Optimised building integrated photovoltaic systems for utilisation on facades in the tropical climate
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Abstract— *Building integrated photovoltaic (BIPV) are becoming a viable solution for clean on-site energy production and utilisation to combat the existing energy crisis. In tropical climates, although rooftops are ideal for photovoltaic (PV) module integration, the available area may be insufficient to meet building energy demand due to the recent high-rise nature of urban buildings, causing a requirement for the utilisation of facades. However, the high angle of solar elevation means that facades are unfavourably oriented towards receiving incident solar irradiation. In addition, the issue exists of high solar heat gains into built spaces. This paper proposes a method to utilise horizontally inclined photovoltaic modules integrated on solar shading devices in order to combat these issues of unfavourable inclination and solar heat gains in commercial office buildings in Colombo, Sri Lanka. Various strategies are introduced and evaluated in terms of their inclination angles and the distance between installations. The results are analysed in terms of PV generation capabilities in order to determine which strategies are capable of producing the most electricity. The results show that horizontal inclinations of PV on facades are capable of generating nearly 8% more electricity as a percentage of the building energy consumption when compared with traditional vertical PV facade installations.*
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Keywords— **building integrated photovoltaics; optimisation; photovoltaic integrated shading systems**

I. INTRODUCTION

The consumption and depletion of conventional energy resources has caused a rise in the cost of energy, and energy conservation and the utilisation of renewable energy is becoming a matter of great importance. Recent urbanisation has also caused a trend in increasing high-rise buildings, furthering the need for energy, and steps are being taken in order to reduce this energy consumption or move towards cleaner sources of energy. The rapidly growing construction sector of Sri Lanka makes up 35% of the national energy consumption (Kumanayake et al., 2018; SLSEA, 2017). Sri Lanka has also identified the requirement to move towards cleaner sources of energy and actions are being put in place decrease the reliance on imported fossil fuels (Ministry of Power and Energy, 2015). The country is located in the tropics, just north of the equator, and therefore has an abundance of solar resources. The building integrated photovoltaic (BIPV) method is ideal to battle this issue of clean energy since it is capable of generating electricity on-site, and thus cuts down on losses caused due to transformation and transmission through grid lines. In regions of higher latitudes, the application of BIPV on the facades of modern buildings has become widespread (Xu et al., 2014; Zhang et al., 2012; Taleb and Pitts, 2009; Roberts and Guariento, 2009; Unnewehr et al., 2012). Due to the fact that PV systems generate electricity during the daytime, office buildings are predominantly appropriate for BIPV applications as they function and require energy during the day (Lam et al., 2003). However, the high angle of solar elevation in Sri Lanka causes incident solar radiation to be spread out over the surface of the PV module, thus reducing the intensity. Halawa et al. (2018) emphasised that constructions with fully glazed facades are not usually recommended for tropical locations even with the use of materials with low emissivity (such as PV modules) without the use of shading. Rooftops are more suited for PV applications in the region, but in high-rise buildings, the rooftop area may not be able to meet the energy demand. This creates a requirement to optimise PV integration on facades.

PV integrated shading strategies provide a creative solution to battle this concern by installing PV at inclined angles on the facade to better receive solar irradiation, whilst also acting as shading strategies to reduce high solar heat gains through building fenestrations. Recent research has focused on maximising the available solar potential in the urban canyon (Martins et al., 2014; Vulkan et al., 2018; Compagnon, 2004; van Esch et al., 2012; Chatzipoulka et al., 2016; Mirkovic and Alawadi, 2017), methods of improving PV cells and systems, evaluating BIPV on facades and rooftops (Mulcué-Nieto and Mora-López, 2017; Athienitis et al., 2018; Urbanetz et al., 2011; Atmaja, 2013; Hachem and Elsayed, 2016; Ghazali et al., 2017; Fung and Yang, 2008; Yoo et al., 1998; Khedari et al., 2004; Hestnes, 1999; Bizzarri et al., 2011), and optimising installation methods for maximum power generation (Hwang et al., 2012; Yang and Lu, 2007; Mandalaki et al., 2014a; Mandalaki et al., 2014b; Stamatakis et al., 2016; Yoo and Lee, 2002). In addition, shading systems and energy performances of facades have also been analysed extensively, especially in tropical climates (Al-Masrani et al., 2018; Ibañez-Puy et al., 2017; Halawa et al., 2018). Research has also been conducted on the various installation methods of PV and PV integrated shading strategies in terms of various shading methods and semi-transparent PV on facades. Hwang et al. (2012) proposed a method of utilising inclined PV in order to increase the aesthetic value of the BIPV and analysed this in terms of PV generation potential, but not in terms of how the installation methods could cause shading. Therefore, there exists a requirement to analyse how PV modules can be used to actually reduce building energy consumption (Yoo and Lee, 2002). However, to the authors' knowledge, little research has been done thus far regarding the evaluation of the proposed PV installation methods as shading strategies in order to also analyse the variation in building energy consumption and the economic potential of the installation strategies.

In terms of analysing solar potential, much of the research done in the past has been concerning physically available solar irradiation and the geographically available area for PV installation. Izquierdo et al. (2008) proposed a hierarchy to evaluate the solar potential in terms of physical potential, geographical potential, technical potential, economic potential, and social potential. The first three concepts have been fairly well researched and established, however the research done in terms of the latter two is rather lacking. In addition, Sri Lanka was only recently declared a developing country, and there is limited government funding available in order to popularise the utilisation of BIPV. Therefore, a requirement exists in order to ensure that PV installations are optimised to be as efficient as possible in order to minimise excess expenditure.

This paper proposes a method to optimise the PV generation capabilities of high-rise commercial office buildings in Colombo, Sri Lanka by considering the economic potential of the PV installation strategies in terms of the available area for installation, and the PV generation. The main aim of this study is to determine optimised PV installation strategies for facades such that the PV generation is maximised at minimal installation cost. The tropical context and climate of Colombo is analysed in terms of the incident solar irradiation on the various PV integrated shading strategies. This is done by taking into account the inclination angle of the installation, the ratio of the distance between the panels to the length of the panels (in order to account for panel-to-panel shading effects), and the orientation of the building facade. However, this method needs to be evaluated in detail in order to determine whether inclined PV installations would be more economically viable than vertical installations, even if the overall PV generation is lower.

II. METHODOLOGY

A. Parametric Analysis

A characteristic commercial office building in Colombo was chosen for this study, with a length and width of 20m and a height of 80m. Floor heights were taken to be 3m, with windows of 2m height positioned at each storey. The PV integrated shading strategies were modelled over the windows of each facade with variations of inclination angle and distance-to-length ratio (D/L). Table 1 shows the intervals of variation for the different variables. A schematic of the building with an example case of the PV integrated shading strategies is shown in Figure 1 below.

Table 1. Variables of PV installation strategies

Variable	Intervals
Facade orientation	North, south, east, west
Inclined angle	0°, 15°, 30°, 45°, 60°, 75°, 90°
D/L ratio	1.0, 2.0, 3.0, 4.0

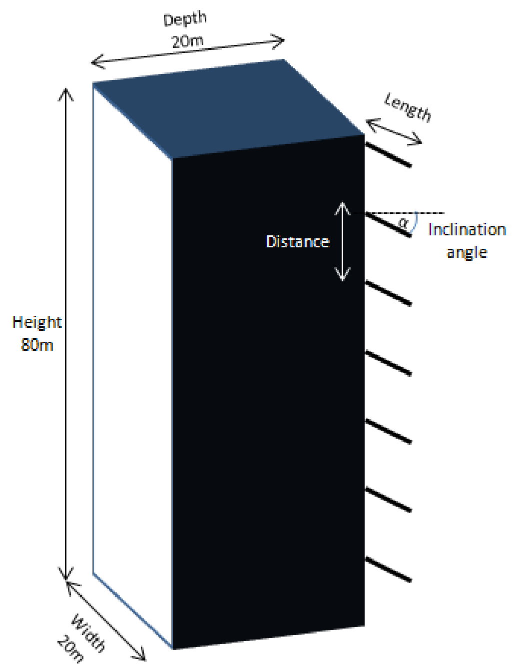
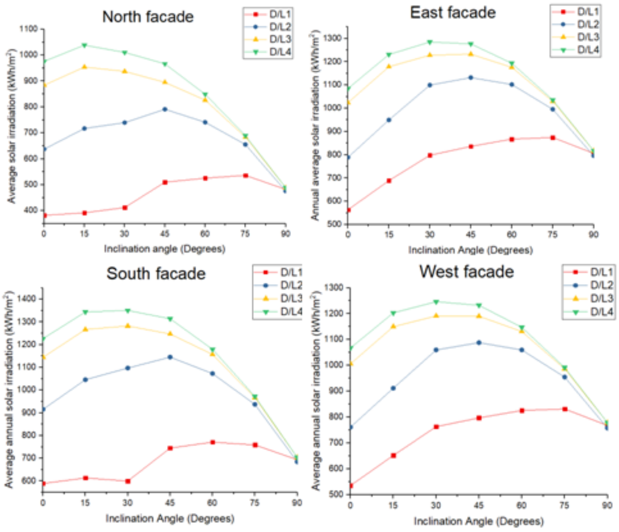


Figure 1: Schematic diagram of PV integrated shading strategies

B. Solar Irradiation

In order to run the solar irradiation modelling, it was initially necessary to establish a validated method and model that could take into account time, location, climatic conditions, and shadow effects. The literature review presented countless existing and validated models that are capable of analysing solar irradiation on buildings and in the urban context, such as Radiance, Daysim, and ArcGIS Solar Analyst (Byrne et al., 2015; Freitas et al., 2015). Radiance was chosen as the most suitable method for this simulation as it is a highly accurate ray-tracing software that considers both specular and diffuse reflections, whilst applying the Perez diffuse radiation model (Perez et al., 1987; Perez et al., 1990). It has been authenticated many times, and has even been used in curved geometries (Ward, 1994; Li and Tsang, 2008; Galasiu and Atif, 2002; Reinhart and Herkel, 2000; Vaisi and Kharvari, 2019), and successfully utilised in many applications for the evaluation of solar potential on building envelopes. Radiance was utilised as a plug-in in Rhino 5, through the Grasshopper interface and the Ladybug and Honeybee tools. Ladybug helps to import standard EnergyPlus weather files into Grasshopper, and Honeybee connects the visual programming environment of Grasshopper to the Radiance simulation engine (Roudsari and Pak, 2013). Grasshopper works as a graphical algorithm interface that is integrated with Rhino's 3D modelling tools. In this way, the programme allows to build an algorithm that can calculate the solar irradiation in a modelled context.

By using the Radiance simulation engine through Rhino and Grasshopper, the solar irradiation simulations were run on the buildings and PV integrated shading strategies. A total of 112 cases were simulated for each of the variations, i.e. the combination of four different steps of distance-to-length ratio, seven different variations of the inclination angle, and the four individual facades. The initial step of analysis included evaluating the solar radiation incident upon the PV in terms of the average annual solar irradiation (kWh/m^2). This could give a better



understanding of the intensity of solar radiation available on the PV surfaces instead of considering the total annual solar irradiation (in terms of kWh).

C. PV Generation

The PV generation capabilities of the cases were calculated by using a PV generation model that could accurately estimate the amount of electricity that could be produced by utilising PV modules on the area being considered. The PV generation model that was made use of is:

$$E_{PV}=(T_{SR}\cdot\eta\cdot PR)/I_A \qquad (1)$$

E_{PV} denotes the total PV output generation in kWh/m^2.yr; T_{SR} denotes the total solar radiation falling on the surfaces in consideration; and I_A denotes the area of the PV surfaces. The typical performance ratio nowadays (PR) nowadays is between 80-90%, and was therefore set as 85% (as established from the literature) for this paper (Kumar and Kumar, 2017). The efficiency of polycrystalline silicon PV (η) was set as 15% (Lv et al., 2018).

III. RESULTS AND DISCUSSION

A. PV Generation

The PV generation capabilities of the various installation strategies was calculated by using equation (1) in order to determine how much total electricity could be produced by the building incorporating the different installation methods. When considering the total annual PV generation on all facades, it can be noted that the optimum generation capabilities lie within horizontally inclined installations of inclination angle 75° with a D/L ratio of 1, with the highest overall generation being at all other installations at D/L1 as well. However, this could be due to the fact that the D/L ratio 1 installation method allows for the highest available area of PV installation, and will therefore produce a larger overall PV output, even if the intensity of solar irradiation on the panels is lower than in other installation methods. This also needs to be further analysed in terms of economic potential in order to determine which installation strategy can produce the most electricity for the lowest cost. Installations at D/L 4 produce the lowest overall PV output, with different facades having different optimised inclination angles for panel installations – similar to the solar irradiation. The overall building PV generation capabilities were also calculated by taking into consideration all facades, where at D/L ratios of 3 and 4, 30° installations are most optimised, and at D/L ratio of 2, 45° inclined installations are most optimised.

Figure 2: PV generation capabilities of individual facades (Source: T Mendis)

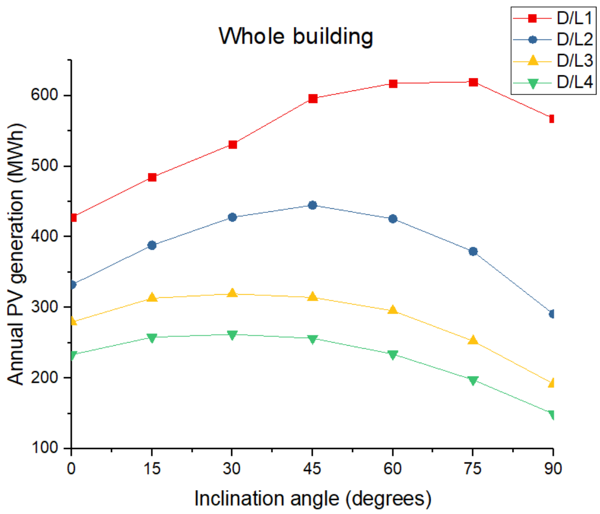


Figure 3: PV generation capabilities of whole building (Source: T Mendis)

B. Payback Period

The In order to obtain a better understanding of economic viability of the PV integrated shading strategies, the payback period for each installation method was calculated. The payback period presents an accurate solution in order to find a relationship between the installation cost of the installation strategy and the effectiveness at which it receives and utilises incident solar irradiation, i.e. how intense the solar irradiation incident upon the PV surfaces is.

Angle	D/L1	D/L2	D/L3	DL/4
0	21	14	11	10
15	19	12	10	9
30	17	11	10	9
45	15	11	10	9
60	15	11	10	10
75	15	13	12	12
90	16	16	16	16

Figure 4: Payback period based on installation strategy (Source: T Mendis)

The results obtained showed that the most economically viable installation strategies are H15DL4, H30DL4, and H45DL4 with a payback period of 9 years. This is a large difference when compared with the payback period obtained for a typical vertical installation of facade PV, which is 16 years. H0DL1 has a long payback period of 21 years, which could be because of the limited spacing between panels and the high level of horizontality, which causes excessive shading effects lower panels. Some of the inclined PV strategies are capable of recovering the PV installation cost within nearly half the time as that of common vertical PV facades. Furthermore, the percentage of profit generated by the 21st year of installation was calculated for each of the installation methods in order to get a better idea of their effectiveness.

IV. CONCLUSIONS

This research was carried out in order to establish a more economically viable method of PV integration on facades in the tropical Sri Lankan context of Colombo. The main motivation behind the research lies in the fact that the high solar elevation angle in Sri Lanka renders common vertical facade installations unfeasible and the rooftop area alone is insufficient in order to meet the building energy demand. A study was carried out into analysing how horizontally inclined PV could be better positioned in order to meet incident solar irradiation, thus generating more electricity per square metre, in comparison with vertical installations. Two main contributions were provided in this paper:

1. Guidelines for a more economically viable method for PV installations on facades in the tropical climate; specifically, Sri Lanka

2. A method to assess the economic potential of PV integrated shading strategies

The results obtained showed that all horizontal inclinations of PV with a distance-to-length ratio of 1 are capable of generating the highest overall amount of electricity when compared to vertical installations, and other inclinations at higher D/L ratios. This is due to the increased amounts of available area in comparison with strategies with higher D/L ratios, and the more favourable inclination angle in comparison with vertical installations. Furthermore, the economic analysis revealed that that most economically viable installation strategies in terms of payback period (with a payback period of nine years) lie between horizontal inclinations of 15° to 45° at a D/L ratio of 4. However, other strategies could also be taken into consideration with higher payback periods of ten or eleven years, since they are also capable of reducing building energy consumption due to the increased shading effects on solar heat gains. A more in-depth analysis on the economic potential of the PV integrated shading strategies, showed that the most economically optimised method is an installation at 45° and D/L ratio of 4. This is 6.9 times (or 585%) more viable than the baseline building with vertical PV installations.

In terms of solar access into the built space, further in-depth analyses need to be conducted on the lighting levels and quality of light entering the building based on the PV integrated shading strategies. Other installation methods should be considered in terms of PV module type (opaque or semi-transparent), and how these affect PV generation capabilities, building energy consumption, and light quality.

The results obtained from this research are significant and could be useful in acting as architectural design guidelines for future plans on incorporating photovoltaic modules in commercial office buildings in Colombo, Sri Lanka.

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