DETECTION OF ROOF SHADING FOR PV BASED ON LIDAR DATA USING A MULTI-MODAL APPROACH

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ABSTRACT: There is a current drive to increase rooftop deployment of PV. Suitable roofs need to be located, especially as regards shading. A shadow cast on one small section of a solar panel can disproportionately undermine output of the entire system. Nevertheless, few shading figures are available to researchers and developers. This paper reviews and categorizes a number of methods of determining shade losses on photovoltaic systems. Two existing methods are tested on case study areas: shadow simulation from buildings and ambient occlusion. The first is conceptually simple and was found to be useful where data is limited. The second is slightly more demanding in terms of data input and mathematical models. It produces attractive shadow maps but is intended for speed and represents an approximation to ray-tracing. Accordingly, a new model was developed which is fast, flexible and accurately models solar radiation.

Keywords: Modelling, Photovoltaic, Ray Tracing, Solar Radiation, Shading

1 INTRODUCTION AND BACKGROUND

Many countries are currently focusing on roof-top PV installations. There is a global trend towards distributed energy production where electricity is generated at point of use, on the roofs of houses, public and commercial buildings. Some roofs are more suitable than others in terms of size, azimuth, tilt and shade received. Decentralised energy requires load management from electricity grid operators so it is essential to identify those roofs which are most suitable for PV, including susceptibility to shading, for potential future deployment.

Photovoltaic system performance is very sensitive to shading. The output of a single cell is reduced in relation to the amount of shade falling upon it. However, due to the fact that cells in a module are connected in series and that the number of bypass diodes per module is generally low, shading just one cell causes a disproportionately large decrease in the current in the bypassed block (Kirchoff's laws). With particular types of shading pattern, a small amount of shade covering only a few cells may reduce the power output of the module to near zero.

Despite the impact of shading on photovoltaic output, there is little detailed data available regarding shading profiles. Commercial data suppliers sometimes retail roof maps as simple binary shaded/not shaded outline polygons, based on manual inspection of aerial photographs. Other possibilities include expensive on-site measurement or customised surveys of just one or two buildings. The latter often produces results by simple projection of building and tree shadows onto the ground. Online tools such as Solar Census Surveyor [1] and Sun Area [2] take LiDAR data as input, but include shade in a PV suitability value determined via patented algorithms.

For accurate PV installation decisions the minimum data requirement is percentage shading of roof. Shade polygons on roofs with area and location are even more useful because they allow the most suitable roof panes to be identified.

The total shade falling on a roof may be categorised as arising from one or more of three causes: (1) Distant topographical features such as hills, cliffs etc; (2) Near features e.g. neighbouring taller buildings, trees, pylons etc; and (3) Self-shading from chimneys, dormers, cross-gables, aerials, vents. This research aims to identify a method which delivers the whole shade from all three causes.

2 REVIEW OF METHODS OF MODELLING SHADE

Several methods have been applied to study shading losses in PV systems. These may be grouped according to the input data they require as follows: shadow simulation from buildings, LiDAR methods and image methods.

Buildings methods need data in the form of building polygons linked to a height attribute. Height information is often obtained by sophisticated analysis of LiDAR data but may also originate from building plans or manual estimations. Sketchup (bought by Trimble in 2012) and ArcGIS Sun Shadow Volume are two examples of this simple method. Both base shadow calculations on latitude and longitude of the site of interest; and time and date. The sun is treated as a point source. In other words only beam effects are reproduced. Building shadow simulation models produce the location of shading only (shadow polygons). The effect of shade on incident irradiance must be computed separately. Dereli et al (2013) [3] applied Sketchup to a case study area, investigating shading from trees on PV in the US MidWest.

LiDAR methods may be subdivided into: hillshade-type, horizon angle computation and sky-dome models. Elementary hillshade models are found in various software, for instance, Hillshade in ArcGIS or Shaded Relief in GRASS. They are more generally utilised to enhance the visualisation of terrain. In the context of photovoltaics, it is the hillshade of the individual roof which is generated, that is, self-shading from aspect and cross-gables. Again, as with the building simulation models, only shadows are produced and not their influence on irradiation. Kassner et al [4] applied the hillshade algorithm to 13 buildings on a university campus. Interestingly, there is no record in the literature of the algorithm being applied twice, once to calculate the shade on the roof from surrounding hills and once to estimate self-shading from the building itself.

Horizon angle computation is employed by a number of solar analysis tools but its implementation as r.sun / r.horizon / r.sunmask in GRASS software is one of the best known. The minimum input requirements for this function are location and date/time to compute the sun position and a gridded elevation map, usually LiDAR. The model calculates beam irradiation for clear-sky conditions from extraterrestrial irradiance. Accuracy may be improved by including a local atmospheric turbidity factor (Linke). The incoming insolation may also be divided into its direct and diffuse fractions by incorporating a coefficient derived from ground-station measurements. Shadowing effects may be pre-calculated as follows. For a given solar incidence angle, the calculation starts on e.g. a roof pane and moves along the path of the incoming sunray. Each height point is checked to ascertain whether it intersects or is higher than the sunray, in which case it will cast shade. In contrast to the previously described building shadow simulation and hillshade techniques, r.sun directly calculates global horizontal irradiation, taking into account the consequences of shading. These GRASS algorithms are computationally intensive but have been successfully applied in both urban [5] and mountainous landscapes [6].

Sky-dome models are found in ray-tracing routines in games and graphics software and in architectural applications whose purpose is to include daylight in building design, as well as photovoltaic applications. A typical sky-dome model comprises a hemispherical dome, divided into segments, positioned over the PV array. Diffuse irradiation originating from various parts of the sky (segments of the dome) may then be modelled.

Image methods apply a completely different approach to the functionality just described. They capture actual shadows as recorded by aerial photography rather than modelling the theoretical location of shadows from sun position. For instance, Bergamasco and Asinari (2011) drew up conditions to define clusters of dark pixels as shadow in images of the whole city of Turin [7]. Image methods will not be considered by this paper. They require powerful computing facilities and automatic detection of shadows visible to the human eye is challenging. Furthermore, "what-if scenarios" of proposed buildings cannot be added.

3 COMPARISON OF RESEARCH METHODS AND FINDINGS

This paper will compare and contrast two shadow modelling methods: building height and sky-dome. A new method, "solarscene.xyz", (developed at CREST) which improves on previous sky-dome based techniques will then be presented.

Case studies of two specific (1km x 1km) areas will be used: Loughborough University West Campus and Prestwich Village, Manchester. The University Campus was selected primarily for ease of validation. The area is landscaped to a slight rise and it encompasses a mix of building types from large lecture theatres and sports halls to small residential homes. There are also wooded areas. Prestwich was selected as the second area because of the range of LiDAR data available there. The gently undulating topography is characterized by the central Roman road and there are many large domestic residences surrounded by generous gardens with mature trees.

3.1 ArcGIS Sun Shadow Volume for Buildings

This facility models shadows as polyhedrons thrown by each building. Sun position is calculated from time of day and year. The building heights data used was Landmap Features Earth Observation Collection [8] which derives heights from LiDAR or aerial imagery. Initial results appear promising (Fig. 1).

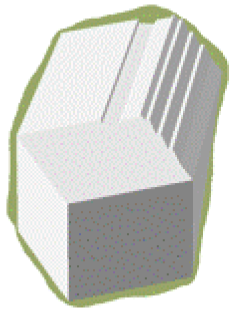

Figure 1: Shadow volume cast each hour 10am – 3pm 22 December 2015 by cube-shaped Henry Ford College, Loughborough

However, each building is treated as a simple cuboid i.e. shading from sloping roofs is not accounted for. Shade from trees and hills is not considered, although these could be modelled separately and the results combined. More difficult to resolve is the fact that this model creates shadows with a set length which is not terminated by any other feature. That is, the shadows may pass through and under other buildings, through hills and into the ground. Hence shade is over-estimated or falsely identified. The tool is also computationally demanding. Therefore, although the Sun Shadow Volume is useful in terms of its simplicity and easily obtained input data, more sophisticated tools were trialed.

3.2 SAGA-GIS Analytical Hillshading sky-dome application

This tool modifies the work of Tarini et al [9]. It utilizes the ambient occlusion global lighting technique. Height data (of terrain, buildings, trees etc) is obtained from LiDAR. For each LiDAR point (see later) on a given roof, rays are projected in every compass direction for a positive z value i.e. upwards. Rays which travel unrestricted to the "sky" provide irradiance. Those which strike another object are given an irradiance value of zero (shadow). The light-blocking effect of objects is exponentially weighted according to the distance of the object. Light is treated as uniform. It is allocated the same value from all directions. The effect is that of cover by a cloudy sky. Ambient occlusion is an approximation to ray-tracing. It was originally developed to visualize graphics at high frame rates and uses as few computational resources as possible.

The height of the roof points is obtained from LIDAR (Light Detection and Ranging) data. This is produced from a sensor mounted on an aircraft. The sensor pulses a laser downwards and times its return.

The number of returns per square metre defines the resolution of the data. In the UK, LiDAR data is now available from the Environment Agency as Open Data (free of charge and restriction) [10]. 2m, 1m, 50cm and 25cm resolution datasets are supplied. However, the datasets were flown in different years and 25cm data covers less than 4% of England and Wales.

The results produced by the SAGA-GIS Analytical Hillshading module using 1m LiDAR appear generally realistic when checked against local observations, although spurious features can be discerned due to the approximation of the method (Fig. 2 and Fig. 3). Detailed percentage shade-on-roof maps may be generated (Fig. 4). Additionally, SAGA software is fast because it is programmed to maximise use of all available computer cores. Shade maps were produced for the 1 sqkm case study areas in under 1 second.

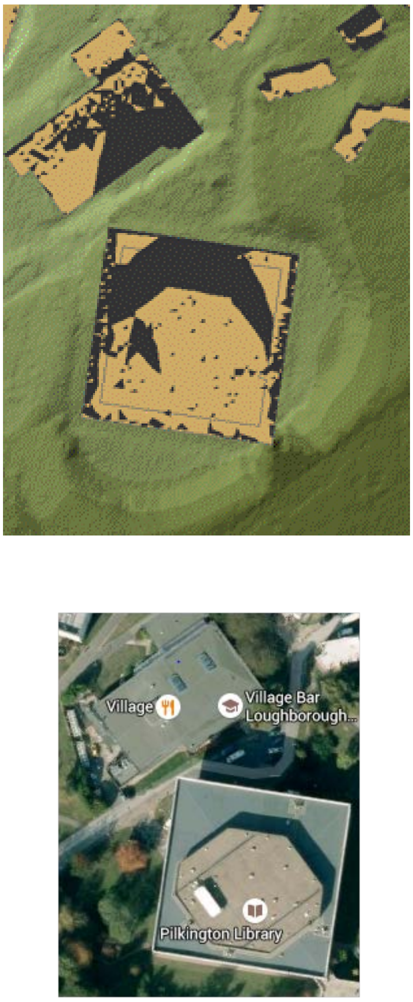

Figure 2: Shade (grey) on roofs of Pilkington Library (square building) and Village Restaurant, at foot of hill, West Campus, Loughborough University, noon 22 December 2015

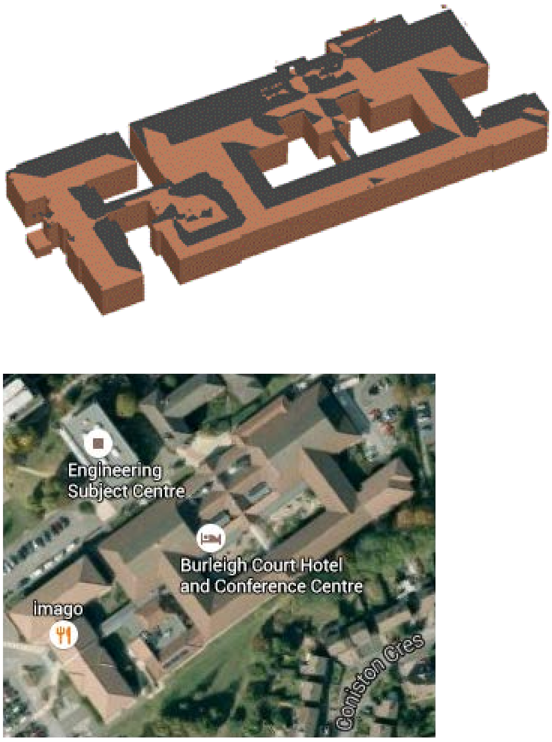

Figure 3: Shade (grey) on roofs of northwest-facing Burleigh Court Hotel, Loughborough, noon 22 December 2015

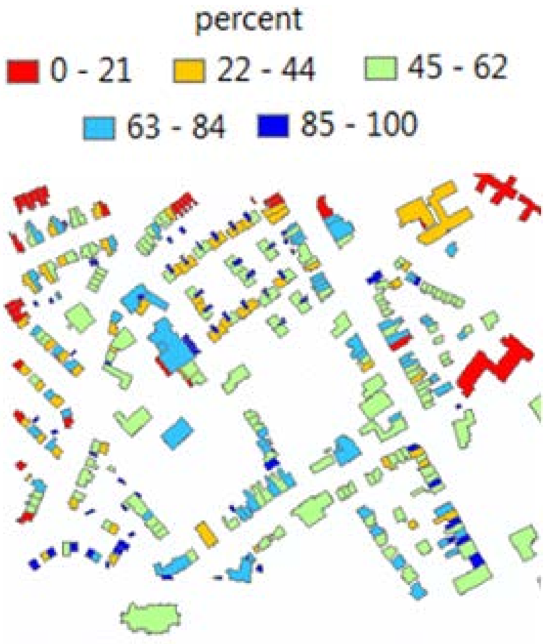

Figure 4: Percentage shading on roofs in Prestwich Village, Manchester, noon 22 December 2015.

The SAGA-GIS Analytical Hillshading module yields lifelike results but there are openings for improvement. It calculates the portion of the sky-dome over each LiDAR point which is not blocked by another feature (building, tree, hill etc). Nonetheless, light is considered to be uniform, recreating conditions only.

3.3 Improved Sky-dome method for LiDAR: solarscene.xyz

This new model develops on the skydome modelling technique described by Goss et al [11] and the ray tracing methodology of Cole & Gottschalg, as used in [12]. The model can accept any form of gridded xyz data and any set of meteorological data with separable beam and diffuse irradiance components at a user defined temporal resolution. The default data inputs, and those used here, are LiDAR data and hourly global horizontal irradiation, produced by interpolation of UK Met. Office data [13]. The model calculates total global in-plane irradiation (beam and diffuse) based on actual sky conditions from measured values.

Previous sky-dome techniques have adopted one of two alternative approaches:

1. Divide the hemisphere into almost equal area segments with varying spacing.
2. Divide the hemisphere into patches equally spaced in elevation and azimuth with different sizes.

The solarscene.xyz model offers a variable input sky-dome. User defined sky-domes and resolutions can be used, the model corrects for sky-patch weightings by means of solid angle calculation and correction. The sky dome used here is the Tregenza dome, as explained in [14].

The model first iterates over each timestamp in the meteorological dataset, computing the relative sun position and distributing the solar irradiation over the sky-dome accordingly. The net irradiation sky dome for the user defined measurement campaign is then held in RAM and the sky-patch locations and intensities used in the ray tracing algorithm, resulting in an extremely fast and efficient model.

In the ray tracing algorithm, solarscene.xyz iterates over each sky-patch in the hemisphere and calculates the longest subjective path of intersections through the 3D environment. This path is then objectified and used as a reference path for the other traces through the 3D environment. This method optimizes the trace procedure as there is only one explicit ray path calculation per sky-patch. The calculation is performed such that, for an individual sky-patch to pixel interaction, the cosine corrected irradiation from the pixel 3D surface normal to the sky-patch vector is either: shaded, half-shaded or unshaded. The same routine is performed for each sky-patch in the sky-dome and the irradiation falling on each pixel in the 3D environment is summed.

solarscene.xyz handles both beam and diffuse irradiance whilst overcoming problems arising from division of the sky-dome. Preliminary results appear very satisfactory (Fig. 5). These were verified locally by comparing with pyranometer readings from CREST meteorological station. Pyranometers are mounted horizontally and south-facing at both 35° and 45° inclination angles. Initial model results checked against these pyranometer readings were found to be within 5% of net annual energy values. Wide area validation is currently underway.

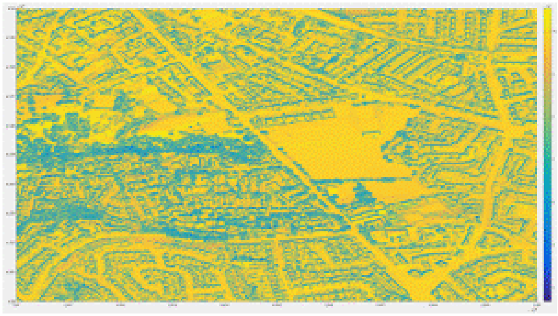

Figure 5: Total Global Horizontal Irradiation for 2014 (kWh) on roofs Prestwich Village, Manchester

4 DETERMINATION OF APPROPRIATE LIDAR RESOLUTION

An experiment was carried out to investigate whether high resolution LiDAR is necessary for shade modelling, or if acceptable results may be produced with medium resolution data. For reasons of brevity, the SAGA-GIS Analytical Hillshading tool was employed, but further investigations will be carried out using solarscene.xyz in the future.

Binary gridded shade maps were created for 10am 22 December 2015 for Prestwich Village using 25cm, 50cm and 1m LiDAR and the results compared. This time was selected because this gives some of the longest shadows in the year. Mathematical comparison of the resultant maps delivered the following outcomes:

- 50cm has 5.7% more grid cells (pixels) shaded but also 2.7% less than 1m (total difference 8.4%).

Unfortunately, the available LiDAR data were flown on different dates. The 25cm and 50cm LiDAR were flown on 27 January 2010 and the 1m LiDAR on 1 February 2013. Consequently, it would be invalid to directly compare this data with respect to resolution due to the significant environmental changes likely to occur over 3 year period. For this reason, the 25 cm and 50cm LiDAR datasets were averaged to 1m resolution to manufacture data for the same year. Differences between the original 1m data and 1m data aggregated from 50 cm are:

- Original 1m has 3.4% more pixels shaded but also 2.2% less than generated 1m (total difference 5.6%)

The differences between the original 1m data and 1m data aggregated from 25 cm are virtually identical to the 1m/aggregated 50cm results, differing by just 3 pixels, as would be expected since these datasets were flown in the same year. Measured 50cm and original 1m data differ by 8.4%, whilst original 1m data and 1m data manufactured by aggregation differ by 5.6%. Therefore about two-thirds of the variation in shadows generated between 50cm and 1m data is not due to resolution but to the three years' time interval which would give opportunity for tree growth and building construction. In fact, only 2.8% of the difference may be explained by the finer resolution.

Further comparisons reveal:

- 25cm has 5% more and 1.4% less grid cells shaded than 50cm (total difference 6.4%).
- 25cm has 8.3% more and 1.4% less pixels shaded than 1m (total difference 9.7%).

So it may be seen that moving from 50cm to 1m resolution produced a 2.8% difference in pixels shaded (0.001% per sqcm). Contrasting 25cm and 50cm data results in 6.4% variation (0.01% per sqcm). This is a much greater relative change.

25cm LiDAR produces more shading than 50cm using the SAGA tool but it is thought that much of this is due to rogue shadowing effects generated by the ambient occlusion technique. The extra shadows may be false. They often appear as tiny shade polygons which could be caused by trees casting dabbled shade or could be a source of error, related to inherent approximations in the method. However, for this method, it seems that 25cm data is no more likely to capture small potential shade producing features such as chimneys than 50cm data.

5 ANALYSIS OF FINDINGS

Tables I, II and III detail similarities and differences between the shading methods reviewed and appraised in this paper. Numbers 1, 4 and 6 underwent extensive trials. The others were tested or reviewed.

Table I: Shading methods: Comparison of Inputs

	Model	Input Data		Extra Inputs
		3D buildings	LiDAR	
1	Building shadow simulation	Yes	No	No
2	Hillshade	No	Yes	No
3	r.sun	No	Yes	Yes
4	Ambient Occlusion	No	Yes	No
5	Image methods	No	No	Yes
6	solarscene.xyz	Yes	Yes	Yes

Table II: Shading methods: Details of Included Models and Options

	Model	Include self-shading, hills and trees	Models diffuse irradiation	Choice of input data & sky-dome
1	Building shadow simulation	No	No	No
2	Hillshade	No	No	No
3	r.sun	Yes	Yes	No
4	Ambient Occlusion	Yes	No	No
5	Image methods	Yes	No	No
6	solarscene .xyz	Yes	Yes	Yes

Table III: Shading methods: Comparison of Outputs and Computer Requirements

	Model	Output		Computer Speed
		Shade Polygons	Global Horizontal Irradiation	
1	Building shadow simulation	Yes	No	No
2	Hillshade	Yes	No	Yes
3	r.sun	Yes	Yes	Yes
4	Ambient Occlusion	Yes	No	Yes
5	Image methods	Yes	No	No
6	New solarscene.xyz	Yes	Yes	Yes

Each of the models has advantages and disadvantages. Some of the models create shadow polygons only. Of these, shadow simulation from buildings (e.g. ArcGIS Sun Shadow Volume) is a simple technique which neglects several sources of shade and is very slow to compute. On the other hand, it is easy to understand and the necessary input data is straightforward to obtain and / or prepare. Hillshade techniques also overlook some shade-producing features. Likewise, these techniques are conceptually simple but have the advantage of greater speed. LiDAR data which, in general, must be purchased or commissioned is a pre-requisite. Image methods too need an aircraft to capture data. Image recognition includes all sources of shade but despite the functionality being relatively clear, are computationally intensive and difficult to implement successfully. Ambient occlusion is a little more demanding upon the user in terms of the mathematical models which form its basis. Here again, LiDAR is a pre-requisite. Ambient occlusion is fast and produces visually attractive results but is inclined to generate spurious shadows. All of the techniques mentioned so far may be implemented via a graphical user interface.

Turning to methods which generate global horizontal irradiation figures (r.sun and solarscene.xyz), they need LiDAR data or other gridded height data, as well as further inputs (e.g. Met. Office data, atmospheric coefficients) which may not be easy to obtain. R.sun runs from the command-line. It may be run with limited data by accepting included default values but accuracy is increased by over-riding with measured values. GUI development for solarscene.xyz is planned for the future. These models which output irradiation data provide the most natural results but understanding how they work can be challenging for the layman.

6 CONCLUSION

With the present focus on increasing the penetration of rooftop PV, there is a need for installers and energy companies to identify the most suitable buildings. The amount of shade falling on a roof greatly influences its appropriateness for PV installation. This paper has examined a number of shade-estimation techniques and presented the new solarscene.xyz model.

The findings demonstrate that choice of shading model depends on:

- The user - programming skill, technical knowledge and amount of time available to dedicate to the task.
- Type of data available.
- Computer resources.
- Outputs required.

The new sky-dome model from CREST, solarscene.xyz, is flexible as regards data inputs, choice of sky-dome model, time-step and outputs. It may take either building heights data or LiDAR, This flexibility as regards elevation data allows what-if analysis. For instance, the impact on a national electricity grid may be estimated if a new housing estate with roof-top PV is constructed. solarscene.xyz relies on ground-based meteorological data. Accurate ray tracing is employed with minimal approximations – those governed by the resolution and accuracy of the input data. It is fast because it is optimized to differentiate between simple and complex terrain. Currently, UK Met. Office data is only obtainable with an hourly timestamp. However, the model accepts user defined datasets at any time resolution. Should there be an opportunity for automated extraction of meteorological data at high temporal resolution, the model will be updated accordingly. solarscene.xyz offers the user a choice of sky-dome model. It provides a sophisticated treatment of diffuse radiation shadow losses as well as manufacturing beam-derived shadows. Lastly, there is the possibility of alternative outputs, either global in-plane irradiation maps or shadow polygons.

Future work will continue validation of the new model. Further investigation will be pursued to determine the optimal LiDAR resolution for use with solarscene.xyz.

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