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Assessing Photo-Voltaic Potential in Urban Environments: A Comparative Study between Aerial Photogrammetry and LiDAR Technologies

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Abstract

Urban development and population growth have significantly increased energy demands, predominantly met by non-renewable resources, negatively impacting nature and climate. Consequently, there has been a global shift towards renewable energy sources, with solar energy being widely adopted. Photovoltaic (PV) potential measures the usable electricity from solar energy using PV technology. With conventional methods, estimating PV potential involves converting 3D point cloud data to 2.5D elevation models, which can affect the accuracy of the estimation. A research gap exists in using adequate 3D point cloud datasets for PV potential estimation considering roof surface area and the surface normal vectors. This study compares aerial photogrammetry and aerial LiDAR point clouds for PV potential estimation against the DSM-based approach. Accurate PV potential estimation must consider solar incidence, roof area, azimuth, tilt angles, and PV efficiency. Traditional 2.5D methods often overlook crucial azimuth and tilt data, limiting the accuracy of the PV estimation. Converting 3D data to 2.5D may result in information loss, while 3D analyses offer higher accuracy. To investigate the mentioned gaps, this research aims to evaluate the capabilities of photogrammetry and LiDAR for urban PV potential estimation, highlighting their feasibility and accuracy over 2.5D methods.

1. Introduction

The energy requirements have been stipulated with the rapid rate of urban developments and rise in the population. Non-renewable resources have widely catered to a significant part of the energy demand, adversely affecting nature and climate(Szabó et al., 2016). Over time, there has been a global shift towards developing and enhancing engagement for renewable energy sources, with a significant transition from conventional to non-conventional resources for energy production(Gassar & Cha, 2021). Solar energy has been widely adopted as an efficient source of renewable energy.

Photo-Voltaic (PV) potential refers to the amount of solar energy that can be harnessed into usable electricity utilising PV technology (Parida et al., 2011; Romero Rodríguez et al., 2017). The current state of the art regarding the photovoltaic potential estimation goes through the conversion and pre-processing of 3D point cloud data to 2.5D elevation models, affecting the accuracy of the estimation process(Bódis et al., 2019). The main advantage of using the 3D point cloud datasets is that they preserve all the semantics and geometric information of the top roof surface area, which is essential for estimating solar radiation received by the specific area (Hofierka & Kaňuk, 2009). Also, the emergence of aerial remote sensing technologies has made acquiring high-resolution datasets for various urban mapping applications convenient. Even when using a 3D point cloud as direct input, the research gap lies between using the effective and efficient point cloud dataset for PV potential estimation and using the roof surface area and normal vectors.

In this research, we have investigated the comparison of aerial photogrammetry and aerial LiDAR point cloud for the estimation of the PV potential and their comparison with the DSM-based approach for PV potential estimation. Both photogrammetry and LiDAR technologies have different functional principles for capturing the Earth's surface, and they both have complementary characteristics. The estimation of PV potential differs between Aerial LiDAR and aerial photogrammetry point clouds due to their characteristic technological differences in the data acquisition sensors (Nelson & Grubesic, 2020). LiDAR provides high-resolution, highly accurate 3D data capable of penetrating vegetation, ensuring detailed surface and structural information, which is critical for precise PV potential assessment (Lingfors et al., 2017). On the other hand, aerial photogrammetry, relying on visible light images, may find a challenge with accuracy in densely vegetated or shaded areas and generally produces less detailed 3D models.

Additionally, LiDAR excels in shading analysis and complex terrain modelling, while photogrammetry is often faster and more cost-effective but with reduced precision. These variations in the data quality and processing impact the reliability and accuracy of PV potential estimations from aerial photogrammetry and aerial LiDAR point clouds. Also, Aerial Photogrammetry results in detailed information with texture and a higher point density, whereas LiDAR yields detailed geometrical information and includes points at occlusions and penetration power through surfaces (Dietmaier et al., 2019).

However, regardless of the method utilised, solar incidence, roof or surface area, azimuth, tilt angles, and PV efficiency of the roof surfaces must be considered to make an accurate PV potential estimation(Alam et al., 2016). Many of the approaches for PV calculations with 2.5D inputs estimate the PV potential by only taking the roof surface area acquired from aerial imagery into account, which is adequate for large-scale studies but lacks the crucial azimuth and tilt angle information required for accurate PV potential estimation (Machete et al., 2018)

In most studies, 3D point cloud data is converted to 2.5D representations before analysis. However, some critical

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information may be lost due to the nature of data conversion, and the full potential of 3D data is not being used(Tiwari et al., 2020). In 3D studies, PV potential can be accurately estimated but requires intensive and time-consuming data processing steps.

The main aim of this research is to identify the capabilities of aerial photogrammetry and LiDAR to estimate the PV for urban built environments.
The primary contributions of the research are:
(i) Estimation and comparison of photovoltaic potential from aerial Photogrammetry, aerial LiDAR point clouds, and 2.5D Digital Surface Models (DSM)
(ii) Investigation of the accuracy of 3D point clouds over 2.5D DSM approaches for PV estimation

2. Study Area and Datasets Description

The study area under consideration for this research work was Castello del Valentino, Torino, in Italy, with an approximate area of 0.2 ha / 2000 m^2. Castello Del Valentino was undertaken as a study area because, within a small dimension, it presents the most common building rooftop structures and sizes in Torino, making it the perfect test site, comprising around 27 rooftops. Another reason for selecting this area was the availability of the existing datasets and processed data products acquired for the Torino Digital Twins project (Boccardo et al., 2024). For this test site, Aerial photogrammetry and aerial LiDAR datasets were acquired on January 28-29, 2022, using the new Leica City Mapper-2, a hybrid digital sensor onboard an aircraft that acquires optical images as well as LiDAR scans of the ground. Figure 1 represents the location of the test site considered in this research work.

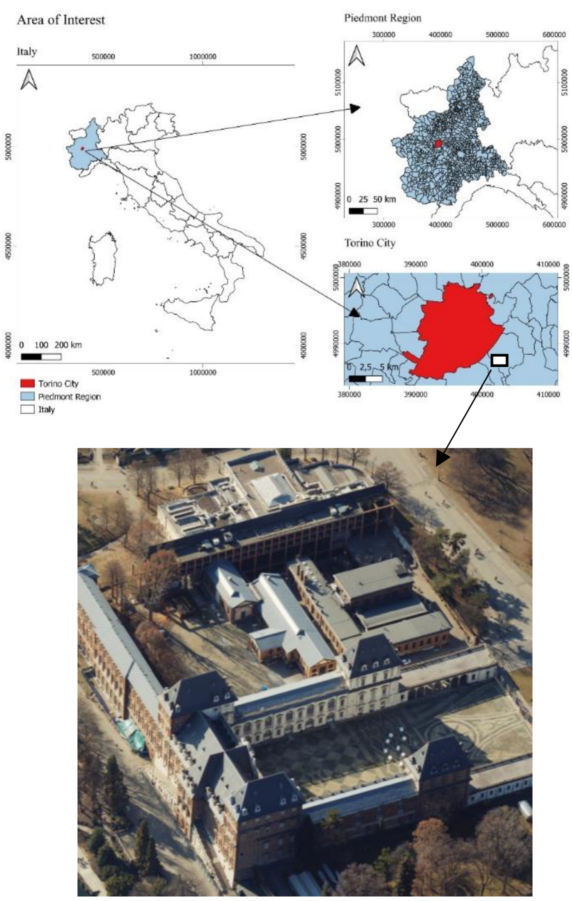


Figure 1: Location and aerial image of the study area Castello Del Valentino, Torino, Italy.

The data acquisition phase involved the utilisation of optical imagery and image orientations derived from an airborne Leica CityMapper-2 system, capturing 358 aerial images with a ground resolution of 5 cm for the selected test area. These images were processed using Agisoft Metashape software to generate a dense point cloud and a digital surface model (DSM) of the study area. The building footprints of the buildings in Castello Del Valentino were obtained from the OpenStreetMap (OSM) Web, which were then used to mask the building rooftop surfaces for the processing phase. This high-resolution data, combined with the detailed building footprints, enabled precise modelling of the selected area's PV potential. The datasets and software tools employed during this study are presented in Table 1, highlighting their relevance/ usage in the research work.

Dataset / Tool	*Source*	*Relevance / Use*
Photogrammetry point cloud	Aerial data acquisition	For estimation of PV potential
DSM_1	Photogrammetry point cloud	For estimation of PV potential
LiDAR point cloud	Aerial data acquisition	For estimation of PV potential
DSM_2	LiDAR point cloud	For estimation of PV potential
Building Footprints	Open Street Map (OSM)	For masking the building rooftops
Agisoft MetaShape	AgisSoft	For processing of aerial photogrammetry data
SPAN plugin	QGIS	Tool to estimate PV potential with 3D point clouds input
Area Solar Radiation Tool	ArcGIS Pro	Tool to estimate Solar potential from a DSM

Table 1: Datasets and software tools employed during this study

3. Case Study and Methodology

In the prominent geospatial analysis Softwares QGIS and ArcGIS, the aerial photogrammetry and LiDAR datasets can be effectively processed and analysed to estimate PV potential. QGIS, an open-source GIS platform, provides robust tools for employing LiDAR and photogrammetry point cloud datasets, enabling users to perform detailed surface analyses and solar radiation simulations to estimate PV potential. Similarly, ArcGIS, with its comprehensive set of geospatial tools, facilitates processing these point clouds to create detailed digital elevation models (DEMs) and conduct advanced spatial analysis to estimate PV potential. The application of these technologies in QGIS and ArcGIS not only enhances the precision of PV potential estimation but also supports decision-making processes in urban planning and sustainable development. The synergy between advanced geospatial technologies and GIS platforms exemplifies the innovative approaches necessary for addressing contemporary environmental challenges and promoting sustainable energy solutions.

3.1 Initial Data Processing

In QGIS and ArcGIS, these datasets were analysed to estimate solar radiation, considering the complex geometries and potential shading effects. LiDAR's accuracy in capturing fine structural details and photogrammetry's efficiency in generating 3D models were both employed to optimise PV panel placement. The integration of these advanced geospatial technologies in GIS platforms supports comprehensive solar potential assessments, facilitating informed decision-making in urban planning and sustainable energy development. This approach underscores the synergy between detailed data acquisition and sophisticated analytical tools, contributing significantly to the advancement of renewable energy strategies.

3.2 Photovoltaic Potential Estimation with 3D point clouds-based approach

For the estimation of PV potential from LiDAR and photogrammetry point clouds, we have used the SNAP plugin in QGIS Software with the consideration of important PV parameters, the azimuth, tilt angles of the roof surfaces, and PV technology to be used, making it a comprehensive approach for PV estimation using point cloud datasets (Özdemir et al., 2023).

The PV potential was estimated with the consideration of various effecting parameters such as PV panel technology to be employed at the roof, peak power, power loss from the system, incidence of solar radiance, and zone of the area. It is to be mentioned that this part of the methodology has been adopted from the work by (Özdemir et al., 2023).

The process begins with the acquisition of high-resolution point clouds, typically obtained from aerial LiDAR or photogrammetry. These point clouds serve as the foundational data for identifying and analysing roof surfaces. The SPAN plugin employs advanced algorithms such as Random Sample Consensus (RANSAC) and Density-Based Spatial Clustering of Applications with Noise (DBSCAN) to process these point clouds, ensuring accurate delineation of roof segments. In the initial stage, the point cloud data is imported into QGIS, where the SPAN plugin is used to extract roof surfaces. The RANSAC algorithm is particularly effective in fitting planar surfaces to the point cloud data, which helps distinguish roof segments from other structures and noise. This step is crucial for isolating the areas that are suitable for PV installation. The DBSCAN algorithm further refines this process by clustering the point cloud data into meaningful groups, thereby enhancing the accuracy of roof segment identification. Once the roof segments are delineated, the SPAN plugin calculates the solar potential for each segment. This involves assessing various factors such as roof orientation, slope, and shading. The plugin simulates the sun's path across the sky, taking into account the geographic location and time of year, to estimate the solar irradiance received by each roof segment. This detailed analysis helps determine the most suitable areas for PV panel installation, ensuring maximum solar energy capture.

The methodology also incorporates atmospheric conditions into the PV potential estimation. Factors like cloud cover, haze, and atmospheric absorption are considered to refine the solar irradiance calculations. By integrating meteorological data, the SPAN plugin provides a more accurate assessment of the solar potential for the building rooftops, which is essential for effective solar energy planning and deployment. Figure 2 summarises the methodology for PV estimation with the aerial LiDAR and photogrammetry point cloud inputs.

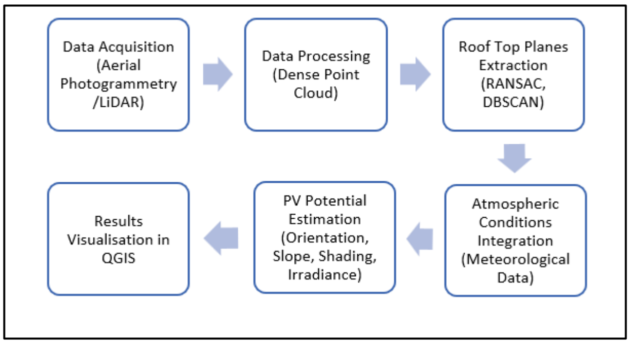


Figure 2: Methodology for PV potential estimation with point cloud inputs

Finally, the results are visualised and analysed within the QGIS environment. The SPAN plugin generates comprehensive maps and reports highlighting each roof segment's solar potential.
In the QGIS SPAN plugin for estimating the PV potential, Epsilon, set at 2, defined the neighbourhood radius for the clustering of the points, while the minimum points parameter of 10, ensured significant clustering. The distance threshold of 0.2 specified the maximum allowable distance from the fitted plane to inlier points, and the iteration number was set to 10,000 for robust plane fitting. The number of seed points was determined to be 5, facilitating initial model parameter estimation. Solar radiation data was sourced from the PVGIS-SARAH database, with a 0.05° × 0.05° spatial resolution. CIS technology was selected for the PV potential estimation, and a system loss of 14% accounted for various inefficiencies involved in harnessing the solar potential. The parameters and values used in this research case study for the estimation of PV potential have been summarised in Table 2.

Parameters	*Relevance*	*Value Used*
Approx Roof Coordinates	Point cloud coordinate system	EPSG:32632 -WGS 84/ UTM zone 32N
Epsilon	set radius for the neighbourhood	2
Minimum points	a specified number of objects in selected neighbourhood	10
Distance threshold	maximum distance from the fitted plane to the inlier points	0.2
Iteration number	number of times model functions to shape the inliners	10000
Number of seed points	smallest number of points that is adequate to model parameters	5
Solar Radiation Database	0.05° × 0.05° spatial resolution database produced by CM-SAF	PVGIS-SARAH
PV Technology	type of module to be used in PV potential estimation.	CIS
System Loss (%)	losses in cables, power inverters, and dirt on modules	14

Table 2: Parameters and values used in this research case study for the estimation of PV potential (Özdemir et al., 2023)

These outputs are invaluable for urban planners, architects, and policymakers in making informed decisions about solar energy investments. By using the capabilities of the SPAN plugin and QGIS, this methodology offers a detailed, scalable, and efficient approach to PV potential estimation, supporting the broader goals of renewable energy adoption and sustainable development in urban settlements. To investigate the accuracy and feasibility of the approach in QGIS with 3D point cloud datasets, the results obtained for 27 building surfaces with LiDAR and Photogrammetry were compared with the PV estimated using a 2.5D DSM-based approach for the similar experimental area selected from the Torino city dataset.

3.3 PhotoVoltaic Potential Estimation with DSM-based Approach

In this study's processing phase, the solar potential was estimated using the '*Area Solar Radiation*' tool in ArcGIS Pro version 3.2.2. This tool calculates solar radiation for a given area by considering multiple parameters such as the sun's position, terrain features (including slope and aspect), and atmospheric conditions (Delphine Khanna, 2023). By simulating the interaction between sunlight and the Earth's surface, the tool generates solar irradiance, indicating the amount of solar energy received per unit area of the building rooftop. These outputs are beneficial for analysing solar potential, identifying optimal locations for solar infrastructure, and understanding the spatial distribution of solar radiation across landscapes. It is to be noted that the DSM used in this phase was obtained by the rasterisation of the aerial photogrammetry and LiDAR point clouds.

One of the primary parameters in this estimation process is the sun's position relative to the Earth's surface, incorporating factors such as time of day, day of the year, and the geographic location of the rooftop. By accurately modelling the sun's movement throughout the day and year, the tool determines the angle at which sunlight strikes the terrain at any given point, thereby estimating the solar radiation received by the rooftop surface. Additionally, the slope and aspect of rooftop surfaces are considered, as these influence the amount of sunlight received. Rooftops with slopes facing towards the sun receive more direct sunlight, resulting in higher levels of solar radiation, while slopes facing away from the sun may experience shading and reduced solar exposure.

Atmospheric conditions, such as cloud cover, haze, and atmospheric absorption, are also incorporated into the solar potential estimation. These factors significantly affect the amount of solar radiation that reaches the Earth's surface by scattering or absorbing sunlight, resulting in only a portion of the solar radiation being received. Therefore, incorporating atmospheric data and regional weather conditions is essential for accurate solar potential estimation. The methodology used for estimating PV potential using a DSM-based approach has been summarised in Figure 3 below.

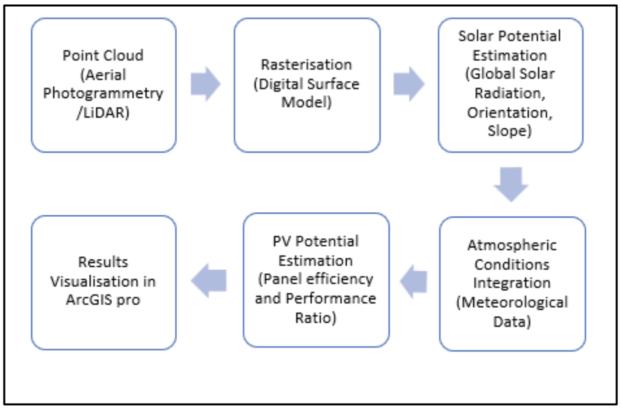


Figure 4: Methodology for PV potential estimation with DSM inputs

This comprehensive approach ensures that the solar potential estimation is precise, enabling the identification of suitable locations for PV installations. PV estimation with DSM input also involved using building footprints obtained from the Open Street Map. The PV from DSM and building footprints were computed in ArcGIS pro software using the Area Solar Radiation Tool, followed by the statistical analysis. Similar PV system power loss and yield values have been used for both the PV estimation approaches with 3D and 2.5D datasets. The PV system's power loss was kept at 14%, and the yield of the PV system was kept at 75%, which was the standard for all the computations. In the final stage, the photovoltaic potential was compared from both point clouds to estimate the efficient datasets for the cities or larger region datasets. Figure 4 represents the complete workflow of the research work.

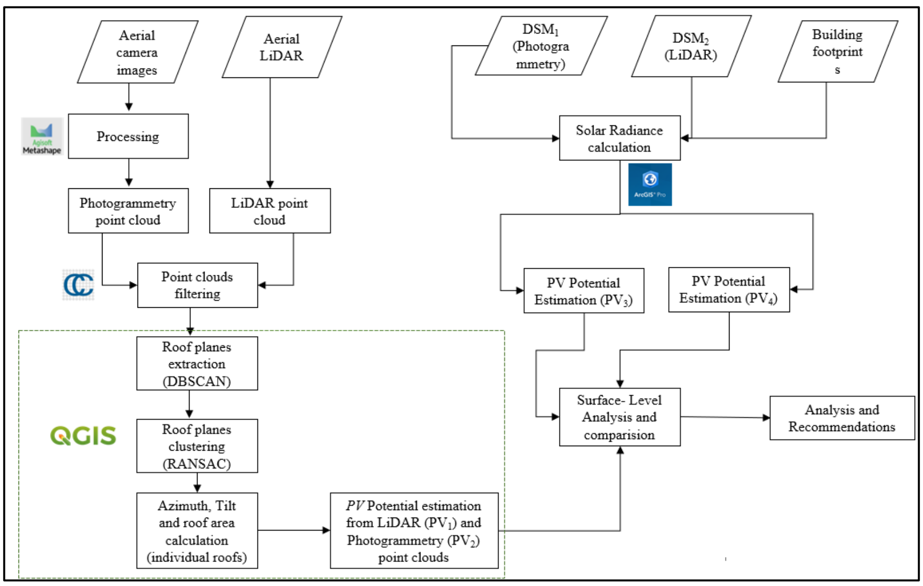
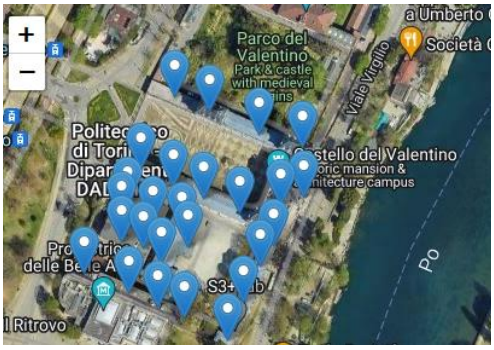


Figure 3: Complete methodology workflow adopted in this research work

4. Results

The annual PV potential was estimated from both LiDAR and photogrammetry point clouds and with DSM of similar building surfaces. PV estimated from the 2.5D DSM-based approach was treated as a reference and compared to the PV estimated from photogrammetry and LiDAR point clouds.
From the approach for PV estimation with point clouds, 27 building surfaces were identified with photogrammetry point cloud, whereas 19 building surfaces were identified from LiDAR point cloud. The PV estimated from the Photogrammetry point cloud was found to be of a closer extent to that estimated from the DSM-based approach. The probable reason could be the higher point density of the photogrammetry point cloud and the inclusion of all the building surfaces in the PV estimation process. The building surfaces identified from the aerial photogrammetry and LiDAR point have been represented in Figure 5 below.



(a)

(b)

Figure 5: Building roof surfaces identified for PV potential from (a) photogrammetry point cloud and (b) LiDAR point cloud.

The PV potential estimated from the point cloud-based approach and DSM-based approach has been summarised in Table 3 below.

Data Input	*Identified Building RoofTop Surfaces Area (m^2)*	*Annual PV potential (MWh)*
Aerial Photogrammetry Point Cloud	955.83	993.838
Aerial LiDAR point cloud	876.91	875.15
DSM_1 (from photogrammetry point cloud)	892.12	852.973
DSM_2 (from LiDAR point cloud)	875.13	836.72

Table 3: Summary of PV potential estimated from point-cloud and DSM-based approaches.

Figure 6 below represents the PV potential estimated for the test site.

Figure 6: Visual representation of the Photovoltaic Potential estimated for Castello Del Valentino, Torino, Italy.

The aerial photogrammetry point cloud identified the largest rooftop surface area of 955.83 square meters, resulting in the highest annual PV potential of 993.838 MWh. In contrast, the DSM from the LiDAR point cloud identified the smallest rooftop surface area of 875.13 square meters, corresponding to an annual PV potential of 836.72 MWh. Percentage differences show that the aerial photogrammetry method resulted in a 6.20% larger identified area and 11.71% higher PV potential than the average, whereas the DSM from the LiDAR method identified 2.76% less area and 5.95% lower PV potential than the average. This analysis indicates that the choice of data input method significantly impacts both the identified rooftop area and the estimated PV potential, with aerial photogrammetry providing the most optimistic estimates. The annual PV potential (MWh) had a mean of 889.6703, a standard deviation of 71.2090, and ranged from 836.72 to 993.838.

A surface-level analysis of the results was also carried out to compare the PV potential results from different roof types. The study site mainly has two types of rooftops: slant (inclined) and flat. It is to be noted that the rooftops have been clustered as slant or flat by slope criterion. Table 4 below summarises the outcomes of the surface-level analysis.

Roof type	*No. of rooftop surfaces*	*Area (m2)*	*Estimated Annual PV potential (MWh)*
Flat rooftop	11	305.86	226.948
Slant (Inclined) rooftop	16	649.96	731.205

Table 4: Summary of the surface-level analysis of PV potential estimation

This research case study also demonstrates the variability in PV potential estimation based on different data sources and highlights the importance of selecting appropriate methodologies for accurate assessment.

5. Discussions

In this study, we investigated the photovoltaic (PV) potential in urban environments using two advanced remote sensing technologies, aerial photogrammetry, and LiDAR, using two approaches. The main aim was to compare the economic efficiency and accuracy of these technologies in generating accurate point clouds for PV potential estimation, utilising the SPAN plugin in QGIS. (Özdemir et al., 2023) and the Area Solar Radiation tool in ArcGIS Pro (Delphine Khanna, 2023). Aerial LiDAR and photogrammetry both provide 3D point clouds, but they differ significantly in accuracy and precision. LiDAR, with its laser-based measurement system, excels in capturing fine details of roof geometries and terrain, even in densely vegetated areas. This high-resolution data is critical for precise PV potential estimation as it ensures accurate modelling of rooftop surfaces and surrounding obstructions. Photogrammetry, on the other hand, relies on high-resolution images to create 3D models. While it is effective in open and less complex environments, its accuracy can be compromised by factors such as varying light conditions and occlusions. (Remondino, 2011; Yadav et al., 2023).

Our analysis of the experiments using the SPAN plugin in QGIS demonstrated that the aerial photogrammetry dataset provided more reliable and consistent point clouds for urban PV assessments. Photogrammetry point clouds, though helpful, required more pre-processing to address noise and inaccuracies, particularly in areas with complex structures and occlusions. However, for the PV potential estimation, the main concern is only rooftop areas, where these datasets have the capacity to produce impressive results at a lower cost than LiDAR technology.

In ArcGIS Pro, the Area Solar Radiation tool provided a robust framework for simulating solar radiation based on various parameters, including sun position, terrain features, and atmospheric conditions. The tool's ability to model solar radiation throughout the year and under different weather scenarios allowed for a comprehensive analysis of PV potential. The combination of DSM from aerial photogrammetry and LiDAR data with the analytical capabilities of ArcGIS Pro resulted in a highly accurate PV potential estimation of the test site. Despite the advantages of both technologies, several challenges were encountered. For LiDAR, the primary challenge comes with the cost and complexity of data acquisition. High-resolution LiDAR surveys are expensive and require specialised equipment and expertise. Photogrammetry, while more cost-effective, faced challenges related to data quality. Variations in lighting, shadows, and occlusions in urban environments impacted the accuracy of the point clouds. Another challenge was the integration of different data sources in GIS platforms. Ensuring compatibility and accuracy across various datasets required significant pre-processing and validation. Moreover, the computational requirements for processing large point clouds and performing detailed solar radiation simulations were substantial, necessitating powerful hardware and efficient algorithms.

The findings of this study have significant implications for urban planning and sustainable development. Accurate PV potential assessments are crucial for maximising the efficiency of solar energy installations in urban environments. The comparative analysis between LiDAR and photogrammetry highlights the importance of selecting the appropriate technology based on specific project requirements and environmental conditions. For urban planners and policymakers, accurately modelling and analysing PV potential supports informed decision-making in renewable energy deployment. By leveraging advanced remote sensing technologies and GIS tools, cities can optimise their solar energy infrastructure, contributing to sustainable energy goals and reducing carbon footprints.

6. Conclusion

This comparative study between aerial photogrammetry and LiDAR technologies for assessing PV potential in urban environments has highlighted the strengths and limitations of each method. LiDAR's high accuracy and ability to penetrate vegetation make it ideal for detailed urban analyses, while photogrammetry offers a cost-effective alternative for less complex environments. The integration of these technologies with GIS tools, specifically the SPAN plugin in QGIS and the Area Solar Radiation tool in ArcGIS Pro, enables comprehensive and accurate PV potential estimation.

This study has comprehensively analysed photovoltaic (PV) potential assessment in urban environments using aerial photogrammetry and LiDAR technologies. By employing point clouds derived from these technologies, we have utilised the SPAN plugin in QGIS and the Area Solar Radiation tool in ArcGIS Pro to estimate solar potential. From the results, the aerial photogrammetry point cloud identified the largest rooftop surface area of 955.83 square meters, resulting in the highest annual PV potential of 993.838 MWh. In contrast, the DSM from the LiDAR point cloud identified the smallest rooftop surface area of 875.13 square meters, with an annual PV potential of 836.72 MWh. The aerial photogrammetry method showed a 6.20% larger identified area and 11.71% higher PV potential than the average, while the DSM from the LiDAR method showed 2.76% less area and 5.95% lower PV potential than the average. These results indicate that the choice of data input method significantly impacts both the identified rooftop area and the estimated PV potential, with aerial photogrammetry providing the most optimistic estimates.

Our findings highlight several key points. Firstly, LiDAR technology demonstrated superior accuracy in capturing detailed surface and structural information. This precision is crucial for urban areas where complex roof geometries and potential shading from surrounding buildings significantly impact PV potential. LiDAR's ability to penetrate vegetation and accurately model fine details allows for a more reliable assessment of solar exposure, leading to optimised PV panel placement.
One limitation of this study is the variation in identified rooftop surface areas and estimated PV potential between different data input methods. The differences in PV potential estimation indicate that the choice of data input method significantly impacts the results, with aerial photogrammetry providing more optimistic estimates.

In conclusion, both LiDAR and aerial photogrammetry have distinct advantages and limitations in the context of PV potential assessment. LiDAR's higher accuracy makes it ideal for detailed urban analyses, while photogrammetry offers a more accessible and faster solution for broader preliminary assessments. The combined use of QGIS and ArcGIS Pro tools has proven effective in processing and analysing these data, contributing valuable insights for urban planners and renewable energy developers. Future research should focus on further refining these methodologies and exploring the integration of additional data sources to enhance the accuracy and applicability of PV potential assessments in diverse urban settings.

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