Investigating the Impact of Ground Albedo on the Performance of PV Systems

Y. Kotak BEng, MSc*, **M. S. Gul** BEng, PhD*, **T. Muneer** PhD, DSc**,

S.M. Ivanova PhD***

* Heriot-Watt University, Edinburgh,UK (yk78@hw.ac.uk, M.Gul@hw.ac.uk)

** Edinburgh Napier University, Edinburgh , UK (T.Muneer@Napier.ac.uk)

*** University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria (solaria@online.bg)

Abstract

Several factors influence the energy generation of Photovoltaic (PV) installations. A ground albedo value of 0.2 is widely accepted and is used in modelling of PV systems. Foreground surfaces may have different albedo and hence a constant albedo value is unsuitable. This paper analysed a real PV facade of a university building. The results show, that in the present case, using a constant albedo value may underestimate the incident ground reflected radiation by 31%. A discussion is also provided on applying white cool paint on foreground surfaces to further increase the receipt of reflected-radiation on PV modules.

Keywords: PV facades, Ground albedo, Ground reflectance, radiation exchange.

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1. Introduction

Currently, the majority of the world's electricity is obtained from fossil fuels such as coal, oil or natural gas. These traditional energy sources bring their own challenges such as depletion of fossil fuels, rising energy prices and growing environmental concerns over the climate change risks associated with power generation. As a result, there is a need to move towards potential alternative renewable energy sources such as solar, biomass, geothermal, hydroelectric and wind (1,2). Solar Photovoltaic (PV) technology is emerging as one of the most rapidly growing renewable sources of electricity (1). The key benefits of installing a solar PV system include the reduction or even complete removal of the purchase of electricity from the electricity provider, reduction in CO_2 emissions helping to tackle climate change, and the added advantage of Feed-in-Tariff. One of the main challenges facing developers during the planning and design of solar PV plants is the lack of accurate spatial and temporal solar resource assessment which impacts the power generation capacity. Several factors such as the type of PV modules, ground albedo (ground reflectance), and building azimuth influence the output of PV implementations.

The total incident radiation on a surface such as a PV panel (vertical or inclined) is the sum of beam, sky-diffuse and ground reflected radiation from various surfaces. On an average, Earth naturally reflects 8% of total solar radiation received from sun (3). Ground albedo or ground reflectance is defined as the ratio between the ground-reflected radiation and the global radiation incident on the ground (4). The ground-reflected component may be significant particularly in the northern latitudes owing to low elevations of the sun and, at times, the presence of highly reflecting snow cover (5). A surface that absorbs all the energy it receives (black surface) has an albedo of 0, whereas a perfect reflector (white surface) has an albedo of 1. The usual approach is to assume a constant value of ground reflectance of 0.2 for temperate and humid tropical localities and 0.5 for dry tropical localities (6). This is despite the fact that the reflectivity of snow-covered ground could be as high as 0.9.

A solar module mounted on an inclined roof can face different ground surfaces such as grass, road made from tar other buildings and snow cover. e. A good estimate of albedo of the surrounding terrain is therefore a pre-requisite for determining the radiation balance of a PV system (5). This study focuses on analyzing the impact of

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varying albedo values on the total incident radiation on PV modules against a constant albedo value of 0.2, proposed by Liu and Jordan (7). This will help to understand the performance of PV modules in terms of whether the output of PV modules increase or decrease.

2. Background Research

2.1 United Kingdom (UK) PV status

According to analysis of NPD Solarbuzz on August 2014 (8), the UK PV installed cumulative capacity has reached up to 5 GW. According to forecast, it is expected that UK will be at fourth position globally by installing 2.5 - 2.9 GW of new solar PV projects in 2014 (9).

At present in the UK, there are four main facilities for electricity generation from solar PV, (a) Domestic: Domestic sector is reliable and well established method of generating electricity. A typical system can be as large as 4kW, (b) Building mounted: Building mounted contains the range of commercial and non-domestic properties, which is between 4kW to 5MW and (c) Ground mounted: Ground mounted facilities are different from building mounted because it mostly supplies electricity to grid and (d) Building Integrated Photovoltaics (BIPV): BIPV generates electricity and functions as a part of the building (10). Figure 1, details the split of UK's cumulative installed solar PV capacity of 5GW.

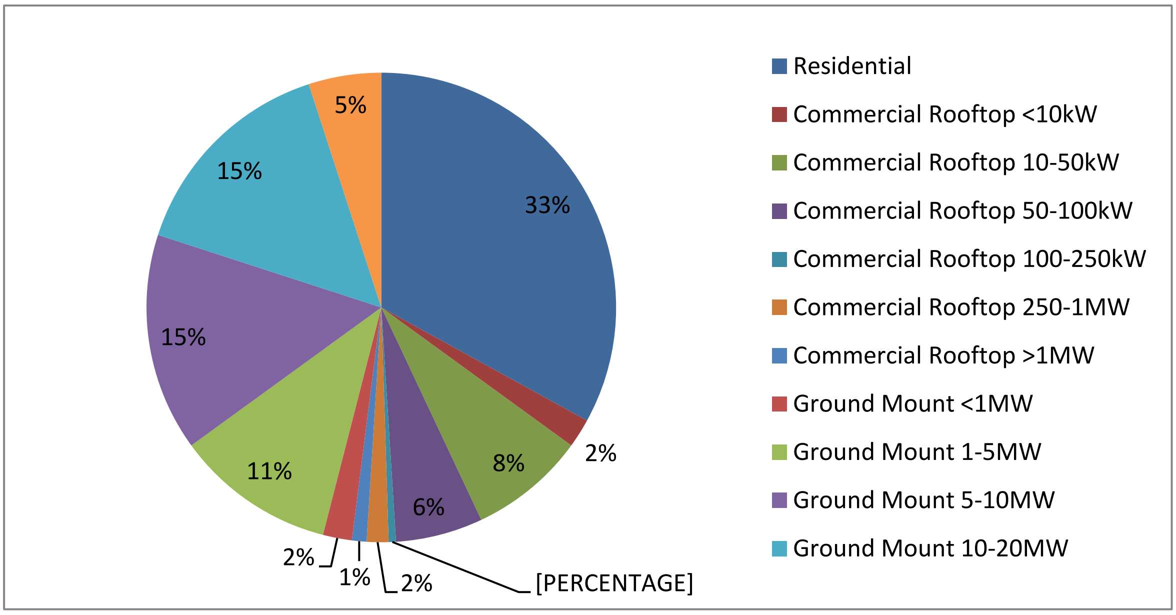

Figure 1 - Categorization of UK's 5GW Solar PV capacity

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2.2 PV System and albedo

The optimal performance of PV system relies upon the appropriate selection of location for the installation with a thorough understanding of electrical and environmental factors. The accurate knowledge of the radiation components incident on PV module (i.e. direct beam, diffuse and ground reflected) is essential for installation of solar PV systems (11). The work of Kambezidis et al (12), Notton et al (13), Muneer (14), Perez et al (15), Psiloglou et al (16), Skartveit and Olseth (17), and Reindl et al (18) may be cited with reference to assessment of ground-reflected radiation, which may in some locations reach up to 100W/m^2 (19). Research done by Liu and Jordan (7) proposed a constant albedo value of 0.2. However, data presented for 27 US and 7 Canadian location by Solmet (20) and Iqbal (21) proved a very strong seasonal dependence. Similarly, Ineichen measured the actual ground reflected radiation and compared with the Liu and Jordan value of 0.2 for Geneva and concluded that the constant value 0.2 is too high and should be abandoned (22). Further, Ineichen, Guisan & Perez, have also claimed the constant value to be unsatisfactory and unrealistic (19). Based on these arguments one may say that the accurate consideration of the ground albedo in contemporary solar energy applications is valuable. Conversely, accurate estimation of ground-reflected radiation would require good knowledge of foreground type (23). This concept was proposed by Davis and Idso (24), Oke (25) and Campbell and Norman (26), who reviewed different ground surfaces' albedo values and observed that, oceans, lakes, and forests have small fraction of reflectivity of incident sunlight and have low albedo whilst snow, sea ice, and deserts reflect higher fractions of the incident radiation. Table 1, provides albedo values for different materials which may be taken into account for PV system calculations. Further, tabulated albedo data for various ground surfaces is mentioned in Army Research Laboratory Report (27) and albedo for Europe locations are included in the European Solar Radiation Atlas (28, 29).

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Table 1 - Typical albedo values of different kind of surfaces (3)

Surface	Albedo
Corrugated roof	0.1 - 0.15
Colored paint	0.15 - 0.35
Trees	0.15 - 0.18
Asphalt	0.05 - 0.2
Concrete	0.25 - 0.7
Grass	0.25 - 0.3
Ice	0.3 - 0.5
Red/Brown roof tiles	0.1 - 0.35
Brick/Stone	0.2 - 0.4
Oceans	0.05 - 0.1
Old snow	0.65 - 0.81
White paint	0.5 - 0.9
Fresh Snow	0.81 - 0.88

2.3 Radiation Exchange

This section describes the radiation exchange between two surfaces i.e. which in this case will be the ground surface and a PV module.

2.3.1 Black body radiation

According to thermodynamics, the net radiant exchange between two surfaces will be proportional to the difference in absolute temperatures to the fourth power,

$$\frac{qnet\ exchange}{A} = \sigma({T_1}^4 - {T_2}^4) \qquad \text{Eq. 1}$$

Similarly, the energy exchange between two black surfaces A_1 and A_2, each maintained at different temperatures can be solved by equation 2, which is known as radiant shape factor. Other names of radiant shape factor are view factor, angle factor, and configuration factor.

$$Q_{1\text{-}2} = A_1\ F_{12}\ (E_{b1} - E_{b2)} = A_2\ F_{21}\ (E_{b1} - E_{b2}) \qquad \text{Eq. 2}$$

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Equation 2, is known as reciprocity relation as well and it can be generalised for any two surfaces m and n, forming equation 3.

$A_m F_{mn} = A_n F_{nm}$ Eq. 3

The cases, which find ready application with respect to building services, are surfaces that are perpendicular to each other and surfaces that are not perpendicular to each other (tilted), rather, they are separated by any given angle ϕ that may or may not be 90 degrees.

(a) Perpendicular surfaces

To measure the radiation exchanged between two perpendicular surfaces (A_1 and A_2) which share a common edge as shown in Figure 2, Siegel and Howell (30) proposed the configuration factor solution as equation 4.

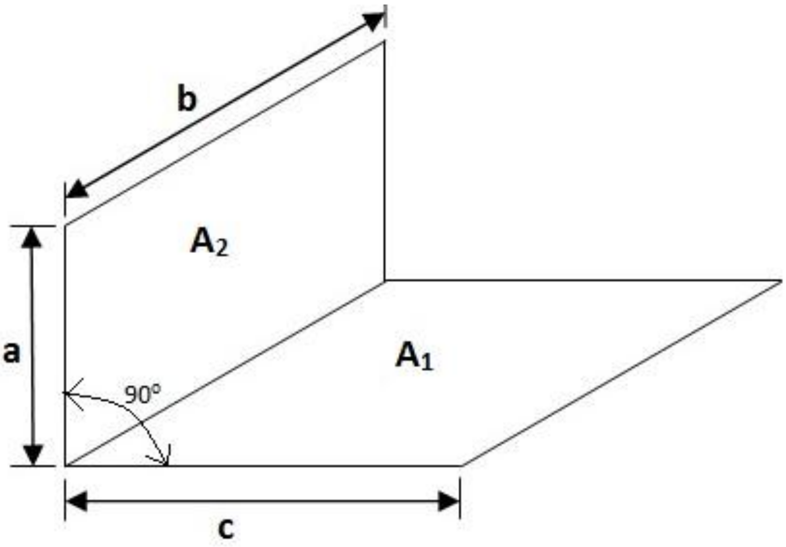

Figure 2 - Radiation exchange between two perpendicular surface sharing common edges

$$F_{1-2} = \frac{1}{\pi L}\left(\begin{array}{l} L\tan^{-1}\left(\frac{1}{L}\right) + N\tan^{-1}\left(\frac{1}{N}\right) - \sqrt{N^2+L^2}\tan^{-1}\left(\frac{1}{\sqrt{N^2+L^2}}\right) \\ +\frac{1}{4}\left\{ \ln\left[\frac{(1+L^2)(1+N^2)}{1+L^2+N^2}\right] + L^2\ln\left[\frac{L^2(1+N^2+L^2)}{(1+L^2)(1+N^2)}\right] + N^2\ln\left[\frac{N^2(1+N^2+L^2)}{(1+N^2)(N^2+L^2)}\right] \right\} \end{array} \right) \quad \text{Eq. 4}$$

where, N = c / b and L = a / b

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However, implementing this equation for solar PV systems, the major drawback noticed is, it is only applicable in the case where both surfaces i.e. ground horizon and PV module are perpendicular to each other and share a common edge, which is quite uncommon for solar PV's.

(b) Inclined/tilted surfaces

This is the most generalised case for solar PV systems, as most of the solar modules are inclined at some angle from the ground surface. Figure 3 shows two surfaces (A_1 and A_2) that are at an angle (ϕ) and equation 5 can provide the radiation exchange between these surfaces. Note that for any given situation the ground reflected radiation may emanate from a conglomeration of surfaces of disparate reflectivities such as grass (ρ=0.24), tarmac (ρ=0.15), soil (ρ=0.12-0.25), other roof tops (0.13), pebbles (ρ=0.14-0.56) or water bodies (ρ=0.05-0.2).

$$
\begin{aligned}
F_{1-2} = & -\frac{\sin 2\Phi}{4\pi B}\left[AB\sin\Phi + \left(\frac{\pi}{2}-\Phi\right)\left(A^2+B^2\right) + B^2\tan^{-1}\left(\frac{A-B\cos\Phi}{B\sin\Phi}\right) + A^2\tan^{-1}\left(\frac{B-A\cos\Phi}{A\sin\Phi}\right)\right] \\
& + \frac{\sin^2\Phi}{4\pi B}\left\{\left(\frac{2}{\sin^2\Phi}-1\right)\ln\left[\frac{(1+A^2)(1+B^2)}{1+C}\right] + B^2\ln\left[\frac{B^2(1+C)}{C(1+B^2)}\right] + A^2\ln\left[\frac{A^2(1+A^2)^{\cos 2\Phi}}{C(1+C)^{\cos 2\Phi}}\right]\right\} \\
& + \frac{1}{\pi}\tan^{-1}\left(\frac{1}{B}\right) + \frac{A}{\pi B}\tan^{-1}\left(\frac{1}{A}\right) - \frac{\sqrt{C}}{\pi B}\tan^{-1}\left(\frac{1}{\sqrt{C}}\right) \\
& + \frac{\sin\Phi\sin 2\Phi}{2\pi B}AD\left[\tan^{-1}\left(\frac{A\cos\Phi}{D}\right) + \tan^{-1}\left(\frac{B-A\cos\Phi}{D}\right)\right] \\
& + \frac{\cos\Phi}{\pi B}\int_0^B \sqrt{1+z^2\sin^2\Phi}\left[\tan^{-1}\left(\frac{z\cos\Phi}{\sqrt{1+z^2\sin^2\Phi}}\right) + \tan^{-1}\left(\frac{A-z\cos\Phi}{\sqrt{1+z^2\sin^2\Phi}}\right)\right]dz
\end{aligned}
\qquad \text{Eq. 5}
$$

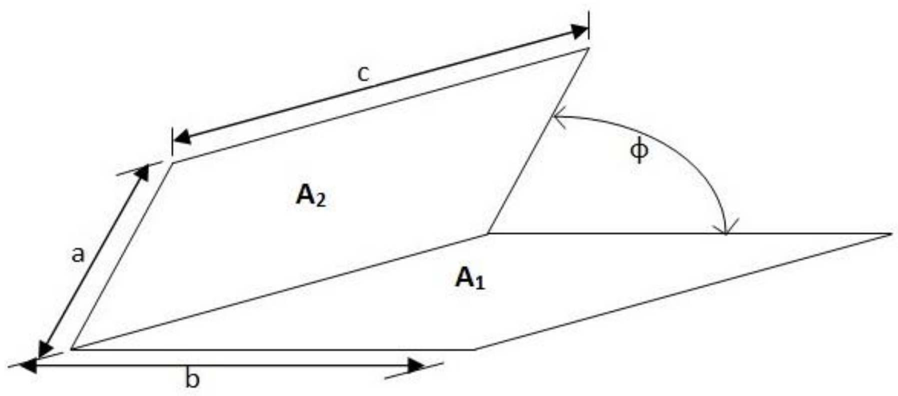

Figure 3 - Radiation exchange between two inclined surfaces

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However, the problem that persists here is that, the last part of the equation is unsolvable integral. In addition, both the surface should share a common edge, which is not always practically possible in the case of solar PV. Hence the only solution for realistic approach is to solve this equation by partial analytical and partial numerical.

3. Methodology

To understand the impact of reflectivity on a PV system, the numerical techniques presented in section 2.3.1 were tested with a real life case study. The case study in question is the major PV facade of Edinburgh Napier University's, Merchiston Campus building. Figure 4 presents the picture of the facade from the roadside (31).

Figure 4 - A street view of Edinburgh Napier University PV facade

Edinburgh Napier University has installed 32 rows of BP Solar silicon modules i.e. total 160 solar modules of 90W each, on a building wall in April 2005 (31). The tilt angle for the modules is 75^o from horizontal with an aspect of 37^o east of South. The building elevation is shown in Figure 5.

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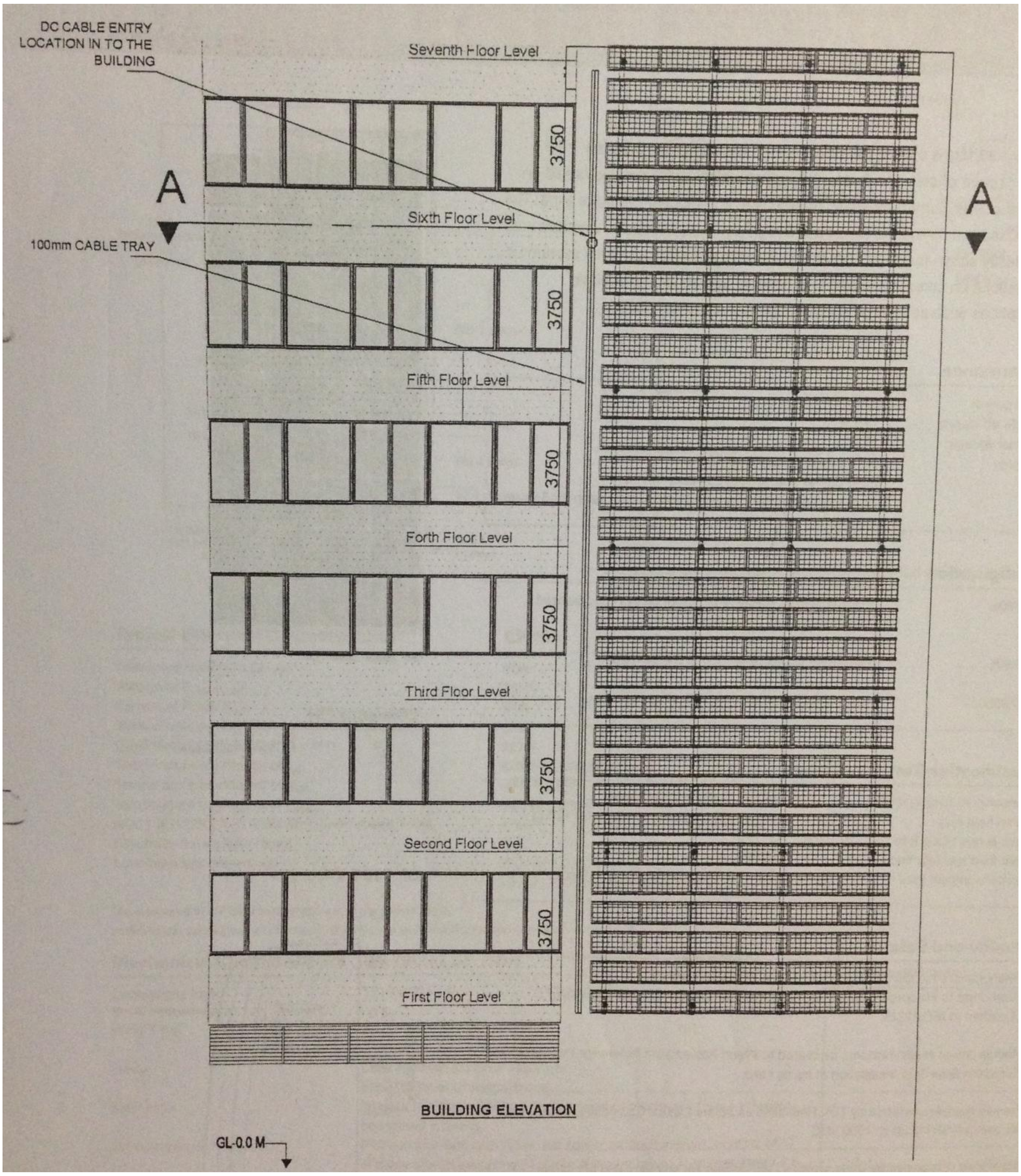

Figure 5 - PV facade elevation with relevant dimensions

Google earth software was used to analyze the impact of albedo on facade, and to include the various type of ground surfaces (road, grass, tree-tops and roof) (refer to Figure 6). This image was taken at an eye altitude of 250m. The selected land area i.e. horizon facing PV facade is 14,682m^2 of which the total roof area is 3766.3 m^2, road area is 3041.2 m^2. The total of grass and tree-top area is 7885.5 m^2.

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Figure 6 - Google earth map

Based on the Google earth image of ground, the complete horizon is transformed to block diagram as shown in Figure 7.

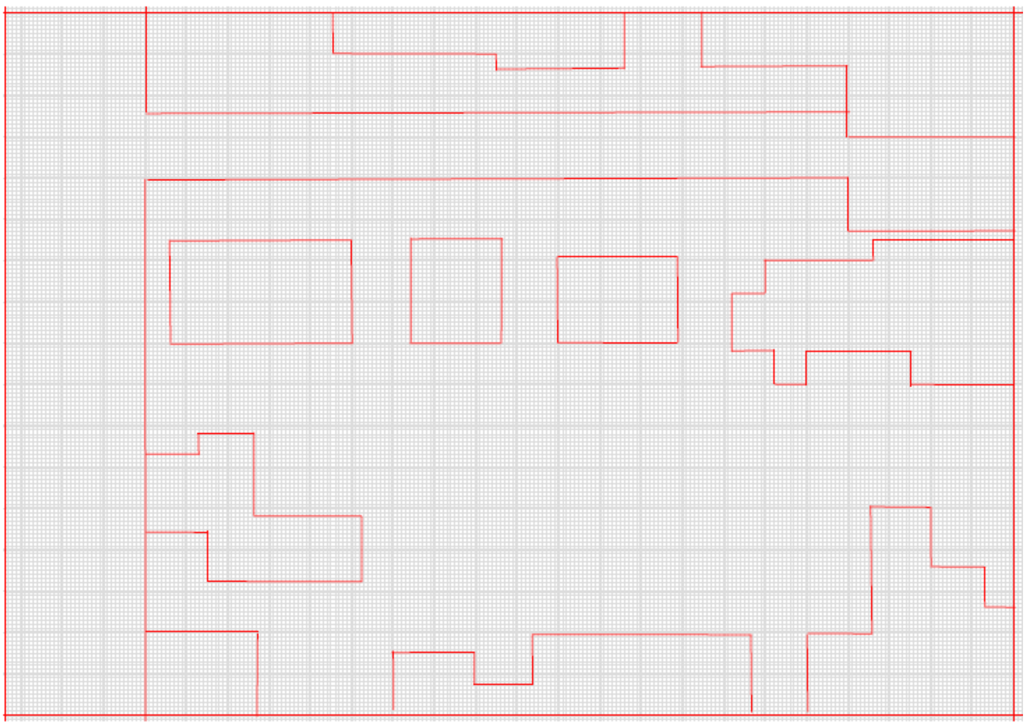

Figure 7 - Topographical sketch of the PV facade horizon

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As identified in section 2.3.1 (b) the last part of equation 5, is unsolvable. Furthermore, the horizon for the PV facade is composed of a number of surface patches, each having its own albedo value. Hence a numerical approach has presently been incorporated to obtain the amount of reflected-radiation from ground to PV facade. The VBA code was written within an MS-Excel environment. Figure 7 shows the relevant grid that is used for the above exercise with the value of reflectance presented in Table 1.

4. Results and discussion

Using the analysis presented in this article the ground-reflected radiation that is incident upon the PV modules is calculated. The horizontal irradiation is assumed as 800 W/m^2. The latter is the irradiation that is frequently experienced in Edinburgh on clear, summer days.

The usual approach, for a surface inclined at an angle β to the horizontal and for infinite horizontal foreground, the geometric view factor for radiation exchange between the foreground and the surface is $\sin^2(\beta/2)$. Liu and Jordan proposed Eq. 6, for daily reflected irradiation from ground,

$$g\beta = \rho G \sin^2(\beta/2) \qquad \text{Eq. 6}$$

G is daily global irradiation on horizontal surface, ρ is average albedo of foreground and gβ is daily reflected radiation on a sloping surface. Keeping ρ as a constant value of 0.2, G as 800 W/m^2 and considering the horizon from PV facade to have an area of 14682m^2, reflected-energy contribution from roof area, road area, grass and trees area near to PV facade, is calculated as 45.2W/m^2.

The present approach then uses the actual values of topography shown in Figure 7. In this case the average albedo values for trees and grass was taken as 0.24, asphalt road surface as 0.2 and red/brown roof tiles as 0.35, which results in a reflected-radiation value of 61.8W/m^2 (compared to the above-mentioned value of 45.2W/m^2 this is a gain of 37%).

The latter reflected-radiation component may be further enhanced by using emerging building materials that offer much higher reflectance. One example is the use of white cool paint with an average reflectivity (ρ) of 0.7.

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For this research it is assumed that all the roof-tops mentioned above are applied with this paint. Then maintaining the rest of the topographical detail the reflected-radiation component now increases to 92W/m^2, which is significantly higher than the classical estimate of 45.2W/m^2.

Taha et al (32) measured the surface temperature of various materials that are used in urban surfaces and their albedo value. The results showed that white elastomeric coatings have an albedo of 0.72 and was 45^{o}C cooler than black coatings. These cool coloured coating can be used on building roofs and walls and they can also be used to manufacture other cool-coloured building materials. Levinson et al (33) showed that cool painted tiles can also have high solar reflectance. Similarly, Simpson and McPherson (34) found that white roofs with an albedo of 0.75 were 20^{o}C cooler than grey and silver paints with respective albedo of 0.3 and 0.5. Lastly, Breg and Quinn (35) have also shown that white painted roads have albedo 0.55 while unpainted road were exhibited an albedo of 0.15. Such paints applied to surfaces in close visual proximity of the PV façade may thus be used effectively to enhance ground-reflected radiation.

By applying white paint to 25% of total ground area as mentioned above, the increased reflection will generate an excess 626kWh/annum of solar electricity. Considering the cost of electricity £0.12/kWh, this will provide an extra income of £75/annum. On the other hand the life-time cost of paint will be £393 which takes into account a coat of paint each five years (36). The cost of applying paint is recovered during the project life with a small profit of £454. Over the 20-year life of the PV plant the extra energy generated will be 12.5MWh.

5. Conclusion

A numerical procedure that disaggregates the estimation of ground-reflected radiation for any viewing surface is presented. This work is based on a tall PV façade that has been in operation in at Edinburgh Napier University for the past 10 years.

The present analysis showed that the constant albedo value (ρ=0.2) proposed by Liu and Jordan is unreliable and unsatisfactory. It does not provide the accurate results for radiation exchange. Comparing the results obtained from the constant albedo

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value and the actual topographical albedo values, there is a noteworthy gain of 31% for ground-reflected radiation.

The emerging building materials technology offers paints of high-reflectance. It was presently shown that in the current example in which 25% of the total ground surface area that is composed of roof-tops if painted white would increase the energy gain by 48%. The cost of applying paint is recovered during the project life with a small profit of £454. Over the 20-year life of the PV plant the extra energy generated will be 12.5MWh. Future work may be undertaken to explore the potential of application of such highly-reflective paints and/or building materials.

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