Feasibility of vertical photovoltaic system on high-rise building in Malaysia: performance evaluation

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Abstract

Photovoltaic (PV) façade, an envelope of the building in an urban area, can potentially produce clean electricity to meet the energy demand of the buildings and also provides protection from weather. This paper focuses on the application of PV technology on vertical façade of the building which is considered as an element of building-integrated PV. The aim of this study is to assess the feasibility with regard to performance evaluation of PV vertical façade based on the built-up model of a high-rise building in Malaysia using system advisor model. The best four vertical façade orientations for PV application in climatic condition of Malaysia are east, west, southeast and southwest as these façades received the highest incident irradiance. Based on the typical high-rise office building in Malaysia, the energy generated through the vertical PV system is between 400 and 700 MWh, whereas the energy generated by the roof system is ~240 MWh annually.

Keywords: building-integrated photovoltaic; high-rise building; vertical façade; performance evaluation

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1 INTRODUCTION

Building sectors in Malaysia consist of commercial, government and residential buildings (high-rise, as well as terraced and single dwellings), and it is estimated that electricity use in these building sectors is ~7750 GWh in 2008 and it is expected to grow rapidly in near future [1]. About 40% of Malaysia's total energy demand in the commercial sector is required for space cooling [2]. The majority of office buildings in Malaysia had Building Energy Index (BEI) in the range of 200–250 kWh/m^2/year, while the maximum requirement for BEI is 136 kWh/m^2/year under MS 1525:2007 Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-residential Building [3, 4].

Photovoltaic (PV) power required a large area of land to concentrate and collect the solar power. Hence, to avoid any new land exploitation in the urban area, utilising surfaces of the building needs to be explored to solve the issue of land use for PV power. With the introduction of building-integrated photovoltaic (BIPV), it can be used as materials for building envelope and also to generate power simultaneously to the building itself [5].

Building's rooftop and facades can be installed with PV panels to generate electricity and also reduce heat gain, and thus reduce the energy demand for the air-conditioning system of the building [6, 7]. The energy generated from BIPV can reduce commercial energy of building's load by offering power benefits on top of the on-site generation of electricity [8]. Furthermore, on-site power delivery capability gives consumers the possibility to negotiate demand contracts with distribution utility.

In the modern urban area, most of the building's height is medium and high which have larger façade (vertical) area compared with the surface of the roofs (horizontal). Rooftops for high-rise buildings are normally reserved for building infrastructure, e.g. elevator engines and ventilator [9]. A vertical façade presents better maintenance because the vertical surface does not accumulate dust and dirt [10].

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The aim of this paper is to assess the feasibility of vertical PV system on a high-rise building in Malaysia with a focus on performance evaluation. Computer simulation of system advisor model (SAM) developed by National Renewable Energy Laboratory (NREL) was used in this analysis to study the effect of incident solar radiation on various vertical and module performances, thus to determine the best vertical orientation of PV façade application in Malaysia. Based on the typical configuration of a high-rise building in Malaysia, the energy production of various design scenarios of PV façade on high-rise building will be evaluated.

2 PROFILE OF MALAYSIAN CLIMATE

SAM is a feasibility screening tool to analyse the performance and the financial model, and it was designed to assist people who are involved in the renewable energy industry in making a decision about the predictions of the performance and the estimation of the cost of energy for the project. A validation study has been done by NREL to analyse the performance of nine projects involving PV system with various PV-modelling tools (SAM, PVsyst, PV*SOL and PVWatts) available today. This study investigated and compared the error of each modelling tool with measured performance data [11]. Table 1 shows the range of annual errors for four modelling tools with measured data. Also in 2014, a collaboration between NREL and Locus Energy had validated SAM results with measured energy from 100 real-world PV systems (various geographies, sizes and configurations). The studies found that SAM model on an annual basis would likely have small errors of around ±3% [12].

Prior to performing the building simulation using SAM, Malaysian tropical climate was analysed to understand the climatic condition at the location of site. Kuala Lumpur city area was selected in this simulation because Kuala Lumpur is the densest city in Malaysia with most of the buildings' height in high-rise buildings. In this simulation, weather data from US Energy Department were used because it provide typical meteorological year data which are commonly used in many building simulation programs. These weather data contain hourly values over typical years for average and long-term measurements. Table 2 shows the latitude and the longitude of Kuala Lumpur and also the annual irradiance obtained from the weather data. Figure 1 shows the monthly global, beam and diffuse irradiance in Kuala Lumpur.

Table 1. *The range of annual errors of four PV performance modelling tools [11].*

Tool	Error range (%)
SAM	−5.0 to 4.1
PVSyst	−1.7 to 5.5
PV * SOL	−5.5 to 1.4
PVWatts	−16.2 to −8.9

3 GENERAL CONSIDERATION

Before we proceed with this simulation, a few basic assumptions of direct current (DC) losses and alternate current (AC) losses in PV application have been made. These assumptions are based on the past research and considered on average means. Accumulated dust and dirt on the surface of a PV module will cause a reduction of incident irradiance reaching the solar cell, thus reducing the generation of power. The mean daily energy loss along a year caused by dirt and dust or soiling losses is around 4.4% [13]. Mismatch losses occur when more than one module is connected in series and the power losses are due to variation in the *I*–*V* characteristic of the modules which is caused by partial shading, and differences in PV modules in series may be contributed to at least 2% loss in system power [14, 15]. The effect of ohmic resistance in the system wiring or DC wiring loss accounted ~3% [16, 17]. Diode and connection loss accounted 0.5%. Meanwhile, the AC wiring losses in SAM will account for electrical losses on the AC side of the system in which the inverter model does not account for, and the derate factor considered in this simulation is 1%.

The performance evaluation will be presented in the amount of nominal radiation on plane-of-array (POA), shading losses, net DC energy, DC and AC losses, net AC energy, module efficiency, performance ratio and capacity factor. The calculation method for performance ratio and capacity factor was adopted from SAM technical reference.

Table 2. *Coordinate, annual irradiance and temperature of Kuala Lumpur.*

City	Kuala Lumpur
Time zone	GMT 8
Latitude	3.12°N
Longitude	101.55°E
Global horizontal	4.28 kWh/m^2/day
Direct normal (beam)	1.02 kWh/m^2/day
Diffuse horizontal	3.50 kWh/m^2/day
Average temperature	27.2°C
Average wind speed	1.6 m/s

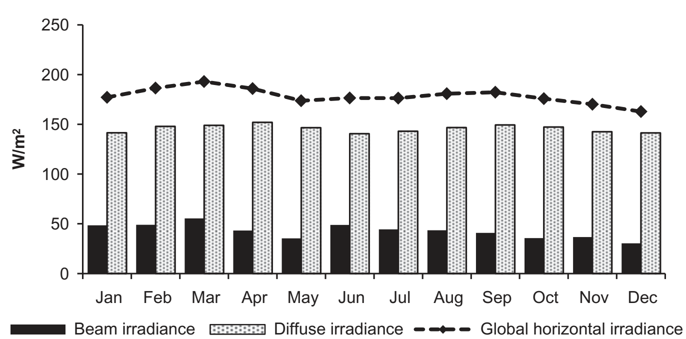

Figure 1. *Average hourly global, beam and diffuse irradiance according to a month in Kuala Lumpur.*

'Performance ratio' in this simulation is a measured DC energy output compared with the nameplate capacity with a consideration of incident solar radiation on PV array [18].

$$\text{Performance ratio, PR} = \frac{\text{Net DC energy, kWh}}{(\text{Annual POA total radiation, kWh})(\text{Module efficiency, \%})}$$

where Net DC energy is the system DC energy output in a year obtained from the simulation. Annual POA total radiation is the total incident solar radiation in a year before shading and soiling losses. module efficiency is the rated nominal efficiency of the modules in the array at standard test condition (STC). Meanwhile, 'capacity factor' is a ratio of predicted DC electrical output in a year to the nameplate output which is equivalent to the quantity of energy each system would generate if we operate at nameplate capacity for every hour in a year [18]:

$$\text{DC energy capacity factor, CF} = \frac{\text{Net DC energy, kWh}}{(\text{System capacity, kWdc})(8760,\ \text{h/yr})}(100\%)$$

Table 3. *Poly-crystalline 50 Wp module specification from manufacturer detail.*

Max power voltage—V_{mp} (Vdc)	18
Max power current—I_{mp} (Adc)	2.78
Open circuit current—V_{oc} (Vdc)	21.8
Short circuit current—I_{sc} (Adc)	2.97
Material	mc-Si
Module area (m^2)	0.3685
Number of cells	36
Number of cells in series	36
Number of cell strings in parallel	1

where Net DC energy is the total annual DC energy, system capacity is the system's total array power based on the nameplate capacity of system design.

4 PV PERFORMANCE ON VARIOUS VERTICAL FAÇADE ORIENTATIONS

4.1 System design and configuration

In this study, eight generic Poly-crystalline 50Wp modules manufactured by Solar Power Mart were used to simulate the performance of PV module on eight different vertical orientations. Table 3 shows the module specification obtained from module data sheet of the manufacturer. These specification data were then logged into SAM to represent the performance of the PV module and calculated a set of parameters at reference conditions using California Energy Commission (CEC) performance model. CEC performance model calculated current and voltage of the module under a range of solar resource conditions using an equivalent electrical circuit, which was determined from a set of five reference parameters [18]. The module nominal maximum power point rating at STC (1000 W/m^2) calculated by SAM is 50.04 Wdc and the module efficiency is 13.58%. There was a slight difference in module efficiency mentioned by the manufacturer which is 12.04%. Each vertical façade orientation in this simulation was considered as a single system that included eight modules and eight inverters where the DC-to-AC ratio is 1.0. This is to make sure that each orientation is simulated with a complete system in the real application.

The arrangement of eight multi-Si modules in this simulation is shown in Figure 2. Each orientation represents eight azimuth angles of vertical façade installed and fixed on a tilt angle of 90°. Table 4 shows the azimuth (degree) angle for each vertical façade orientation which is used as a reference in this analysis. In SAM, the indication of 0° azimuth angle is facing north, 90°

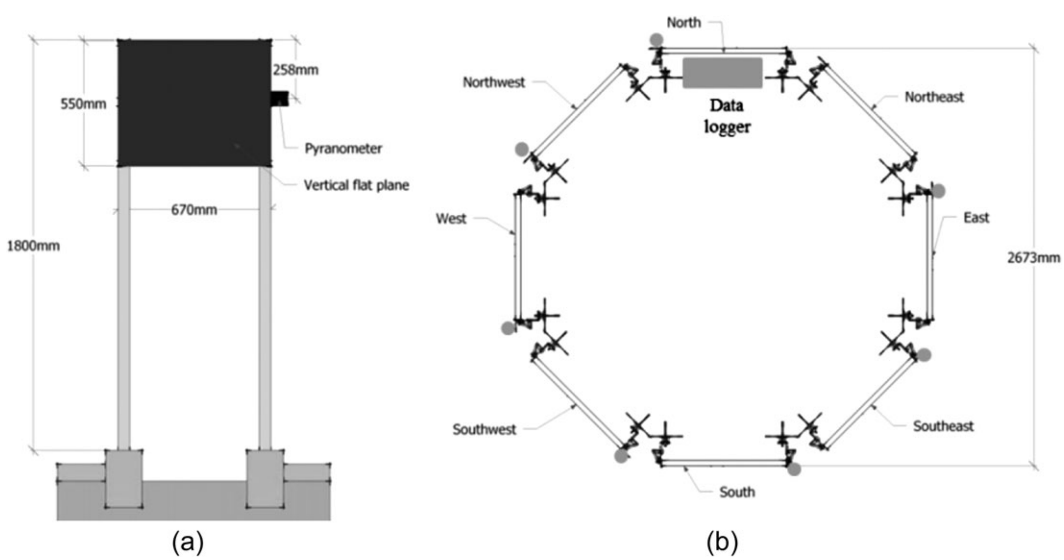

Figure 2. *(**a**) Elevation view of the single module. (**b**) The arrangement of eight modules in eight different orientations.*

= east, 180° = south and 270° = west, regardless of whether the array is in the northern or the southern hemisphere [18]. Each module was installed 900 mm above ground and a gap of 300 mm was set between each module to avoid shade from an adjacent module. Meanwhile, the mismatch loss was not considered in this part of simulation as the module was single and there was no connection in series between modules.

4.2 Results and discussion

In this simulation, eight multi-Si modules with different azimuth angles were simulated simultaneously under the same climatic condition. Figure 3 shows the hourly POA total irradiance and irradiance after shading and soiling. East and west façades received the highest irradiance compared with other façades with 91.4 and 88.7 W/m^2, respectively. Meanwhile, north and south façades received the lowest mean hourly POA irradiance. The variation of nominal irradiance on each vertical orientation is due to the variation of position of the sun throughout the year. In Malaysia, east and west vertical façade orientations are exposed more to the solar radiation in a year.

Figure 4 shows the mean hourly module efficiency and cell temperature according to each façade orientation. In this simulation, the module efficiency calculated by SAM is 13.58% under STC. The result showed that the measured module efficiency significantly differed from the STC on each orientation. modules on east and west façades have the highest measured efficiency (5.78%) compared with other façades; this is due to higher nominal incident irradiance on this façade orientation. Meanwhile, the cell temperature on east and west modules is also higher when compared with other modules. North and south modules have the lowest cell temperature as both façades received low-irradiance level throughout the year.

After considering the DC and AC losses, Figure 5 shows the mean hourly DC array power and net AC output. It can be seen that the higher amount of POA on east and west façades was able to generate more power. On an hourly average, a module on 90° and 270° generate ~3 and 2.9 W AC energies, while north and south modules remain low.

Figure 6 shows the percentage of DC module-modelled loss on each vertical orientation. The DC module-modelled loss is the thermal loss, incidence angle-related loss, efficiency variation loss and light-induced degradation loss of the module itself. North and south façades have the highest module-modelled loss (15% and 14.7%, respectively), while east and west façades are the lowest, accounted ~13.8% and 13.9%, respectively.

Figure 7 shows the annual energy generated in a year and performance ratio each 50 Wp muti-Si module in eight different vertical façade orientations. The best four vertical façade orientations for PV application in climatic condition of Malaysia are east, west, southeast and southwest with annual energy generated of 26.03, 25.08, 24.46 and 23.72 kWh per year, respectively. These façade orientations received the highest incident solar radiation compared with north, south, northeast and northwest. For a comparison, a module on the horizontal façade generates more energy compared with the vertical façade. The performance ratios for east and west modules (64.9% and 64.5%) are the highest. Table 5 shows the summary of annual energy generation and performance on each façade orientation module.

Table 4. *Reference of each orientation and azimuth angle.*

Orientation	Azimuth (degree)
North (N)	0
Northeast (NE)	45
East (E)	90
Southeast (SE)	135
South (S)	180
Southwest (SW)	225
West (W)	270
Northwest (NW)	315

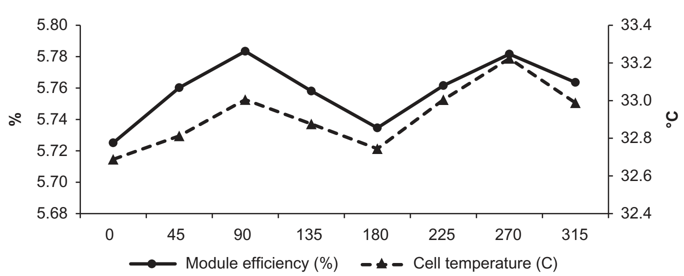

Figure 4. *Mean hourly module efficiency and cell temperature.*

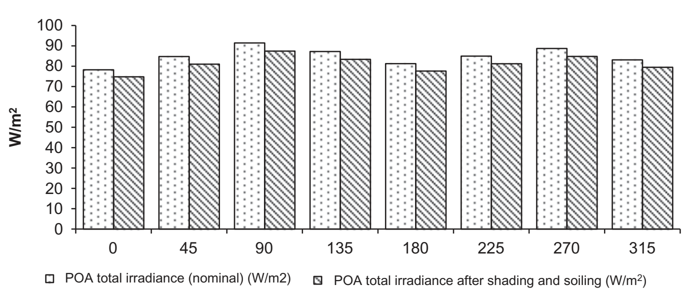

Figure 3. *Hourly POA irradiance, irradiance after shading and soiling.*

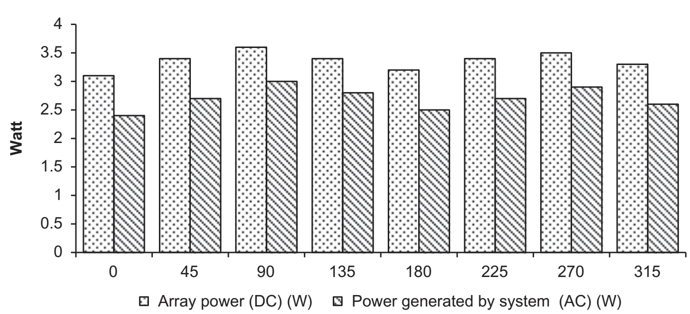

Figure 5. *Mean hourly array power (DC) and power generated by system.*

5 PERFORMANCE EVALUATION OF VARIOUS PV VERTICAL FAÇADES ON HIGH-RISE BUILDING IN MALAYSIA

5.1 System design and configuration

The high-rise building in Kuala Lumpur city area is designed with various shapes and forms. The average gross floor area (GFA) for high-rise building in Kuala Lumpur is 1225 m^2 with an average height of 120 m and the floor-to-floor height is 4 m [19]. Based on this configuration, a built-up model of a high-rise building in Kuala Lumpur is developed. The shape of the building is square with a 1:1 ratio of width and length so that each vertical façade has an equal surface area for comparison. Figure 8 shows the dimension of the built-up base model and Table 6 shows the configuration of the built-up base model for a high-rise building in this study. The entire building surfaces were considered as opaque solar collector surface. The solar insolation received by exposed surface was estimated as the sum of the solar radiation on its facades acting like a flat solar collector [20].

Figure 9 shows the possible PV design on high-rise building based on five scenarios. East (90°), west (270°) and roof (horizontal) façades were selected in this simulation as these façades received the highest incident solar radiation and generated more energy compared with other facades. Heterojunction intrinsic thin-film silicon (HIT-Si) module was used in this simulation because this was manufactured by Sanyo, giving the highest module efficiency available in the market today with a nominal efficiency of 15.62% and a maximum power of 180 Wdc. HIT-Si technologies also have low process temperature and comparatively high efficiency when compared with other crystalline silicon (c-Si) solar cells [21].

Meanwhile, the weighted efficiency for DC to AC inverter is 95%. Each design in this simulation used the same module's

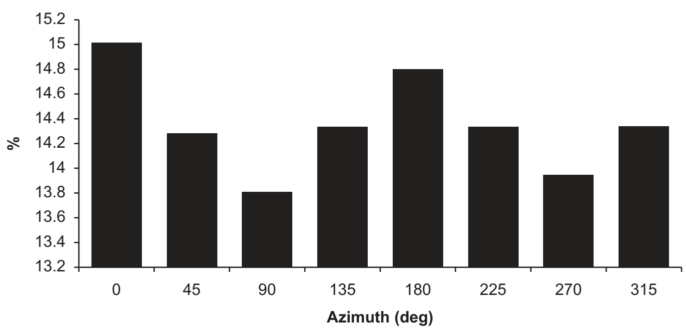

Figure 6. *DC module-modelled loss.*

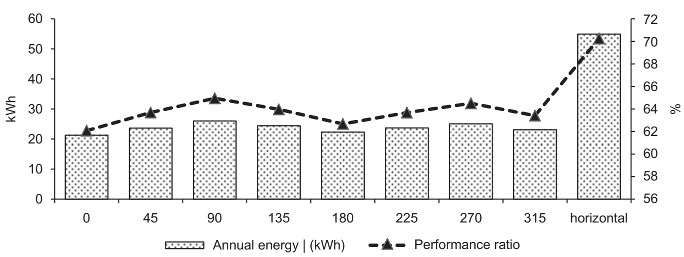

Figure 7. *Annual energy and performance ratio.*

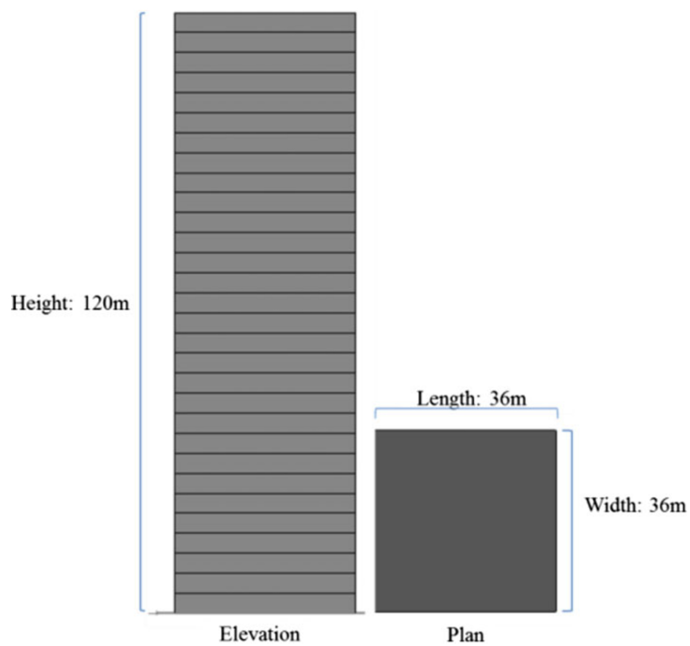

Figure 8. *Dimension of the built-up model of high-rise building.*

Table 5. *Summary of annual energy generation and performance on each façade orientation module.*

Azimuth (°)	Annual POA total radiation (nominal) (kWh)	Nominal DC energy (kWh)	Net DC energy (kWh)	Gross AC energy (kWh)	Annual energy (kWh)	Performance ratio
0	252.58	32.78	26.89	21.51	21.29	0.62
45	273.57	35.51	29.38	23.90	23.66	0.64
90	295.13	38.31	31.87	26.29	26.03	0.65
135	281.54	36.55	30.22	24.70	24.46	0.64
180	262.39	34.03	27.98	22.56	22.33	0.63
225	274.26	35.60	29.44	23.96	23.72	0.64
270	286.31	37.17	30.87	25.33	25.08	0.65
315	268.36	34.83	28.80	23.34	23.11	0.63
Horizontal	575.61	74.72	62.13	55.47	54.91	0.70

Table 6. *Built-up base model configuration.*

Gross floor area	1296 m^2
Height	120 m
Vertical façade surface area	4320 m^2
Horizontal roof surface area	1296 m^2
Floor-to-floor height	4 m

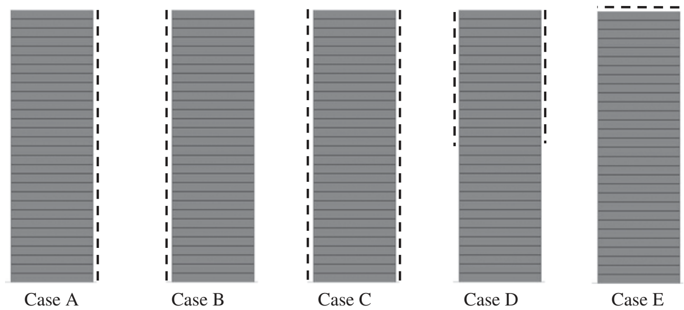

Figure 9. *Possible PV application on high-rise building. Case A: 90° azimuth, east façade. Case B: 270° azimuth, west façade. Case C: 90° and 270° azimuth. Case D: upper half of building. Case E: roof.*

type and inverter in order to compare the energy and the cost. Tables 7 and 8 show the module and the inverter configuration obtained from Sandia PV module database and CEC Inverter database, respectively. Each system design has a different configuration based on the nameplate capacity and the module area. Table 9 shows the configuration at reference condition for each possible design with a number of modules used, total module area, the number of inverters used and also module allocated for each subarray.

5.2 Results and discussion

The performance evaluation will be presented in the amount of nominal radiation on POA, shading losses, net DC energy, DC and AC losses, net AC energy, module efficiency, performance ratio and capacity factor. Figure 10 shows the nominal DC energy according to the design system on a high-rise building in Malaysia. Nominal DC energy is the energy generated by module after considering the shading and soiling loss based on the nominal POA total radiation. PV installed on both east and west (Case C) façades of a built-up base model of high-rise building has higher nominal DC energy. East façade (Case A) generates 15.4 MWh of DC energy more than west façade (Case B). Meanwhile, PV system on upper half of the base model generates better DC energy compared with the system on east and west.

Figure 11 indicates the percentage of power losses without the fixed DC and AC losses in each design system. The DC module modelled for PV system on the west (Case B) is higher compared with other systems and ~0.27% compared with the same amount of module on east façade. Meanwhile, Cases C and D have the same percentage of module-modelled loss, 9.73%. Each system in this study used the same model of power

Table 7. *module characteristic at reference condition based on Sandia PV array performance model with module database.*

Module	Sanyo HIP-J54BA2 (2004 E)
Nominal efficiency (%)	15.62
Maximum power—P_{mp} (Wdc)	179.663
Max power voltage—V_{mp} (Vdc)	54
Max power current—I_{mp} (Adc)	3.3
Open circuit current—V_{oc} (Vdc)	66.4
Short circuit current—I_{sc} (Adc)	3.6
Physical characteristic	
Material	HIT-Si
Module area (m^2)	1.15
Number of cells	96
Number of cells in series	96
Number of cell strings in parallel	1

Table 8. *Inverter characteristic at reference condition based on inverter CEC database.*

Inverter type	ABB:PVI-CENTRAL-50-US (208 V) 208 V [CEC 2008]
CEC weighted efficiency (%)	94.923
European weighted efficiency (%)	94.348
Maximum AC power (Wac)	50 000
Maximum DC power (Wdc)	52921.8
Power consumption during operation (Wdc)	451.852
Power consumption at night (Wac)	33
Nominal AC voltage (Vac)	208
Maximum DC voltage (Vdc)	600
Maximum DC current (Adc)	170
Minimum MPPT DC voltage (Vdc)	330
Nominal DC voltage (Vdc)	372.087
Maximum MPPT DC voltage (Vdc)	600

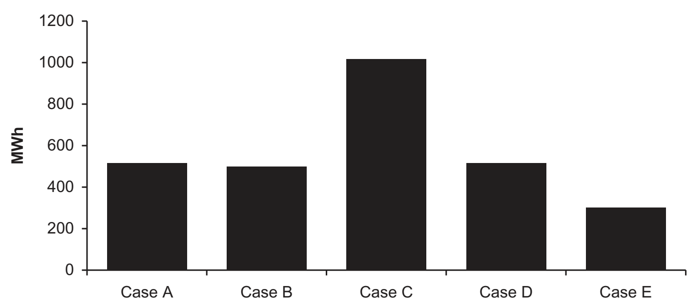

Figure 10. *Nominal DC energy on each design system.*

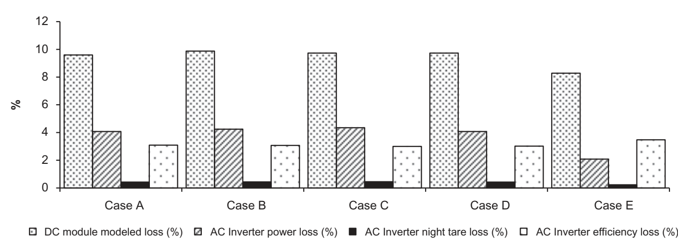

Figure 11. *DC and AC losses in system.*

Table 9. *System configuration and module allocation on each subarray at reference condition.*

Configuration at reference conditions	Case A	Case B	Case C	Case D	Case E
Modules					
Nameplate capacity (kWdc)	672.094	672.094	1348.188	684.155	201.222
Number of modules	3744	3744	7504	3808	1120
modules per string	8	8	8	8	8
Strings in parallel	468	468	938	476	140
Total module area (m^2)	4305.6	4305.6	8629.6	4379.2	1288
String V_{oc} (V)	531.2	531.2	531.2	531.12	531.2
String V_{mp} (V)	432	432	432	432	432
Inverters					
Total capacity (kWac)	600	600	1250	600	200
Total capacity (kWdc)	635.061	635.061	1323.045	635.061	211.687
Number of inverters	12	12	25	12	4
Maximum DC voltage (Vdc)	600	600	600	600	600
Minimum MPPT voltage (Vdc)	330	330	330	330	330
Maximum MPPT voltage (Vdc)	600	600	600	600	600
Subarrays					
Subarray 1					
Strings allocated to subarray	468	468	469	238	140
Tilt (degree)	90	90	90	90	0
Azimuth (degree)	90	270	90	90	0
Subarray module area (m^2)	4305.6	4305.6	4314.5	2189.6	1288
Number of modules	3744	3744	3752	1904	1120
Subarray 2					
Strings allocated to subarray			469	238	
Tilt (degree)			90	90	
Azimuth (degree)			270	270	
Subarray module area (m^2)			4314.5	2189.6	
Number of modules			3752	1904	

inverter with the same weighted efficiency (94%, CEC weighted efficiency), but the inverter AC losses are varied on each design system. The AC inverter power loss on Case C has the highest loss with 4.34%, while for the roof system, ~2.08%. It can also be seen that AC inverter power loss for vertical façade area is higher compared with roof façade. In contrast, the AC inverter efficiency loss for the PV system on the roof façade is higher compared with the PV system on vertical façade.

After considering the shading, soiling, DC and AC losses, Figure 12 shows the annual energy generated from each PV system design. The PV system in Case C has generated 794.4 MWh energy in a year, the highest being compared with another design system. The PV system on whole east façade generated more energy compared with the west façade. Meanwhile, the PV on roof façade generated ~244 MWh energy per year.

First-year annual energy per nameplate capacity ratio and annual energy per module area ratio have used this analysis to measure the effectiveness of each design system as shown in Figure 13. Between four vertical façade system designs (Cases A, B, C and D), it can be seen that PV installed on whole east façade of the building has a better effectiveness compared with other vertical installations with 94 kWh/m^2 and 600 kWh/kW in a year. On one hand, west façades are least effective with 91 kWh/m^2 and 580 kWh/kW. On the other hand, the effectiveness of design system on whole east–west façade is less compared with upper half east–west façade.

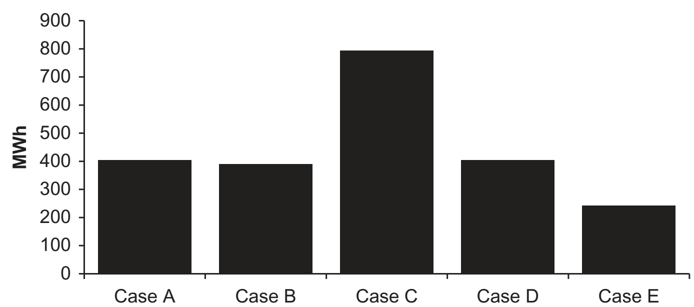

Figure 12. *Annual energy generated.*

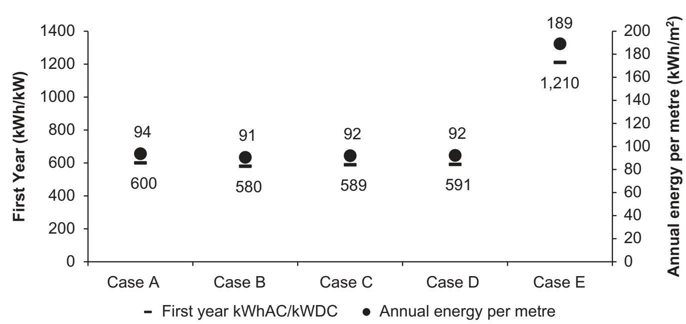

Figure 13. *Annual energy per nameplate capacity and annual energy per module area ratio.*

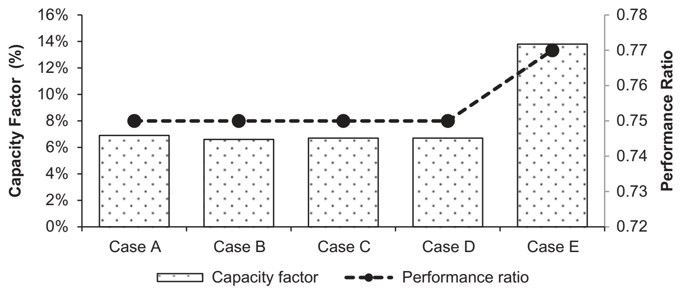

Figure 14. *Performance ratio and capacity factor.*

Performance ratio and capacity factor between each design system have also been calculated as shown in Figure 14. In Cases A, B, C and D, the PV system installed on vertical façade has only the same performance ratio of 0.75 regardless of a different number of modules and module's area. Meanwhile, PV installation on the roof has the highest performance ratio of 0.77 and a capacity factor of 13.8%. However, the capacity factor for a module on east façade (Case A) was slightly higher compared with Cases B, C and D.

6 CONCLUSION

Based on the analysis of PV performance on various vertical façade orientations in Malaysia, east and west façade orientations received the highest incident solar radiation compared with other orientations. This scenario makes the east and west vertical façades as the most favourable orientation for the PV application on buildings in Malaysia, which are followed by southeast and southwest orientations. PV modules on this orientation have shown significant higher module efficiency, performance ratio and lower DC module-modelled loss compared with other PV modules on other orientations.

Based on the five possible designs of PV vertical façade on the built-up model of a high-rise building in Malaysia, the feasibility of the design in terms of performance has been evaluated using SAM simulation. On one hand, by maximising both east and west vertical façades with PV system, we were able to generate significantly higher electricity of ~800 MWh of energy annually due to the larger surface area. On the other hand, east façade orientation generates more energy compared with west orientation with 400–390 MWh annually. However, the effectiveness of the PV vertical façade system based on the first-year annual energy per nameplate capacity ratio and energy per module area ratio has shown that the PV system on east façade orientation is the most effective design with 94 kWh/m^2 and 600 kWh/kW. The capacity factor for each system design also indicates that east orientation is better for vertical PV application on buildings in Malaysia. The performance ratio for PV system on roof façade is higher compared with vertical façade.

This analysis has shown that PV installation on vertical façade of a high-rise building in Southeast Asia countries, especially in Malaysia, is able to generate energy, thus contributing to reducing the electricity cost of the building. Maximising the whole building surface, especially in an urban area with PV system, will benefit the building owner, thus the government to enhance the utilisation of renewable energy resources towards sustainable socio-economic development in this region.

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