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The Relationship between Building Typology and Solar Energy Harvesting Potential

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Abstract

High-density cities face many challenges approaching urban sustainability, including the potential to utilize clear energy such as harvesting solar energy. Due to their compact urban forms, buildings in high-density cities have substantial mutual and self-shading and, consequently, relatively less suitable surface areas to deploy solar energy collection equipment such as photovoltaic panels (PV) or Building Integrated PV (BiPV) system. Although different building typologies can be implemented to achieve the same built density in a given urban context, their implications in various environmental performance areas may vary significantly. Therefore, it is very important to examine and optimize the potential to harvest solar energy for different urban and architectural design proposals, especially in the early urban planning stage when the potential for optimization is the greatest.

This study investigated the potential of harvest solar energy from a design perspective by examining thirty representative generic building typologies in a fixed built density in terms of electricity produced by PV or BiPV in relation to building envelope surfaces where a minimum annual cumulative irradiance threshold is met, using the weather data for the high density tropical city of Singapore as an example. Several planning and geometric variables, such as site coverage, building compacity and depth, roof-to-floor area ratio, etc., were also calculated for each typology and their relationship with the floor area normalized electricity generated from PV was examined, and the key design parameters that have significant impacts on solar energy harvesting were identified.

The findings highlight the importance of urban and architectural design in solar energy harvesting from a typological perspective. The simulation-based workflow can provide vital support for performance optimization oriented planning and design exploration in both academic research and design practice.

Keywords: Building typology, solar energy, BiPV, urban planning, architectural design

1. Introduction

High-density cities face many challenges approaching urban sustainability, including the potential to utilize clear energy such as harvesting solar energy. Due to their compact urban forms, buildings in high-density cities have substantial mutual and self-shading and, consequently, relatively less suitable surface areas to deploy solar energy collection equipment such as photovoltaic panels installed on rooftop (Figure 1).

Although different building typologies can be implemented to achieve the same built density in a given urban context, their implications in various environmental performance areas may vary significantly. Therefore, it is very important to examine and optimize the potential to harvest solar energy for different urban and architectural design proposals, especially in the early stage of urban planning when the potential for optimization is the greatest.

This study investigated the potential of harvest solar energy from a design perspective by examining thirty representative generic building typologies in a fixed built density in terms of electricity produced by PV panels attached to building envelope surfaces where a minimum annual cumulative irradiance threshold is met.

This study aims to have a better understanding on the following two questions: 1) What is the solar harvesting potential for different building typologies under the same planning conditions? and 2) What are the significant planning parameters and geometric variables regarding solar energy harvesting potential?

Figure 1: Panoramic view of the PV panels installed on the rooftop of Blk183 of the Edgefield Plains precinct, Punggol new town, Singapore. (Source: the authors)

2. Method

2.1. Case study of building typologies

A case study approach was implemented and thirty generic urban block typologies representing different urban design strategies were analysed through simulation-based study to examine the relationship between building typology and solar energy harvesting potential.

As shown in Figure 2 each case was studied within a 3x3 array which is composed of the same typology as itself so as to examine its performance in a theoretically homogenous urban context [1]. Several urban planning parameters were controlled to be the same across all cases so as to ensure a common ground for performance comparison, such as the built density as indicated by plot ratio of 3.0, the area of the square-shape site of 10,000 m^2, and the spacing between each plot of 15m representing the width of typical neighbourhood road.

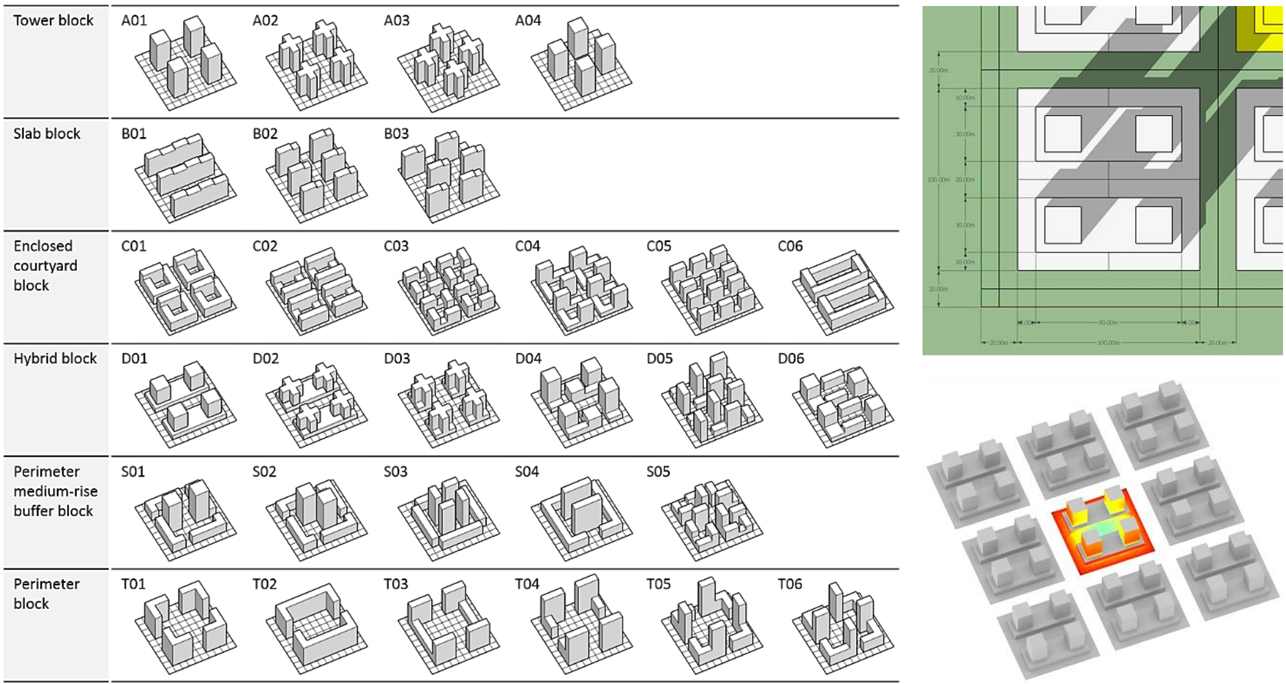
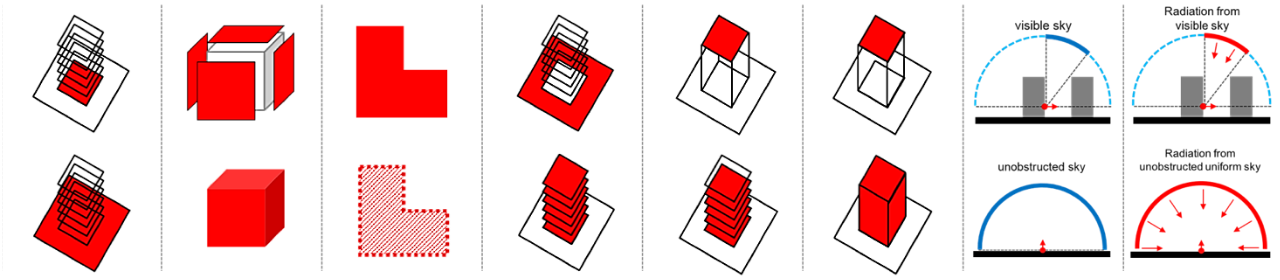


Figure 2: The thirty generic urban block typologies and the controlled simulation context

2.2. Planning and design factors and performance indicators

Several planning parameters and geometric variables were calculated that capture different spatial and geometric characteristics of the built form of the typologies examined here. Table 1 shows the diagrams illustrating the concepts of these parameters and variables.



Building Site Coverage	Compacity	Area-to-Perimeter Ratio	Open Space Ratio	Roof-to-floor Area Ratio	Roof-to-envelope Area Ratio	Sky Exposure Factor	Sky View Factor

Table 1: Planning parameters and geometric variables examined.

Building site coverage is calculated as the percentage of the site area that is covered by building footprints. Compacity [2], calculated as the ratio between building envelope area and building volume, is an indicator of the compactness of a built form. Area-to-perimeter ratio [3] is an indicator of the depth of floor. Open Space Ratio [4] indicates the amount of outdoor open space per unit floor area.

Since flat horizontal roof surfaces usually have the highest potential to collect solar energy in the area close to the Equator, two variables, roof-to-floor area ratio and roof-to-envelope area ratio, were defined to quantify the proportion of roof areas for a given built form. Lastly, two additional geometric variables, Sky Exposure Factor (SkyEF) [5] and Sky View Factor [6], were also calculated for each case, the former, calculated as the percentage of visible sky, quantifies the level of obstruction for a given point on building envelope which may have direct implication on solar radiation receivable at that point, the latter quantifies the ratio of radiation receivable for a given point on a building surface within a particular urban context to that from the unobstructed sky hemisphere.

The maximum solar energy harvesting potential for a given building surface is highly dependent on its location in relation to its physical context which may obstruct or reflect solar radiation receivable on itself. It also depends on the irradiance threshold level receivable on the surface below which the solar energy collection equipment such as PV or BiPV may not run up to its full potential. Table 2 illustrates the percentage of qualified building envelope surface areas calculated according to different minimum annual cumulative irradiance levels for a particular urban block typology.

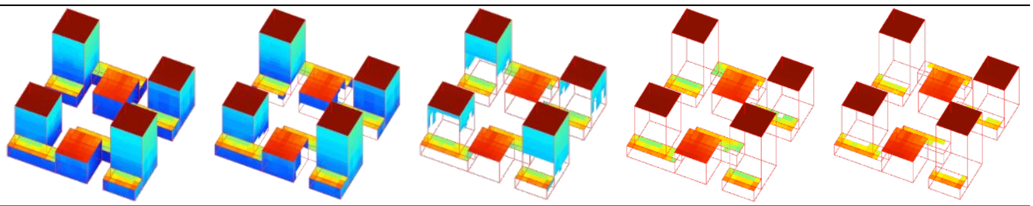
Visualization of the qualified building envelope surface areas with annual cumulative irradiance level above a given threshold value					
Minimum annual cumulative irradiance level	>= 0 kWh/m^2	>= 300 kWh/m^2	>= 500 kWh/m^2	>= 800 kWh/m^2	>= 1000 kWh/m^2
% of qualified envelope area	100%	86.2%	48%	18.6%	16.5%

Table 2: Percentage of qualified envelope surface area based on different irradiance threshold levels.

To evaluate solar energy harvesting potential for each typology, two performance indicators were calculated in this study that quantify the total usable floor area, or Gross Floor Area (GFA), normalized annual cumulative electricity generated by PV, i.e. the electricity generated by PV attached to building surfaces per unit floor area, one been calculated assuming the entire building envelope surfaces were covered by PV, and the other one been calculated only for the qualified envelope surfaces which receive annual cumulative irradiance no fewer than 1000 kWh/m^2 [7], the former is denoted as “the overall surface performance indicator” and the latter “the qualified surface performance indicator” in this paper.

2.3. Integrated workflow

To facilitate the simulation and performance evaluation, an integrated workflow (Figure 3) was created on the commonly used Rhinoceros3D+Grashopper software platform, using its Ladybug and Honeybee component groups for daylight, radiation and energy modelling[1]. This customized workflow integrated the functions of parametric 3D modelling of buildings, performance simulation, calculation of performance indicators and geometric variables, data analysis, and results visualization in a seamless way.

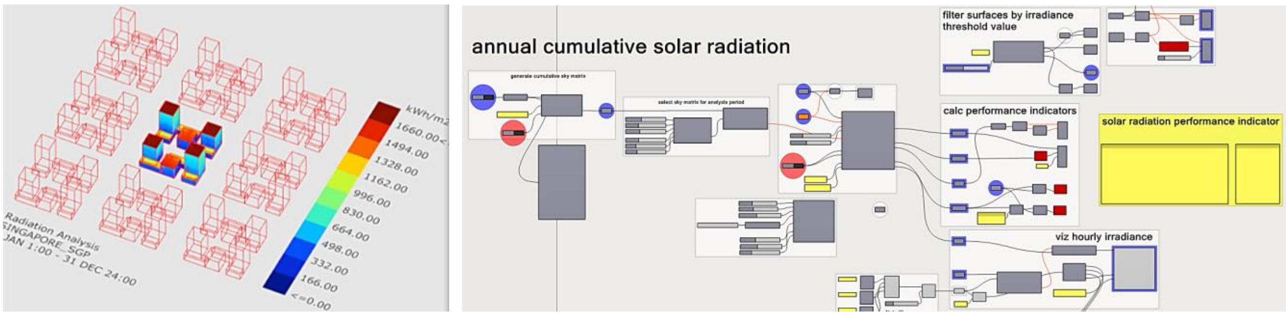


Figure 3: Part of the integrated workflow for modelling, simulation, calculation, analysis and visualization.

As for annul cumulative irradiance simulation, the validated Radiance software package[2] was used. For estimation purpose, the EnergyPlus Weather File for Singapore[3] was used as the input for the simulation which includes the statistically representative data for some of the key meteorological parameters, such as hourly global horizontal radiation, direct normal radiation and diffuse horizontal radiation for a whole year. The annual cumulative irradiance level was simulated for the entire building envelope surfaces for each typology on a grid of virtual receivers positioned in 2m spacing, both vertically and horizontally. A typical PV conversion efficiency value of 12% was used to estimate the annual cumulative electricity potentially generated based on the annual cumulative irradiance as simulated.

3. Results

3.1. Solar energy harvesting potential of different building typologies

Figure 4 shows the visualization of the simulated annual cumulative irradiance level on building envelope surfaces and the two performance indicators as calculated based on the simulation results for the thirty typologies.

Generally speaking, the cases within the enclosed courtyard typology group perform relatively the best regarding both performance indicators, with an average of 58.4 kWh electricity generated from the entire building envelope per unit floor area and an average of 24.2 kWh per unit floor area generated from the qualified envelope surfaces. This is followed by the cases in the hybrid typology group, the typologies with medium-rise buffer block, and the perimeter block typologies. The cases in the slab block and tower block typology groups perform the worst. The tower block and the slab typologies have 24.7% and 15.9% lower average performances, respectively, than that of the enclosed courtyard typologies, according to the overall surface performance indicator; and they have 50.7% and 46.9% lower average performances, respectively,

[1] http://www.grasshopper3d.com/ and http://www.grasshopper3d.com/group/ladybug
[2] https://www.radiance-online.org/
[3] https://energyplus.net/weather

than that of the enclosed courtyard typologies, regarding the qualified surface performance indicator.

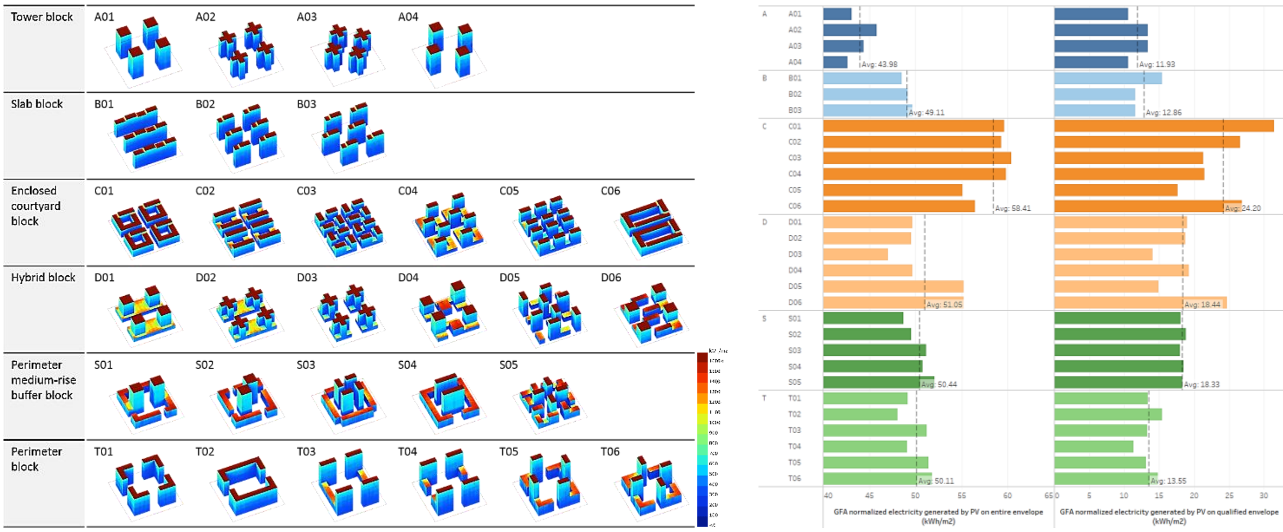


Figure 4: Visualization of annual cumulative irradiance level on building envelope surfaces and the two performance indicators calculated for the 30 typologies.

More specifically, the performance of the best typology (C03) is 41.6% higher than that of the worst typology (A04), according to the overall surface performance indicator; and the performance of the best performing typology (C01) is 198.1% higher than that of the two worst performing typologies (A01 and A04), according to the qualified surface performance indicator (Figure 5).

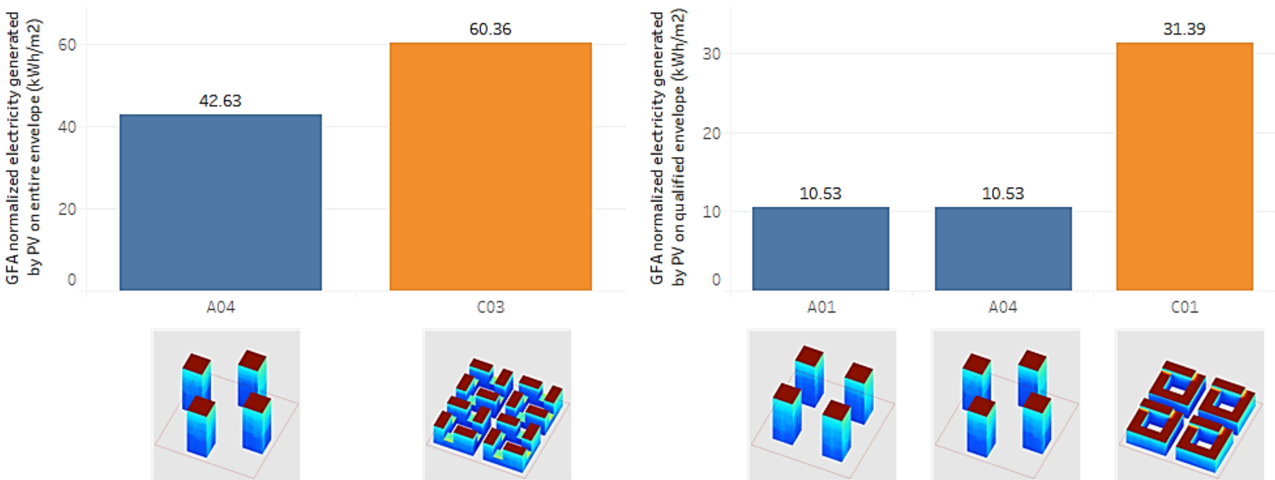


Figure 5: The difference in performance between the best and the worst performing typologies according to the overall surface performance indicator and the qualified surface performance indicator.

As shown in Figure 6, the cases in the enclosed courtyard building typology and the hybrid typology groups have relatively higher roof-to-floor area ratio and roof-to-envelope area ratio which leads to higher ratio of qualified envelope surface area. This explains the relatively better performance of both typologies which can be attributed to their relatively greater proportions of unobstructed horizontal building surfaces as compared to the other typologies.

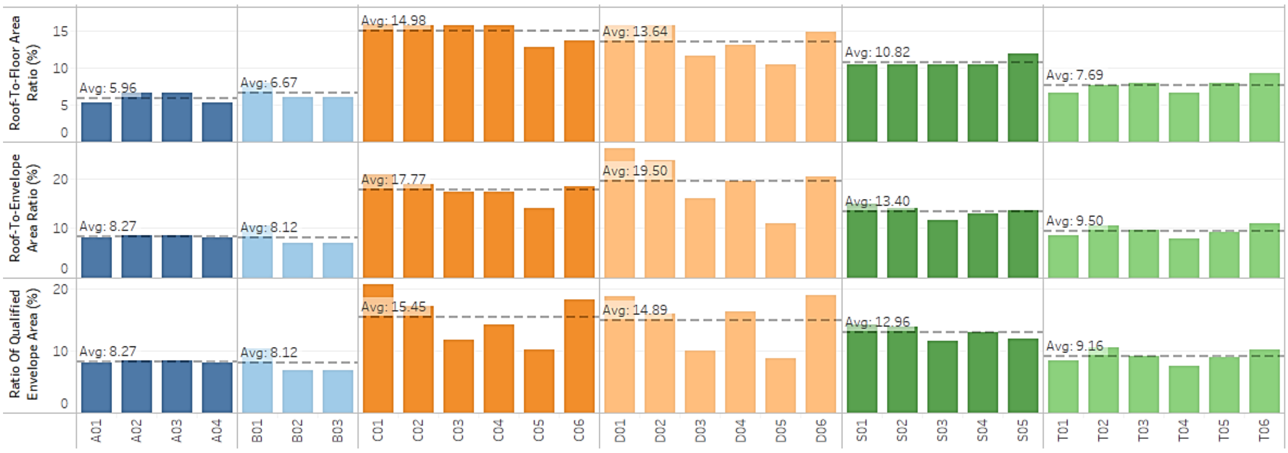


Figure 6: Roof-to-floor area ratio, roof-to-envelope area ratio and the ratio of qualified envelope surface area calculated for the 30 typologies.

3.2. Relationship between solar energy harvesting potential and building typology

Table 3 summarizes the key performance indicators, planning parameters and geometric variables calculated for the 30 building typologies. Linear regression analysis was conducted by considering both performance indicators as dependent variables and each of the planning parameters and the geometric variables as independent variable, and the results are shown in the scatter plots in Figure 7.

Typology ID	GFA normalized electricity generated by PV on entire envelope (kWh/m2)	GFA normalized electricity generated by PV on qualified envelope (kWh/m2)	Net Building Coverage (%)	Compacity (m^-1)	Average Area-to-Perimeter Ratio	Open Space Ratio	Roof-To-Floor Area Ratio	Roof-To-Envelope Area Ratio	GFA normalized envelope SkyEF (%/m2)	GFA normalized envelope SVF (%/m2)
A01	43.09	10.53	16.00	9.79	5.00	0.28	0.05	0.08	28.77	24.91
A02	45.79	13.33	20.00	11.75	4.17	0.27	0.07	0.08	28.44	26.20
A03	44.41	13.33	20.00	11.75	4.17	0.27	0.07	0.08	27.08	25.56
A04	42.63	10.53	16.00	9.79	5.00	0.28	0.05	0.08	27.07	24.69
B01	48.49	15.38	24.00	11.41	4.29	0.25	0.08	0.10	32.94	28.16
B02	49.15	11.60	18.00	12.91	3.73	0.27	0.06	0.07	34.28	28.45
B03	49.68	11.60	18.00	12.91	3.73	0.27	0.06	0.07	33.75	28.83
C01	59.59	31.39	48.00	11.47	3.75	0.17	0.16	0.21	34.77	31.97
C02	59.29	26.56	48.00	12.56	4.00	0.17	0.16	0.19	36.12	32.22
C03	60.36	21.32	48.00	13.74	3.33	0.17	0.16	0.17	36.58	32.31
C04	59.75	21.49	48.00	13.74	3.33	0.17	0.16	0.17	34.73	32.36
C05	55.09	17.63	40.00	13.82	3.33	0.19	0.13	0.14	35.82	30.55
C06	56.40	26.81	40.00	11.03	3.75	0.21	0.14	0.18	33.46	30.73
D01	49.69	19.02	48.00	9.06	5.77	0.17	0.16	0.26	28.25	27.10
D02	49.52	18.72	48.00	10.01	5.23	0.17	0.16	0.24	28.32	27.50
D03	47.01	14.06	36.00	10.92	4.94	0.21	0.12	0.16	28.38	26.57
D04	49.64	19.24	40.00	10.09	5.19	0.20	0.13	0.20	29.46	27.71
D05	55.23	14.87	32.00	14.37	3.47	0.22	0.11	0.11	34.13	30.43
D06	55.20	24.72	44.00	10.77	4.97	0.19	0.15	0.21	31.93	30.29
S01	48.73	18.02	32.00	10.58	4.96	0.22	0.11	0.15	29.96	27.56
S02	49.52	18.83	32.00	11.29	4.73	0.22	0.11	0.14	29.77	27.80
S03	51.12	18.00	32.00	13.66	3.55	0.22	0.11	0.12	32.26	28.56
S04	50.75	18.48	32.00	12.12	4.14	0.22	0.11	0.13	31.97	28.60
S05	52.08	18.34	36.00	13.26	3.69	0.21	0.12	0.14	30.80	28.60
T01	49.14	13.33	20.00	11.75	4.17	0.27	0.07	0.08	31.67	27.86
T02	48.04	15.38	24.00	11.00	4.62	0.24	0.08	0.11	30.69	27.40
T03	51.18	13.28	24.00	12.25	3.87	0.25	0.08	0.10	33.02	29.23
T04	49.10	11.32	20.00	12.36	3.92	0.26	0.07	0.08	32.41	28.30
T05	51.43	13.11	24.00	12.79	3.68	0.25	0.08	0.09	32.45	29.14
T06	51.76	14.85	28.00	12.75	3.70	0.24	0.09	0.11	31.40	29.01

Table 3: The key performance indicators, planning parameters and geometric variables calculated for the 30 building typologies.

Regarding solar energy harvesting potential on the whole building level, i.e. the GFA normalized electricity generated by PV on the entire building envelope surfaces, The GFA normalized envelope SVF is the most significant factor (R^2=0.97, $p<0.0001$) which can account for 97% of the variance in the overall surface performance indicator. This suggests the electricity generated from PV on the entire building envelope, or the total solar radiation receivable on building envelope, is significantly and positively related to the total SVF for the entire building envelope. This is understandable since SVF quantifies the radiation exchange between urban surfaces and sky hemisphere. The higher the SVF for a given building surface, the larger the amount of solar radiation it can receive, and consequently, the higher the electricity output of PV panel covering that surface.

The GFA normalized envelope Sky Exposure Factor is also a significant and positive factor, though to a lesser extent (R^2=0.67, $p<0.0001$), accounting for 67% of the variance in the overall surface performance indicator.

Although Sky Exposure Factor quantifies the ratio of visible sky, or level of visual obstruction of the sky, for a given building surface, and therefore, affecting the amount of solar radiation receivable on that surface, it is not the sole determining factor of the latter which is also affected by the relative view angle between the surface and the visible sky patch. In other words, two identical building surfaces with the same Sky Exposure Factor may receive different amounts of solar radiation, depending on their orientations relative to the visible sky. This may account for the relatively lesser predictive power of this factor as compared to that of SVF.

The rest of the planning parameters and geometric variables examined in this study are also significantly related to the overall surface performance indicator, thought to various extents. Both roof-to-floor area ratio and building site coverage are positive factors, account for 56% and 55% of the variation in the overall surface performance indicator, respectively. On the other hand, both Open Space Ratio and area-to-perimeter ratio are negative factors, accounting for 55% and 31% of the variance, respectively. Compacity and roof-to-envelope area ratio are the positive factors with the least predictive power, account for only 27% and 26% of the variance, respectively.

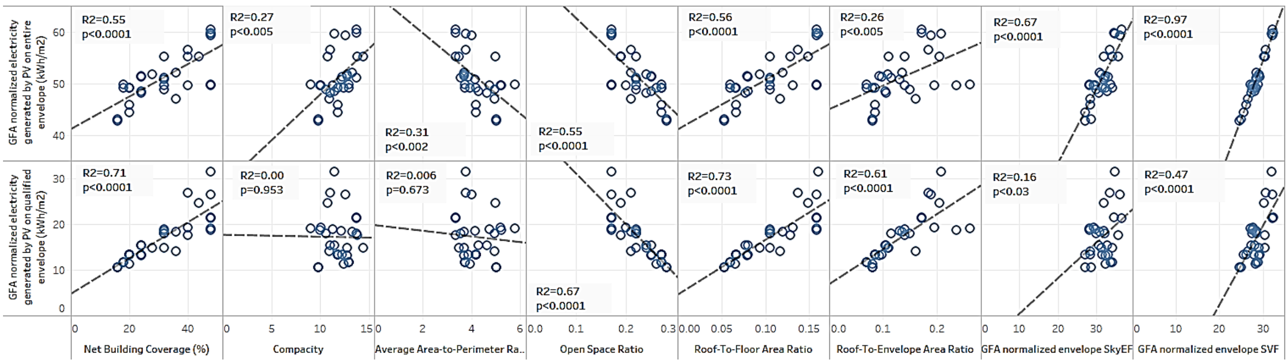


Figure 7: Scatter plots between the performance indicators and the planning parameters and the geometric variables.

As to the solar energy harvesting potential considering only the qualified building envelope surfaces, i.e. the GFA normalized electricity generated by PV on qualified building envelope surfaces annually, roof-to-floor area ratio is the most significantly factor (R^2=0.73, $p<0.0001$), accounting for 73% of the variance in this performance indicator. This suggests that, depending on the building typology implemented, the higher the ratio of the area of roof surfaces to that of the total usable floor area, the higher the amount of electricity produced by PV on building surfaces reaching the annual cumulative irradiance level threshold. This is followed by the positive factors of building site coverage (R^2=0.71, $p<0.0001$) and roof-to-envelope surface area ratio (R^2=0.61, $p<0.0001$) and the negative factor Open Space Ratio (R^2=0.67, $p<0.0001$). The geometric variables related to SVF and SkyEF have relatively the least impact, accounting for only 47% and 16% of the variance in the performance indicator, respectively. On the other hand, compacity and area-to-perimeter ratio were found to have no significant impact on the performance indicator.

4. Discussion and conclusions

The results of the study on the thirty generic urban blocks in six different typologies provide convincing evidences that building typology has significant impact on solar energy harvesting potential. Given a set of fixed planning conditions, the difference in the solar energy harvesting potential for qualified building surfaces between different building typologies can be as high as 198.1%. In other words, the electricity output from PV or BiPV can be tripled, depending on the building typology adopted, which can contributes to significant reduction in the use of electricity from the existing power grid.

The results also suggest that, for a given built density, the enclosed courtyard urban block typology composed of medium-rise perimeter blocks and the hybrid typology composed of alternating high-rise and medium-rise blocks have far greater potential in solar energy collection, considering either the entire building envelope surfaces or those surfaces qualified by a minimum annul cumulative irradiance threshold only.

On the other hand, the free-standing tower blocks and parallel linear slab blocks perform relative the worst among all the typologies examined here, with as large as 50% lower potential on average than that of the enclosed courtyard typologies. As shown in Figure 8, the rooftop spaces of the high-rise residential tower blocks are usually covered by utility equipment such as water tanks and pipelines and telecommunication facilities, leaving only limited roof spaces to be considered for the installation of PV panels, not to mention the difficulties posed by the ventilation insulation tiles and the restrictions on safety setback distance from the edges of the roof. As illustrated in Figure 9, the actual rooftop spaces potentially suitable for PV deployment as highlighted in the diagram could be less than half of the area of the floor plan.

Figure 8: Rooftop spaces of typical high-rise residential tower blocks. (Photos courtesy Sunseap, 2017)

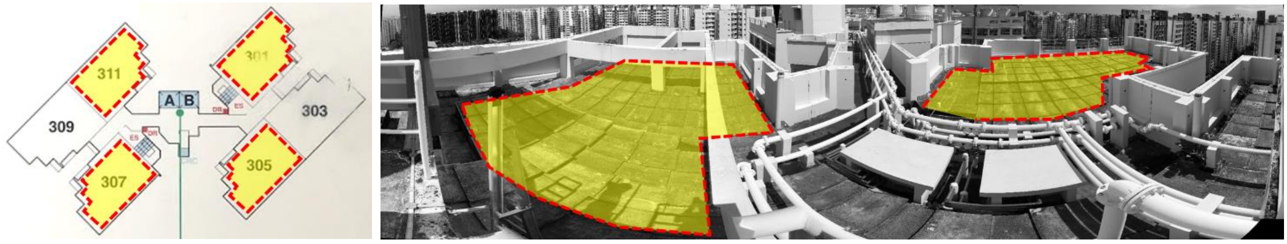


Figure 9: Building floor plan and panoramic view of the rooftop space of Blk614B of the Edgefield Plains precinct, Punggol new town, Singapore. (Source: the authors)

Considering the fact that the tower and slab block typologies are commonly adopted in the public housing new towns in Singapore currently, the findings of this study further emphasize the importance and necessity of exploring and testing alternative building typologies in public housing planning and building design which may have higher potential in solar energy harvesting as compared to the widely implemented design options currently.

This study also identified some of the key planning parameters and architectural design factors that may have significant impact on solar energy harvesting potential across different building typologies. The findings suggest that Sky View Factor, frequently cited as a key factor related to Urban Heat Island, can be adopted as a proxy factor for preliminary evaluation of solar harvesting potential on the whole-building scale if detailed local weather data is not available. The other factors as identified can serve as reference for design guidelines to optimize solar energy harvesting. For example, in order to maximize PV electricity collected from qualified building surfaces, it could be considered to increase roof-to-floor area ratio, building site coverage, roof-to-envelope area ratio or reduce Open Space Ratio.

To summarize, the observations drawn from this study imply that building typology matters to a great extent in terms of optimizing building design to maximize on-site clean energy generation from solar radiation collection, especially in the early stage of urban planning and architectural design when schematic design matters the most. The rigorous methodology and the flexible simulation-based workflow can be customized and applied in studies of solar energy harvesting potential in relation to urban planning and architectural design in other geographic locations or regions taking into consideration of the local planning and climatic context.

5. Acknowledgement

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