INTRODUCTION AND BACKGROUND

Photovoltaic (PV) technologies are commonly utilized to reduce greenhouse gases as a part of many national development plans across the world.\(^1,2\) Approximately 94.8 GW PV components were installed worldwide as of 2018, a 23\% increase over 2017 reaching a cumulative capacity of 496.8 GW.\(^3\)

The existing literature on built environment applied photovoltaics (BEAPV) includes several articles on building applied photovoltaics (BAPV). For example, Prasad et al\(^4\) summarized different PV module applications in urban structures with a special focus on buildings. PV modules can also provide energy for zero-energy buildings (ZEBs), which is regarded as “a building where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site.”\(^5\)

Choongwan et al\(^6\) analyzed the potential of a rooftop PV system in supplying solar power to net-zero-energy buildings (NZEBS). Carrilho da Graça et al\(^7\) explored the feasibility of solar NZEBs systems for a typical single-family home in the mild southern European climate zone.

In addition to BAPV, Scognamiglio et al\(^8\) discussed in detail the design and application of PV landscapes. They suggest an inclusive design approach that not only focuses
on the overall energy efficiency of the system but extends to additional ecological and landscape objectives. PV modules have been applied in carparks for charging an electric vehicle (EV).\cite{9,10} PV modules have been installed in urban transportation systems including acoustic barriers,\cite{11,12} road surfaces,\cite{13,14,15} and canopies\cite{16} in Switzerland, the United States, and the Netherlands. PV applications in NZEBs have been explored in regard to both buildings and landscapes.\cite{17} PV street lamps, trash bins, water surfaces, and other urban infrastructure components have also grown increasingly popular.

These diverse PV technologies have enhanced the PV potential in the built environment. The research on PV potential at the urban scale mostly centers on buildings. Three levels of PV application potential are defined as physical potential, geographical potential, and technical potential.\cite{18,19} The major differences among various potential evaluation methods involve the collection of geometrical information and analysis of PV area statistics.

There are five potential evaluation methods currently available. (a) Collecting statistics for urban building roof areas by using urban planning data (eg, land use type, building type, urban district).\cite{20,21,22} (b) Obtaining the geometrical information for existing building roofs and calculating the PV potential using Remote Sensing Digital Ortho-photo Map (RSDOM).\cite{23,24,25} (c) Collecting geometrical information buildings via the Web-based interface method.\cite{26,27,28} (d) Developing a point cloud model for target buildings using light detection and ranging (LiDAR) and Geographic Information System (GIS) to calculate the PV potential of the building roof and elevation.\cite{29,30,31,32,33,34,35,36,37} (e) Using the image three-dimensional (3D) geometrical reconstruction to obtain geometrical information, which involves the building only and lacks consideration of its surroundings.\cite{2}

There is insufficient research on built environment applied photovoltaics (BEAPV) potential outside of buildings themselves. Neumann et al\cite{10} used image processing to evaluate the PV potential for existing carparks in built environment (BE) and then simulated the PV potential for 48 carparks in Frauenfeld; they found that the potential can support 15%-40% of highway passenger transportation capacity. Nordmann et al\cite{11,12} studied the PV potential for the acoustic barrier in Swiss expressways. Hernandez et al\cite{15,16} evaluated the potential for solar-powering the entire state of California. Shekhar et al\cite{14} evaluated the annual electricity-generation potential for solar energy on roads in North Holland according to solar radiation; they used the information to assess the potential for PV application in both roadways and carparks. Gardner et al\cite{47} studied the application of PV modules in open spaces in eight cities to assess the potential for application in urban environment.

BEAPV helps to minimize the fossil energy consumption and optimize the land use. Evaluating the potential of BEAPV is beneficial to both the allocation of energy resources and policy making. In terms of energy resources, BEAPV potential evaluations can support urban power-supply management practices as well as the active regulation and control of energy. In terms of policy making, these evaluations can support governmental authorities in developing reasonable goals for PV applications and upgrading their jurisdictions’ urban energy structures.

An economical and accurate approach to evaluate the potential of BEAPV, particularly on the horizontal surfaces, is proposed in this paper. We use unmanned aerial vehicles (UAV) to obtain the images of BE and then categorize the urban areas according to the relevant constraints as urban infrastructure (UI), ecological infrastructure (EI), and solar radiation for installing PV modules with the combination of image 3D point cloud reconstruction and GIS analysis, which reveals areas best suited to PV application after computing the PV potential. We evaluated the PV potential in a carpark and rooftop in Singapore as a case study to validate the method’s feasibility and effectiveness.

The methodology discussed in this paper is mainly aims at evaluating the horizontal PV application potential in built environment. However, this paper mainly introduces a spatial analysis method based on the GIS platform. It could be used as a decision-making tool in assessing and determining the PV potential in BE in the future, especially on the PV carpark. It can be further applied to select locations for the urban green transportation battery-switch and charging stations. The proposed method is discussed in detail below following a comparison of various currently available methods in Section 21. The case studies are presented in Section 32.3.4. The last section of this paper discusses the future application of the proposed method.

## 2 Methodology

The configuration of the BEAPV system is discussed in this section, followed by a comparison among several available...
methods commonly used to collect BE geometric information. A reliable, inexpensive, and accurate method for evaluating BEAPV potential, particularly on the horizontal surfaces, is thereafter proposed.

2.1 | Configuration and constraints

2.1.1 | PV module installation

The generation power of PV components is positively correlated to solar radiation intensity, but negatively correlated to PV surface temperature. PV modules need to be appropriately positioned at the correct angle to maximize the working efficiency while maintaining low working temperature and proper ventilation.

The effects of installed BEAPV on the urban social, economic, and aesthetic environment also need careful consideration. The social environment refers to conditions provided by residents to facilitate work and home living. The economic environment represents public production functions reflective of the conditions for financial development in the city. The aesthetic environment reflects an external representation of the city's image and temperament.

2.1.2 | Constraints

Urban infrastructure and ecological infrastructure

An installed BEAPV should not damage the surrounding urban infrastructure (UI) or ecological infrastructure (EI). The BEAPV should seamlessly work in tandem with existing functions of the city, providing sufficient energy supply that does not alter the city planning, natural scenery, or ecological balance of its surroundings. The existing EI should be maintained and the green space system at perimeter zones and woodland, farmland, nature reserves, and nature-based cultural reserves inside the city should be kept intact while developing BEAPV systems, as urban plants are effective in reducing any urban heat island effects. Offsetting the EI such as trees is to reduce the adverse impact of PV modules on growth, prevent the normal growth of EI in the built environment, and ensure the green possession. At the same time, the adverse effects of trees on the PV modules are also reduced. The power generation efficiency of the PV modules is prevented from being affected by various factors such as fallen leaves.

Solar radiation condition

The solar radiation conditions of the studied location shall be assessed before determining whether the area is suitable for PV modules. The PV modules should be free from shade; shading any single cell of the PV module drastically reduces the output of the entire PV module. Typical culprits include shadows cast by tall trees and neighboring buildings. Areas shaded by trees, buildings, or even PV components themselves should be prevented. Governmental authorities and other organizations have also regulated the solar radiation conditions required by PV application. Areas utilizing PV modules should not be shaded at any time from 9:00 to 15:00 in the calendar year, and the solar irradiation threshold should be set at 80% of maximum annual irradiation for a specific location.

Considering the size of the conventional 72 PV cells module is 1 m × 2 m, the computational grids for solar radiation analysis are suggested to be divided into 1 m × 1 m.

2.2 | Comparison among BE geometrical information collection methods

Currently, the existing methods for collecting geometrical information in the process of evaluating BEAPV potential are mainly based on drawings, Web-based interface, urban planning parameters, RSDOM, LiDAR, and image.

The drawing-based method is one of the most commonly used approaches to evaluate BEAPV potential. It involves gathering geometrical parameters of urban buildings and infrastructures to assess the PV potential of roofs and façades. However, EI information (eg, trees and shrubs) cannot be accurately identified, and thus, the radiated areas cannot be accurately assessed.

Web-based interface methods such as PVGIS, PVMAPS, and urban planning parameters are mainly used for evaluating building roofs in terms of PV potential; they are rarely applied for BE evaluations except for buildings. These two methods are time-efficient in assessing the physical potential and geographical potential at the urban scale but come with greater likelihood of errors.

The RSDOM-based method is mainly used to evaluate the PV potential of building rooftops and public carparks using GIS. However, this method cannot be used to determine altitude data in BE, especially in regard to the height of trees. Its dependence on software and empirical values for sunlight analysis is also inconvenient and may introduce significant errors.

Obtaining BE geometrical information by LiDAR is a widely used and accurate method to evaluate PV potential. In this method, LiDAR is used to develop a BE point cloud model; sunlight and PV potential analyses are then conducted in GIS. Karteris et al. and Li et al. used the LiDAR and GIS method to gather geometrical information of buildings and calculate PV potential. This method yields highly accurate BE geometrical information, especially in the Air-Ground Coordination operation mode, from two orientations (air and ground). However, LiDAR equipment is extremely expensive, especially the components necessary for measuring large buildings or large areas.

There are three image-based methods which differ in output after image processing: The Sky View Factor (SVF)
method reconstructed the 3D geometry method, and reconstructed the 3D point cloud method (also referred to as photogrammetry). Differing from other two image-based methods, the SVF method takes a 360° panorama picture of the measured field at the installation level, rather than the 3D modeling of the installation site. The SVF method acquires data for PV installation areas by accessing the percentages of buildings, trees, and other vertical elements that have an influence on the yield of PV installations around the field. Neumann et al. used image processing in combination with SVF software to find that areas suitable for PV modules in carparks of Frauenfeld, in Switzerland, have physical and geographical potential, but not technical potential. The image-based 3D geometrical reconstruction method is applicable to evaluate the PV potential of a building itself, but lacks considerations for its surroundings. The method of photogrammetry does effectively yield complete, comprehensive EI geometrical information with similar accuracy to LiDAR, however, and is more economic than LiDAR.

In addition, some researches combined these methods to acquire geometric data. For example, Awrangjeb et al. developed the method to combine LiDAR and aerial imagery. And Adeleke et al. applied this method to evaluate the PV potential on the urban rooftops in Cape Town, South Africa. The integration of LiDAR data with imagery provided complementary benefits in extracting features, especially for building rooftops, as each technique compensates for the shortcomings of the other. Although this method is accurate in the automatic processing of large area rooftop plane data, the cost is greatly increased.

The methods discussed above are all useful in evaluating the BEAPV potential, and each serves for specific purposes. Obtaining the geometrical information via the original drawings yields comprehensive and accurate results, but such drawings may be absent from the database. The drawings also lack information for surroundings (like trees), which may introduce error to the PV potential analysis. Collecting information via Web-based interface and urban planning parameters can rapidly yield regional-scale geometrical information, which is convenient for estimating the PV potential but does not resolve the tree information problem. The RSDOM method yields geometrical information quickly, but the lack of height data leads the results to be inaccurate. The LiDAR method reveals information quickly and accurately, but requires aerial LiDAR to reach higher areas. LiDAR equipment is very expensive, especially for aerial LiDAR with aircraft. The use of 3D geometrical reconstruction information applies to buildings with regular geometrical shapes by manual operation, but not the facilities and trees surrounding the buildings. This method has limited application scope and does not provide complete information. Coupling the photogrammetry with GIS, however, can acquire comprehensive information of the built environment with high accuracy at a reasonable cost (especially compared to LiDAR). Unfortunately, this technique does not yield façade information. The existing methods described above are summarized in Table 1.

As discussed, most researchers mainly focus on building roofs, only few studies have been published on the PV potential analysis on carpark sheds. Therefore, in this paper, we develop an evaluation method for PV application potential

### Table 1 Existing methods for BEAPV potential evaluation

| Method of geometrical information acquisition | Obtaining the complete information | Applicable scope |
|---------------------------------------------|-----------------------------------|-----------------|
| Based on drawings                            | Complete drawings may not include geometrical information for trees | All BE with intact and accessible drawings |
| Based on Web-based interface or parameters of urban planning | Accessible (inaccurate) | BE at the regional scale |
| Based on LiDAR                               | Except high-rise rooftop information (high-price equipment) | BE at the block scale (low-rise and multistory buildings) |
| Terrestrial LiDAR                            | Accessible (high-price equipment) | BE at the block scale |
| Aerial LiDAR                                 | Accessible (3D geometrical reconstruction is limited to regular geometric models) | BE at the block scale (eg, low-rise buildings, multistory buildings, carparks, and roads) |
| Based on photogrammetry                      | Except high-rise rooftop information (3D geometrical reconstruction is limited to regular geometric models) | BE at the block scale |
that can be applied to the horizontal plane in the built environment by UAV. It can be applied not only to building roofs, but also to other elements in the built environment, including carparks, corridors, reservoirs, roads, and other horizontal plane. Using a carpark as a case study, this paper analyzes the energy production and energy usage potential of the carpark, as well as the potential benefits to green mobility. Carpark could be turned into a critical node in the green mobility by charging electricity to vehicles and supplying power to urban power grid, contributing to green and environmentally sustainable communities.

2.3 | Procedures of BEAPV potential evaluation

The proposed method for evaluating BEAPV potential through Photogrammetry and GIS (as shown in Figure 1) applies to horizontal surfaces such as building rooftops, corridors, carparks, roads, and reservoirs. This approach includes four steps: preparation, information acquisition, setting of constraints, and results analysis.

2.3.1 | Preparation

The preparation phase includes four tasks: site investigation, literature review, meteorological data collection, and flight design.

**Site investigation**

Site investigation is conducted to determine four environmental factors of BE, namely, the physical, social, economic, and aesthetic environment based on which BEAPV can be designed. Whether the PV system in question is connected to the grid or an off-grid system is also determined to provide necessary data for evaluating energy consumption.

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**FIGURE 1** BEAPV potential evaluation process
Literature review
Local laws and regulations, especially regulations on unmanned aerial vehicles (UAV) and specifications for PV application, are reviewed in this step. Low-altitude aerial photography is used to collect BE geometrical information.

BE meteorological data collection
Public meteorological data are sourced from The United States Department of Energy (accessible in Energy Plus Energy Simulation Software), National Aeronautics and Space Administration (NASA), and a local meteorological database.

Flight line design
The flight lines and ground control points are designed according to the site investigation and literature review of the laws and regulations for UAV.

2.3.2 | Information acquisition
The information acquisition phase includes the acquisition of BE geometrical information, establishment of BEAPV, forecasts of generated electricity usage, and energy consumption calculation.

Acquisition of BE geometrical information
The 3D point cloud model is reconstructed based on images captured by UAV through a predesigned route to obtain the required geometrical information. Control points can improve the accuracy of 3D point cloud models with actual GPS coordinates.

BEAPV establishment
The previous investigation obtains the suitable heights, angles, and orientations for the installation of PV modules. The preliminary design of PV modules is achieved by defining the areas for PV installation with considerations on the surrounding environment. As shown in Figure 1, “manually selected” refers to judge the area where PV modules are expected to be used, and select the area where PV module is needed through observation and investigation of the site.

Generated electricity and energy consumption calculations
Information such as available parking spaces and electricity consumption per hundred kilometers of electric vehicles (EVs) for PV carpark is collected for subsequent analysis.

2.3.3 | Establishing constraint conditions
As described in Section 2.12, the constraints in the BEAPV potential evaluation including UI, EI, and solar radiation information should be set according to the actual working environment.

In this study, we use ArcGIS software to process the 3D point cloud of the built environment. ArcGIS is a frequently applied platform software among other GIS commercial software. Besides, ArcMap is a map-centered software in the ArcGIS platform and can be used for editing, displaying, querying, and analyzing map-related data. We outline the target areas in ArcMap 10.3 according to the applicable constraints, as illustrated in Figure 2.

Step 1 is to import the 3D point cloud into GIS. The 3D point cloud data are transformed into LiDAR format (.LAS) data and imported into ArcMap to produce a digital surface model (DSM1) with 1 m × 1 m cell size corresponding to the size of PV modules (1 m × 2 m). The LAS dataset is a simple container definition of one or more LAS files that represents a single and logical unit. In this study, the point cloud files are stored in LAS form; DSM refers to a digital model or 3D representation of a terrain’s surface.

The resolution of the acquired 3D point cloud is 0.1 m, and it can be even finer with the help of the control points with GPS coordinates. According to the resolution of the 3D point cloud, the cell size of the DSM1 can be set to 0.1 m × 0.1 m in step 1. The DSM1 with 0.1 m × 0.1 m cell size can be used for offsetting the boundary of UI and EI accurately and consider the effects of small-scale UI and EI, such as outdoor unit of split air conditioners, aerial cable, and potted plants. However, in this work, we observed in filed investigation that there is no such small-scale UI and EI. The difference in results due to DSM resolution of 1 and 0.1 m turns out to be negligible, and thus, the cell size of 1 m × 1 m is adopted in this research for faster data processing.

Step 2 is to determine the area and height for PV installation. DSM1 data are used to generate the polygons with contours to represent the surfaces of the built environment elements in the evaluation area. Areas that are higher than the elevation of PV installation are deleted. The installation height of PV modules depends on the space usage below the PV module and safe distance to be kept during the future maintenance of PV module. For example, in the PV carpark, the height of the carpark shedding needs to be sufficient to ensure safe parking for vehicles and pedestrians. At the same time, the installation height here refers to the lowest height of PV modules when they are installed at an inclined angle.

Then, the elevated polygons with contours are transformed into a raster, which is defined as the installation plane of the PV modules. The raster has mounting height information of the PV modules. The installation height here refers to the sum of ground elevation data and net installation height of PV modules. Thus, we have the installation surface of PV modules, which is DSM2 in Figure 2. Since evaluating the potential of PV needs to consider shading of the surrounding environment on PV modules, it is necessary...
to combine DSM of construction environmental elements which are higher than the installation surface of PV modules with the installation surface DSM of PV modules so as to calculate the applicable area in the PV installation surface. The original DSM1 and the generated DSM2 are combined by using the “Is Null” and “Con” tool. “Is Null” identifies the deleted areas as “true,” namely the areas with trees and buildings higher than the PV modules installation height, as marked in dark blue in Figure 3A. The “Con” tool is applied to set the “Conditional Raster” as the results of “Is Null,” and then, the original DSM1 containing the height of trees and other building surroundings is input into these areas (marked by the third line in Figure 3B). Remaining areas identified as “false” by “Is Null” are assigned to the height of PV modules (fourth line in Figure 3B). This generates the DSM3 of the PV installation surface of PV modules without the information underneath (fifth line in Figure 3B). Hereto, the PV installation surface (DSM2) of PV modules and the built environmental factors above the installation surface combine together to form the DSM3.

Step 3 involves the analysis of solar radiation and the offsetting of UI and EI. Solar radiation analysis is

FIGURE 2 Setting constraint conditions for BEAPV potential evaluation based on 3D cloud point image reconstruction and GIS

FIGURE 3 (A) Results of “Is Null” tool as evidence for conditional function; (B) “Con” tool interface
conducted for the DSM3. The technical parameters are set according to the collected local requirements for sunshine hours and solar irradiance. The results are coupled to generate a “contour line” to determine areas meeting the requirements for minimum sunshine hours and solar irradiance. As shown in Figure 4A, the dark blue line is a contour line generated by Solar Radiation Graphics using contour line tool. Then, we need to delete areas that do not meet the requirements. The solar radiation tool in ArcGIS is used to calculate the solar radiation irradiance and sunshine hours. ArcGIS Solar radiation tools adopt methods using the hemispherical view shed algorithm developed by Rich et al. It considers multiple environmental parameters in the calculation, including the site latitude and elevation, steepness (slope) and compass direction (aspect), daily and seasonal shifts of the sun angle, and effects of shadows cast by surrounding topography, atmospheric effects include atmosphere transmissivity. Refer to Jakubiec et al and Verso et al research, the solar radiation tool in ArcGIS can predict the sunshine hours and solar irradiance accurately.

For UI and EI offset, buffer zones are created around UI and EI using the data in DSM1 to subtract these areas from PV installation. As shown in Figure 4B, the red areas represent the buffer zones.

Step 4 is to determine the final areas for PV installation considering all the constraints for BEAPV. The areas with the sunshine hours and solar irradiance lower than PV installation requirements, together with those within the buffer zones of UI and EI, are dissolved and eliminated from PV installation. As shown in Figure 4C, the purple part is the unsuitable area and the white part is the suitable area for PV installation.

### 2.3.4 Interpretation of results

After obtaining the suitable area for PV installation, simulation or mathematical models can be used to calculate the PV potential for certain climatic conditions. The collected information with regard to the allocation of energy can also be integrated to support the development of a geographical database for BEAPV.

### 3 CASE STUDY AND ANALYSIS

#### 3.1 Case study on PV potential evaluation in carpark

We select an outdoor carpark in Singapore as the testing field (approximate location: 1°18’N and 103°51’E) to verify the proposed approach. There are three reasons we selected a public carpark for this purpose. (a) The environment surrounding the carpark includes buildings and trees and is thus sufficiently complex. (b) Evaluating the PV potential of a carpark will provide a reference for installing a charging station in the future to accommodate the increasing popularity of EVs. (c) The PV carpark provides shade to improve the comfort inside the vehicles.

Our approach to evaluate BEAPV works consists of four steps.

Step 1 encompasses the preparation work including a site investigation, literature review, meteorological data collection, and flight design. After site investigation, the information such as the number and size of trees, buildings, and vehicles is collected. In our study area, we found that a large portion is shaded by high buildings and trees; most of the vehicles (both freight and passenger types) in the lot are oversized.

The UAV DJI PHANTOM 3 Advanced, equipped with a 12-megapixel RGB camera FC300S, was used to carry out the field survey. The camera has the f/2.8 lens that offers 94° field of view. According to Singapore’s official regulations, if the UAV weighs <7 kg, it can be used in specified areas without censorship, while the chosen DJI PHANTOM 3 Advanced weighs only 1.28 kg. The planned overlap of the flight route is about 80%, while the overlap between consecutive strips is 60%. In the end, a total number of 178 images are taken in the carpark.

The performance of PV modules and systems is affected by the orientation and tilt angle, as these parameters
Zhong et al. determined the amount of solar radiation received by the surface of a PV module in a specific region. Yong Sheng Khoo et al. used three sky models to estimate the tilted irradiance, which would be received by a PV module at different orientations and tilt angles in Singapore (1.37°N, 103.75°E) from June 2011 to May 2012 and found out that the PV system tilted 10° facing east demonstrated the highest specific yield with appropriate self-clean characteristic. Thus, we set our experiment device in this way.

Urban meteorological data are collected from The United States Department of Energy (meteorological data in Energy Plus Energy Simulation Software). The line of flight is designed according to the local regulations and landscape features.

In Step 2, we acquire information for the carpark. The UAV captured 178 images which we use to build a 3D point cloud model in Photoscan (AgiSoft LLC, Russia) (Figure 5A). Two processing steps of Photoscan are required to obtain the detailed reconstructed 3D point cloud: photo alignment and detailed scene construction. The photo alignment is completed via structure from motion (SFM) technique, an algorithm which detects the image feature points and monitors their movement to estimate their locations before rendering the data into a sparse point cloud. The detailed point cloud is constructed by applying a dense, multiview stereo-reconstruction on the aligned image set and operating on the pixel values. The fine details are presented as a mesh. Photoscan is an integrated but affordable toolbox that works with both still and motion pictures while providing high accuracy.

We also use Photoscan to eliminate the vehicles in the carpark (Figure 5B) while retaining the point cloud of trees and other UIs by manual operation. In this case, the scope of parking shed is the yellow area in Figure 5A. A 6 m high parking shed is constructed and connected with the cable-based PV system. PV modules are tilted 10° facing east. A total number of 226 vehicles are allowed in this area. For the maximum energy consumption of each vehicle, we take reference from the research findings by He et al. It is thus adopted that the energy consumed by an electric bus BJD6100-EV in the urban driving environment was 94.46 kWh per hundred kilometers.

In Step 3, we set the constraints and determined the available area for PV modules. Point cloud documents obtained by the “Make LAS Dataset Layer” command are imported into ArcMap. The command “Las Dataset to Raster” is used to establish the DSM shown in Figure 6A with 1 m × 1 m cell size. The DSM is used to generate polygons with contours. The polygons which are higher than 6 m above the target ground are deleted. Here, 6 m means the net height from the ground is 6 m, which refers to the height relative to the ground elevation. The height of the carpark is chosen to be 6 m because the highest vehicle in the carpark, the double-decker, is 4.5 m. The remaining section is set as the PV installation plane. The elevation field is added (Figure 6B). “Is Null” and “Con” conditional tools are then used to produce new DSM leaving only the area above PV installation, as shown in Figure 7A.

The tool “Solar Radiation Graphics” is employed to simulate the solar radiation for this new DSM. As shown in Figures 7B and 8A, the simulation results of sunshine hours and solar irradiance are obtained separately. We select the area with annual solar irradiance threshold up to 1000 kWh/m² refer to the solar irradiation threshold for PV installation from R. Compagnon’s research and full sunshine hours from 9:00 to 15:00 on December 21. The protection of UI and EI must be considered in addition to the constraint on solar radiation, so trees and structures inside or surrounding the carpark were
offset by 1.5 m. As it was described in Section 2.3.3, DSM of vehicles in the carpark generated by point cloud would have contour line operation to generate UI and EI border, including border lines of tree crowns, which are shown by the yellow line in Figure 4B. Then, to offset UI and EI border by the use of buffer zone operation, the calculation results are shown by the red area in Figure 4B. Moreover, we will combine these two parts. The purple area in Figure 4C is the area which is not suitable for PV modules installation. The area suitable for PV modules in the carpark is finally determined under the combination of all the above constraint conditions as the green area shown in Figure 8B.

In Step 4, we estimate the PV potential of the carpark. Currently, the existing software for this purpose includes TRNSYS, PVSOL, and PVGIS. We select PVSYST as provided by the Energy Group of the University of Geneva, Switzerland, which refer to Wu’s and Kumar’s research. PVSYST is specialized in calculating the energy production of installed PV systems. Energy production is calculated based on two models: The One-Diode Model for PV module and the Perez Plane of Array (POA) for solar radiation. The software is integrated with a large database of technological components including PV modules, inverters, and batteries available on the market. The software also offers a climatic database with several locations all over the world and supports the manual input of meteorological data. The advantages of PVSYST are that it offers a diverse database, is convenient to operate, and yields accurate simulation results. Besides, PVSYST software is a PV potential evaluation software widely used in the engineering field, with high accuracy. Axaopoulos et al. have validated the accuracy of PVSYST software using field measurement results in the United Kingdom and concluded that the accuracy of the software is satisfactory.

In this paper, the PV potential is simulated by using PVSYST 5.0 software. Typical annual meteorological data in Singapore were applied in the simulation with suggestions for PV installation from the literature (10° tilt, facing east), as shown in Figure 9A. The available area of this carpark suitable for PV application is approximately 4800 m², covering almost 50% of the original area of the carpark. Assuming the available area is fully covered with Polycrystalline
silicon, the annual power generated in the lot can reach about 659,300 kWh or an average of 1810 kWh/day, as shown in Figure 9B. Assuming all 226 vehicles are electric motor coaches, the travel distance can be achieved by all coaches in the carpark using the daily generated electricity is 8.48 km, which was calculated by the following equation:

\[
L = \frac{P}{N \times P_0} \times 100
\]

Where \( P \) is the existing carpark PV potential for one day, \( N \) is the number of vehicles in the carpark, \( P_0 \) is the maximum energy consumption of each vehicle per hundred kilometers, and \( L \) is the travel distance can be achieved by all coaches in the carpark using the daily generated electricity.

This suggests that even if the carpark is filled with oversized buses, the vehicles can still complete a fuel-free ride if a PV carpark is distributed every 8 km along the road. Therefore, the carpark can be designed as an electric vehicle battery-switch and charging station, thus not only meeting demand of electric vehicles, but also meeting the requirements of rapid power changing of vehicles. In practice, this would significantly reduce the consumption of fossil energy and the emission of carbon dioxide across the entire transportation system.

3.2 | Case study on PV potential evaluation on the rooftop

We next investigate a rooftop of a building in Singapore to further verify the feasibility of the proposed method. As shown in Figure 10A, the plane is complex and includes many facilities and plants on the rooftop. This test is described only
brevily, as the stepwise process of the proposed method is discussed in detail above.

We first take images of the rooftop via drone. Next, we generate the 3D point cloud model and input it into ArcGIS to create the DSM with 1 m × 1 m cell size, as shown in Figure 10B. The boundaries of the plants and facilities above the PV installation plane 1 m above the roof are offset by 1.5 m. Combined with the solar radiation analysis (Figure 11A,B), the available area for PV application is determined to be about 450 m² as shown in Figure 12A. The proposed approach proved applicable to the rooftop. Finally, we input the results into PVSYSST5.0 to calculate the PV application potential of fully installed polycrystalline silicon modules. The potentially annual generating capacity of this roof is approximately 61 200 kWh (Figure 12B).

The case study described above demonstrated the feasibility of the proposed method for carpark and rooftops. We also compare several methods of obtaining geometrical information (Section 2.2) and discuss the approach to combine the photography with GIS.

The method combines photogrammetry and GIS can be used to accurately obtain BE geometrical information with high accuracy and low cost at the building scale. The method is suitable for evaluating the PV potential of BEs including carparks, corridors, reservoirs, roads, and other horizontal plane. The constraints for BEAPV mostly consist of buildings and trees, which are consistent with the test environment we used in this study. The proposed method is also applicable to evaluate the PV potentials of integrated roof gardens in existing buildings.

4 CONCLUSION

In this paper, we adopted a method which combines photogrammetry and GIS that can provide an accurate geometrical model and comprehensive analysis of the PV potential in BE, with a much lower cost compared with LiDAR-based method. The available area for the installation of PV modules in BE can be obtained after setting constraints in GIS. This paper takes the lead in using UAV to evaluate the PV potential in a carpark. Moreover, it provides scientific support for the future urban planning in green mobility and upgrade of an existing carpark into battery-switch and charging station. Furthermore, the generalization of this evaluation method can be extended to all available built environment infrastructures, which can be served as a guidance for the development plan of solar energy utilization in urban areas.

Although this method is only used to evaluate BEAPV potential on horizontal plane, it has advantages in the engineering application field. Firstly, compared with LiDAR-based method, the cost of this method and associated equipment is much lower. In terms of accuracy, the accuracy of this method is similar to LiDAR and it can meet the requirements of PV potential estimation. In addition, the method adopted in this paper also takes into account all the factors affecting PV application in BE, such as UI and EI. In the process of PV potential evaluation, the UI and EI are offset through the buffer zone, to ensure an accurate estimation of the PV application area.

However, the method has some limitations. Although the elevation information is obtained, it is not covered in the calculation of the PV application potential on facades. The authors would like to develop an estimation method for the PV potential on building façades in the future, using the obtained high-precision point cloud model. In addition, a small UAV can directly obtain the geographical information of an area with a radius of less than 500m, as demonstrated in the case studies at the building scale in this paper. However, according to the research of Baltzavig et al.63 N. Ngadiman et al90 and JF Hernandez et al91 UAV can also obtain the geographic information at the estate and city block scale. The authors would like to consider using UAV to evaluate the PV potential of BE at the city block scale in the future.

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REFERENCES

1. Lee M, Hong T, Kang H, Koo C. Development of an integrated multi-objective optimization model for determining the optimal solar incentive design. Int J Energy Res. 2017;41(12):1749-1766.
2. Zhang W, Zhang Y, Li Z, Zheng Z, Zhang R, Chen J. A rapid evaluation method of existing building applied photovoltaic (BAPV) potential. Energy Build. 2017;135:39-49.
3. IEA. World. Energy Outlook 2018. Int. Energy Agency Paris, Fr., p. 28, 2018.
4. Prasad D, Snow M. Designing with Solar Power: A Source Book for Building Integrated Photovoltaics (BiPV). Abingdon: Routledge; 2014:10-183.
5. Hernandez P, Kenny P. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). Energy Build. 2010;42(6):815-821.

6. Koo C, Hong T, Park HS, Yun G. Framework for the analysis of the potential of the rooftop photovoltaic system to achieve the net-zero energy solar buildings. Prog Photovolt Res Appl. 2014;22(4):462-478.

7. Carrilho da Graca G, Augusto A, Lerer MM. Solar powered net energy houses for southern Europe: feasibility study. Sol Energy. 2012;86(1):634-646.

8. Scognamiglio A. 'Photovoltaic landscapes': design and assessment. A critical review for a new transdisciplinary design vision. Renew Sustain Energy Rev. 2016;55:629-661.

9. Bhatti AR, Salam Z, Aziz M, Yee KP, Ashique RH. Electric vehicles charging using photovoltaic: status and technological review. Renew Sustain Energy Rev. 2016;54:34-47.

10. Neumann HM, Schär D, Baumgartner F. The potential of photovoltaic carports to cover the energy demand of road passenger transport. Prog Photovolt Res Appl. 2012;20(6):639-649.

11. Nordmann T, Clavadetscher L. PV on noise barriers. Prog Photovolt Res Appl. 2004;12(6):485-495.

12. Hernandez P, Kenny P. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). Energy Build. 2010;42(6):815-821.

13. Nordmann T, Goetzberger A. Motorway sound barriers: recent results and new concepts for advancement of technology. 24th IEEE Photovoltaic Specialists Conference, vol. 1. pp. 766-769, 1994.

14. Dezfooli AS, Nejad FM, Zakeri H, Kazemifard S. Solar pavement: a new emerging technology. Sol Energy. 2017;149:272-284.

15. Northmore AB, Tighe SL. Solar energy potential assessment and electricity peak load offsetting at the municipal scale. Comput Environ Urban Syst. 2015;52:58-69.

16. Assouline D, Mohajeri N, Scartezzini J-L. Quantifying rooftop photovoltaic solar energy potential: a machine learning approach. Sol Energy. 2017;141:278-296.

17. Assouline D, Mohajeri N, Scartezzini J-L. Quantifying rooftop photovoltaic solar energy potential: a machine learning approach. Sol Energy. 2017;141:278-296.

18. Hong T, Lee M, Koo C, Jeong K, Kim J. Development of a method for estimating the rooftop solar photovoltaic potential by an analytical power transfer. Proc. 31st Eur. Photovolt. Sol. Energy Conf. Exhib. Hamburg, 14–18 Sept., 2015; Authors version, 2015.

19. Izquierdo S, Fueyo N. A method for estimating the geographical distribution of the available roof surface area for large-scale photovoltaic energy-potential evaluations. Sol Energy. 2008;82(10):929-939.

20. Vardimon R. Assessment of the potential for distributed photovoltaic electricity production in Israel. Renew Energy. 2011;36(2):591-594.

21. Vardimon R. Assessment of the potential for distributed photovoltaic electricity production in Israel. Renew Energy. 2011;36(2):591-594.

22. Vardimon R. Assessment of the potential for distributed photovoltaic electricity production in Israel. Renew Energy. 2011;36(2):591-594.
42. Brito MC, Freitas S, Guimarães S, Catita C, Redweik P. The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data. *Renew. Energy*. 2017;111:85-94.

43. Suomalainen K, Wang V, Sharp B. Rooftop solar potential based on LiDAR data: bottom-up assessment at neighbourhood level. *Renew. Energy*. 2017;111:463-475.

44. Kodysh JB, Omitaomu OA, Bhaduri BL, Neish BS. Methodology for estimating solar potential on multiple building rooftops for photovoltaic systems. *Sustain Cities Soc*. 2013;8:31-41.

45. Hernandez RR, Hoffacker MK, Field CB. Efficient use of land to meet sustainable energy needs. *Nat Clim Chang*. 2015;5(4):353-358.

46. Hernandez RR, Hoffacker MK, Murphy-Mariscal ML, Wu GC, Allen MF. Solar energy development impacts on land cover change and protected areas. *Proc Natl Acad Sci USA*. 2015;112(44):13579-13584.

47. Abbate-Gardner C. Open public spaces and street furniture: the potential for increased use of photovoltaics in the built environment. *Prog Photovolt Res Appl*. 1996;4(4):269-277.

48. Dubey S, Sarvaiya JN, Seshadri B. Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world – a review. *Energy Procedia*. 2013;33:311-321.

49. Cosgrove D. The meaning of the built environment: a nonverbal communication approach. *J Rural Stud*. 1986;2(1):71-73.

50. Handy SL, Bournet MG, Ewing R, Killingsworth RE. How the built environment affects physical activity: views from urban planning. *Am J Prev Med*. 2002;23(2 Suppl. 1):64-73.

51. Torres-Sibille AC, Clouqell-Balsteller V-A, Clouqell-Balsteller V-A, Artacho Ramírez MA. Aesthetic impact assessment of solar power plants: an objective and a subjective approach. *Renew Sustain Energy Rev*. 2009;13(5):986-999.

52. Wong NH, Yu C. Study of green areas and urban heat island in a tropical city. *Habitat Int*. 2005;29(3):547-558.

53. Zhao Q, Wentz EA, Murray AT. Tree shade coverage optimization in an urban residential environment. *Build Environ*. 2017;115:269-280.

54. Eltawil MA, Zhao Z. Grid-connected photovoltaic power systems: technical and potential problems—a review. *Renew Sustain Energy Rev*. 2010;14(1):112-129.

55. GB 50797–2012, Code for design of photovoltaic power station. China: Ministry of Housing and Urban-rural Development of People’s Republic of China; 2012. (In Chinese).

56. Compagnon R. Solar and daylight availability in the urban fabric. *Energy Build*. 2004;36(4):321-328.

57. Luque A, Hegedus S. *Handbook of Photovoltaic Science and Engineering*. Hoboken, NJ: Wiley; 2011:1036-1037.

58. GB 50797–2012, Code for design of photovoltaic power station. China: Ministry of Housing and Urban-rural Development of People’s Republic of China; 2012. (In Chinese).

59. Building and Construction Authority of Singapore Government. *Handbook for Solar Photovoltaic System*. The Guardian. https://www.bca.gov.sg/publications/others/handbook_for_solar_pv_systems.pdf

60. Karteser M, Theodoridou I, Mallinis G, Papadopoulos AM. Façade photovoltaic systems on multifamily buildings: an urban scale evaluation analysis using geographical information systems. *Renew Sustain Energy Rev*. 2014;39:912-933.

61. Gautam BR, Li F, Ru G. Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal. *Energy Build*. 2015;86:735-744.

62. Li Z, Zhang Z, Davey K. Estimating geographical PV potential using LiDAR data for buildings in downtown San Francisco. *Trans GIS*. 2015;19(6):930-963.

63. Baltsavias EP. A comparison between photogrammetry and laser scanning. *ISPRS J Photogramm Remote Sens*. 1999;54(2–3):83-94.

64. Awrangjeb M, Ravanbakhsh M, Fraser CS. Automatic detection of residential buildings using LiDAR data and multispectral imagery. *ISPRS J Photogramm Remote Sens*. 2010;65(5):457-467.

65. Adeleke AK, Smit JL. Interrogation of LiDAR data with aerial imagery for estimating rooftop solar photovoltaic potentials in city of Cape Town. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. 2016;41:617-624.

66. Brumana R, Oreni D, Van Hecke L, et al. Combined geometric and thermal analysis from Uav platforms for archaeological heritage documentation. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. II-5/W1, no. September, pp. 49-54, 2013.

67. Valavanis KP, Vachtsevanos GJ. *Handbook of Unmanned Aerial Vehicles*. Berlin: Springer; 2015:1547-1576.

68. Dai F, Lu M. Assessing the accuracy of applying photogrammetry to take geometric measurements on building products. *J Constr Eng Manag*. 2010;136(2):242-250.

69. Fu P, Rich PM. A geometric solar radiation model with applications in agriculture and forestry. *Comput Electron Agric*. 2002;37(1-3):25-35.

70. Fu P, Rich PM. Design and implementation of the Solar Analyst: an ArcView extension for modeling solar radiation at landscape scales. Proceedings of the nineteenth annual ESRI user conference. Vol. 1. USA: San Diego, 1999.

71. Verso A, Martin A, Amador J, Dominguez J. GIS-based method to evaluate the photovoltaic potential in the urban environments: the particular case of Miraflores de la Sierra. *Sol Energy*. 2015;117:236-245.

72. Civil Aviation Authority of Singapore (CAAS). Flying of Unmanned Aircraft. http://www.caas.gov.sg/caas/en/ANS/unmanned-aircraft.html. Accessed August 26, 2017.

73. Khoo YS, Nobre A, Malhotra R, et al. Optimal orientation and tilt angle for maximizing in-plane solar irradiation for PV applications in Singapore. *IEEE J Photovolt*. 2014;4(2):647-653.

74. Verhoeven G. Taking computer vision altool - archaeological three-dimensional reconstructions from aerial photographs with photoscan. *Archaeol Prospect*. 2011;18(1):67-73.

75. Ullman S. The interpretation of structure from motion. *Proc. R. Soc. London. Ser. B. Biol. Sci.*, vol. 203, no. 1153, p. 405 LP-426, 1979.

76. Seitz SM, Curless B, Diebel J, Scharstein D, Szeliski R. A comparison and evaluation of multi-view stereo reconstruction algorithms. 2006 IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit. - Vol. 1, vol. 1, pp. 519-528, 2006.

77. Scharstein D, Szeliski R, Zabih R. A taxonomy and evaluation of multi-view stereo reconstruction algorithms. *2006 IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit. - Vol. 1, vol. 1, pp. 519-528*, 2006.

78. Seitz SM, Curless B, Diebel J, Scharstein D, Szeliski R. A comparison and evaluation of multi-view stereo reconstruction algorithms. *2006 IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit. - Vol. 1, vol. 1, pp. 519-528*, 2006.

79. He H, Sun F, Xu X. Analyst of energy consumption of BJD6100-EV Bus in urban driving. *Bei Jing Li Gong Da Xue Bao*. 2015;40(2):68-74.

80. Johnson GR, Wilt O. Protecting trees from construction damage: a homeowner’s guide. *Construction*, pp. 1-29, 1999.
81. Axaopoulos PJ, Fylladitakis ED, Gkarakis K. Accuracy analysis of software for the estimation and planning of photovoltaic installations. *Int J Energy Environ Eng*. 2014;5(1):1-8.
82. Manfren M, Caputo P, Costa G. Paradigm shift in urban energy systems through distributed generation: methods and models. *Appl Energy*. 2011;88(4):1032-1048.
83. Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl Energy*. 2010;87(4):1059-1082.
84. Laudani A, Riganti Fulginei F, Salvini A. Identification of the one-diode model for photovoltaic modules from datasheet values. *Sol Energy*. 2014;108:432-446.
85. Hay JE. Calculation of monthly mean solar radiation for horizontal and inclined surfaces. *Sol Energy*. 1979;23(4):301-307.
86. Ekici BB. Variation of photovoltaic system performance due to climatic and geographical conditions in Turkey. *Turk J Electr Eng Comput Sci*. 2016;24(6):4693-4706.
87. Perez R, Ineichen P, Seals R, Michalsky J, Stewart R. Modeling daylight availability and irradiance components from direct and global irradiance. *Sol Energy*. 1990;44(5):271-289.
88. Wu X, Liu Y, Xu J, et al. Monitoring the performance of the building attached photovoltaic (BAPV) system in Shanghai. *Energy Build*. 2015;88:174-182.
89. Kumar NM, Kumar MR, Rejoice PR, Mathew M. Performance analysis of 100 kWp grid connected Si-poly photovoltaic system using PVsyst simulation tool. *Energy Procedia*. 2017;117:180-189.
90. Ngadiman N, Kaamin M, Sahat S, et al. Production of orthophoto map using UAV photogrammetry: a case study in UTHM Pagoh campus. *AIP Conference Proceedings*. Vol. 2016. No. 1. *AIP Publishing*, 2018.
91. Fernández-Hernandez J, González-Aguilera D, Rodríguez-Gonzálvez P, Mancera-Taboada J. Image-based modelling from unmanned aerial vehicle (UAV) photogrammetry: an effective, low-cost tool for archaeological applications. *Archaeometry*. 2015;57(1):128-145.

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