Study on environment conscious technologies in a super tall building: Evaluation of PV performance considering aerological climate

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Abstract. In recent years, buildings have tended to be taller, and their energy potential is expected to be used effectively. Photovoltaics is considered one of technologies affected by air temperature, outside air velocity, and solar radiation from the aerological climate of supertall buildings with a height of 390 m. The energy potential of the "height" of photovoltaic power generation systems is affected by two factors: aerological climate and shadows cast by surrounding buildings. Taking these effects into account, the predicted annual power generation amount was calculated. At 390 m above ground, it was confirmed that the power generation amount was greater than that on the ground, when considering the effectiveness of photovoltaic systems. Then, we calculated the predicted annual power generation amount on each wall and roof surface of a tall building with a height of 390 m above the ground. By evaluating the energy-saving effect of adopting photovoltaic systems, we evaluated the photovoltaic system using the wall surface from the viewpoint of the primary energy reduction and primary energy consumption of the building.

1 Introduction

In recent years, buildings have become taller, and thus are expected to effectively utilize the potential energy possessed by the "height" of a supertall building. [1]. Moreover, it is thought that a tall building and a supertall building can function as a vertical city, but their usefulness, efficiency, etc., are unknown.

In a previous report [2], we calculated the energy-saving effect when adopting small wind power generation, free cooling, and a cooling system utilizing outside air. In this study, we evaluate the possibility of adopting a photovoltaic system by comparing a supertall building with a height of 390 m that is expected to be completed in 2027 and a tall building with a height of 60 m, in which applications for structural performance evaluation of tall buildings are required (in Japan). Table 1 shows the outline of construction of this research subject.

2 Research content

At 390 m above the ground, the outside air velocity is greater than at 60 m above the ground, and the outside air temperature is expected to decrease. Moreover, a supertall building is not influenced by the shadows cast by surrounding buildings, and the outer wall of a supertall building has a large surface area. Photovoltaic systems are among the technologies that utilize such energy potential at 390 m above the ground. In a supertall building, it is important to install a photovoltaic power generation

system that uses walls to realize Net Zero Energy Building (ZEB).

Table 1. The outline of construction of this research subject.

Planned area	Chiyoda ward, Tokyo
Main application	Office, store,
Total floor area	About 490,000 m ²
Floor/Maximum Height	61 floors above the ground 5 underground floors/approx. 390 m
Construction (scheduled)	2023
Completion (planned)	2027

$$U_Z = U_R \left(\frac{Z}{Z_R} \right)^\alpha \quad (1)$$

$$T_{(Z)} = T_{(Z_R)} - \Gamma(Z - R) \quad (2)$$

$$J_n = J_{n0} \times P^m \quad (3)$$

$$m = \eta \times m_0 \quad (4)$$

$$\eta = \left(1 - \frac{Z_E}{44308} \right)^{5.527}$$

$$m_0 = \{ \sin h + 0.15(h + 3.885)^{-1.253} \}^{-1} \quad (6)$$

$$P = P_0 + a(t - 12)^2 \quad (7)$$

* All calculation formulas are based on references [2, 3, 4] and Bouguer's equation

Generally, as the amount of solar radiation increases, the temperature and surface temperature of the solar cell module rises accordingly while the power generation efficiency of the solar cell decreases. It is thought that the temperature rise of the solar cell module can be suppressed and the decrease in power generation efficiency can be prevented by the influence of the outside air temperature and air velocity at the tall part of the building. Also, in a photovoltaic power generation system, the amount of solar radiation is a measure of the amount of power generated. Two types of solar radiation, normal direct insolation and horizontal direct insolation, are necessary for generating power. Among them, normal direct insolation is related to the atmospheric mass. The atmospheric mass is defined as the air resistance until the sunlight reaches the surface of the earth, and it depends on the altitude. Thus, we evaluated the change in power generation amount due to altitude change.

For photovoltaic power generation systems in a supertall building, efficient power generation can be achieved by increasing the power generation amount according to the influence of aerological climate and shadows cast by surrounding buildings. First, aerological climate forecasting was performed to calculate the outside air velocity, outside air temperature, and normal direct insolation at the installed height of the solar cell array. Using the results of aerological climate forecasting, the amount of power generated on the roof surface and the wall surface in each direction was obtained. Furthermore, the power generation amount was compared at an altitude, and the increased amount with rising altitude was obtained. In addition, shadow analysis using analytical software was carried out to model the surrounding area of the target site and shadows by assuming the installation of a solar cell array on the roof surface and each wall surface of the supertall building 390 m above the ground. The power generation amount, taking into consideration only the influence of shadows, was calculated.

Then, the annual power generation amount in each direction of the wall surface and roof surface of a supertall building 390 m above ground, taking into account the improvement in photovoltaic power generation efficiency owing to both aerological climate and shadow effects, is calculated to determine the energy-saving effect of adopting photovoltaic systems as the primary energy source of buildings.

3 Aerological climate forecast

In order to estimate the power generated at each installation height of the photovoltaic power generation system, it is necessary to calculate the outside air velocity from extended Automated Meteorological Data Acquisition System (AMeDAS) weather data (standard year 2001–2010) at the "Tokyo" point for each installation height of the assumed solar cell array, outdoor air temperature, and normal direct insolation. The extended AMeDAS weather data used was the hourly data collected from December 2015 to November 2016.

3.1. Outside air velocity prediction

The outside air velocity at each solar cell array installation height was predicted from Eq. 1. The standard height of the outside air velocity was set to 6.5 m. In this study, it was calculated using the exponential law for outside air velocity prediction.

3.2. Outside air temperature prediction

The reference height of the outside air temperature was set to 1.5 m, and the outside air temperature at each solar cell array installation height was predicted with Eq. 2. The lapse rate used to predict the sky temperature represents the temperature decrease when the altitude increases by 1 km. This lapse rate was calculated based on the observation values of the Aerological Observatory in Tsukuba from December 2015 to November 2016. Fig. 1 shows the average value of Aerological Observatory data for October 2016. Table 2 shows the monthly temperature decrease based on Aerological Observatory data in Tsukuba City.

Fig. 1. Average value of Aerological Observatory data for October 2016.

Table 2. Monthly temperature decrease rate based on Aerological Observatory data.

Month/Year	Monthly temperature decrease rate [$^{\circ}\text{C}/\text{km}$]
December 2015	− 6.14
January 2016	− 8.14
February 2016	− 9.88
March 2016	− 7.68
April 2016	− 8.35
May 2016	− 7.66
June 2016	− 7.54
July 2016	− 9.42
August 2016	− 8.01
September 2016	− 7.92
October 2016	− 10.70
November 2016	− 7.37

3.3. Normal direct insolation forecast

The normal direct insolation of each solar cell array installation height was predicted with Eq. 3 to Eq. 7. At this time, if the amount of solar radiation is predicted from the calculation formula, weather effects cannot be taken into consideration. Therefore, we decided to convert the calculated solar radiation into the increment ratio of each installation height and multiply this by meteorological data. Specifically, by using the extended AMeDAS weather data, the normal direct insolation and horizontal direct insolation were calculated by separating the total solar insolation amount in Tokyo from the direct dispersion. In addition, we adopted the Perez model [5] as the method of direct separation by referring to past research.

3.4. Forecast results of aerological climate

Table 3 shows the difference in weather conditions between 60 m above the ground and 390 m above the ground. Fig. 2 shows the monthly average outside air velocity. Fig. 3 shows the monthly average outside air temperature, and Fig. 4 shows the monthly average normal direct insolation. The difference in outside temperature due to the height from the ground also depends on the lapse rate. Therefore, when comparing heights of 60 m and 390 m above the ground, Fig. 2 shows the largest temperature difference in outside temperature of approximately 3.5°C in October, when the lapse rate was the largest. Throughout the year, the difference was approximately $2.0\text{--}3.5^{\circ}\text{C}$. Similarly, for outside air velocity prediction, the average outside air velocity in April was the largest. There was an outside air velocity difference of approximately 4.2 m/s at 60 m and $3.1\text{--}4.2\text{ m/s}$ at 390 m above the ground. The difference between the normal direct insolation is small and the influence on the power generation amount is also considered to be small. The influence of aerological climate on the power generation amount was examined from these predicted values of outside air velocity, outside air temperature, and normal direct insolation.

Table 3. Difference in weather conditions between 60 m above the ground and 390 m above the ground.

	Month with the largest value difference	Range of value difference over the year
Outside air velocity	April 2016	$3.1\text{--}4.2\text{ [m/s]}$
Outside air temperature	October 2016	$2.0\text{--}3.5\text{ [}^{\circ}\text{C}]$
Normal direct insolation	January 2016	$0.006\text{--}0.017\text{ [MJ/m}^2\text{h}]$

Fig. 2. Monthly average outside air velocity.

Fig. 3. Monthly average outside air temperature.

Fig. 4. Monthly average normal direct insolation.

4 Photovoltaic system and aerological climate

4.1. Calculation method

We used the power generation calculation program for a photovoltaic power generation facility [6]. Using the aerological climate forecast results and calculation conditions in Table 4, the power generation amount on the roof surface and each wall surface was calculated. In this calculation program, data on the solar altitude angle, solar azimuth angle, and horizontal direct insolation from extended AMeDAS weather data were used along with the outside air velocity, outside air temperature, and normal direct insolation calculated by aerological climate

prediction. Since the temperature of the solar cell module depends on the outside air velocity and outside air temperature, the power generation amount is compared at each altitude, and the increase in power generated with the increase in altitude was obtained. The solar cell array on the roof surface sets the power generation surface facing south and the inclination angle was arbitrarily set. Each wall of the target building in this study was rotated approximately 20° clockwise. The azimuth angle is 0° in the south, and indicates the degree of clockwise rotation.

Table 4. Calculation conditions.

Calculation period	1 year
Region classification (in Tokyo, Japan)	6 *[6]
Yearly solar radiation area classification (in Tokyo, Japan)	A3 *[6]
Type	Crystalline silicon type
System capacity	1 kW
Rated load efficiency of power conditioner	95 %
Calculation item	(1) Roof plane (inclination angle 0° to 90°) (2) Each direction wall surface (inclination angle 90°) and entire wall (excluding North) South wall (azimuth angle 20°) West wall (azimuth angle 110°) East wall (azimuth angle 200°)

4.2. Calculation results of increased power generation by aerological climate

Fig. 5 shows the change in power generation amount with the rise in altitude. Table 5 shows the power generation ratio at 390 m above the ground compared with 60 m above the ground. The rise in altitude caused the outside air temperature to decrease and outside air velocity to increase, and the increase in power generation amount owing to the increase in solar radiation amount was confirmed. At 390 m above the ground, the maximum amount of power generated increased by 8.2% (inclination angle 30°) compared with near the ground, which is the maximum; compared with 60 m above the ground, this represents a 4.1% increase (inclination angle 30°). Likewise, on the south wall surface, the power generation amount at 390 m increased by 6.4% compared with near the ground, and 3.7% compared with 60 m above the ground. At inclination angle of 0° on the roof surface, where maximum number of solar cell arrays can be installed, the power generation amount at 390 m increased by 7.4% compared with near the ground, and by 3.7% compared with 60 m above the ground. Compared with the installation of the solar cell array on the wall surface, the increase in the power generation amount associated with arrays installed on the roof surface of the tall building became higher.

Table 5. The power generation ratio at 390 m above the ground compared with 60 m above the ground. [%]
(Considering only the influence of aerological climate)

Roof plane (inclination angle setting)		Wall surface	
0°	+3.7	Entire wall (excluding North)	+3.3
15°	+4.0	South wall (azimuth angle 20°)	+3.7
30°	+4.1	West wall (azimuth angle 110°)	+2.8
90°	+3.5	East wall (azimuth angle 200°)	+3.4

Fig. 5. The rate of increase in power generation due to aerological climate for each height based on power generation from the ground. [%]

5 Photovoltaic system and shadow

5.1. Method of analysis

Using the photovoltaic system simulation software "Solar Pro 4.5," peripheral models of target buildings were created and the influence of the shadows cast by surrounding buildings was evaluated. The power generation amount on the wall surface was calculated for each direction and each floor (system capacity 12.15 kW) of a tall building with height of 60 m, and compared with that of a supertall building with a height of 390 m. The roof surface was calculated by assuming that the installation area of the solar cell array is 1/4 of the building area. The analysis conditions are listed in Table 6 [7]. The solar cell array installation positions on the wall surface are shown in Fig. 6. Fig. 7 shows the analytical model of a supertall building with a height of 390 m and a tall building with a height of 60 m. The solar cell arrays on the wall surface were mounted just above the glass wall on each floor.

Table 6. Analysis conditions.

Usage data		NEDO (New Energy and Industrial Technology Development Organization) (in Japan) Annual hourly solar radiation volume database (METPV-11)
Analysis period		1 year
Solar cell type		Maximum output: 270 W Module conversion efficiency : 16.40 %
Solar cell installation location	Wall surface	Each wall designation position (inclination angle 90°) 1 PCS per floor * See Figure 6
	Roof surface	1/4 of the building area, Installation area: approx. 2,400 m ²
Solar cell installation location	Wall surface	45 modules (system capacity: 12.15 kW) of 9 (parallel number) × 5 (serial number) per PCS (1 PCS per floor)
	Roof surface	<ul style="list-style-type: none"> 800 modules (system capacity 216 kW) of 5 units (PCS) × 10 (parallel number) × 16 (serial number) [the inclination angle is 15° 634 modules (system capacity 171.18 kW) of 4 units (PCS) × 10 (parallel number) × 16 (serial number) [the inclination angle is 30°

Fig. 6. Solar cell array installation position on the wall surface.

A supertall building with a height of 390 m above the ground.

A tall building with a height of 60 m above the ground.

Fig. 7. Analytical model.

5.2. Analytical result of generation change by day shadows

Fig. 8 shows the analysis results of the predicted annual power generation on each wall of the supertall building 390 m above the ground. Table 7 shows the array installable areas of higher floors not affected by the shadows of surrounding buildings. Table 8 shows the power generation ratio at 390 m above the ground based on the reference height of 60 m above the ground, considering only the influence of shadows. Areas that are considered unaffected by surrounding buildings are the 29 floors on the south wall (155.2 m above the ground), 39 floors on the east wall (215.7 m above the ground), and 30 floors on the west wall (170.2 m above the ground) or higher. In addition, the maximum installable area for solar arrays is 3,344 m² on the south wall. This is one of the advantages of installing the photovoltaic power generation system on the wall.

Fig. 8. Analysis results of the annual predicted power generation amount on each wall of the super tall building 390 m above the ground. [kWh/y]

Table 7. Array installable area of higher floors not affected by shadows of surrounding buildings.

	Array installable area [m ²]
South wall	3,344 (29F–61F)
West wall	3,240 (30F–61F)
East wall	2,299 (39F–61F)

Table 8. The power generation ratio at 390 m above the ground based on the reference height of 60 m. [%]
(Considering only the influence of shadows by surrounding buildings)

Roof plane (inclination angle setting)		Wall surface	
0°	+18.1	Entire wall (excluding North)	+27.4
15°	+20.4	South wall (azimuth angle 20°)	+32.1
30°	+21.6	West wall (azimuth angle 110°)	+7.9
90°	+23.9	East wall (azimuth angle 200°)	+40.5

6 Calculation of power generation amount considering aerological climate and shadows

6.1. Calculation method

The energy potential of the "height" of the photovoltaic power generation system can be exploited by meeting two conditions: "influence of aerological climate" and "not affected by shadow." Taking these effects into account at the same time, the predicted annual power generation was calculated. The annual power generated on each floor by each wall of the supertall building and tall building, considering only the influence of shadows by surrounding buildings and the annual predicted power generation on the roof surface, were obtained in Section 5.2. By multiplying the increase ratio of the power generation amount due to the aerological climate obtained in Section 4.2, the annual power generated by each wall surface and roof surface in each building was calculated. We used the weighted value according to the analytical model used for shadow analysis as the rate of increase in power generation by aerological climate. For the purpose of comparison, the power generation amounts were calculated by integrating up to the 10th floor, 20th floor, and 30th floor from the highest level to the lowest level.

6.2. Calculation results

Table 9 shows the power generation ratio at 390 m above the ground based on the reference height of 60 m upon consideration of both aerological climate and shadow effects. Fig. 9 shows the comparison of the integrated power generation amount. The amount of power generated by considering both aerological climate and shadows at 390 m above the ground increased by 10.4% (west wall) and 44.1% (east wall) compared with 60 m above the ground. Approximately 200,000 – 300,000 kWh/y of electricity was generated for 30 floors (from the 32th floor to the 61st floor) accumulation of power generation on each wall surface. On all wall surfaces except the north, the electricity generated for 10 floors (from the 52th floor to the 61st floor wall surface) accumulation of power generation is the same as that generated for 30 floors accumulation on each wall surface. In addition, when the inclination angle of the array on the

roof surface was set at 15°, approximately 260,000 kWh/y of power was generated at 390 m above the ground.

Table 9. The power generation ratio at 390 m above the ground based on the reference height of 60 m above the ground . [%]
(Considering only the influence of aerological climate and shadow by surrounding building)

Roof plane (inclination angle setting)		Wall surface	
0°	+22.8	Entire wall (excluding North)	+30.7
15°	+25.5	South wall (azimuth angle 20°)	+35.7
30°	+26.8	West wall (azimuth angle 110°)	+10.4
90°	+28.7	East wall (azimuth angle 200°)	+44.1

Fig. 9. Comparison of the integrated power generation amounts. [kWh/y]

7 Primary energy reduction

7.1. Calculation method

From the cumulative power generation amount calculated in Section 6.2, the primary energy reduction for the supertall building 390 m above the ground was calculated. The calculation conditions are listed in Table 10. The unit of energy consumption is 1,949 MJ/m² with reference to the office applications of the "Tokyo energy saving carte 2015 results" (in Japanese) [8]. The primary energy consumption of the first floor was also divided among 66 floors (61 floors above ground and 5 floors below ground) of the entire building.

7.2. Calculation results

Fig. 10 shows the ratio of the primary energy reduction and primary energy consumption per floor while Fig. 11 shows the comparison of the primary energy reduction. The building size is large; the total primary energy consumption of the building is 950,000 GJ; and the primary energy consumption per floor is expected to reach

14,000 GJ. In the case of the 30 floors (from the 32th floor to the 61st floor) accumulation of power generation on the entire wall surface excluding the north, the primary energy consumption of 7,748 GJ can be reduced and it is possible to cover approximately 54% of the primary energy compared with the primary energy consumption of each floor. Compared with the same system capacity, because the primary energy reduction is more than 525 GJ for the 30 floors accumulation of power generation on the south wall surface than the 10 floors accumulation for the entire wall surface excluding the north, the superiority of the south wall surface for photovoltaic power generation is recognized.

At inclination angle of 15° for the roof surface installation, a primary energy reduction of 2,568 GJ is expected at an installation area of approximately 2,400 m². Compared with the primary energy consumption of each floor, it was able to cover approximately 18% of primary energy. In addition, when the inclination angle of the roof surface installation (system capacity 216 kW) was 15°, and in the case of the 10 floors accumulation of power generation on the entire wall surface excluding the north (system capacity 364.5 kW), the primary energy reduction was equivalent. Thus, in order to generate power on the wall equivalent to that generated on the roof surface, depending on the installation conditions, the system capacity of the solar cell module must be approximately 1.4 to 1.7 times greater and it is necessary to secure a wide installation area.

7.3. Comparison of environmentally conscious technologies

In the previous report, we calculated the energy-saving effect when adopting small wind power generation, free cooling, and cooling system utilizing outside air. We compared these environmentally-conscious technologies and photovoltaic power generation from the viewpoint of primary energy reduction.

Fig. 12 shows the comparison of primary energy reductions for each environmentally-conscious technology. The amount of primary energy reduced by photovoltaic system varies depending on conditions such as solar cell array footprint and system capacity, but the primary energy reduction is larger than that of wind power generation, free cooling, and the energy potential of the "height" of PV systems. Thus, it is considered a technology that effectively utilizes the potential of a supertall building.

Table 10. Calculation conditions of primary energy reduction.

Total floor area	490,000 m ²
Primary energy conversion coefficient (power generation)	9.76 MJ/kWh
Unit of energy consumption	1,949 MJ/m ²
Primary energy consumption (building as a whole)	955,010 GJ
Primary energy consumption (each floor)	14,470 GJ

Fig. 10. Percentage of primary energy reduction to primary energy consumption per floor. [%]

Fig. 11. Comparison of the primary energy reduction amount. [MJ/m²]

Fig. 12. comparison of primary energy reductions for each environmentally conscious technology. [MJ/m²]

8 Summary

We propose a new method to calculate the amount of power generated by a photovoltaic system, taking into account the shadows cast by surrounding buildings and the aerological climate. We also clarified the possibility of using the walls of supertall buildings with height of 390

m above the ground. Considering both effects, the power generation amount at 390 m above the ground is larger than that at 60 m above the ground depending on the installation conditions, although the influence of the shadows cast by surrounding buildings is greater than the influence of the aerological climate, with an increase of 46%. Like the target building in this study, the scale of the supertall building is extremely large; thus, the ratio of the power generation amount and the energy consumption amount tends to be small, but the effective use of the generated power is desired. In recent years, various efforts have also been made to realize ZEB. For example, in order to promote ZEB in a supertall building, it is effective to install photovoltaic systems not only on the roof of the building but also on the wall surfaces to increase the energy self-sufficiency of the building.

Variable notation

Z	Height from the ground [m]	U_Z	Air velocity at Z[m] [m/s]
Z_R	Reference height (=35.3 [m])	α	Roughness sub category (=0.35)
U_R	Air velocity at Z_R [m] [m/s]	$T_{(z)}$	Average temperature at Z[m] [°C]
Γ	Temperature decrease rate [K km ⁻¹]	$T_{(ZR)}$	Average temperature at reference altitude Z_R [m]
J_n	Normal direct insolation [MJ/m ² h]	J_{n0}	Solar constant [MJ/m ² h]
P	Atmospheric permeability	m	Atmospheric mass
η	Correction to altitude	m_0	Atmospheric mass at sea level
Z_E	Altitude [m]	h	Solar altitude (degrees)
t	Time [hour]	a	Correction to time
P0	District average (Yonago, Japan) of atmospheric permeability of science chronology [1971–2000] (in Japanese)		

- Meteorological Data System Co., Ltd., Separating direct and diffuse insolation and calculation of insolation on tilted surfaces (in Japanese), (2017)
<http://www.metds.co.jp/wp/wp-content/contents/documents/technical-writing/tyokusan.pdf>
- The National Research and Development Corporation Building Research Institute, Method and explanation of calculation and judgment in a manner conforming with 2013 energy saving standard (II House) (in Japanese), (2013)
- Mitsubishi Electric Co., Public / industrial solar power generation system Solar cell module specification list (in Japanese), (2017)
http://www.mitsubishielectric.co.jp/ldg/ja/energy/products/pv/module/advantage_03.html
- Bureau of Environment (Tokyo Metropolitan Government), Tokyo energy saving carte 2015 results (in Japanese), (2017)
http://www.kankyo.metro.tokyo.jp/climate/large_scale/data/karte.files/karte_1_20171213.pdf

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References

- ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems, (2015)
- Y. Onozaka, Study on Environment Conscious Technologies at 390 m above Ground (Part 1)Utilization of wind and thermal energy potential, *SHASE Convention Academic Lecture Summary Collection*, **10**,81(2017)
- S. Ishida, Method and apparatus for power generation prediction in photovoltaic power generation system (in Japanese), 2011-216604 (2011)
- K. Kimura, Exercise on fundamental theory of building equipment (in Japanese), Gakkensha (1970)