Exploring urban building solar envelop potential with geospatial integrated building information modelling

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Abstract

As urban populations grow, energy demands and environmental impacts in cities intensify, necessitating sustainable solutions such as building-integrated photovoltaics (BIPVs). This study investigates the integration of geospatial analysis and Building Information Modelling (BIM) to evaluate BIPV potential at an urban precinct level. The proposed framework utilizes GIS and BIM to address urban-scale solar potential and detailed building-level simulations. By utilizing geospatial data from Melbourne and advanced simulation tools, this framework assesses the energy generation, economic viability, and environmental benefits of BIPV systems. The evaluation considers factors such as shading, building orientation, and architectural features, providing a comprehensive analysis that supports urban planning and BIPV implementation. The results highlight the varying solar potential across different building heights and orientations, emphasizing the importance of both detailed architectural modelling for accurate simulations and geospatial analysis of the urban environment dynamics. Additionally, the economic analysis of BIPV systems demonstrates varying profitability based on system type and placement relative to shading. This integrated approach bridges the gap between macro-scale urban analysis and micro-scale building modelling, offering a scalable and automated solution for urban planners and architects.

Keywords: Building-Integrated Photovoltaics (BIPVs), Geospatial Analysis, Building Information Modelling (BIM), Urban Solar Potential, Sustainable Urban Planning

1. INTRODUCTION

With over half of the global population now residing in urban environments, a figure expected to rise to 68% by 2050 (United Nations, 2019), the energy demands and environmental impacts of urban areas are of growing concern. Urban activities consume substantial amounts of energy, contributing to adverse environmental effects such as the heat island effect, air pollution, and significant contributions to climate change.

To foster sustainable and livable urban environments, the integration of building-integrated photovoltaics (BIPVs) on building surfaces emerges as a promising solution for urban areas. Currently, BIPV represents one of the fastest-growing industries worldwide (Tripathy et al., 2016). Research on BIPV implementation strategies and optimal designs has gained momentum, particularly through the application of building information modelling (BIM) concepts and tools (Wijeratne et al., 2019, Samarasinghalage et al., 2022, Yang et al., 2023). However, urban environments pose unique challenges to BIPV design and implementation due to complex factors such as shading, building envelope reflections, and potential micro-climate impacts. While BIM is an effective tool for analyzing BIPV performance as a building element, restricting the analysis to a single building risks overlooking significant factors affecting BIPV performance beyond the building itself.

1.1. Geospatial analysis approach for solar potential mapping on urban surface

Geographic information system (GIS)-based approaches are advantageous for urban-scale analysis due to the inherent capabilities of the GIS platform. These methods are widely used for their strong ability to represent spatial data using real-world inputs for visualization and simulation purposes (Saretta et al., 2019). The typical process involves inputting two-dimensional (2D) or 2.5D (2D with value representation for height or other attributes) models and applying solar irradiance computation algorithms to calculate the solar potential on building surfaces. Machete et al. (2018) emphasized that GIS-based models are the most powerful for conducting solar irradiation simulations at the urban scale, given their robust spatial representation abilities.

Despite their strengths in processing and storing large amounts of data for urban areas, GIS-based approaches have notable limitations. Building models in GIS typically exhibit a relatively low level of detail (LOD), omitting architectural features such as windows, doors, or balconies. These details are crucial for accurate solar irradiation simulations and for identifying BIPV installation potential. The inaccuracies resulting from missing information can be mitigated by introducing reduction factors, as demonstrated by Wegertseder et al. (2016). Additionally, acquiring GIS data can be expensive due to the need for technical and specialized equipment. Therefore, the costs associated with establishing 3D models must be carefully weighed against the potential benefits.

1.2. Building information modelling (BIM) approach for solar energy simulation

BIM-based approaches utilize 3D models constructed with BIM software (e.g., SketchUp, Rhino, and Revit) to simulate solar irradiation. Several software and plug-ins have been specifically developed for BIM models to facilitate these simulations. Examples of such approaches can be found in the works of Amado and Poggi (2014), Costanzo et al. (2018) and Lobaccaro et al. (2012).

One key advantage of BIM-based approaches is the ability to create detailed architectural models. The accuracy of solar irradiation results on building surfaces depends significantly on the level of detail within the model. While creating detailed building models is generally less difficult and costly compared to GIS-based models, it can be time-consuming, especially when modelling large urban areas. BIM-based approaches, originally designed for individual buildings, are now being adapted for urban-scale analyses. However, their computational capacity is often less powerful than that of GIS-based methods, making them less suitable for extensive spatial analysis. One way to improve analysis efficiency is to divide the study area into smaller tiles, allowing the analysis process to be conducted in batches or parallel. The final results are then aggregated from all the individual tiles.

1.3. An integrated analytic framework for solar envelop in the urban environment

As reviewed in the previous section, different studies utilize varying models, ranging from GIS-based to CAD/BIM-based models. There are three possible ways to assess solar irradiation in the urban environment, depending on the available input model of the urban area. However, there is limited research investigating the opportunities of combining GIS approaches and BIM approaches to achieve optimal outcomes with both robustness against urban environment uncertainties and accurate building representations. This study aims to demonstrate an integrated approach combining geospatial analysis and BIM for BIPV performance analysis at the urban precinct level. In this study, an integrated evaluation framework was developed based on the literature review by Zhao et al. (2023). A case study was carried out using the geospatial and building information data of an urban precinct in the City of Melbourne.

2. EVALUATION FRAMEWORK AND ANALYSIS PROCESS

This study collected data from two data sources. The geospatial data was collected from the City of Melbourne’s Open Database (CoM, 2019), which includes laser imaging, detection, and ranging (LiDAR) based digital surface models (DSM) of Melbourne central business district (CBD). The weather data was collected from the Bureau of Meteorology, Australian Government (BoM, 2023), which was based on the closest weather station at Olympic Park, Melbourne, VIC.

A solar building envelope evaluation framework was proposed and tested, integrating the geospatial analysis approaches with BIM approaches (seen in Figure 1). This evaluation framework enables the analysis of building envelope solar potential, shading impacts, and the operational performance of BIPV applications including energy generation, levelized cost of electricity (LCOE), and net present value (NPV).

The framework begins with the acquisition of LiDAR and geospatial imagery datasets, alongside weather data, to create a detailed DSM. This model is then used to calculate building envelope surface slopes, aspect angles, and shading effects. Numeric data from these calculations are exported to solar simulation tools to assess solar irradiation on building surfaces. In the BIM environment, georeferenced building surface data are utilized to detail architectural features such as orientation, dimension, tilt angle, material, and transparency of the building envelope elements. This comprehensive information is employed to develop 3D models of building envelopes and BIPV systems, followed by the simulation of BIPV operation. The final step involves analyzing and visualizing BIPV systems as BIM elements.

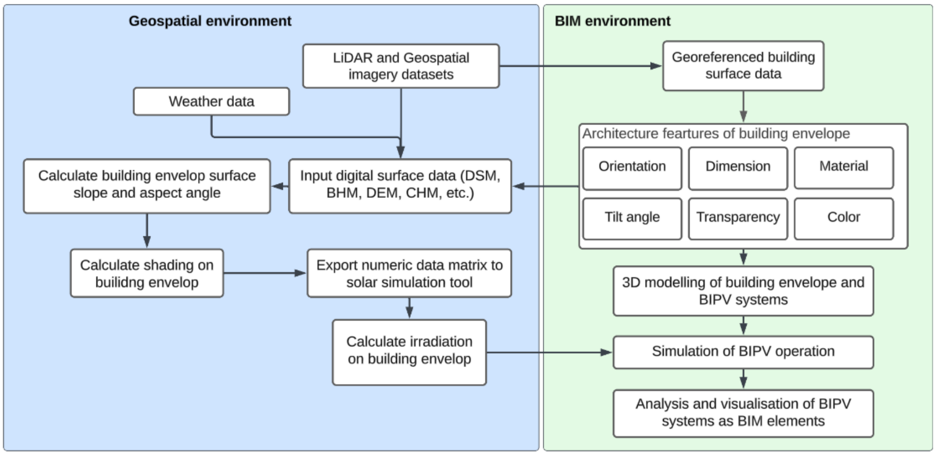

Figure 1 Integrated evaluation framework for solar building envelope in the urban environment

The simulation process for the solar potential and BIPV operation was based on the hourly time series data of ambient air temperature, wind speed, direct normal irradiance, and diffuse horizontal irradiance. A geoprocessing tool was programmed in Python and MATLAB based on the Sandia National Lab’s PVlib simulation tools (Holmgren et al., 2018). The shading impact simulation followed the same time interval to estimate the hourly sun path and shadow volume content created by obstructions. The geoprocessing tool was developed in Python based on the 2D Solar Energy on Building Envelopes model (Lindberg et al., 2015).

A case study was carried out utilizing the research framework for five selected building blocks in the City of Melbourne, as shown in Figure 2. The study area represents typical urban blocks in the CBD of Melbourne. The number of buildings studied in each block is also labelled in the figure. A total of 21 buildings were investigated in the study. In the following sections, three buildings in Block 1 are presented in detail, followed by the overall results for all case buildings.

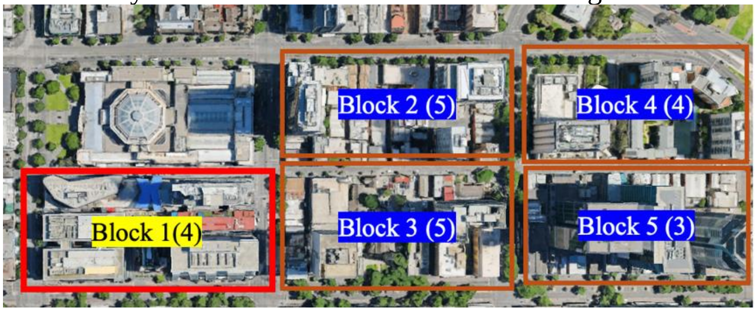

Figure 2 Case study area in the City of Melbourne

3. RESULTS AND DISCUSSIONS

3.1. Simulation results on building level

Based on the framework, this study incorporates building-level digitalization and modelling to investigate the solar building envelope potential for individual buildings. Within the case study area, three buildings (i.e. Building A, B and E) within Block 1 were selected for the detailed building-level simulation. Among the three buildings, Buildings A and B are medium-rise commercial/retail buildings and Building E is a high-rise residential tower.

The building-level simulation considered the suitability of different types of BIPV systems based on the building's architectural features. Specifically, two types of BIPV systems were applied: semi-transparent BIPV for curtainwall, and opaque BIPV system for cladding, rain screen, and balcony. The simulation process computed the electricity generation for each 1 m^2 tile on the building envelope with the consideration of different conversion efficiencies of the semitransparent/opaque PV module, solar potential, and shading impact.

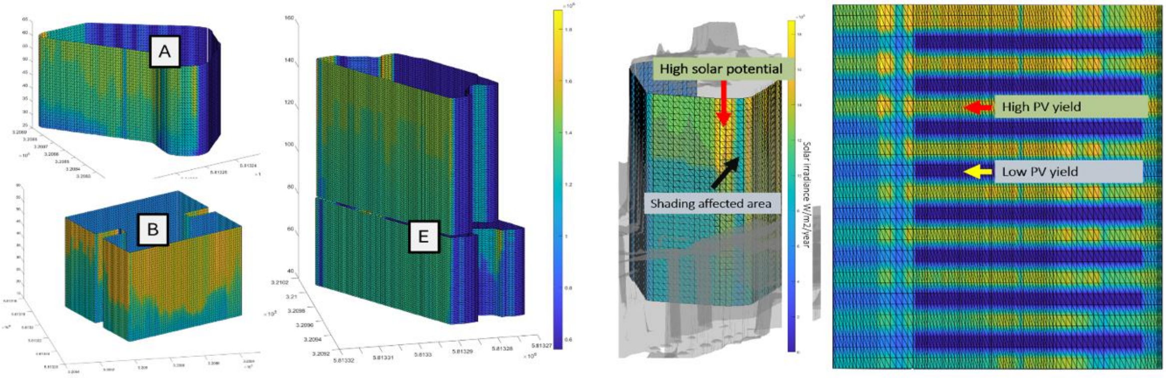

Figure 3 Demo reconstructed building envelopes models with BIPV performance mapping

Figure 3 demonstrates the reconstructed 3D building envelopes based on the geospatial data and architectural features extraction as outlined in Figure 1. This approach presents an effective approach for building envelope solar potential identification and BIPV deployment. It should be noted that the reconstruction process of building envelopes into BIM objects did not apply any commercialized BIM software. Instead, this process was realized through programming the georeferenced vertices and surfaces in MATLAB. This approach ensured that the proposed evaluation framework is scalable, and the simulation process is highly automated. The reconstructed 3D models contain the geometry features of the building envelopes with attributes of annual total solar potential, BIPV generation, and annual average shading height.

Figure 4 presents the histogram plot of the simulation results of each type of BIPV system 25-year net present value (NPV) of investment. The NPV is calculated considering the cost saving through consuming the generated electricity as the revenue and the BIPV cost and installation cost as the initial capital investment. It can be observed that the opaque BIPV systems (i.e. cladding, rain screen, and balcony) have a generally better profit margin compared to the semi-transparent system for curtain wall, which is the result of the reduced absorption of solar irradiance of the semi-transparent module. It can also be found that the average shading height on the building envelopes has a significant impact on the potential economic performance of the BIPV systems, with the modules placed below the average shading height showing generally lower NPV than those above the average shading height.

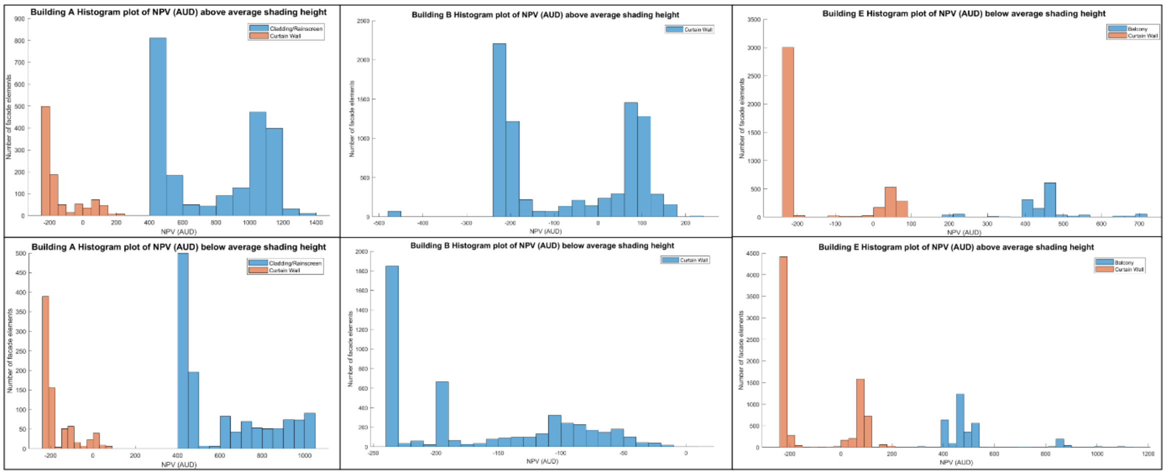

Figure 4 Economic performance of different types of BIPV on building envelopes

3.2. Simulation results on urban precinct level

From the individual buildings, there are a total of 21 buildings investigated in the selected blocks using the proposed framework. Table 1 presents the exploratory data analysis of the electricity generation capability of the solar building envelope within the case study area at different heights. Seven categories were established to represent the range of building heights, namely H1-H7. Among these categories, H1-H6 were categorized with 10-meter increments, while H6 and H7 represent medium high-rise buildings and high-rise buildings respectively. This ensures that each category of the building height has a similar sample size. In addition, four orientations were also categorized for each building height, which makes it easier to compare. For the same orientation, it is highlighted in the same color as shown in Table 1.

According to the results, the north-oriented building envelopes tend to have the highest electricity potential at all height options, followed by the east-oriented envelopes. Orientation plays a crucial role in maximizing the performance of solar building envelopes. It is also noticeable that the mean value of energy generation tends to decrease as the height increases, which may be due to the high variation of the shading on the high-rise building envelopes and stronger impacts of the self-shading. Among all four orientations, the north orientation shows the largest variance of the mean value from H1 to H7 followed by west orientation, which indicates these two orientation are more sensitive to building height. Despit the decreasing mean generantion with increseaing building height, it is also found that the maximum value for the generation of the north appears in H3, followed by H7, which is the high-rise building. This also implies that high-rise buildings have the potential to effectively integrate BIPV systems with careful design and consideration of the placement of PVs. Further study will investigate this trend in more detail.

Table 1 Electricity generation (kWh/m^2/year) of the solar building envelope at different heights

Height	Orientation	Mean	Minimum	Maximum	Median	Standard Deviation
H1 0-10m	North	203.67	153.33	238.17	205.29	16.18
	East	178.85	117.70	234.65	182.74	23.27
	South	96.05	81.98	202.74	94.26	11.14
	West	142.06	95.31	200.22	142.61	18.70
H2 10-20m	North	198.96	153.80	243.62	200.74	17.07
	East	177.97	117.65	235.00	181.66	24.09
	South	95.23	81.93	182.44	92.23	11.64
	West	137.37	95.67	199.34	137.65	19.27
H3 20-30m	North	194.51	152.38	250.55	195.03	19.03
	East	179.04	117.23	243.94	183.22	25.29
	South	96.24	81.90	153.07	94.30	12.19
	West	132.90	95.49	207.14	132.64	19.90
H4 30-40m	North	194.40	151.83	243.89	194.83	18.69
	East	176.62	117.13	234.04	180.00	25.09
	South	96.17	81.92	185.84	93.55	12.24
	West	133.64	95.13	201.82	133.08	20.16
H5 40-50m	North	190.36	151.81	237.18	190.60	18.94
	East	175.80	117.00	229.26	180.20	25.49
	South	95.96	81.91	145.16	94.08	12.11
	West	131.35	95.31	206.88	131.19	19.92
H6	North	189.11	151.46	243.29	189.35	19.28
50-100m	East	176.44	116.82	233.31	180.65	25.90
	South	96.36	81.91	182.50	94.57	12.27
	West	130.36	95.09	206.53	129.15	19.74
H7 >100m	North	187.51	151.35	244.17	187.87	19.33
	East	172.89	116.73	233.13	177.15	27.15
	South	95.49	81.93	202.57	94.06	11.87
	West	129.40	95.06	192.03	128.45	18.81

4. CONCLUSION

In summary, this study proposed and tested an evaluation framework for analysing BIPV application at the urban precinct level. This framework integrates the geospatial analysis and BIM approaches, which enables the consideration of both urban environment dynamics such as shading impacts and orientations, and the building factors such as geometry, building height, and architectural features. The workflow proposed in this study mitigates the gap between urban-level digital data and 3D building modelling. It provides a solution for analysing ‘micro’ building elements on a ‘macro’ urban scale, which has the potential to support the decision-making of urban planners, architects, and property developers to recognize the opportunities and challenges of adopting solar energy for building envelopes in complex urban environments.

Using Melbourne CBD as the case study, the capability of the workflow has been demonstrated, showing the evaluation for individual buildings as well as the urban block. However, it should be noted that one of the limitations of the proposed evaluation framework is its complexity in terms of multiple datasets and tools applied to the data processing and analysis. For the entire urban environment, the simulation process can be time-consuming and resource-intensive. To enhance the efficiency of large-scale evaluations in urban environments, it is recommended that future studies may consider a machine learning-based solution to simplify the data processing tasks within this study.

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