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Assessing the Impact of Urban Block Typologies on Solar and Photovoltaic Potential in the Tropical Urban City of Colombo, Sri Lanka

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Abstract— The increasing global energy crisis has brought about a shift towards the utilisation of renewable energy, particularly towards building-integrated photovoltaics. When considering the assessment of photovoltaics (PV) in urban regions, previous studies have focused on methods that take into consideration the urban block typologies, urban density, urban compactness indicators, or urban form. However, a requirement still exists to assess how the use of PV in tropical regions can be optimised via the use of facades. Coupled with the fact that semi-transparent PV implemented on windows can perform a dual role in generating electricity whilst minimising building cooling loads, it is imperative to understand how urban block typology can affect PV potential based on the shading effects caused within the block. This paper assesses four different urban block typologies in the urban and climatic context of Colombo, Sri Lanka and how they affect the total and average solar irradiation and the total photovoltaic generation capabilities of opaque and semi-transparent PV installed on building roofs and facades based on their orientation. It was found that although facades are unfavourably inclined towards tropical solar irradiation, they can generate higher amounts of electricity due to the more expansive façade area in high-rise buildings. Further, it was established that the building form in addition to the block typology affects the PV generation, especially when coupled with the building orientation, and that this can have a significant impact on the effectiveness of building envelopes for PV generation.

Keywords: *urban block typology, photovoltaic potential, building form*

I. INTRODUCTION

The growth in urbanisation and global conventional energy demand has brought about an increase in the cost of energy and carbon dioxide emissions (Poponi et al., 2016). Cities account for more than half of the world's population and 66% of the total energy demand. This has brought about a shift towards the utilisation of renewable energy resources. Photovoltaic (PV) technology provides a convenient method of onsite electricity generation and consumption with minimised transformation and transport losses, and it is imperative to account for the efficiency of PV systems when considering their implementation in urban environments. The utilisation of solar energy in urban environments, however, is not only dependent on the PV cell or system technology, which have also made significant advancements in recent years. Rather, the efficient utilisation of solar energy is determined by the intensity of solar irradiation present on the surface of the PV cell, which can be dependent on a variety of factors, such as the geographic latitude, climate conditions, urban context, and availability of installation space.

The installation of PV modules in high density cities face more challenges in comparison to low density cities when accounting for the shading and occlusion effect from neighbouring buildings and available area for panel installation. It has been found that different building blocks with varying building typologies but constant built density (Martin and March, 1972) could still have significantly varying effects on solar energy utilisation potential (Heng, Malone-Lee and Zhang, 2017). This brings about a need to carefully assess the utilisation potential of solar energy in urban contexts based on different architectural or urban design plans (Ratti, Raydan and Steemers, 2003).

A further issue is brought about when taking into consideration high-rise, high density cities in tropical regions. In these regions, it is generally agreed upon that roof photovoltaics are the most feasible form of installation, as they are optimally inclined towards capturing solar irradiation (Mendis et al., 2020). However, the increase in high-rise buildings in these urban areas has brought about an increase in the building energy consumption relative to available roof area for PV deployment (Zhang et al., 2012). Thus, the installation of PV on high-rise building roofs may be unable to meet the building energy demand in tropical region), which brings about the next viable means of implementation – building facades. Although building facades are unfavourably oriented towards harvesting solar irradiation in these climates, it has been shown that photovoltaic integrated shading strategies can be a creative solution towards maximising solar energy utilisation potential in such contexts (Mendis et al., 2019; Hwang, Kang and Kim, 2012; Halawa et al., 2018). It is, however, necessary to obtain an understanding of the effects of neighbouring building shading effects on incident solar irradiation and corresponding PV electricity generation potential in tropical urban contexts.

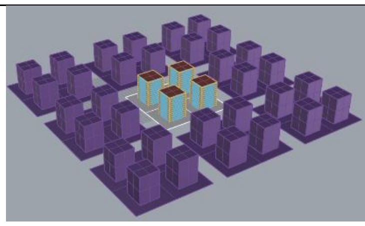
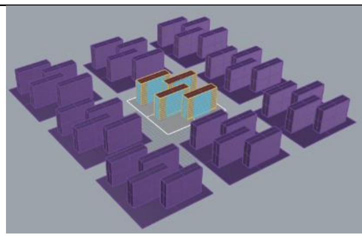
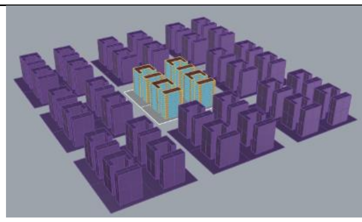
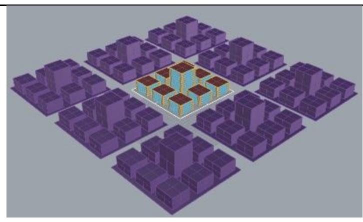
Given these, this paper makes an initial attempt into studying the effects of varying urban block typologies in Colombo, Sri Lanka on the solar and PV potential in order to determine optimised methods of PV implementation in high-rise, high density urban blocks in a tropical city.

II. METHODOLOGY

A. Urban Block Modelling

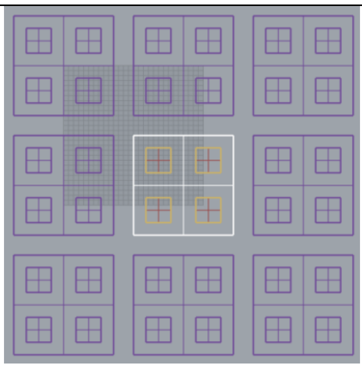
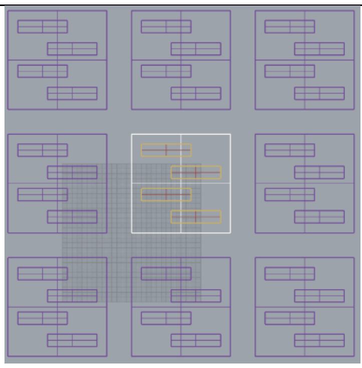
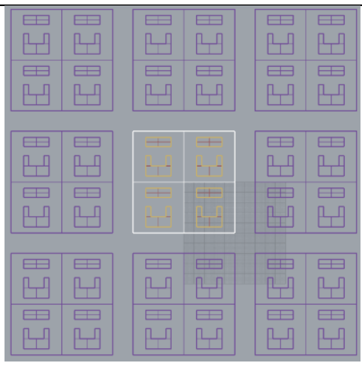
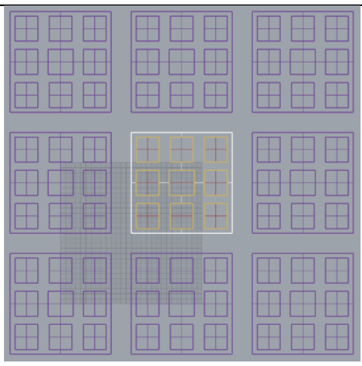
For the purposes of this paper, four urban block typologies were selected for evaluation. A survey was carried out to identify characteristic urban blocks in Colombo and their respective building forms, in order to determine the layout of each block. Through the survey, four generic urban blocks were identified in different typological categories: (1) regular tower, (2) staggered slab, (3) regular courtyard, and (4) regular centre block typology (Tables 1 and 2). The tower typology is considered to consist of standalone high-rise tower buildings with even spacing, whilst the slab typology consists of parallel rectangular buildings with even spacing. In addition, the courtyard typology consists of building(s) with a central courtyard, whilst the centre typology consists of low-rise buildings surrounding a central high-rise building.

Table 1. Perspective views of urban blocks used in the study

Block No.	**Block Type**	**Perspective View**
Block 1	Regular Tower	
Block 2	Staggered Slab	
Block 3	Regular Courtyard	
Block 4	Regular Centre	

Source: Author

Table 2. Plan views of urban blocks used in the study

Block No.	Block Type	Plan View
Block 1	Regular Tower	
Block 2	Staggered Slab	
Block 3	Regular Courtyard	
Block 4	Regular Centre	

Source: Author

Each urban block is considered to be the smallest unit in urban planning, surrounded by external roads. In order to maintain standardisation within the blocks, several parameters were kept constant. It is intended to assess the solar potential of the block in relation to the surrounding urban context which is mirrored by the block, i.e. the overall assessment was carried out in an array of 3x3 blocks with the assessed block being placed in the centre of the array, and the surrounding blocks being considered as shading elements in the overall urban context. This was done to evaluate the performance of the block in relation to a reflection of its own shading (references page 516). The parameters that were controlled include the maintenance of the site area of the block and the total built area within the block. For this, the site area was maintained at 10,000m^2 and the Gross Floor Area (GFA) was maintained at 30,000m^2, i.e. the plot ratio of each block would be 3.0, where the plot ratio is the ratio between the total built area within the block to the site area of the block. The window-to-wall ratio (WWR) of the facades of the buildings were maintained at 0.4. In order to represent a typical road, the spacing between blocks was set to 20m, and the distance between the edge of the site and the buildings was either 5m or 10m. Modelling of the urban blocks was carried out on Google Sketchup with the OpenStudio plug-in, along with importing the files to Rhino 6 in order run the solar irradiation simulation.

Although it is not perfect in recreating the real urban context, this method of homogenous simulation allows to derive at conclusions which are not context-specific, in contrast to other studies that are done in real urban contexts. By expanding the number of cases and block types in homogenous simulation, it is possible to arrive at conclusions for various block typologies which could be implemented in the real case.

B. Solar Irradiation Simulation

In order to run the solar irradiation simulation, Rhino 6 was used together with the Grasshopper plug-in, coupled with the Ladybug and Honeybee simulation tools. This method is capable of taking into account how time, location, climate, and shadows can affect the incident solar radiation. There are many validated models discussed in the literature, including Daysim, Radiance, ArcGIS Solar Analyst (Feitas et al., 2015), and it was found that Radiance is an accurate raytracing software that has been validated multiple times through previous studies and is used as the simulation engine through the Ladybug and Honeybee tools. These tools help to investigate the environmental performance of buildings via a visual programming language and validated simulation engines. They make use of algorithmic modelling and neural networks to simulate building and environmental performance.

By making use of this method, the solar irradiation on the building surfaces of the central block were modelled on the individual facades – including the walls and windows individually, and the roofs of the buildings.

C. Photovoltaic Generation Calculation

In order to assess between the PV implementation feasibility of difference surfaces, it was necessary to calculate their PV generation capabilities. For this purpose, the following formula was made use of, where EPV denotes the total PV electricity generated; TSR denotes the total solar irradiation incident upon the surface; η denotes the efficiency of the PV module; PR denotes the performance ratio of the system; and A denotes the total area of the surface under consideration.

$$E_{PV} = \frac{T_{SR} \cdot \eta \cdot PR}{A}$$

The performance ratio is typically between 80% and 90% and was set at 85% for this paper (Kumar and Kumar, 2017), and the efficiency of semi-transparent PV was set at 5% and the efficiency of polycrystalline silicon PV was set at 15%. It was assumed that semi-transparent PV was made use of on the total surface area of the windows, whilst polycrystalline PV was used on the total wall area.

III. RESULTS AND DISCUSSION

The results from the simulation were analysed by considering for various aspects, two primary factors being the total solar irradiation and the average solar irradiation. The total solar irradiation represents the overall solar irradiation incident (kWh) upon the entire surface or surfaces under consideration, whilst the average solar irradiation accounts for the solar irradiation intensity (kWh/m²) on the surface, i.e. the energy present per square metre of surface area.

Figure 1 shows the overall total and average solar irradiation in each of the four blocks as an accumulation of all of the building surfaces (roofs, walls and windows). It can be noted that Block 3 (Regular Courtyard) receives the lowest average irradiation of 530kWh/m² in contrast to the highest average irradiation of 818kWh/m² received by Block 4 (Regular Centre). Further, the highest variation in total and average irradiation is present in Block 3, where it could be interpreted that although the building forms in the block provide for a greater envelope area, the compactness of the block is such that the overall shading effect on the envelope is increased, thus bringing about a decrease in the irradiation intensity on the surfaces. In contrast, Block 1 receives the second highest average irradiation (737kWh/m²) in comparison to the lowest total irradiation (1245700kWh). The opposite could be interpreted in this case, where the tower shaped building forms provide less surface area in comparison to Block 3, whilst minimising inter-building shading effects, bringing about an increase in the overall solar irradiation intensity on the surfaces.

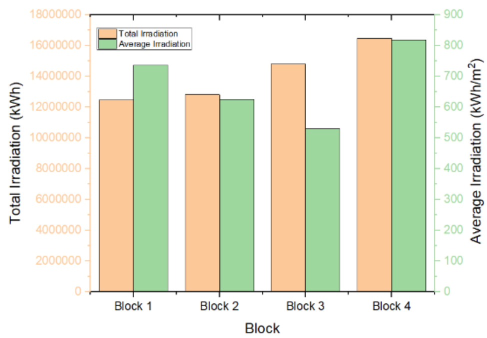


Figure 1. Overall total and average solar irradiation in each block
Source: Author

It can be seen that in Blocks 1, 2, and 3 (Regular Tower, Staggered Slab, Regular Courtyard), the highest total solar irradiation is achieved by the building facades, whereas in Block 4 (Regular Centre), the highest total irradiation is achieved by the roof (Figure 2). This could be assumed to be because although the compactness of Block 4 is increased, it is composed of many low-rise buildings surrounding a single high-rise building.

Since the plot ratio (and therefore, GFA) of each block is maintained at a constant, this means that the total building footprint – and hence, roof area – in Block 4 is increased, allowing for a greater area for total incident solar irradiation. However, when looking at Figure 3, which shows the average solar irradiation based on the building surface, it can be noticed that Block 4 receives the lowest irradiation intensity on the roof (1855kWh/m^2). This could infer that although a greater roof area is achieved through the building forms of Block 4, there is a greater shading effect from the high-rise building to the surrounding low-rise buildings, bringing about a decrease in the solar irradiation intensity on the roofs of the block. In contrast, Blocks 1, 2, and 3 all receive the same average solar irradiation (1934kWh/m^2) on the building roofs, since there is neighbouring building shading effect caused onto the building roofs. The average irradiation on the facades is highest in Block 1 (529kWh/m^2) and lowest in Block 3 (404kWh/m^2), which could confirm the results deduced from Figure 1 – where the tower shaped building forms in Block 1 create less shading on the building facades in comparison to the courtyard shaped buildings in Block 3, which create a greater façade surface area, but increase building-to-building shading effects.

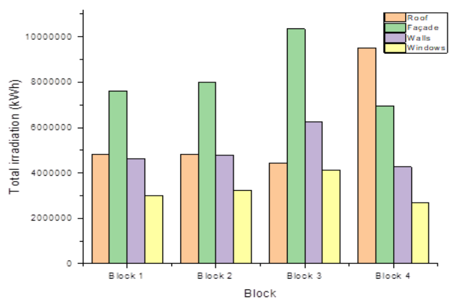


Figure 2. Total solar irradiation in each block based on surface; Source: Author

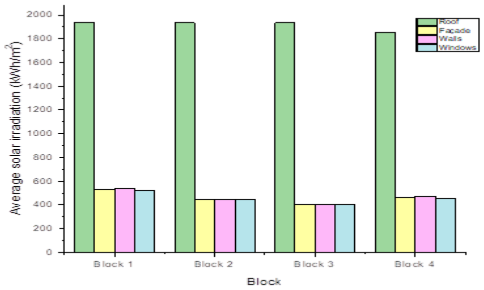


Figure 3. Average solar irradiation in each block based on surface; Source: Author

When looking at a more in-depth analysis of the total irradiation on the facades based on their irradiation as shown in Figure 4, it can be seen that Blocks 2 and 3 receive the highest total irradiation on the south façade. This could be because the building forms in these blocks are elongated in the east-west axis, and therefore the south façade has a greater surface area in comparison for solar irradiation capture. In addition, Block 2 receives higher amounts of total irradiation on the north façade as well in comparison to the east and west facades, although Block 3 receives the lowest amount of irradiation on the north façade in comparison to the other three facades. It can be deduced that this is due to the inter-building shading effect caused in Block 3 due to the compactness within the block. Blocks 1 and 4 appear to receive higher amounts of irradiation on the east and west facades in comparison to the south façade, which could be due to the effects of the sun path in the location and the constant shading caused on all surfaces due to the standardised nature of the building forms.

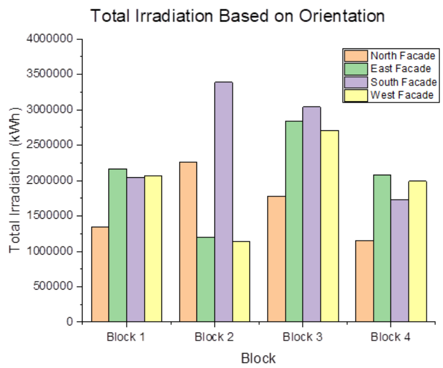


Figure 4. Total solar irradiation based on surface orientation in each block; Source: Author

Figure 5 represents the average solar irradiation based on the building surface orientation in each block, which includes the four facades and the roof. Understandably, the roof receives the highest average irradiation in all four blocks due to the favourable inclination angle, but it can also be seen that the north façade receives the lowest average irradiation in contrast, which could be due to the unfavourable solar elevation angle. Further, it is apparent that the east and west facades receive the highest average irradiation in all four blocks from the four facades, which is due to the solar elevation angle and pathway based on the location.

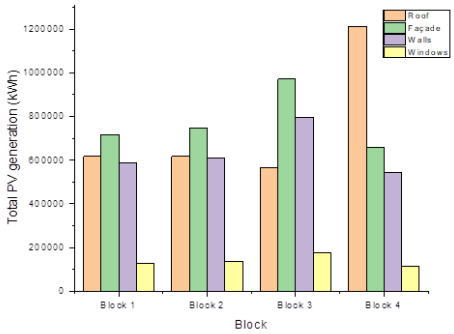


Figure 5. Average solar irradiation based on surface orientation in each block; Source: Author

Figure 6 shows the total PV generation based on the building surface in each block. This figure breaks down the overall PV generation capabilities of the roofs, walls, and windows separately of all buildings within the block. The facades account for the total average components of the walls and windows together. As described in the methodology, it was assumed the polycrystalline silicon PV of efficiency 15% was made use of for the roofs and walls, whilst semi-transparent PV of efficiency 5% was made use of for the windows. It is apparent that the windows generate the least total PV electricity due to the lower surface area for panel installation. In contrast, Block 4 generates the most PV electricity via the building roofs due to the expansive roof area whilst the total façade generation is reduced, presumably due to the reduced façade surface area caused by an increased number of low-rise buildings. Block 3 generates a significantly high proportion of façade PV in comparison to roof PV due to the increased façade area available. However, these values need to be compared with those shown in Figure 7, which represents the total PV generation based on the surface orientation in each block for the walls, windows, and both combined. This shows us that the south façade in Block 2 generates the most electricity, a major proportion of which is carried out by the walls. Further, the north and south facades generate more electricity in this block than the east and west facades. In Blocks 1 and 4, the east and west facades generate higher amounts of electricity, but are closely followed by the south facades. It can also be noted that the walls consistently generate more electricity than the windows due to the cumulative effects of higher panel efficiency and greater available surface area.

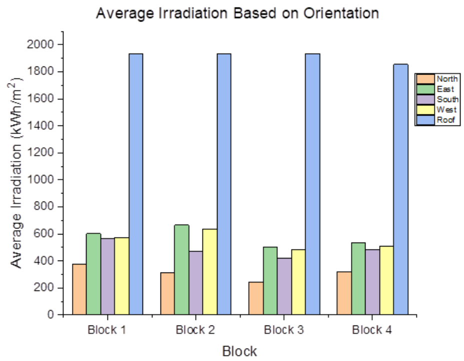


Figure 6. Total PV generation based on building surface in each block; Source: Author

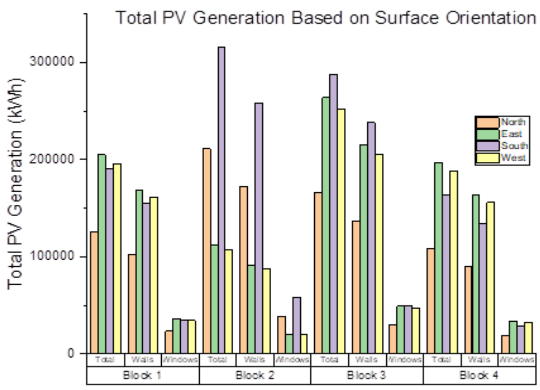


Figure 7. Total PV generation based on surface orientation in each block; Source: Author

IV. CONCLUSIONS

This paper looked into understanding the effects of urban block typology on solar and PV potential in urban contexts. Four distinctive generic urban blocks typologies were modelled for the location and climate of Colombo, Sri Lanka based on a homogenous form. The software, Rhino 6, was made use of coupled with the Grasshopper plugin, Ladybug and Honeybee tools, and the Radiance simulation engine in order to simulate the solar irradiation incident upon the building surfaces in each of the urban blocks. It was then assumed that photovoltaic panels were to be installed on the building envelope, with polycrystalline silicon PV (of 15% efficiency) being used for the building roofs and walls, and semi-transparent PV (of 5% efficiency) being used for the windows.

The results were analysed based on the total and average solar irradiation incident upon the separate building surfaces, whilst also accounting for their orientations, after which, the PV generation capabilities of each surface was accounted for as well. From the results, the following deductions could be made:

i. Although the windows provide a greater surface area for PV installation in comparison to the roofs, the PV electricity generation capabilities of the roofs are greater than those of the windows due to the limited efficiency of semi-transparent PV panels and unfavourable inclination angle.
ii. Most blocks generate more electricity via façade PV in contrast to roofs due to the greater surface area available for installation.
iii. Due to the increase in the number of low-rise buildings in Block 4, and thus an increase in the building density and site coverage, the roofs are capable of producing more electricity via PV in comparison to the facades due to the expansive roof area available for panel installation.
iv. The south façades in Blocks 2 and 3 are capable of generating a greater proportion of electricity due to the elongated building form.

The above deductions open the way for more questions considering the effect of the urban block typology on PV potential. An interesting point to study would be whether a change in the orientation of Block 2 towards the east-west directions would bring about a greater increase in PV generation in comparison to its current form. Further, since semi-transparent PV installed on windows are capable of minimising the solar heat gains into the building, it could be studied on how this affects the overall building energy consumption when considering for cooling loads. Although this paper looked into the effects of four urban block typologies on solar and PV potential, more factors need to be taken into consideration in order to make this study more comprehensive, such as the effects of various WWR on both the PV potential and building energy consumption, and also the effects of different block typologies in various orientations. Further, a comparative assessment could be carried out considering the varying use of semi-transparent PV on windows in contrast to photovoltaic integrated shading strategies and their effects on minimising building cooling loads. Considering the developing context of a region like Colombo, it is also imperative to take into account the calculation of economic potential of these strategies, in order to ensure that the implementation methods studied are region-sensitive and feasible.

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