SHADOW EFFECT OF SURROUNDING BUILDINGS ON BIPV SYSTEM PERFORMANCE

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Abstract

The building-integrated photovoltaic (BIPV) system has recently become a hot research topic. In this study, three main factors–the position and height of a building and the distance between buildings--were thoroughly investigated as to their shadow effect on BIPV system performance in office buildings. A simulation model was made using EnergyPlus, which was validated with actual experiment data from 'K' laboratory that was recently constructed in the vicinity of Seoul, Korea for the conduct of various environment-friendly experiments, including experiments on BIPV system performance. The effect of shadows on BIPV power was analyzed through parametric studies. First, generated BIPV power depending on shadows decreased at the highest rate of 59% when the BIPV system was located on the east side of adjacent buildings. Second, the generated BIPV power of the base model building decreased at the rates of 13%, 54%, and 59% due to the shadows of adjacent buildings with heights of 13m, 26m, and 39m. Third, the generated BIPV power decreased by 54%, 24%, and 11% when the adjacent buildings were 5m, 13m, and 26m away from the base model building, respectively.

Keywords: Building-integrated photovoltaic (BIPV) system, Power generation, Simulation model validation, Shadow effect, Distance between buildings

1. Introduction

Studies on the development of substitutive energy are being actively conducted to address problems with environment contamination and depletion of fossil energy, and the use of renewable energy for a certain proportion of the energy consumed in buildings is obligated to activate the use and supply of renewable energy. The PV generation systems that have been applied to or designed for buildings are commonly installed on rooftops and roofs. This form restricts the use of PV systems, though. Accordingly, when a building-integrated photovoltaic (BIPV) system is combined with the exterior materials of buildings, solar energy may be more effectively used. The shadows on PV installed in buildings degrade the systems' performance. Such shadows are caused by adjacent buildings or by the elements of most architectural buildings in downtown Korea. Thus, the properties of PV modules based on such shadows must be considered from the design phase. Accordingly, studies that can generate basic design data, and case studies that involve analysis of the generation of shadows effect in BIPV systems, are required. In this paper compared the BIPV generation power through simulations and actual BIPV generation power data from K laboratory, which installed BIPV system in curtain-wall-structure office. Furthermore, the BIPV system that is currently installed on the south side of the building was virtually installed with same PV system on the other three side of the building (east, west, and north) to evaluate the changes in the generated BIPV power based on weather conditions and the features of the generated BIPV power based on the other side direction, and to study the possibility of application to lighting or equipment load. The factors that shading effect generated by adjacent buildings were categorized in this study as the location, height, and distance of the adjacent buildings using the verified model, and case studies on the effects of differences in such factors were studied.

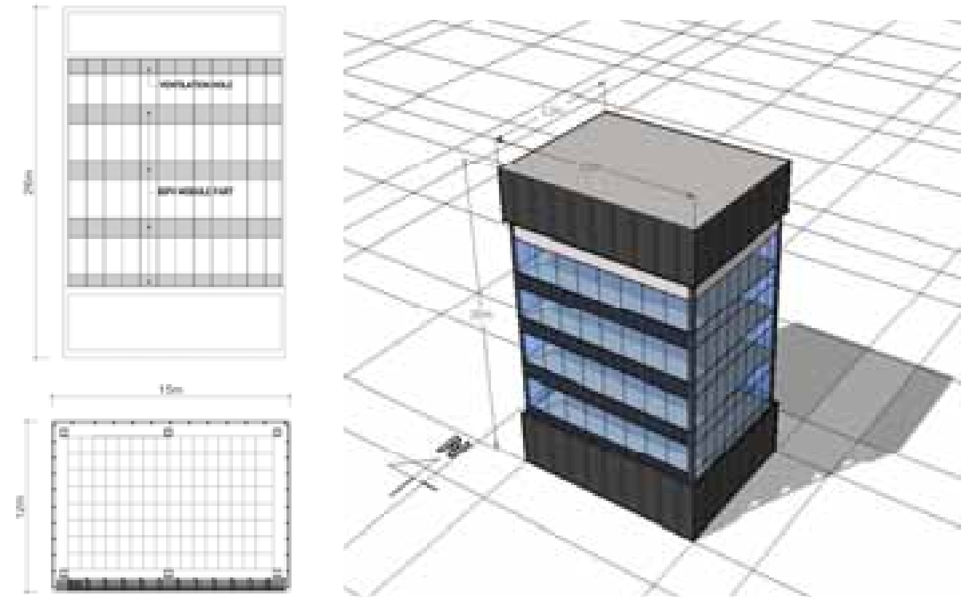


Fig. 1: Building modeling figure

2. Building Modeling and Validation

2.1. Modeling of the subject building

The subject buildings were modeled as shown in Figure 1 by separating the office sector of K laboratory that is located in Yongin, Republic of Korea and that has six floors above the ground and one floor below the ground. The building is 15m wide, 12m deep, and 26m tall, and BIPV systems are installed on the spandrel sections between floors on the south side of the building. The PV module is integrated with the external building materials through its insertion in the cavity wall between two glasses of double-layered windows. The performance details of the installed BIPV module are shown in Table 1. The installed BIPV system is a polycrystalline photovoltaic module, and its maximum generation power is 5.4 kW.

2.2 Validation of the measured and simulated BIPV power

The measured BIPV power and simulated BIPV power of the building was verified and EnergyPlus 6.0 which is computer simulation program was used. The term of the validation was one week, from April 4 to 10, 2011. Table 2 summarizes the meteorological data during the period of validation from the Korea Meteorological Administration.

Tab. 1: PV module performance

Item	Open circuit voltage(V_{oc})	Short circuit current(I_{sc})	Maximum power(P_{max})	Voltage at maximum power(V_{mp})	Current at maximum power(I_{mp})	Conversion efficiency
Unit	V	A	W	V	A	%
Value	25.9	9.3	153.8	19.9	7.72	15.2

Tab. 2: Weather data during 4~10, April

Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Average temperature(℃)	10.1	10.7	10.6	9.6	11.4	9.9	10.8
Average cloudiness	0.3	-	6.4	10.0	4.0	1.3	7.1
Precipitation(mm)	-	-	-	7.0	-	-	1.5

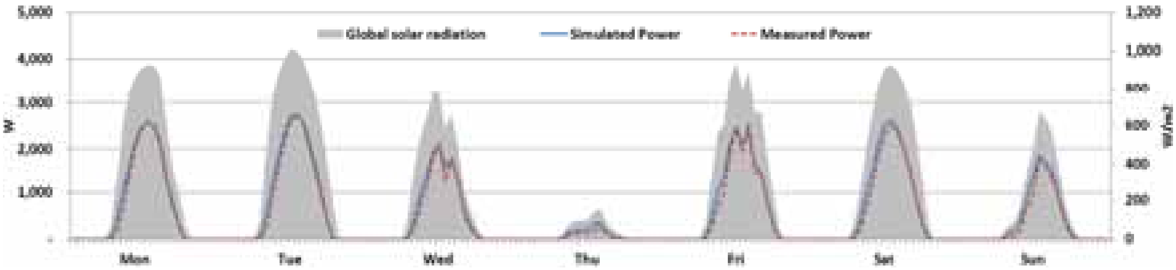


Fig. 2: Hourly profile between measured and simulated BIPV power.

The validation period was appropriate for the comparative validation of the generated BIPV power because the period had clear days, cloudy days, and rainy days. Figure 2 compares the measured and simulated BIPV power within the validation period. The result of validation showed a well-fitted hourly profile and Cv(RMSE) value of 27.6%, which is close to the 30% proposed by the M&V guidelines of the US DOE as an acceptable calibration tolerance rate.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} P_{sim} - P_{mea}}{n}} \qquad \text{(eq. 1)}$$

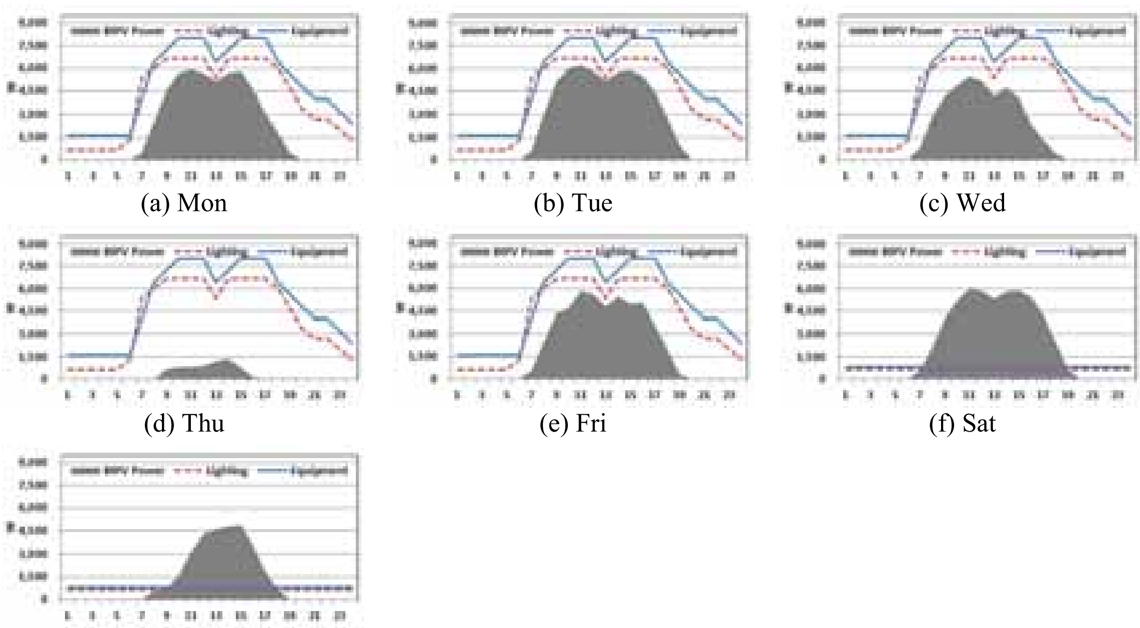
$$\mathrm{Cv(RMSE)} = \frac{RMSE}{P_{mea,avg}} \times 100 \qquad \text{(eq. 2)}$$

P_{sim} : simulated power(W), P_{mea}: Measured power(W), n : A number of data

$P_{mea,avg}$: Average of measured data

3. Analysis of the Power Generated BIPV System Installed on the Four Sides of the Building

The measured and simulated BIPV power installed on the south side of the building, as mentioned in the previous chapter, was verified. The same BIPV system was applied on the east, west, and north sides. Generated BIPV power on the four sides of the building was compared through a simulation.



(a) Mon (b) Tue (c) Wed (d) Thu (e) Fri (f) Sat (g) Sun

Fig. 3: Hourly generated BIPV power and lighting, and equipment loads

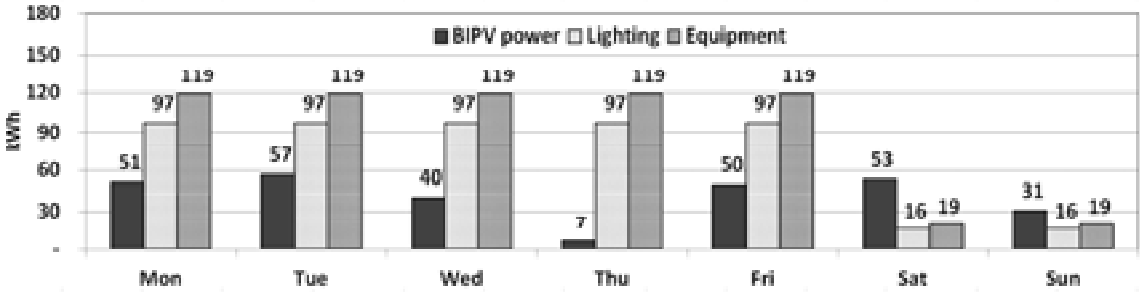


Fig. 4: Sum of the generated BIPV power and lighting and equipment loads

Shown in Figure 3 are the changes in the hourly generated BIPV power during the week. The generated BIPV power was greatest on Tuesday and Wednesday generated BIPV power is lower than on Tuesday due to heavy clouds. The generated BIPV power was lowest on Thursday, when there were heavy clouds and rain.

When a lighting load of 10 W/m^2 and an equipment load of 12 $W/\ m^2$ were used in the building, the generated BIPV power was used for the building load, except on Thursday, when the weather was poor. Also, 84kWh of the generated BIPV power was accumulated over the weekend, when there was no lighting or equipment load, and the accumulated power was used for the building load the following week. Shown in Figure 4 is the sum of the generated BIPV power during the week. On Tuesday, when there was a high generated BIPV power, approximately half of the lighting load was covered by the generated BIPV power.

Shown in Figure 5 are the photoelectric conversion efficiency and temperature of the PV cell and the generated BIPV power on Tuesday. The photoelectric conversion efficiency was determined based on the proportion of electric energy released and the amount of light energy that entered the cell, which was calculated using equation (eq. 3). The generated BIPV power on the east and west sides showed higher efficiency than on the south and north sides, and the efficiency slightly decreased when the cell temperature increased.

$$\eta = \frac{E_o}{E_i} \times 100 \qquad \text{(eq. 3)}$$

E_o : Generated PV power (W/m2)

E_i : Solar radiation energy (W/m2)

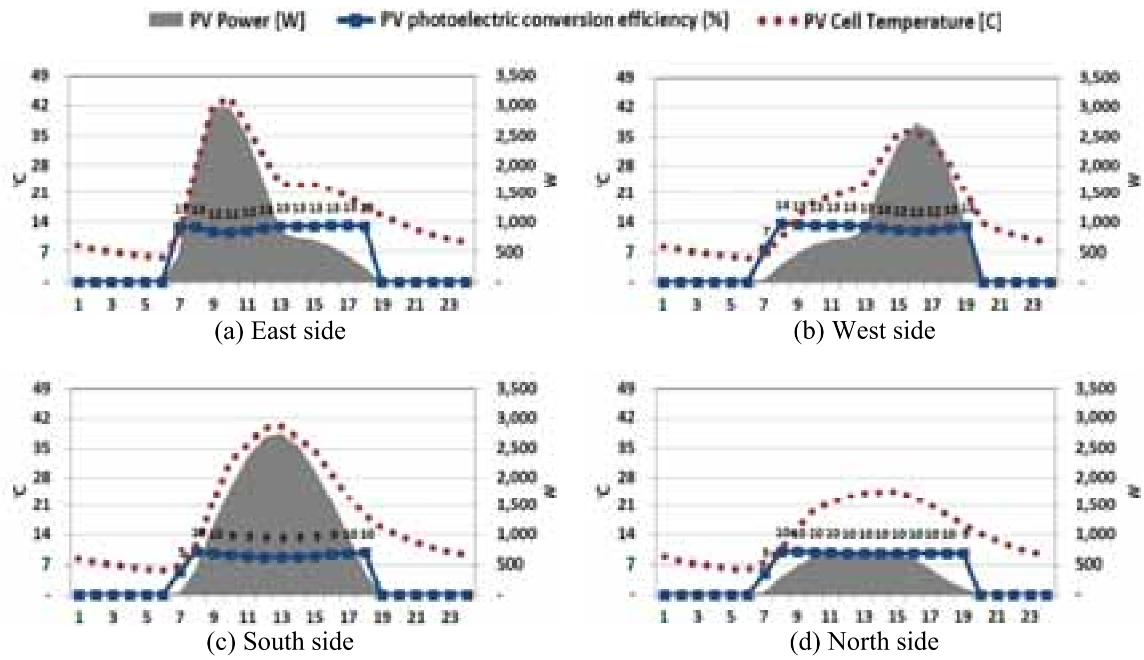


Fig. 5: Analysis of the generated BIPV power, photoelectric conversion efficiency, and cell temperature

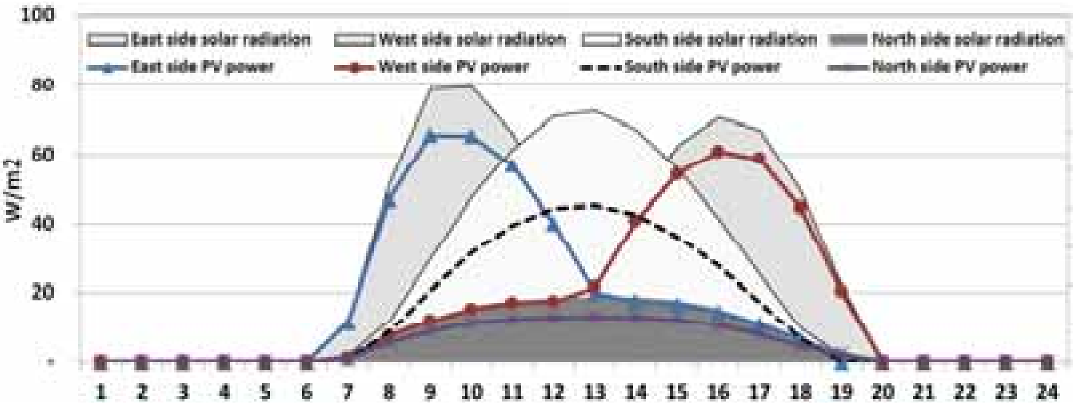


Fig. 6: Generated BIPV power per unit area and solar radiation on the cells on Tuesday

Shown in Figure 6 are the solar radiation rate per unit area on the PV cell, and the generated BIPV power per unit area on Tuesday. The solar radiation rate per unit area was higher on the east and west sides per unit area, and thus, the generated BIPV power on these sides were higher than on the south or north side. Because the solar radiation rates and the generated BIPV power per unit area on the east and west sides were higher, the east and west sides showed greater generation efficiency than the south and north sides.

Shown in Figure 7 is the generated BIPV power hourly profile and the total generated BIPV power on the four sides of the building for the week. The greatest generated BIPV power is on the south side, and approximately 4kWh more power on the east side than on the west side. The figure also shows hourly generated BIPV power on the east, west, south, and north sides. The greatest generated BIPV power is on Tuesday, with more power on the east side than on the west side and stronger solar radiation in the morning. On Wednesday, more power was generated in the morning (east side) than in the afternoon (west side); and on Sunday, more power was generated in the afternoon (west side) than in the morning (east side). It is thus concluded that the generated BIPV power on the east and west sides differed based on the meteorological conditions.

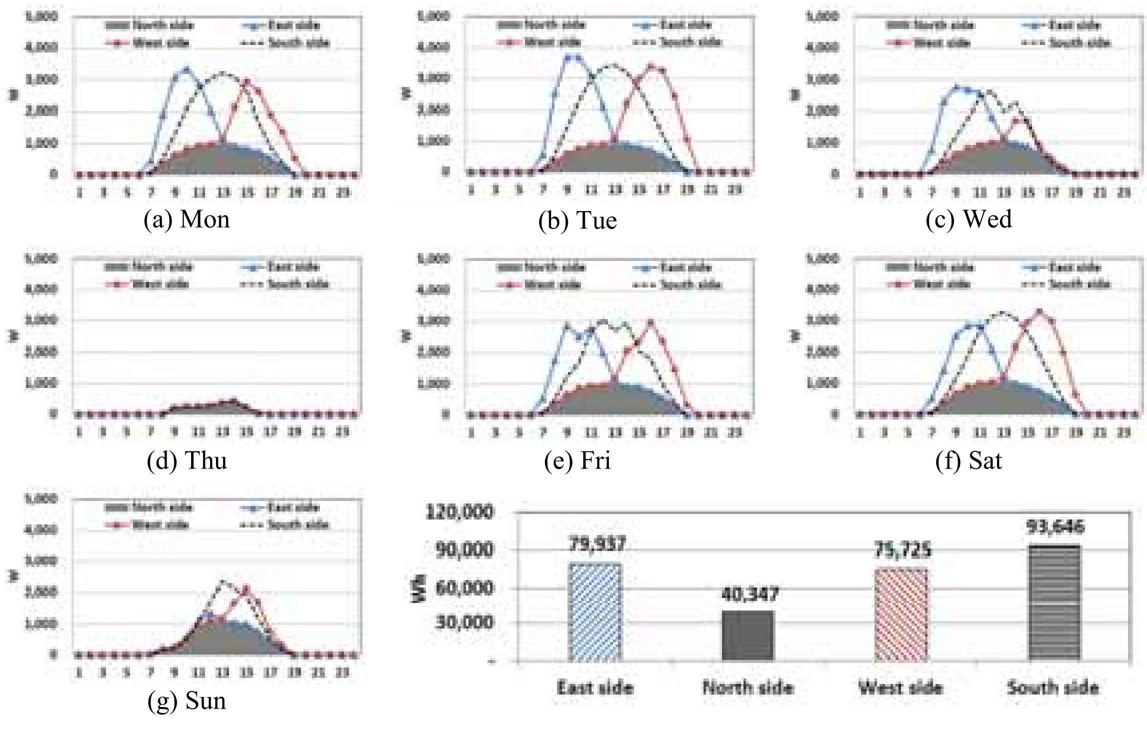


Fig. 7: Hourly generated BIPV power profile and sum of the generated BIPV power on four sides of the building

4. Analysis of the Generated BIPV Power Effect by Shadows of Adjacent Buildings

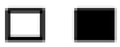
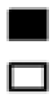
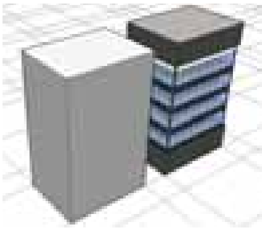
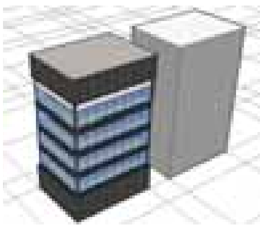
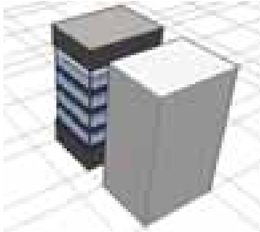
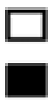
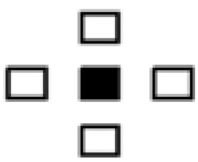
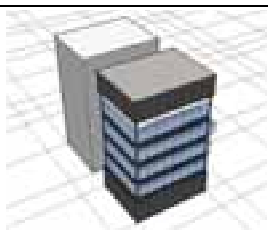
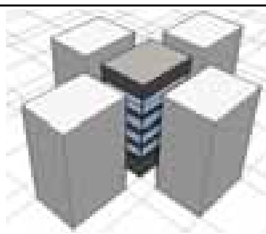
The PV module is generally affected by shadows. For BIPV systems installed in downtown areas, the PV generation rate decreases due to surrounding buildings. Accordingly, the changes in the generated BIPV power in a building based on the location, height, and distance of adjacent buildings from the base building were examined from Monday, April 4, to Sunday, April 10, 2011 using a model building, on the east, west, south, and north sides of which BIPV systems were installed, as mentioned in the previous chapter; and the relationship of shadow effects and the power generation properties of the BIPV systems installed on the four sides of the building were analyzed through a simulation.

4.1. Analysis of generated BIPV Power depending on the location of adjacent buildings

The features of the generated BIPV power depending on the location of adjacent buildings were analyzed through a simulation. All the adjacent buildings were located 5m away from the base building. Five case studies were conducted with different locations of adjacent buildings (Table 3). The sizes of the adjacent buildings were identical to the size of the base building. Because the buildings were close to the base building, shadows were formed during the day, which affected the generated BIPV power of the base building.

Shown in Figure 8 is sum of the generated BIPV power of the base model and four cases for one week. The generated BIPV power depending on the location of adjacent buildings decreased by 59% on the east side, by 50% on the north side, by 58% on the west side, and by 49% on the south side. The generated BIPV power decreased more on the east and west sides than on the south side, and was affected more by the shadow effects formed by adjacent buildings than in the base model.

Tab. 3: Case classification based on the location of adjacent buildings

Base Model	Case1 (West)	Case2 (East)	Case3 (South)
			
			
	Case4 (North)	Case5 (All)	
			
			

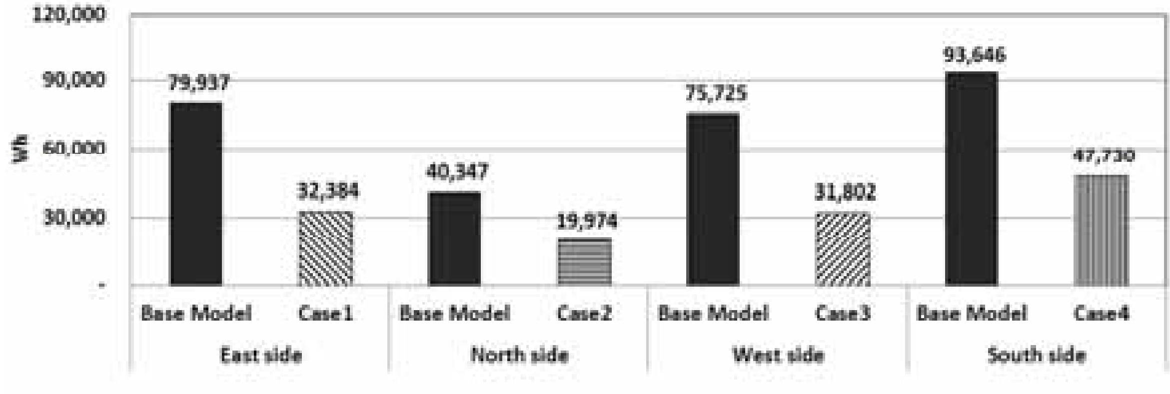


Fig. 8: Sum of generated BIPV power of the base building and the BIPV power generated in all the cases

Shown in Figure 9 is the generated BIPV power at hourly profile of the base model building and with adjacent buildings during the one-week. Especially, the generated BIPV power feature on the east and north sides were similar profile when located adjacent building during one week. When the incidence angle of sun was height, the generated BIPV power on the south side decreased at noon because adjacent buildings blocked the solar radiation. The generated BIPV power was generally low on the north side, and was generally affected by diffuse radiation than by direct normal radiation.

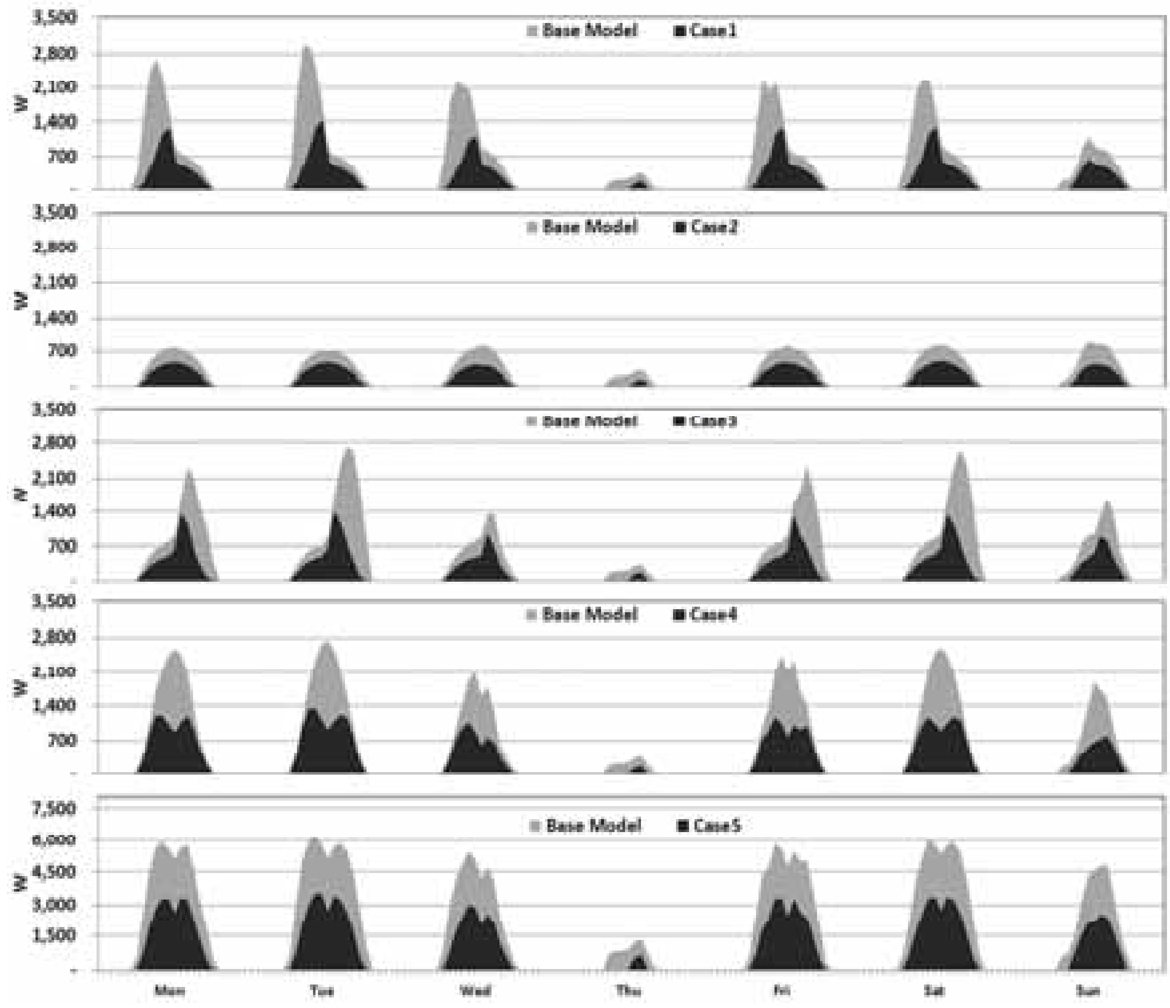
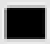
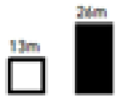
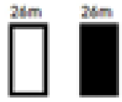
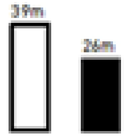
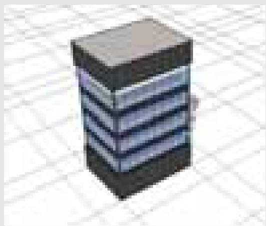
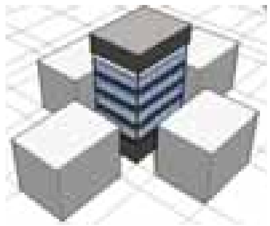
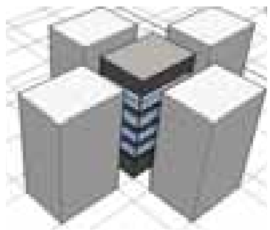
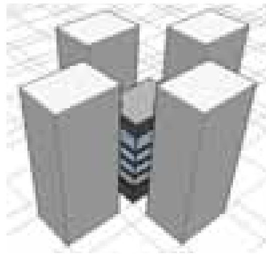


Fig. 9: Generated BIPV power in the base model building and in all the cases

Tab. 4: Case classification based on the height of adjacent buildings

Base Model	Case1	Case2	Case3
			
			

4.2. Analysis of generated BIPV power depending on the height of adjacent buildings

The generated BIPV power is affected by the height of adjacent buildings in downtown areas. In this study, all the adjacent buildings were located 5m away from the base model building. Three case studies were conducted with different locations of the adjacent buildings (Table 4). In Case 1, the height of the adjacent buildings was set at half the height of the base model, or 13m; in Case 2, the same as the height of the base model building of 26m; and in Case 3, 13m higher than the base model building. The changes in the generated BIPV power were analyzed with the different heights of the adjacent buildings.

Shown in Figure 10 are the generated BIPV power on the east, north, west, and south sides of the base model, according to the different heights of the adjacent buildings during the week. The generated BIPV power decreased by 18% on the east side, 14% on the north side, 16% on the west side, and 7% on the south side in the case of the 13m-tall adjacent buildings. In Case 2, with the adjacent buildings as high as the base model building, the generated BIPV power decreased by 59% on the east side, 50% on the north side, 58% on the west side, and 49% on the south side. Case 3 showed a little generated BIPV power decrease than Case 2 except south side. Accordingly, the shadow effect to the generated BIPV power of the greater height of the base model (26 m) was small.

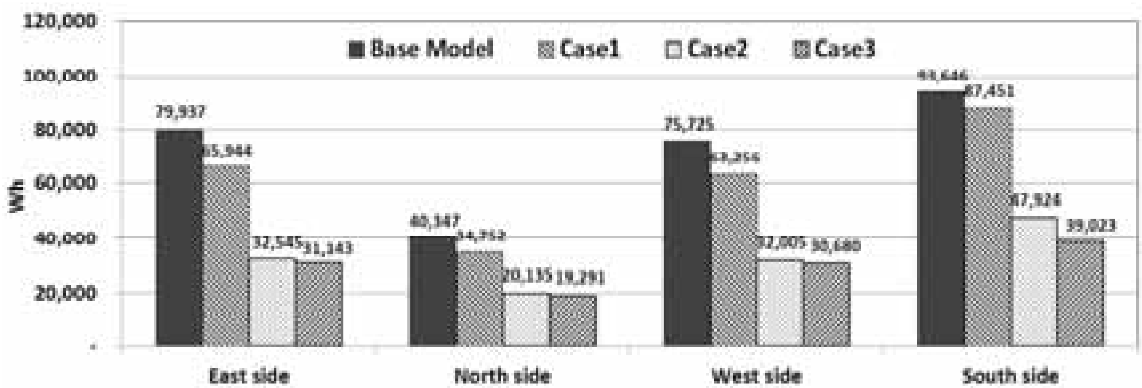


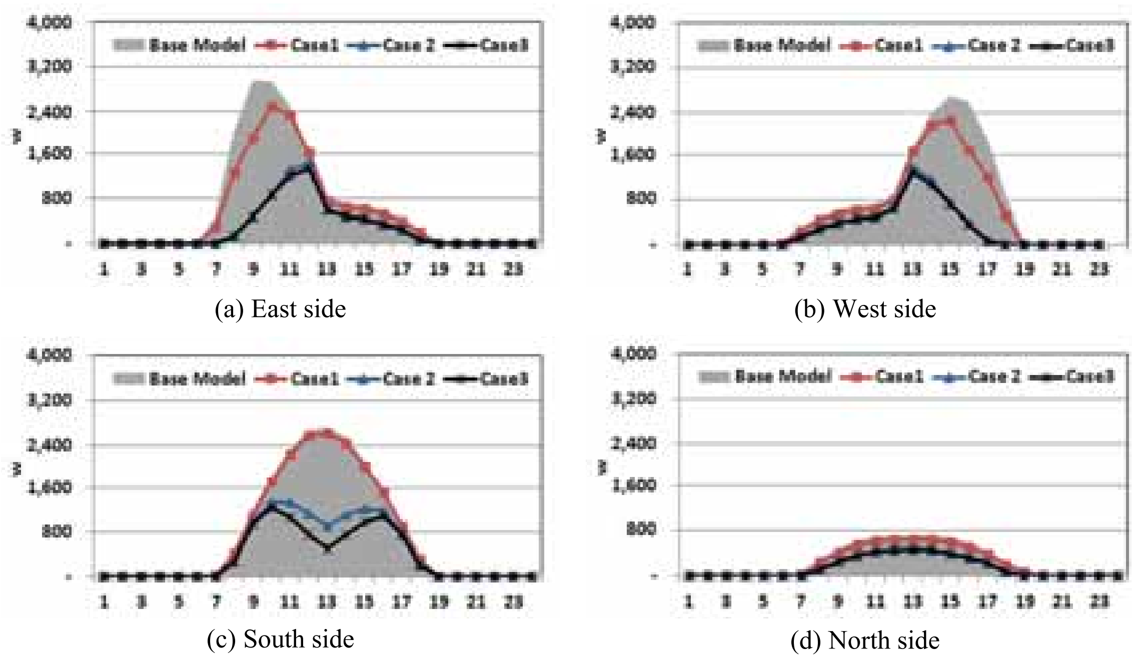
Fig. 10: Generated BIPV power of the base model and in all the cases

Tab. 5: Sum of the generated BIPV power of the base model building and each case

Day	Base Model Power (Wh)	Case 1			Case 2			Case 3		
		Power (Wh)	Decreased Power (Wh)	Decreasing Rate (%)	Power (Wh)	Decreased Power (Wh)	Decreasing Rate (%)	Power (Wh)	Decreased Power (Wh)	Decreasing Rate (%)
Mon	51,399	44,965	6,433	13	24,410	26,989	53	22,078	29,321	57
Tue	57,226	49,287	7,939	14	26,455	30,771	54	24,036	33,190	58
Wed	40,406	35,033	5,373	13	18,554	21,852	54	16,878	23,528	58
Thu	6,614	5,537	1,077	16	1,049	5,565	84	812	5,802	88
Fri	49,765	43,277	6,488	13	23,403	26,362	53	21,226	28,539	57
Sat	53,452	46,413	7,039	13	24,964	28,488	53	22,656	30,796	58
Sun	30,793	26,891	3,902	13	13,773	17,020	55	12,452	18,341	60
Sum	289,655	251,403	38,252	13	132,608	157,047	54	120,138	169,517	59

Table 5 shows the sum of generated BIPV power in each case, depending on the heights of the base model and the adjacent buildings during the week from Monday to Sunday. The generated BIPV power decreased by approximately 13% when there were adjacent buildings that were half as tall (13 m) as the base model, and the generated BIPV power decreased by 54% when there were adjacent buildings that were as high (26 m) as the base model. The difference between the generated BIPV power in Cases 2 and 3 depending on the shadows formed by the adjacent buildings that were taller than the base model building (26 m) was 4%, which is small.

Shown in Figure 11 are the generated BIPV power on the east, west, south, and north sides on Tuesday, when the weather was best during the week. The generated BIPV power decreased in Case 1, in which the adjacent buildings were 13 m tall, but it showed a general tendency to follow the generated power of the base model. The generated power greatly decreased when the adjacent buildings were as high as or higher than the base model, such as in Cases 2 and 3, and the generated power was based on diffused radiation than on direct normal radiation due to the adjacent buildings. The generated power was low on the north side, and there was a little difference in generated power among the individual cases.

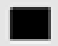
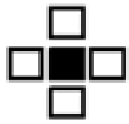
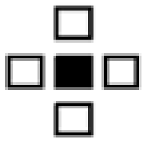
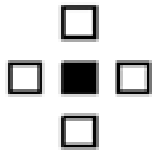
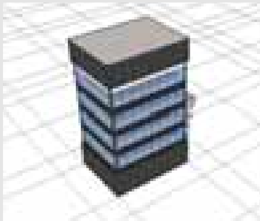
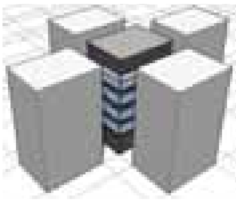
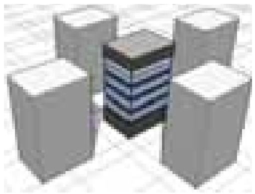
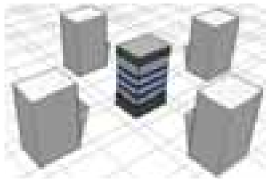


(a) East side (b) West side

(c) South side (d) North side

Fig. 11: Generated BIPV power variations in the base model building and in each case on Tuesday,

Tab. 6: Case classification based on the distance of the adjacent buildings from the base model building

Base Model	Case1 (5m)	Case2 (13m)	Case3 (26m)
			
			

4.3. Analysis of generated BIPV power depending on the distance of adjacent buildings

The generated BIPV power changes depending on the distance of the adjacent buildings from the base building. Three case studies were conducted with adjacent buildings that were 5m, 13m, and 26m away from the base model building (Table 6). The 13m distance of the adjacent buildings from the base model is half the height of the base model building, and the 26m distance of the adjacent buildings from the base model building is same height of the base model building. The changes in the generated BIPV power were analyzed with the changes in the distance of the adjacent buildings from the base model building.

Shown in Figure 12 are the generated BIPV power on the east, north, west, and south sides of the base model building depending on the changes in the distance of the building from the adjacent buildings over the week. The generated power decreased by 59% on the east side, 50% on the north side, 58% on the west side, and 49% on the south side in the case of the 5m-distant building. In the case of the 13m-distant building, Case 2 showed a generated power reduction of 33% on the east side, 26% on the north side, 31% on the west side, and 11% on the south side. In Case 3, the distance from the base model to the adjacent buildings was 26 m, and the generated BIPV power decreased by 16% on the east side, 11% on the north side, 15% on the west side, 5% on the south side. Moreover, the generated BIPV power on the east and west sides, where the sun rises and sets, respectively, were greatly affected by the shadows formed by the adjacent buildings.

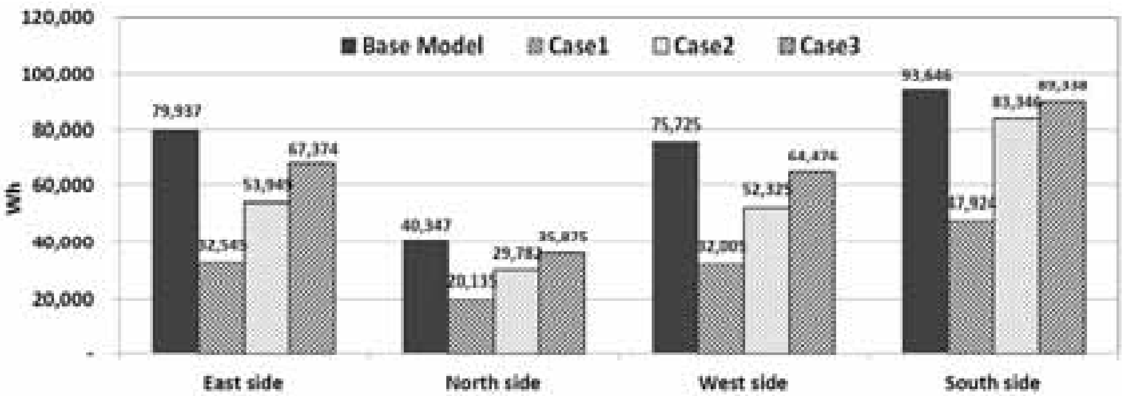


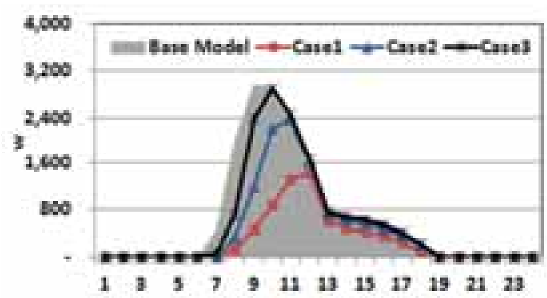
Fig. 12: Generated BIPV power of the base model building and in each case

Tab. 7: Sum of the daily generated BIPV power of the base model building and in all the cases

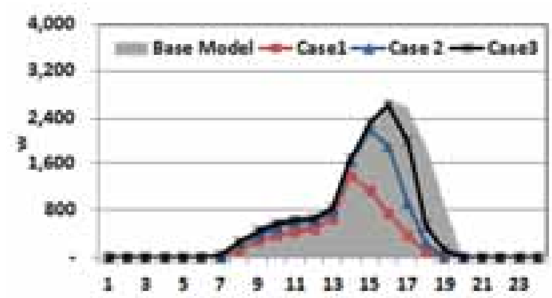
Day	Base Model Power (Wh)	Case 1			Case 2			Case 3		
		Power (Wh)	Decreased Power (Wh)	Decreasing Rate (%)	Power (Wh)	Decreased Power (Wh)	Decreasing Rate (%)	Power (Wh)	Decreased Power (Wh)	Decreasing Rate (%)
Mon	51,399	24,410	26,989	53	39,632	11,767	23	45,809	5,590	11
Tue	57,226	26,455	30,771	54	42,772	14,454	25	49,945	7,281	13
Wed	40,406	18,554	21,852	54	30,453	9,953	25	35,740	4,666	12
Thu	6,614	1,049	5,565	84	4,461	2,153	33	5,903	711	11
Fri	49,765	23,403	26,362	53	37,882	11,883	24	44,186	5,579	11
Sat	53,452	24,964	28,488	53	40,678	12,774	24	47,382	6,070	11
Sun	30,793	13,773	17,020	55	23,523	7,270	24	28,100	2,693	9
Sum	289,655	132,608	157,047	54	219,401	70,254	24	257,065	32,590	11

Table 7 shows the generated BIPV power in each case depending on the distance between the base model building and adjacent buildings during the week from Monday to Sunday. With a distance of 5m between the base model building and adjacent buildings, Case 1 showed a power generation rate decrease of 54%. When the adjacent buildings were placed 13m away from the base model building, which distance is half the height of the base model building, the BIPV power generation rate decreased by approximately 24%; and in Case 3, when the adjacent buildings were placed 26m away from the base model building, which distance is identical to the height of the base model building, the generated BIPV power decreased by 11%.

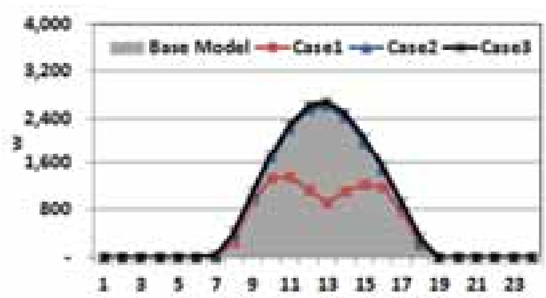
Shown in Figure 13 are the hourly generated BIPV power on the east, west, south, and north sides of the base model building depending on its distance from the adjacent buildings. The generated power was smaller when the base model building was closer to the adjacent buildings, and was a little affected by the shadows of the adjacent buildings when the base model building was more than 26m away from the adjacent buildings. Especially, there was considerably decrease in the generated power when the distance of the base model building from the adjacent buildings on the south side was 5m, but the shadows had little effect when the distance was greater than 13m.



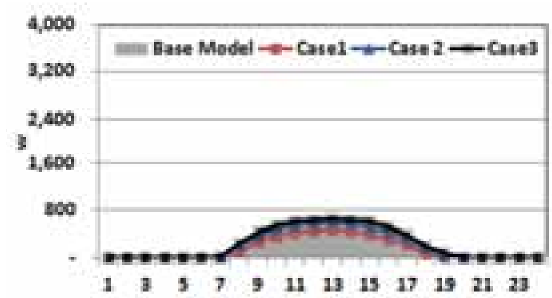
(a) East side



(b) West side



(c) South side



(d) North side

Fig. 13: Generated BIPV power variations in the base model building and in all the cases on Tuesday,

5. Conclusion

This paper studied the relationship between the shadows formed by buildings in the vicinity of a building and the power generation features of BIPV systems installed on the spandrel sections between floors of the building, based on the commonly applied curtain wall structure of office buildings.

The results of this study are summarized as follows.

(1) Validation between measured BIPV power and simulated BIPV power on the south side building was satisfactory at 27.6% Cv(RMSE).

(2) BIPV systems were installed on the four sides of the building with the same form using validated simulation building. The total generated BIPV power within the one-week were 79kWh on the east side, 40kWh on the north side, 75kWh on the west side, and highest at 93 kWh on the south side, with the generated power on the east side slightly higher than on the west side, and with the generated power on the north side not even half that on the south side. Decreased efficiency was seen with a higher PV cell temperature.

(3) The relationship between the generated power and the shadows formed by buildings in the adjacent of the base model building on four sides of which a BIPV system was installed was categorized depending on the location, height, and distance of the adjacent buildings from the base model building, and case study was conducted. When the adjacent buildings which is 5m away from the base model, the east, west, south, and north sides of the base model building, the generated BIPV power decreased by 59% on the east side, 50% on the north side, 58% on the west side, and 49% on the south side depending on the shadows. The decreases in the generated BIPV power depending on the different shadows formed by the different heights of the adjacent buildings were 13%, 54%, and 59% in the cases of the 13m-, 26m-, and 39m-tall adjacent buildings, and 54%, 24%, and 11% in the cases of the 5m-, 13m-, and 26m-distant adjacent buildings.

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