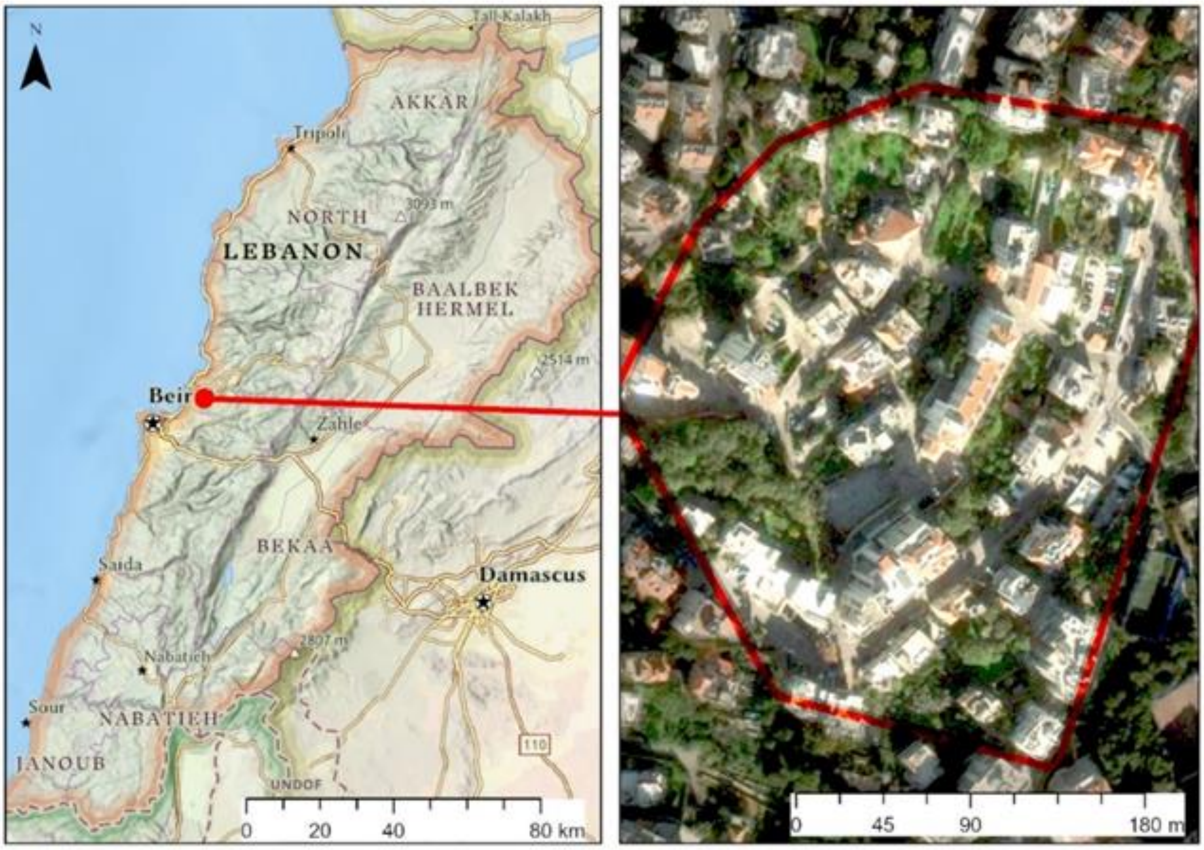

Figure 1. Study area.

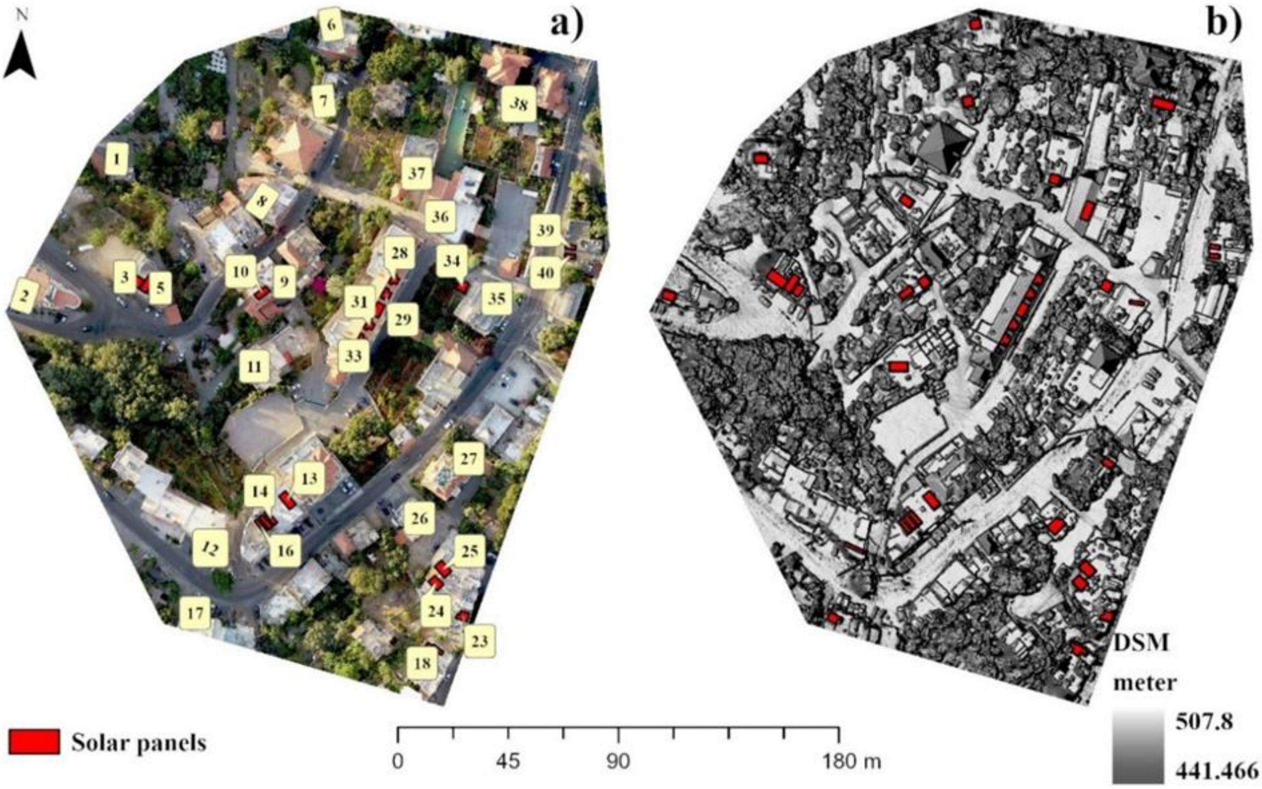

Figure 2. a) Ortho mosaic with the numbers of PV solar panels, b) The DSM with the PV solar panels.

For the photogrammetry mission, a DJI Phantom 4 with a 20-megapixel camera was employed. The drone was flown at a height of 100 meters from the take-off point, capturing 46 aerial frames with an 80% overlap and 70% side lap. These overlaps would generate a dense point cloud for Ortho mosaic and DSM production.

To ensure accuracy, 10 control points were strategically placed on the ground and surveyed using a differential Global Navigation Satellite System receiver. This receiver boasted a horizontal accuracy of 0.5 cm and a vertical accuracy of 2 cm, which proved to be more than adequate for solar study purposes.

The resulting Ortho mosaic, with a spatial resolution of 4 cm, was employed to digitize the PV solar panels in Figure 2a. Figure 2 depicts 40 PV units, each of which could consist of 2 or more panels.

Concurrently, a DSM was generated with a spatial resolution of 7 cm to be used for solar radiation and solar duration calculations.

Figure 2a of the Ortho mosaic showcases the 40 digitized PV units composed of solar panels with varying areas and orientations. These panels were installed without prior studies and are predominantly oriented towards the East-South direction.

Figure 2b of the DSM illustrates elevation intervals above sea level, ranging from 441 to 507 meters, effectively displaying building and tree heights.

Solar radiation received from the sun stands as the primary energy source for PV panels, rendering an understanding of its significance at landscape scales crucial for comprehending an array of natural processes and human activities.

Within landscape scales, topography emerges as a pivotal determinant of the spatial fluctuations in solar radiation. These fluctuations evolve with the progression of the day and the shifting of seasons, contributing to the variations in microclimates. These microclimatic differences encompass elements like air and soil temperatures, evapotranspiration, patterns of snowmelt, soil moisture, and light accessible for photosynthesis.

The computation of solar radiation was executed through the utilization of the area solar radiation tool within ArcGIS Pro, aligned with the DSM derived from drone-based photogrammetry as the primary input. However, this study did not delve into investigating the accuracy and quality of the resulting DSM.

The ArcGIS Pro Spatial Analyst extension facilitates the mapping and analysis of solar effects employing techniques rooted in the hemispherical viewshed algorithm [5]. This approach incorporates considerations for atmospheric influences, site latitude and elevation, slope steepness, compass direction (aspect), daily and seasonal variations in solar angles, and the impacts of shadows cast by surrounding topography, as expressed by the DSM grid.

The latitude (33.9304) at the center of the study area is employed in calculating solar declination and solar positioning. Given that the analysis is tailored for micro scales, the practice of utilizing a single latitude value for the entire DSM is generally acceptable. However, for global scales, insolation outcomes would notably diverge across distinct latitudes, necessitating division into zones characterized by different latitudes.

Solar effects are computed based on distinct seasonal periods—Fall, Winter, Summer, and Spring. When determining the most suitable orientation for installations, it is crucial to account for the sun's relative angular position throughout the year and day.

During Summer in the Northern Hemisphere, the region is inclined towards the sun, leading to more direct solar rays striking the ground from the first of June until the first of September. Conversely, in Winter, spanning from the first of December till the first of March, the Northern Hemisphere is oriented away from the sun [18].

Considering these factors, for installations within the Northern Hemisphere, a southern exposure is typically considered optimal for capturing the highest intensity of sunlight overall [19,20].

The solar radiation output raster data in Figure 3 are of the floating-point type and are measured in units of Kilowatt hours per square meter (kWh/m^2).

In the SAGA GIS software, the seasonal average solar duration was computed using the DSM derived from drone data. The resulting solar duration output, presented as an integer raster, represents the mean value across Fall, Winter, Spring, and Summer, measured in hours.

It's worth noting that the performance of PV solar power plants is generally not significantly impacted by temperature [12]. The value of solar radiation estimates the potential electricity generation within each PV unit.

The seasonal solar energy production is determined by the dimensions of the PV solar panels, which are outlined in a shape file digitized from the Ortho mosaic. The unit of solar electricity power (UP) is calculated following the method [21] outlined by Equation 1.

$$UP = A \times SR_{Season} \times 0.163 \times 0.8592 \quad (1)$$

UP = Unit Power (kWh)
r = 16.3% PV solar panel efficiency of PV modules
PR = 85.92% performance ratio (PV Watts Calculator: 14.08% system losses)
SR is the mean solar radiation received per unit area (kWh/m^2) each season,
A is PV solar panel unit area (m^2),

The value of the efficiency (r) used is adopted from the National Renewable Energy Laboratory of the USA [21].

To accurately estimate solar radiation across the study area throughout the four seasons, a high-resolution solar radiation raster was computed using the solar radiation module within ArcGIS Pro. This module considers a variety of factors, including atmospheric influences, site latitude and elevation, slope steepness, compass direction (aspect), daily and seasonal shifts in the sun angle, and the impacts of shadows cast by surrounding topography. It provides the flexibility to adjust the coefficient of atmospheric transmissivity, as detailed by [12].

The model's calculations encompass the summation of direct and diffuse radiation across all sectors of both sun maps and sky maps. The primary input parameters employed in this model were derived from the DSM generated through drone-based photogrammetry, as depicted in Figure 2b.

Following the GIS processing steps for generating slopes, aspect, SR, SD, and UP values, a zonal statistics analysis was conducted for the PV units. This analysis facilitated the extraction of the geometric and solar characteristics of the 40 photovoltaic units.

3. Results and Discussion

The 40 PV units of solar panels were delineated from the ortho mosaic generated. Then utilizing the integrated DSM within ArcGIS Pro, the seasonal Solar Radiation (SR) depicted in Figure 3 was produced.

Four raster data displaying the average solar duration for each season—Fall, Winter, Spring, and Summer were generated. These raster data were developed by considering the elevations from the DSM data, utilizing SAGA software.

The Unit Power of the solar panels was calculated according to equation number 1.

In the fall season, the maximum solar radiation reaches 338.208 kWh/m^2, and this value declines to 252.428 kWh/m^2 during the winter period, as illustrated in Figure 3b. These calculations do not consider the influence of atmospheric conditions. Moving into the spring season, solar radiation increases to 473.158 kWh/m^2, further reaching an average of 537.235 kWh/m^2 during the summer. This increase is pronounced on rooftops and in open areas, exemplified by the red regions in Figure 3d.

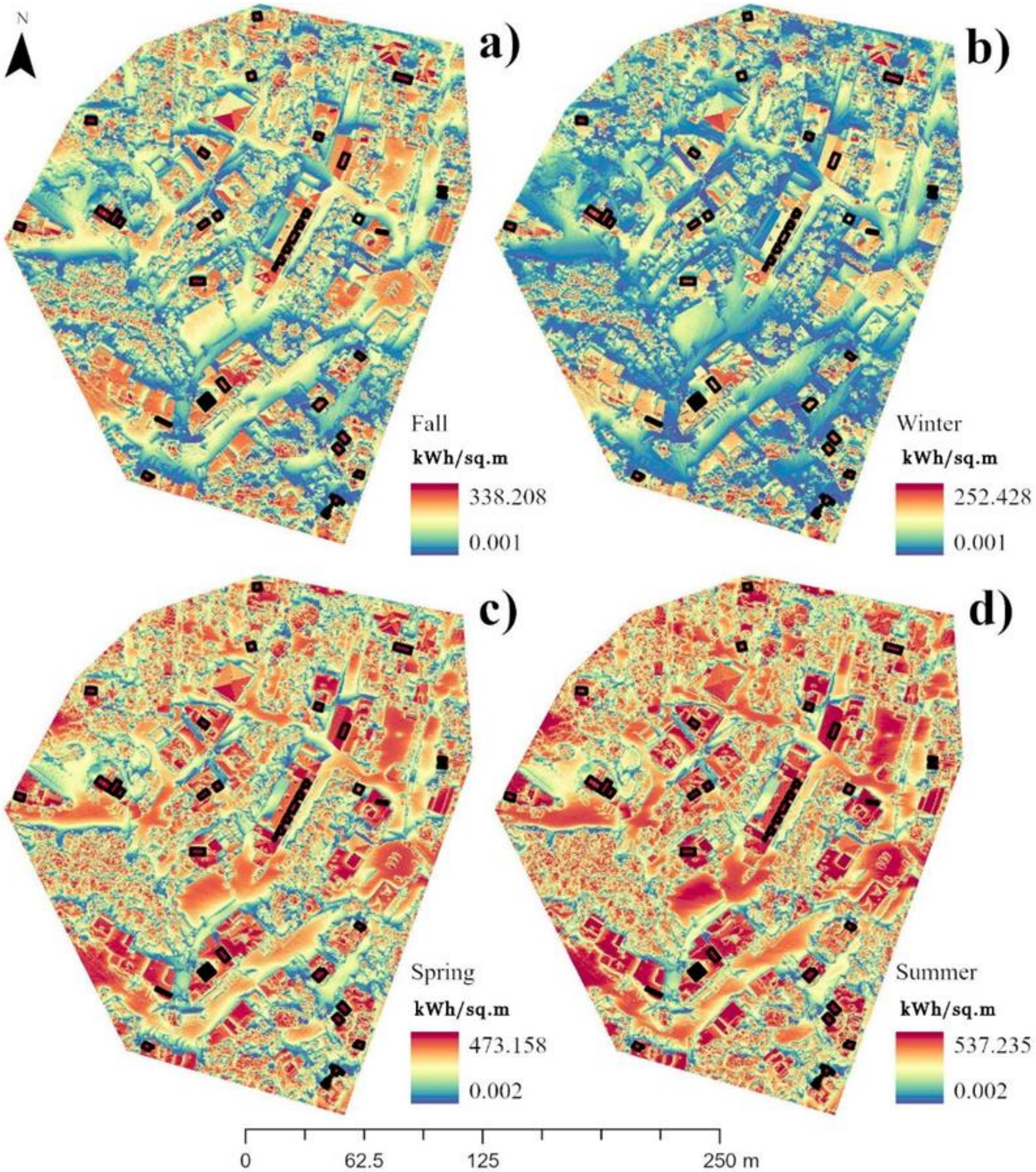

Figure 3. Seasonal solar radiation, a) Fall, b) Winter, c) Spring, and d) Summer.

The geometry of the PV solar panel units is defined by the area they cover, their orientation angle regarding the North direction (measured in degrees), and the slope of the installed panels (also in degrees).

The areas of the PV unit solar panels vary, ranging from 1.5 m^2 to 32.7 m^2. More than 20 PV solar panels among the 40 units under study have areas exceeding 20 m^2.

Figure 4 provides insights into the seasonal characteristics of the solar panels as determined by this study. These include the mean solar radiation (SR), the mean solar duration in hours, and the solar unit power (UP) measured in kWh.

Determining the optimal placement for photovoltaic (PV) panels involves a multitude of factors, encompassing geographical location, climate, available space, and the specific objectives of the PV system. The key considerations of the most suitable orientation for PV placement are listed in Table 1:

Table 1. Factors affecting the optimal PV panel orientations.

Factors	Affections
Solar Angle and Latitude	The angle of the sun and the latitude of the location affect the optimal panel orientation.
Direction	The cardinal direction (north, south, east, west) affects the exposure of the panels to sunlight.
Tilt Angle	The tilt angle of the panels can affect their efficacy in capturing sunlight.
Shading	Avoiding shading from nearby structures or vegetation is crucial to maximize energy production.
Energy Consumption Patterns	Aligning panel production with peak energy consumption times can optimize system performance.
Climate	Weather patterns, temperature, and cloud cover influence panel orientation choices.
Economic Factors	The costs associated with installations and potential energy savings play a role in orientation decisions.

In our study area, the PV panel units were installed with roof-oriented panels numbered 28, 29, 30, 31, 32, and 33. These panels are predominantly oriented to the South and Southwest, depending on installation feasibility.

PV panels with high Solar Radiation (SR) values are oriented between 180 and 233 degrees, corresponding to the south and southwest directions. However, the orientations associated with high Solar Duration (SD) values differ across seasons. In the fall season, the interval is between 228 and 231 degrees, in winter it's 227 to 233 degrees, in spring the high SD values are achieved with orientations between 180 and 195 degrees (toward the south), and in summer, when solar rays directly strike the ground, the interval tends towards the southwest (225-231 degrees).

The average slope of the installed PV unit solar panels with high SR values shows distinct patterns across seasons. Specifically:

Fall and Winter: Panels with high SR values have an average slope of 26 to 34 degrees.

Spring: High SR panels display an average slope ranging from 22 to 24 degrees.

Summer: Panels with low slope angles, typically between 6 and 16 degrees, attain higher SR values due to the direct solar rays striking the ground.

Interestingly, the PV units of solar panels that exhibit high SR values for the fall and winter seasons remain relatively consistent for spring and summer. However, the summer season introduces a shift in high SR values, where the panels that receive the most direct solar rays, such as panels numbered 14, 15, 16, and 24, achieve the highest SR values. This adjustment is noteworthy as these panels differ from those with high SR values in fall and winter (panels numbered 1, 23, 35, and 37). The result is a noticeable increase in SR values for panels 14, 15, 16, and 24 during the summer season.

In Figure 2, small areas housing PV solar panels 14, 15, and 16 exhibit high SR (Solar Radiation) values. These panels are on the same rooftop and share identical orientations with PV solar panel number 13. However, they are positioned at an elevated level and possess a slightly smaller inclination angle within the range of 6 degrees. Conversely, PV solar panels with a steeper inclination angle of 15.8 degrees (as stated in Figure 2) capture comparatively less solar radiation.

This observation highlights that PV solar panel units with lower inclinations (specifically, panels 14, 15, and 16) experience greater solar radiation across all seasons.

During the summer season, PV units of solar panels numbered 14, 15, 16, and 26 experience the highest Solar Duration, with 12 hours of sunlight each day. But in the winter season, the PV unit solar panel numbered 34 records the lowest solar duration of 3 hours per day Figure 4. This lower value in winter can be attributed to panel 34's location, in a lower area surrounded by taller buildings that cast shadows.

When considering the combination of high-power capacity and large panel areas (ranging from 25 to 32 m^2), panels numbered 3, 26, 36, and 38 stand out. In the summer season, these panels exhibit capacities between 509 and 517 kWh/m^2. Conversely, PV units of solar panels with high SR values and smaller areas, specifically panels numbered 14, 15, and 16, achieve a slightly higher capacity of 533 kWh/m^2 during the same season.

To confirm the accuracy of the acquired results for the Summer UP (Unit Power) during the season, data was collected on the 15th of August at noon. This data involved the solar power readings extracted from the inverters of specific PV solar panels, namely numbers 4, 8, 13, 24, and 38 as illustrated in Figure 5. The solar power produced by these inverters correlates with the Summer UP values of the respective PV solar panels. These values are arranged in ascending order: 8, 24, 4, 13, and 38. This identical order also aligns with the arrangement of UP values. These consistent findings validate the relationship between solar power production, utilization performance, and the specific characteristics of the mentioned PV solar panels.

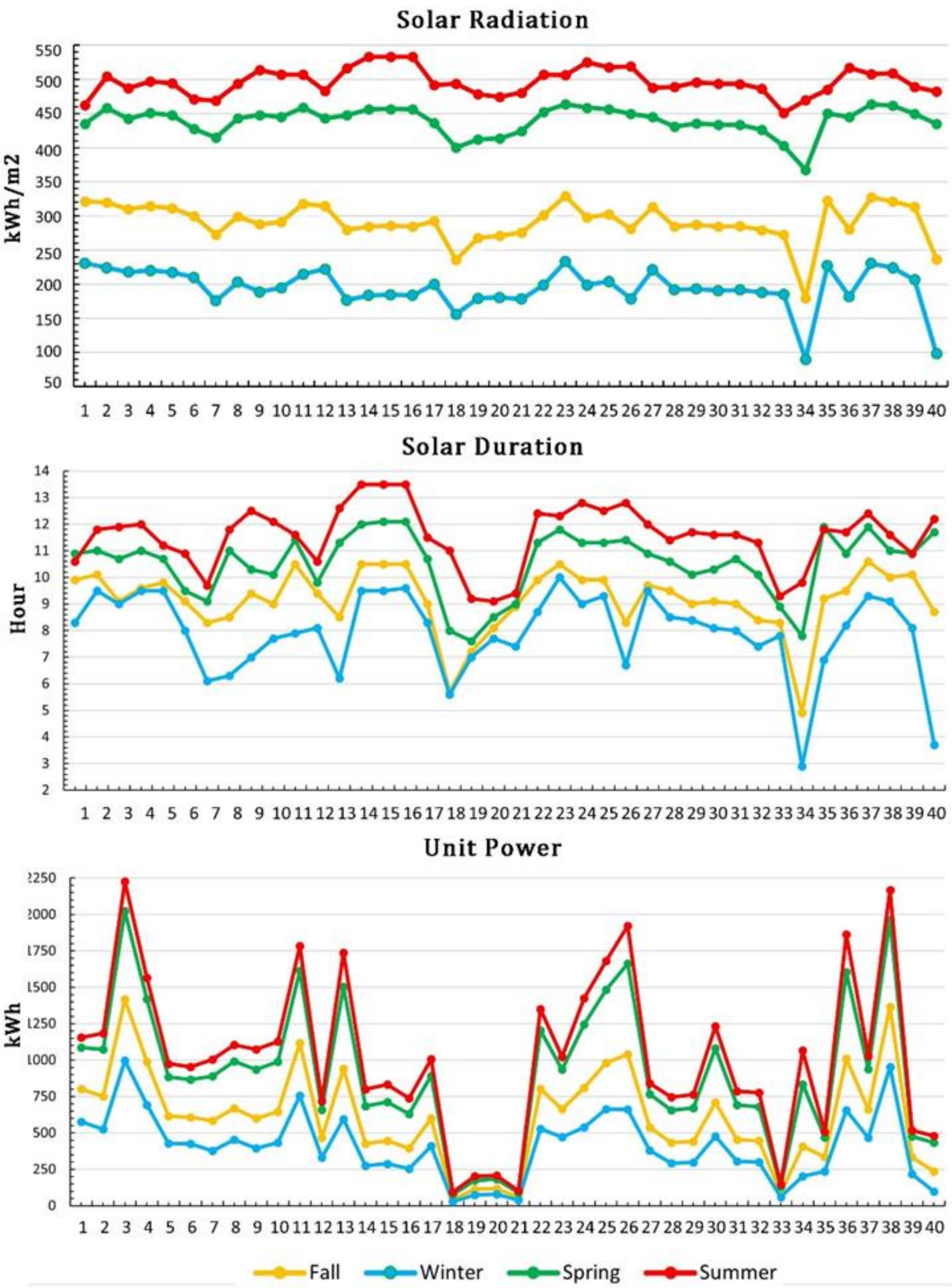

Figure 4. The season mean Solar radiation, mean solar duration and the unit power of the 40 photovoltaic units.

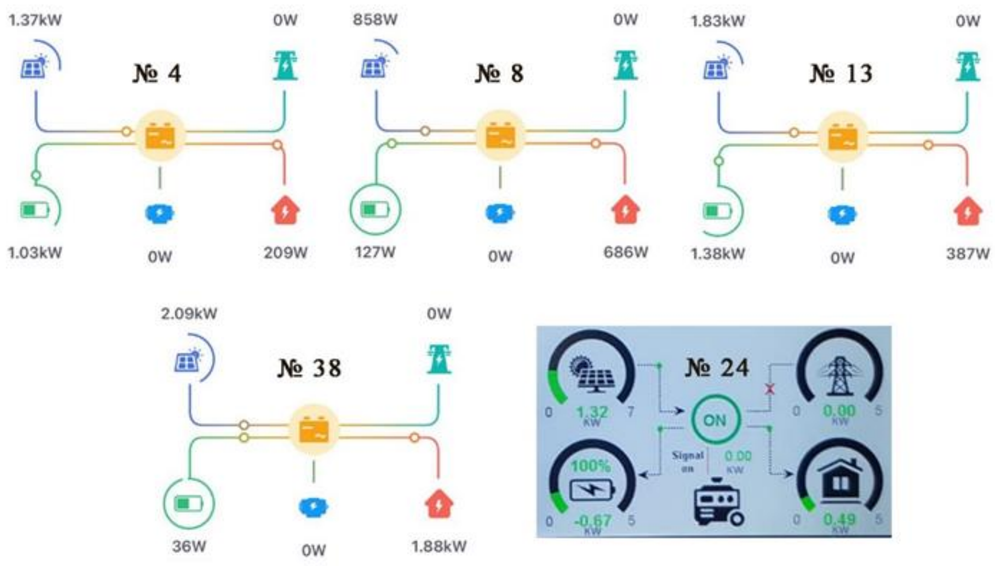

Figure 5. Solar power of the inverters of the PV Solar panels number 4,8,13,24 and 38.

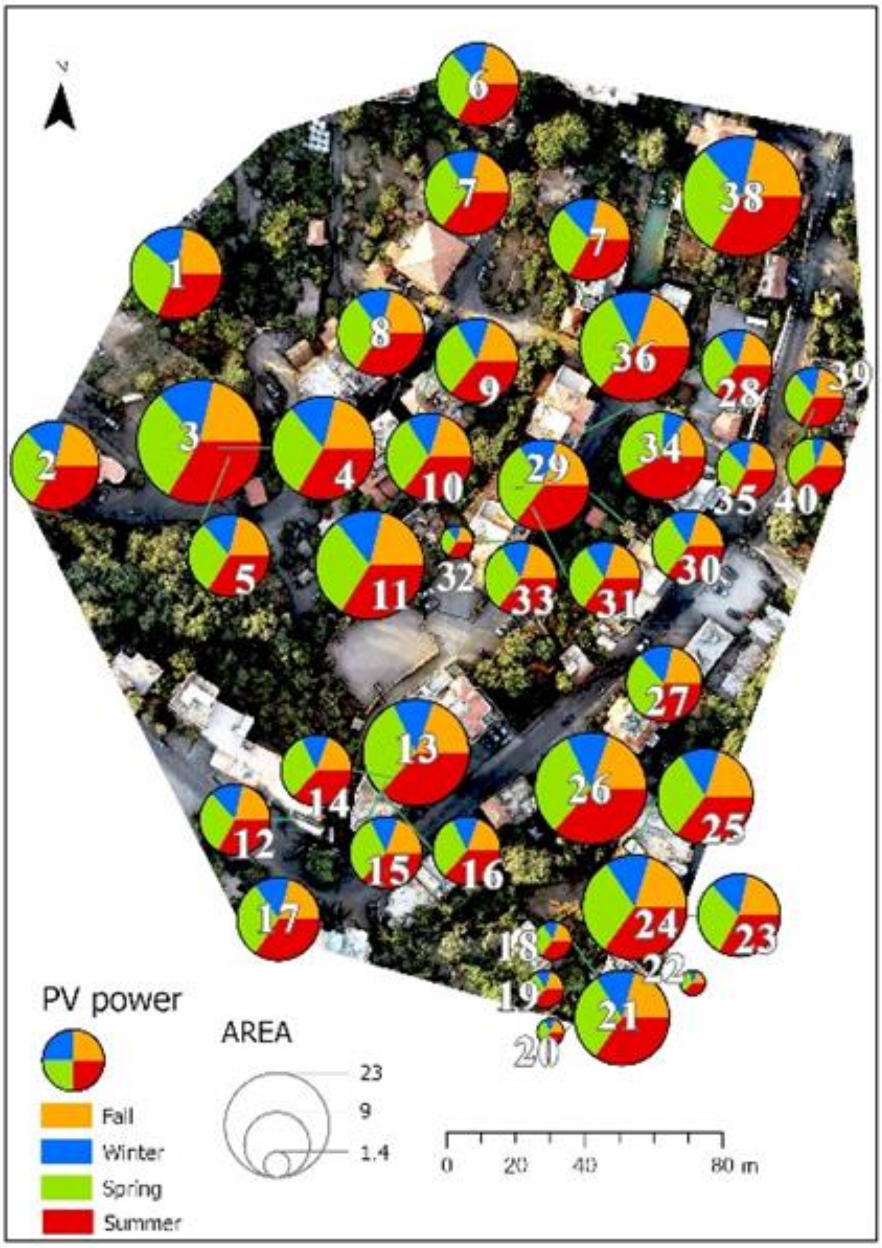

Figure 6. Bivariable map of seasonal PV solar unit power and area.

The bivariate map (Figure 6) showcasing Solar Power and Unit Area illustrates the seasonal solar power for each unit alongside the corresponding panel area. An evident pattern emerges wherein the solar power across all units and seasons—Fall, Winter, Spring, and Summer—is directly proportional to the unit's solar panel count and their respective areas. A notable example of this trend is observed with units numbered 38 and 3.

To gain a deeper comprehension of the relationships between PV units of solar panels within the study area, with a focus on seasonal power variations, the Agglomerative Hierarchical Clustering (AHC) technique was employed. This method, put forth by [22], facilitates the clustering of similar PV units based on their characteristics.

The Agglomerative Hierarchical Clustering (AHC) algorithm treats each PV unit's seasonal power values as a distinct cluster. It then calculates the similarity or dissimilarity between every pair of PV units utilizing the Euclidean distance metric.

In Figure 7 of the dendrogram, the vertical axis measures the dissimilarity or distance between clusters, providing insights into the relationships and groupings among clusters.

This involves identifying the proximity between clusters and merging the closest clusters based on the selected similarity metric. The process continues as the algorithm recomputes the similarity between the new clusters, ultimately generating an output comprising four distinct clusters, labeled as Moderate, High, Low, and Very Low solar power, as depicted in Table 2 which answers the study question.

How can PV solar panels be categorized based on their efficacy?

During this merging process, the AHC algorithm constructs a hierarchical structure of clusters, visually represented as a dendrogram. In this dendrogram, each leaf node corresponds to an individual PV unit, while the branches symbolize the evolving clustering hierarchy. This visual representation is presented in Figure 7.

Table 2 shows the four clusters' centroid values (average) of PV units' solar power in the four seasons. The first cluster C1 englobe all the PV units of moderate power, C2 cluster contains the high efficacy of solar power PV units.

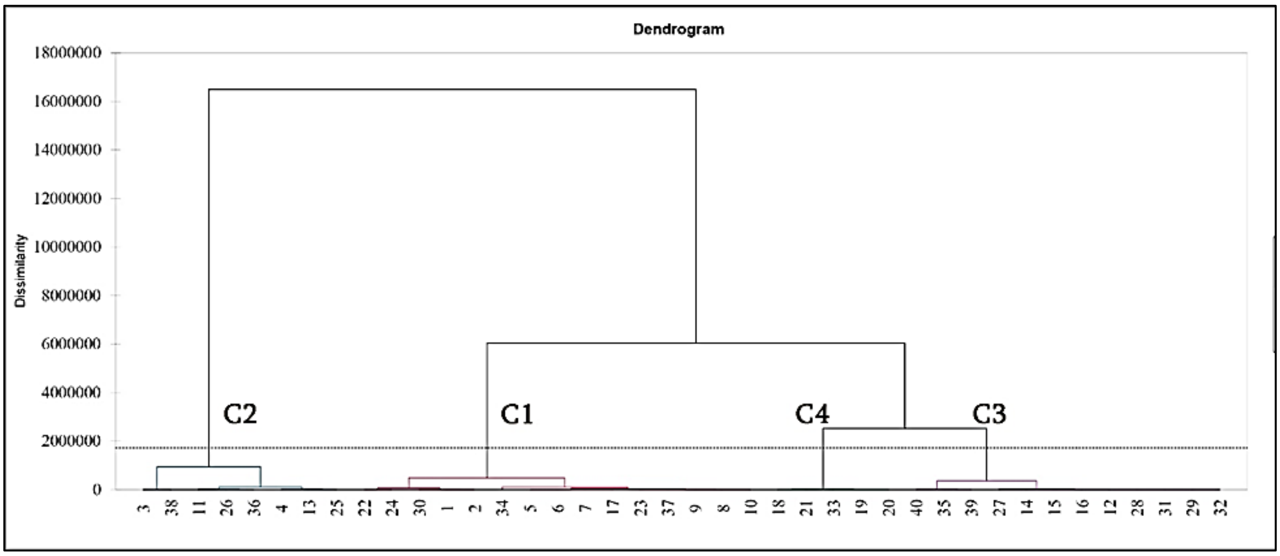

Figure 7. Dendrogram of the PV units clustering.

Table 2. Cluster centroid of PV solar panels based on solar power.

Cluster	PV №	Fall	Winter	Spring	Summer	Efficacy
C1	1,2,5,6,7,8,9,10,17,22,23,24,30,34,37	661.696	447.039	989.746	1113.559	Moderate
C2	3,4,11,13,25,26,36,38	1107.480	746.292	1659.153	1868.114	High
C3	12,14,15,16,27,28,29,31,32,35,39,40	412.772	273.003	627.339	708.448	Low
C4	18,19,20,21,33	84.765	56.542	130.570	150.578	Very low

The four clusters, namely C1, C2, C3, and C4, encompass PV solar panels that exhibit similar solar power levels across all seasons.

Cluster C2 comprises high-efficiency solar panels, with their performance influenced by factors such as installation position, orientation, and the number of panels (area). Cluster C4 includes panels with very low solar power output, suggesting that they do not yield the desired energy generation results. It is advisable to consider relocating these panels to enhance their productivity.

The productivity of solar panels within clusters C2 and C4 remains reasonable despite their fixed positions on the rooftops. This implies that, even in their current locations, these panels contribute a certain level of energy output.

To address the second research question, the PV units displaying elevated solar radiation and power possess specific geometrical and solar attributes. The most effective PV solar panels within the study area are those oriented between 195 and 225 degrees. These panels are positioned at a shallow inclination angle of 6 degrees and encompass a larger surface area or a greater number of individual panels. These factors collectively contribute to their enhanced performance in capturing solar radiation and generating power.

4. Conclusion

In a world grappling with energy crises and environmental concerns, solar photovoltaic (PV) panels have emerged as a promising solution. This study presents a comprehensive analysis of the capacity and efficacy of rooftop-installed PV solar panels within the El Meten region of Lebanon. Through integrating geospatial technologies like drone-based photogrammetry for DSM generation and GIS, a thorough examination of geometric and solar characteristics, seasonal solar radiation, solar duration, and unit power was conducted for 40 PV units.

The research unveiled critical insights regarding optimal panel orientation, seasonal power variations, and the clustering of panels based on their solar power efficacy. The Agglomerative Hierarchical Clustering (AHC) algorithm facilitated the categorization of panels into four distinct clusters: moderate, high, low, and very low solar power outputs. This clustering approach aids in identifying panels contributing efficiently to energy generation, those with potential for improvement, and those that may require reevaluation or relocation.

The study's outcomes offer valuable guidance for future solar installations in the region, enabling informed decisions on panel positioning, orientation, and efficacy optimization. As solar energy gains momentum as a sustainable power source, the findings of this study contribute to the ongoing dialogue on maximizing energy generation while reducing reliance on conventional fossil fuels. By harnessing the power of geospatial technologies and data-driven analysis, the research not only advances the understanding of rooftop solar panel efficacy but also promotes the broader adoption of renewable energy solutions to address pressing global energy challenges.

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Conflicts of interest

The authors declare no conflicts of interest.

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