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## Assessment of potential for photovoltaic roof installations by extraction of roof tilt from LiDAR data and aggregation to census geography

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# Assessment of potential for photovoltaic roof installations by extraction of roof tilt from light detection and ranging data and aggregation to census geography

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**Abstract:** Large-scale adoption of solar photovoltaics (PV) in the built environment requires automation of roof suitability surveying over large geographical areas. Furthermore, as local PV installation density increases, electricity network operators require clearer information on the overall impact the large number of different rooftop PV systems will have on the stability of the local network. Knowledge of roof features (tilt angle, azimuth angle and area) and localised in-plane irradiance data is essential to meet both of these requirements. Such information is currently not available (except by individual roof surveying by PV consultants) and has to be generated. This study demonstrates the automated extraction of building roof plane characteristics from existing wide-area, aircraft-based light detection and ranging data. These characteristics are then aggregated statistically and scaled-up to produce a UK-wide map of average roof tilt variation. Validation of roof tilt with site measurements taken by four different methods demonstrates a mean absolute error of 3°. For major roof plane azimuth angles, banded into compass octants, accurate detection was achieved in 100% of cases, validated by inspection of aerial photography. This is sufficient for calculating in-plane irradiance for a more detailed automated assessment.

## 1 Value of roof characteristics to photovoltaic deployment

Knowledge of roof tilt and azimuth angles is necessary to calculate the electricity yield and generation time profile of an existing or potential photovoltaic (PV) installation. Currently, this information is only available for small areas from commercial suppliers whose techniques include use of bespoke light detection and ranging (LiDAR) flights, manual interpretation of aerial photographs and generalised assumptions of building azimuth in relation to road network. Most methods lack validation or are very costly to perform. A method of assessing roof features from data which is available is given here. An innovative demonstration is presented as to how these building characteristics may be augmented to provide countrywide assessment of the potential for PV installation. Ultimately this will impact the supply network.

The assessment of solar energy potential to inform PV installation development requires knowledge of plane-of-array (POA) irradiation which is generally calculated from the more widely available global horizontal irradiation measurements. The other necessary inputs to this set of algorithms are: times and dates of the period of interest; latitude and longitude of the site; tilt angle (usually roof tilt) of the array; and azimuth angle (the compass direction the roof faces). Of these, the last two are most difficult to obtain by automated methods and hence are the focus of this research. In the UK, the national housing stock database does not document these details and house-builders do not routinely maintain suitable records or do not make them available to the wider public. Internationally, the situation is similar. Government organisations do not normally maintain building attribute databases. An Internet search discovered only a few small areas of Germany with three-dimensional (3D) building data available via CityGML. There may be other sources of data but they could not be identified and may not be so widely disseminated.

The azimuth of a PV system has two effects on the energy yield. First, the annual energy yield is affected. Second, the timing of

energy generation is influenced. The POA is a measure for the absolute energy on a surface. Different POAs are assessed by transposing horizontal irradiance to the POA of interest. Normally one does not have measurements which relate to the specific tilt, azimuth and location of interest. Fig. 1 presents POA irradiation in Sutton Bonington, modelled from UK Meteorological Office station observations [1]. This mathematically generated data illustrates that more favourable (i.e. southerly) azimuths for PV installation may receive twice the amount of irradiation (for the same tilt) than the least favourable compass directions (i.e. east or west) for solar panels. Increasing inclination from the horizontal through its peak performance only heightens irradiation values by 15% between 0° and 45° tilt with a constant south-facing azimuth (Fig. 2).

The data illustrated in Figs. 1 and 2 was produced by interpolating UK Met Office weather station global horizontal hourly irradiation data [1] by kriging. The Strous Sun geometry algorithm [2] (1) was employed for reasons of speed and simplicity. Such fast solar position algorithms generally have an uncertainty of <0.01°. The equations used to determine the position of the Sun are:

*Strous Sun geometry algorithm*

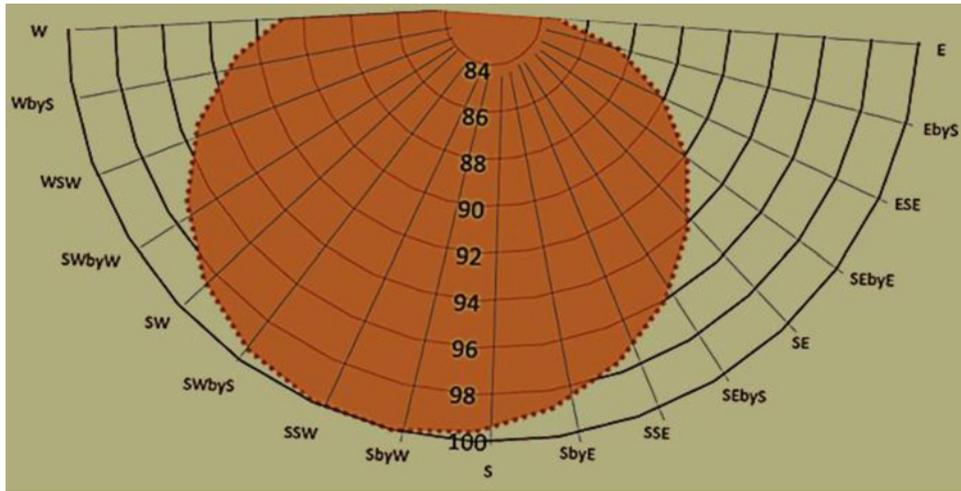
$$\text{declination} = \arcsin(\sin(\text{eclong}) \times \sin(23.45)) \quad (1)$$

where Eclong is the Earth-centred longitude calculated from Julian Date.

The position of the Sun is then used to separate global irradiation into beam and diffuse components using the method of Ridley *et al.* [3] (2):

*Ridley et al. separation algorithm*

$$\text{Diffuse fraction} = 1/1 + \text{Exp}(-5.38 + 6.63 kt + 0.006AST - 0.007\alpha + 1.75 kt + 1.31\varphi) \quad (2)$$



**Fig. 1** Influence of azimuth on irradiation received. Normalised average net hourly POA per compass point for Sutton Bonington Weather station, UK for 10 years 2009–2014 kWh/m<sup>2</sup> at a constant inclination of 38°

where  $kt$  is the clearness index,  $AST$  is the apparent solar time,  $\alpha$  is the solar altitude and  $\varphi$  is the persistence factor (average clearness index over 2 h). The last step in converting global horizontal to POA irradiation is to transpose the irradiation constituents to the required tilt angle, using the Hay and McKay equation [4] (3) with Reindl's correction [5] (4).

*Hay and McKay equation*

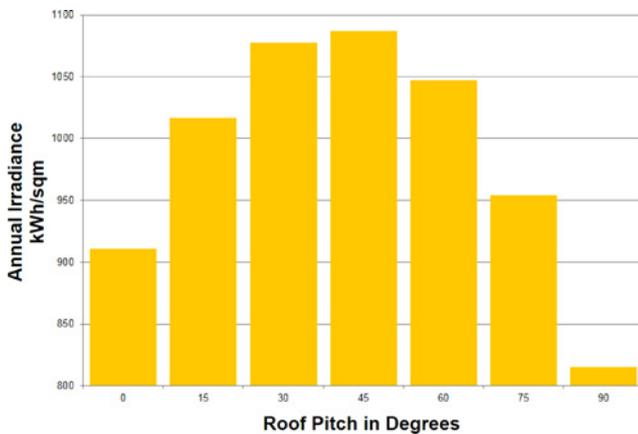
$$\begin{aligned} &\text{Diffuse tilt irradiation} \\ &= \text{Diffuse horizontal irradiation} * (1 - k) * (1 + \cos \beta) / 2 \quad (3) \end{aligned}$$

where  $k$  is the beam irradiation/extra-atmospheric irradiation (anisotropy index) and  $\beta$  is the inclination angle of the surface (degrees).

*Reindl's correction*

$$\begin{aligned} &\text{Diffuse tilt irradiation} \\ &= 1 + \sqrt{(\text{horizontal beam/global horizontal}) \sin(\beta/2)^3} \quad (4) \end{aligned}$$

Comparison against other methods and validation against Loughborough data has identified this combination of algorithms providing the most accurate reflection of reality for this location.



**Fig. 2** Influence of tilt on irradiation annual POA irradiation in Loughborough 2014 kWh/sqm compared with tilt angle (constant south-facing azimuth)

The Sun's path and peak daily elevation vary throughout the year. The optimum plane tilt/azimuth combination for PV represents a compromise which maximises overall annual performance. Fig. 3 illustrates that, for the Sutton Bonington weather station in 2014, a south-south-west (SSW) azimuth and tilt of 38° delivered the greatest possible annual irradiation harvest. Similar values are typical for the UK. Averaged over 10 years, south-facing panels with a 30°–40° tilt deliver the highest yearly output but this example focuses on a single year, slightly skewing the azimuth to SSW. Azimuth becomes less important as the tilt becomes shallower.

In domestic installations, there is often no choice in terms of azimuth as this is determined by the roof structure. This results in a difference in the timing of the energy generation. West-facing PV panels see more energy than south-facing ones in the evening because they are positioned towards the sunset thus Lambertian losses are lower. Fig. 4 demonstrates a representative example. If these are combined with an east-facing system on the other side of the house, maximum output meets maximum demand during the morning and evening peaks when the population rises and returns from work. Thus although total performance is reduced, electricity is generated when it is used and stress on the National Grid is limited.

The situation is similar with tilt angles. Although increasing the tilt beyond its optimum value of ~30°–40° reduces annual yield, steeper tilts favour energy production in the winter months when UK energy demand is greatest (Fig. 5).

The effects of system azimuth are complex in the context of optimisation of energy harvest and the mitigation of supply and demand mismatch. For these reasons, it is essential to be able to acquire information on roof characteristics. A new method to identify these is presented here based on publically available data. This will be essential for assessing domestic systems (or building added/integrated systems in general) and their effects on the infrastructure.

## 2 Background to topic

However, automated extraction of 3D urban features is a challenging problem. It has been intensively studied and further work is still ongoing. National Renewable Energy Laboratory [6] review 35 studies and 6 patents in order to define 3 categories of roof potential estimation methods: manual selection, constant value and geographic information system (GIS) based. The manual selection methods were found to produce detailed results but were labour-intensive. The constant value methods were quick. On the other hand, these did not reproduce local characteristics. GIS-based methods supplied detailed maps and may be automated.

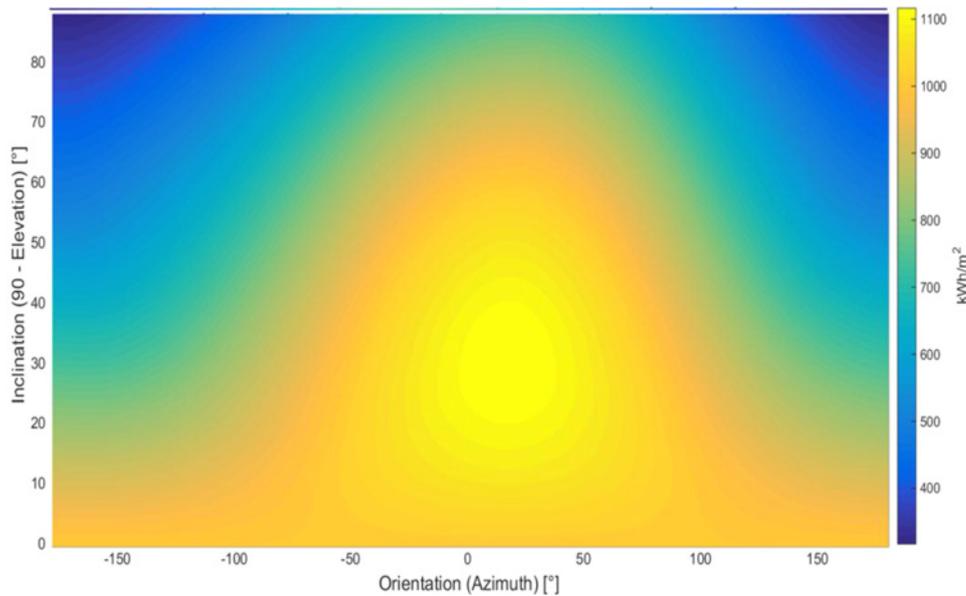


Fig. 3 Sutton Bonington: 2014 annual irradiation (colour) for tilt ( $y$ ) and azimuth in degrees west of south ( $x$ ) pairings

They require either orthophotography or LiDAR data as input for their models.

LiDAR is now widely accepted as an economical technique for obtaining high resolution feature height data across sizeable areas. LiDAR is attainable at various resolutions for most of the UK. In this paper, a GIS-based method is employed to accurately obtain roof tilts and azimuths from LiDAR data. A test case for a single UK city (Plymouth) is presented here to show the potential of this method. This is then scaled-up to the entire country using a constant value method.

There is no single GIS-based method of rooftop analysis which outperforms the others when speed, detail and user-friendliness are all taken into consideration. The basis of all the GIS-based methodologies is the separation of the roof into planes. These methods are complex, require very high resolution LiDAR and are computationally intensive. Additionally, most have been trialled over fairly small areas (e.g. 4 km<sup>2</sup>) and often require visual inspection as part of the input parameterisation process. Visual inspection for parameter determination is not possible in large scale (nation-wide) applications. Therefore, this research employs a simpler technique, which is applied to an entire city and, other than verification, does not demand manual intervention.

Rönholm *et al.* [7] utilise a method based on Canny edge detection to identify roof ridges in a test site in Finland. This algorithm marks local maxima in the LiDAR as edges and

discards all pixels not in line to give a thin ridge. Another roof segmentation formula is the Douglas Peucker line simplification algorithm (1973), which has been used on test sites in Germany [8]. This procedure removes redundant points to 'smooth' the ridge line within a given tolerance. Other line fitting techniques, e.g. Hough transform and random sample consensus, generally used in image analysis, have also been applied to LiDAR data.

In this research, roof tilt (termed slope in GIS) and azimuth (termed aspect in GIS) are calculated by weighted least squares fit of a plane to a 3 × 3 neighbourhood centred on each LiDAR point, as recommended in best practice for this type of analysis [6]. This slope computation is used by most GIS software but it is more usual to find it determining slope of large terrain features such as hills, rather than looking at relatively small buildings. Details of the technique are shown in Fig. 6.

The constant-value method of rooftop-feature estimation used by this research estimation applies a multiplier to the whole region (entire UK), in common with similar techniques. That is it applies a simple multiplier to a UK administrative zone statistic, in this case population and house classification. Ladner-Garcia and O'Neill-Carrillo [9] apply a constant value to the total number of buildings per census area. Lehmann and Peter [10] correlate rooftop area with population density.

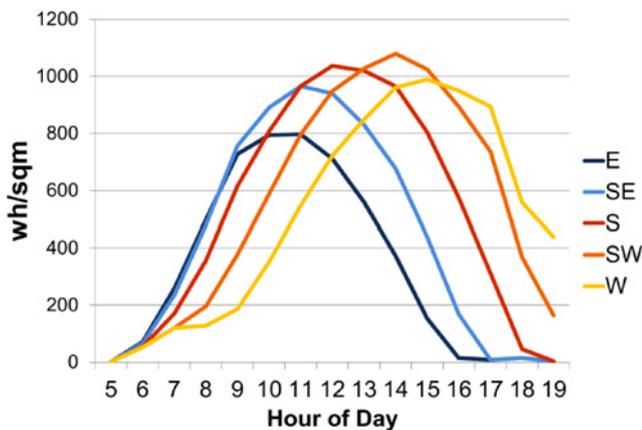


Fig. 4 POA irradiation in Loughborough 3 May 2014 (30° tilt) for five azimuths

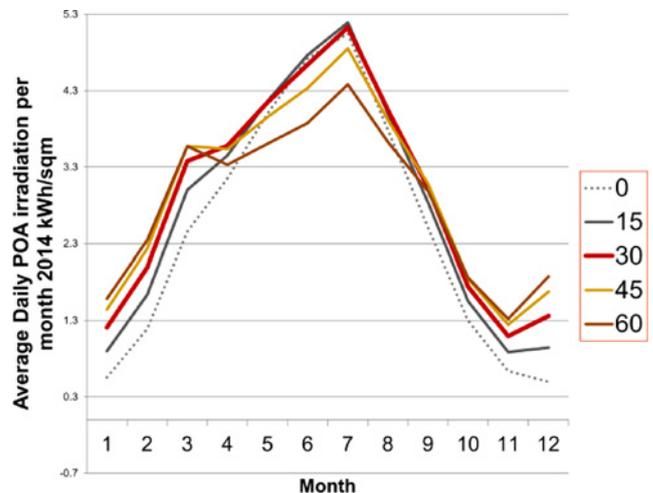


Fig. 5 Annual POA irradiation in Loughborough 2014 (south-facing) for five tilt angles

A	B	C
D	E	F
G	H	I

Let E be the cell for which to calculate Tilt:

$$\frac{dz}{dx} = \frac{((A + 2D + G) - (C + 2F + I))}{8w_{\text{cell}}}$$

Where  $w_{\text{cell}}$  is the width of an individual pixel

$$\frac{dz}{dy} = \frac{((A + 2B + C) - (G + 2H + I))}{8h_{\text{cell}}}$$

Where  $h_{\text{cell}}$  is the height of an individual pixel

$$\text{Slope}_{\text{degrees}} = \tan^{-1} \left( \sqrt{\left( \left[ \frac{dz}{dx} \right]^2 + \left[ \frac{dz}{dy} \right]^2 \right)} \right) * 57.3$$

$$\text{Azimuth} = \text{atan2} \left( \frac{dz}{dy}, -\frac{dz}{dx} \right) * 57.3$$

Fig. 6 Tilt and azimuth calculations

### 3 Data

LiDAR data is available at no cost for non-commercial use from the UK Environment Agency [11]. 2 m resolution coverage is extensive, but not total, for England and Wales. Only small areas of Scotland have been captured. Hence, some form of scale-up is necessary, even at this low resolution. 1 m data is missing for Scotland, much of Wales, Pennines, Yorkshire and Lincolnshire, whilst 50 and 25 cm data only exist for high flood risk areas. This research has focussed on establishing what may be achieved with the more wide-ranging 2 and 1 m data.

Three case study areas are used. Individual residences in the commuting area around Loughborough supply the results to verify the tilt and azimuth calculations, as do individual public buildings in Bodmin. The roof tilt of every building in Plymouth was ascertained for the country-wide scale-up operation.

### 4 Slope/tilt and aspect/azimuth method

The Environment Agency supply LiDAR data in the form of rasters, i.e. arrays of numbers which represent height. There are two coverages for each area: the digital terrain model (DTM) or 'bare-earth model' of elevation and the digital surface model (DSM) which is elevation plus surface features such as trees and buildings. So, it may be seen that the data is already partly prepared. It is only necessary to subtract the DTM from the DSM in order to obtain building height above ground level.

Once the building height raster has been prepared, building footprints from MasterMap [12] are used to cut out points on roofs. This avoids the need for building detection and extraction. Even though these LiDAR points are positioned within known building outlines, problems with the data may still arise. The building heights span -14 to 64 m for Loughborough. Mapping the points revealed that the 64 m elevation is correct because it represents features on top of the University's Towers Hall, one of the tallest structures in the area. On the other hand, negative and low values are obviously incorrect. These are not actual building features but are artefacts of signal scattering from basements, patios, window ledges and so on. Two methods of elimination described in the literature were tried. First, 'rogue points' were removed by creating a 1 m internal buffer of the building outline and classifying all points within the buffer as suspect [13]. This resulted in tilts on test buildings of up to 6° lower than reality, so an alternative method of applying a threshold value as described by [14] was tried. Different

thresholds are more appropriate across various countries as building stock changes with culture and climate. For the UK, a minimum roof height cut-off of 2 m (to allow for low eaves on bungalows) was found to give accurate results.

Having created an appropriate roof point height map, the slope and aspect algorithms may be run. The result is a tilt and azimuth for every 1 m<sup>2</sup> pixel within each building outline. These are averaged to give the mean value for each building (tilt) or each roof plane (azimuth). The entire building average is taken for the tilt because sub-dividing small buildings gives inaccurate results due to lack of data points. However, in the case of the azimuth, the data is binned (N, NE, E, SE, S, SW, W and NW) which causes less problem with few data points. Therefore, roof segmentation and potential solar panel size may be obtained from azimuth plane. Of course, roof tilts may vary both due to measurement inaccuracies and real physical structures such as dormers, but the majority of pixels will have values in the same range. Roof ridges and dormers account for between 1% (large public buildings) and 10% (small family homes) of pixels.

### 5 Scale-up method

Expanding tilt/azimuth results from a single city to countrywide extent involves finding the average for administrative zones within that city and their relationship to an administrative statistic, the 'multiplier', e.g. population, which is known for every area of the UK. It was decided to choose lower super output areas (LSOAs) – zones of 400–1200 households – as the administrative unit because these are extensively used for economic and socio-demographic data. Experiments were carried out with several multipliers in order to discover which is most precise.

The following values were calculated for Plymouth:

- (i) Average roof tilt per LSOA. (This is the actual value against which estimations are checked).
- (ii) The net average tilt of a roof in Plymouth divided by the average number of buildings per LSOA. This is multiplied by the actual number of buildings per LSOA to learn how well building number works as a multiplier where tilt is not known.
- (iii) The tilt per square metre of roof in Plymouth to be multiplied by building area per LSOA.

Next, buildings were categorised to investigate if accuracy could be improved. The age and class categories from Landmap Features Earth Observation Collection [15] were obtained for all buildings in Plymouth. The average tilt for each of the 7 age categories in this dataset for Plymouth as a whole was reckoned, e.g. sixties 26.9°. Next, the average tilt for each of the 19 class categories was figured, e.g. Very Tall Flats 11°. Finally, an age/class combination was computed as an average for the entire city, e.g. Victorian Terrace 34.24°. The 7 age and 19 class categories in the Landmap collection give a maximum of 133 well-defined categories. These average tilts can then be multiplied by the number of buildings in each category to estimate roof tilt where no LiDAR data exists.

Unfortunately, Landmap data is limited to the larger metropolitan areas, so for the purposes of this paper, a map of roof tilt was produced for England and Wales using an ONS dataset [16]. This has fewer house type classes which necessitates matching the Landmap classes to them as closely as possible.

The final step in the scale-up task is to analyse the roof data with an alternative boundary size to discover whether any systematic inaccuracies are occurring. This is a frequent problem when geographic data is grouped into units for analysis. Postcode districts were selected for this purpose.

### 6 Results and discussion

#### 6.1 Individual building's roof tilt

Initially, the roof tilt of individual buildings calculated from GIS weighted least squares fit were compared with values from a

**Table 1** GIS-derived weighted least squares fit mean roof tilt in degrees compared with measured tilts on nine buildings using 2 and 1 m LiDAR

Bldg	Tilt method	Accuracy of method	Tilt measure	GIS – 2 m LiDAR	2 m diff.	2 m % diff.	GIS – 1 m LiDAR	1 m diff.	1 m % diff.
1	inclinometer	±0.1°	29.9	30.0	-0.1	-0.3	No Data	N/A	N/A
2	photo trigonometry	±2°	44.0	36.0	8.0	18.2	40.3	3.7	8.4
3	PV install	±7°	28.1	27.0	1.1	3.9	28.3	-0.2	-0.7
4	PV install	±7°	25.0	25.0	0.0	0.0	30.0	-5.0	-20.0
5	PV install	±7°	33.0	23.0	10.0	30.3	32.5	0.5	1.5
6	trigonometry	±1°	33.0	29.0	4.0	12.1	29.0	4.0	12.1
7	trigonometry	±1°	45.0	32.0	13.0	28.9	38.0	7.0	15.6
8	trigonometry	±1°	25.8	27.0	-1.2	-4.7	24.1	1.7	6.6
9	trigonometry	±1°	32.7	30.0	2.7	8.3	30.1	2.6	8.0
	average		32.9	28.8	4.2	10.7	31.5	1.5	3.4
	standard deviation		6.8	3.6			5.0		
	mean absolute error				5.0			3.1	

variety of sources in order to establish the accuracy of this technique. The results from large public buildings were very encouraging. For instance, the GIS method produced a mean roof tilt of 26° for the Radial Building in Bodmin, when the architect's plans suggest a value of 26.5°. Unfortunately, values for smaller homes and student residences did not quite match this, as shown in Table 1.

Table 1 compares the calculated roof tilt to roof tilts obtained from colleagues' homes using a range of methods compared with the GIS least squares slope calculation method at resolutions of 1 and 2 m. Measurement by inclinometer is arguably the most accurate way of acquiring roof tilt data, when a quality instrument is operated by an experienced person. Trigonometry from counting the bricks in the gable can also be precise. On the other hand, trigonometry of photographs has inexactness due to oblique camera angle or tiny mismeasurements (e.g. 1 mm) resulting in large variability. The tilts quoted by PV installers are variable. They may be precise or erroneous, depending on the company and operative. Details of the buildings in Table 1 are as follows. Bldg 1 is a two-storey semi-detached house and roof tilt was obtained by solatronic inclinometer. Bldg 2 is a three-storey student hall. Tilt was calculated from rise/run measurements from a wall-end photograph. Bldgs 3–5 (semi, terrace, semi) have solar panels and the tilts are provided by the installer. Bldgs 6–9 comprise one detached two-storey house, one semi two-storey house and two bungalows. In each case, roof tilt was calculated by measurement of the apex.

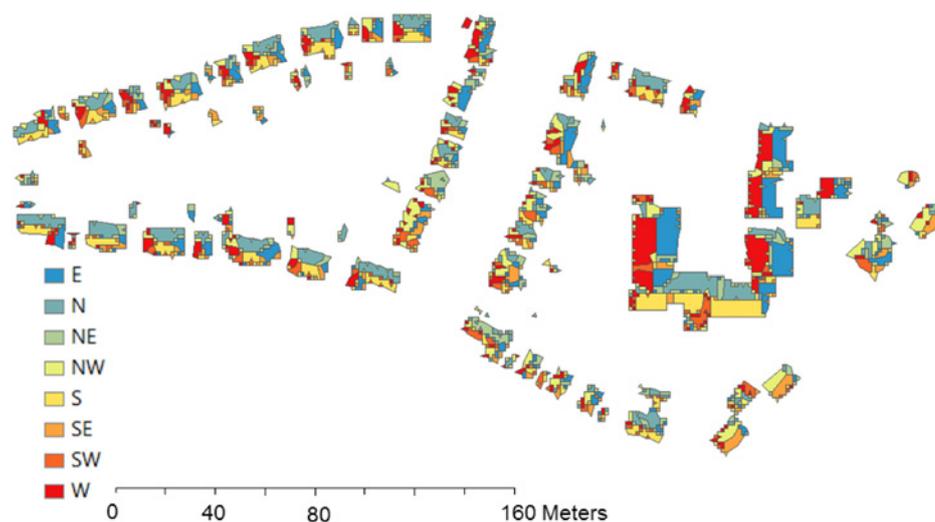
These results indicate that a LiDAR resolution of at least 1 m is necessary for reliable roof tilt estimates. Validation of roof tilt is known to be difficult, due to a lack of data and that fact that all

the methods of measuring it have their own inherent imprecision. For this reason, the GIS technique was further checked by matching the tilts from houses of the same type in the same street. For instance, a cul-de-sac of semi-detached bungalows and sets of detached houses were investigated. In theory, each home should have an identical tilt to that of its neighbour but actually for 1 m LiDAR, homogeneous houses vary by ~3°. This observation is probably due to actual small variations between buildings built to the same specification, rather than inaccuracies in the LiDAR. This fits well with the differences noted in Table 1.

Table 1 also appears to demonstrate less agreement between measurements and LIDAR derived tilt angles when the tilt angle is larger (i.e. Bldgs 2, 5, 6 and 7). This phenomenon is probably due to small buildings containing proportionately more LiDAR measurements relating to the flat roof ridge than larger structures. For instance, the larger student hall (Bldg 2) differs 3.7° from the measured tilt of 44° whereas Bldg 7 (a family home) differs 7° from the measured tilt of 45° (1 m LiDAR).

## 6.2 Individual buildings azimuth

In contrast to the results achieved for the roof tilt calculation, the azimuth diagrams generated were excellent (Fig. 7). The calculated azimuths were validated against compass measurements taken on ten individual houses. In addition, over one hundred buildings on Loughborough University campus were checked against map direction in Google Earth. These range from small warden's houses to large office blocks and sports facilities (Fig. 8). Azimuth

**Fig. 7** Roof azimuth panes of community centre and homes, Loughborough

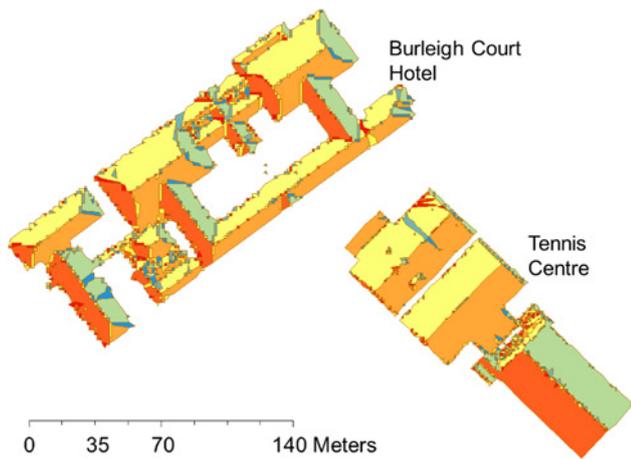


Fig. 8 Roof azimuth panes, Loughborough University

of major sloping roof panes (for instance of about 20 m<sup>2</sup> in size) was effectively 100% accurate within a given compass octant. This result may be explained by the fact that averaging is being employed. All points falling on the roof pane (e.g. 20 LiDAR points on an average house roof face) are each allocated at azimuth estimation in degrees (0–360). The azimuth values are reclassified into eight bins of 45° which reflect the points of the compass (N, NE, E, SE, S, SW, W and NW). Thus the azimuth of a whole roof face comprises an average of, e.g. 20 points and each point is rounded to the nearest 45°. More compass bins could be tried but each would contain fewer points and detract from the statistical robustness of the results. Eight bins represent a compromise between the influence of azimuth on energy yield and the low number of LiDAR points which fall inside the boundary of a typical home. The high accuracy of the azimuth algorithm is helpful because this characteristic has the greatest influence on PV yield.

Smaller roof panes, for instance extensions or porches of 7 m<sup>2</sup> or less were not detected using this technique, due to the LiDAR scale (1 m). Fig. 9 illustrates the inconsistencies which may occur, caused by scale and LiDAR angle of incidence. On this house, the major east and west roof faces are easily visible. The north-facing front porch is detectable, although smaller than in reality since it extends the full width of the building. However, the rear extension is confused with the main roof azimuths and is difficult to discern. Then again, these housing features are unsuitable for PV installation and these inaccuracies are irrelevant for the intended use.

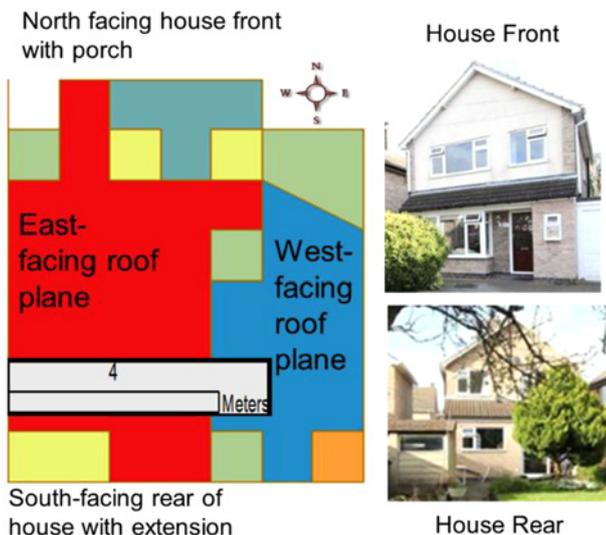


Fig. 9 House with minor roof panes (front porch and rear extension)

Table 2 Comparison of GIS-derived average roof tilt per LSOA for 162 areas in Plymouth to that calculated from multipliers

Multiplier	Average difference in degrees from GIS tilt calculation	Range of differences in degrees from GIS tilt calculation
building age	0.45	–3.85 to 8.32
building type (e.g. semi)	0.85	–4.63 to 9.57
age and type	0.39	–3.6 to 8.25

### 6.3 Regional variations

There are clear differences in roof tilt and azimuth of buildings between the case study areas. In Loughborough, the most frequently occurring roof tilt is 30°. There are also many buildings with flat roofs, owing to the presence of the University, business parks and industrial units. In Plymouth, the modal average for roof tilt is 32°. This suggests that, in general, roofs tend to be steeper in Plymouth than in Loughborough. This may possibly be linked to the different age mix of housing in the two towns, influenced by historical events. In Plymouth, 37% of houses are from the 1945 to 1964 post-war regeneration era (Landmap data). Roof tilts were still relatively steep during this period because interlocking concrete tiles were not introduced until about 1960 [17]. Loughborough has many estates dating from the 60's and 70's and later, following completion of Midlands section of the M1 in 1968.

In Loughborough, a major portion of the buildings tend to face NE/SW or NW/SE. The A512 road which joins the town to the M1 motorway has an obvious impact on housing azimuth. A significant portion of Plymouth buildings are oriented N/S or E/W, probably influenced by the coast and River Tamar. These findings are in contrast to those of Jacques *et al.* (2014) [18] who applied roof segmentation algorithms in Leeds. This group found small buildings could face any azimuth, although large buildings did display a preference for southerly azimuth. They concluded building azimuth was not controlled by the location of roads or rivers. However, Leeds is yet a different area and the disparity in housing types across the UK's regions is documented by the English Housing Survey [19].

### 6.4 Scaled-up values

Once reasonable individual roof tilts were achieved, the agreement between GIS-calculated average roof tilt per administrative area (LSOA) and scaled-up tilt was investigated. Attempts to scale-up



Fig. 10 Roof tilt per LSOA – England and Wales (pale = shallow, dark = steep)

using number of houses and building area resulted in unacceptable values. More complex multipliers correspond much more closely to reality (Table 2).

Age performs better than type, but age and type in combination is preferable. At this time, though, lack of data necessitated creating a national map using Type only with an accuracy of  $\pm 2.22^\circ$  (Fig. 10). (Accuracy calculated by comparing the difference between LiDAR-derived average tilt per LSOA and tilt per LSOA produced by scaling tilt per building type by number of buildings of that type). All multipliers are twice as likely to under-estimate roof tilt than over-estimate it. This is probably caused by roof ridge pixels with a tilt of zero currently being included in the calculation. No relationship was found between steepness of tilt and size of error. The average roof tilt was  $28.47^\circ$  for the 162 LSOAs and  $28.46^\circ$  for 90 postcode districts in Plymouth. Thus there is little difference depending on area of analysis.

## 7 Conclusion

Information about roof characteristics is a basic requisite of roof-mounted PV modelling. This paper presents a method for determining tilt, azimuth and roof pane size. It utilises medium resolution LiDAR, accurate building outlines and socio-economic data which are free for educational use in the UK, based on recommendations of previous literature. Therefore, this procedure is economical. The steps involved are well-documented and relatively simple. This method is efficient and computationally feasible, capable of being fully automated to produce nationwide coverage. A mean bias of  $\pm 1.5^\circ$  (circa 3%) and a mean absolute error of  $3^\circ$  on roof tilt were realised, together with an accuracy of 100% performance on major roof pane azimuth within the chosen compass octant. Fig. 2 illustrated that irradiation values increase by 15% between  $0^\circ$  and  $45^\circ$  tilt. It may be observed that this trend is not constant, rising steeply at first, then more gradually. Irradiation increases by 0.7% between  $0^\circ$  and  $15^\circ$  tilt, by 0.4% between  $15^\circ$  and  $30^\circ$  tilt and by 0.1% between  $30^\circ$  and  $45^\circ$  tilt. Therefore, the  $\pm 1.5^\circ$  roof tilt accuracy achieved by this research will deliver an irradiation prediction error of between 2 and 0.1% for roof tilts between  $0^\circ$  and  $45^\circ$ . Domestic properties have steeper roofs, so irradiation may be predicted for these with very high accuracy.

Long-term, a statistical method will be worked out to draw improved accuracy from accessible data.

With increasing penetration of PV, accurate knowledge of output is required in order to model the impact on the grid. More grid-connected PV systems are being inserted into the UK residential low voltage distribution network. With falling manufacturing costs and competition, systems are no longer being placed solely at optimal tilt and south-facing. Recognising that tilt, and in particular azimuth, affect electrical performance, this paper achieves improved modelling accuracy by providing a method for the algorithmic extraction of these parameters for buildings nationwide with freely accessible data. For domestic PV installations, roof tilt and azimuth are dictated by the building type and location, which is in turn influenced by region of the country.

Variations in roof tilt influence energy production from season to season, whereas a range of azimuths causes energy output to peak at different times during the day. Consequently, it is essential to have good knowledge of roof characteristics in order to identify where problems (if any) may arise in the National Grid and where mitigation measures may be necessary. This research describes how the required roof characteristics may be obtained together with expected percentage errors.

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