A morphological based PV generation and energy consumption predictive model for Singapore neighbourhood

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Abstract. The Singapore government emphasises the importance of sustainable development of the country and set an ambitious target for the adoption of solar power in 2014. Though solar energy is the most promising renewable energy source for Singapore, there is insufficient space for large scale PV panels deployment and hence PV systems have to be integrated into the building environment. Urban morphology determines the effectiveness of PV panels in the urban environment and hence it is important to design the new developments carefully. However, there is a lack of tool and knowledge to estimate the solar energy potential of a new planning zone, so this study developed morphological based PV output and energy consumption predictive models to identify the urban form for effective PV systems deployment by multilinear regression. Three equations are built for predicting the building cooling energy consumption, PV generation on rooftop and façade and the $R^2$ of these three equations are 0.33, 0.44 and 0.48 respectively. The regression equations show that the urban setting for maximizing PV generation and minimizing cooling energy consumption is different. Furthermore, the low $R^2$ values of the three equations reflects that building the predictive models by linear regression may not be the most suitable option and other machine learning algorithms should be explored.

1. Introduction

Solar energy is the most promising renewable energy source for Singapore. In 2014, the Singapore government set a target to increase the adoption of solar power to 350 MWp by 2020, which is equivalent to 5% of the projected national peak electricity demand. Being a completely urbanized city-state country, Singapore has limited space for large scale solar panels deployment, therefore one of the key measures is to integrate solar PV systems into the urban environment via building rooftops and façades. Urban morphology is a key factor for effective solar panels deployment in the urban environment, therefore careful planning at early design stage is important as it determines the overall urban morphology of the neighbourhood to be developed.

The impact of urban morphology on environmental performances of the built environment has been studied by previous studies, including building solar energy potential [1-5] and energy consumption [6]. However, the morphological studies on building solar energy potential were mostly conducted in the European context. Also, there are very few studies that aim to develop a morphology based predictive model for both the building solar potential and energy consumption.

Therefore, this study aims to build a morphological based building solar energy potential and energy consumption predictive metamodel in Singapore context by using parametric regression method. The
regression model is developed based on the simulation results of building cooling energy consumption and PV electricity generation, instead of the insolation that falls on the building façades that is commonly adopted in previous studies. The tool is expected to be useful for urban planners to design the new neighbourhood developments so that the building solar energy contribution can be optimized.

2. Methodology
This study has two stages: 1) scenario building and data collection; and 2) predictive metamodel building.

At stage 1, simulations for PV electricity generation are performed on 3D models of various archetype pavilion urban forms. Archetype urban form approach can limit the complexities found in the exiting urban form and pavilion type building form is chosen for this study because it represents tall tower buildings in an urban area [7]. To generate enough data for model building, a “scenario builder” is developed to iterate different archetype urban forms. The urban form scenario is controlled by five settings, they are number of buildings, site coverage (SC), average building height, orientation and the difference in building heights. The simulation site (400 m * 400 m) is surrounded by eight other contextual sites that bring shadow to the buildings for simulation, the urban form configuration of the contextual sites is identical to the simulation site. A typical scenario is illustrated in Figure 1.

![Figure 1](attachment:image1.png)

**Figure 1** A typical pavilion type architype form scenario (buildings of study in yellow; contextual buildings in blue)

Ladybug (adopts RADIANCE as its simulation engine) and Honeybee (adopts EnergyPlus as its simulation engine) for Grasshopper are employed for performing the simulations in this study. Firstly, irradiance simulation is performed by Ladybug to determine the PV installation area as this study assumes the panels are only installed on the building surfaces that receive sufficient irradiance (the irradiation thresholds for the installation of PV systems on rooftop and vertical façade are referenced from the rule of thumb suggested by Compagnon [8] and are set for 1,200 kWh/m² and 520 kWh/m² respectively) (See Figure 2). The panels are defined on the detached surfaces above building rooftop and façade, and hence these panels also function as shading devices that would bring impact on the cooling energy consumption. After defining the number of panels installed, the PV electricity output and cooling energy consumption are simulated by Honeybee directly. For PV panels, the specification of the panels is referenced from the Tallmax framed 72-cell module which has a cell efficiency of 17.5% and power output per module of 340 W. Whereas for energy consumption simulation, the EnergyPlus default setting of the chiller plant is adopted and it has a constant COP of 1.

![Figure 2](attachment:image2.png)

**Figure 2** PV panels installation area (blue) of one scenario
At stage 2, the predictive metamodel is built by multilinear regression by using the simulation results as the input. The independent variables of the models, i.e. the relevant morphology parameters, are chosen by referencing the eight principles set by Luc [9]. As such, three morphology parameters, including sky view factor (SVF), plot ratio, and height-to-width ratio are chosen. This study adopts the “cosine-weighted definition” of SVF [10], which estimates the proportion of radiant flux from the sky to a point. Three equations are defined, one for building cooling energy consumption and the other two for PV generation by panels on rooftop and façade. A typical multiple linear regression equation is in the form of

\[ y = b_1 x_1 + b_2 x_2 + b_3 x_3 + C + \epsilon \]

where \( y \) is the dependent variable, i.e. either the predicted PV electricity output or the cooling energy consumption; \( x_i \) is the predictor, i.e. the selected morphology parameter; \( b_i \) is the regression coefficient value of the parameter; \( C \) is the intercept point when all the parameters are zero. After the models are built, the significant test and collinearity test are performed.

3. Results and Discussion

3.1. Simulation result

In total, 100 simulations are performed and the statistical summary of the morphology parameters is presented in Table 1. The statistical summary of the simulation results, i.e. energy consumption by cooling, electricity generation by PV panels installed on rooftop and façade, normalized by floor area of the buildings within the site of study, is presented in the table below (Table 2). Whereas the statistical summary of electricity generation by PV panels, normalized by rooftop / façade surface area is presented in Table 3.

| Parameters                  | Range          |
|-----------------------------|----------------|
| Number of buildings         | 1 to 16        |
| Average building height     | 28 m – 84 m    |
| Plot ratio                  | 3 – 21         |
| Site coverage               | 30% - 70%      |
| Height to width ratio       | 0.15 – 5.14    |
| Difference in building height| 0 m – 42 m     |
| Sky view factor (rooftop)   | 0.97 – 1.00    |
| Sky view factor (façade)    | 0.09 – 0.48    |

Table 1: Statistical summary of the archetype form cases

| Parameters                  | Range          |
|-----------------------------|----------------|
| Energy consumption (Cooling) (kWh/m²/year) | 184.2          |
| PV generation (rooftop) (kWh/m²/year)       | 16.8           |
| PV generation (façade) (kWh/m²/year)        | 1.5            |
| Mean                                      | 101.8          |
| Standard deviation                    | 7.7            |

Table 2: Statistical summary of the normalized simulation results (normalized by floor area)

| Parameters                  | Range          |
|-----------------------------|----------------|
| PV generation (rooftop) (normalized by rooftop area) (kWh/m²/year) | 277.6          |
| PV generation (façade) (normalized by façade area) (kWh/m²/year)   | 19.4           |
| Mean                                      | 18.4           |

Table 3: Statistical summary of the normalized simulation results (normalized by rooftop or façade surface area)

From Table 2, it is observed that the average cooling energy consumption is significantly higher than PV generation. In average, PV panels can contribute to 12% of the cooling energy consumption (max 37%; min 4%). For PV output, panels installed on rooftop are less affected by shading and hence they can provide a consistent output among all scenarios, whereas the variation of urban form, which
determines the shading effect from neighborhood buildings, has a larger impact on the output of the panels installed on facade (see Table 3).

3.2. Parametric study

Before developing the predictive models, Pearson correlation tests are performed to understand the linearity between the normalized simulation results and the morphology parameters.

For irradiation falls on building surfaces and for the simulated PV generation normalized by building surface (rooftop or facade) area, SVF has a strong linear correlation performance ($r = 0.90$ and $0.71$ for rooftop and facade respectively) (see Table 4). The finding of SVF has a strong linear correlation with irradiation agrees with the previous studies [11]. Whilst height to width ratio also has a strong linear correlation performance with annual average irradiation on facade ($r = 0.95$).

| Table 4 Pearson correlation performance ($r$) table for the normalized simulated PV generation (normalized by rooftop or facade surface area) and irradiation results |
|-------------------------------------------|
|                                           |
| Annual average irradiation on rooftop (kWh/m²/year) | PV generation (rooftop) (normalized by rooftop area) (kWh/m²/year) | Annual average irradiation on facade (kWh/m²/year) | PV generation (façade) (normalized by facade area) (kWh/m²/year) |
| Plot ratio | -0.09 | -0.04 | -0.67 | -0.51 |
| Height to width ratio | -0.31 | -0.29 | -0.95 | -0.56 |
| Sky view factor (rooftop) | 1.00 | 0.90 | 0.33 | 0.21 |
| Sky view factor (façade) | 0.31 | 0.30 | 0.99 | 0.71 |

For the simulation results normalized by floor area, plot ratio has the highest linear correlation performance and the absolute values of $r$ are around 0.6. SVF on facade also has a relatively strong correlation performance with the normalized simulated results of energy consumption by cooling and PV generation by panels installed on facade. However, the linear correlation between sky view factor on rooftop and PV generation by panels installed on rooftop is weaker than plot ratio and height to width ratio.

| Table 5 Pearson correlation performance ($r$) table for the normalized simulation results (normalized by floor area) |
|-------------------------------------------|
|                                           |
| Energy consumption (Cooling) (kWh/m²/year) | PV generation (rooftop) (kWh/m²/year) | PV generation (façade) (kWh/m²/year) |
| Plot ratio | -0.57 | -0.66 | -0.66 |
| Height to width ratio | -0.39 | -0.39 | -0.41 |
| Sky view factor (rooftop) | 0.15 | 0.17 | 0.03 |
| Sky view factor (façade) | 0.44 | 0.37 | 0.51 |

3.3. Predictive model building

Three models are built for predicting the energy consumption by cooling, PV generation by panels installed on rooftop and facade. Multilinear regression is applied to build the predictive models, based on the selected morphology parameters. The dependent variable, $y$, in the three models are normalized by floor area. Gross floor area is chosen as the common parameter for normalization for two reasons: 1) to ensure that the PV output and energy consumption models are comparable; and 2) to reveal the true impact of urban morphology on energy consumption and effectiveness of PV panels deployment.

For the equation for predicting the energy consumption by cooling $y_{\text{cooling}}$ (kWh/m² yr), plot ratio $x_1$, H/W ratio $x_2$ and sky view factor (façade) $x_3$ were first selected for the parameters of the equation. However, the P-values of $x_2$ and $x_3$ are found to be >0.05 in the multilinear regression equation and hence they are statistically insignificant at 0.05 level. Therefore, only plot ratio $x_1$ is adopted and the equation is expressed in the form of:

$$y_{\text{cooling}} = -12.4 \text{ (kWh/m}^2\text{yr)} \cdot x_1 + 304.3 \text{ (kWh/m}^2\text{yr)}$$
The R^2 of this equation is 0.33 and the P-value of predictor is <0.05 and hence it is statistically significant at 0.05 level. The equation indicates that the higher the plot ratio, the lower the energy consumption by cooling. The plot of the regression is illustrated in Figure 3.

For the equation for rooftop PV output prediction $y_{rooftop}$ (kWh/m^2 yr), plot ratio $x_1$, H/W ratio $x_2$ and sky view factor (rooftop) $x_3$ were first selected for the parameters of the equation. Again, the P-values of $x_2$ and $x_3$ are found to be >0.05 in the multilinear regression equation and hence they are statistically insignificant at 0.05 level. Therefore, only plot ratio $x_1$ is adopted and the equation is expressed in the form of:

$$y_{rooftop} = -1.1 \text{ (kWh/m}^2\text{yr)} \cdot x_1 + 27.2 \text{ (kWh/m}^2\text{yr)}$$

The R^2 of this equation is 0.44 and the P-value of predictor is <0.05 and hence it is statistically significant at 0.05 level. The equation shows that the higher the plot ratio, the lower the cooling energy consumption. The plot of the regression is illustrated in Figure 3.

Finally, for the equation for façade PV output prediction $y_{façade}$ (kWh/m^2 yr), plot ratio $x_1$, H/W ratio $x_2$ and sky view factor (façade) $x_3$ are selected for the parameters of the equation. The multilinear regression equation is expressed in the form of:

$$y_{façade} = -0.15 \text{ (kWh/m}^2\text{yr)} \cdot x_1 + 0.84 \text{ (kWh/m}^2\text{yr)} \cdot x_2 + 0.84 \text{ (kWh/m}^2\text{yr)} \cdot x_3 - 0.77 \text{ (kWh/m}^2\text{yr)}$$

The adjusted R^2 of this equation is 0.48 and all the P-values of predictors are <0.05 and hence they are statistically significant at 0.05 level. The collinearity test for examining the collinearity of the predictors is performed. The Variance Inflation Factor (VIF) values between the predictors are between 1.8 and 7.2, which are <10 and means that the collinearity between the predictors is not strong and hence collinearity is not a problem in the equation.

The percentage (%) of building cooling energy consumption supported by PV energy can be calculated by:

$$(y_{façade} + y_{rooftop})/y_{cooling} = \text{Contribution of PV energy to cooling energy consumption}$$

By the above equations, the morphological settings for maximizing building PV generation and minimizing cooling energy consumption can be realized. Furthermore, there are two items worth to be noticed from the above equations, they are 1) the urban settings for maximizing PV generation and
minimizing cooling energy consumption contradicts, e.g. increasing plot ratio would reduce cooling energy consumption, but it would also reduce the PV output at the same time; and 2) as the values of $R^2$ of the equations are low, linear regression may not be the most suitable model building method and other machine learning methods should be explored.

4. Conclusion
This study analyses the impact of urban morphology on both building cooling energy consumption and PV electricity generation in Singapore context. Among the three morphology parameters, plot ratio, H/W ratio and sky view factor, sky view factor (SVF) has the strongest linear correlation performance with annual average irradiation that falls on building surfaces and PV generation normalized by building surface area. However, the linear correlation performance is weaker when the simulation results are normalized by building floor area.

Multilinear regression is adopted for building the predictive models for building cooling energy consumption and PV electricity generation. For the building cooling energy consumption and rooftop PV output prediction models, two parameters, H/W ratio and sky view factor are statistically insignificant in the multilinear regression equations. This indicates that most morphology parameters may have a more complexed relationship with the potential building PV generation and cooling energy consumption. Future studies can focus on finding the most suitable model building techniques, e.g. non-parametric machine learning algorithm, to build the predictive models with the normalized building cooling energy consumption and PV electricity generation, and identify whether the prediction accuracy can be improved or not.

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