Analysis of solar PV potential for roofs and façades in high dense residential urban scenario of Singapore

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Abstract. This paper aims to understand the potential of solar photovoltaics (PV) on building’s roof and façades in the dense residential neighborhoods of Singapore. The physical urban morphological parameters such as height, built form, distance between the buildings, orientation, plot ratio, building volume ratio and site coverage have impacts on the solar irradiation on the roof and façades at various intensities. With these parameters in consideration, solar irradiation has been simulated and analyzed for 12 existing neighborhoods of Singapore along with 36 additional modified neighborhoods.

1. Introduction
Singapore is a high dense city with a population of 5.6 million as of 2018 in a land area of 721.5 km\textsuperscript{2} \cite{1}. Among the limited renewable options available, solar energy seems to be the most promising source of renewable energy in Singapore. As the residential built stock constitutes 73\% \cite{2} of the overall building footprint, Singapore demonstrates a greater potential for solar PV deployment in residential neighbourhoods. Thus, the government agencies are trying to accelerate the deployment of solar PV systems across Singapore on public residential blocks to produce 420 GWh of electricity annually \cite{3}.

As effective solar PV deployment is mostly dependent on the overall urban form, the first question targeted in this study is whether there are ways to provide urban design guidelines in order to improve potential for PV deployment and therefore renewable energy production. Although Singapore receives a favourable solar irradiance throughout the year, considering the high densities of the residential neighbourhoods, and the variety of buildings shapes and orientations, not all building surfaces are suitable for PV installation. Moreover, residential neighbourhoods are planned by the Housing Development Board (HDB) per group of buildings and not on an individual building basis.

The intent of this study is therefore to analyse to what extent urban morphology parameters at the neighbourhood scale might affect overall PV potential and to provide urban design guidelines at the master planning stage that could optimize the PV generation potential while ensuring standard requirements of high density residential estates.

2. Methodology
As determined by previous studies, the solar irradiation on the roof and facades is affected by orientation and urban compactness factors such as plot ratio, site coverage, and building volume ratio in the neighbourhood level \cite{4}. Plot ratio\textsuperscript{1} is a critical indicator of urban density which determines the height and number of levels for any building with respect to the plot area. Site coverage\textsuperscript{2} helps to understand the density and compactness of the site in a two-dimensional plane that determines the availability of

\textsuperscript{1} Total built surface area divided by the total site area of the neighborhood
\textsuperscript{2} Total percentage of space covered by the building footprint within the site area
open space and built form. The building volume ratio\(^3\) helps to understand the physical massing density of the neighbourhood. The purpose of the study is to analyse the link between these urban morphology parameters and the PV potential on real residential neighbourhoods of Singapore, through a methodology shown in the Figure 1 using simulations and modifications of urban forms.

Figure 1. Overview of the Research Methodology

2.1. Selection of Urban Samples
For the study, 12 existing sites of 500m x 500m were selected from typical residential areas, which comprise of 40 to 50 buildings on average [5]. The sites include 4000-5000 dwelling units in total and accommodate population between 10,000 and 17,000. The samples have been chosen across various parts of Singapore with a varied mix of typical residential block types along with low-rise car parks and civic amenities blocks (Figure 2). The typical residential blocks in each of the neighbourhoods have been classified into four types of physical built form such as slab block, point block, shape block and hybrid block as on figure 3.

Figure 2. Selection of 12 existing residential sites across Singapore

Figure 3. Residential building types a) Slab block, b) Point block, c) Shape block, d) Hybrid block.

2.2. Simulations
The PLANTING v4 model has been developed to conduct the simulations based on 3D models to calculate solar irradiation on the roofs and facades of the buildings, taking into account the shadow casting [6] [7]. The simulation software works with LOD1 City-GML format as building shapes and TMY3 format as the weather data input. Based on input data, the PLANTING model defines the 3D objects as walls, roofs, and ground surfaces. These surfaces are then defined with a sensor grid of 10m x 10m. Sky view factor and solar irradiation (W/m\(^2\)) is calculated based on the hourly sun position and the latitude, longitude of the location.

2.3. Sample modification & process
The simulation results produced from the 12 existing neighborhood samples were insufficient for a statistical analysis to understand the impact of the morphological parameters on solar irradiation

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\(^3\) Total volume of the buildings divided by the total site area.
received on the building surfaces. Therefore more samples were generated by modifying each of the 12 real samples following three modification strategies that affect urban morphology parameters, while respecting typical urban design and architecture guidelines such as sufficient daylighting, ventilation and accessibility. An example of the 3 modification strategies named Coupling, Densification and Orientation is described below and an example for a given original sample is displayed in Figure 4.

2.3.1. Coupling. This modification is developed by stacking 20% of the built stock that is less than 10 storeys tall, thereby reducing the site coverage, but not exceeding a height of 20 storeys height limit. This will also increase the open space and facilitate better daylighting and ventilation.

2.3.2. Densification. This modification is developed by changing the old residential blocks in the neighbourhood and replacing them with a high dense block from the same neighbourhood. A 20% increase in density is uniformly followed across all the samples to withstand the future increase of population in Singapore.

2.3.3. Orientation. This modification is developed by changing the orientation of the blocks with the longer side of the facades facing north and south, thereby not affecting other building and urban morphological parameters. The blocks are oriented north south as it proves to be the best orientation in tropical Singapore.

![Figure 4. Example of Original sample and the three modifications of Bukit Panjang site.](image)

3. Results & Analysis

Total irradiation and PV electricity generation in absolute terms are mostly related to the available surface area. The intent of the study is therefore not to compare samples in absolute terms, but in terms of reaching the full potential of available surfaces. To this end, the study uses solar suitability indicator, which indicates what percentage of a roof and facade surface are receiving enough solar radiation for PV systems to be economically viable.

Due to the close proximity of Singapore 2°N to the equator, the island is regarded as a favorable site for solar PV with annual solar irradiation of 1663 kWh/m², equivalent of receiving 4.55 peak sun hours/day [8]. As suggested by (Mohajeri et al., 2016), for this solar simulation study, an average annual solar irradiation threshold of 1000 kWh/m² for roofs and 600 kWh/m² for the façades have been set, beyond which roofs and facades are considered economically suitable for solar PV deployment [4].

From the solar simulation analysis of the 12 existing urban samples, 90% of roof surfaces have solar suitability (irradiation higher than 1000kWh/m²) whereas only 8% of the facade surfaces are suitable for solar PV (irradiation higher than 600kWh/m²) (Figure 5). The blocks that are over 10 storeys and higher in general receive higher solar irradiation compared to the low-rise blocks and the multi storey car park (MSCP) blocks below 10 storeys are shaded most of the year due to the surrounding high-rise residential blocks.
Among the typical built forms, the slab block, point block and the hybrid block typologies receive solar irradiation on the roof that is well above the specified threshold (Figure 6). The higher number of floors in the shape block typology receives unobstructed solar irradiation that is suitable for façade PV. JW1 and Clementi have the highest solar suitability surfaces for façade PV with 10% and 14% of the façade surface respectively, above the threshold of 600kWh/m². This is mainly due to the newly built hybrid and shape block typologies that are more than 30 storeys tall and receiving unobstructed solar irradiation on the facades.

3.1. Samples analysis

From the analysis of the original and modified samples, the Orientation option shows an increase of 3% on the roof and coupling option shows an increase of 5% on the façade for solar PV suitability as shown in figure 7.

In Figure 8, solar suitability of roofs and façades is analyzed against plot ratio, building volume ratio and site coverage across all 48 samples. For roof surfaces, the plot ratio (p=0.016) and building volume ratio (p=0.016) had a significant negative relationship with solar suitability, while site coverage (p=0.023) had significant positive relationship with solar suitability. However, the urban morphological factors did not have a significant impact on the solar suitability of façade surface.
3.2. Plot ratio
As the plot ratio increases from 2 to 4.2, the original samples show a decline in the solar suitability on the roof. A reduction of 15% is observed as the plot ratio increases. In the modified options the coupling samples show 30% decline on the roof, whereas the densification and orientation options do not show a varying trend. But the orientation option performs better than original options as the plot ratio increases. With the plot ratio of 3.5 the orientation option performs 10% higher than the original option. The Yuhua coupling option is an outlier due to the lower plot ratio of 0.8 and with the solar suitability of 94% on the roof. This is mainly due to the reduced variation in the height of the blocks within the neighborhoods and thereby avoiding the shadow on the roof. The solar suitability trend on the façade remains flat with the increase in plot ratio. However, the densification option shows an increase of 5% on received solar irradiation above the threshold. The outliers in here is the Geylang coupling option where the façade has 30% of the overall surface suitable for façade PV. This is due to the increased distance of more than 50m on average between the blocks and thereby avoiding the shadows from the neighboring buildings.

3.3 Site coverage
In the original samples as the site coverage increases from 18% to 32%, as expected there is 8% drop in the roof solar suitability. The orientation option shows only a 4% decline as density increases. However, the coupling and densification options show an overall reduction on the solar suitability compared to the original samples, as there is an increase of 6% and 7% on the roof solar suitability as the site coverage increases. This is due to the change in new building typologies, predominantly shape blocks that reduce the variation in the height of the buildings. In the original samples as the site coverage increases from 18 to 32% there is a slight increase of 3% in the solar irradiation on the façade. The Clementi orientation option has close to 20% of the façade suitable for solar PV with site coverage of 25%. This is primarily due to the few high dense blocks that have higher surface area and receive more unobstructed solar irradiation due to the higher number of floors.
3.4 Building volume ratio

As the building volume ratio varies from 6 to 11, the solar irradiation decreases by up to 15% in the original sample. For every unit increase in building volume ratio there is a drop of more than 2% in the solar irradiation. The JW2 densification option shows 90% solar suitability that is higher than the average solar suitability (85%) of original samples. This is mainly due to the uniformity on building heights. On the facades the trend remains mild with the densification option that has an increase of 4% of solar PV suitability as the building volume ratio increases to 12. This is due to the two outliers Senkang07 and JW2 densification options. These two options have predominantly shape blocks with tall blocks on the periphery and shorter blocks in the center. This had made the façade irradiation to increase up to 15%.

4. Conclusion

The analysis on original and modified neighbourhood samples shows that the urban morphological parameters have a positive impact on the direct solar irradiation in turn affecting the solar PV suitability on roof and façade in residential neighborhoods of Singapore. The roof surfaces can become 95% suitable for PV from the current 90% with modifications such as standardising block heights thereby avoiding the effect of shadow. For the façades, a higher percentage of solar suitable surfaces can be reached with modifications in urban morphological parameters such as reducing the variation of building heights, predominance of slab block and hybrid block types, with building inter-distance of more 45m in average, with longer façade oriented to North-South, with site coverage in the range of 24% to 26%, and high plot ratio of 3.5 to can accommodate a population of above 15000. These results will provide guidelines for architects, urban planners and facility managers to make informed decisions in designing solar ready future residential estates and optimize decisions for developments in existing neighborhoods.

5. Limitations

Due to the lack of available data on real neighbourhoods, only a small number of sample sites were used. Future work should include more sample neighborhoods in order to further establish the significance of the morphological parameters on solar suitability.

PLANTING model only takes direct and diffuse radiation into account in calculating the solar irradiance. As reflected radiation accounts for a minimal percentage in Global Radiation the impact is assumed to be insignificant (Šúri et al., 2004) [6] [9]

References

[1] D. o. S. Singapore, “Population and Population Structure,” August 2018. [Online]. Available: https://www.singstat.gov.sg/find-data/search-by-theme/population/population-and-population-structure/latest-data.
[2] B. L. S. B. Tso-Chien Pan, “Singapore Building Inventory Database - Analysis & Classification,” Institute of Catastrophe Risk Management, NTU, Singapore, 2005.
[3] HDB. “SolarNova,” 2014. [Online]. Available: https://www.hdb.gov.sg/cs/infoweb/about-us/our-role/smart-and-sustainable-living/solarnova-page.
[4] G. U. A. G. D. A. Nahid Mohajeri, “Effects of urban compactness on solar energy potential,” Renewable Energy, vol. 93, pp. 469-482, 2019.
[5] E. LSE Cities, “CITIES AND ENERGY - Urban Morphology and Heat Energy Demand,” 2014.
[6] A. L. S. P. Syed Monjur Murshed, “PLANTING: Computing high spatio-temporal resolutions of photovoltaic potential of 3D city models,” no. https://doi.org/10.1007/, 2018.
[7] J. W. e. al. “Rapid development of semantic 3D city models for urban energy analysis based on free and open data sources and software,” no. DOI: 10.1145/3152178.3152193, 2017, 2017.
[8] D. N. S. D. N. P. L. a. T. H. G. D. T. K. Doshi, “The Economics of Solar PV in Singapore,” Energy Studies Institute, Vols. Discussion Paper EE/11-01, 2011.
[9] J. H. Marcel Suri, “A New GIS-based Solar Radiation Model and Its Application to Photovoltaic Assessments,” vol. Transactions in GIS, no. 8(2): , p. 175–190, 2004.