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Neighbouring shading effect on photovoltaic panel system: Its implication to green building certification scheme

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ABSTRACT

Nowadays, photovoltaic (PV) system is one of the commonly adopted renewable energy systems. Many countries promote the application of PV system in buildings through green building certification schemes. On a building rooftop, there are various building facilities which may cast shadow on PV panels, resulting in reduction in electricity generation. Currently, there is rare attention to the neighbouring shading effect (NSE) on the performance of rooftop PV system. This study investigates the performance of PV system under NSE, using weather data of seven cities located at different geographical latitudes. These seven cities are Singapore (1.37° N), Hong Kong (22.3° N), Shanghai (31.17° N), Beijing (39.8° N), Harbin (45.72° N), Washington, USA (38.98° N) and London, UK (51.15° N). By comparing the building cases with and without considering NSE, the results unveil a substantial percentage difference in PV electricity generation and energy payback time (EPBT) ranging from −12.62% to −28.34% and −14.43% to −39.55%, respectively. Moreover, it reveals the dependence of percentage difference in PV electricity generation and EPBT on the latitude of a city. For the current green building certification schemes, mandatory requirement to take NSE into account for assessing the performance of rooftop PV system is recommended.

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1. Introduction

In most developed countries and cities, energy policy is formulated with an objective to meet the energy need of a community safely, reliably and efficiently. Nowadays, electricity energy generated by renewable energy systems is one of the prevailing directions in energy policy for clean and sustainable energy supply. Photovoltaic (PV) system is one of the commonly adopted renewable energy systems and can be installed for building application such as building-integrated PV glazing/panel system attached on building external wall and free-standing PV panel system installed on building roof.

From the view point of building owners, a number of factors such as extra capital investment, space occupied, aesthetics value of a building, etc. may be obstacles to the utilization of PV system in a building. In many modern countries, the local governments promote the application of PV system in buildings through various types of green building certification schemes such as Green Mark adopted in Singapore [1,2], BREEAM (Building Research Establishment's Environmental Assessment Method) in UK [3], LEED (Leadership in Energy & Environmental Design) in USA [4], BEAM (Building Environmental Assessment Method) Plus scheme in Hong Kong [5], DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) in Europe [6], PGB50189 – 2015: *Design standard for energy efficiency of public buildings* [7] and GB/T 50378–2019: *Assessment standard for green building* [8] in Mainland China. There is no argument that clean energy can be produced by a PV system without the consumption of fossil fuel.

In addition, for a holistic assessment on the application of a PV system, its environmental feasibility should be taken into consideration. In this regard, Energy Payback Time (EPBT) is a widely adopted index for this assessment. It is a ratio between the total embodied energy of a PV system and the annual electricity energy generated by the system. The length of an EPBT should be at least equal to or even shorter than the lifespan of a PV system so that the extra embodied energy can be offset by the electricity energy produced by the PV system.

1.1. Problem identified

Building-integrated photovoltaic (BiPV) system (installed on

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Nomenclature

G_T	Total solar radiation incident on PV array
$G_{T,ref}$	Total solar radiation incident on PV array at reference condition
I	Terminal current
I_D	Diode current
I_L	Photocurrent
$I_{L,ref}$	Photocurrent at reference condition
I_o	Diode reverse saturation current
$I_{o,ref}$	Diode reverse saturation current at reference condition
k	Boltzmann constant, 1.381×10^{-23} J/K
q	Electron charge constant, 1.602×10^{-19} C
R_s	Series resistance
T_a	Ambient air temperature
T_c, $T_{c,ref}$	Cell temperature, actual and at reference condition
U_L	PV array thermal loss coefficient
V	Terminal voltage
γ	Empirical PV curve-fitting parameter
η_c	PV module conversion efficiency
τ	PV module transmittance
$\tau\alpha$	PV module transmittance-absorptance product

vertical building façade, as shown in Fig. 1) and free-standing photovoltaic (PV) panel system (installed on building roof, as shown in Fig. 2) are commonly adopted renewable energy systems in building application. For buildings located in highly dense urban area, BiPV system cannot provide effective performance due to adjacent shading effect cast by surrounding buildings. On the other hand, free-standing PV panel system is generally installed on the rooftop of a building where the effect of adjacent shading from surrounding buildings is comparatively insignificant [9].

Nonetheless, a free-standing PV panel system may still receive substantial shading effect which can significantly reduce its electricity energy generation. On the rooftop of a typical commercial building, there is a number of objects such as building services equipment, pump room, water tank, lift machine room, etc. which may cast shadow on the solar panels of a PV system, incurring a reduction in PV electricity energy produced.

In most of the current green building certification schemes, there is no consideration on the shading effect caused by nearby facilities and machine rooms when evaluating the energy performance as well as the life-cycle assessment of a rooftop PV panel system. Among the various green building certification schemes and standards, there are two schemes: Green Mark from Singapore [1] and BEAM Plus from Hong Kong [5] in which partial shading from on-site building rooftop mechanical and electrical services has to be taken into account for solar energy feasibility study. It is noted that these two cities are located at low geographical latitudes (Singapore: 1.29° N and Hong Kong: 22.3° N). On the contrary, for the other green building certification schemes such as BREEAM, LEED and Chinese National Building Energy Standards implemented in the cities located at comparatively higher geographical latitudes (UK, USA, Canada and Mainland China), there is no mandatory requirement to take the neighbouring shading effect (NSE) shadowed by rooftop facilities into consideration.

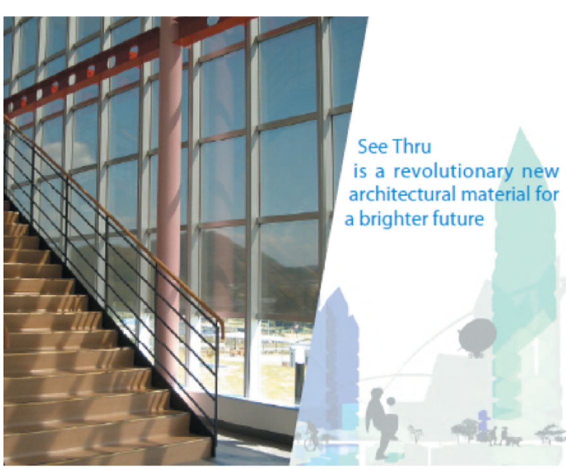


Fig. 1. Building integrated PV glazing system(Photo Credit: Suntech Power Co., Ltd.).

Fig. 2. Free-standing PV panel system (Photo Credit: Green Field Solar Solution Pvt. Ltd.).

Although it is straightforward that ignoring the NSE from surrounding facilities or machine rooms may result in over-estimation on the electricity energy generation of a rooftop PV panel system; and the EPBT of a PV panel system may be inaccurately calculated, there is no detailed study or information on the order of magnitude of the error incurred. Moreover, for assessing the performance of a rooftop PV panel system, a correlation between the effect of neighbouring shading and the latitude of a city is unknown. It is worthy studying the characteristic and significance of NSE on the electricity energy generation as well as the EPBT of a PV panel system surrounded by nearby facilities and machine rooms on the rooftop of a building, under various climatic conditions of different cities located at different geographical latitudes.

1.2. Research objectives

The objective of this study is to investigate the effect of neighbouring shading on the energy performance of free-standing PV panel system installed on the rooftop of commercial building with surrounding facilities and machine rooms; and the impact on the life-cycle assessment of PV panel system. Moreover, as the influence of NSE on a PV panel system is also dependent on the variation of solar angles over a year, seven cities located at different geographical latitudes were selected for this research work with an aim at evaluating the correlation between NSE on a PV panel system and the latitude of a city. The findings from this study can form a basis for policy makers to formulate a mandatory requirement on the current green building certification schemes to take NSE into account for assessing the energy and environmental performance of a rooftop PV panel system, as part of the approach for reliable and sustainable energy supply in a city.

1.3. Previous studies

There are various researches on the impact of shading effect on the performance of PV system by worldwide researchers. Study on the effective structure/configuration of PV system for improving PV generation performance under shading condition is one of the major research directions. Sugumar et al. have developed an on-time partial shading detection technique for electrical reconfiguration in solar PV system [10]. By using a static reconfiguration and a modified couple matching technique, the difference in row voltage can be estimated for mitigating the partial shading condition on solar PV array.

In India, Winston and his research team proposed new PV array topologies to improve the performance of PV system during partial shading conditions [11]. In their study, eight different shading patterns were considered in an analysis for seven types of array configurations. Similar studies including non-overlapped bypass diode PV array configuration [12], cross diagonal view configuration [13], automatic switching reconfiguration algorithm [14], and new PV system structure combining conventional maximal power point tracking (MPPT) technique and PV physical arrangement [15] have been carried out by various researchers.

In order to optimize the performance of PV systems under partial shading condition, various MPPT algorithms have been investigated worldwide. Examples of these tracking algorithms include artificial neural network, fuzzy logic controller, evolutionary algorithm, swarm intelligence, Chaos theory, etc. [16].

In addition to the application of MPPT algorithms, Ramli & Salam applied a dc power optimizer (DCPO) - a specialized dc-dc converter to harvest the energy output from a shaded PV panel [17]. Another team of researcher (Gupta et al.) [18] replaced the bypass diode of a PV system by an electromagnetic relay through an efficient alternative approach that consumes less power and offers higher efficiency under partial shading condition of a solar module.

Some researchers developed new methods to assess the power loss as well as the PV energy generation under partial shading condition including Shading Factor by Rodrigues et al. [19], Reduction Factor by Piccoli et al. [20] and Shading Fraction by Chepp & Krenzinger [21].

On the rooftop of a typical commercial building, there is a number of objects such as building services equipment, pump room, water tank, lift machine room, etc. which may cast shadow on the solar panels of a PV system, incurring a reduction in PV electricity energy produced.

In most of the current green building certification schemes, there is no consideration on the shading effect caused by nearby facilities and machine rooms when evaluating the energy performance as well as the life-cycle assessment of a rooftop PV panel system.

Taking a green building certification scheme - the Hong Kong BEAM [5] as an example, 1 to 5 credits can be allotted to a project building under evaluation where the minimum percentage of 20%–100% of the building footprint is covered by PV panels and/or other renewable energy generation facility. If NSE must be taken into account in the current green building certification schemes, the actual energy and environmental performance of a rooftop PV panel system under neighbouring shading effect can be accurately evaluated.

The above literature review unveils that shading effect is vital and should be included in evaluating the performance of a PV system. However, there is rare study on the energy performance and environmental feasibility of rooftop PV panel system, taking into consideration the NSE which is cast by nearby facilities and machine rooms. It is worth investigating the effect of neighbouring shading on the energy and environmental performance of rooftop PV panel system under various climatic conditions; and the feasibility of incorporating NSE into the current green building certification schemes.

2. Research methodology

This study investigates the energy and environmental performance of free-standing rooftop PV panel system with NSE, under various climatic conditions in different cities. The research methodology is detailed as follows.

2.1. Gathering roof plans of existing commercial buildings

Through liaison with the management companies of three commercial buildings, the floor plans with dimensions of three existing building roofs in Hong Kong were acquired. The gathered information was used to model a free-standing PV panel system which was assumed to be installed on the rooftops of these three commercial buildings. The structure and facilities on the building roofs such as parapet wall, machine rooms, building services equipment, etc. were included in computer modelling so that their shading effect cast on the PV panel system was taken into account in computer simulations.

2.2. Evaluating the electricity energy produced by free-standing rooftop PV panel system under neighbouring shading effect

The free-standing PV panel systems on the three building roofs were modelled by a building energy simulation program EnergyPlus [22]. This is a widely adopted simulation program and is commonly used by worldwide engineers and researchers to evaluate the energy and thermal performance of various types of energy systems and buildings [23–26]. EnergyPlus can be used to calculate the building thermal loads as well as the energy consumption of a HVAC (heating, ventilating and air-conditioning) plant based on the input of a building and the associated energy systems [27–30]. Moreover, renewable energy systems can be modelled and their energy performance can be simulated and evaluated by this building energy simulation program [31–33].

In this study, an “Equivalent One-Diode” model (also known as TRNSYS PV model) was adopted and run in the building energy simulation program EnergyPlus, for determining the energy produced by a PV panel. This model was developed by Townsend [34] and it was incorporated into a component for the TRNSYS simulation program by Eckstein [35].

This model adopts a “four-parameter” equivalent circuit (as shown in Fig. 3 below) to model crystalline (both mono and poly) PV modules; and to predict the current-voltage characteristics of a PV module.

The terminal current I of a PV cell is expressed as follows:

$$I = I_L - I_D \tag{1}$$

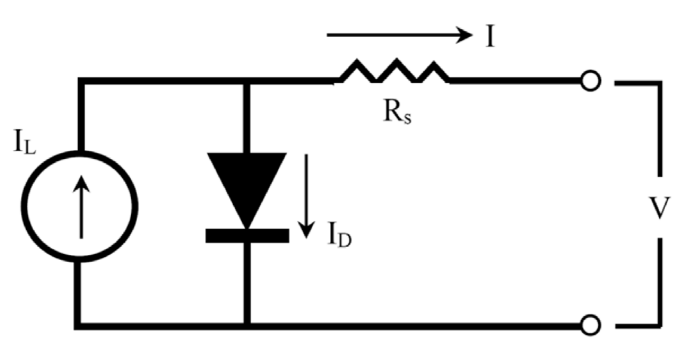


Fig. 3. A four-parameter equivalent circuit of the Equivalent One-diode Model.

$$I = I_L - I_o\left[exp\left(\frac{q}{\gamma k T_c}(V + IR_s)\right) - 1\right] \tag{2}$$

The photocurrent I_L depends linearly on the incident radiation as shown below. A value of 1000 W/m^2 was used for the reference insolation $G_{T,ref}$.

$$I_L = I_{L,ref}\frac{G_T}{G_{T,ref}} \tag{3}$$

The diode reverse saturation current I_o is a temperature dependent quantity which will be determined by Eq. (4).

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3 \tag{4}$$

In this TRNSYS PV model, I_L is a function of irradiance and cell temperature; and I_o is a function of temperature only. This PV model uses an iterative search routine in these equations to calculate the equivalent circuit characteristics. The cell temperature of the PV module is calculated by Eq. (5) [36], as expressed below. This is based on a standard NOCT (Nominal Operating Cell Temperature) measurement to compute the module temperature T_c at each timestep.

$$T_c = T_a + \frac{1 - \frac{\eta_c}{\tau}}{G_T \tau\alpha / U_L} \tag{5}$$

In EnergyPlus, there is a Shadow Algorithm for computing NSE, taking into consideration the solar angles and the geometry of a PV panel system and its surrounding objects.

In this study, seven cities located at different geographical latitudes were selected for evaluation. The first one is Singapore located at 1.37° N, 103.98° E where a green building certification scheme Green Mark [1] is being implemented. Another four cities come from China. China is a populous country in the world and the area is approximately equal to 9.6 million km^2. It has 662 cities that fall into a range of latitudes from 3.50° N (Zengmu Shoal of the Nansha Islands) to 53.31° N (the northern edge of Mohe in the far Northeast). Due to this large range of latitude, China has a variety of climate which is primarily divided into five climate zones namely (i) Severe Cold, (ii) Cold, (iii) Hot Summer and Cold Winter, (iv) Mild, and (v) Hot Summer and Warm Winter, as depicted in Fig. 4.

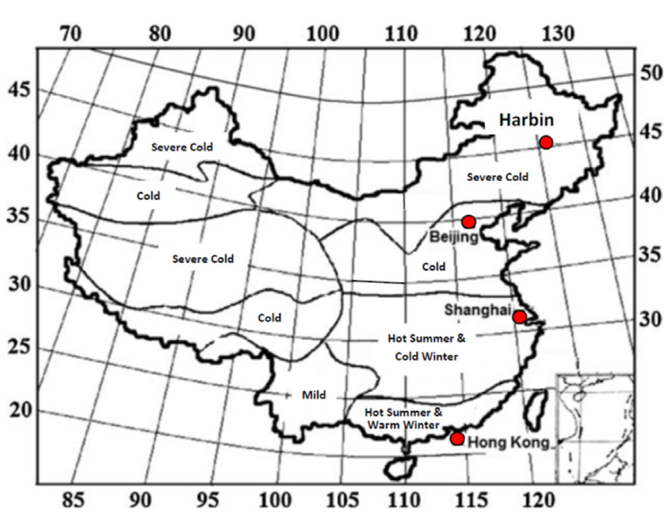


Fig. 4. A map of China showing five major climate zones and the four cities selected for this study.

The four selected cities from China are Hong Kong (22.3° N, 114.17° E), Shanghai (31.17° N, 121.43° E), Beijing (39.8° N, 116.47° E) and Harbin (45.72° N, 126.68° E). They are located at four different climate zones in China – Hot Summer and Warm Winter; Hot Summer and Cold Winter; Cold; and Severe Cold, respectively. A green building certification scheme BEAM Plus [5] is applied in Hong Kong. On the other hand, two national building energy standards: PGB50189–2015 and GB/T 50378–2019 [7,8] are adopted in the other three cities in China. The remaining two cities are Washington DC, USA (38.98° N, 77.47° W) and London, UK (51.15° N, 0.18° W). The green building certification schemes used in these two cities are LEED [4] and BREEAM [3], respectively.

In this study, the adopted free-standing PV system consists of six PV panels, with 300 Wp each, and the dimensions of each PV panel are 1 m (W) x 2 m (H). They were set at a tilt angle equivalent to the latitude of each city, facing the southwest or south direction which could give a maximum annual solar radiation in a city. Computer simulations were run with hourly weather data file of each city [37] to evaluate the electricity energy generated by the PV panel system under the influence of NSE.

2.3. Evaluating the energy payback time of PV panel system under neighbouring shading effect

Life cycle assessment forms a vital part on assessing the environmental feasibility of a PV system in which embodied energy for material extraction, manufacturing and assembly should be involved. For a free-standing PV panel system, the major components include front (low-iron) glass, PV module, aluminium thermal absorber, insulation material, steel stand & accessories, electric wiring and inverter. In this study, an index termed as Energy Payback Time (EPBT) was used for assessing the environmental performance of the PV panel systems installed on the rooftops of the selected buildings with NSE, under various climatic conditions of the seven selected cities. EPBT can be interpreted as the number of years a PV system takes to generate electricity energy for offsetting its extra embodied energy consumed, as shown in Eq. (6) below. A PV system is deemed environmentally feasible if the EPBT is equal to or shorter than the lifespan of the system.

$$\underset{(\text{yrs.})}{\text{Energy Payback Time (EPBT)}} = \frac{\text{Embodied Energy of a PV System (MJ)}}{\text{Annual Electricity Energy Generated (MJ/yr.)}} \tag{6}$$

3. Research findings

3.1. Roof plans of three commercial buildings

Through liaison with three property management companies, the roof plans of three existing commercial buildings in Hong Kong were collected. The detailed drawings of these three building roofs (named as building roofs R1, R2 and R3) are shown in Figs. 5-7 respectively. The design of the building roofs is deemed as typical and is independent of the geographical location of a city as the roof area is generally occupied by various building services equipment and machine rooms. In each of these building roofs, an area (bound by a blue rounded-rectangle as shown in these three roof plans) had been identified and selected for installing a free-standing PV panel system for electricity energy generation.

On the building roof R1 as shown in Fig. 5, a flat area (originally reserved for maintenance work) located at the north-western corner of the roof plan was selected to house a PV panel system

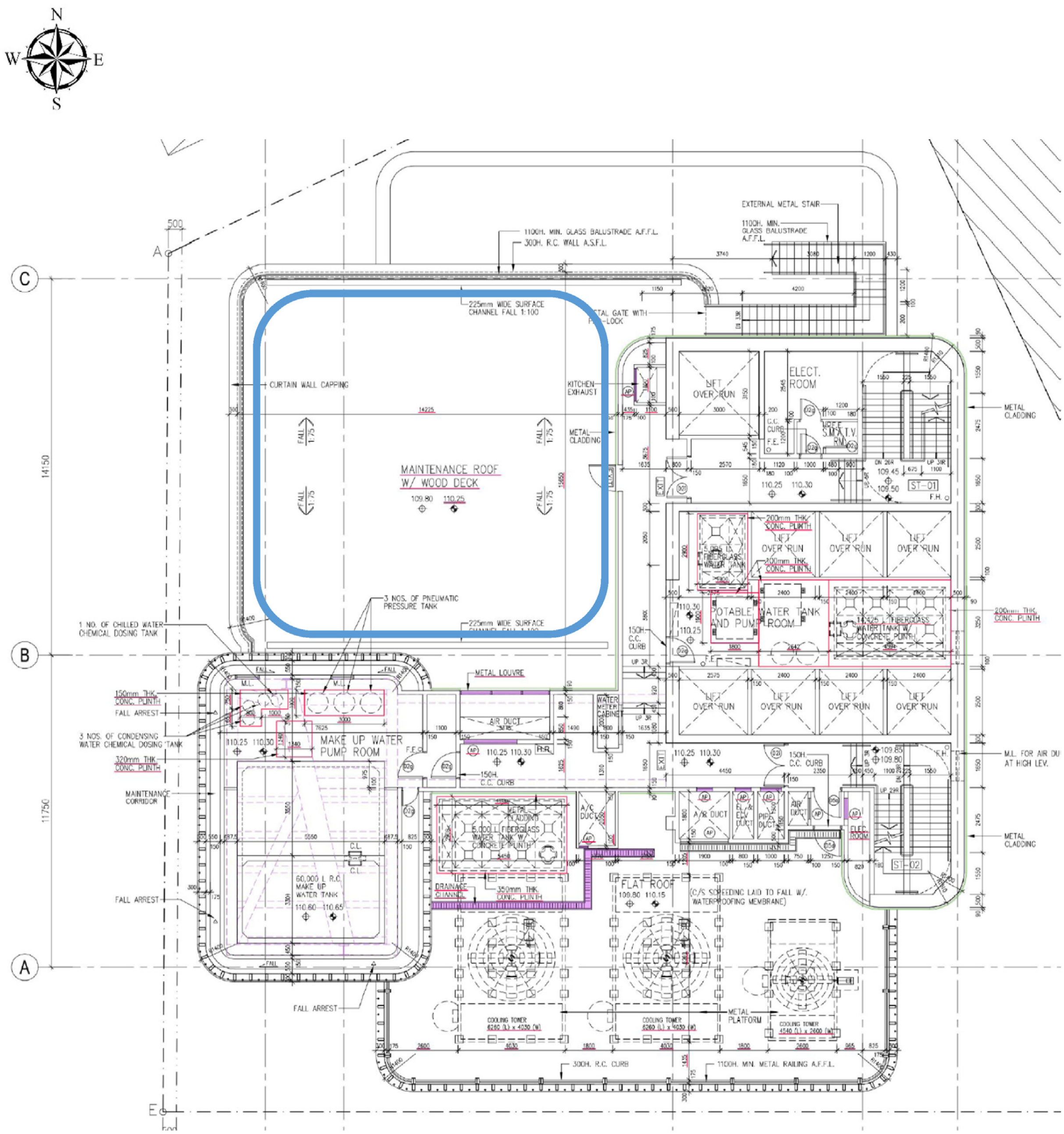


Fig. 5. Roof plan of commercial building roof R1.

in this study. On the east of this flat area, electric switch room, lift shaft, water tank and pump room were constructed. Moreover, there are water tanks, pump room, and cooling towers located at the southern side of the flat roof area. In the western and northern directions of this flat roof area, there is no any nearby object or building structure.

For the building roof R2 depicted in Fig. 6, an empty space located at the northeast corner of the roof plan was used to install a PV panel system. This area is surrounded by pump room, A/C (air-conditioning) plant room and lift machine room at its western side; while there is no neighbouring shading from the other three directions of this empty space.

On the last building roof R3 (as shown in Fig. 7), the PV panel system was installed on the north-eastern corner of this roof area. There are lift machine room, cooling tower, pump room and emergency generator room located at the south-western and north-western sides of this selected area.

According to the various studies by worldwide researchers, a south-facing [38–41] or a southwest-facing [42–44] fixed PV panel located in the Northern Hemisphere can give higher electricity yields. As described above, the neighbouring shading effect on the PV panel on building roof R1 mainly comes from the facilities at the eastern and southern sides. In order to achieve higher PV electricity generation, the PV panel is set towards the southwest of this building roof. On the other hand, as the western part of building roof R2 is largely occupied by various building services equipment, the PV panel on this roof is installed towards the south. On building roof R3, the machine room and the cooling towers (mainly located at the northwest) cast shadow on the PV location. As a result, the PV panel is set at the southwest direction.

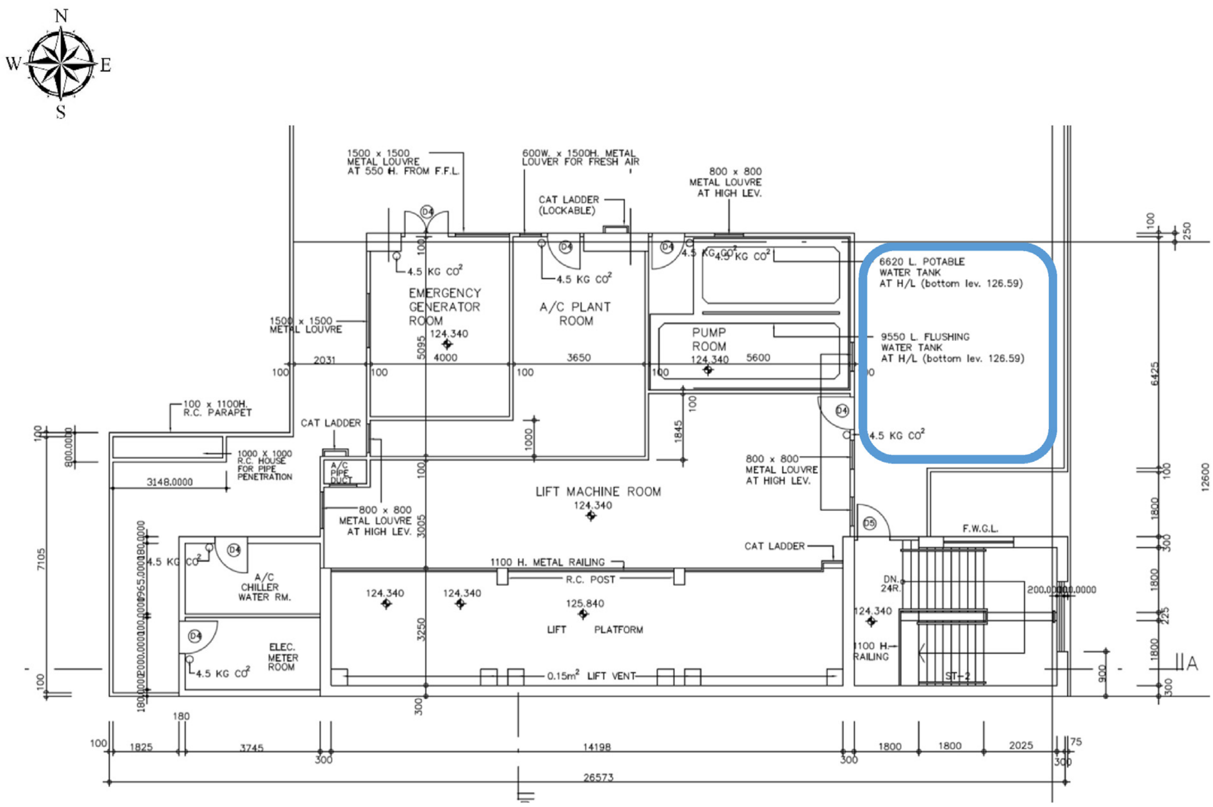


Fig. 6. Roof plan of commercial building roof R2.

3.2. Solar radiation in the seven selected cities

Hourly weather data including direct and diffuse solar radiations (Wh/m^2) were acquired from typical meteorological year (TMY) weather files supplied by the Building Technologies Office, U.S. Department of Energy [37]. The monthly variations of the direct and diffuse solar radiations of the seven selected cities were plotted in Fig. 8 for illustration.

Fig. 8 (a) is a graph of the monthly direct and diffuse solar radiations in Singapore. It shows that there is no large variation in the diffuse solar radiation over the whole year. On the other hand, the monthly direct solar radiation is quite stable except November and December in which relatively lower monthly direct solar radiations were recorded. It is also noted that the monthly diffuse solar radiation is generally higher than the monthly direct solar radiation in this city.

The monthly profiles of solar radiation in Hong Kong are depicted in Fig. 8 (b). It shows that the monthly diffuse solar radiation is higher than the monthly direct solar radiation in the first half of the year, while opposite situation appears in the second half of the year. The diffuse solar radiation follows a typical seasonal variation, i.e. minimum value is found in January, rising to a maximum in July and then falls to low values in the winter months. Fig. 8 (c) shows the monthly pattern for Shanghai. Despite the larger fluctuation in the monthly direct solar radiation, the profiles are similar to that in Hong Kong.

In Washington DC, both the direct and diffuse solar radiations have similar monthly profiles (Fig. 8 (d)). Moreover, the monthly direct solar radiation is higher than the monthly diffuse solar radiation over the entire year. Another city, London, has a similar pattern of variation as that in Washington except two months – March and June in which the monthly diffuse solar radiations are higher than the monthly direct solar radiations (Fig. 8 (g)).

Fig. 8 (e) & (f) shows that Beijing has a similar trend of monthly variation in the direct and diffuse solar radiations as that in Harbin. In both cities, the maximum direct and diffuse solar radiations appear in March–April and July–August, respectively.

3.3. Electricity energy generated by PV panel systems

3.3.1. Monthly electricity energy generated

The simulation results of electricity energy generated by the free-standing PV panel systems on the three building roofs under seven different climatic conditions are plotted in Fig. 9. The first column lists the results for building roof R1 and the graphs are arranged in an order according to the latitudes of the seven cities. The first graph was plotted for Singapore (1.37°N). For the building case without NSE, the monthly electricity energy generated ranges from 573 MJ (in November) to 669 MJ (in April) and the annual electricity energy is 7524 MJ. The corresponding annual electricity energy generated under NSE was 6575 MJ. By comparing the PV electricity energy generated from the building cases with and without NSE, it reveals that the percentage differences range from −8.98% (in July) to −15.84% (in October), with an annual percentage difference of −12.62% which was primarily caused by the NSE of the surrounding facilities and machine rooms.

The results of the other six building cases (when the building roof R1 is located in the other six cities) are presented in a similar format in the rest of the first column in Fig. 9. It discloses that the percentage differences in PV electricity energy generation between the cases with and without NSE are comparatively high in the winter months while smaller percentage differences are found in

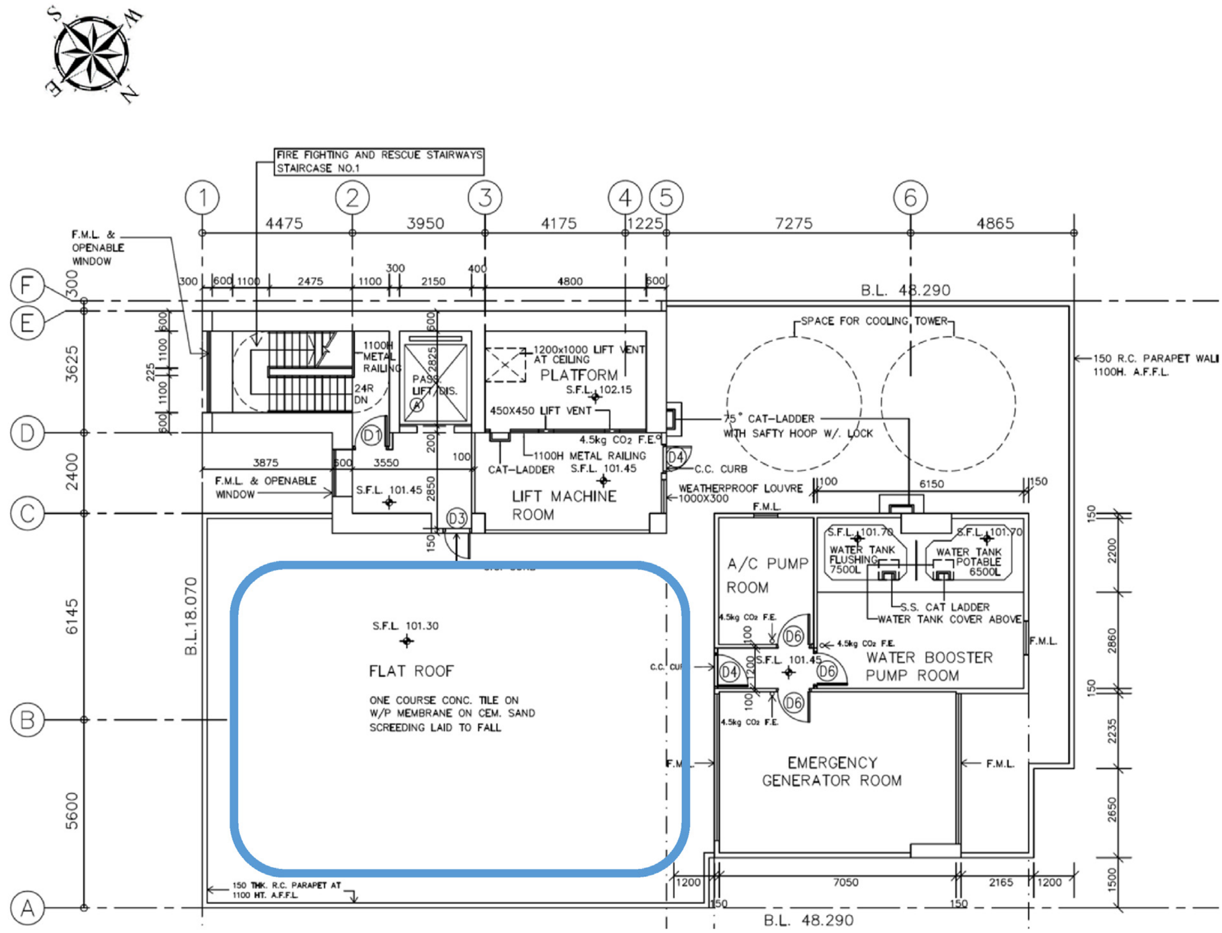


Fig. 7. Roof plan of commercial building roof R3.

summer season. For instance, in the Hong Kong city, a maximum monthly percentage difference of −34.15% is found in December while July gives a minimum monthly percentage difference of −8.51%. This phenomenon becomes more significant for the other cities located at higher north latitudes. It can be explained with the aid of stereographic sun-path diagrams of these cities depicted in Fig. 10.

For the building roof R1, neighbouring shading is primarily cast by the facilities and machine rooms located in the south/southeast direction (pls. refer to Fig. 5). Solar angles (solar altitude) at 11:00 in a summer month and a winter month are used for illustration. As shown in Fig. 10, the solar altitudes at 11:00 in June of all the seven cities range from 50° in Singapore (1.37° N) (as shown in Fig. 10 (a)) to about 75° in Shanghai (31.17° N) (as shown in Fig. 10 (c)), which are relatively high. In contrast, the corresponding values of solar altitude in December are much lower. The stereographic sun-path diagrams show that the solar altitude at 11:00 (in December) in Singapore is 50° (as shown in Fig. 10 (a)) and this solar angle drops to about 15° in London (as shown in Fig. 10 (g)). Compared to the situation in summer month, a lower angle of solar altitude in the winter month makes the NSE cast by the nearby facilities and machine rooms more significant, leading to a higher percentage difference in PV electricity energy generation between the cases with and without NSE, as shown in the first column of Fig. 9.

The second row of Fig. 9 shows the simulation results for building roof R2. Unlike the results from building roof R1, smaller percentage differences in monthly PV electricity generation between the cases with and without NSE are found in the winter months. Taking Shanghai as an example for illustration, a smallest percentage difference of −9% is found in December while the maximum percentage (−24.35%) occurs in July. This effect appears more significant for cities located at higher latitudes.

In building roof R2, the PV panel system was set towards the south direction and the dominant NSE came from the machine rooms located at the southwest of the PV panel (Pls. refer to Fig. 6). As seen from the stereographic sun-path diagrams in Fig. 10, a city has an earlier time of sunset in winter season than that in summertime. For instance, the time of sunset in December is 17:00 in Shanghai (31.17°N) (see Fig. 10 (c)) while the time of sunset in June is 19:00. The time of sunset in summer is 2 h later than that in winter. This leads to more amount of solar radiation received by the PV panel in building roof R2 without NSE than that of a building case with NSE during the summer months, resulting in a higher percentage difference in PV electricity energy generation in the summer season.

In contrast, there is no solar radiation coming from the southwest direction after 17:00 in December, no matter there is nearby shading object or not, resulting in a comparatively lower percentage difference in PV electricity energy generation caused by NSE during the winter season. As the difference in the time of sunset becomes larger for cities located at higher north latitudes, the above effect becomes more significant in these cities.

The last column in Fig. 9 lists the simulation results for building roof R3. The PV panel system faces the southwest and is surrounded by nearby facilities and machine rooms at its southwest and northwest directions. The graphs of the first five cities (Singapore,

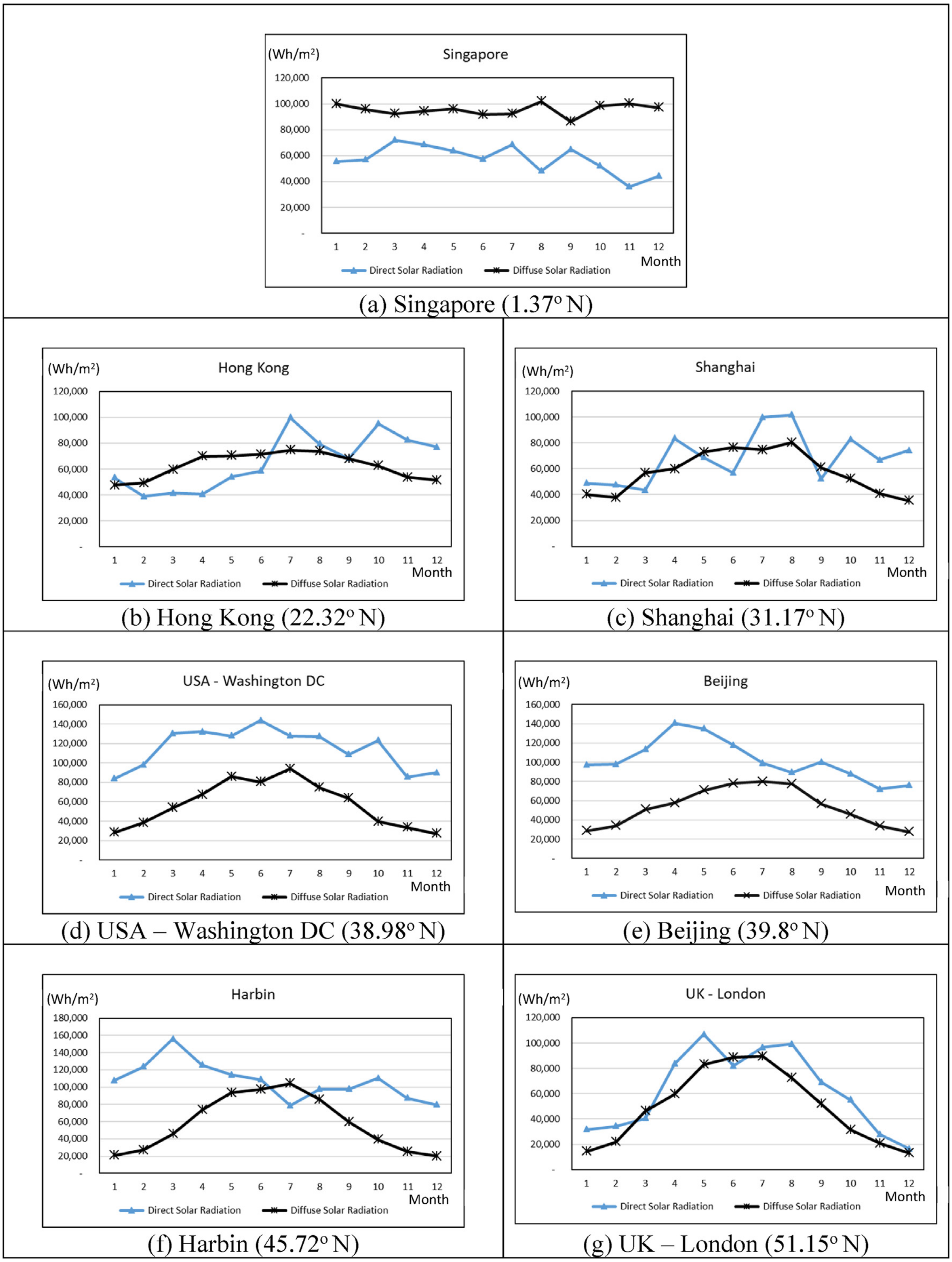


Fig. 8. Monthly solar radiations (Wh/m^2) of the seven cities selected for this study.

Hong Kong, Shanghai, Washington and Beijing, as shown in Fig. 9 (o)–(s)) indicate that the monthly percentage differences in PV electricity generation in each individual city are quite even over the 12 months. In the remaining two cities, only a few numbers of comparatively higher percentage differences are found in January (Harbin) (as shown in Fig. 9 (t)) and May to August (London) (as shown in Fig. 9 (u)).

3.3.2. *Annual electricity energy generated*

The annual percentage differences in PV electricity generation for building roofs R1, R2 and R3 between the cases with and without NSE, under the seven climatic conditions are tabulated in Table 1 for comparison. For building roof R1, the annual percentage differences in PV electricity generation are −12.62% (Singapore: 1.37° N), −15.09% (Hong Kong: 22.32° N), −20.50% (Shanghai:

31.17° N), −22.11% (USA: 38.98° N), −24.71% (Beijing: 39.8° N), −28.34% (Harbin: 45.72° N), and −21.76% (UK: 51.15° N), respectively. Obviously, there is a dependence of percentage difference on the latitude of a city and the correlation is directly proportional. For a city located at a relatively higher latitude, a more substantial NSE against the solar radiation coming at a lower angle of solar altitude will be resulted, especially in the winter season.

The corresponding simulation results for the PV panel system installed in building roof R3 are tabulated in last three columns of Table 1. Since the orientation of the PV panel system in building roof R3 is identical to that in building roof R1 (both face the southwest), these two building roofs have the same monthly and annual PV electricity energy generated for the building cases without NSE. In terms of percentage difference in annual PV electricity energy generation, the building cases in roof R3 have a similar trend of results as that from building roof R1, i.e. a city located at a higher latitude gives a more significant shading effect on a PV panel system which is caused by the nearby facilities and machine rooms on the rooftop of a building. The annual percentage differences of the building cases in roof R3 range from −17.15% (Singapore: 1.37°N) to −25.03% (Harbin: 45.72° N).

The simulation results for the building cases of roof R2 are shown in the middle column of Table 1. It is interesting to note that there is a declining trend in the annual percentage differences in PV electricity energy generation with the increasing latitudes of the cities. Unlike the results from building roofs R1 and R3, Singapore (at a low latitude of 1.37° N) gives a comparatively higher annual percentage difference in PV electricity energy generation of −22.95%. The corresponding values from the other six cities are −19.20% (Hong Kong: 22.32° N), −16.99% (Shanghai: 31.17° N), −15.75% (USA: 38.98° N), −14.79% (Beijing: 39.8° N), −13.29% (Harbin: 45.72° N), and −14.92% (UK: 51.15° N), respectively.

As analysed in Section 3.3.1 above (for the monthly PV electricity generation), the PV panel system in building roof R2 was set towards the south direction and the dominant NSE came from the machine rooms at the southwest of the PV panel. A city located at a low latitude has a later time of sunset than a city at a relatively higher latitude. This leads to more amount of solar radiation received by a PV panel (without NSE) in building roof R2 than that of a building case with NSE, under the solar radiation in a location at a low latitude. This results in a higher percentage difference in PV electricity energy generation between the building cases with and without NSE. On the contrary, for a city located at a higher latitude, there is smaller amount of solar radiation coming from the southwest direction due to an earlier time of sunset, no matter there is nearby shading object or not, resulting in a comparatively lower percentage difference in the annual PV electricity energy generation caused by NSE.

The above findings reveal that the effect of neighbouring shading on the electricity generation of a rooftop PV panel system is substantial, not only for the cities located in tropical/subtropical regions (at low geographical latitudes). Based on the simulation results of the seven cities located at different geographical latitudes in this study, it is found that the annual percentage difference in PV electricity generation ranges from −12.62% to −28.34%. Moreover,

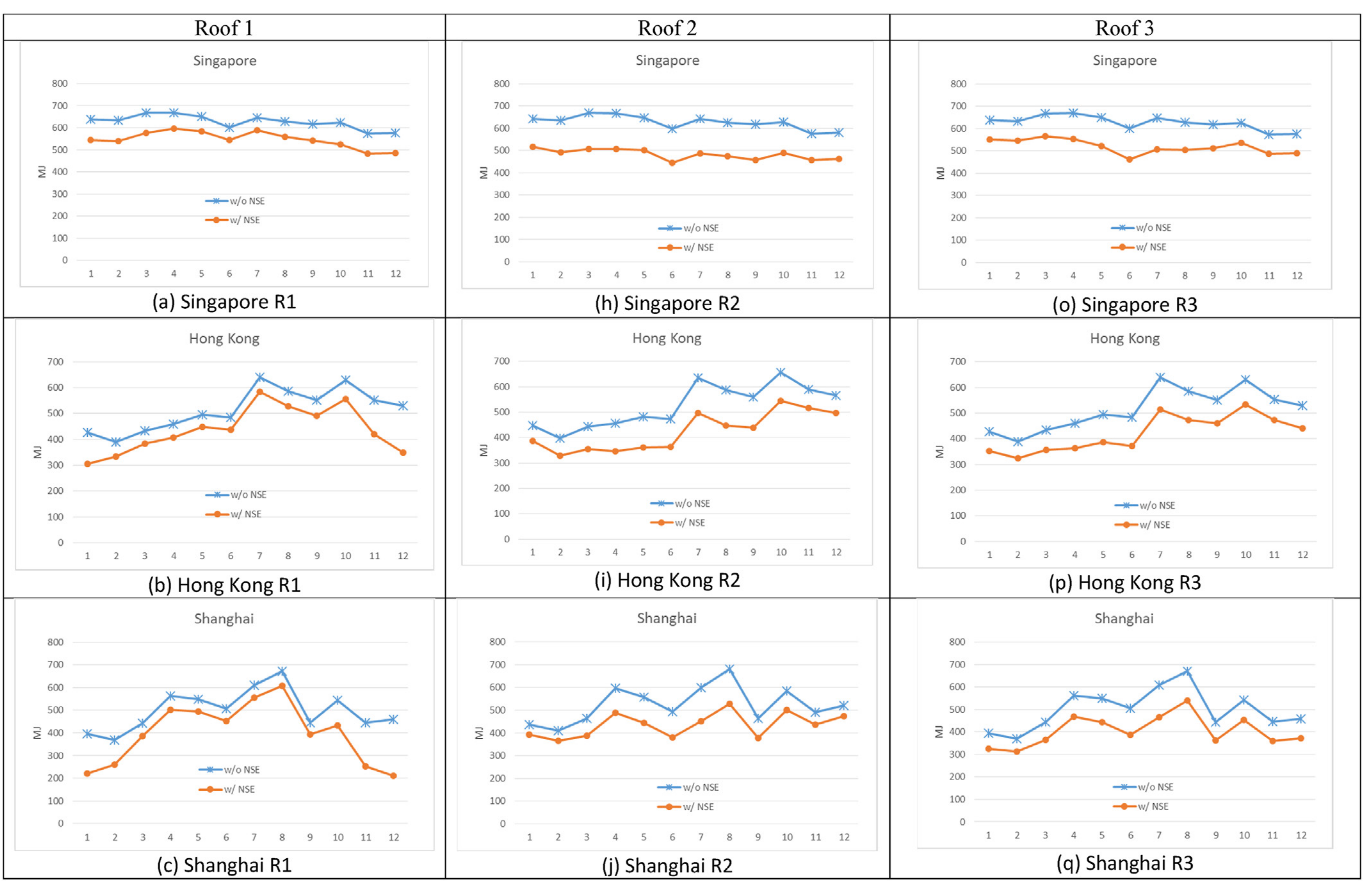


Fig. 9. Electricity energy generated by PV panel systems on building roofs, with and without neighbouring shading effect (NSE), under seven climatic conditions.

the correlation between the percentage difference in PV electricity generation and the latitude of a city may be directly or inversely proportional, depending on the relative positions of a PV panel system and its neighbouring shading object.

3.4. Energy payback time of PV panel systems

In a typical free-standing PV panel system, the major components involved are front glass pane, solar cells laminated onto aluminium thermal absorber, insulation material, steel stand with accessories, electric wiring and inverter. For calculating the energy payback time (EPBT) of the PV panel system in this study, the values of embodied energy are primarily acquired from three sources - Ecoinvent database [45], ICE (Inventory of Carbon and Energy) database [46], and EDGE database [47].

A sample of detailed EPBT calculation for a PV panel system in building roof R1 with NSE, under Singapore climatic condition, was presented in Table 2. The embodied energy of each component of the PV panel system (in column (c)) was calculated by multiplying the embodied energy intensity of each component (in column (a)) by the corresponding mass or area (in column (b)). Then the EPBT equals to the total embodied energy divided by the annual PV electricity energy generated under NSE, giving a result of 8.96 yrs.

The EPBTs of the PV panel systems for all the three building roofs (R1 to R3), under different climatic conditions in the seven selected cities, were calculated by using the same procedure. Then the percentage differences in EPBT between the cases with and without NSE were determined and plotted against the latitudes of the seven cities as shown in Fig. 11. Obviously, the EPBTs from the building cases with NSE are longer than that of the building cases without NSE. This result is mainly caused by the shadow of surrounding facilities and machine rooms cast on the PV panel system, resulting in a reduction in PV electricity energy generated and hence a longer EPBT. Taking building roof R1 in Singapore as an example, the values of EPBT for the cases without and with NSE are 7.83 yrs and 8.96 yrs respectively, giving a percentage difference of 14.43%.

Under the climatic conditions of the seven cities, the percentage differences in EPBT of building roof R1 range from 14.43% to 39.55%. The corresponding ranges of percentage difference for building roofs R2 and R3 are 15.32%–29.76%; and 22.41%–33.37%, respectively. The correlations between the EPBTs of these three building roofs with the latitudes of the cities are similar to that derived for

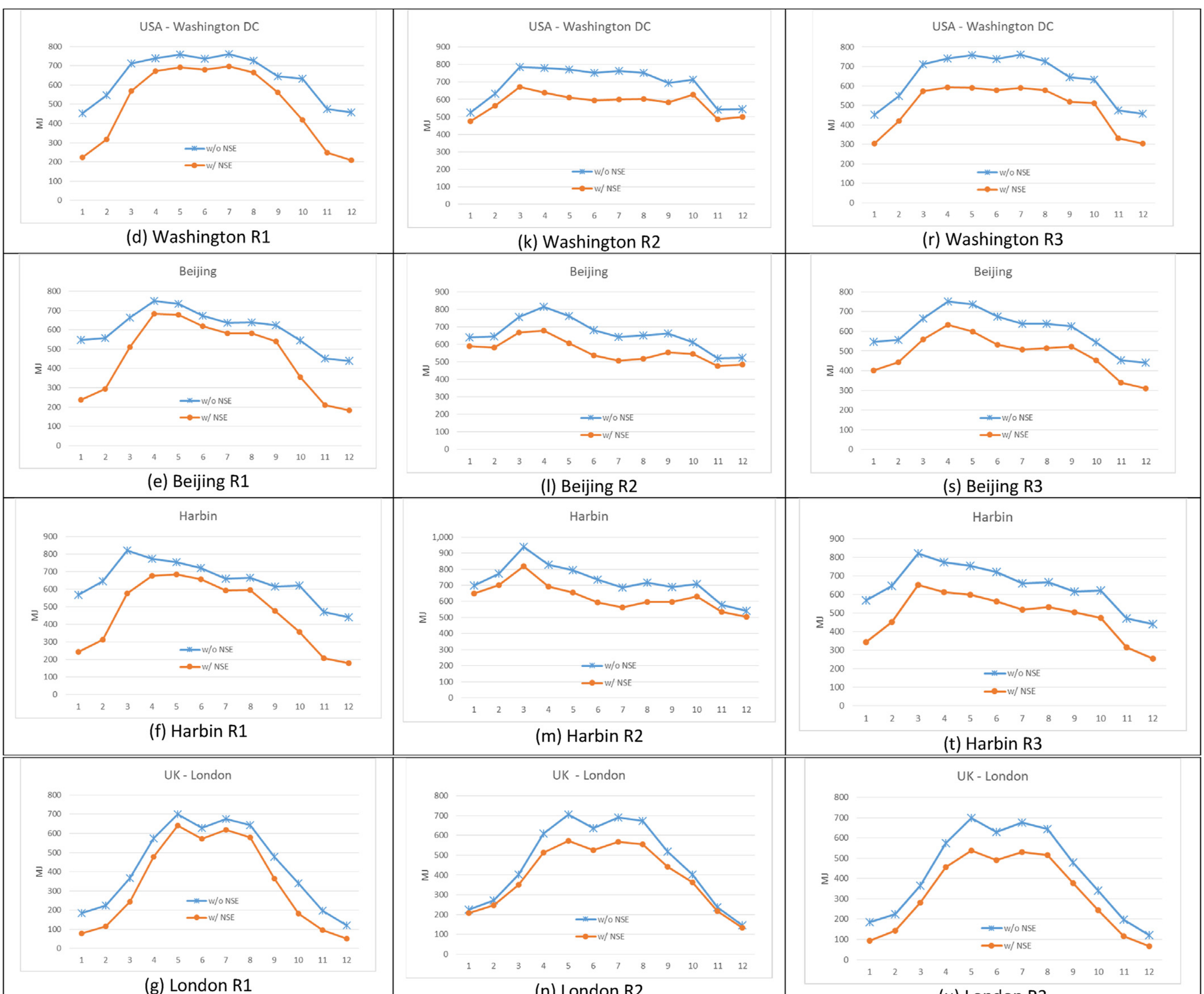
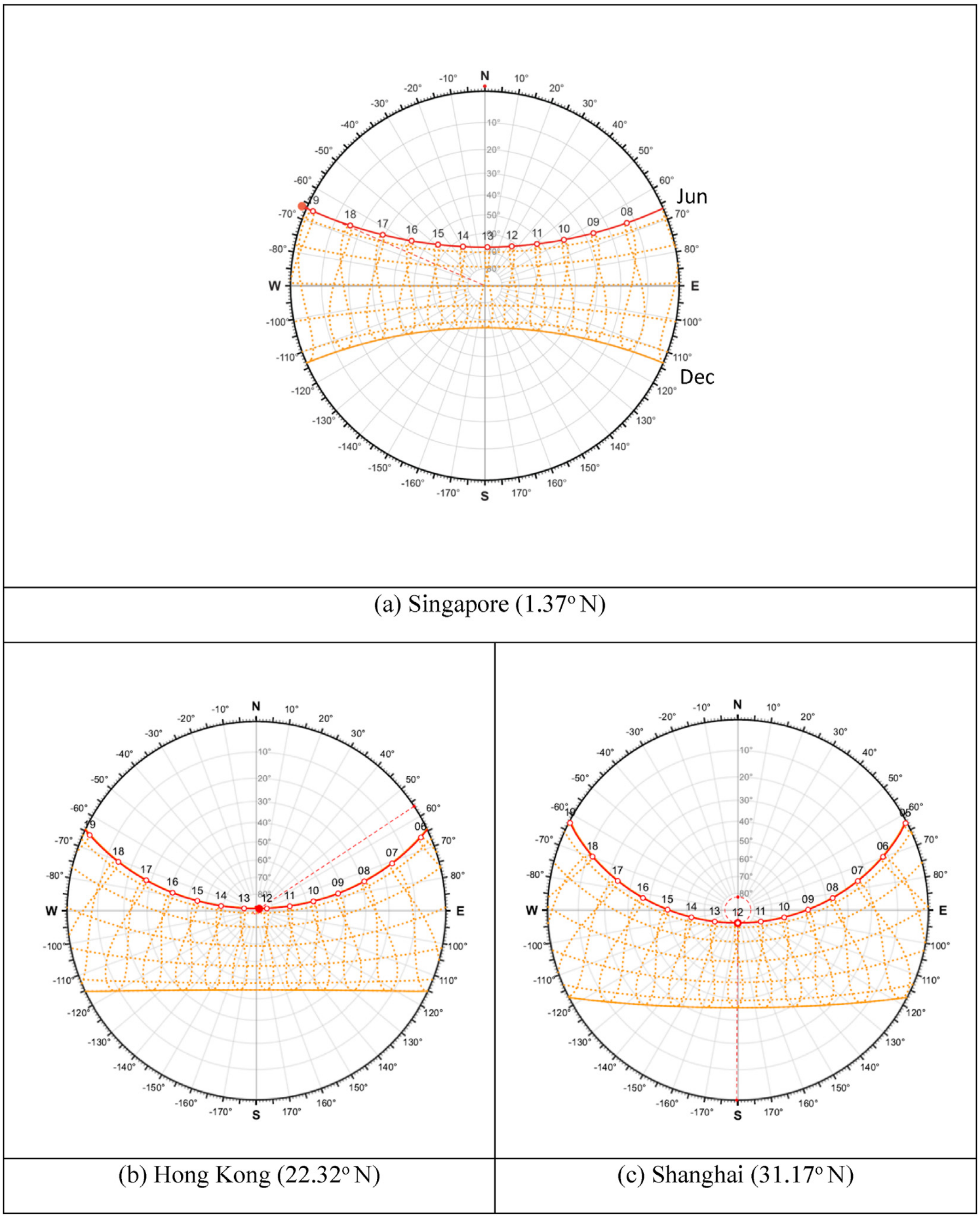


Fig. 9. (*continued*).



(a) Singapore (1.37° N)

(b) Hong Kong (22.32° N)

(c) Shanghai (31.17° N)

Fig. 10. Stereographic sun-path diagrams of the seven cities in this study.

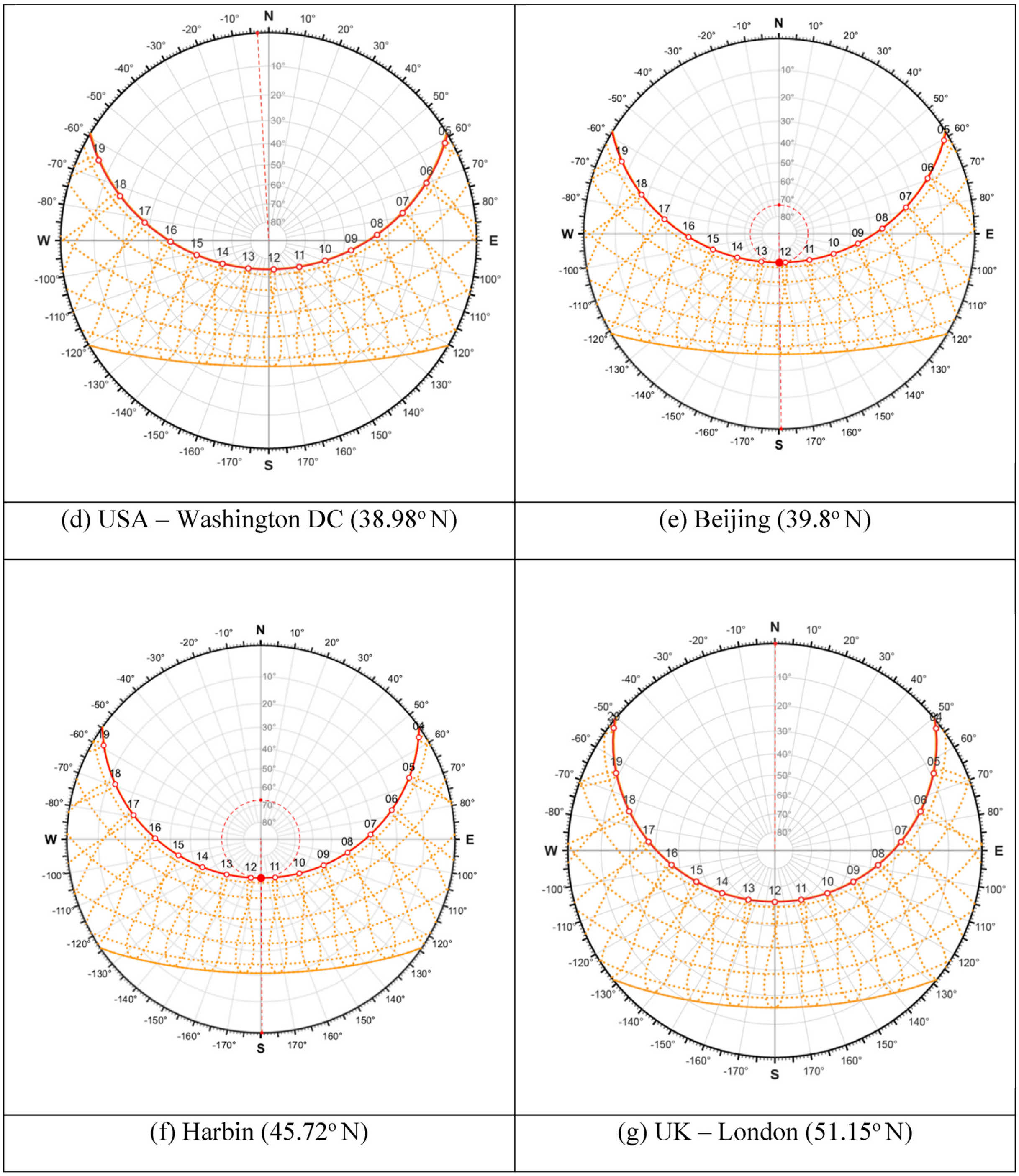


Fig. 10. (*continued*).

Table 1
Summary of percentage differences in annual PV electricity generation for building roofs R1, R2 & R3 with and without neighbouring shading effect, under seven climatic conditions.

	R1			R2			R3		
	w/o NSE (MJ)	w/NSE (MJ)	% Difference	w/o NSE (MJ)	w/NSE (MJ)	% Difference	w/o NSE (MJ)	w/NSE (MJ)	% Difference
Singapore (1.37° N)	7524	6575	−12.62	7525	5797	−22.95	7524	6234	−17.15
Hong Kong (22.32° N)	6174	5242	−15.09	6287	5080	−19.20	6174	5043	−18.32
Shanghai (31.17° N)	6000	4770	−20.50	6299	5229	−16.99	6000	4857	−19.06
USA (38.98° N)	7644	5954	−22.11	8257	6956	−15.75	7644	5894	−22.90
Beijing (39.8° N)	7269	5473	−24.71	7926	6753	−14.79	7269	5816	−20.00
Harbin (45.72° N)	7752	5555	−28.34	8686	7532	−13.29	7752	5812	−25.03
UK (51.15° N)	5131	4015	−21.76	5518	4695	−14.92	5131	3856	−24.84

Table 2
Calculation of energy payback time for building roof R1 with PV panel system under NSE in Singapore.

No.	Material	(a) Embodied Energy Intensity (MJ/kg or MJ/m^2)	(b) Mass (kg) or Area (m2)	(c) Embodied Energy (MJ)
1	(Low-iron) glass	13	107.4	1396
2	PV module (Multicrystalline silicon)	3343	11.8 (m^2)	39,347
3	Aluminum thermal absorber	146	61.8	9027
4	Insulation material (Glass wool mat)	47	13.9	653
5	Steel stand & accessories	20	148.1	2975
6	Electric wiring	10	7.4	71
7	Inverter	711	7.6	5419
			Total Embodied Energy =	58,889
			Annual Energy Generated =	6575
			Energy Payback time =	8.96 yrs.

the percentage difference in PV electricity energy generated (tabulated in Table 1 above). This EPBT calculation indicates the significance to take NSE into consideration in the environmental assessment of a PV panel system under NSE in order to prevent an over-estimation of EPBT.

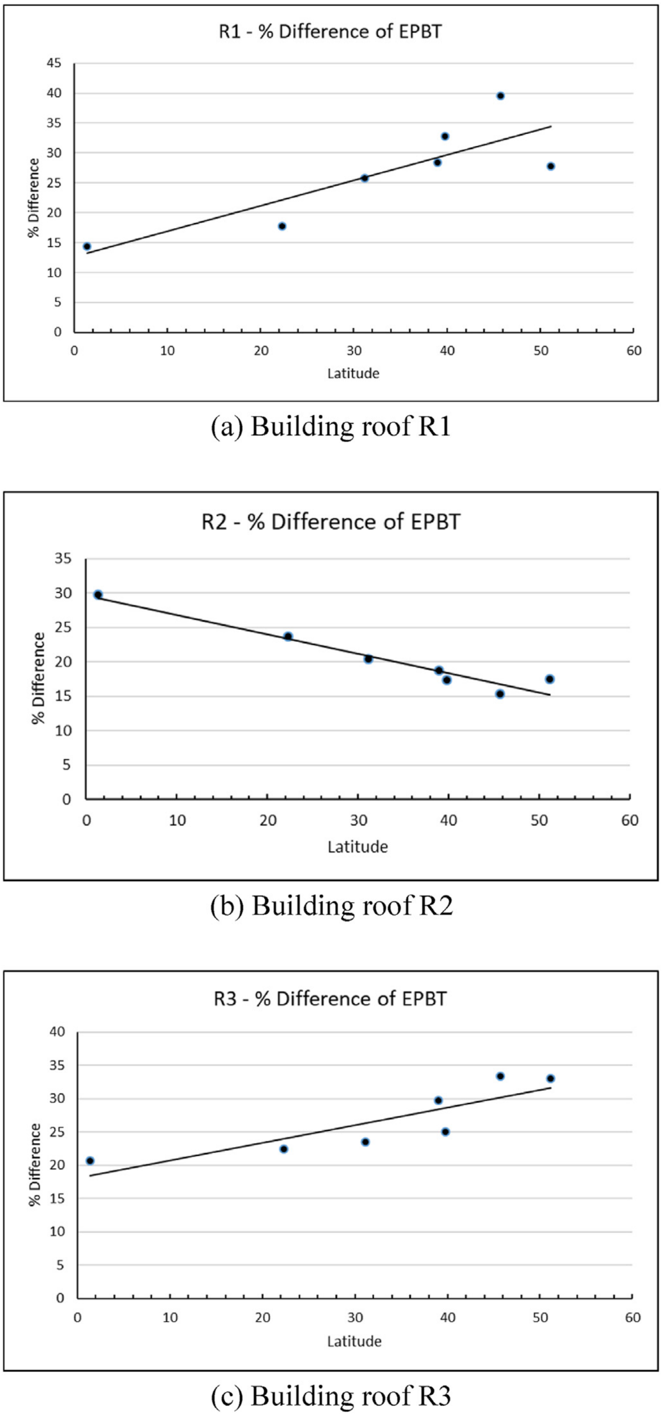
4. Conclusion

This study investigates the effect of neighbouring shading on the energy performance and environmental feasibility of free-standing PV panel system installed on the rooftop of commercial building with nearby facilities and building structure. Roof plans of three existing commercial buildings were acquired from three property management companies. The building structure and electrical & mechanical facilities on the building roofs were included in computer modelling so that their shading effect cast on the PV panel system was taken into account in this study. Through computer modelling and simulations for a PV panel system installed on these three building roofs with weather data of seven selected cities at different geographical latitudes (ranging from 1.37° N (Singapore) to 51.15° N (London, UK)), it reveals that the effect of neighbouring shading on annual PV electricity energy generation and energy payback time (EPBT) is very substantial. Comparing the building cases with and without neighbouring shading effect, the values of percentage difference in PV electricity energy generation range from −12.62% to −28.34% and the corresponding range of values for EPBT is −14.43% to −39.55%.

In addition, this study finds that there is a dependence of percentage difference in PV electricity energy generation and EPBT on the latitude of a city. The correlation may be directly proportional (i.e. larger percentage difference was found in a city at high latitude) or inversely proportional (smaller percentage difference in a city at high latitude), depending on the relative positions of a PV panel system and its neighbouring shading objects. In the performance evaluation of a PV panel system installed on the rooftop of a building, a number of factors including the location of nearby shading object, orientation of PV panel, and the latitude of a city should be considered.

Promoting the application of renewable energy systems through green building certification scheme is part of an energy policy for clean, reliable and sustainable energy supply. In most of the green building certification schemes, scoring system is adopted in which credits are awarded under various categories. Taking the Hong Kong BEAM Plus scheme as an example, a building can be awarded with 1–5 credits if 0.5–2.5% of the building energy is supplied from renewable energy system. In Hong Kong, PV panel system installed on the rooftop of a building is a commonly adopted renewable energy system. The amount of renewable energy generated is mainly estimated during the design stage of a building in which the neighbouring shading effect is generally ignored. In a real operating condition, shadow may be cast on a PV panel system by the nearby facilities and machine rooms, incurring a substantial reduction in solar radiation received as well as the PV electricity energy produced.

Through literature review, it is found that most green building certification schemes do not consider any partial shading from on-site building rooftop structure and mechanical & electrical services for solar energy feasibility study, except two schemes - Green Mark from Singapore and BEAM Plus from Hong Kong. These two cities are located at comparatively low geographical latitudes at 1.37° N and 22.3° N, respectively. The present study reveals that the effect of neighbouring shading on annual PV electricity energy generation and energy payback time is very substantial, not just for these two cities. Based on the findings from this study, it is recommended to take into account the neighbouring shading effect in evaluating the energy and environmental performance of PV panel system installed on the rooftop of commercial building. Policy makers are advised to incorporate this requirement as mandatory into the current green building certification schemes so that the actual energy and environmental performance of a rooftop PV panel



(a) Building roof R1

(b) Building roof R2

(c) Building roof R3

Fig. 11. Percentage differences in energy payback time for building roofs R1, R2 & R3 with and without neighbouring shading effect, under seven climatic conditions.

system under neighbouring shading effect can be accurately evaluated, as part of the approach for a reliable and sustainable energy supply in a city.

CRediT authorship contribution statement

Lok Shun Chan: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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